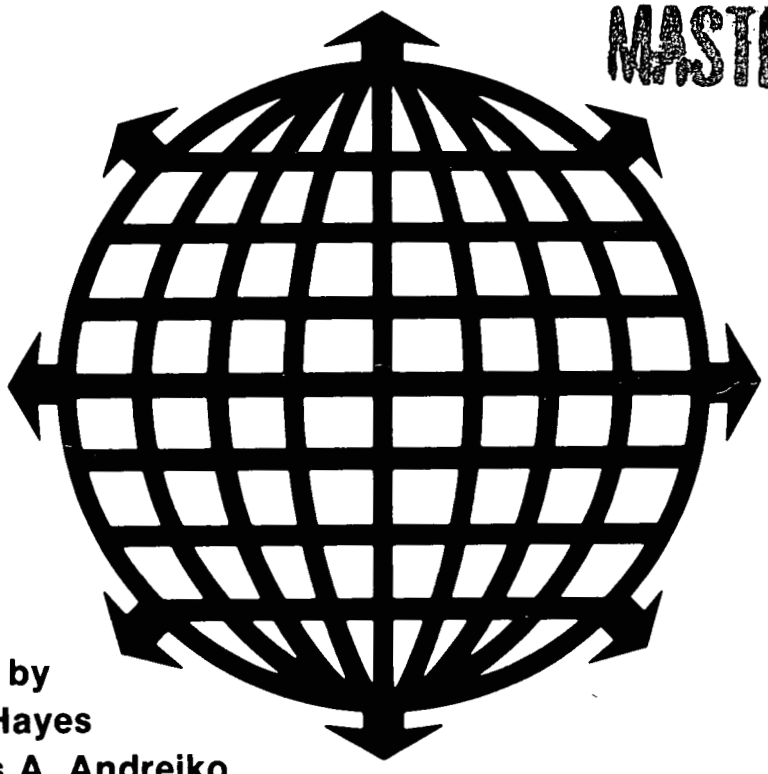
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# 8th National Passive Solar Conference

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MASTER



**Edited by**
**John Hayes**
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# Progress in Passive Solar Energy Systems

*Including the Proceedings of the National Passive Solar Conferences*

**Editors**

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Marlboro College

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**Volume 8**

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# FOREWORD

The First National Passive Solar Conference was held in Albuquerque in 1976. Coming back to New Mexico for the Eighth National Passive Solar Conference at Glorieta, we have closed the circle. We readily acknowledge the return to the roots of the modern passive solar renaissance as we reflect for a moment on progress in the field.

In the infancy of the solar field at Albuquerque, we were rediscovering the architecture of bygone eras, some of which dates to the beginnings of civilization. We made many mistakes: direct-gain spaces, many of which were overglazed, had intolerable temperature swings; early Trombe wall designs without window penetrations were cave-like; and our leaky, $5/ft$^2$ sunspaces performed poorly and were ill suited to $40/ft$^2$ houses.

In Philadelphia at the Second National Passive Solar Conference, we began to cut our teeth on more rational designs. We talked of rules of thumb, and the first methods for correlating climate and building thermal integrity with performance were proposed.

In San Jose at the Third Passive Conference, we took our first halting steps toward understanding how real buildings worked as we reported on the performance of the ever-expanding number of new installations. The rules of thumb took on a climate-specific nature, and people began to talk about cooling.

We held a second conference in 1979, the Fourth Passive Conference in Kansas City, where the infancy of our designs passed into adolescence as a larger number of architects joined us. We established the exciting Emerging Architecture series, and the early analytical tools emerged as well, although they were only used by researchers with main-frame computers.

Our work came of age in Amherst in 1980 at the Fifth Passive Conference, where the results of several years of DOE-sponsored research were reported. Terms such as SLR, BLAST, DEROB, TEANET, PEGFLOAT and Unutilizability became ingrained in our vocabulary. Here, builders participated in large numbers.

Our monitoring of real buildings matured in Portland in 1981 at the Sixth Passive Conference. The large-scale monitoring efforts were falling into place, and the earlier rules of thumb were being widely adopted by builders, designers and homeowners outside the movement. We began to see the results of community-scale projects.

Full maturity was demonstrated in 1982 at Knoxville at the Seventh Passive Conference, where we ran head-to-head with the World's Fair in the backyard of TVA, that giant monument to coal-fired and nuclear power. But we had already established our credibility: employees from TVA demonstrated with many conference papers that the utility is serious about energy conservation and solar energy. The U.S. Pavilion Exhibits at the World's Fair gave equal and even treatment to solar energy (though some attendees felt that it should have received top billing) as a giant sunsphere dominated the Fair's skyline. At least the world was taking notice of our efforts.

At Passive 83 we have achieved some of the wisdom of age. These proceedings contain the finest accumulation of papers in solar energy to date. Finally, we have widespread validation of our design tools. Analytical tools which handle commercial buildings and daylighting are increasingly accessible. Analytical tools for microcomputers are being developed and offered. The trade-offs between south glass and energy conservation can now be calculated easily. Materials research has paid off in products which make Trombe and water wall performance outstanding and which allow season-long net heat gains for north glass!

This maturity analogy should not suggest, however, that we have reached the zenith in passive solar research. There is more to be done. Our analytic and correlative tools need to be refined further and translated into usable, easily accessible design aids. Much more development is required with new materials: we need architectural integration of phase-change materials; we need to develop seasonal shading devices; and we need ways to convert beam radiation into usable daylighting, to name a few. And we are in dire need of design tools for passive cooling.

Thus, we bring to our passive solar birthplace in New Mexico a significantly maturer field than what we had seven short years ago. Unfortunately, though, we have not escaped one of the major national trends in recent years — towards poorer communications skills. We remain convinced that although some authors may be technically sophisticated they do need remedial training in syntax, punctuation, spelling and style. Unconvinced? Take the following test to see where you stand.

Select the correct answer in each of the following:

1. a. auxillary b. auxiliary c. auxilliary d. auxilary
2. a. aperature b. aperture c. aperiture d. apperature
3. a. acomodate b. accomodate c. acommodate d. accommodate
4. a. Balcolm b. Balcomb c. Balcolmb d. Balcome
5. a. Mazeria b. Mazaria c. Mazria d. Mazzria
6. a. trombe Wall b. Trombe Wall c. trombe wall d. Trombe wall e. Trombe' wall
7. a. KWH b. kwh c. Kwh d. kWh e. kWH
8. a. BTU b. btu c. Btu d. BTUs e. btus f. Btu's
9. a. MM b. mm c. Mm d. mM e. M f. m (for million as a prefix)
10. a. 80s b. 80's c. '80's d. '80s (for the decade)
11. a. It effects me. b. It affects me. c. It doesn't matter.
12. a. He effected a change b. He affected a change.
13. a. He sized the glazing, and developed a method.
    b. He sized the glazing and developed a method.
    c. He sized the glazing; and developed a method.
14. a. He sized the glazing; she developed the method.
    b. He sized the glazing, she developed the method.
    c. He sized the glazing she developed the method.
15. a. Tom, the solar entrepreneur bought the stock.
    b. Tom, the solar entrepreneur; bought the stock.
    c. Tom the solar entrepreneur, bought the stock.
16. a. Tom bought the stock; but he sold it immediately.
    b. Tom bought the stock, but, he sold it immediately.
    c. Tom bought the stock, but he sold it immediately.
    d. Tom bought the stock but he sold it immediately.
17. a. Doug said "use the LCR method".
    b. Doug said 'use the LCR method'.
    c. Doug said "use the LCR method."
    d. Doug said 'use the LCR method.'
18. a. Choose one of the following; mass, Trombe and water wall.
    b. Choose one of the following: mass, Trombe and water wall.
    c. Choose one of the following, mass, Trombe and water wall.

Scoring: (People who have not been recent ASES authors may skip 7, 8 & 9.)

0 Wrong — Expert
1 Wrong — Above Average
2 Wrong — Someone should proofread your papers
3 Wrong — A professional should proofread your papers
4 or More Wrong — Remedial work suggested

In the words of the authors of the proceedings, although in perhaps a slightly different context, we offer a bit of advice: if you must be obscure, "be obscure clearly." Also, you can avoid a lot of trouble in your designs by not being "half massed."

We wish to thank Barbara Bradley for her professionalism in putting these proceedings together.

John Hayes
Marlboro College

Dennis A. Andrejko
SUNY at Buffalo and
Andrejko & Associates

**Answers:** 1b, 2b, 3d, 4b, 5c, 6d, 7d, 8c, 9a, 10d, 11b, 12a, 13b, 14a, 15b, 16c, 17c, 18b.

# DEDICATION



This conference is dedicated to the memory of Peter van Dresser, who died in June of this year at the age of 74. He was a solar pioneer, a founder of the New Mexico Solar Energy Association, and one of the originators of the Annual Life Technics Conference.

Born in New York, Mr. van Dresser worked as an architect, economic researcher and conservationist in the East and Florida before coming to New Mexico. He was also a pioneer in the development of early rockets, helping to develop the first liquid fueled rocket motor in 1938. He was a charter member of the American Rocket Society, with many of his papers now being held by the Smithsonian Institution. He built his first solar houses in El Rito and Sante Fe, New Mexico in the 1950s and he led the Sun Dwellings Design Team efforts which resulted in the well-known passive test building at Ghost Ranch, New Mexico in the 1970s.

He was the author of many articles and books expressing a long-held decentralist philosophy. He taught and worked for gradual evolutionary change to occur in the smallest community unit, the village, and called for a more balanced relationship with the land as the basis for healthier growth.

His breadth of vision, his quiet tenacity, and his elegant expressiveness will be sorely missed.

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Release for Announcement in Energy Research Abstracts

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# PASSIVE SOLAR/GAS FIRED HEATING SYSTEM CHARACTERIZATION AND DEVELOPMENT

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## ABSTRACT

An overview of the work presently being performed in the REPEAT facility is presented. The physical characteristics of the building and the instrumentation are described. Some collected data are next presented and discussed. A brief treatment of parameter estimation ensues which concludes the paper with an example calculation.

## 1. INTRODUCTION

The REPEAT (REconfigurable Passive Evaluation Analysis and Test) facility is one of the DOE Class A test facilities in which detailed performance data are collected. These data are used to validate computer simulation codes and to define fundamental heat transfer parameters. The present research is being funded by the Gas Research Institute (GRI) and DOE and involves analyses of: (1) the integration of gas-fired heaters with passive solar buildings, (2) energy flow patterns in the REPEAT facility, and (3) some passive cooling options for buildings that are located in heating dominated (less humid) climates.

Increasing numbers of residential and small commercial buildings contain some type of passive solar energy design feature. Most of these buildings have electric resistance auxiliary heating. However, gas-fired furnaces with forced air distribution systems have some inherent advantages over competing electric baseboard heating systems. If properly designed, the hot air systems can control the air circulation patterns in a building and providing a greater level of thermal comfort. In addition, they can ensure higher air quality due to air recirculation.

We plan to investigate this problem through the mechanisms of data collection, parameter estimation and nodal simulation. The collection of data will enable thermal comfort correlations including themal radiation to be developed. By collecting data and performing parameter estimation both with and without gas fired heating, energy efficiency and comfort levels can be quantified in a relative sense, and economic maxima may then be sought. This paper presents our nascent efforts in the areas of data collection and parameter estimation.

The physical characteristics of the REPEAT facility are given. The instrumentation and the data acquisition systems are described. Some representative data are presented, followed by a presentation of the parameter estimation methods being used to analyze the data. The present results include the filtered parameters which globally represent the entire building. These parameters correspond to the parameters used in the LANL SLR design method, but are derived from experimental data instead of from computer simulations. Due to space limitations, the discussions of the specific instrumentation and parameter estimation methods [1-4] have been severely abbreviated.

## 2. THE BUILDING

The design philosophy for the REPEAT facility emanated from the following criteria: (1) separate testing could be performed on systems having extremes of building characteristics (e.g. high/low thermal capacitance, high/low glazing areas, etc.), (2) zone to zone energy transfer could be tested in a variety of configurations, (3) many different types of systems could be tested and (4) an instrumentation energy balance could be performed on the building. As the design of the building progressed, some of these goals were reduced in scope due to budget limitations, yet the building does meet these criteria to a high degree. Furthermore, the building is very similar to many large residential/small commercial passive solar buildings being erected presented as may be seen by viewing the physical characteristics of the building as given in Table 1.

The lower story was designed to have excessive thermal capacitance with 0.203m (8") of concrete in the floor slab and with 0.254m (10") of concrete in the basement walls.

The building is also earth-bermed on the north of the lower story which provides further thermal capacitance. The upper story is constructed of 0.0508 m x 0.152m (2 " x 6" ) stud walls 0.406m (16 ") on center with 0.152m (6" ) of fiberglass insulation between the studs and 0.0762m (3 ") of Styrofoam on the exterior of the studs. The facia is textured plaster with a medium brown pigment applied over the Styrofoam. This composite provides an R-5.28 $^{o}C-m^{2}/W$ (R-30 $ft^{2}$-hr-$^{o}F$/Btu) wall of low thermal capacitance. By insulating and sealing between the two floors, the extremes in thermal capacitance of systems may thus be tested. Alternatively, the flooring between the two stories may be removed and a system of representative thermal capacitance may be tested. The air may be left to mix between the two zones by natural convection, or it may be mechanically mixed by fan.

The system was designed with an excess of south glazing area to enable testing over the gamut of glazing areas by masking appropriate portions of the south windows. Another factor contributing to this decision was the observed overheating [5] that is apparently characteristic of passive solar systems in the summertime. It was felt that the Los Alamos design decision of a completely shaded glazing on the summer solstice at noon was not conservative enough and that a sage design process would be to increase the glazed area by expanding in the horizontal direction and then to increase the overhang. Thus, our geometry provides complete shading at solar noon from May 18 to July 25. A clerestory is also provided so that the effects of solar penetration into the north part of the building may be studied. For simplicity, the overhang/window systems on both floors and the clerestory are geometrically similar. There are also east and west windows which are presently masked for the initial tests. Finally, operable windows have been installed on the bottom of both floor glazings and the clerestory to provide ventilation when appropriate.

The design of such a large glazed area subjected to regularly occuring wind loads in excess of 100 mph necessitated the use of large square steel support columns and the cross-bracing thereof. The vertical steel on the south face was tied into horizontal H-beam girders, thus accomplishing the support of the movable and removable floor joists which support the 0.0254m (1 ") flooring sheets. Because the soil is bentonite clay, a large amount of reinforcing rod was used in the floor and walls. The slab floor is free-floating and the walls are supported by concrete columns poured down to the bedrock. A blower door was used to test the infiltration rate of the building. After performing repeated tests and applying additional caulking (about 50 tubes were used) the infiltration rate was found to be 0.07 air changes per hour at 4 Pascals, which is very tight. Great effort was expended to achieve this hiatus in order that air-to-air heat exchanges may be tested independently from the wind conditions.

A 6.6m high double width brick wall has been erected 2.9m behind the south glazings, thus providing an enclosed sunspace system. The top 0.6m remaining above the wall to the ceiling has been blocked off with an R-3.34 ($m^{2}-^{o}C/w$) (R-19 $^{o}F-ft^{2}$-hr/Btu) masonite wall; the lower vents in the wall have been blocked with Styrofoam. The brick are of different colors in order that varied testing may be performed.

## 3. THE INSTRUMENTATION

Presently, total horizontal, shadowband horizontal and total vertical solar radiation values are being recorded. It is also planned to place pyranometers both outside and inside the south glazing, facing both out and in. These instruments will be resituated at various heights and horizontal positions. In this fashion, we hope to perform an instrumentation solar energy balance on the building. This should circumvent the approximations inherent in all solar radiation processors, with are legion [6,7]. We also plan to mount sundry pyranometers inside the building upon various surfaces. This should enable the radiative energy transfer to be directly calculated as the surface temperatures will be known. To assess spatial variation errors will be difficult; it will nonetheless be attempted.

These detailed tests are to be performed in the "Mystery Room" which is thermally isolated from the remainder of the building with insulation and an excess of caulking. The Mystery Room is dedicated to separating radiative from convective heat transfer and occupies a floor area of 11.8 $m^{2}$ in the southwest corner of the lower floor. The north wall of the Mystery Room is the brick wall which has been insulated on the side away from the Mystery Room (as has the east wall) in order to isolate this test room from the remainder of the building. Presently, 100 channels of data from the Mystery Room are being logged by a combination HP-85/3497 on small cassette tape. This provides an areal density of instrumentation that is approximately 20 times that of the remainder of the building. In addition to internal and external pyranometers, there are shielded air temperature sensors, black globe temperature sensors, and embedded and surface thermocouples that provide data from the Mystery Room. The sensors for both the Mystery Room and the remainder of the building are enumerated by location and type in Tables 2 and 3.

Our plan is to perform flow visualization tests in order to qualitatively assess the flow field in the room. A 55 gallon drum

will be filled with smoke and then be allowed to come into thermal equilibrium with the room. Smoke can then be injected at low momentum rates at various locations without fear of disturbing the flow with thermal plumes. The optical acquisition of data will be accomplished with snapshots and video movie tapes.

A great deal of effort was expended to ensure that the data being collected are of the highest quality. Every sensor in the facility has been tested prior to installation. All of the pyranometers have been calibrated by NOAA prior to installation. Great care was taken to ensure that the thermocouple connections are isothermal, and that these wires are sufficiently well shielded. We estimate that the thermocouple data are accurate to $0.05^{\circ}C$. To this date, we have no confidence in the heat flux meters, so there have been only four installed as test instruments. Finally, tests indicate that the standard, double-shielded air temperature sensors may give errors of up to $1.5^{\circ}C$ when exposed to very strong sunlight ($1000\ W/m^2$). However, the data reported herein are not subject to these inaccuracies as the sunlight incident upon these sensors was much smaller than this value.

## 4. THERMAL PERFORMANCE DATA

The data collected from 5:15 a.m. (Mountain Standard Time) April the 11th through April the 18th, 1983, include two radiation and eight temperature values at 1/4 hour intervals. Weather data are included as total horizontal and total vertical solar radiation shown in Figure 1, and the ambient temperature which is shown as a solid line in Figures 2 and 3. Figure 2 also includes two separate thermal storage wall temperatures and a basement temperature. As can be seen from Figure 2, the thermal storage wall is close to isothermal. This was also observed to be the case for the basement. The large amount of thermal capacitance in the basement is reflected in the relatively steady temperature shown in Figure 2.

The sunspace is observed to be fairly isothermal from Figure 3 and is observed to substantially overheat during periods of strong sunshine. The north zone temperatures shown in Figure 3 are seen to follow the same pattern of fluctuation as the sunspace, yet the fluctuations are reduced in magnitude as expected due to the increased thermal capacitance and the small clerestory area.

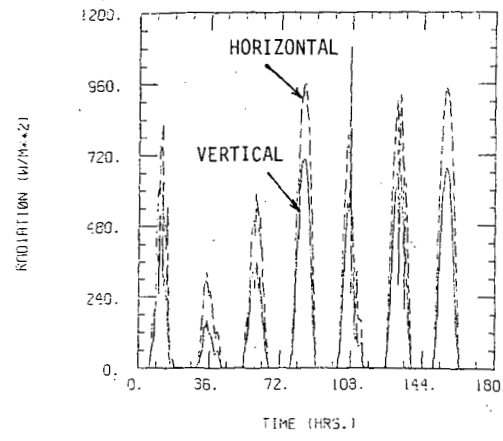



Fig. 1. TOTAL SOLAR RADIATION VALUES.

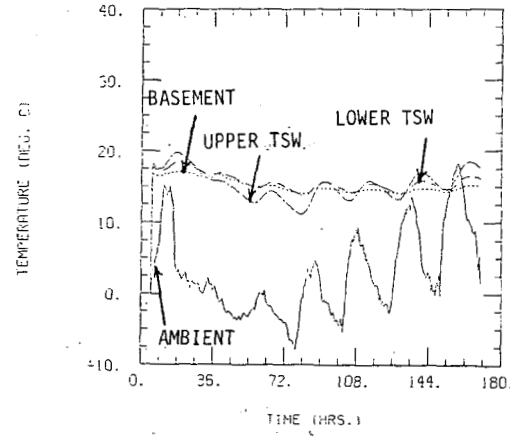



Fig. 2. AMBIENT, TSW AND BASEMENT TEMPS.

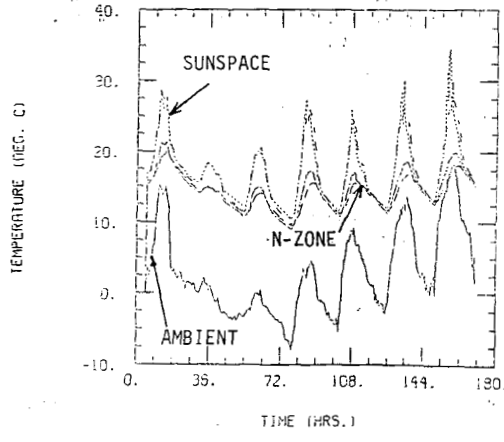



Fig. 3. AMBIENT, N. ZONE AND SUNSPACE TEMPS.

It is observed that the various portions of the building are performing exactly as the design philosophy dictates. It should therefore be possible to exercise a large variety of different physical situations by isolating various zones. Such selective testing will allow detailed testing of specific systems and components, and various thermal mechanisms.

The formulation of the sequential linear least squares algorithm is well-developed elsewhere [8,9] and will not be repeated herein.

Instead, the use of the technique will be presented by example. Suppose that j parameters $x_j$ are to be identified from the measured values A, which multiply the parameters and $y_k$, which appear separately. Mathematically,

$$A_{kj}\ x_j = y_k \qquad (1)$$

where k denotes the k'th measurement. The system becomes overdetermined when k becomes greater than j, and no general solution is then possible. Rather, the system must be solved for the parameters that satisfy some global criterion. It is convenient to choose this criterion to be the minimization of the L-2 norm of the errors in the parameters.

## 5. APPLICATION OF THE SEQUENTIAL LEAST SQUARES ALGORITHM

To illustrate the application of parameter estimation to heat transfer in building systems, a one-node thermal model will be applied to the average of the temperatures depicted above. In the future, we shall apply more detailed models to the data. However, the logical starting point is the simplest thermal model (i.e. one node).

To this extent, the seven interior temperatures depicted above are averaged at each discrete point in time to lump the spatial variations as follows:

$$\bar{T}\ (t) = \frac{1}{7} \sum_{i=1}^{7} T_i\ (t) \qquad (2)$$

The following one-node thermal model is adopted as consistent with this lumping:

$$m\ c_p \frac{d\bar{T}}{dt} = (UA)\ (T_\infty - \bar{T}) + S\ A_g \qquad (3)$$

To obtain a non-homogeneous linear set, equation (3) is divided throughout by $m\ c_p$. If the thermal parameters are considered as "effective" so that they are consistent with the model, they can no longer be calculated a priori, but are dependent upon a variety of factors including the quality of the model, the quality of the data, etc. These "effective" parameters may be estimated from the data through the application of a sequential least squares filter.

Thus, the parameters $x_j$ are seen to represent the effective values of

$$x_1 = (UA/m\ c_p)_{eff} = 0.0131\ (1/HR) \qquad (4)$$

$$x_2 = (Ag/m\ c_p)_{eff} = 0.0000404\ (^{\circ}C\text{-}m^2/W\text{-}HR) \qquad (5)$$

The right-hand side, $y_k$ is formulated as a central difference in time, and only data where $S > 0$ are included in the set. The convergence of the parameters is depicted in Figures 4 and 5 for $x_1$ and $x_2$, respectively. It is seen that there are probably enough data points in the set as the locally averaged values are observed to level off after about two days. However, the fluctuations observed after this time indicate that the one-node model is inappropriate as the building responds differently to the model during the course of the day.

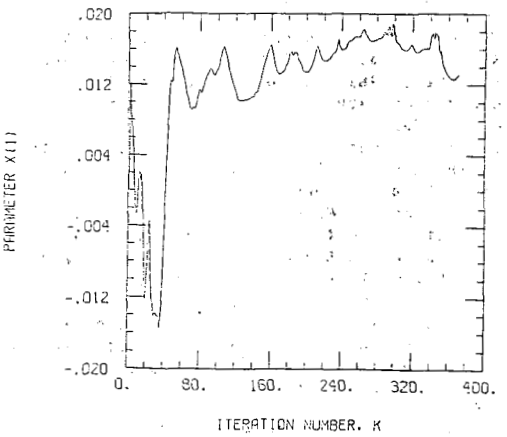



Fig. 4. PARAMETER 1 VS. ITERATION NUMBER.

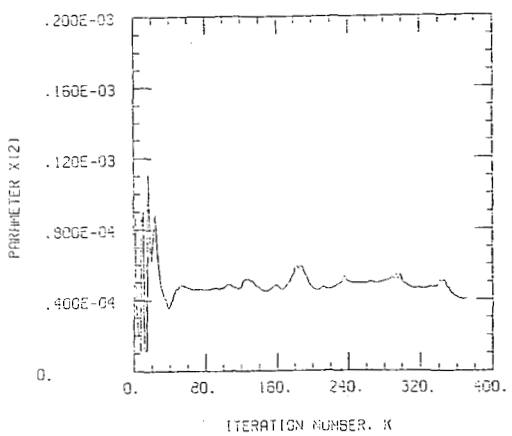



Fig. 5. PARAMETER 2 VS. ITERATION NUMBER.

$x_1$ as estimated from the data compares favorably with the value of 0.0089 (1/hr) as calculated from ASHRAE values. However, $x_2$ as estimated from the data is an order of magnitude smaller than the calculated value of 0.0011 ($^{o}C$-$m^2$/W-hr). This indicates that a one-node model for the building is inappropriate. To assess the nature of the error, a resimulation of the data was done using these estimated parameters. This is shown in Figure 6. The agreement is fair, considering the crude nature of the model.

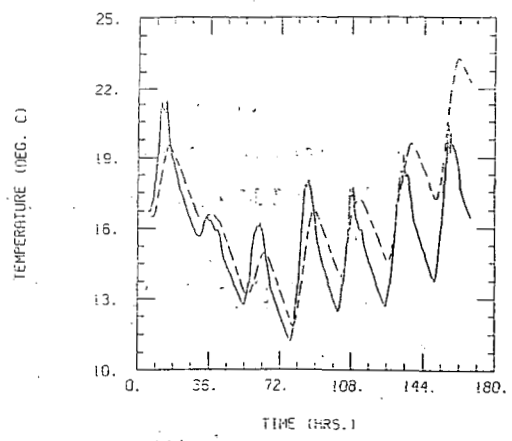



Fig. 6. CALCULATED AND MEASURED BUILDING TEMPS. SOLID-MEASURED, DASHED-CALCULATED

## 6. CONCLUSIONS AND RECOMMENDATIONS

The design philosophy of the very versatile REPEAT facility has been presented. A brief overview of the instrumentation was included, and this was followed by a discussion of the inherent inaccuracy in the overall sensor/data-acquisition system. Preliminary data indicate that the building is responding as expected in the various zones. The application of parameter estimation to a crude thermal model representing the entire building found the model to be lacking sufficient detail in the spatial discretization, however the number of data points appeared to be of sufficient quantity. Further studies should be much more interesting if more spatial detail is included.

## 7. ACKNOWLEDGEMENTS

We wish to acknowledge the following firms who have donated either labor or materials without which we would not be operating: Marvin Windows of Warroad, Minnesota, for the donation of all the windows used in the building, Dr. Benno Klank for use of the Enercorp Infiltrometer; the Des Champs Corp. (and Mike Scofield) for supplying the air-to-air heat exchangers at cost, Robco, Inc. of Denver, Colorado, for donation of the brick used in the thermal storage wall, and Soderberg Masonary of Fort Collins for donation of the labor to construct the wall. Funding for this work was provided by DOE (Contract # DE-AC02-80-CS-30259) and GRI (Contract # 5082-243-0728). We also wish to acknowledge Ed Flowers of NOAA in Boulder for calibrating the pyranometers. Finally, thanks to wonderful Donna for typing this on the usual short notice.

## 8. NOMENCLATURE

- $A$ - area of south glazing ($m^2$)
- $A^g_{kj}$ - kth row of coefficient matrix for the estimation of j parameters (various)
- $c$ - specific heat (J/kg-$^{o}C$)
- $m^p$ - mass (kg)
- $S$ - absorbed solar radiation per unit area of south glazing - calculated from a solar processor ($W/m^2$)
- $\underline{T}$ - temperature ($^{o}C$)
- $T$ - average temperature defined by equation (2) ($^{o}C$)
- $t$ - time (hr)
- $x_j$ - unknown parameters (various)
- $y^j_k$ - kth known value of the right-hand-side of equation (1) ($^{o}C$/hr)

### Subscripts

- eff - denotes effective
- i - pertaining to a measured temperature
- ∞ - ambient

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TABLE 1. REPEAT CHARACTERISTICS

Two story, large residential/small commercial building
Floor Area: 2560 $ft^2$
Volume: 29,360 $ft^3$
Passive Solar Features:
802 $ft^2$ of south facing glass including 173 $ft^2$ of clerestory, 8' thick concrete north, east and west walls on the lower story, 8' thick brick thermal storage south facing wall located 10' behind the south glazings forming an attached sunspace.
Energy Conservation Features:
Partial earth berming, R-30 stud walls, R-40 ceiling, double glazed windows, air-to-air heat exchangers, all openings sealed and caulked very well.

TABLE 2. INSTRUMENTATION

| | | |
|---|---|---|
| 1. | PYRANOMETERS | |
| | total horizontal - | 1 ea. |
| | total vertical - | 1 ea. |
| | shadowband horizontal - | 1 ea. |
| | behind clerestory - | 1 ea. |
| | behind 1st floor glass - | 1 ea. |
| | behind basement glass | 1 ea |
| 2. | GLAZING THERMOCOUPLES (TC's) | |
| | Inside - | 11 ea. |
| | Outside - | 11 ea |
| 3. | SHIELDED AIR TC's | |
| | N zone, 1st floor - | 6 |
| | N zone, Basement - | 6 |
| | Sunspace - | 18 |
| 4. | GLOBE TC's | |
| | N zone, 1st floor - | 6 |
| | N zone, Basement - | 6 |
| | Sunspace - | 18 |
| 5. | EARTH TC's | |
| | Under concrete slab - | 6 |
| | In berm, north of N. Basement Wall - | 4 |
| 6. | EMBEDDED TC's | |
| | Concrete Wall, Basement N-zone - | 20 |
| | Sunspace - | 10 |
| | Concrete Floor, Basement - | 10 |
| | Concrete Floor, Sunspace - | 25 |
| | Thermal Storage Wall - | 197 |
| 7. | HEAT FLUX METERS - | 4 |
| 8. | ENERGY (WATT-HOUR) METERS | |
| | Total Energy - | 1 |
| | Electric Baseboard Heat - | 1 |
| 9. | RELATIVE HUMIDITY | |
| | Sunspace - | 1 |
| | N zone, basement - | 1 |
| | N zone, upstairs - | 1 |
| 10. | SURFACE THERMOCOUPLES | |
| | Interior surfaces, 1st floor - | 10 |
| | Exterior surfaces - | 13 |
| 11. | SENSORS ON 2 m, WEATHER STATION | |
| | Ambient Temperature - | 1 |
| | Wind Speed - | 1 |
| | Wind Direction (ordered) | |
| | Relative Humidity - | 1 |
| | Total Channels Being Logged | 198 |

TABLE 3. INSTRUMENT LIST FOR THE MYSTERY ROOM

| | | |
|---|---|---|
| 1. | PYRANOMETERS | |
| | Surface Irradiation - | 6 |
| | Total Vertical, External - | 1 |
| | Total Vertical, Internal - | 1 |
| | Other - | 2 |
| 2. | SHIELDED AIR TC's - | 12 |
| 3. | BLACK GLOBE TEMPERATURE - | 12 |
| 4. | EMBEDDED TC's - | |
| | Concrete Floor - | 5 |
| | Thermal Storage Wall - | 20 |
| 5. | SHIELDED AMBIENT TC's - | 3 |
| 6. | GLAZING TC's | |
| | Internal - | 9 |
| | External - | 9 |
| 7. | SURFACE TC's - | 45 |
| | Total Channels Being Logged | 98 |

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# ANALYSIS OF VALIDATION DATA SETS IN THE CLASS A PERFORMANCE EVALUATION PROGRAM*

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## ABSTRACT

The primary objective of the DOE Passive Solar Class A Performance Evaluation Program is to collect, analyze, and archive detailed test data for the rigorous validation of analysis/design tools used for passive solar research and design. This paper presents results of the analysis and qualification of several one- and two-week data sets taken at three Class A test sites for the purpose of validating envelope and thermal-storage-energy-transfer processes in passive solar analysis/design tools. Analysis of the data sets consists of editing the measured data and comparing these data with simulated performance results using public-domain, passive solar analysis tools and a standard reporting format developed for the Class A program. Comparisons of the measured data with results using the DOE-2 computer program are presented.

## 1. INTRODUCTION

Under the DOE Passive Solar Class A Performance Evaluation Program, in progress since 1980, detailed hourly performance data are being collected, analyzed, and archived for the primary purpose of rigorous validation of analysis and design tools (both component models and complete tools) used for passive solar research and design. The Los Alamos National Laboratory, working closely with the Solar Energy Research Institute (SERI), is coordinating this effort.

The Class A program, originally outlined in a SERI report (1), has been developed and expanded as described in Ref. 2; SERI and the National Bureau of Standards (NBS) have been actively involved in the program since its beginning. Although the initial thrust involves test cells, small unoccupied test buildings, and a residence, the program is to be expanded later to include commercial buildings and other test facilities.

Validation of several public-domain, hour-by-hour computer programs is essential to instill confidence in the research community in their use for passive solar research and applications. Furthermore, because virtually all simplified design tools used by passive solar designers are based on correlations of results using the hour-by-hour programs, validation of these primary, reference programs is essential.

This paper presents results of the analysis and qualification of several one- and two-week data sets taken at three Class A test sites for the purpose of validating envelope and thermal-storage-energy-transfer processes in hour-by-hour passive solar analysis/design tools. Analysis of the data sets consists of checking, screening, and reformatting the data within the context of the validation methodology developed under the Class A program (3).

## 2. PROCEDURES FOR COLLECTION AND ANALYSIS OF TEST DATA

To check the usability and effectiveness of data sets and the empirical tests in the Class A validation methodology (3), we compared the measured data sets with simulated results using public-domain, passive solar analysis/design tools and a standard reporting format. To illustrate the data analysis procedures, we compared hourly space temperatures and auxiliary energy use with simulations using the DOE-2 building-energy-analysis computer program.

Data sets for full-program validation have been collected at several Class A passive heating test facilities; the representative data sets discussed here were collected at the SERI Validation Test House in Golden, Colorado; at the NBS Passive Test Facility in Gaithersburg, Maryland; and at the Lo-Cal House in Champaign, Illinois.

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Upon receipt of raw data tapes from a given site, the data were checked for accuracy and completeness, missing data periods were deleted or the missing data were filled in using average values for adjacent hours, or were correlated with known variables. The data were edited using a specialized input preprocessor for the DOE-2 program; this placed the measured weather data and building-operating data in a DOE-2 readable format.

Drawings and specifications of the facility, together with conversations with the site operators, provided detailed building-construction data and dimensions. Measured thermophysical property data were obtained wherever possible.

With this information and the measured site-weather data, we prepared DOE-2 input that reflected the description of the building and its operation during the one- to two-week period for which performance data were measured. DOE-2 was then run, generally for a single-week, continuous period; measured hourly temperatures and/or auxiliary-heating energy were then compared with the simulated results. The measured and predicted results were then compared and analyzed on an hourly and total-run-period basis. Summary data plots and statistics were prepared in a standardized format developed for the Class A program.

## 3. ANALYSIS OF EXAMPLE DATA SETS

Examples of the data-analysis procedures are given below:

### 3.1 SERI Validation Test House: April 1982 Data

A data tape from the SERI Validation Test House, for the period April 17-26, 1982, has recently been analyzed. The SERI Validation Test House, an unoccupied single-story frame house of approximately 93.5 $m^2$ (1005 $ft^2$) in floor area, is well insulated and tightly constructed. It includes a crawl space and an attic, and has substantial south-facing glazing for direct gain. A layer of bricks has been placed on the living room and south bedroom floors to provide thermal storage mass. A multizone tracer-gas monitoring system was used to take hourly infiltration measurements. Hourly weather and solar radiation data were also taken at the site. A detailed description of the building and its instrumentation is given in Ref. 4.

The period chosen for analysis was April 20-26, 1982, during which the auxiliary heating was controlled to maintain a 24.4°C (76°F) setpoint. First, a four-zone simulation was performed using DOE-2 with tabulated design values (5) for thermophysical properties and operating characteristics, but using weather data measured at the site. This represents the characteristic precision of input data available to an analyst familiar with the building, but not having measured property and operating data.

Figure 1 shows the weather patterns and a comparison of measured and predicted temperatures for the kitchen. Note that the temperature comparison is not particularly good, with an rms difference for the 168 hours of 3.4°C (6.1°F). This is primarily because a typical, residential, internal-heat-gain rate for a family of 4 (0.88 kW or 18,000 Btu/person-day) was used in DOE-2, whereas the measured value was significantly lower. However, results for the south bedroom are better, with an rms difference of 1.1°C (2.0°F). Similar results are obtained for the auxiliary-heating energy for the kitchen. DOE-2 overpredicts the auxiliary heating required; the rms difference for all the 168 hours is 0.31 kW, but with a strong overprediction bias.

Figures 2 and 3 show similar results, except that measured input values for selected thermophysical properties (wall and ceiling insulation, exterior-surface absorptances, window conductances, and ground reflectances) and operating characteristics (infiltration, internal heat gains, thermostat set points, and ground temperatures beneath the building) were used in the simulation. The comparison is improved to an rms temperature difference of only 1.15°C (2.1°F), and an rms auxiliary-heating difference of 0.03 kW.

A statistical summary of the predicted vs measured data for the case where measured input values were used is shown in Table I. Root-mean-square, mean, and maximum differences are presented for hourly space-air temperatures and auxiliary-heating energy, for each of the four zones: these are aggregated for the building as a whole for the auxiliary-heating energy. These results indicate excellent agreement in the temperatures, with rms differences typically about 1°C (1.8°F), and maximum differences about 2-3°C (3.6-5.4°F). Auxiliary heating for the building is typically predicted to within 0.4 kW on an hourly basis. Peak heating loads for the full-run period are predicted to within 9%.

### 3.2 NBS Direct-Gain Test Cell: October 1981 Data

A data tape has been processed for the October 20-26, 1981, period for the NBS Direct-Gain Test Cell. This single-zone 30.7 $m^2$ (330 $ft^2$) slab-on-grade test cell includes south-facing patio door units and a clerestory window for solar gain (6). Thermal mass is contained in the 10-cm (4-in.)-thick floor slab and in a 20-cm (8-in.)-thick, solid-core-concrete-block

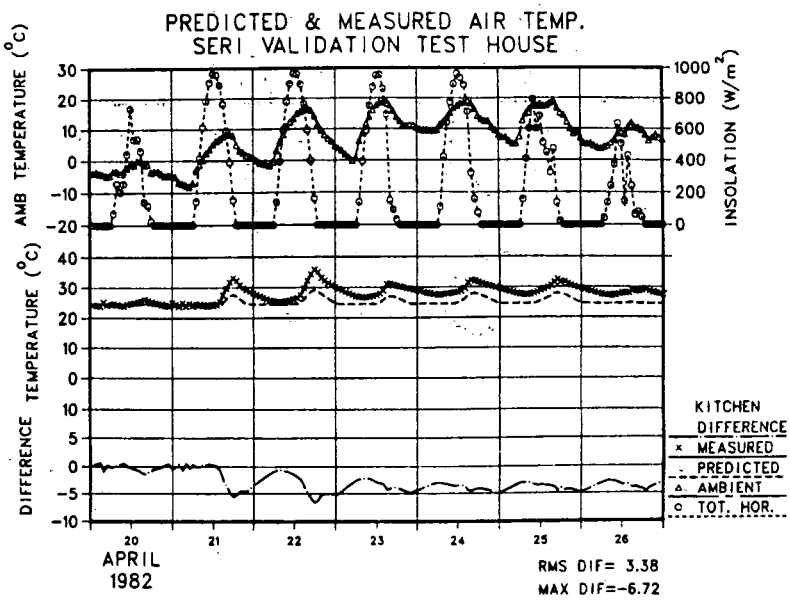



Fig. 1. Predicted vs measured space-air temperatures for the SERI Validation Test House--base care with tabulated input values.

thermal storage mass on the north wall. During the unoccupied October 1981 test period, the cell was operated in a floating temperature mode with no night insulation on the apertures.

DOE-2 input for the test cell was prepared using detailed drawings and specifications and measured properties for the concrete slab and concrete-block wall, and tabulated properties (5) for all other materials. Measured values of solar absorptances of exterior and interior surface materials, as well as infiltration and internal heat gains (measured on an hour-by-hour basis), were used for the DOE-2 input.

A comparison between measured space temperatures in the test cell and those predicted by DOE-2 is shown in Fig. 4. Note that the difference between predicted and measured temperatures is small except for the cloudy days of October 21-22 where DOE-2 overpredicts the space temperature. This difference is quantified by the 2.1°C (3.8°F) rms difference noted for the 168-h test period. The consistent bias we noted toward overprediction is likely a result of the fairly crude earth-contact heat transfer model in DOE-2 that does not properly account for the effective storage mass in the floor slab. Careful analysis also revealed that the low-intensity solar radiation measurements were not reliable.

### 3.3 Lo-Cal House: January-February 1982 Data

A data tape for an unoccupied 6-day period during late January and early February 1982 at the Lo-Cal House has also been analyzed. These data are from the 158-$m^2$ (1700-$ft^2$), single-family residence when the space temperature was controlled by thermostats on electric resistance heaters placed in several rooms of the house (7). The sun-tempered house uses moderate south glazing for direct gain, but contains no extra thermal mass.

The house was modeled as a single zone using the DOE-2 computer program with measured infiltration and internal gains, but with tabulated material properties. A comparison between measured space-air temperatures and those predicted by DOE-2, is shown in Fig. 5. For this case agreement is good, with an rms difference of 0.9°C (1.6°F).

## 4. CONCLUSIONS

Through our analysis of Class A data sets to date, we have concluded the following:

(1) Archivable data sets are available from

a. SERI Validation Test House: April 1982,

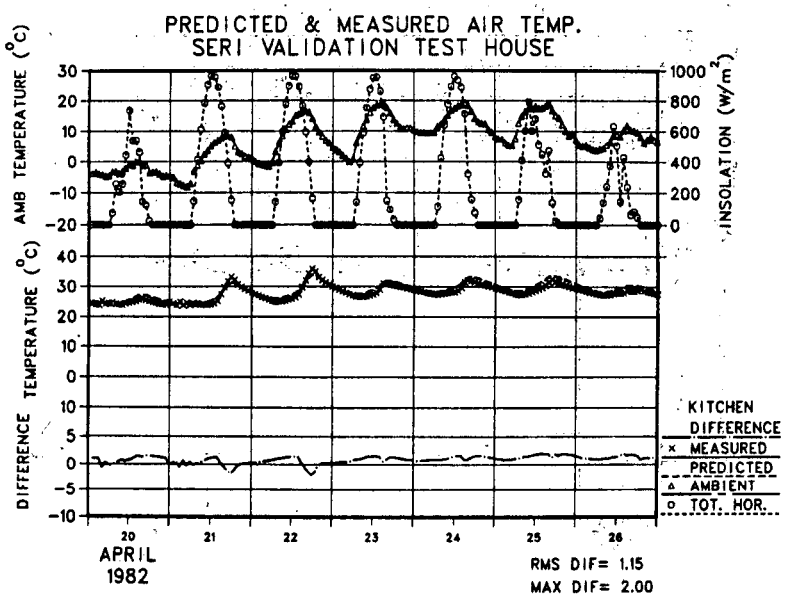



Fig. 2. Predicted vs measured space-air temperatures for the SERI Validation Test House--measured input values.

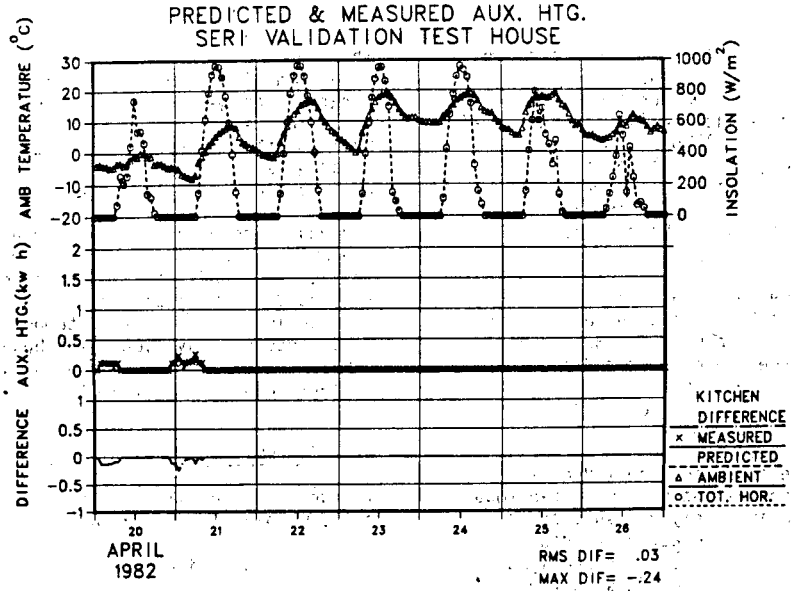



Fig. 3. Predicted vs measured auxiliary-heating energy for the SERI Validation Test House--measured input values.

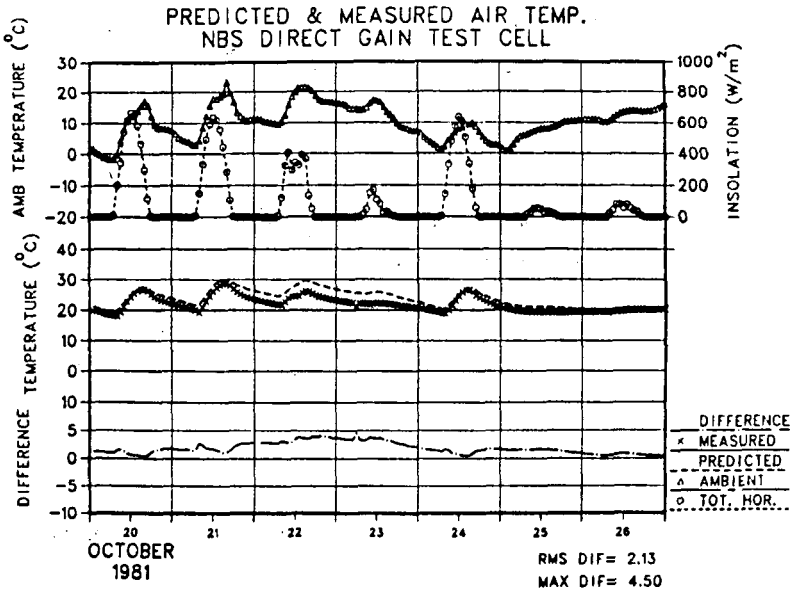



Fig. 4. Predicted vs measured space-air temperature for the NBS Direct-Gain Test Cell--measured input values.

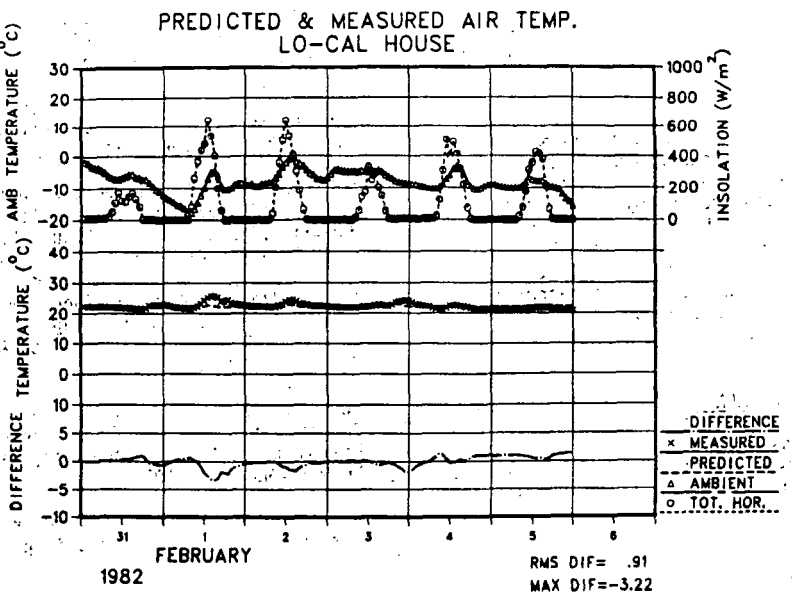



Fig. 5. Predicted vs measured space-air temperature for the Lo-Cal House--measured input values.

TABLE I

SUMMARY STATISTICS FOR PREDICTED/MEASURED COMPARISON
FOR SERI VALIDATION TEST HOUSE
(APRIL 1982 DATA WITH MEASURED INPUT VALUES)

| Zone | Hourly Temperature Difference (°C) | | | Hourly Auxiliary-Heating Difference (kW) | | | Peak Heating-Load Difference (%) |
|---|---|---|---|---|---|---|---|
| | rms | mean* | max | rms | mean* | max | |
| Kitchen | 1.15 | 1.03 | 2.00 | .03 | .01 | -.24 | -42 |
| Living/Dining Room | 1.01 | .72 | 3.17 | .17 | .12 | -.51 | -9 |
| South Bedroom | .79 | .53 | 2.61 | .11 | .08 | -.29 | -2 |
| North Bedroom | 1.23 | .94 | 3.22 | .20 | .14 | -.73 | -12 |
| Building | | | | 0.43 | 0.32 | -1.28 | -9 |

*Mean absolute difference.

b. NBS Direct-Gain Test Cell: October 1981,

c. Lo-Cal House: January-February 1982.

Several other Class A data sets have been taken but have not yet been analyzed.

(2) A standard Class A reporting format for predicted vs measured hourly space-air temperature data, and for hourly and total-run-period, auxiliary-heating energy data, has been developed. This reporting format is highly useful for quantifying predicted vs measured comparisons and for facilitating comparisons among different sites.

(3) The predicted vs measured comparisons shown in this paper provide a preliminary validation of the envelope and thermal-storage-energy-transfer processes in the DOE-2 building-energy-analysis computer program. For a well-controlled test building, rms temperature differences of about 1°C (1.8°F) can be expected over a 1-week run period.

## 5. ACKNOWLEDGEMENTS

The expert assistance of G. S. Lazarus in running the DOE-2 computer program and preparing the output plots is gratefully acknowledged.

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(7) "Lo-Cal House Site Handbook," Los Alamos National Laboratory report in preparation.

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# RESULTS FROM THE PALA PASSIVE SOLAR PROJECT

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ABSTRACT

The Pala Passive Solar Project consists of a set of eight test buildings devoted to side-by-side testing of passive concepts. Each of seven of the buildings tests a major passive solar feature with the eighth building of conventional design. The two room test buildings are fully instrumented and have been in continuous operation since early 1981. Some of the buildings' special features and construction details are presented. Conclusions drawn from the project during both winter and summer are discussed along with some examples of typical data from the project.

## 1. INTRODUCTION

The eight test buildings of the Pala Passive Solar Project are located at a site approximately 50 miles northeast of San Diego. The project is funded by San Diego Gas & Electric Co. and Southern California Gas Co. and is operated by Solar Energy Analysis Laboratory.

The project has four main goals:

- Side-by-side comparison of major passive solar concepts in two-room buildings.
- Demonstration of design elements to builders, architects and homebuyers.
- Experimental validation of computer models and design methods.
- Investigation of the interface between passive buildings and electric and gas utilities.

Construction was completed in early 1981 and operation will continue at least until the end of 1983. Some future plans will be discussed below.

Many of the project's goals have already been met. Comparisons among various passive features have improved our understanding of their advantages and disadvantages in this region. More than 1000 visitors to the site have (almost without exception) been very supportive and approving of the project, and numerous architects and builders have indicated plans to include passive solar features in their future projects. The project has tied in nicely with our work on incorporating a passive design method into city and county building codes so that a successful response to passive solar opportunities would be required in all new residential construction.

Test buildings in the project were designed to be intermediate in size compared to most previous passive solar projects. The two-room buildings are large enough to display heat transfer characteristics similar to those occurring in real houses, while retaining the control and some of the geometric simplicity of small test cells. Data from occupied houses, while benefiting from realism, do not in most cases allow drawing of generally applicable conclusions.

In order to facilitate comparisons among the buildings and demonstrate the concepts in a familar setting, construction is wood frame, concrete slab on grade, with carpeted floors and aluminum frame windows--all standard for Southern California. The test buildings are identical except for where necessary to incorporate the passive features to be tested. All buildings have east-west interior walls (equipped with a standard interior doors). Exteriors are stucco; interiors are drywall. Walls are insulated to R-11 and ceilings to R-19. The small windows in each building are single glazed, but large solar windows are double glazed. All these features were chosen to comply with state mandated energy conservation requirements in this climate.

The general layout of the test buildings at the site is shown in Fig. 1. Buildings which require south wall solar access are located in the south row and are unaffected by obstructions throughout the year.

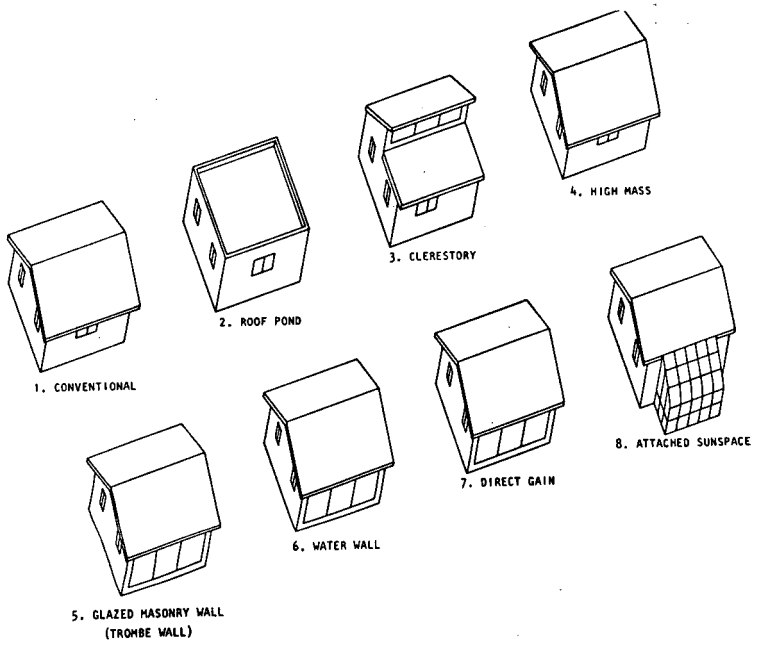



Fig. 1. Pala Project Buildings

TABLE 1. Building Measurements

| Building | Interior Floor Area ($ft^2$) | Major Solar Aperture | Window Area ($ft^2$) South | West | East | North |
|---|---|---|---|---|---|---|
| Conventional | 267 | None | 9.5 | 9.3 | 9.3 | 9.5 |
| Roof Pond | 256 | Horiz. Water Bags (253.5 $ft^2$) | 9.5 | 9.3 | 9.3 | 9.5 |
| Clerestory | 262 | Clerestory Windows (37.2 $ft^2$) | 46.5 | 9.3 | 9.3 | 9.5 |
| High Mass | 255 | None | 9.5 | 9.3 | 9.3 | 9.5 |
| Trombe Wall | 252 | TW Glazing (104.5 $ft^2$/54.2 $ft^2$) | 0 | 9.3 | 9.3 | 9.5 |
| Water Wall | 267 | Water Wall (88.2 $ft^2$) | * | 9.3 | 9.3 | 9.5 |
| Direct Gain | 268 | Large South Windows | 88.2 | 9.3 | 9.3 | 9.5 |
| Greenhouse | 267 | Attached Sunspace | 0 | 9.3 | 9.3 | 9.5 |

*Some south direct gain through and between water tubes.

| Building | Added Thermal Mass |
|---|---|
| Conventional | None |
| Roof Pond | 5 in. Water Bags (253.5 $ft^2$) |
| Clerestory | 8 in. Concrete Block Wall (127.3 $ft^2$) |
| High Mass | 4 in. Exterior and Interior Walls |
| Trombe Wall | 12 in. Trombe Wall (127.3 $ft^2$/63.7 $ft^2$) |
| Water Wall | 12 in. Tanks (48.8 $ft^2$) & Five 12 in. diam. by 7.8 ft Tubes |
| Direct Gain | 8 in. South Room Slab & 8 in. Interior Wall (107.6 $ft^2$) |
| Greenhouse | 8 in. Concrete Block Wall (79.2 $ft^2$) |

Some building measurements of interest are shown in Table 1. Window areas given are for glass area only. The large south solar apertures listed for the south row buildings do not represent our idea of proper sizing. They were intentionally oversized so that experiments covering a full range of possible sizes could be conducted by simply blocking parts of the south walls. For example, one set of experiments has looked at approximately half-sized Trombe walls.

Also shown in Table 1 is a listing of thermal mass which was included in the design of each building above the thermal mass of the conventional building.

Individual test buildings will not be discussed in detail, but certain features of a a few of the buildings will be shown as examples of the scope of the project. A schematic view of the clerestory building is shown in Fig. 2.

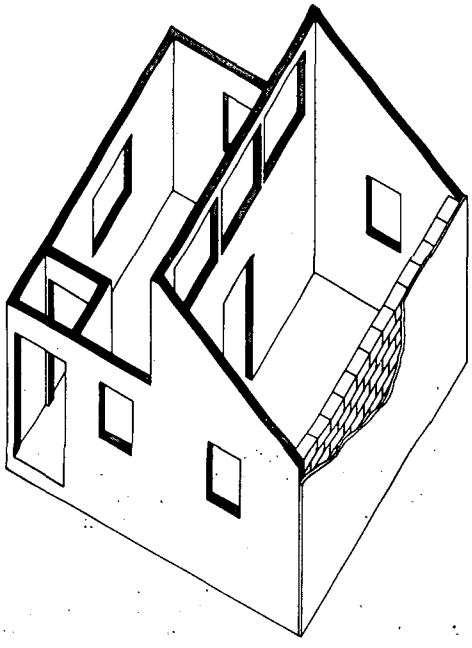


Fig. 2. Clerestory Test Building

Note the small "air lock" next to the exterior door. This double door arrangement allows entering and exiting the building without a large data-disrupting interchange of inside and outside air in the relatively small buildings. All test buildings in the project are equipped with air lock doors.

The exterior door in the clerestory building is located in the southeast corner as shown to avoid interference with the north mass wall. In all other buildings, exterior doors are in the northeast corner.

A section view of this building is shown in Fig. 3. The geometry of the clerestory windows with overhang and massive north wall was chosen to maximize winter heating but cut off all sunlight during the summer. The flat roof on the south room is covered with white gravel to improve reflectivity.

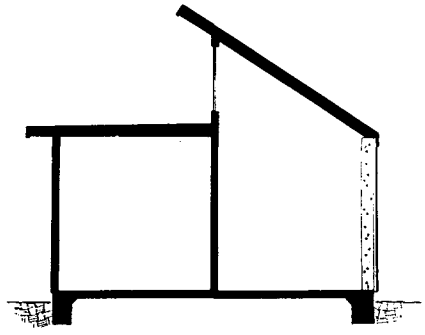


Fig. 3. Clerestory Test Building

The Trombe wall test building is shown in Fig. 4. The east half of the wall is solid concrete and the west half is solid grouted concrete block. Interior wall and door are typical of the test buildings.

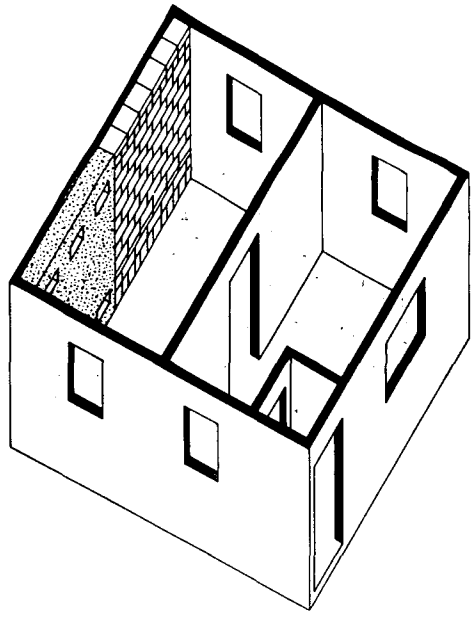


Fig. 4. Trombe Wall Test Building

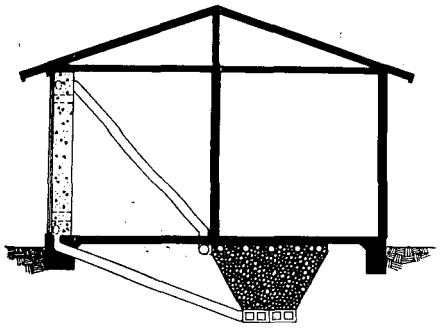


Fig. 5. Trombe Wall Test Building

Some of the other features of the Trombe wall building can be seen in the section of Fig. 5. Ducts allow air circulation from the glazing space through a vertical feed rock bed located under the north room. Many of the features of the test buildings (including the separation into north and south rooms) are intended to investigate heating of rooms which are remote from passive solar elements. In the Trombe wall building, air can be circulated from the top outside surface of the Trombe wall through the rock bed and return to the bottom of the wall. Heat flow from the rock bed is by passive conduction through the overlying floor slab.

The direct gain and greenhouse buildings are also equipped with north room underfloor rock beds. Different horizontal floor designs were used in the two cases.

The Trombe wall is also equipped with vents (normally plugged) to allow direct heating of south room air. An exterior, movable, insulating, and reflective door (not shown) can also be placed in operation.

The water wall test building is shown in Fig. 6. The east half of the water wall consists of specially fabricated steel tanks and the west half is translucent fiberglass tubes. In operation with the west half, there is considerable direct solar gain into the south room, through and between the tubes. For this reason, the south room floor of the water wall building is covered with ceramic tile. Likewise, the south room floor of the direct gain building is covered with tile. The direct gain building is identical to the water wall building, minus the water tanks and tubes.

All floors, except the two mentioned above, are covered with typical pads and carpeting. For certain special experiments, the carpet has been removed. These include comparisons of heat flow from underfloor rock beds when carpet and pad is in place and when they are removed and the floor is bare slab.

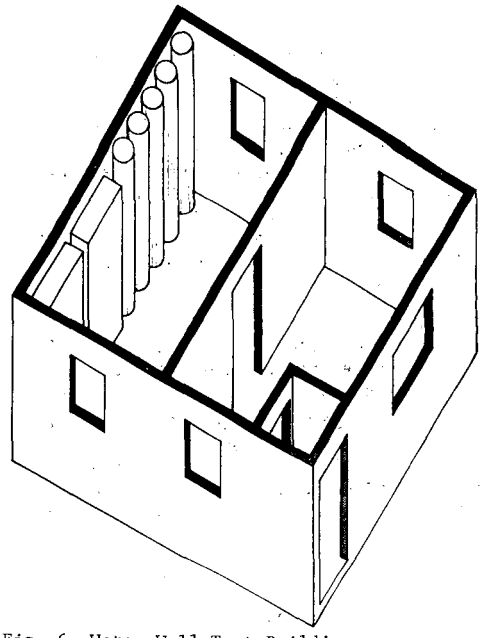


Fig. 6. Water Wall Test Building

## 2. INSTRUMENTATION

The data-acquisition system at the site monitors approximately 120 temperatures and weather parameters. Sensors are connected through a cabling network to Hewlett Packard scanners and digital voltmeter, which are under control of a small computer (North Star). Building temperatures which change slowly are sampled every 20 minutes. Other temperatures and weather and solar radiation measurements are taken every minute and averaged into 20 minute values.

Readings are displayed on an on-site terminal and transferred to floppy discs for permanent storage. One disc stores 9 1/2 days of data (180 kbytes) using special coding for the 8640 readings per day.

All temperature sensors are platinum resistance elements, individually calibrated and built into stainless steel tubes. Two temperature sensors are placed near the center of each of the two rooms in each building. One is inside a black plastic sphere and measures globe temperature, the other is in a shiny metal sheath and measures air temperature. In addition to these 32 sensors, other temperatures sensors are placed in locations of interest in the various buildings. Overall accuracy of temperature measurements is about 0.03 °F.

Total solar radiation is measured by Eppley PSPs (horizontal and south vertical); direct normal radiation is measured by a tracking Eppley NIP. Wind speed and direction are also recorded.

Auxiliary heating and cooling for the test buildings are provided by a circulating water system. Each building is equipped with a fan-coil unit, controlled by a wall thermostat (which allows timed setbacks). Energy demand in each building is determined by the temperature drop across the fan-coil and the water flow rate through the system. One nice feature of this design is that the same system supplies summer cooling by a simple changeover from primary hot water heater to water chiller.

## 3. HEATING SEASON RESULTS

The great quantity of data from the project prevents a complete discussion here, so only some specific examples will be cited. Also, preliminary conclusions will be discussed.

Room temperature data (north and south room air temperatures are averaged) for the three direct gain type test buildings are shown in Fig. 7 for a typical two day winter period. All data shown below are from times in which the buildings were "free-running" (no auxiliary heating or cooling). 2-6-82 was sunny and 2-7-82 was mostly cloudy. Note that ambient was cool overnight, but warm in the afternoon. Large ambient temperature swings are characteristic of the climate at the site--a favorable feature to help elucidate dynamic building response.

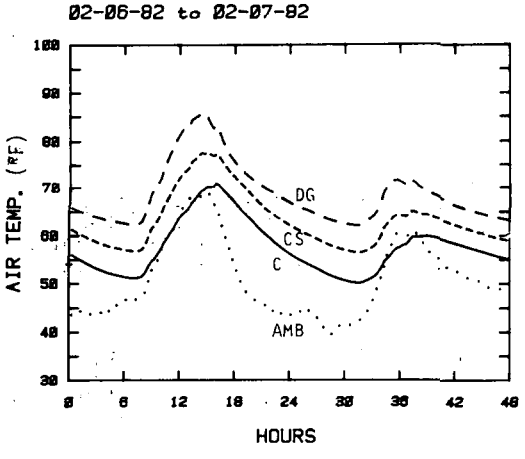



Fig. 7. Typical Heating Season Results for Direct Gain, Clerestory, and Conventional Test Buildings

Behavior of the three buildings is easily understood considering the areas of their south windows (see Table 1). Temperatures are fairly parallel indicating that thermal mass in the direct gain and clerestory buildings keep temperature swings modest even in the presence of greatly increased solar gain.

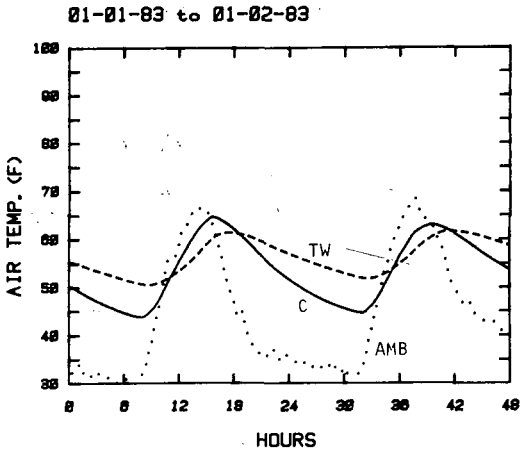



Fig. 8. Typical Heating Season Results for Trombe Wall and Conventional Buildings

In Fig. 8, the time lag associated with the Trombe wall is clearly apparent. Overnight minima in the Trombe wall building are 7-8F higher than in the conventional building. These and subsequent data apply to the half sized Trombe wall (see Table 1).

Consider a building's 24 hour average temperature minus the 24 hour average ambient temperature. In the absence of solar gain (or any other heat inputs), this "temperature gain" is zero. In the presence of solar gain, it is a good measure of solar heating. Gain on a typical winter day is shown in Fig. 9 for each of the buildings (the roof pond was not operable at this time). Gain values for sunny days were compared and it turns out that a simple linear correlation closely fits the results. With an offset of 7°F (solar gain with zero south window area), gain values are proportional to south window area for every building (Trombe wall and greenhouse buildings fall lower because Trombe walls are not as efficient as windows).

Another good measure of building behavior is temperature swing, shown in Fig. 10 for each of the buildings and ambient. It should be noted that reduced temperature swing (greater thermal mass) is not always desirable. The high mass building exhibits such a low temperature swing that it is hardly ever comfortable in the winter, while the conventional building (with the same average solar gain) is at least comfortable for a few hours on sunny days. Generally, of course, thermal mass is desirable, and is increasingly desirable in the presence of increased solar gain.

The roof pond building can achieve exhibits excellent heating perfor mance. Sunny day gain values vary from 15-°F through the winter and spring. Difficulties with the building have been in achieving reliable operation of the insulating roof panels.

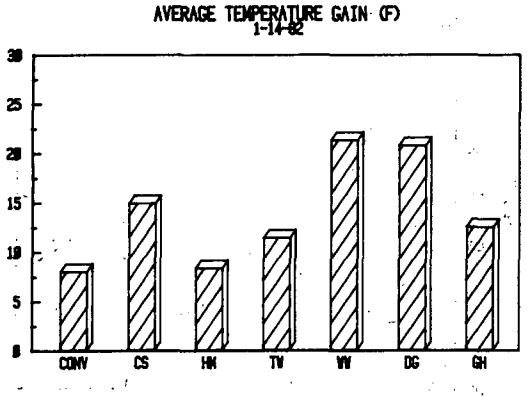



Fig. 9. Gain on Typical Winter Day

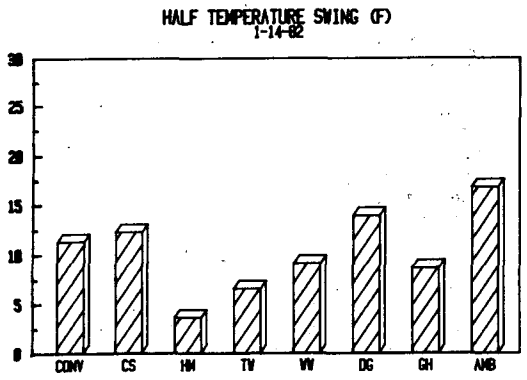



Fig. 10. Half Temperature Swing
= (max - min) /2

## 4. COOLING SEASON RESULTS

Southern Californ[illegible]pically experiences cool springtime weather, with a few periods of excessive heat in the fall. Fall periods with solar geometry identical to cool spring periods can exceed 90°F and therefore, movable shades are almost a necessity in large direct gain designs. Building behavior on two typical sunny days is shown in Fig. 11.

Note that in late June, solar gain values for the passive buildings do not significantly exceed the solar gain value for the conventional building. An exception is the greenhouse which accepts considerable horizontal sunlight. Greenhouse venting, not in operation at this time, greatly reduces mid-summer overheating in the greenhouse building.

Exact south orientation and small overhangs protect the buildings during early and mid-summer periods, but in the fall, building geometry cannot know whether or not heating is needed, with building gain values at winter magnitudes. Subsequent experiments include venting, shading, and rock-bed charging to help control building overheating.

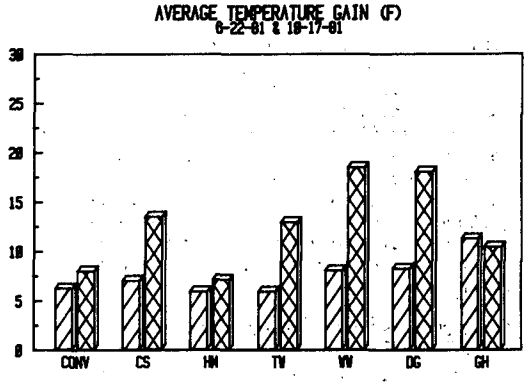



Fig. 11. Gain on Typical Summer Day (left bars) and Fall Day (right bars)

When operating properly, the roof pond building can achieve very low (or negative) "gain" values. That is, keeping the insulating doors open at night, but closed during the day, can dump more heat than is absorbed by the building during daylight hours.

## 5. FUTURE WORK

Experiments at the test site, most of which have been completed, include auxiliary heating and cooling (normal and off-peak), movable insulation, venting, room-to-room, heat transfer, rock bed charging and discharging, roof pond glazing effectiveness, ground mounted reflectors, and indirect evaporative cooling of the water wall.

A program of comparing measured results to simulation analyses (initiated by Anthony Sebald at the UCSD Energy Center) continues. The general conclusion of this work so far is that an inordinate degree of caution and circumspection is required before either handbook values of heat transfer coefficients are believed or models are applied to situations different from those that "validated" the method.

Future plans at the test site include possible construction of an adobe test building and a novel interior water wall building with an attic mounted parabolic reflector.

## 6. ACKNOWLEDGEMENTS

The author would like to thank Jeff Sherman for his exemplary work on the project, Judy F.L. Clinton, who designed the buildings and prepared the building drawings, Robin Taylor, Jim Miles and Eric Pulliam of SDG&E and William Wong and Michael Eaves of So Cal Gas, for their continued interest and support, and Anthony Sebald, Joseph Perry, and George Webb for many valuable discussions.

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# A GENERALIZED MODEL FOR PASSIVE SOLAR DIRECT GAIN

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## ABSTRACT

The correlational model for direct gain developed by the Los Alamos Scientific Laboratory group on Passive Solar Systems, was generalized.

While maintaining the general form of the predictive equations the new model, the "Predictive Model for Direct Gain" (PMDG) replaces the original Constants, applicable to the different "reference" cases, by functions depending on the thermal properties of the building and/or the components of the solar system.

By this transformation the LASL model for direct gain becomes a generalized one. The new model predict the performance of buildings heated by direct gain with any heat capacity, glazing and night insulation as functions of their thermo-physical properties and the climatic conditions.

## 1. INTRODUCTION

The LASL correlational formulas for predicting the performance of passive solar heating systems (1, 2) are widely utilized in many countries and they provide easy to use design tools. An experimental validation study (3) has found good agreement between the auxiliary heating computed by the LASL model and the measured values.

The LASL model provides a set of general formulae for predicting the performance of various types of passive solar heating systems. The formulas were generated for a number of "Reference Designs" and contains a number of "Constants" which have to be inserted in the general formulas. Different "Constants" are specified within any given energy system for different "Reference" buildings. By this structure of the model it can be strictly applied only to buildings and energy systems which conform, more or less, to the reference designs.

However, the variations in the values of the constants for the different "reference" buildings represent the effects of the various levels of heat capacity and/or glazing properties.

A set of such formulae has been developed (4) which gives very close agreement with the values of the constants in the LASL model for buildings identical to the reference buildings which are given in the original model.

With this transformation of the constants into functions the LASL model for direct gain has become a generalized one, applicable to any building with a Direct Gain passive heating.

## 2. SUMMARY OF THE LASL MODEL FOR DIRECT GAIN

To provide a starting point, the predictive formulae for the SSF and the indoor temperatures expected in buildings heated by solar direct gain, as presented in Ref. 1 and 2 are reviewed.

### 2.1 The Formulae for the Solar Saving Fraction

The predictive general formula developed at LASL for the SSF (2) is SSF = 1-(1-F)K
where:
$K = 1 + G/LCR$,
$F = B-C \cdot \exp(-D \cdot X)$, $X > R$,
$F = A \cdot X$ , $X < R$.
If $F > 1$, then set $F = 1$
$X = (S/DD)/(LCR \cdot F)$.

Where:
S = monthly solar radiation penetrating the glazing
DD = Degree Days,
LCR = building heat load coefficient collection area.

### 2.2 The Formulae for the Auxiliary Energy Consumption (2)

The auxiliary energy consumption (monthly) is computed by:

Aux = (NLC) (DD) (1-SSF)
where:
Aux = Auxiliary energy (Btu/month),
DD = Monthly Degree Days (see discussion later on),
NLC = Net load coefficient (without the solar element).

The constants A, B, C, D, G and R are given as descrete values for different design details of the building (its thermal storage capacity, the nominal mass thickness, the mass-to-glazing area ratio, the number of glazings and the night insulation conditions.

## 3. THE DERIVATION OF THE FORMULAE FOR THE "CONSTANTS"

In order to develop the formulae for computing the various constants, the relationship between each one of them (A,B,C,D,G,R) and various design details have been examined.

When a clear relationship was apparent between a given constant and a parameter of the building, or the solar glazing, a formula was derived to compute this "constant" as a function of the relevant parameter.

When such relationship was not clearly apparant, a formula was derived so as to yield an "SSF" close to the value computed by the LASL model for the same system design.

### 3.1 The "G" Constant

The "G" constant is applied in order to transform calculations based on the "net" heat loss coefficient to a new basis of the total loss. Examination of the variations of the "G" constant among the various types of buildings and glazing, with and without night insulation, suggests that it represents the effect of the values of the glazing total heat loss coefficient during the night hours, $U_g^{night}$, including night insulation when it is provided.

Expressing the specified "G" values as a function of this factor, by a linear formula, seems to provide close approximation to the values given in Table 2, namely:

$$G = 17 \times (U_g \text{ at night}).$$

### 3.2 The "A" and "R" Constants

With small values of "X", i.e., low solar gain relative to the heat demand, all the penetrating radiation is actually utilized so that the "F" and "SSF" increase linearly with "X". The "A" constant then represents the slope of F vs. X for each building type. The "R" constant is the limit of this "linear zone" in terms of the "X" value.

The original values of the "A" and "R" constants on the LASL model for the various "reference" buildings do not form clear mathematical relationships with the heat capacity of these "references." A general pattern of increasing values of both "A" and "R" with the heat capacity is evident buy these trends could be expressed mathematically only by complex functions.

Therefore, in the case of these two constants, linear functions were developed which have yielded an overall good agreement with the SSF values predicted by the LASL model for the "reference" cases.

Two separate formulas were derived for computing the "R" and "A" values: one for buildings without night insulation over the glazing, and the other for buildings with any night insulation. The effect of the insulation value itself is expressed by the "G" value, as discussed above.

For building without night insulation:
$R = 0.5 + 0.001 * H$
$A = 0.4 + 0.00075 * H \; ; \; A > 0.53$

For buildings with night insulation:
$R = 0.65 + 0.0006 * H$
$A = 0.48 + 0.0005 * H \; ; \; A > 0.56$

When H (heat capacity) is per unit area of the glazing ($Whr/Cm^2$). Heat capacity of 150 $Whr/Cm^2$ is the lowest limit of the range for which the model is applicable at present (due to the applicable range of the original LASL model).

### 3.3 The "B", "C" and "D" Constants

These three constants appear in the formula relating the "F" to the "X" values, i.e., relating a measure of the performance to a measure of the solar load ratio (SLR), beyond the linear zone:

$$F = B - C \exp(-D \cdot X), \text{ when } X > R.$$

The values of the "B" constant for the different "reference" building, range from 0.9715 to 1.0090. An examination of the effect of these variations on the resulting SSF has shown that very small changes will result if a constant value of 1.0 would be applied. Therefore the formula for "F" was modified to:

$$F = 1 - C \exp(-D \cdot X).$$

The constants C and D can be approximated very closely by linear funcitons of the heat capacity of the space (HC) per unit area of glazing ($Whr/C \cdot m^2$). The equations derived for C and D, under the different night insulation conditions, are:

Without night insulation:
$C = 0.56 + 0.0028 \; (HC)$,
$D = 0.0042 \; (HC)$.

With night insulation:
C = 0.71 + 0.0025 (HC),
D = 0.36 + 0.0032 (HC).

## 4. CHANGES IN THE FORMATE OF THE MODEL

In order to make the model more directly related to the building design process, and to enhance its applicability as a design tool, the size of the solar glazing, its transmission and the actual thermal mass were expressed directly and explicitly in the functions.

Thus the parameter S was replaced by:

$S = I \cdot t.$

When I is the impinging radiation and t is the solar transmission of the glazing.

The heat capacity, H was replaced by:

$H = M*c/A_g$

where M is the mass in tons, c is the specific heat (220 Whr/Cton) for most materials) and Ag is the projected vertical area of solar glazing ($m^2$).

## 5. OVERALL COMPARISON BETWEEN THE LASL AND THE NEW MODELS

Strict comparison between prediction of performance of the LASL model and any other model can be done only for the "reference" building designs.

By replacing the constants of the LASL model with functions generating the values of the constants, deviations from the original values are expected in each one of the values of the constants when they are applied to the "reference" cases. The deviations in the various constants are in either direction so that the final outcome can be checked only by comparing the SSF values (or the auxiliary heating) obtained by the two, or more, models.

In order to evaluate the effect of the above modifications on the predictions of the SSF, two sets of computations were done, using the LASL and the new model, on the performance of the 9 reference buildings. Four conditions were assumed: 2 levels of NLC (6000 and 12000 Whr/C-day)$_2$ and 2 sizes of the solar glazing (15 and 30 $m^2$-month, DD = 220/month.

The results of this comparison are presented in Table 1. As can be seen from Table 1, there is close agreement between the prediction by the new model and the LASL model. This agreement indicates that the variations in the constants of the LASL model are indeed functions of the variations in the heat capacity and glazing among the different Reference Designs.

## 6. CONCLUSIONS

The correlational predictive formulae which were developed for direct gain passive heating by the Los Alamos "Passive" Group have been transformed into a generalized model which can be applied to any building with direct gain solar heating, regardless of (and taking into account) its actual heat capacity and the properties of its solar glazing.

Comparint "predictions" by the modified model and by the original LASL formula shows very good correspondence. However, the new model is not restricted to buildings similar to the "reference" cases of the LASL model.

## 7. ACKNOWLEDGEMENT

The research was supported jointly by the MInistry of Energy and Infrastructure and the United States Department of Energy.

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| NLC | Ag | Mass (tons) | Double Glaz. | | | | Triple Glaz. | | | | Night Insul. | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | LASL | | New | | LASL | | New | | LASL | | New | |
| | | | SSF | Aux. | SSF | Aux | SSF | Aux. | SSF | Aux | SSF | Aux | SSF | Aux |
| 6000 | 15 | (170) 11.6 | .36 | 847 | .37 | 835 | .45 | 730 | .42 | 767 | .51 | 653 | .50 | 657 |
| | | (340) 23.2 | .48 | 691 | .47 | 697 | .57 | 567 | .55 | 591 | .58 | 558 | .59 | 541 |
| | 30 | (170) 23.2 | .56 | 583 | .56 | 578 | .69 | 414 | .64 | 470 | .77 | 303 | .77 | 301 |
| | | (340) 46.4 | .78 | 289 | .78 | 284 | .85 | 204 | .84 | 208 | .83 | 164 | .88 | 152 |
| 12000 | 15 | (170) 11.6 | .20 | 2124 | .21 | 2092 | .25 | 1986 | .24 | 2017 | .24 | 1006 | .25 | 1984 |
| | | (340) 23.2 | .24 | 2011 | .24 | 2017 | .29 | 1876 | .27 | 1940 | .28 | 1897 | .28 | 1903 |
| | 30 | (170) 23.2 | .36 | 1693 | .37 | 1671 | .45 | 1459 | .42 | 1534 | .51 | 1305 | .50 | 1314 |
| | | (340) 46.4 | .48 | 1382 | .47 | 1394 | .57 | 1135 | .55 | 1183 | .58 | 1117 | .59 | 1083 |

TABLE 1. GENERAL COMPARISON OF PREDICTIONS OF SSF AND AUXILIARY HEATING BY LASL AND THE NEW MODELS. CLIMATIC CONDITIONS: S = 85000 Whr/$m^2$-month, DD = 220/month.

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# INTERACTIVE COMPUTERS IN THE ENERGY-CONSCIOUS DESIGN PROCESS

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## ABSTRACT

This paper describes a microcomputer program that analyzes microclimates around buildings. User input is via a graphics tablet; analysis is computed by the Brown/Novitski method of climate analysis with SOLMET data (1) from the National Oceanic and Atmospheric Administration (NOAA). The program evaluates the microclimates around a user-defined building in terms of the number of hours in the year that various areas are thermally comfortable as a result of the way the sun and wind behave around the building.

## 1. INTRODUCTION

Over the past several years, in collaboration with G. Z. Brown, I have been developing architectural design criteria which aid designers in dealing with the complexities of climate variation (2). Our work is predicated on the idea that thermal comfort in and outside of buildings is possible, through the moderation of the sun and wind, far more often than conventionally perceived. It is our goal to understand and communicate the behavior of the sun and wind in ways that can be used by designers directly and easily.

This computer system presents information in such a way that it becomes "design-generative," and not merely factual or analytical. This means that the designer interacts directly with the computer, in electronic media similar to familiar graphic media, and with immediate and useful feedback, in a form which is also primarily graphic. The purpose of this program is to allow a designer to experience a simulation of the year's climate experience and to see how that climate is modified by a proposed design.

## 2. TECHNICAL BACKGROUND

The background for the analytic portion of this program is the Brown/Novitski climate analysis research. It began with the premise that buildings that are "designed with climate" consume less energy than conventional buildings. In addition, outdoor spaces which are designed for sun and wind are far more usable than those which are not and can reduce the need for built spaces. Unfortunately, modern designers have lost the intuitive understanding of climate that enabled "primitive" cultures to design sophisticated responses to their climate conditions.

Through our research, we have found that the proportion of the year that is potentially thermally comfortable (for all locations studied) is far greater than usually perceived. It is possible to achieve thermal comfort, for example, when the outside air temperature is as low as 5°C (41°F) as long as the wind is blocked and there is sufficient solar radiation to offset the chill. Similarly, it is possible to be comfortable at approximately 40°C (100°F) or somewhat higher or lower depending on relative humidity, as long as the sun is blocked and there is enough breeze for cooling. This redefines the extremes for which heating and cooling systems in buildings need to be designed. By studying the hour-by-hour correspondence of actual temperature, solar radiation, wind speed, and relative humidity from NOAA SOLMET data, we have discovered that the percentage of potentially comfortable time can be increased dramatically through appropriate design.

The problem is to communicate this bulky information to the designer who is embroiled in the already complex

design process. When during the year do you need the sun for heating? Where is it when you need it? Where is it when you need to shade it? When do you need the wind for cooling? Which direction is it blowing from when you need it? Where is it when you need to block it? These are the questions that this computer simulation can answer. And it can answer them at an early point in the preliminary design process, when only building massing has been determined, so that changes can be made more readily. As a result, this process is likely to be repeated several times, each time improving the thermal performance of the design.

## 3. "Micro-CLIMATES" SYSTEM DESCRIPTION

The system I have developed is called Micro-CLIMATES, an acronym for Micro-Computer Laboratory of Interactive Methods for Analyzing the Thermal Environments around Structures.

The user sits down to an Apple II+ which has at least one disk drive, a graphics tablet and, optionally, a printer. The disk containing the program, data, and eventual design information is "booted" automatically when the power is turned on, and the program begins with no additional action on the part of the user.

The "Main Menu" appears, representing the principal command mode of the system. See Figure 1. The eight boxes show the options from which the user may choose. The user selects from the eight procedures by moving the pen over the graphics tablet, making the cursor on the screen fall within one of the boxes and then pressing the pen to register the response. The selected procedure begins automatically.

**Micro-CLIMATES**

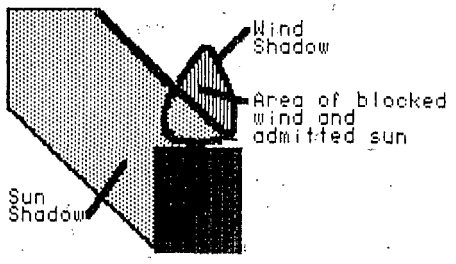
Main Menu

Use the pen to select a function.
For more information, select 'HELP'.

| | | | |
|---|---|---|---|
| HELP | CATALOG | DRAW | ANALYZE |
| NEW DATA | DEMO | PRINT | QUIT |

Fig. 1."Micro-CLIMATES" Main Menu.

If the "Demo" is selected, the user is relatively passive, simply observing a demonstration of the system as they would see it if they were watching someone else perform all the interactive functions. A pre-programmed, cube-shaped building is drawn by the computer on the screen, and a year's worth of climate phenomena are animated around it. The computer provides a running commentary on what is happening and finishes by evaluating selected points around the building and returning the user to the Main Menu. Figure 2 shows an example of the kind of information that would be available.




Simple Cube -- 44 north latitude
May 21, 10 am
Need to block wind and admit sun

Fig. 2. Sample results from the Demonstration Program.

The next option selected will typically be "Draw." This option provides a grid to draw on as well as another menu of its own to aid in defining various characteristics of the design, such as scale and height. (See Figure 3.)

The user then "draws" a building plan on the graphics tablet, and the image simultaneously appears on the screen. When the drawing is complete, the pertinent data are saved on a disk data file. Like all functions, this is done easily, by simply selecting the proper menu item with the pen.

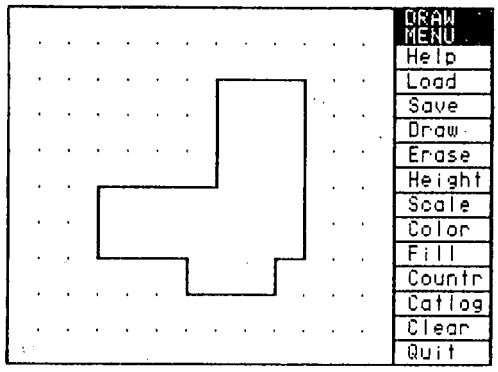



Fig. 3. The "Draw Menu" with a building plan drawn on it.

Selecting the "Analyze" option from the Main Menu begins the climate simulation. See Figure 4. The user watches while the sun and wind behaviors are animated, to resemble their actual movements throughout the day and year, but modified by the building design. At the same time as the computer is animating the path of the sun and wind around the designed shape, it is applying a selected analysis to the same movement. This analytic process calculates the percentages of time that the building is modifying the surrounding microclimates to produce thermally comfortable conditions.

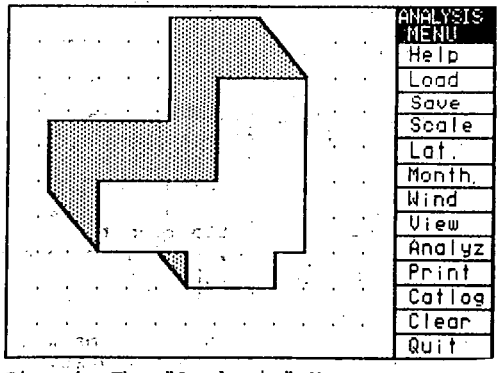



Fig. 4. The "Analysis" Menu.

At the end of the simulation, an objective evaluation is provided, to back up the visual evaluation provided by the animation. The evaluation assigns a "score" to each area around the buiing, indicating how often during the year that area will be thermally comfortable. This evaluation is given for each season separately and for the total year. Optionally, the evaluation can be printed on paper, in both graphic and tabular format.

On the basis of these conclusions, the user then draws a modified design on the tablet to try to maximize the size or performance of the various exterior microclimates, and the process starts over.

## 4. ISSUES

This computer program attempts to embody a set of ideals that I have developed for interactive computer programs, especially as they relate to designers or anyone with a graphic bent. These issues are concerned with making the relationship between designer and machine as easy, "friendly," natural, and graphic (non-verbal, non-numeric) as possible. I'll discuss these issues in reference to Micro-CLIMATES, but I believe most of them to be appropriate for all microcomputer programs.

### 4.1 Documentation

Ideally, a microcomputer program should have no written documentation except necessary technical references. It should be self-explanatory enough so that someone who knows how to insert the program disk can proceed in a self-guided fashion without having to read anything beyond occasional explanations within the course of the program itself.

This ideal can be approached by a well-organized programmer. It requires "help files" within the program, clear prompting, default values for input that represent the most likely user selection at any given moment, and continuous protection against inappropriate responses which could otherwise "crash" the system.

In Micro-CLIMATES, the only written documentation is a brief brochure. It provides a technical overview of the analtical methodology, instructions for using the hardware, and a reference for all of the menu functions. However, most of the how-to instructions are provided within the program itself. The program continually suggests what to do next while allowing deviations from a standard progression. The user quickly learns that nothing he does will do any harm, so he can feel free about experimenting.

### 4.2 Graphic Input

Of all the technological advances that have accompanied the advent of

microcomputers, none has inspired the interest of designers as much as the graphics tablet. This is a 30cm (12") square digitizing pad which looks like a drawing pad. It is wired to an electronic stylus which looks like an ordinary pen. Movements of the pen on the pad are registered as movements of a cursor on the high-resolution graphics screen. Since the tablet sends its signal to the computer in terms of the X,Y coordinates of every plotted point, any information that is input as a graphic image can also be subjected to mathematical analysis. This graphic input of information frees a designer from the burden of describing visual images in artificial numeric codes from the keyboard. It facilitates input in a familiar form that corresponds closely with the user's mental image of the problem and visual training in general. In Micro-CLIMATES, I have reduced keyboard input to the absolute minimum and set up graphic input procedures that will feel comfortable to designers.

As with any drawing process, particularly at preliminary phases, erasures and corrections are not only a necessity, but a normally accepted standard procedure. The graphics tablet screen can be programmed to erase as easily as it can draw. It can erase single lines, or the entire drawing, or anything in between.

A major question that arises when programming the graphics tablet is how to provide the user with information about drawing modes and options. When many options are available at once, probably the best method is to have them displayed on a mylar sheet which is taped down to the graphics tablet itself. The user then selects one by touching with the pen the appropriate box on the sheet. This method has the disadvantage of requiring that the user's attention be continuously drawn away from the screen, to the tablet, and back again. When there are relatively few modes to select from at a given level in the program, and when the drawing screen size does not need to be maximized, which is the case with Micro-CLIMATES, it is more convenient for the menus to be displayed directly on the screen. Using the pen, the user can align the flashing cursor with the chosen option and make the selection without looking away from the screen. This is the method I prefer, and it is the principal mode for all system commands.

4.3 Numeric Input

In the same spirit with which I've tried to optimize the use of graphics for communicating with the computer, I have simultaneously minimized user input of numeric data. This is partly to limit the amount of time that the user's hands are involved with the keyboard instead of the pen and partly to minimize that kind of mental abstraction which does not enhance the designer's visual understanding of the problem. Since it is far easier, from a programmer's standpoint, to deal with numbers than with graphic data, it is very important to resist the temptation to rely on the keyboard any more than is absolutely necessary.

For the analytical portion of the program, quite a bit of numeric information is needed which is site-specific. The more flexibility allowed for specific sites, the more time the user must spend in providing detailed information about that site. Conversely, the easier the input process, the more restricted the freedom of choice of locations to analyze.

For the purposes of this pilot program, the resolution of this conflict was to limit site information to a choice of the four major locations that have been studied to date in the Brown/Novitski research. (These are Charleston, South Carolina; Dodge City, Kansas; Madison, Wisconsin; and Phoenix, Arizona.) The user may select the one that most closely resembles his or her own climate location. For initial training purposes, this is an acceptable compromise because general trends can be demonstrated and common design situations mastered without a great deal of meticulous attention to detail. For example, shading problems will be similar throughout the southeast even though there may be latitude differences of up to 15 degrees. Wind blocking problems will be similar throughout the midwest, even though the actual wind directions may change from one location to another.

When any of the four locations is chosen, a data file is automatically read from the disk with information such as latitude, solar angles, wind directions, and a "miniature" simulated year of climate data condensed by the Brown/Novitski methods. In this way, the user has minimal involvement with the technical issues and can concentrate on the way

the drawn building is behaving within that complex climate.

This simulated year is made up of 10 to 20 representative days, including all the actual day types, each weighted according to how many real days it represents. The data include temperature, wind speed, solar radiation, etc., for each hour in typical days, so that the change in climate conditions throughout the day can be observed.

4.4 Graphic Output

In a graphically interactive computer session, when the topic is as dynamic as that of climate, the graphic output must be animated. In the case of climate simulation, this means showing the sun and wind movements together with visible overlaps. In addition, Micro-CLIMATES shows, to one side, a description of the actual climate condition pattern and requirements for achieving comfort.

At the same time, the program is flexible enough to allow for a variable speed in the simulations. The user can slow down the speed to watch particular motions more carefully, or speed it up so that large time spans can be covered quickly and generalizations assimilated rapidly. One speed option is zero; the user can select a specific point in time to study. This variation in speed is easily controllable via the tablet and pen.

At times, it is impossible to speed up the action to faster than a certain (slow) rate; in fact, when there is a large block of calculation, or, more frequently, when there is some slow disk input or output going on, this can be disguised. Micro-CLIMATES takes advantage of these pauses to present supplementary information about what will happen next, or simply some diversionary text. I've found that whenever there is something for the user to read or watch, the delay is less noticeable. Even text with minimum content is preferable to "dead air." These screens are always carefully formatted in a way that make them easy to read.

When an evaluation is being calculated, this is an opportunity to provide a running commentary about the climate and whether conditions are being modified appropriately. Every time a new part of the program is loaded, some disk activity brings everything else to a halt. This is an opportunity to provide a graphic illustraton of a climate or the building design.

4.5 Color Graphics

One on hand, it is desirable to use colors in graphic displays, since another dimension of information can be coded in this way without requiring a lot of explanation. For example, climate conditions can be color-coded so that reds indicate hot weather and blues cold weather.

Unfortunately, there are a few drawbacks to the use of color with Apple computers. One is that most hardware that is commonly used with microcomputers (ordinary color televisions) has a poor quality of display that is distracting if not painful, expecially when displaying text. Typically, those users who have color TVs in their computer systems do most of their work on black and white monitors (or green screens) most of the time anyway, to avoid eye strain. Good hardware (color monitors designed specifically for microcomputer graphics) is available, but it is expensive and not universally owned. Indeed, it is not safe to assume that a potential user has access to color of any quality.

Therefore, Micro-CLIMATES has been designed to operate on both color and monochrome screens. Colors are selected which, when translated into black and white, still provide enough contrast in shades of grey to communicate the intended information. If colors are never mentioned explicitly, a black and white monitor user will never know what he is missing. At the same time, the colors can be used in simple and consistent ways so that they convey subliminal information for the color user.

4.6 Sound

There is also a sound capability in Apple computers, which can be used to distinguish another level of information, in much the same way color does. Simple sounds accentuate certain screen activity. For example, on the menus, whenever a new function is selected, a bell sounds, to indicate that the function has been registered. A double bell is used for warnings or error messages. A soft clicking sound is used during animation sequences when it is

important to distinguish between frames. This tends to give the frames a certain "presence" and subtly changes the user's attitude towards the phenomena he is observing.

### 4.7 Printer Output

Periodically in the design -- analyze process, the user needs printed documentation of the developed building configuration and its evaluation. To facilitate this, the "Print" option on the main menu provides a list of all the drawings that have been stored on disk. (It is the users' responsibility to select sufficiently descriptive labels throughout the design session so they can recall the contents of each file.)

Selected files are printed with a header, a reproduction of the drawing, some descriptive information about the location, and a chart that gives a summary of the evaluation. The summary, in tabular form, shows the performance scores for each microclimate around the building for each season and for the total year. Even though this is really the "final conclusion" of the whole process, it is simplified as much as possible. Any excess of numerical information will be ignored by most users, I believe, espcially those who prefer to operate in more visual and less analytical modes. Besides, the most important aspect of this exercise is the process of designing -- improving -- redesigning. To end with a lot of complicated tables and summaries would distract attention away from the process.

## 5. CONCLUSIONS

The "Micro-CLIMATES" program has been described in terms of both its technical performance and the lessons it teaches about graphic user/computer interaction. This latter issue is extremely important if microcomputers are to achieve a standing as commonplace design tools. Designers must lose any intimidation they may feel towards complex machines. Well designed software can help in this process by being as easy to use as possible and by taking advantage of the graphics tablet and other media that resemble the ordinary media that designers already use.

As microcomputers become more commonplace in architectural practice, it is essential that good software be provided for the profession by other professionals. Software designers who have an interest in passive energy resources have a unique opportunity now to make an impact on the building professions that surpasses the impact of current conventional engineering software.

## 6. ACKNOWLEDGEMENTS

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Micro-CLIMATES is not yet available for public distribution. For more information, write to the author.

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# AUTOMATED GENERATION OF SHAPE FACTORS FOR MEAN RADIANT TEMPERATURE MEASUREMENT

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## ABSTRACT

Thermal radiation is a significant factor affecting thermal comfort in many types of artificial environments, such as passive solar architecture and radiant panel systems in buildings. Mean Radiant Temperature (MRT) is a measurement of this thermal radiant exchange. The term Operative Temperature (OT) combines the effects of both MRT and air temperature to reflect better the human perception of thermal comfort within an environment.

This paper discusses the theory and computer program that calculates the MRT of a person standing anywhere within a rectilinear enclosure for a particular period of time. The use of this program can help the designer achieve optimum thermal comfort conditions and reduce initial and operating costs of heating equipment.

## 1. INTRODUCTION

Heating is a term which has been applied to that part of physical science whereby through artificial means a comfortable condition for living can be achieved. Radiant heating, or that heating portion due to the radiant energy waves from a source, includes such sources as the sun, electric panels, infra-red lamps, or any heated surface within the enclosed environment.

Radiant heating has been used in many applications to achieve a comfortable environment. In 1908, radiant heating was introduced on a commercial basis with the development of hot water pipes embedded in plaster or concrete. More recently, electric radiant panels and solar heated walls have been used in environments to reduce energy costs.

Radiant heating and its effects has a significant input in the thermal comfort of any environment. Various studies linking human comfort with different indices of thermal measurements in simulated environments have arrived at generally accepted parameters for human comfort. ASHRAE comfort standard 55-74, one of the most widely accepted standards today, determines that a human's acceptable thermal comfort range is defined by the major parameters of indoor air temperature and relative humidity. The limiting criteria is that the indoor air temperature must be equal to his (or her) Mean Radiant Temperature (MRT). MRT is a measurement of the radiant conditions between a person and his/her surrounding surfaces. There are, however, many instances when MRT will vary from the indoor air temperature due to such circumstances as solar heated walls, radiant heating panels, or a cold expanse of glass. A term which includes the effects of both MRT and air temperature is the Operative Temperature (OT), developed earlier in the 1930s by Pierce Laboratory. The inclusion of both temperatures are critical in determining thermal comfort within radiantly heated environments.

Because past thermal comfort standards had not allowed for the varying effects of MRT from the environmental air temperature, P. O.

Fanger through his work at the Technical University of Denmark and at Kansas State University has formulated a general thermal comfort equation called the Fanger Comfort Equation (1). The major parameters in this equation are MRT, indoor air temperature, relative humidity, internal heat production, thermal resistance of clothing, and air velocity.

Determining Mean Radiant Temperature at various points within an artificial environment is time consuming without the use of an electronic computer. To save time and effort, simplified heat transfer analyses were used by Fanger at the expense of accuracy. Shape factors from a person to various surfaces were developed into graphs by P. O. Fanger in the early 70's. However, surface to surface shape factors are often ignored, which is justified only when there are small surface temperature variations within an enclosure. However, this assumption can cause a large error in the MRT when there are substantial surface temperature differences, such as in the case of a solar heated wall at 100°F facing 50°F windows and 70°F walls.

Penn State's Low Temperature Radiant Heating (LTRH) Research Group has developed a computer program to evaluate Mean Radiant Temperature by considering both surface to surface and person to surface shape factors. Fanger's shape factor graphs are reduced to 2 equations and numerous surface to surface shape factors which are handled by five subroutine programs.

## 2. COMPUTER PROGRAM

### 2.1 General

The PSU-MRT computer program finds the mean radiant temperature of a person standing anywhere on the floor of an enclosure for the instantaneous period of time in question. Indoor temperatures must be assumed as inputs, and the enclosure must be of rectangular shape. The program can be used with practically any arrangement of heated surfaces (heaters, solar walls) windows, and doors. Input parameters for this program are room surface geometries and thermal properties, outdoor and indoor temperatures, sol-aire temperatures, heat source inputs, and the occupant's position within the enclosure. The major categories making up the computer program are shown in Fig. 1.

### 2.2 Radiation Shape Factors

The analysis of radiant interchange is dependent on shape factor analysis. The analysis assumes diffusely emitting and reflecting surfaces. Figs. 2 to 4 show the four types of surface shape factors used in rectilinear enclosures. The algorithms and their subroutine constructions are as detailed in reference (2).

The computer program uses Fanger's original curves to find the mean radiation shape factors between a standing person and vertical and horizontal surfaces as shown in Fig. 6. In order to automate the shape factor process, the curves prepared by Fanger were digitized and analyzed by William Formwalt (3) of the LTRH Research Group in the Architectural Engineering Department of The Pennsylvania State University. His work dealt with trying to reduce the plots containing several nonlinear curves down to two equations with high verisimilitude which could be converted into a function to be used in the computer subroutine's formulation of a numerical value for the shape factors of a thermal environment.

### 2.3 Heat Transfer Analysis

The following assumptions are made in the heat transfer model:

1. isothermal surfaces
2. gray surfaces
3. diffuse reflectance and emittance of surfaces
4. one-dimensional heat flow through surfaces
5. steady state conditions
6. reflections are considered negligible
7. room air temperature is assumed known for the period of calculation.

Assumption number one says that all primary and secondary surface elements have temperatures that are constant throughout their respective boundaries; i.e., no local temperature gradients. Assumption number two says that the surface elements, being gray, are un-

selective in their spatial characteristics (4). In other words, the absorptance ($\alpha$) and the emittance ($\varepsilon$) of each surface element does not vary at any radiation wavelength. This leads to the conclusion that the absorptance ($\alpha$) is equal to the emittance ($\varepsilon$) of each gray surface, or $\alpha = \varepsilon$. Assumption number three says that the intensity of the reflected and emitted energy are uniformally distributed. Also all radiation shape factors have been derived using this premise. Assumption number four says that heat flow is in one direction, normal to all surface elements (not multi-dimensional heat transfer). Assumption number five says that all surfaces have reached thermal equilibrium (no transient effects); therefore, the sum of the conduction, convection, and radiation transfer modes of each surface element equals zero, such that,

$$Q_{cond} + Q_{conv} + Q_{rad} = 0 \qquad [1]$$

Assumption number six says that since most building materials have emittances of approximately 0.9, their reflectances are approximately 0.1; reflections are considered to be zero.

A heat balance method is used to balance simultaneously the modes of heat transfer of each inside surface element for an instantaneous period of time. The linearized form of the radiation heat transfer equation is (1):

$$Q_{rad_i} = \varepsilon_i \sigma \sum_{j=1}^{N} (T_i - T_j) F_{i-j} A_{i-j} \qquad [2]$$

for i=1,N, where:

$$A_{i-j} = (T_i^4 - T_j^4)/(T_i - T_j)$$

The conduction heat transfer equation is:

$$Q_{cond,i} = (1/\Sigma\eta)(T_i - T_\infty) \qquad [3]$$

The convection heat transfer equation is:

$$Q_{conv,i} = \bar{h}_i (T_i - T_\eta) \qquad [4]$$

The temperature matrix solution for all horizontal and vertical unheated surfaces is as given below. Substituting equations [4], [3], [2] into [1] and expanding them into matrix form in order to solve for the simultaneous surface temperatures yields:

$$\sum_{j=1}^{N} X_{i-j} T_j = \eta_i \qquad [5]$$

where:

The X matrix yields

$$X_{i-j} = (1/\Sigma\eta_i) + \bar{h}_i + \varepsilon_i \sigma \sum_{j=1}^{N} A_{j-N} F_{j-N}$$

for all i = j, and if i ≠ j then:

$$X_{i-j} = -\varepsilon_i \sigma A_{i-j} F_{i-j}$$

The T matrix yields the inside surface temperatures, $T_j$

The matrix yields

$$\eta_i = \frac{1}{\Sigma R_i} T_\infty + \bar{h}_i T_\eta$$

The radiosity matrix solution follows. Once the surface temperatures have been found the radiosities $B_j$ of all surface elements can be obtained. The radiosity matrix solution is:

$$\sum_{j=1}^{N} X_{i-j} F_j = \eta_i \qquad [6]$$

where:

The X matrix yields for i=j

$X_{i-j} = F_{i-j}$ if i = j, or,

$X_{i-j} = (\quad_i{}^{+1})/\varepsilon_i) F_{i-j}$, if i ≠ j

The B matrix yields the inside surface radiosities $B_j$

The $\eta$ matrix yields

$$\eta_i = e_{b,i} = \sigma T_i^4$$

The Mean Radiant Temperature (MRT) is defined as the uniform surface temperature of a black body enclosure in which an occupant exchanges the same amount of radiant heat as in an actual nonuniform space [6]. The resulting MRT equation is:

$$T_{MRT}^4 = B_1 F_{H-1} + B_2 F_{H-2} + \cdots B_N F_{H-N} \qquad [7]$$

## 2.4 Example Computer Run

The PSU-MRT computer program has been written so as to allow a user to determine the Mean Radiant Temperature experienced inside an enclosure with a specific room layout and surrounding conditions. In order

to check the validity of the program a test was performed.

The test room that was used in the analysis was 20ft. long and 14 ft. wide with a ceiling height of 8.25 feet. A large window is located in one corner of a 20 x 14 foot wall and a second window is located in the other corner of the same wall. On the wall containing the windows two heaters will be placed at the wall's approximate center between the two windows. The heater size will remain constant and the position of both heaters will be held constant, thus reducing variables in the determination of a favorable MRT in the enclosure. Two additional heaters will be used on the ceiling. Both of the heaters will be of the same size and will be placed at various positions on the ceiling of the room. Fig. 7 represents the room layout and orientation in the stationary X, Y, Z coordinate system. Fig. 8 shows the room's secondary surface dimensions and locations.

A study was performed in order to determine the heater positions that will give the most favorable MRT. The term "most favorable MRT" is defined as yielding the temperature at all locations in the room as constant as possible.

The study was conducted so that the number of variables were kept to a minimum; therefore the room dimensions, window size and their location remained constant. Two constant position heaters were used which also had fixed power inputs. The MRT was found at various locations by letting the occupant travel a prescribed imaginary grid superimposed on the floor. The grid size was fixed at 2 foot intervals in both the X and Y coordinates. The grid's starting point was also fixed at 1 foot from the stationary axes associated with the room's orientation coordinate system. The moving heaters traveled a prescribed path in the Y direction of the room in 4 foot intervals excluding the first position, which was 1 foot away from wall number one.

An isothermal plot, Fig. 9, reveals that a stationary area of high intensity thermal radiation is present around the two stationary heaters. This is due to the fact that the man's shape factors to those surfaces is increasing as he approaches the heaters.

The situation observed in the isothermal plot would not be considered a "favorable design" because of this area of high intensity. In order to accomplish the task of designing a space that does not contain areas of extreme intensity, different heater positions, number of heaters, and heater power input must be tried. In order to demonstrate this concept, the two stationary heaters will be placed above the windows at prescribed location and the heater size and power input will remain the same. The moving heaters will be moved towards the center of the room.

A final plot was made, which appears in Fig. 10 in which the ceiling heaters were placed directly in the center of the room. The isotherms are more uniform. By changing the size, number, and power input to the heaters optimum isotherm uniformity can be achieved.

## 3. RESULTS AND CONCLUSIONS

The previously described room was taken from the actual blue prints and specifications of Dr. Luis Summers' residence in State College, Pennsylvania. His home is to be used later as a test facility to correlate data for further MRT studies. The MRT in the residence will be found by placing electronic globe thermometers at the same positions prescribed by the grid used in the program. The surfaces of the room have been equipped with thermocouples to determine the actual surface temperatures needed in the determination of the MRT. All the collected data will be used to determine how well the computer simulation correlates to the actual physical situation experienced in the room. All measurement has been automated, and data will be gathered, and reduced by a 32 channel Analog to Digital (A to D) board hooked to a microcomputer.

The program is also being used by Penn State's LTRH group to conduct radiant heating experiments. The testing results will then be transformed into a manual by which consumers will be able to attain the maximum efficiency from radiant

heaters and ensure a more comfortable environment and concommitant energy savings. This program will then be used with modifications to estimate the net energy consumption of a room fitted with radiant surfaces versus an identical room with a conventional heating system.

The MRT computer program can be used as an additional tool for environmental control designers, and most advantageously to highly radiative environments such as passive solar architecture and buildings using radiant panel systems. Passive solar environments are subject to large solar fluxes and highly variable wall surface and indoor air temperatures. Through the MRT program thermal comfort can be determined so that an environment can be designed to maximize comfort. Also as an aid to conserving energy the MRT program can help the designer establish a minimum acceptable indoor temperature that an auxiliary heating system would maintain during periods of high heating loads.

The MRT program can help the designer increase heating efficiency by maximizing the shape factors between various radiating sources and an occupant. For example, in a residence floors usually have the highest shape factors, followed by ceilings, and then by a portion of the walls located from the floor level to approximately four feet in height.

## 4. NOMENCLATURE

A = surface are ($ft^2$)
B = surface radiosity (Btu/hr - $ft^2$)
F = radiation shape factor
$\bar{h}$ = mean convection heat transfer coefficient (Btu/hr - $ft^2$ - $^oF$)
$Q_{cond}$ = conduction heat transfer (Btu/hr - $ft^2$)
$Q_{conv}$ = convection heat transfer (Btu/hr - $ft^2$)
$Q_{rad}$ = radiation heat transfer (Btu/hr - $ft^2$)
$\eta$ = material thermal resistance (hr - $ft^2$ - $^oF$/Btu)
T = temperature of surface ($^oF$)
$T_{MRT}$ = Mean Radiant Temperature ($^oF$)
$T_r$ = room temperature ($^oF$)
$T_\infty$ = outdoor or adjacent air temperature ($^oF$)
$\alpha$ = absorptivity
$\varepsilon$ = emissitivity
e = reflectance
$\sigma$ = Stefan-Boltzman constant

### 4.1 Subscripts

i = surface i
j = surface j
N = total number of surfaces
H = refers to particular occupant

## 5. REFERENCES

(1) Fanger, P. O. Thermal Comfort: Analysis and Applications in Environmental Engineering. New York: McGraw Hill, 1972.

(2) Steinman, M. Computer Simulation of Radiant Heating in Cubical Enclosures - Part 1. University Park, PA: Department of Architectural Engineering, The Pennsylvania State University, May 1983.

(3) Moszczienski, J. Computer Simulation of Radiant Heating in Cubical Enclosures - Part 2. University Park, PA: Department of Architectural Engineering, The Pennsylvania State University, May 1983.

(4) Sparrow, E. M. Radiation Heat Transfer. New York: McGraw-Hill, 1978.

## 6. NOTES

The temperature matrix solution for all horizontal and vertical surfaces, $Q_{cond,i}$ = Constant Value is not shown in section 2.3 for reasons of economy of space.

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Ed. Note: A list of metric-English-metric appears immediately preceding the Author Index.

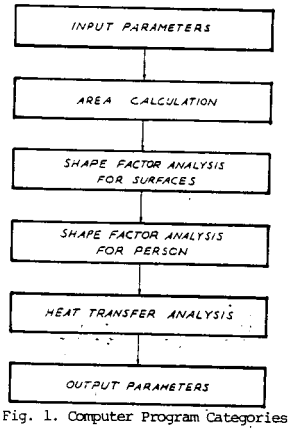



Fig. 1. Computer Program Categories

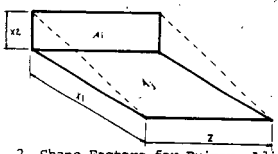


Fig. 2. Shape Factors for Primary Adjacent Surfaces Within Box-Shaped Enclosures

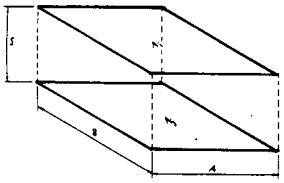


Fig. 3. Shape Factors for Primary Opposite Surfaces Within Box-Shaped Enclosures

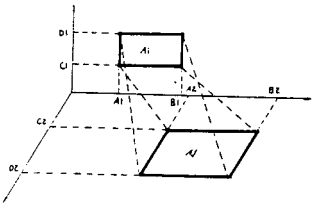


Fig. 4. Shape Factors for Secondary Adjacent Surfaces Within Box-Shaped Enclosures

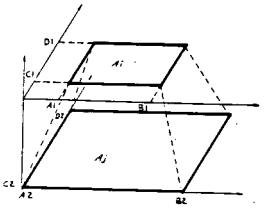


Fig. 5. Shape Factors for Secondary Opposite Surfaces Within Box-Shaped Enclosures

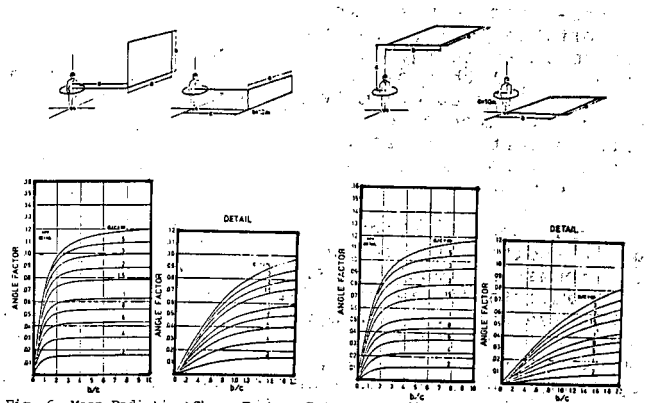



Fig. 6. Mean Radiation Shape Factors Between Standing Person and Vertical and Horizontal Surfaces

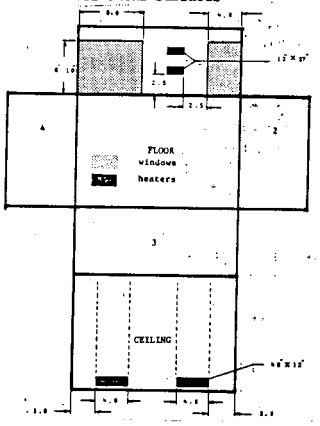



Fig. 8. Room layout, including heaters and windows.

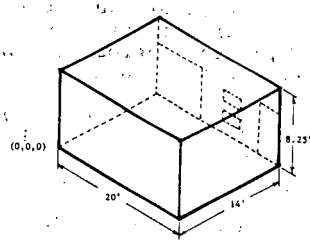



Fig. 7. Room orientation and dimensions.

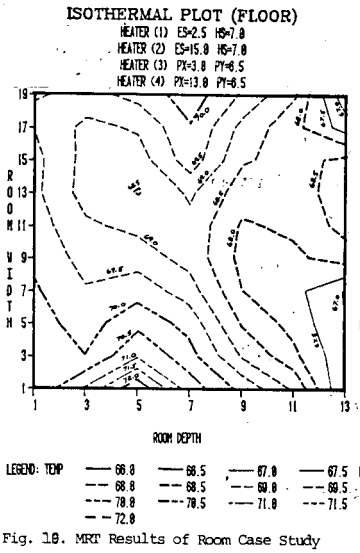



Fig. 10. MRT Results of Room Case Study

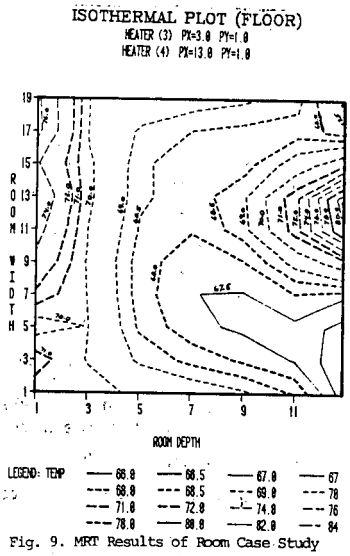



Fig. 9. MRT Results of Room Case Study

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# A METHOD TO ADJUST HEATING AND COOLING LOAD CALCULATIONS FOR DIFFERENT ALTITUDES

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## ABSTRACT

This paper describes a method to adjust the Degree Day factor for a specific site that differs in altitude from the reporting station.

## 1. THE ADJUSTMENT METHOD

The need for an altitude adjustment calculation became apparent while performing quantitative energy and solar audits at radically different altitudes along the Colorado Front Range. The audit is designed to produce data on annual heating load, solar feasibility, solar savings fraction and simple payback. With altitude differences of up to 3000 feet from that of the reporting station, significant deviation in actual heating loads are introduced to the calculations.

This method employs an atmospheric lapse rate to track increased or decreased load as a function of altitude. First, the altitude differential of the site and the reporting station is determined from topographic maps. The altitude differential (expressed in thousands of feet) is then multiplied by a lapse rate of 4.3° F. This is a weighted lapse rate applicable to the lower 10,000 feet of the atmosphere. This product is multiplied by a "heating season duration factor" (discussed below) which yields an increase or decrease of Degree Days (DD) from that of the reporting station. This difference is then added to (increased altitude) or subtracted from (decreased altitude) the reporting station DD base figure and applied to building load calculations.

The "heating season duration factor" is the number of days in a heating season. Before this method can be used, the factor must be determined. In practice, any month of the year with more than 350 DD should be considered as a 30 day "heating month." Then, the number of "heating months" determined from DD charts is simply multiplied by 30 to obtain the "heating season duration factor." This simple rule can be used with reasonable confidence.

If necessary, a more accurate "heating season duration factor" can be derived by applying the formula to two or more reporting stations of similar climate and comparing the adjusted DD results. Increasing or decreasing the duration factor to the appropriate number of days per year will result in nearly identical DD for the compared reporting stations.

Example: The closest reporting station is at an altitude of 7040 feet and experiences 7836 DD per year.

The site in question is located at 8600 feet. Therefore, the altitude differential is: 8600 feet - 7040 feet = 1560 feet.

| (differential) | | (lapse rate) | | |
|---|---|---|---|---|
| 1.56 | x | 4.3 | = | 6.708 |

There are eight months in excess of 350 DD per month.

| (heating months) | | (days) | | (duration factor) |
|---|---|---|---|---|
| 8 | x | 30 | = | 240 |

| (rate) | | (duration factor) | | (DD difference) |
|---|---|---|---|---|
| 6.708 | x | 240 | = | 1610 |

| (DD difference) | | (Station DD) | | (adjusted DD) |
|---|---|---|---|---|
| 1610 | + | 7836 | = | 9446 |

The annual load calculations should be based on 9446 DD per year. In this example, the actual heating load is 20% greater than predicted by the "closest station" method.

This method can be proven by applying it to two reporting stations (as in the "heating season duration factor" derivation). In fact, the above example is based on the Evergreen, Colo., reporting station (7040 feet, 7836 DD per year) and the Grant, Colo., reporting station (8600 feet, 9471 DD per year). The adjustment method predicts 9446 DD. The actual Grant Station reported annual average is 9471 DD per year - an accuracy of 99.7%.

Adjustments within +/- 3% can be expected. This is considerably more accurate than the "closest station" method.

This method, by tracking the effect of altitude on building load, can significantly increase the accuracy of load calculations. The method can be applied to annual heating load, cooling load, solar savings fraction and many economic feasibility calculations. By applying only the lapse rate portion of the method, one can also adjust the Design Temperature base for heating or cooling plant sizing calculations. This method should be applied in mountainous areas or in regions with widely separated reporting stations.

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# EXTENSION OF THE UN-UTILIZABILITY METHOD FOR MULTIPLE-APERTURE PASSIVE SYSTEMS PERFORMANCE

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## ABSTRACT

The utilizability concept has been successfully applied to performance prediction for passive solar buildings. The method has the advantage of including many design variables in the calculations explicitly, rather than as location-dependent correction factors. The utilizability correlations as originally developed apply only to south-facing collector surfaces. By calculating utilizability from an instantaneous solar model which integrates incident radiation in short time intervals, a first order approximation of an equivalent utilizability for surfaces not facing true south is calculated. Where multiple passive solar apertures contribute to solar gains, the sum of the instantaneous solar gains from the apertures is used to define utilizability for the combination. Thus the method, while requiring an instantaneous solar model, allows for the possibly beneficial or detrimental effects of the relative timing of gains from various window configurations. An example calculation is given for a building with south and southeast-facing windows is given to illustrate the methodology and indicate its usefulness.

## 1. INTRODUCTION

The utilizability concept has been successfully applied to both active and passive solar system design (1)(2)(3). It frees the designer from constraining assumptions about the nature of the load regarding required temperatures and heat delivery rates. Passive system design methods such as Solar Load Ratio are correlations of computer simulation results which assume thermostat settings and allowable temperature swings (4). Sensitivity curves are provided to allow estimation of the effect of changes in these assumptions, but are limited to a few locations. Further, application of several sensitivity curves to one system is discouraged due to the possibility of non-linear effects. The un-utilizability passive solar design method allows changes in system design parameters to be included explicitly in the performance calculations. The primary limitation on the usefulness of the un-utilizability method is the restriction of the utilizability correlations to surfaces facing essentially true south. Passive solar buildings often have multiple apertures for solar gain, and these may be in walls or roofs with different orientations. In sunny climates such as the Southwest, solar gains from east and west facing windows are usually adequate to make up for the conduction losses through them and certainly contribute to the warmup and ventilation characteristics of buildings. This paper addresses these issues by showing that utilizability can be calculated for non-south surfaces, and the effects of multiple apertures can be estimated in the process.

Average daily utilizability is defined as the integral over the month of the difference between the instantaneous solar gain, $I_t$, and the critical level, $I_c$, divided by the integral of $I_t$ (5).

$$\bar{\phi} = \sum^{N} \sum^{n} (I_t - I_c)^+ / \sum^{N} \sum^{n} I_t \qquad (1)$$

where the integration is converted to a summation over n discrete intervals per day over the N days in the month. The critical level is defined as the level of incident radiation which just meets the immediate load. The critical level is calculated in various ways depending upon the particular type of solar system. Correlations of average utilizability for various conditions of tilt and clearness are given in (5).

For surfaces not facing true south, utilizability can be estimated by

integration, requiring a model of solar position and radiation. These models are available in several forms, and their details are beyond the scope of this paper. For the purposes of the calculations presented later, a model based on the ASHRAE clear sky methodology (6) is used. To summarize its characteristics, the atmospheric extinction coefficient and the diffuse fraction are adjusted until the total horizontal radiation for the day matches the desired value. In this manner half-hourly radiation values can be estimated from daily radiation values. However, as illustrated in Figure 1, using the monthly average daily radiation to calculate the utilizability can produce misleading results. Therefore, it is suggested that the utilizability be calculated for a clear day ($\bar{K}_t$=0.8) and for a cloudy day ($\bar{K}_t$=0.3) and the two combined in a weighted average for the actual $\bar{K}_t$ to provide the utilizability for the month. This process could be refined by adding a third intermediate clearness day to the average.

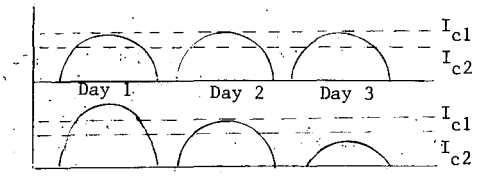



Fig. 1. Gain above $I_c$ is stored or vented.

The calculation of utilizability for multiple apertures is simplified by altering the terms being integrated from incident radiation levels to incident absorbed radiation multiplied by the effective collection area. Thus for multiple apertures, the utilizability is defined by

$$\bar{\phi} = \frac{\sum_{N}\sum_{n}\sum_{a}\left[(I_t\ \overline{ta})_a - L_c\right]^{+} A_a}{\sum_{N}\sum_{n}\sum_{a}(I_t\ \overline{ta})_a A_a} \qquad (2)$$

where $I_t$ is now a weighted average of the clear and cloudy incident radiation values for time increment n, $(\overline{ta})$ is the instantaneous transmittance-absorptance product, and $L_c$ is the critical load, defined as the monthly average space heating rate to keep the building at the thermostat set temperature. The summation over the subscript, a, is for the various apertures. This procedure is formidable for hand calculation but can be readily performed on a small computer.

## 2. DIRECT GAIN UN-UTILIZABILITY FOR MULTIPLE APERTURES

For direct gain systems (2) shows that the system performance can be characterized by two parameters: the solar/load ratio, X, and the storage/dump ratio, Y, defined as

$$X = \bar{H}_t(\overline{ta})AN/L \qquad (3)$$

$$Y = C(\Delta T)/\bar{\phi}\bar{H}_t(\overline{ta})A \qquad (4)$$

where N is the number of days in the month, L is the monthly load, C is the effective thermal mass of the building, and $\Delta T$ is the allowable building temperature swing. For multiple aperture buildings, the load can be proportionally divided among the apertures by the ratio of the aperture's gain to the total gain. This weighting factor, $W_a$, is

$$W_a = \left[\bar{H}_t(\overline{ta})A\right]_a \Big/ \sum_{a}^{a}\left[\bar{H}_t(\overline{ta})A\right]_a \qquad (5)$$

where the subscript a indicates the value for aperture a. The load seen by aperture a, $L_a$, is

$$L_a = W_a\ L \qquad (6)$$

The correlation parameters for the aperture are then

$$X_a = NW_a \sum_{a}^{a}\left[\bar{H}_t(\overline{ta})A\right]_a / L_a = X \qquad (7)$$

$$Y_a = W_a / \bar{\phi}_a\left[\bar{H}_t(\overline{ta})A\right]_a \qquad (8)$$

where $\bar{\phi}_a$ is the un-utilizability for the aperture based on a critical load of $L_cW_a$. If all the apertures are supplying heat to a single zone, then $\bar{\phi}=\bar{\phi}_a$ with the result that $Y_a$=Y and the solar fraction for the aperture is equal to the solar fraction for the building with

$$X = N\sum_{a}^{a}\left[\bar{H}_t(\overline{ta})A\right]_a / L \qquad (9)$$

$$Y = C(\Delta T) / \bar{\phi}\sum_{a}^{a}\left[\bar{H}_t(\overline{ta})A\right]_a \qquad (10)$$

## 3. TROMBE WALL UN-UTILIZABILITY FOR MULTIPLE APERTURES

The un-utilizability method for Trombe walls characterizes the performance of the building by two parameters, the infinite mass solar fraction, $F_i$, and the storage dump ratio, Y, which are

$$F_i = (\ L_w + Q_{in}\ ) / (\ L_{ns} + L_w\ ) \qquad (11)$$

$$Y = (\ S_b + 0.047\ S_w\ ) / Q_{dump} \qquad (12)$$

where $L_w$ is the heat loss through the wall if there were no solar gain, $Q_{in}$ is the heat conducted through the wall, and $L_{ns}$ is the building heat load if the wall transferred no heat. $S_b$ and $S_w$ are the thermal storage capacity of the building and wall, respectively. $Q_{dump}$ is the heat gain in excess of that used

to meet the immediate load. These variables are all formally defined in (3).

$Q_{dump}$ is defined as

$$Q_{dump} = \frac{U_k A(\overline{ta})}{U_k + U_L} \sum^{N} \sum^{n} ( I_t - I_c )^+ \qquad (13)$$

where $U_k$ is the conductance of the wall and $U_L$ is the conductance from the outer wall surface to the ambient air. Both of these quantities are formally defined in (3). The critical level $I_c$ is defined as

$$I_c = \frac{(T_r - \overline{T}_o)}{(\overline{ta})\ A} \left\{ (UA)_{ns} \left[ \frac{U_L + U_k}{U_k} \right] \left[ \frac{T_b - \overline{T}_o}{T_r - \overline{T}_o} \right] + U_L A \right\} \qquad (14)$$

Substitution of Eq 14 into Eq 13 and summing over multiple apertures gives

$$Q_{dump} = \sum^{N} \sum^{n} \left( \frac{U_k A}{U_L + U_k} \right)_a \left[ \overline{H}_t(\overline{ta}) - U_L(T_r - \overline{T}_o) \right]_a - (UA)_{ns} (T_b - \overline{T}_o) \Big\}^+ \qquad (15)$$

where $(UA)_{ns}$ is the building heat loss coefficient without the Trombe walls, $T_b$ is the degree day base temperature for the building, $T_r$ is the thermostat set temperature, and $\overline{T}_o$ is the outdoor air temperature. The summation over N days is again made by a proportional number of clear and cloudy days to match solar radiation data for the location. Once $Q_{dump}$ is determined by summation over the apertures, the solar fraction for the combined systems can be found from

$$Y = S_b + 0.047 \sum^{a} (S_w)_a \ / \ Q_{dump} \qquad (16)$$

$$F_i = (\sum^{a} L_w + \sum^{a} Q_{in}) \ / \ (L_{ns} + \sum^{a} L_w) \qquad (17)$$

where $L_w$ and $Q_{in}$ are calculated for each Trombe wall individually just as for a single aperture system.

## 4. NOTES ON COMBINED DIRECT GAIN/TROMBE WALL SYSTEMS

An estimate of the passive performance of buildings with a combination of Trombe walls and direct gain can be made by a procedure similar to that outlined above. The heat load is divided between the two types of systems in proportion to their relative solar gain and solar fractions calculated for each. These fractions are then averaged using the same weighting factor. If these fractions differ significantly, then the load proportioning may have to be adjusted and the calculation performed again. This is to prevent one system from being estimated to operate more efficiently at the expense of the other.

The critical load used to determine the un-utilizability or Q for the systems provides a means of calculating an upper and lower bound on combined system performance. If a portion of the immediate load is used to calculate the critical load for each system, an assumption that the two systems deliver heat simultaneously is implicit. Heat delivery from Trombe walls is delayed significantly by the time required for conduction through the wall, so the un-utilizability for the combination will be less. The upper bound on combined performance can be calculted by using the entire immediate load to calculate the critical load for each system, implying that the systems' heat delivery schedules do not overlap at all, i.e, the building has cooled to its thermostat set point before heat is delivered by the Trombe wall.

## 5. EXAMPLE CALCULATION

Performance calculations for a building in Taos, New Mexico, are summarized in Tables 1-3. The building has 28 square meters (300 $ft^2$) of direct gain glazing and an appropriate amount of thermal mass. Its performance is shown with two different configurations for the glazing. The system labelled "S" in Table 3 has the entire glazing on the south side, while the system labelled "S/SE" has one third of the glazing facing southeast. With the building data shown in Table 1 and the weather data shown in Table 2, the two designs' performance is shown in Table 3. The annual auxiliary energy required by the buildings is nearly identical. This result is somewhat suprising since the "S/SE" system has much lower solar/load ratios during the heart of the heating season. This is a result of better use being made of the solar gain as indicated by the lower un-utilizability shown by the "S/SE" system. A further important effect is that the same solar fraction can be provided with lower solar load ratios during the winter. This indicates that a greater degree of comfort is provided due to lower temperature swings, particulary in high solar fraction buildings. It should be noted that this is indicated despite the fact that lower morning outdoor temperatures would further decrease the un-utilizability if they were taken into account. Increased ventilation for the "S/SE" system during April, May, and September is also indicated in Table 3 by the higher solar load ratios for those months.

## 6. CONCLUSION

A means exists to apply the un-utilizability passive solar design method to multiple aperture systems. It involves an instantaneous solar radiation model to calculate the un-utilizability

by integration, but requires significantly less computational effort, weather data, and building description data than a network simulation. The technique preserves the utility of the original method while expanding upon it to allow the effects of the timing of solar gains to be taken into account. It allows an estimate of upper and lower bounds of combined direct gain/Trombe wall system performance to be made, and points out the need for research on the timing of solar heat transfer through Trombe walls.

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TABLE 1. BUILDING DATA

| | | | | |
|---|---|---|---|---|
| Location: | Taos, New Mexico | | Latitude 36.5 degrees N | |
| Building Load Coefficient: | 570 | $kJ\text{-}hr^{-1}\text{-}{}^{o}C^{-1}$ | 300 | $Btu\text{-}hr^{-1}\text{-}{}^{o}F^{-1}$ |
| Total Solar Glazed Area: | 28 | $m^2$ | 300 | $ft^2$ |
| Overall Load Coefficient: | 850 | $kJ\text{-}hr^{-1}\text{-}{}^{o}C^{-1}$ | 450 | $Btu\text{-}hr^{-1}\text{-}{}^{o}F^{-1}$ |
| Thermostat Set Temperature: | 18 | $^{o}C$ | 65 | $^{o}F$ |
| Ventilation Temperature: | 24 | $^{o}C$ | 75 | $^{o}F$ |
| Internal Heat Generation: | 114 | $MJ\text{-}day^{-1}$ | 60000 | $Btu\text{-}day^{-1}$ |
| Effective Internal Mass: | 27 | $MJ\text{-}{}^{o}C$ | 14000 | $Btu\text{-}{}^{o}F$ |

TABLE 2. WEATHER DATA

| Month | Average Horizontal Radiation | | Clearness Index | Average Outdoor Temperature | | Heating Degree Days | |
|---|---|---|---|---|---|---|---|
| | $kJ\text{-}m^{-2}\text{-}day^{-1}$ | ($Btu\text{-}ft^{-2}\text{-}day^{-1}$) | | $^{o}C$ | ($^{o}F$) | 15.2°C base | (59.4°F base) |
| Sept | 19100 | (1950) | .72 | 15 | (59) | 50 | ( 100) |
| Oct | 14800 | (1510) | .72 | 9 | (49) | 190 | ( 340) |
| Nov | 10600 | (1080) | .68 | -1 | (31) | 480 | ( 870) |
| Dec | 8600 | ( 870) | .64 | -3 | (27) | 550 | ( 980) |
| Jan | 9500 | ( 970) | .65 | -4 | (25) | 590 | (1070) |
| Feb | 12700 | (1300) | .67 | -1 | (31) | 440 | ( 800) |
| Mar | 16900 | (1730) | .68 | 3 | (38) | 370 | ( 660) |
| Apr | 21600 | (2210) | .71 | 8 | (47) | 230 | ( 410) |
| May | 24900 | (2550) | .73 | 13 | (55) | 100 | ( 180) |

TABLE 3. SYSTEM PERFORMANCE COMPARISON

| Month | Heating Load GJ | (MMBtu) | System | Solar Load Ratio | Storage Dump Ratio | Un-Utiliz-ability | Solar Fraction | Auxiliary Energy GJ | (MMBtu) |
|---|---|---|---|---|---|---|---|---|---|
| Sept | 1.1 | ( 1.0) | S | 7.39 | .56 | .99 | 1.00 | 0.0 | (0.0) |
| | | | S/SE | 7.73 | .53 | .99 | 1.00 | 0.0 | (0.0) |
| Oct | 3.8 | ( 3.6) | S | 2.93 | .46 | .86 | .94 | 0.2 | (0.2) |
| | | | S/SE | 2.78 | .49 | .85 | .93 | 0.3 | (0.3) |
| Nov | 9.8 | ( 9.3) | S | 1.21 | .54 | .69 | .56 | 4.3 | (4.1) |
| | | | S/SE | 1.11 | .61 | .66 | .55 | 4.4 | (4.2) |
| Dec | 11.1 | (10.5) | S | 1.03 | .59 | .65 | .52 | 5.4 | (5.1) |
| | | | S/SE | .94 | .68 | .62 | .51 | 5.5 | (5.2) |
| Jan | 12.1 | (11.5) | S | .99 | .61 | .63 | .51 | 5.9 | (5.6) |
| | | | S/SE | .90 | .70 | .60 | .50 | 6.0 | (5.7) |
| Feb | 9.1 | ( 8.6) | S | 1.15 | .61 | .65 | .58 | 3.8 | (3.6) |
| | | | S/SE | 1.08 | .67 | .63 | .57 | 3.9 | (3.7) |
| Mar | 7.5 | ( 7.1) | S | 1.22 | .76 | .61 | .64 | 2.6 | (2.5) |
| | | | S/SE | 1.23 | .77 | .65 | .65 | 2.5 | (2.4) |
| Apr | 4.6 | ( 4.4) | S | 1.32 | 1.12 | .67 | .77 | 1.1 | (1.0) |
| | | | S/SE | 1.52 | .94 | .69 | .82 | 0.8 | (0.8) |
| May | 2.0 | ( 1.9) | S | 2.06 | 1.41 | .79 | 1.00 | 0.0 | (0.0) |
| | | | S/SE | 2.67 | 1.02 | .84 | 1.00 | 0.0 | (0.0) |
| Year | 61.1 | (57.9) | S | | | | .62 | 23.3 | (22.1) |
| | | | S/SE | | | | .62 | 23.4 | (22.2) |

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# A NEW PASSIVE SOLAR SPACE HEATING SYSTEM DESIGN METHOD FOR THE UNITED STATES

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## ABSTRACT

This paper presents a new method for predicting the annual auxiliary space heating requirements of passively heated solar houses in the United States. It features closed-form, analytical expressions for solar system performance that are amenable to use by architects, engineers, or homebuilders with the aid of an inexpensive, programmable calculator. The method is applicable to direct gain, water storage wall, or mass storage (Trombe) wall passive solar heating systems and is general in practice in that it does not restrict the user to a particular "reference" system. It permits the rapid assessment of the performance effects of variations in such system features as south glazing, thermal storage, or movable insulation. Furthermore, the auxiliary energy estimates of the thermal performance model upon which the method is premised have been compared with measured auxiliary energy usage data from owner-occupied, passively heated solar houses. Substantial agreement exists between predicted and measured results for a number of houses over a series of months within the 1981-82 space heating season. While this in no sense constitutes a complete validation of the thermal performance model, it does demonstrate its viability when applied to actual passively heated solar houses.

## 1. INTRODUCTION

An analytical, passive solar space heating system thermal performance model developed by Gordon and Zarmi (1) and Typical Meterological Year (2) weather data were utilized to develop specific annual passive solar space heating system performance expressions for each of 26 United States locations. The thermal performance model links the passive solar system performance to the solar-to-load ratio, SLR. In concept, annual system performance represents a summation of individual daily results over the heating season. In practice, the method is relatively easy to implement and yields the annual auxiliary space heating requirements of a proposed residence without requiring intermediate, monthly calculations. The estimation of annual performance typically requires several minutes with the use of a programmable calculator and is particularly useful through the schematic design phase. The necessary site-specific inputs to the method have been tabulated by location in Table 1 in the Appendix.

The development of annual performance expressions from the analytical model is described and the steps in using the method delineated. An example is worked for a direct gain system in Albuquerque, New Mexico, illustrating the method's simplicity and flexibility. Additionally, the results of a study are presented in which the auxiliary energy estimates of the performance model were compared with actual measured auxiliary energy usage in eleven owner-occupied, passively heated solar residences. Actual space heating auxiliary energy usage of solar heated houses often differs substantially from the designers' estimates, in part due to the variations of yearly weather patterns, mechanical system efficiencies, and occupant effects. In some instances, the design tool may have been improperly implemented or unsuitable for the task. Although uncertainty will always persist in the solar design process, the systematic monitoring of solar heated houses provides valuable information with which researchers may examine the appropriateness and limitations of design tools and report the results to the design community. In this particular study, the performance data used were those obtained by personnel in the Class B Passive Solar Performance Monitoring Program (3) conducted by the Solar Energy Research Institute (SERI) for the United States Department of Energy. These data have recently been archived at SERI, and the results of the monitoring program for the 1981-82 space heating season were published (4).

## 2. ANNUAL PERFORMANCE EXPRESSION DEVELOPMENT

The thermal performance model specifically calculates daily system performance within each of two distinct daily periods, the daytime and nighttime. In equation form:

$$SHF_d = c_d \, SLR \qquad (1a)$$

$$SHF_n = c_n \, SLR \qquad (1b)$$

The terms $c_d$ and $c_n$ are dependent upon both the type of proposed passive solar heating system and its geographical location. Physically, they are a measure of effectiveness of the thermal storage mass in absorbing and storing transmitted solar radiation for subsequent conditioning of the room air. The reader is referred to Ref. 1 for the specific expressions with which to calculate $c_d$ and $c_n$ for direct gain, water storage walls, or Trombe wall systems.

The daily solar heating fraction is determined by weighting the solar fraction in each period by the fraction of the space heating load attributable to each. In equation form:

$$SHF = SHF_d F_d + SHF_n F_n \qquad (2)$$

The required daily auxiliary energy requirement is:

$$Q_{aux,d} = (1 - SHF) \, L_d \qquad (3)$$

Closed-form expressions similar to Eqs. 1-3 for annual system performance preclude the need to perform distinct calculations for each day in the heating season. These have been derived using a statistical model, unique for each location, that represents the anticipated frequency of occurrence of the various SLR values over the heating season. In effect, daily performance results are summed through the process of mathematical integration. The resulting annual performance expression for any location is presented in Eq. 4 for the daytime period.

$$SHF_{ann,d} = 1- \{A + [B + (C + [D + EV_d]V_d)V_d]V_d\}V_d \qquad (4)$$

The terms A,B,C,D, and E represent the particular SLR statistical function for a given location. The expression for the nighttime period is similar in form except $V_d$ is replaced by $V_n$ where:

$$V_d = (.176 \, UA)(A_c \bar{\tau}\bar{\alpha} c_d)^{-1} \qquad (5a)$$

$$V_n = (.176 \, UA)(A_c \bar{\tau}\bar{\alpha} c_n)^{-1} \qquad (5b)$$

Eq. 4 is simple to implement. Once the general form of the equation is programmed into the calculator, changes to a proposed residence or its passive solar space heating system are introduced through variations in the terms $V_d$ and $V_n$.

The annual auxiliary energy requirement is:

$$Q_{aux,a} = (1- (SHF_{ann,d}F_{a,d} + SHF_{ann,n}F_{a,n}))L_{ann} \qquad (6)$$

where $L_{ann}$ is the annual heating load net of internal gains.

The average daytime and nighttime space heating fractions, $F_{a,d}$ and $F_{a,n}$, have been determined for each location. Also tabulated are the terms R, S, and T. R represents the daytime and nighttime solar heating fraction above which Eq. 4 is valid. S is utilized in an intermediate calculation to determine, in effect, an average SLR over the heating season. T is the average hourly length of the daytime period and is used in the determination of $c_d$ and $c_n$.

## 3. COMPARISONS OF THE THERMAL PERFORMANCE MODEL WITH MEASURED DATA

The Class B Passive Solar Performance Monitoring Program monitored the thermal performance of owner-occupied, passively heated solar houses in a variety of climates employing standardized monitoring and reporting procedures (5). A microprocessor-based data-acquisition system was installed in each home to monitor continuously up to 14 analog or digital channels and 8 status channels. Their hourly averages or totals were recorded on magnetic tape for subsequent analysis. Other key thermal parameters required to maintain an overall energy balance on the home were determined with a series of on-site tests prior to the commencement of monitoring. Included were the steady-state conduction loss of the building envelope (6), its effective leakage area (7), and for non-electric auxiliary heating systems, the system efficiency in delivering heat to the living zone. The leakage area, for example, permits an estimation of the dynamic infiltration rate using techniques developed at Lawrence Berkeley Laboratory (7). A typical system used a gas furnace relay switch coupled with a known rate of energy delivery to determine the hourly auxiliary energy input to the living zone. Internal gains were estimated from occupancy data and other measured purchased energy not attributable

to the space heating system. A manual for each site was prepared, detailing the data acquisition system, the construction of the house, anomalies in the monitoring effort, and other pertinent information.

Sufficient information was available for the Class B buildings to calculate daily SLR values, estimate corresponding auxiliary energy requirements, and compare them to measured values. Each of the houses was selected for its relative simplicity in design. All but one was modeled as a direct gain passive solar heating system, the exception being a Trombe wall. One system was essentially a sun-tempered design with the thermal storage mass consisting primarily of sheetrock on the walls. Table 2 in the Appendix contains specific information for each house including its location, passive system type, and months of applicable measured performance data. Days were analyzed only if 24 continuous hours of data were available. In developing a database for overall model comparisons which would reflect general thermal performance trends, the month was selected as a period of time in which to determine average daily measured and estimated auxiliary energy usage. Complete months of continuous data were generally unavailable due to routine maintenance and equipment downtime.

Measured and simulated daily average auxiliary energy usage values are plotted in Fig. 1 for all houses studied. The graph suggest a strong linear relationship between the data points. A least squares fit of the data confirms this observation, yielding a slope of .96, a Y-intercept of 1911 Wh $day^{-1}$ (6520 Btu $day^{-1}$) and a Pearson Product-Moment correlation coefficient (r) of .95. Furthermore, a t-test indicates that at the 5 per cent level of significance, the difference between the means of measured and simulated values is statistically indistinguishable from zero. These absolute and statistical comparisons lend credibility to the thermal performance model, although they will remain tenative until the systematic evaluation of the accuracy of the Class B monitoring system has been completed. This work is currently in progress.

## 4. THE METHOD ILLUSTRATED: AN EXAMPLE CALCULATION

Consider a house in Albuquerque, New Mexico, with a direct gain, passive solar space heating system. The solar aperture consists of 23.2$m^2$ (250 $ft^2$) of south facing, vertical glazing ($\bar{\tau}$ = .673) and is unshaded. The heat loss coefficient of the building, including infiltration, is 257.4 $W°C^{-1}$ (488 Btu $hr^{-1}°F^{-1}$). The thermal storage mass consists of a 15.2cm (6 in) thick concrete slab-on-grade with a surface area of 23.2$m^2$ (250 $ft^2$) and an absorptance of .8. The effective absorptance of the living zone to transmitted radiation is .95, and interior furnishings restrict 20 per cent of the transmitted radiation from impinging upon the storage mass. Night insulation is not used.

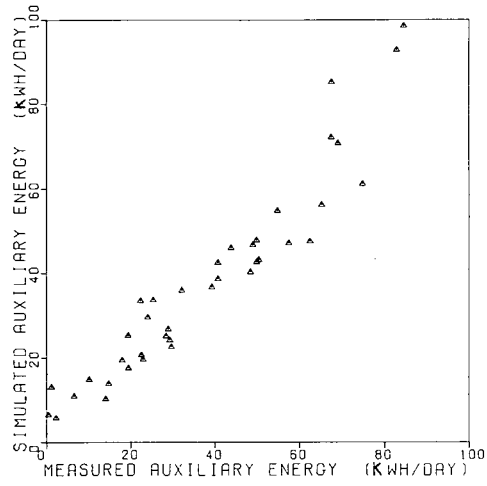



Fig. 1. MEASURED VERSUS SIMULATED AVERAGE DAILY AUXILIARY ENERGY USAGE

The five steps the designer must use are as follows:

Step 1. From Table 1 select the Terms A, B, C, D, E, $F_{a,d}$, $F_{a,n}$, R, S, and T for the location in question.
For Albuquerque:

| | |
|---|---|
| A = -.0191663 | $F_{ad}$ = .367 |
| B = .0448628 | $F_{an}$ = .633 |
| C = -.0076262 | R = .299 |
| D = .0005513 | S = 3.437 |
| E = -.0000152 | T = 10.6 |

Step 2. Calculate $c_d$ and $c_n$ using the appropriate expressions from Ref. 1.

For Albuquerque: $c_d$ = 1.939
$c_n$ = .455

Step 3. Determine if either $SV_d^{-1}$ or $SV_n^{-1}$ are less than R. If so, then

$$SHF_{ann,d} = SV_d^{-1}$$

or, $$SHF_{ann,n} = SV_n^{-1}$$

For Albuquerque:

$$SV_d^{-1} = (3.437)(1.575)^{-1} = 2.183$$

$$SV_n^{-1} = (3.437)(6.710)^{-1} = .512$$

The condition is not satisfied. Proceed to Step 4.

Step 4. Using Eq. 4, calculate $SHF_{ann,d}$ and $SHF_{ann,n}$.

For Albuquerque: $SHF_{ann,d} = .945$
$SHF_{ann,n} = .502$

Step 5. Using Eq. 7, calculate the annual auxiliary energy space heating requirement.

For Albuquerque: The annual degree days, base 18.3°C (65°F), are 2384 (4292).

$$Q_{aux,a} = (1- ((.945)(.367) + (.502)(.633))$$

$$\times(2384) \times (24) \times (257.9)$$

$$Q_{aux,a} = 4.95 \text{ mWh yr}^{-1} \text{ (16.89 MMBtu yr}^{-1})$$

If the concrete slab were 7.6 cm (3 inches) thick:

$C_d = 2.198$ $c_n = .306$

$SHF_{ann,d} = .959$ $SHF_{ann,n} = .339$

$Q_{aux,a} = 6.40 \text{ mWh yr}^{-1} \text{ (21.82 MMBtu yr}^{-1})$

If night insulation with a thermal resistance of 28.4 Wh $m^{-2}$ $°C^{-1}$ (5 Btu $ft^{-2}$ $°F^{-1}$) was used over the south glazing during the nightime period:

$F_{a,d} = .422$ $F_{a,n} = .578$

$c_d = 1.686$ $c_n = .498$

$SHF_{ann,d} = .927$ $SHF_{ann,n} = .642$

$Q_{aux,a} = 3.74 \text{ mWh yr}^{-1} \text{ (12.76 MMBtu yr}^{-1})$

## 5. CONCLUSIONS

A rapid and accurate method has been presented for estimating the annual auxiliary energy requirements of passively heated solar houses. Its relative simplicity permits individuals with a fundamental understanding of building physics to evaluate the thermal performance of present or proposed passive solar space heating systems. Two significant attributes are its applicability to "non-reference" systems and inexpensive, programmable calculator hardware requirement. The method is particularly valuable in the schematic design phase when the economic tradeoffs among building components are being investigated.

## 6. NOMENCLATURE

- A - location dependent SLR statistic coefficient
- $A_c$ - net area of south facing, vertical glazing, $m^2$ ($ft^2$)
- B - location dependent SLR statistic coefficient
- Btu - British thermal unit
- C - location dependent SLR statistic coefficient
- °C - degrees Celsius
- $c_d$ - term relating SLR to the daytime solar heating fraction
- $c_n$ - term relation SLR to the nightime solar heating fraction
- cm - centimeter
- D - location dependent SLR statistic coefficient
- E - location dependent SLR statistic coefficient
- $F_d$ - fraction of the space heating load occurring in the daytime for a particular day
- $F_n$ - fraction of the space heating load occurring in the nightime for a particular day
- $F_{a,d}$ - average daytime load fraction over the heating season
- $F_{a,n}$ - average nightime load fraction over the heating season
- °F - degrees Fahrenheit
- $ft^2$ - square feet
- in - inch
- kWh - kilowatt hour
- $L_d$ - the space heating load for a particular day, kWh (Btu)
- $L_{ann}$ - the annual space heating load, mWh (MMBtu)
- mWh - megawatt hour
- $m^2$ - square meters
- MMBtu - million Btu
- $Q_{aux,a}$ - net auxiliary energy requirement for the heating season, mWh (MMBtu)

$Q_{aux,d}$ - net auxiliary energy requirement for a particular day, kWh (Btu)

R - the annual daytime or nighttime solar heating fraction above which Eq. 4 is valid

S - location dependent term used in calculating an average SLR over the heating season

SHF - the solar heating fraction for a particular day

$SHF_d$ - the daytime solar heating fraction for a particular day

$SHF_n$ - the nighttime solar heating fraction for a particular day.

$SHF_{ann,d}$ - the annual daytime solar heating fraction

$SHF_{ann,a}$ - the annual nightime solar heating fraction

SLR - the ratio of daily net transmitted radiation to the space heating load

T - the average length of the daytime period over the heating season, hours.

UA - the average heat loss coefficient of the building envelope including infiltration and south glazing, $W°C^{-1}$ ($Btu\ hr^{-1}°F^{-1}$)

$V_d$ - term used in calculating the annual daytime solar heating fraction

$V_n$ - term used in calculating the annual nightime solar heating fraction

W - watt

Wh - watt hour

yr - year

$\bar{\tau}$ - the average transmittance of south facing, vertical glazing over the heating season to both direct beam and diffuse radiation

$\bar{\alpha}$ - the net absorptance of the passive solar space heating system to transmitted radiation

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## 8. APPENDIX

TABLE 1
SITE SPECIFIC TERMS FOR THE METHOD

| | A | B | C | D | E | $F_{a,d}$ | $F_{a,n}$ | R | S | T |
|---|---|---|---|---|---|---|---|---|---|---|
| Ft. Worth, TX | .0321866 | .0095586 | -.0015698 | .0001074 | -.0000028 | .340 | .660 | .355 | 4.487 | 10.5 |
| Lake Charles, LA | .0255433 | .0140682 | -.0024463 | .0001594 | -.0000036 | .293 | .707 | .314 | 3.969 | 10.6 |
| Columbia, MO | .0259708 | .0383422 | -.0083978 | .0007148 | -.0000220 | .392 | .608 | .326 | 2.390 | 10.4 |
| Apalachicola, FL | .0070367 | .0078421 | -.0009139 | .0000440 | -.0000008 | .319 | .681 | .551 | 5.557 | 10.6 |
| Brownsville, TX | .0167815 | .0069509 | -.0007930 | .0000375 | -.0000007 | .102 | .898 | .456 | 6.394 | 10.6 |
| Charleston, SC | .0022360 | .0325494 | -.0055085 | .0003884 | -.0000103 | .322 | .678 | .304 | 3.397 | 10.5 |
| Nashville, TN | .0267145 | .0664989 | -.0173327 | .0019119 | -.0000842 | .375 | .625 | .320 | 1.838 | 10.3 |
| Dodge City, KS | -.0048881 | .0666626 | -.0129489 | .0009202 | -.0000197 | .384 | .616 | .226 | 2.106 | 10.5 |
| Caribou, ME | .0133573 | .2943295 | -.1463973 | .0292388 | -.0021463 | .421 | .579 | .289 | 1.110 | 10.6 |
| Madison, WI | .0480057 | .2331796 | -.1150020 | .0225717 | -.0016323 | .403 | .597 | .292 | 1.217 | 10.3 |
| El Paso, TX | -.0083467 | .0174987 | -.0013154 | .0000020 | .0000018 | .331 | .669 | .329 | 4.510 | 10.5 |
| Albuquerque, NM | -.0191663 | .0448628 | -.0076262 | .0005513 | -.0000152 | .367 | .633 | .299 | 3.437 | 10.6 |
| Ely, NV | -.0231983 | .0831832 | -.0177532 | .0015197 | -.0000474 | .395 | .605 | .201 | 2.253 | 10.9 |
| Phoenix, AZ | -.0030952 | .0094425 | -.0006568 | .0000144 | .0000000 | .238 | .762 | .394 | 6.919 | 10.3 |
| Santa Maria, CA | -.0028175 | .0127112 | .0001977 | -.0001630 | .0000077 | .311 | .689 | .348 | 4.293 | 11.2 |
| Bismark, ND | -.0076824 | .3647010 | -.2017385 | .0463027 | -.0039692 | .393 | .607 | .318 | 1.115 | 10.1 |
| Great Falls, MT | .0126627 | .1771985 | -.0705043 | .0113912 | -.0006813 | .390 | .610 | .302 | 1.461 | 10.2 |
| Medford, OR | .0398285 | .1397344 | -.0582003 | .0095633 | -.0005689 | .382 | .618 | .331 | 1.796 | 10.5 |
| Seattle, WA | .0617372 | .1871966 | -.0891900 | .0164693 | -.0011006 | .405 | .595 | .300 | 1.240 | 10.6 |
| Fresno, CA | .0232922 | .0298990 | -.0058628 | .0004793 | -.0000150 | .336 | .664 | .327 | 3.222 | 10.3 |
| Cape Hatteras, NC | .0046452 | .0292313 | -.0043473 | .0002508 | -.0000052 | .385 | .615 | .264 | 3.997 | 10.6 |
| Washington, DC | .0226693 | .0904003 | -.0264681 | .0030428 | -.0001271 | .385 | .615 | .284 | 2.006 | 10.5 |
| Boston, MA | .0943264 | .1286896 | -.0580661 | .0100897 | -.0006495 | .404 | .596 | .284 | 1.312 | 10.4 |
| New York, NY | .1064910 | .1019380 | -.0367830 | .0043726 | -.0001482 | .405 | .595 | .224 | 1.236 | 10.4 |
| Omaha, NE | .0096667 | .0888594 | -.0251150 | .0028028 | -.0001131 | .399 | .601 | .308 | 1.978 | 10.3 |
| Denver, CO | -.0081587 | .0577701 | -.0110331 | .0008405 | -.0000232 | .376 | .624 | .185 | 2.715 | 10.6 |

TABLE 2
CLASS B SITE DESCRIPTIONS

| SERI Site Code | Location | Building Type | Passive Heating System | Auxiliary Heating System | Months of Data Used |
|---|---|---|---|---|---|
| DMD | Golden, Co. | Single-Family | Direct Gain | Natural Gas Forced Air | 3 |
| DMF | Arvada, Co. | Single-Family | Direct Gain | Natural Gas, Forced Air | 5 |
| DMH | Denver, Co. | Multi-Family | Direct Gain | Natural Gas, Forced Air | 4 |
| DMI | Denver, Co. | Single-Family | Direct Gain | Natural Gas, Forced Air | 6 |
| DMK | Aurora, Co. | Single-Family | Trombe Wall | Natural Gas, Forced Air | 2 |
| DML | Aurora, Co. | Single-Family | Direct Gain | Natural Gas, Forced Air | 4 |
| MBA | Boulder, Co. | Single-Family | Direct Gain | Electrical Resistance Forced Air | 5 |
| MAC | Eau Claire, Wis. | Single-Family | Direct Gain | Propane Gas, Forced Air | 3 |
| MAB | Cedar Rapids, Ia. | Single-Family | Direct Gain | Electrical Resistance Forced Air | 2 |
| NEC | Tolland, Conn. | Single-Family | Direct Gain | Electrical Resistance Baseboard | 2 |
| NED | Newport, Vt. | Single-Family | Direct Gain | Electrical Resistance Baseboard | 3 |

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# ANNUAL THERMAL UTILITY OF INTERNAL GAINS

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## ABSTRACT

In energy-efficient homes the energy used for space heat has been reduced to a small fraction of the energy used for lights, appliances and water heat. Further energy savings can be obtained by reducing the energy used by appliances. However, in such homes the waste heat from appliances provides a large portion of the space heat. Reducing the appliance gains will increase the space heating energy and decrease the space cooling energy.

This paper presents an analysis of the impact of internal gains on thermal loads. Two designs were considered: a standard design with windows equally distributed and low thermal storage and a passive solar design with mostly south glass and high thermal storage. In each case, the level of internal gains was cut in half, and the resulting change in thermal loads was noted. The ratio of the change in annual thermal loads to the change in annual internal gains was defined as the utility of the gains. The utility was found to correlate well with the annual space heat. The results are presented both graphically and in a form suitable for use on a pocket calculator.

## 1. INTRODUCTION

In energy-efficient homes, space heating has been reduced to a small fraction of the total energy consumption of the building. A group of efficient homes in Eugene, OR, is an example. These homes average 1130 square feet of floor area. They are moderately well-insulated with R-38 roofs, R-19 walls and floors, double glazing, and about .34 air changes per hour. The over-all heat loss rates are about 230 Btu/°F-h. The consumption for space heat, water heat, and appliances has been monitored for more than four years. The annual consumption of these homes averaged 17171 kWh. Of this, 5825 kWh was for water heat, 8379 kWh for appliances, and 2967 kWh for space heat. Thus, space heat is only 17 percent of the total consumption. In designs which are super-insulated, the space heat consumption will be even less.

However, in these low-energy buildings, the heat released from appliance usage provides a large portion of the space heating. Further energy savings will require reductions in the appliance and water heating energy. This will result in some increase in the space heating energy. It will also result in a decrease in space cooling energy. This interaction between conservation of space conditioning energy and appliance energy must be quantified in order to make accurate estimates of the over-all energy savings.

Only a portion of the appliance energy is released as heat inside the insulation envelope of the home. In this paper we will refer to the sensible heat released to the interior of the home due to occupancy as internal gains. Internal gains also include heat released from the bodies of people and pets. Latent heat effects which can be of importance in hot, humid climates are not considered here. The magnitude of internal gains is difficult to estimate because of the wide variation in ownership and use of appliances. The fraction of energy from a given appliance which contributes to internal gains varies from 0 to 100 percent. A widely used set of estimates for the average annual consumption of several appliances and the portion which is released as sensible heat is shown in Table 1. In this estimate, which assumes all of the appliances are within the insulation envelope, approximately 50 percent of the annual appliance energy is released as heat.

The internal gains are not totally useful in reducing space heat. During the summer, for instance, appliance energy will not contribute to the space heating because no space heating is required. In fact, the appliance gains may create additional cooling loads. This is more likely to be true in homes with passive solar design features.

This paper builds on previous work by the

authors (1) which used a slightly different approach and was limited to consideration of the impacts on space heating. Here, the results are extended to include the effects on cooling energy as well.

## 2. METHODOLOGY

The basic approach compares simulated thermal loads at two levels of annual internal gains: 5133 kWh and 2567 kWh. The higher level reflects typical assumptions about the level of internal gains while the lower level is one half as great. In other words, we ask what happens to thermal loads if the level of internal gains is reduced to one half of the original value.

The simulations were performed with a prototype building. The floor area was 1350 square feet. Two designs were considered: a standard design with windows equally distributed to the North, South, East, and West; and a passive solar design with 100 sqft of windows facing South and the remainder divided between East and West. In each case, the total glass area was 146 square feet. The internal gains were assumed constant for each hour of the year. The heating thermostat was set at 65°F and the cooling thermostat at 76°F. For the standard design the effective building heat capacity was assumed to be 4000 Btu/°F. This corresponds to standard wood-frame, gypsum wall board construction. For the solar design it was assumed to be 14000 Btu/°F This corresponds to a thermal mass equivalent to a concrete floor.

For each design we used 26 values of overall steady-state heat loss rate ranging from 152 to 615 Btu/°F-h For a house of this size, the highest loss corresponds roughly to R-11 roof, R-11 walls, R-0 floor, single glazing, and 0.6 air changes per hour. The lowest value corresponds roughly to R-60 roof, R-38 walls, R-42 floors, quadruple glazing, and 0.2 effective air changes per hour using an air-to-air heat exchanger.

Runs were made in each of four climate areas: Portland, OR, a cloudy climate with 4792 heating degree days, Spokane, WA, a sunnier climate with 6835 degree days, Missoula, MT, a cloudy climate with 7772 degree days, and Albuquerque, NM, a very sunny climate with 4292 degree days.

All simulations were made with the SUNDAY program developed at Ecotope. This is a microcomputer program which works on a daily time scale. It has been extensively bench-marked against the SUNCODE and SERIRES detailed hourly simulation programs. In all cases, the annual space heat loads matched those of the hourly programs within one percent or 293 kWh per year, whichever is larger. The annual cooling loads agreed within about ten percent.

The gross annual cooling loads were divided by a factor of 4 to account for a portion of the loads being met by opening doors and windows and the efficiency of the air-conditioner. The heating load was assumed to be met with electric resistance heat at 100 percent efficiency.

The heating loads and combined loads were then compared between the high internal gains case and the low internal gains case. The difference in loads was then divided by the difference in annual internal gains. This provides a dimensionless number between 0 and 1. We refer to this as the utility of

TABLE 1. ESTIMATED AVERAGE APPLIANCE ENERGY AND INTERNAL LOADS

| Source of Internal Loads | Annual Energy Per Unit | Percent Internally Released | Sensible Heat Load |
|---|---|---|---|
| Refrigerator | 1125 kWh | 100 | 1125 kWh |
| Range (cooking) | 1200 kWh | 100 | 800 kWh |
| Freezer | 950 kWh | 100 | 950 kWh |
| Lighting | 1150 kWh | 90 | 1038 kWh |
| Water Heater | 5000 kWh | 20 | 1000 kWh |
| Television (2000 hr) | 200 kWh | 100 | 200 kWh |
| Clothes Dryer | 900 kWh | 17 | 150 kWh |
| Dishwasher | 250 kwh | 0 | 0 kWh |
| Miscellaneous | 300 kWh | 100 | 300 kWh |
| Total | 11075 kWh | | 5563 kWh |

Source: Modified from reference 2.

the internal gains. For the space heat loads, the utility is the fraction of the change in internal gains which is manifested as an increase in heating loads. For the combined heating and cooling loads, the utility is the fraction of the decrease in internal gains which is manifested as an increase in the combined loads.

For a given design, and a given climate, this measure of utility was found to correlate well with the heating energy per square foot of the high gains case. The resulting curves were very close to logarithmic in shape for all points corresponding to non-zero heating loads for the low internal gains assumption. This included all points for Portland, Spokane, and Missoula, and the Albuquerque standard design. For the Albuquerque solar design only the 12 points of highest heat loss rate were used.

Logarithmic curves were fit by the method of least squares for each case. The resulting equations have the form:

$$F = A + B*Ln(Q) \qquad [1]$$

where F = the heating or combined utility of internal gains
A,B = coefficients
Ln = the natural logarithim
Q = the annual heating load for the high gains case in kWh/ft$^2$

The coefficients are given in Table 2 for each case. The goodness of fit is shown by R2, the coefficient of determination, which is the percentage of total variation of the data points explained by the curve fit.

These formulas can be used on a pocket calculator to estimate the utility of internal gains given an estimate of the initial heating loads.

## 3. RESULTS

The results for heating loads are shown in Fig. 1 for the standard design and in Fig. 2 for the passive solar design. The results for the combined loads are shown in Fig. 3 for the standard design and in Fig. 4 for the passive solar design. An examination of Figs. 1 to 4 reveals several general trends:

1. In all cases the utility decreases with decreasing heating energy.

2. The utility is highest for Portland and Missoula, the cloudiest climates, and least for Albuquerque, the sunniest climate.

3. For each climate and design the combined utility is less than the heating-only utility.

4. Both the heating utility and the combined utility are lower for the solar designs. The difference is greatest for Portland and Missoula and least for Albuquerque.

The combined utility of internal gains varies from about .4 to .6 with an initial heating usage of 8 kWh/ft$^2$. For a super-insulated, solar design using only 1 kWh/ ft$^2$ the combined utility of gains ranges from about .1 to .3. The interaction of appliance energy conservation and thermal energy conservation is quite significant over the range of interest. Therefore, the evaluation of appliance efficiency improvements must include the effects of this interaction.

For example, a performance-based building code proposed for new residences in the Pacific Northwest (3) limits space heat consumption to 2 kWh/ft$^2$ in Portland. For the 1350 ft$^2$ prototype this is 2700 kWh per year. A home of standard design built to this code would have a heating utility of 0.48 for the internal gains. If appliance

TABLE 2. COEFFICIENTS FOR USE IN EQUATION 1.

| | Heating Utility | | | Combined Utility | | |
|---|---|---|---|---|---|---|
| Standard Design | A | B | R2 | A | B | R2 |
| Portland | .3976 | .1126 | .9975 | .2933 | .1429 | .9981 |
| Spokane | .3686 | .1136 | .9987 | .2397 | .1461 | .9985 |
| Missoula | .3887 | .1277 | .9987 | .2700 | .1592 | .9989 |
| Albuquerque | .2883 | .0920 | .9980 | .1480 | .1201 | .9981 |
| Solar Design | | | | | | |
| Portland | .3634 | .1159 | .9926 | .2523 | .1497 | .9948 |
| Spokane | .3081 | .1267 | .9943 | .1618 | .1675 | .9948 |
| Missoula | .3591 | .1269 | .9926 | .2287 | .1627 | .9953 |
| Albuquerque | .2590 | .1011 | .9956 | .1194 | .1287 | .9978 |

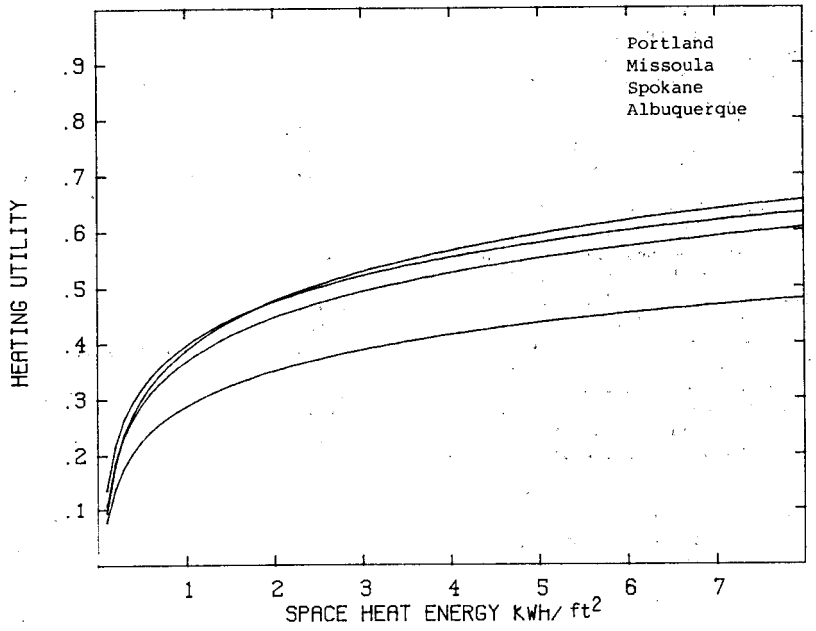



Fig. 1. Fraction of a Decrease in Internal Gains Which is Manifested as an Increase in the Original Heating Load Shown as a Function of the Original Heating Load in Four Climates.

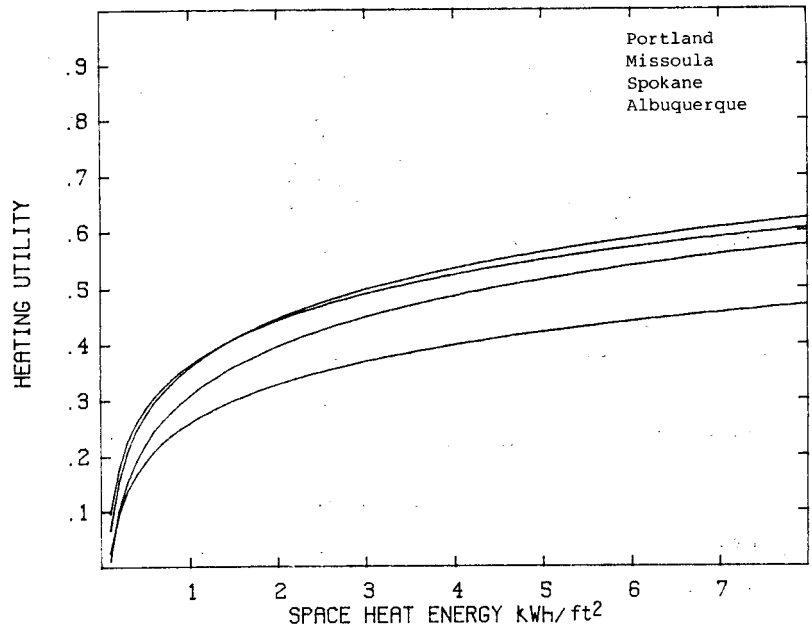



Fig. 2. Fraction of a Decrease in Internal Gains Which is Manifested as as Increase in the Original Heating Load Shown as a Function of the Original Heating Load in Four Climates.

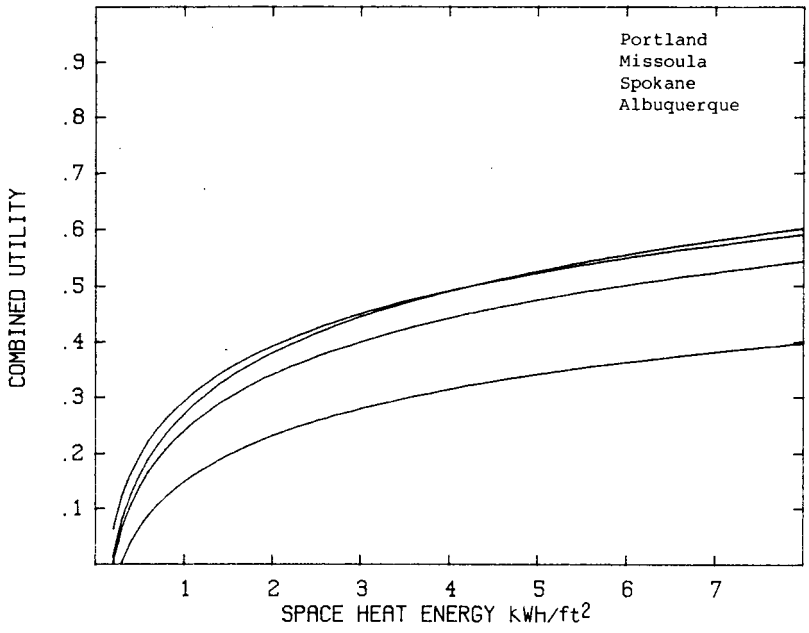



Fig. 3. Fraction of a Decrease in Internal Gains Which is Manifested as an Increase in the Original Combined Heating and Cooling Load Shown as a Function of the Original Heating Load in Four Climates.

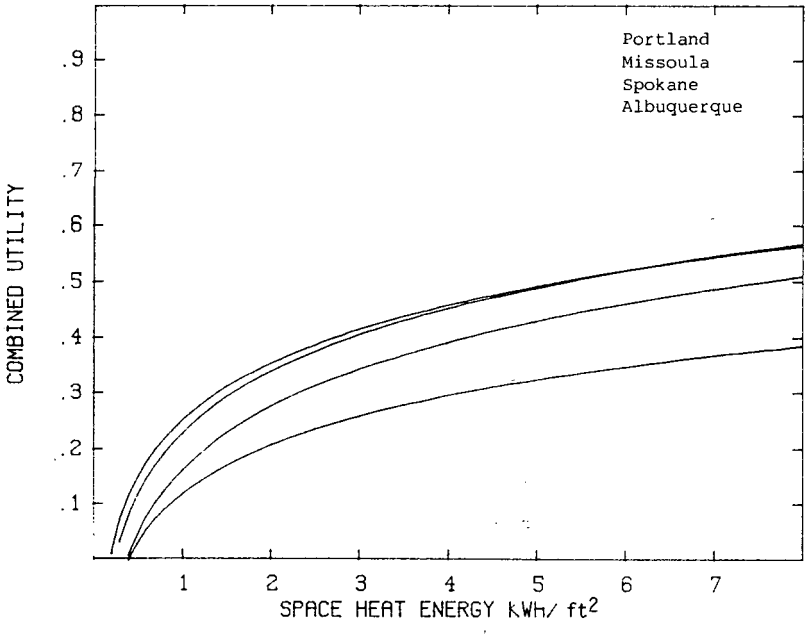



Fig. 4. Fraction of a Decrease in Internal Gains Which is Manifested as an Increase in the Original Combined Heating and Cooling Load Shown as a Function of the Original Heating Load in Four Climates.

efficiency improvements reduced internal gains from 5133 to 2567 kWh per year, the space heat energy would be increased by 48 percent of the reduction in gains or 1232 kWh per year. If the change in internal gains was from appliances which release all of their heat internally, then the overall energy savings from these improvements will be only 52 percent of the expected 2566 kWh per year or 1334 kWh per year. It follows that the cost effectiveness of such improvements is reduced in the same proportion.

In using the results of this paper, one should distinguish carefully between appliance energy and internal gains. The correction of thermal loads depends only on the change in internal gains, not on the change in overall appliance energy. Through careful accounting procedures (See Table 1) it is possible to estimate the change in internal gains resulting from any particular efficiency improvements.

The space heating utility should be adjusted for homes which have a heating system seasonal efficiency which is not 100 percent. This is easily done by use of the equation:

*New Utility = Old Utility x 100/Efficiency*

where the seasonal efficiency is expressed in percent. This adjustment will work for either homes with heat pumps or with gas furnaces.

The sensitivity of these correlations to changes in the initial level of internal gains, the percentage change in internal gains, size of home, and climate has not been fully explored. However, for the standard design, runs were made for homes with a wide spread of floor areas. We also examined the effect of using different initial levels of gains and different percentage reductions in the gains. The results were relatively insensitive to variations in these assumptions over the range of interest expected in most practical applications.

## 4. SUMMARY

The impact of changes in internal gains on building thermal loads was explored through annual simulations for four climate zones. The thermal utility of internal gains was found to correlate well with the space heating load. The resulting curve fits provide a simple means of quantifing the thermal impacts of reduced internal gains. This allows a more accurate evaluation of the overall energy savings when both thermal efficiency measures and appliance efficiency measures are under consideration.

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# PASSIVE SOLAR DESIGN ANALYSIS UTILIZING ELECTRONIC SPREADSHEETS

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## ABSTRACT

This paper presents a method of analyzing passive solar designs using an electronic spreadsheet program such as Visicalc™ or Supercalc™. A simplified solar load ratio method developed at Los Alamos National Laboratory has been implemented on a spreadsheet program. This method offers several advantages over manual or specialized computer programs:

1. Parametric analysis of conservation and passive solar options is easily implemented because the worksheet is automatically recalculated each time a value is changed.

2. The user does not have to purchase or learn how to use a specialized program; the spreadsheet program that the user has can be used.

3. This method is not dependent upon a specific operating system or type of hardware.

## 1. INTRODUCTION

Evaluation of passive solar building and design options has evolved from large simulation computer programs that required mini or mainframe computers to monthly correlation methods that could be done manually but were normally implemented on microcomputers. A project at Los Alamos National Laboratory has simplified the process by one more step by developing a yearly performance correlation that requires only one parameter to characterize the passive system and one parameter to correlate the performance of the solar option during the coldest month to its yearly performance. This method has simplified the evaluation procedure to a degree that it can easily be done manually or implemented on a spreadsheet program.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

## 2. THE FAST SOLAR LOAD RATIO METHOD

The evaluation method developed at Los Alamos National Laboratory is based upon the solar load ratio method (Ref 1). The development of the fast solar load method was presented at the Seventh Passive Solar Conference (Ref 2) and will only be summarized in this paper. The building load coefficient (BLC) is calculated using the following relationships:

BLC (Btu/DD)

$$BLC = L_w + L_n + L_f + L_r + L_i \quad (1)$$

Walls ($L_w$)

$$L_w = 24\ A_w/R_{WALL} \quad (2)$$

Nonsouth Window ($L_n$)

$$L_n = 26\ A_n/NGL_n \quad (3)$$

Floor ($L_f$)

Perimeter (slab on grade)

$$L_f = 100\ P_g/(R_{PERM} + 5) \quad (4a)$$

Floor over crawl space

$$L_f = 24\ A_g/(R_{FLOOR}) \quad (4b)$$

Basement

$$L_f = 256\ P_g/(R_{BASE} + 8) \quad (4c)$$

Roof ($L_r$)

$$L_r = 24\ A_r/R_{ROOF} \quad (5)$$

Infiltration ($L_i$)

$$L_i = 0.432(ACH)(ADR)(H)(A_f) \quad (6)$$

The annual heating load (QL) can now be calculated.

$$QL = [BLC + (G)(A_c)]\ DD_y \qquad (7)$$

The load collector ratio (LCR) and minimum scaled solar load ratio (SLRm*) are calculated as follows:

$$LCR = BLC/A_c \qquad (8)$$

$$SLRm^* = F(SLRm) \qquad (9)$$

$$SLRm = \frac{VT_m/DD_m}{LCR + G} \qquad (10)$$

The ratio of yearly auxiliary heating requirement (QA) to total yearly heating load (QL) and yearly solar heating fraction (SHFy) can now be calculated using the following relationships:

$$\frac{QA}{QL} = e^{-SLRm^*}\ [a(e^{-SLRm^*} - 1) + 1]$$

. . . . . (11)

$$SHFy = 1 - \frac{QA}{QL} \qquad (12)$$

Yearly costs for the heating load (CL) and the auxiliary heating cost (CA) are calculated using fuel cost (c) in $/MMBtu and Equations 7 and 11:

$$CL = QL(c) \qquad (13)$$

$$CA = \frac{QA}{QL}\ (QL)(c) \qquad (14)$$

## 3. USING THE ELECTRONIC SPREADSHEET

The fast solar load ratio method is easily implemented using a spreadsheet program. A spreadsheet program allows the use of cell positions in formulas. For this reason recalculation of the spreadsheet is done whenever a value is changed. Complicated functions, such as exponent, summations, etc., can be used to calculate cell values. Figure 1 shows the simple example using a spreadsheet program. Figure 2 shows the implementation of the fast solar load ratio method using the spreadsheet positions as variable names. Formulas for calculated values are shown next to the cell position. An I next to the cell position indicates that the data are input.

| | | |
|---|---|---|
| PROJECT NAME | | SAMPLE |
| LOCATION | | DODGE CITY |
| ALTITUDE | | 2582 |
| DIMENSIONS | | |
| FLOOR AREA | $FT^2$ | 1500 |
| PERIMETER | FT | 160 |
| HEIGHT | FT | 8 |
| WINDOW AREA | $FT^2$ | 65 |
| SOLAR AREA | $FT^2$ | 390 |
| CONSERVATION | | |
| WALL R-VALUE | | 19 |
| ROOF R-VALUE | | 25 |
| FLOOR R-VALUE | | 12 |
| # OF GLAZINGS | | 2 |
| AIR CHANGES | | .65 |
| BLC CALCULATION | | |
| WALL | | 1042 |
| WINDOW | | 845 |
| ROOF | | 1440 |
| FLOOR | | 941 |
| INFILTRATION | | 3109 |
| TOTAL | BTU/DD | 7377 |
| SOLAR SYSTEM VALUES | | |
| TYPE | F | .76 |
| CONDUCTANCE | G | 1.68 |
| WEATHER | A | .51 |
| ENVIRONMENTAL | | |
| DEGREE DAYS | | 4400 |
| INSOLATION/DD | | 28.98 |
| ENERGY COST $/MMBTU | | 20.00 |
| HEATING LOAD | MMBTU | 32.46 |
| COST W/O SOLAR | | 649.16 |
| SOLAR CALCULATIONS | | |
| LCR | | 18.92 |
| SLR MINIMUM | | 1.07 |
| QA/QL | | 0.23 |
| AUXILIARY HEAT REQUIREMENTS | | |
| ENERGY | MMBTU | 7.41 |
| COST WITH SOLAR | | 148.17 |
| SAVINGS | | |
| ENERGY | MMBTU | 25.05 |
| COST | | 501.00 |

Figure 1. Sample problem using spreadsheet program.

| VARIABLE | CELL | FORMULA |
|---|---|---|
| ALTITUDE | D3 I | |
| FLOOR AREA | D6 I | |
| PERIMETER | D7 I | |
| HEIGHT | D8 I | |
| WINDOW AREA | D9 I | |
| SOLAR AREA | D10 I | |
| WALL R-VALUE | D13 I | |
| ROOF R-VALUE | D14 I | |
| FLOOR R-VALUE | D15 I | |
| # OF GLAZINGS | D16 I | |
| AIR CHANGES | D17 I | |
| WALL (Lw) | D20 | 24*(D7*D8-D9-D10)/D13 |
| WINDOW (Ln) | D21 | 26*D9/D16 |
| ROOF (Lr) | D22 | 24*D6/D14 |
| FLOOR (Lf) | D23 | 100*D7/(D15+5) |
| INFILTRATION (Li) | D24 | .432*D17*D6*D8*(-.3/100000*D3+1) |
| TOTAL (BLC) | D25 | @SUM(D20,D21,D22,D23,D24) |
| SYSTEM TYPE (F) | D28 I | |
| CONDUCTANCE (G) | D29 I | |
| WEATHER (A) | D30 I | |
| DEGREE DAYS (DD) | D33 I | |
| INSOLATION/DD (VT/DD) | D34 I | |
| ENERGY COST (c) | D36 I | |
| HEATING LOAD (QL) | D38 | +D25*D33/1000000 |
| HEATING COST (CL) | D39 | +D38*D36 |
| LCR | D42 | +D25/D10 |
| SLR MINIMUM (SLRm*) | D43 | +D43/(D42+D29)*D28 |
| QA/QL | D44 | @EXP(-D43)*(D30*(@EXP(-D43)-1)+1) |
| AUXILIARY ENERGY (QA) | D47 | +D44*D38 |
| AUXILIARY COST (CA) | D48 | +D47*D36 |
| ENERGY SAVINGS (SE) | D51 | +D38-D47 |
| COST SAVINGS(SC) | D52 | +D51*D36 |

Figure 2. Implementation of the fast solar load ratio method using a spread sheet program.

As an example, suppose that the area for solar features is changed. The following values would automatically be recalculated:

| Variable | Cell |
|---|---|
| $L_w$ (wall) | D20 |
| BLC (total) | D25 |
| QL (heating load) | D38 |
| CL (heating cost) | D39 |
| LCR | D42 |
| SLR minimum | D43 |
| QA/QL | D44 |
| QA (auxiliary energy) | D47 |
| CA (auxiliary cost) | D48 |
| SE (energy savings) | D51 |
| SC (cost savings) | D52 |

This recalculation takes place in less than 5 seconds. Another major advantage is that worksheets can be set up to handle specific cases. For instance, if there was a need to evaluate multiple solar features, a worksheet can be set up specially for that type of evaluation using area weighting techniques. The worksheets can be stored on the user's disk using different names. Simple evaluations can be performed using simple worksheets as in Figure 1. More complicated evaluations would use another worksheet. Figure 3 shows a worksheet that includes multiple solar features. The worksheets can also be set up using different arrangements. The examples use a single-column format. This could easily be changed to a row or multiple-column format.

## 4. SUMMARY

The fast solar load ratio method was developed at Los Alamos National Laboratory to simplify the evaluation of buildings with passive solar features. This method of evaluation is easily implemented using electronic spreadsheet programs. This type of program is easy to use, provides for parametric evaluation, and can use almost any spreadsheet program. The use of the spreadsheet program to perform analysis of buildings with passive features will make it possible for the designer to make many quick and reliable evaluations of the proposed building and passive features.

## 5. REFERENCES

1. J.D. Balcomb et al. Passive Solar Design Handbook, Volume 2, Passive Solar Design Analysis, Department of Energy, Report No. DOE/CS-0127/2. Washington, D.C., Jan. 1980.

2. W.O. Wray et al. "A passive solar design manual for the United States Navy," in Proceedings of the Seventh National Passive Solar Conference, American Solar Energy Society.

| | | |
|---|---|---|
| PROJECT NAME | | SAMPLE |
| LOCATION | | DODGE CITY |
| ALTITUDE | | 2582 |
| DIMENSIONS | | |
| FLOOR AREA | $FT^2$ | 1500 |
| PERIMETER | FT | 160 |
| HEIGHT | FT | 8 |
| WINDOW AREA | $FT^2$ | 65 |
| Solar area1 | $ft^2$ | 190 |
| Solar area2 | $ft^2$ | 200 |
| SOLAR AREA | $FT^2$ | 390 |
| CONSERVATION | | |
| WALL R-VALUE | | 19 |
| ROOF R-VALUE | | 25 |
| FLOOR R-VALUE | | 12 |
| # OF GLAZINGS | | 2 |
| AIR CHANGES | | .65 |
| BLC CALCULATION | | |
| WALL | | 1042 |
| WINDOW | | 845 |
| ROOF | | 1440 |
| FLOOR | | 941 |
| INFILTRATION | | 3109 |
| TOTAL | BTU/DD | 7377 |
| SOLAR SYSTEM VALUES | | |
| Type 1 | f | .7 |
| Type 2 | f | .9 |
| TYPE | F | 0.80 |
| Cond 1 | g | 1 |
| Cond 2 | g | 3 |
| CONDUCTANCE | G | 2.03 |
| WEATHER | A | .51 |
| ENVIRONMENTAL | | |
| DEGREE DAYS | | 4400 |
| INSOLATION/DD | | 28.98 |
| ENERGY COST | $/MMBTU | 20.00 |
| HEATING LOAD | MMBTU | 32.46 |
| COST W/O SOLAR | | 649.16 |
| SOLAR CALCULATIONS | | |
| LCR | | 18.92 |
| SLR MINIMUM | | 1.11 |
| QA/QL | | 0.22 |
| AUXILIARY HEAT REQUIREMENTS | | |
| ENERGY | MMBTU | 7.03 |
| COST WITH SOLAR | | 140.67 |
| SAVINGS | | |
| ENERGY | MMBTU | 25.42 |
| COST | | 508.50 |

Figure 3. Sample problem with multiple solar features.

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# PRODUCING SOLAR SAVINGS CALCULATIONS USING A CP/M-BASED ELECTRONIC SPREAD SHEET

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## ABSTRACT

Proper design of a passively heated (or cooled) structure is a complex thermodynamic problem, involving many variables. Well-documented work by Balcomb, et al (1), provides the solar community with the solar load ratio (SLR) method for quickly analyzing different options. However, many hand calculations are needed to produce detailed month-by-month results. This paper will discuss a method of producing estimates and graphs of monthly solar savings fractions using a CP/M-based electronic spreadsheet program, and will show how to integrate either program input or output with a word processor or data base program. This work is based on Passive Solar Design Handbook, Volume 2. This approach replaces tedious with rapid calculations, and should enhance communication between solar designers and their clients. The computer "template" created will be provided to ASES for distribution.

## 1. INTRODUCTION

The low cost and availability of microcomputers is bringing the "electronic" office into more and smaller businesses. As a result, many useful programs are being written and marketed. One type of product is the "electronic spreadsheet" program, which gives the user immediate access to each variable used in a calculation, rather than "interfacing" with data through a programmer's input editor. This attribute yields quick, easy access to useful (albeit limited) computing capabilities without requiring programming skills from the user. This paper is not intended as a primer in spreadsheet programs: however, it will discuss some limitations encountered in trying to compress a large quantity of information into a small container. The spreadsheet has been set up on an Osborne 1 portable computer (2) with 64k user memory and CP/M 2.2 operating system (2). Although most of the preliminary work was done on a unit with double density disks (185k per disk), all portions of the spreadsheet have been operated on a single density system (90k per disk). Spreadsheet software used was the SUPERCALC (2) program. Data from this program were transferred to the WordStar (2) word processor, and to dBase II (2), a relational data base program. All programs used were standard as provided through Osborne Computer Corporation.

## 2. SPREADSHEET LAYOUT

When "empty", the SUPERCALC program provides 23k of user workspace. This proved to be too small to install the necessary calculations. Thus, the procedure is broken up into four separate spreadsheets, or templates: site data, radiation conversions, setting up calculations, and final calculations.

### 2.1 Site Data

Site data is stored in a template called SITEDATA. In the disk provided, this file contains site data for various locations in Kansas and Colorado. The template uses the same format as does reference (1), Appendix A. Once a site has been chosen for use, that small portion of the SITEDATA template is saved as a separate file, with a user-supplied file name.

### 2.2 Radiation Adjustment Factors

Reference (1), Appendix C provides

the radiation adjustment factors needed for analyzing a design (varieties of azimuths, glazing angles, etc.). The modifying coefficient equations are stored in the template RADIDATA. Coefficients for a maximum of four correction factors can be used by shuffling copies of the data into a common block, and then saving this block in a manner similar to site data, with a user-supplied file name.

### 2.3 Setting up calculations

The SETUP template acts as the "input editor". Selected data is entered directly, such as night insulation values. Other data are entered indirectly, such as site data, and radiation adjustment factors. This is done by recalling the small SITEDATA and RADIDATA files from disk, and inserting them into the proper locations within SETUP. Care must be taken, since changing the spacing of lines, or changing the location of data on the screen will disrupt the logic of the template (what you see IS what you get). SETUP does provide for the use of six variations of radiation adjustment factors. Three of these can be modified after each calculation; the other three are intended to be used as constants, but may be varied by manually changing the numbers. (While coefficients for four factors can be moved from RADIDATA, only three can be used at one time, due to memory limits). Herein lies the usefulness of the spreadsheet: a variety of overhangs, azimuths, sites or other factors can be examined in a short time by changing a small number of variables. Each variable is under more direct user control than in many software packages.

The output of SETUP is the monthly values for S, transmitted energy per month per square foot, for a maximum of two systems. Additional comparisons could not be provided in this template due to the useful size of spreadsheet memory. The calculation results are stored to a user-named output file, using the (V)alue option of the SUPERCALC "/Save" command. This procedure frees additional memory space, and allows further calculations to be performed by the FINAL template. The time involved in producing multiple calculations can be reduced by producing many SETUP output files before changing to the FINAL template.

### 2.4 Final calculations

FINAL allows the user to examine either a single system, or a combination of two systems. It will determine the combined degree day base (Tbs), and interpolate the degree day values (DDs). The only input required in FINAL is the data stored from the SETUP templates. Results of the calculation are monthly solar savings fraction, annual auxiliary energy input, and annual solar savings fraction. Output from FINAL may be stored using a user-supplied file name.

## 3. DATA OUTPUT

### 3.1 Output to Printer

Both tabular and graphic outputs are produced by FINAL. The template has been formatted to provide tables of both the input variables and calculation results on a standard 8-1/2 x 11 inch page. Graphic output requires printing a second page. If a wide-carriage printer is available, all output can be produced on one page. All formats are based on 10 point printing. The simple graphics are a result of the SUPERCALC "*" output format, which converts a value into a string of asterisks of appropriate length. The graphic values have been modified to insure that the asterisks will not overrun the available space.

### 3.2 Output to WordStar

Examining a disk catalog will show that when the SUPERCALC "/Save" command is used to store data on disk, the file stored is named "filename.CAL". Files stored with the ".CAL" suffix cannot be input by WordStar. The SUPERCALC "/Output" command converts a portion, or all, of a template into a format which WordStar can utilize, and stores the data with a .PRN (print) suffix. A drawback is that a .PRN file cannot be read by SUPERCALC, thus a separate .CAL file must be maintained. Tables 1 and 2 are examples of data output by SUPERCALC, and transferred to WordStar.

### 3.3 Output to dBase II

Standard SUPERCALC files (.CAL) suffix) cannot be input by dBase II. However, the .PRN file created for use by WordStar can be input by dBase II. The syntax is: "APPEND FROM

yourfile.PRN SDF". SDF means "standard data file", and tells dBase II the expected order to receive data. A dBase II file will have a .DBF suffix, which cannot be read by SUPERCALC or WordStar.

The many uses for dBase II input may not be as apparent when compared with conversion to a WordStar file. Remember, however, that both input and output data can be utilized by dBase II. Anyone wishing to examine solar developments between a variety of locations could use the site data as input for a search routine, looking for certain climatic conditions. Or, someone building reflectors could write a routine which could locate areas of optimum performance for their product; the point being that any data useful in a SUPERCALC file can be transferred to a dBase II file.

### 3.4 Sample Output

Tables 1 and 2 are provided to show typical template outputs. The data is taken from the two-system example problem found in Reference (1), Chapter F. The resulting solar savings fraction agrees well with the reference value. Graphic output is produced with a similar format as the example, that is, total energy requirements and solar production are plotted, with the difference being auxiliary requirements.

Moving data from SITEDATA or RADIDATA to SETUP takes about two minutes each. Loading all data into SETUP takes about five minutes. Each calculation in SETUP takes three minutes. Saving results from SETUP uses another 30 seconds. FINAL performs calculations in about 90 seconds. From start to finish, three options can be examined, and results printed in about 30 minutes. Output values differ from published examples by less than 2%.

## 4. CONCLUSION

The purpose of this paper is threefold:

1) to provide a common method for storing and using existing data;

2) to simplify month-by-month solar savings fraction calculations; and

3) to provide a means for passing existing data between commonly used microcomputer programs.

Only three programs have been discussed in this paper. It goes without saying that other programs can use this data, and can output data to be used by other programs.

The spreadsheet programs are very useful, but they are not a cure-all, but used properly, they can provide much information, in a usable format, in a short amount of time.

## 5. REFERENCES

(1) Balcomb, J. Douglas, et al., Passive Solar Design Handbook, Volume 2, DOE/CS-0127/2, 1980.

(2) The following are trademarks used in this paper: Osborne 1--Osborne Computer Corporation; CP/M--Digital Research; WordStar--MicroPro International Corporation; dBase II--Aston-Tate; SUPERCALC--Sorcim.

TABLE 1.
FINAL GRAPHIC OUTPUT

```
Max load 8.07
million
Btu/mnth   % of Maximum Load
             .25  .50  .75 1.00
    month....*....*....*....*

base  sep
solar
base  oct ****
solar     ****
      nov ************
          *********
      dec ******************
          *********
      jan ********************
          **********
      feb ***************
          *********
      mar ***************
          *********
      apr ******
          *****
      may **
          **
      jun

              ....*....*....*....*
```

TABLE 2.
FINAL TABLED OUTPUT

PROJECT Lonesome Pine Residence Date 06/20/83
Location dodge city, Ks By lvm
Latitude 37.8

1) SYSTEM TYPE [ 1] ( 1--DG, 2--TW, 3--WW)
SOLAREA,sqft[ 156]
NI R VALUE[ 4]

2) SYSTEM TYPE [ 3] ( 1--DG, 2--TW, 3--WW)
SOLAREA,sqft[ 234]
NI R VALUE[ 4]

3) LOAD, Btu/hr[ 20100] TEMP, in degF[ 70]
TSET,deg F [ 70] out degF[ 51]
QINT,Btu/day[ 40000]

4) BLC 7422 Tbns 64.61
LCR 19.03 Uc1 .3 Uc2 .2
DDns 4960 Tbs 65.86

S Y S T E M # 1 calculated user entered

| month | (L-D) /100 | VS, Btu/ mon sqft | fctr1 | fctr2 | fctr3 | fctr4 | fctr5 | fctr6 | S, Btu/ mon sqft |
|---|---|---|---|---|---|---|---|---|---|
| sep | .35 | 42510 | .62 | .86 | 1.00 | 1.00 | 1.00 | 1.00 | 22806 |
| oct | .47 | 47585 | .67 | .94 | 1.00 | 1.00 | 1.00 | 1.00 | 30168 |
| nov | .56 | 41070 | .70 | .98 | 1.00 | 1.00 | 1.00 | 1.00 | 28313 |
| dec | .61 | 38998 | .71 | .99 | 1.00 | 1.00 | 1.00 | 1.00 | 27409 |
| jan | .59 | 41695 | .71 | .98 | 1.00 | 1.00 | 1.00 | 1.00 | 28937 |
| feb | .52 | 41048 | .69 | .97 | 1.00 | 1.00 | 1.00 | 1.00 | 27535 |
| mar | .41 | 44516 | .65 | .90 | 1.00 | 1.00 | 1.00 | 1.00 | 25976 |
| apr | .29 | 38190 | .60 | .80 | 1.00 | 1.00 | 1.00 | 1.00 | 18265 |
| may | .19 | 32953 | .57 | .75 | 1.00 | 1.00 | 1.00 | 1.00 | 14068 |
| jun | .15 | 31950 | .56 | .76 | 1.00 | 1.00 | 1.00 | 1.00 | 13672 |

S Y S T E M # 2 calculated user entered

| month | (L-D)VS, Btu/ /100 | mon sqft | fctr1 | fctr2 | fctr3 | fctr4 | fctr5 | fctr6 | S, Btu/ mon sqft |
|---|---|---|---|---|---|---|---|---|---|
| sep | .35 | 42510 | .64 | 1.00 | 1.00 | .95 | 1.00 | 1.00 | 25644 |
| oct | .47 | 47585 | .67 | .98 | 1.00 | .95 | 1.00 | 1.00 | 29859 |
| nov | .56 | 41070 | .70 | .97 | 1.00 | .95 | 1.00 | 1.00 | 26379 |
| dec | .61 | 38998 | .70 | .97 | 1.00 | .95 | 1.00 | 1.00 | 25228 |
| jan | .59 | 41695 | .70 | .97 | 1.00 | .95 | 1.00 | 1.00 | 26934 |
| feb | .52 | 41048 | .69 | .98 | 1.00 | .95 | 1.00 | 1.00 | 26254 |
| mar | .41 | 44516 | .65 | .99 | 1.00 | .95 | 1.00 | 1.00 | 27381 |
| apr | .29 | 38190 | .61 | 1.01 | 1.00 | .95 | 1.00 | 1.00 | 22426 |
| may | .19 | 32953 | .58 | 1.03 | 1.00 | .95 | 1.00 | 1.00 | 18702 |
| jun | .15 | 31950 | .57 | 1.05 | 1.00 | .95 | 1.00 | 1.00 | 18102 |

| month | cmposit S, Btu/ mon sqft | DDs,base 65 dd/mon | DDs,base 70 dd/mon | DDs cmposit dd/mon | S/DDs, Btu/mon sqft/dd | Mnth SSF | Aux 10e6 Btu/mon | ANNUAL SOLAR SAVINGS FRACTION |
|---|---|---|---|---|---|---|---|---|
| sep | 24509 | 41 | 118 | 54.28 | 451.49 | .9996 | .00016 | |
| oct | 29983 | 247 | 382 | 270.29 | 110.93 | .9743 | .0516 | |
| nov | 27152 | 666 | 816 | 691.88 | 39.24 | .7272 | 1.4006 | SSF, % = |
| dec | 26100 | 980 | 1135 | 1006.74 | 25.93 | .5147 | 3.6259 | |
| jan | 27735 | 1060 | 1215 | 1086.74 | 25.52 | .5072 | 3.9744 | 62.63 |
| feb | 26766 | 834 | 974 | 858.15 | 31.19 | .6146 | 2.4546 | |
| mar | 26819 | 738 | 893 | 764.74 | 35.07 | .6738 | 1.8516 | |
| apr | 20761 | 344 | 482 | 367.81 | 56.45 | .8614 | .37838 | |
| may | 16848 | 115 | 218 | 132.77 | 126.90 | .9810 | .01876 | |
| jun | 16330 | 21 | 51 | 26.18 | 623.87 | .9972 | .00054 | |
| TOTAL | | 5046 | 6284 | 5259.58 | | | 13.76 | |

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# USE OF ELECTRONIC SPREADSHEETS AS DESIGN TOOLS

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## ABSTRACT

Simplified energy evaluation methods using electronic spreadsheets are efficient and easily understandable tools, providing the user has a reasonable knowledge of how spreadsheets work. Generic advantages of using spreadsheets for such purposes are emphasized, with suggestions on set-up and organization of the sheets. Two applications are presented as examples for investigating typical design concerns: 1) a bin method analysis used to evaluate heating and cooling loads in internally load-dominated buildings; and 2) a glazing optimization to identify energy loads and costs for six window strategies, as well as demand charges, first costs, and payback period. Input parameters and results of the examples are explained, to illustrate the processes and types of information required. Benefits to the designer are discussed, as well as limitations and validity of such applications.

## 1. INTRODUCTION

With the penetration of microcomputer technology into the workplace, many offices have access to electronic spreadsheet programs such as VISICALC™, VISICALC ADVANCED VERSION™, SUPERCALC™ and MULTIPLAN™, which can be used to estimate the energy consumption of proposed design strategies[1]. Spreadsheets, with their ability to generate arrays of numbers using formulas and cross-referencing, provide the designer with quick and understandable information. For commercial and residential buildings, a designer can develop heating, cooling and lighting costs by using simplified methods such as balance point analysis that can be easily manipulated on a few spreadsheets. This is in contrast to other design tools and programs which are often more difficult to use and to understand.

## 2. GENERIC USES OF SPREADSHEETS

The major difference between spreadsheets and other design software is that assumptions and calculations are explicit and transparent to the user. The ease of customizing a spreadsheet for a particular application makes it much more versatile than most packaged computer programs. Even if one were proficient in writing code, the amount of input and output required for changes usually cannot be justified for individual applications. By contrast, spreadsheet formats are easily controlled by the users, and facilitate the presentation of numerical information in an orderly fashion.

## 3. LIMITATIONS

Some energy analyses generate many intermediate results en route to the bottom line of analysis (see Tables 1-4). As a result, spreadsheets can get so large that they are cumbersome. More typically, one runs out of memory while setting up a large or complex sheet. Our experience with VISICALC™ suggests that 32K of memory is just barely adequate for most purposes. Using several spreadsheets to perform a particluar analysis has significant drawbacks in that intermediate results must be saved in data interchange files, and reloaded into a second file. It makes the process much slower and unwieldy, and increases the chance of error during the calculation proceedure. Given the rapidly changing market and the advent of 64K machines, these limitations are becoming less restrictive.

## 4. BIN METHOD ANALYSIS AS A DESIGN TOOL

Designers of commercial buildings often require feedback on numerous issues relating to overall building energy consumption; including the effects of daylighting, building geometry, wall and roof insulation,

glazing areas, solar shading strategies and economizer operation. Often, many of the basic decisions which affect heating and cooling loads are made early in the design and may change in advancing stages of the design process. As a result, timely information must be obtained by the designer.

Hourly simulations of commercial buildings performed on main-frame computers are time consuming, expensive, and require special expertise. A simpler analysis, such as presented here on a spreadsheet,is more appropriate for most purposes. It is nothing more than spreadsheet rendition of a procedure previously done by hand, using an accepted ASHRAE methodology [2] which estimates heating and cooling loads in the following manner: 1) All heat gains and losses on a building or zone are calculated as function of outdoor temperature (5° F bins); 2) Loads are summed to determine whether heating or cooling is required; 3) Annual bin loads are estimated by multiplying hourly occurrences of temperature bins by associated heating or cooling loads and summed; 4) Mechanical system performance and consumption is calculated using annual COP or equipment performance curves.

Parts of a bin method analysis are shown below, using the Prudential Enerplex South Building (Princeton, NJ) as an example of a building which utilizes many interesting and energy conserving design features. The intent is to show the applicability of electronic spreadsheets to this method, and not so much to interpret the numbers themselves. However, comparisons of bin method estimates with DOE2.1A hourly simulations for this project yielded variances of 5% to 10% for heating, and 20% for cooling. This accuracy is usually sufficient to assess the relative importance of particular strategies in preliminary design.

## 5. CALCULATIONS OF HEATING AND COOLING LOADS ON A SPREADSHEET

Table 1 shows all of the loads on the Enerplex South building as a function of the ambient temperature (Column 1). The table represents a daytime occupancy period, and assumes that the building is a single zone with an attached atrium. Similar tables (not presented) have been formulated for the night hours and weekend daytime hours. All inputs required by the spreadsheet are placed in the top half of the sheet. The various loads are calculated below for each temperature bin. At a glance, one can easily see how each load affects the total. For example, solar gains from all glazing except the atrium are among the highest throughout the year. If one were designing this building, clearly a sun control strategy would be clearly recognized a top priority in reducing cooling loads. A glance at the "Atrium Glazing to Offices" column indicates that atrium solar gain is not nearly as influential in overall heat gain.

One can also observe that latent gains are quite significant in the summer, that economizing has been used at outdoor ambient temperatures of less than 70°F, and that the building's balance point (change-over from net cooling to net heating) occurs at about 30°F ambient temperature. The ventilating system distributes 120,000 cfm overall of which typically 17% is make-up (outdoor) air. In the input section one can see that summer and winter thermostat settings (Column 2) are 75°F and 68°F respectively, and that 32% natural daylighting has been assumed. 700 people occupy the building in the daytime. If the user wishes to want to change any one of these inputs to assess its impact on overall performance, it would be a simple matter of recalculating with a few changes.

Table 2 shows a summary of daytime, nighttime and weekend loads. The corresponding frequency of hours of occurrence are shown adjacent to each bin load, and a third column in each mode of operation records the total load in KBtu/yr. All the negative and positive loads are summed to obtain the total annual heating and cooling loads respectively, as expressed in MMBtu/yr and Btu/ft$^2$ yr. The hourly frequency data [3] directs the designers' attention to issues such as whether an economizer is useful or whether a heat pump is appropriate. In this case, during roughly half of the daytime hours, the HVAC system can use an economizer cycle. Also, it is evident that a reasonable portion of the heating load occurs at night with a fairly high percentage of hours below 35°F. This means that one might want to look more closely at the energy consumption of an air to air heat pump which would likely operate with heavy reliance on resistance heat. These types of observations are extremely useful in various design stages.

## 6. PARAMETRIC VARIATIONS

Table 3 shows the reference case loads of heating, cooling, lighting and fan energy consumption (lighting and fans compiled separately). In addition, some of the previously mentioned design changes are evaluated by varying one design element or assumption from the reference case. Note that the use of an economizer and daylighting have the greatest impact on energy loads. However, the designer also needs to know mechanical equipment

TABLE 1. TYPICAL BIN LOAD SPREADSHEET FOR CALCULATING HEATING AND COOLING LOADS, SHOWING INDIVIDUAL COMPONENTS OF LOADS AS A FUNCTION OF TEMPERATURE BINS.

**Enerplex South Building: Daytime Bin Loads On Office Zones**
**REFERENCE CASE: With Daylighting, no Venetian blinds, 20% atrium solar gain to offices.**

| Ambient Bin Temp | Set-Points For Thermostat: | Cond-Loss Walls & Roof | Glass Conduct Cond-Loss | O.A. Load Sensible | O.A. Load Latent Gain | Ambient Lights Gain | Task and Equip Gain | People Heat Gain | Solar Gain Non-Atrium Glass | Solar Gain Atrium to Office | Sol-Air Gain Walls & Roof | BIN TOTAL | Economiser Coolth | NET BIN TOTAL w/ Economiser |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Winter 68 | UxA 6899 | UxA 10736 | CFMvent 120000 | gr/#ex 118 | Watts 154000 | Watts 53000 | People 700 | | | BTUHmax 233000 | | CFMvent 120000 | |
| | Summer 75 | | | % O.A. 17 | gr/#in 66 | dlgt% 32 | | Sensible 255 | | | Design 95 | | % avail 83 | |
| | | | | | | | | Latent 255 | | | | | UAecon 108000 | |
| To | To-Ti | KBtu/h | KBtu/h | KBtu/h | KBtu/h | KBtu/h | KBtu/h | KBtu/h | KBtu/h | KBtu/h | KBtu/h | KBtu/h | KBtu/h | KBtu/h |
| 97 | 22 | 0 | 236 | 475 | 743 | 357 | 181 | 357 | 767 | 59 | 248 | 3423 | 0 | 3423 |
| 92 | 17 | 0 | 183 | 367 | 654 | 357 | 181 | 357 | 767 | 59 | 211 | 3136 | 0 | 3136 |
| 87 | 12 | 0 | 129 | 259 | 566 | 357 | 181 | 357 | 777 | 59 | 175 | 2860 | 0 | 2860 |
| 82 | 7 | 0 | 75 | 151 | 477 | 357 | 181 | 357 | 787 | 61 | 138 | 2585 | 0 | 2585 |
| 77 | 2 | 0 | 21 | 43 | 389 | 357 | 181 | 357 | 797 | 64 | 102 | 2311 | 0 | 2311 |
| 72 | -3 | -21 | -32 | -65 | 301 | 357 | 181 | 357 | 817 | 67 | 66 | 2028 | 0 | 2028 |
| 67 | -8 | -55 | -86 | -173 | 212 | 357 | 181 | 357 | 827 | 69 | 29 | 1718 | 600 | 1118 |
| 62 | -13 | -90 | -140 | -281 | 124 | 357 | 181 | 357 | 837 | 71 | 0 | 1417 | 1200 | 217 |
| 57 | -15 | -100 | -156 | -313 | 35 | 357 | 181 | 179 | 797 | 64 | 0 | 1043 | 1043 | 0 |
| 52 | -16 | -110 | -172 | -346 | 0 | 357 | 181 | 179 | 727 | 53 | 0 | 869 | 869 | 0 |
| 47 | -21 | -145 | -225 | -454 | 0 | 357 | 181 | 179 | 722 | 56 | 0 | 670 | 670 | 0 |
| 42 | -26 | -179 | -279 | -562 | 0 | 357 | 181 | 179 | 717 | 60 | 0 | 473 | 473 | 0 |
| 37 | -31 | -214 | -333 | -670 | 0 | 357 | 181 | 179 | 712 | 63 | 0 | 275 | 275 | 0 |
| 32 | -36 | -248 | -386 | -778 | 0 | 357 | 181 | 179 | 707 | 65 | 0 | 76 | 76 | 0 |
| 27 | -41 | -283 | -440 | -886 | 0 | 357 | 181 | 179 | 707 | 65 | 0 | -120 | 0 | -120 |
| 22 | -46 | -317 | -494 | -994 | 0 | 357 | 181 | 179 | 707 | 65 | 0 | -316 | 0 | -316 |
| 17 | -51 | -352 | -548 | -1102 | 0 | 357 | 181 | 179 | 707 | 65 | 0 | -513 | 0 | -513 |
| 12 | -56 | -386 | -601 | -1210 | 0 | 357 | 181 | 179 | 707 | 65 | 0 | -709 | 0 | -709 |
| 7 | -61 | -421 | -655 | -1318 | 0 | 357 | 181 | 179 | 707 | 65 | 0 | -905 | 0 | -905 |
| 2 | -66 | -455 | -709 | -1426 | 0 | 357 | 181 | 179 | 707 | 65 | 0 | -1101 | 0 | -1101 |

TABLE 2. TYPICAL SUMMARY SPREADSHEET FOR CALCULATING ANNUAL HEATING AND COOLING LOADS, SHOWING BIN LOADS, HOURS OF OCCURRENCE, AND FINAL ACCUMULATION OF LOADS.

**ENERPLEX SOUTH BUILDING ANNUAL HEATING & COOLING LOADS: REFERENCE CASE**

| Ambient Temp | DAYTIME OPERATION (occupied) | | | NIGHT OPERATION (unoccupied) | | | WEEKEND OPERATION (unoccupied) | | |
|---|---|---|---|---|---|---|---|---|---|
| deg F | KBtu/hr | hrs/yr | KBtu/yr | KBtu/hr | hrs/yr | KBtu/yr | KBtu/hr | hrs/yr | KBtu/yr |
| 97 | 3423 | 11 | 37899 | 396 | 4 | 1387 | 1446 | 4 | 6406 |
| 92 | 3136 | 44 | 139146 | 287 | 15 | 4276 | 1303 | 18 | 23136 |
| 87 | 2860 | 107 | 305621 | 180 | 46 | 8325 | 1172 | 43 | 50082 |
| 82 | 2585 | 182 | 470060 | 71 | 123 | 8705 | 1041 | 73 | 75701 |
| 77 | 2311 | 229 | 528534 | 69 | 288 | 19737 | 370 | 91 | 33802 |
| 72 | 2028 | 232 | 471429 | 66 | 487 | 31895 | 0 | 93 | 0 |
| 67 | 1118 | 218 | 243580 | 64 | 504 | 32034 | 0 | 87 | 0 |
| 62 | 217 | 209 | 45309 | 61 | 466 | 28244 | 0 | 84 | 0 |
| 57 | 0 | 193 | 0 | -81 | 435 | -35091 | 0 | 77 | 0 |
| 52 | 0 | 190 | 0 | -223 | 424 | -94417 | 0 | 76 | 0 |
| 47 | 0 | 202 | 0 | -363 | 404 | -146822 | 0 | 81 | 0 |
| 42 | 0 | 223 | 0 | -502 | 454 | -228174 | 0 | 89 | 0 |
| 37 | 0 | 225 | 0 | -642 | 522 | -335208 | 0 | 90 | 0 |
| 32 | 0 | 158 | 0 | -781 | 407 | -317750 | -9 | 63 | -566 |
| 27 | -120 | 88 | -10613 | -920 | 242 | -222229 | -148 | 35 | -5229 |
| 22 | -316 | 52 | -16559 | -1059 | 149 | -157594 | -287 | 21 | -6016 |
| 17 | -513 | 25 | -13045 | -1199 | 81 | -97545 | -427 | 10 | -4343 |
| 12 | -709 | 9 | -6329 | -1338 | 39 | -51511 | -566 | 4 | -2021 |
| 7 | -905 | 3 | -2505 | -1477 | 13 | -19388 | -705 | 1 | -781 |
| 2 | -1101 | 0 | -197 | -1616 | 2 | -2829 | -844 | 0 | -60 |
| Heat Loss | | | -49248 KBtu/yr | | | -1708559 KBtu/yr | | | -19017 KBtu/yr |
| Heat Gain | | | 2241578 KBtu/yr | | | 134603 KBtu/yr | | | 189126 KBtu/yr |
| Floor Area | | | 130660 sf | | | | | | |
| ANNUAL HEATING LOAD | | | 1777 MMBtu/yr | | | 13599 Btu/sf-yr | | | |
| ANNUAL COOLING LOAD | | | 2565 MMBtu/yr | | | 19633 Btu/sf-yr | | | |

TABLE 3. SUMMARY OF BUILDING LOADS AND MECHANICAL/ELECTRICAL ENERGY USE.

| BUILDING LOADS (Btu/sf-yr): | HEATING | COOLING | LIGHTING | FANS | TOTAL | Change vs #1 (%) |
|---|---|---|---|---|---|---|
| 1 reference case | 13599 | 19633 | 11704 | 10300 | 55236 | --- |
| 2 omit economiser | 13599 | 31519 | 11704 | 10300 | 67122 | 22 |
| 3 no daylighting | 13402 | 21218 | 15171 | 10300 | 60091 | 9 |
| 4 50% makeup air reduction | 13236 | 18168 | 11704 | 10300 | 53408 | -3 |
| 5 atrium to office, 40% | 13471 | 20350 | 11704 | 10300 | 55825 | 1 |
| 6 atrium to office, 10% | 13676 | 19268 | 11704 | 10300 | 54948 | -1 |
| 7 add venetian blinds | 14389 | 16659 | 11704 | 10300 | 53052 | -4 |
| 8 R5 night insul, non-atrium | 9830 | 19585 | 11704 | 10300 | 51419 | -7 |
| 9 run #1 with #4,6,7,8 | 9999 | 14798 | 11704 | 10300 | 46801 | -15 |
| Seasonal COP | 4 | 5.4 | 1 | 1 | --- | |

| MECHANICAL AND ELECTRICAL USE: (Btu/sf-yr) | HEATING | COOLING | LIGHTING | FANS | TOTAL | Change vs #1 (%) |
|---|---|---|---|---|---|---|
| 1 reference case | 3400 | 3636 | 11704 | 10300 | 29039 | --- |
| 2 omit economiser | 3400 | 5837 | 11704 | 10300 | 31241 | 8 |
| 3 no daylighting | 3351 | 3929 | 15171 | 10300 | 32751 | 13 |
| 4 50% makeup air reduction | 3309 | 3364 | 11704 | 10300 | 28677 | -1 |
| 5 atrium to office, 40% | 3368 | 3769 | 11704 | 10300 | 29140 | 0 |
| 6 atrium to office, 10% | 3419 | 3568 | 11704 | 10300 | 28991 | 00 |
| 7 add venetian blinds | 3597 | 3085 | 11704 | 10300 | 28686 | -1 |
| 8 R5 night insul, non-atrium | 2458 | 3627 | 11704 | 10300 | 28088 | -3 |
| 9 run #1 with #4,6,7,8 | 2500 | 2740 | 11704 | 10300 | 27244 | -6 |

consumption, not building loads, since one pays for energy used by equipment. At Enerplex South, the mechanical system for heating and cooling is a very efficient ground-water heat pump. Typically the COP's are 4 for heating, 5.4 for cooling. Electric lighting and fan motor consumption have an inherent COP of 1. Thus, given that the designers are using a very efficient mechanical system, variations in heating and cooling loads are less significant in the total equipment energy usage than they might appear at first. This suggests that as a general philosophy of design, one should emphasize either a highly efficient mechanical system, or architectural design strategies that minimize building loads. It might not be cost effective to do both. This also explains why daylighting is important in commercial building design. Given an auxiliary lighting COP of 1, turning lights off can have one of the greatest impacts on energy consumption. In this case full auxiliary lighting would result in a 13% increase in total energy consumption.

## 7. GLAZING OPTIMIZATION ON SPREADSHEETS

The choice of glazing and window configuration is an important issue in the design of most buildings. Since windows can be a major energy liability or asset, quantitative information about the performance of various schemes can be very valuable to a designer. Any spreadsheet or design tool which performs this function must be fairly versatile owing to the multitude of issues. For some utilities, demand charge may not be an important factor to consider; for others, it is a critical consideration. Daylighting may or may not be an issue critical to the outcome of analysis. Hence, the more parameters one considers, the more one is likely to understand the complete picture. On the other hand, if a spreadsheet gets too complicated, it will be difficult to grasp and may require unnecessary inputs.

One advantage of using a spreadsheet for glazing optimization is that it may be varied to suit the needs of each project. For example, the spreadsheet shown in Table 4 compares window treatments of equal area, and could not, as it stands, be used if one wanted to replace part of a window with a wall. With minor modification, a change in format can be made (and, in fact, was made) for a subsequent project. Another advantage of a well laid-out spreadsheet is that it allows the designer to understand the subtler issues that determine the final result. It does not replace the need for intelligent determination of input values, it simply provides a basis for seeing them in the context of how they relate to each other.

## 8. INPUT REQUIREMENTS

The spreadsheet in Table 4 was used to identify the best glazing and shading system for and shading large south facing lobby. The designers recognized that there were trade-offs between heating and cooling cooling operating costs and initial capital costs. To establish the relative merit of different strategies, an economic evaluation of six alternatives was performed with clear, unshaded insulating glass units as a

TABLE 4. GLAZING AND SHADING SYSTEM PERFORMANCE STUDY.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Window Area = | 605 | Oper. Hrs.=9 to 11 | | Elec. Cost = | .068 | $/kWh | |
| Mullion Fact = | .92 | Days/Week = | 7 | Demand Chg = | 4.34 | $/kW | |
| Net Gl. Area = | 557 | Design FC = | 30 | Steam Cost = | 13.00 | $/Mlb | |
| Discount Rate= | 10.5 | WINDOW ALTERNATIVES | | | | | |
| Escalation = | 12 | | | | | | |
| Clg Cost/Ton = | 1250 | Clear | Tint. | Heat | Int. | Int. | Ext. | |
| Clg. kW/Ton = | 1.02 | Glass | Glass | Mirror | Blind | Curtn | Blind | Units |
| SHADING COEFFICIENT | | | | | | | | |
| SC of Window | | .88 | .55 | .41 | .51 | .48 | .15 | - |
| SUMMER COOLING COSTS | | | | | | | | |
| SHGF* Total May-Sept | | 97.2 | 97.2 | 97.2 | 97.2 | 97.2 | 97.2 | MBtu |
| Shading Coefficient | | .88 | .55 | .41 | .51 | .48 | .15 | - |
| Net Solar Gain | | 85.54 | 53.46 | 39.85 | 49.57 | 46.66 | 14.58 | MBtu |
| Days/Week | | 7 | 7 | 7 | 7 | 7 | 7 | - |
| Net Glass Area | | 557 | 557 | 557 | 557 | 557 | 557 | sf |
| Total Seasonal Gain | | 47.61 | 29.76 | 22.18 | 27.59 | 25.97 | 8.12 | MMBtu |
| Cooling Energy Use | | 4.05 | 2.53 | 1.89 | 2.35 | 2.21 | 0.69 | mWh |
| Cooling Energy Costs | | 275.18 | 171.99 | 128.21 | 159.48 | 150.10 | 46.91 | $ |
| SOLAR GAIN DEMAND CHG | | | | | | | | |
| Maximum SHGF* | | 200 | 200 | 200 | 200 | 200 | 200 | Btuh |
| Shading Coefficient | | .88 | .55 | .41 | .51 | .48 | .15 | - |
| Net Peak Solar Gain | | 176 | 110 | 82 | 102 | 96 | 30 | Btuh |
| Net Glass Area | | 557 | 557 | 557 | 557 | 557 | 557 | sf |
| Peak Solar Gain | | 97.96 | 61.23 | 45.64 | 56.77 | 53.43 | 16.70 | MBtuh |
| Max. Elec. Power | | 28.13 | 17.58 | 13.11 | 16.30 | 15.34 | 4.80 | kW |
| Demand Charge | | 122.09 | 76.31 | 56.88 | 70.76 | 66.59 | 20.81 | $ |
| WINTER HEATING COSTS | | | | | | | | |
| Net Glass Area | | 557 | 557 | 557 | 557 | 557 | 557 | sf |
| U-value Nighttime | | .49 | .49 | .23 | .43 | .43 | .45 | Btuh/F |
| Degree Days Base 65F | | 4865 | 4865 | 4865 | 4865 | 4865 | 4865 | - |
| Hrs. Shading On | | 0 | 24 | 24 | 14 | 14 | 14 | - |
| Total Heat Loss | | 31.84 | 31.84 | 14.95 | 29.57 | 29.57 | 30.33 | MMBtu |
| SHGF* Total Oct-Apr | | 162 | 162 | 162 | 162 | 162 | 162 | MBtu |
| SC** When Open | | .88 | .55 | .41 | .71 | .88 | .88 | - |
| Avg. Utilizability | | .35 | .35 | .35 | .35 | .35 | .35 | - |
| Net Glass Area | | 557 | 557 | 557 | 557 | 557 | 557 | sf |
| Useful Solar Gain | | 27.77 | 17.36 | 12.94 | 22.41 | 27.77 | 27.77 | MMBtu |
| Net Heat Loss | | 4.07 | 14.49 | 2.01 | 7.16 | 1.80 | 2.56 | MMBtu |
| Steam Required | | 4.71 | 16.77 | 2.32 | 8.29 | 2.08 | 2.96 | Mlb |
| Steam Costs | | 61.27 | 217.97 | 30.21 | 107.77 | 27.05 | 38.46 | $ |
| SUBTOTAL COSTS | | 458.55 | 466.27 | 215.31 | 338.01 | 243.74 | 106.17 | $ |

| | WINDOW ALTERNATIVES | | | | | | |
|---|---|---|---|---|---|---|---|
| | Clear Glass | Tint. Glass | Heat Mirror | Int. Blind | Int. Curtn | Ext. Blind | Units |
| LIGHTING COSTS | | | | | | | |
| Avg. Daylight Trans. | 80 | 67 | 56 | 67 | 80 | 80 | % |
| Avg. D.F. @ 24' in | 6.5 | 5.4 | 4.6 | 5.4 | 6.5 | 6.5 | % |
| Ext. Illum. Reqd. | 460 | 560 | 650 | 560 | 460 | 460 | fc |
| Daylight Avail. (9-5) | 93 | 91 | 90 | 91 | 93 | 93 | % |
| Installed Lighting | 6000 | 6000 | 6000 | 6000 | 6000 | 6000 | Watts |
| Effect. Utilizability | 100 | 100 | 100 | 100 | 75 | 100 | % |
| Lighting Energy Use | 13.80 | 13.97 | 14.06 | 13.97 | 15.83 | 13.80 | mWh |
| Lighting Energy Cost | 855.32 | 866.15 | 871.57 | 866.15 | 981.28 | 855.32 | $/yr |
| MAINTENANCE COSTS | | | | | | | |
| Cost/Area | 0 | 0 | 0.00 | 0.10 | 0.10 | 0.10 | $/sf/yr |
| Gross Window Area | 605 | 605 | 605 | 605 | 605 | 605 | sf |
| Total Maint. Cost | 0.00 | 0.00 | 0.00 | 60.50 | 60.50 | 60.50 | $/yr |
| PREVIOUS SUBTOTAL | 458.55 | 466.27 | 215.31 | 338.01 | 243.74 | 106.17 | $/yr |
| ANNUAL OPERATING COST | 1313.9 | 1332.4 | 1086.9 | 1264.7 | 1285.5 | 1022.0 | $/yr |
| ANNUAL OPER. SAVINGS | 0 | -18.56 | 226.99 | 49.20 | 28.34 | 291.87 | $/yr |
| DESIGN LOAD REDUCTION | | | | | | | |
| Total Peak Gain | 97.96 | 61.23 | 45.64 | 56.77 | 53.43 | 16.70 | MBtu |
| Cooling Tonnage | 8 | 5 | 4 | 5 | 4 | 1 | Tons |
| Marginal Plant Cost | 10000 | 6250 | 5000 | 6250 | 5000 | 1250 | $ |
| REPLCMT EQUIP SAVINGS | 0 | 3750 | 5000 | 3750 | 5000 | 8750 | $ |
| ESTIMATED ADDITIONAL INSTALLED COSTS | 0 | 1000 | 4025 | 7380 | 7300 | 10710 | $ |
| SIMPLE PAYBACK | | negative | 17.7 | >100 | >100 | 36.7 | yrs |
| w/tonnage credit | | *** | +++ | 73.8 | 81.1 | 6.7 | yrs |
| DICOUNTED PAYBACK | | negative | 17.5 | >100 | >100 | 32.5 | yrs |
| w/tonnage credit | | *** | +++ | 55.5 | 30.1 | 7.1 | yrs |

| | | | | | |
|---|---|---|---|---|---|
| * = Solar Heat Gain Factor | Tint. Glass | Heat Mirror | Int. Blind | Int. Curtn | Ext. Blind |
| ** = Shading Coefficient is for winter incl. recess | | | | | |

*** = Immediate present payback, but negative savings each year.

+++ = Immediate present payback, with further savings each yr.

reference case. Energy costs attributable lighting, heating, cooling and demand were established. First costs and annual maintenance costs were compared against energy savings. Simple and discounted payback periods were determined, with and without credit for reduction in required plant capacity. A brief overview of the inputs needed for the example shown on Table 4 follows.

Shading Coefficients were either determined from manufacturer's data or ASHRAE recommended values. Under Summer Cooling Costs, solar heat gain from May through September was calculated by obtaining the average insolation transmitted on that surface for each month and multiplying by the number of days. Here the designer must exercise judgement as to the length of cooling season to be considered. Shading coefficients, days per week and glass areas are then applied to obtain the total seasonal gain, which is translated into equipment operating costs using the factors noted at the top of the spreadsheet. Similarly, Solar Gain Demand Charges imposed by solar gain were calculated using peak solar heat gain factors. This might be the sum of each month's maximum gain across the cooling season, or somewhat less, depending on the diversity of loads in the building. The diversity factor is an area of judgement on the part of the designer, or an area where an experienced engineer could provide useful input. Conceivably an additional line utilizing a diversity factor might render the analysis more complete, and allow a quick sensitivity study of the role of demand charges in the economic outcome.

The space derives a passive solar benefit in winter due to massive construction and large area of south facing glass. To account for this, credit was alloted under Winter Heating Costs. But not all the incoming solar gain contributes to a reduction in the heating load. The gains were pro-rated by a utilizability factor. Such a factor can be determined from a solar load ratio correlation, thermal simulation, or by drawing upon previous experience. A sensitivity study can be simply executed to determine the role of the utilizability factor on the final result.

Since daylighting is an option in this design (see Lighting Costs) an estimate of the daylight factor at a representative reference point was determined. Then, using daylight availability tables [4] or some other means, the daylight available to meet the footcandle requirements is entered. A utilizability factor may be included to take into account daylight reductions due to curtains and blinds.

Finally, Maintenance Costs for each window treatment are evaluated. The additional installed capital costs over the reference system must also be estimated for the purposes of cost/benefit comparison.

This should give an idea of the kinds of information necessary to set up similar spreadsheets. The usefulness of the results should be fairly obvious, along with the ultimate dependence on knowledge and information which the user must bring to any task.

## 9. CONCLUSIONS

As with most tools, the results are only as good as the inputs and the formulas in which they are used. The operating assumptions are typically more explicit and transparent to the user. Use of a spreadsheet does not relieve the designer of making intelligent decisions about the energy parameters that form the basis of the calculations. Rather, it provides the framework for comparing many issues simultaneously and getting a comprehensive evaluation. The standardization of this framework can also help prevent procedural oversights. Once all the inputs and formulas have been entered, the computer yields results such as annual operating savings and payback comparisons, or anual heating and cooling loads. Perhaps more important than the "bottom line" is the understanding the designer achieves of the causes of energy costs or savings. This knowledge may well lead to consideraton of other alternatives or design strategies. The designer who uses a spreadsheet for energy evaluation will have a much better feel for the issues than one who simply gets results without knowing why. Understanding, flexibility, and ease of use, make spreadsheets valuable design tools, not simply "after-the-fact" performance indicators.

## 10. REFERENCES


[1] For a comparison of spreadsheet programs see "Popular Computing," June 1983.

[2] ASHRAE Handbook and Product Directory, 1976 SYSTEMS Volume. ASHRAE; New York.

[3] "Engineering Weather Data." Departments of the Air Force, the Army, and the Navy, 1978; NAVFAC P-89, AFM 88-29, TM 5-785.

[4] IES Lighting Handbook, 1981 Reference Volume. Illumminating Engineering Society of North America; Waverly Press, Baltimore.

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# A VECTOR COMPUTER GRAPHIC PROCEDURE FOR CALCULATING THE IRRADIATED AREA OF COLLECTOR SURFACES IN BUILDINGS

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## ABSTRACT

This paper describes the strategy and mathematical algorithms used in the Solar Graphics computer program for determining the portion of a solar collector area exposed to the sun at any given time. A hidden line algorithm is used in conjunction with simple vector algebra to redraw the outline of the irradiated portion of the collector and to compute its area. Work is currently under way at the University of Wisconsin-Milwaukee to merge this capability with SHOW, an interactive computer graphic program, and with FCHART 4.0, a solar design program. The combined program that is being developed is called Solar Graphics. The vector/hidden line procedure, however, is written as a stand alone subroutine to Solar Graphics called Solar Test (SOLTST) that could be incorporated into other FORTRAN main programs with graphics capabilities.

## 1. INTRODUCTION

Existing methods for calculating the solar gains are based on trigonometric algorithms that compute gains from the reference point of the collector. Equations are derived that define the relationship between the sun, the collector or window and a shading device (if applicable) that is fixed to or near the window. Based on these mathematical relationships and on the orientation of the window, instantaneous or hourly solar gains for the window can be computed.

For a simple, south facing, collector on an open site, the above approach is straightforward and accurate. However, when the design conditions are not simple, as in the case of many actual designs, the math involved quickly becomes laborious. In order to retain program efficiency, the complexities associated with shading devices or non-southerly orientations are often modeled through statistically derived correlations. Dimensionless coefficients are developed and tested to determine their accuracy in paralleling results from larger programs based more closely on the principles of solar geometry radiation transmittance. Few computer simulation methods can handle context, such as shading from surrounding buildings on an urban site, or even off south orientations with accuracy and efficiency.

### 1.1 The Solar Graphics Program

In Solar Graphics, buildings are modeled by inputting X, Y, Z point coordinates corresponding to the shape of a building. This can be done interactively at a computer terminal or by calling previously created data storage files. By typing in commands in the form of code numbers, the designer can have the computer draw a picture of the building from any viewing angle desired. Other commands allow the designer to change the shape of the building before displaying it again.

The interactive nature of Solar Graphics makes it possible to study hundreds of design changes during the course of a several hour computer session. Using a feature in the program called "sunshot," a three-dimensional object can be drawn as seen from the sun on any given day and hour. The SOLTST subroutine adds the capability to compute the solar collection areas that are displayed in a sunshot projection. By inputting the three dimensional coordinates of adjacent buildings and landscape features, along with the

solar building being studied, the impact of external objects on solar performance can be accounted for.

## 2. THEORY OF OPERATION

The SOLTST subroutine uses a vector computer graphic algorithm to determine solar gains. A specialized hidden line capability is at the heart of the subroutine. In the original SHOW program, the computer picture generated will display all the lines of the object or building and its context. If a sunshot view is specified, the computer screen projection will be generated from the sun's position. The SOLTST subroutine then selects points from a given sunshot that represents the outline of the irradiated portion of a collector being tested. This new set of point coordinates can be used to draw the shape of the irradiated window area or to calculate the instantaneous solar gains for that area.

### 2.1 Point Coordinate Data Files

Several conditions must be placed on the point coordinate data files processed by SOLTST that are not normally required of point coordinate arrays that will only be used to draw a picture. These are listed below.

1. Each set of point coordinates must be defined as either a solar collection area or as a potential shading surface. Collector areas are referred to in the program as openings and may actually represent windows, clearstories, or collector-storage walls in the design of the building. Shading surfaces, called shaders in the program, include any opaque surfaces in the computer model being studied as well as trees and other landscape forms that may shade an opening.

2. All point coordinates in any given set must be coplaner. Many of the tasks performed by SOLTST rely on knowing the relative proximity of different sets of points to each other and to the sun. The computations involved are simplified if it can be assumed that all the points in a set lie in the same plane. In many cases distinctions between sets can be made by comparing the equations of the planes or by comparing the equations of the

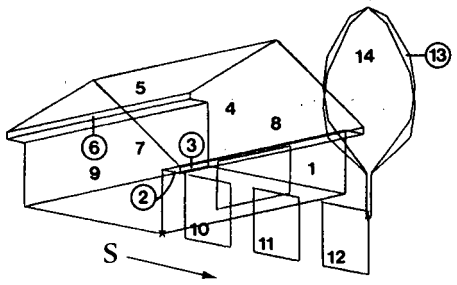



Fig. 1. Shader sets in a computer model of a house. 1 south wall, 2 south soffit, 3 south facia, 4 south roof, 5 north roof, 6 north facia, 7 north wall, 8 east wall, 9 west wall, 10 north fence, 11 center fence, 12 south fence, 13 tree shape, 14 tree shape

SHADER SETS REMAINING - 5
2,3,4,10,11

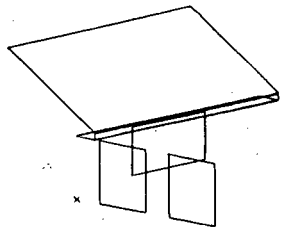


Fig. 2.

SHADER SETS REMAINING - 2
10,11

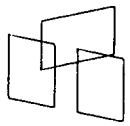


Fig. 3.

SOLSET 1

| | XP | YP |
|---|---|---|
| SOLSET(1,1) | 14.14 | 4.89 |
| SOLSET(1,2) | 14.14 | 6.85 |
| SOLSET(1,3) | 18.85 | 5.87 |
| SOLSET(1,4) | 19.80 | 6.07 |
| SOLSET(1,5) | 19.80 | 12.72 |
| SOLSET(1,6) | 8.49 | 10.37 |
| SOLSET(1,7) | 8.49 | 8.02 |
| SOLSET(1,8) | 10.61 | 7.58 |
| SOLSET(1,9) | 10.61 | 4.16 |
| SOLSET(1,10) | 14.14 | 4.89 |



Fig. 4.

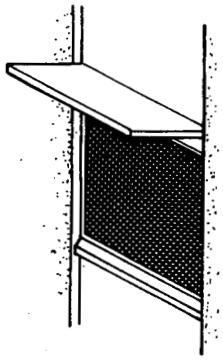


Fig. 5

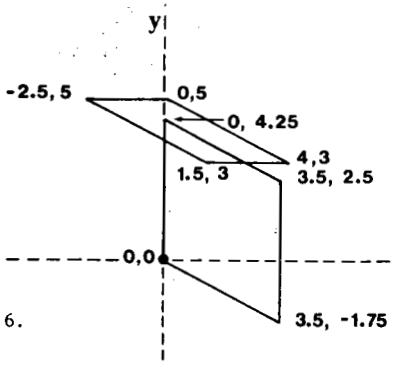



Fig. 6.

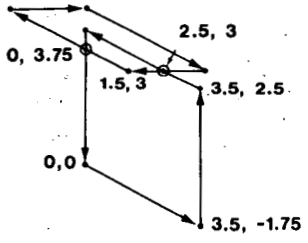



Fig. 7.

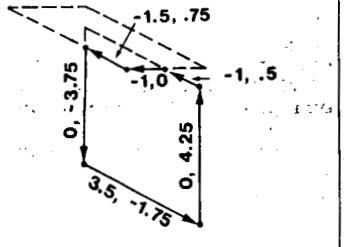



Fig. 8.

normal vectors to the planes.

3. The sequential construction of lines on a graphics screen when the computer draws a set is referred to as "chaining." A convention is established in SOLTST for the order in which vectors of a set are chained. Opening sets are chained in a counterclockwise direction, while shaders are chained in a clockwise direction. This convention is arbitrary and could have been reversed. The display screen sequence of chaining is established by the order in which point coordinates are stored in the corresponding files.

4. All sets of point coordinates must close. In other words, the last point in a set must be the same as the first. Graphically, this means that the lines of the set when displayed will form a complete polygon.

## 2.2 Vector Procedure

The conditions given above make it possible to compute the area inscribed within any polygon directly from the array of point coordinates that define the outline of the polygon. The following example explains how the vector computer graphic procedure can be used to determine the irradiated portion of a window that is partially shaded by an overhang.

Fig. 5 is an orthogonal view of a window (opening) and overhang (shader) as seen from the sun's viewpoint. The computer screen representation is shown in Fig. 6, along with the X, Y screen coordinates of the endpoints of the lines that make up the picture. The X and Y values of each coordinate pair are given in relation to the screen origin. Fig. 7 is the vector equivalent of the simple shader and opening shown in Fig. 6. Point coordinates have been transformed into a series of vectors with the head of each vector terminating in the tail of the next vector. The vectors indicate the direction of chaining the computer follows in drawing the window and overhang. Point coordinates that define the outline of the irradiated portion of the opening are also given. Taken in a counterclockwise order (following the direction of the vectors) these coordinates are used to create a new

set called SOLSET. The new set follows the outline of the opening with the exception of the notch where the shader overlaps the opening. Points of intersection for the two sets (0, 3.75) and (2.5, 3) and the shader point that is inscribed in the opening (1.5, 3) are located and are spliced into the vector chain for the new SOLSET array.

In order for the area of the SOLSET polygon to be computed, the X, Y coordinates corresponding to its vertices must first be mapped into U, V notation. U, V coordinates give the length and direction (positive or negative) traveled by a vector relative to that vector's starting point or its tail. Conversion to U, V notation (Fig. 8) is performed mathematically by subtracting the coordinates of each vector's ending point (head) from its starting point (tail).

$$X_2 - X_1 = U$$

$$\begin{aligned} 3.5 - 0 &= 3.5 \\ 3.5 - 3.5 &= 0 \\ 2.5 - 3.5 &= -1 \\ 1.5 - 2.5 &= -1 \\ 0 - 1.5 &= -1.5 \\ 0 - 0 &= 0 \end{aligned}$$

$$Y_2 - Y_1 = V$$

$$\begin{aligned} -1.75 - 0 &= -1.75 \\ 2.5 + 1.75 &= 4.25 \\ 3 - 2.5 &= .5 \\ 3 - 3 &= 0 \\ 3.75 - 3 &= .75 \\ 0 - 3.75 &= -3.75 \end{aligned}$$

Once the U,V coordinates have been established, they are stored sequentially in a new data storage matrix chaining in consecutive order. Multiplication of this matrix by its inverse will produce a scalar value equal to the net irradiated area.[1] Using standard vector algebraic notation, the coordinates for the irradiated area shown in Fig. 8 would be written in two rows, one above the other. Each row is referred to as a row "vector." The term vector is used here to denote a quantity or set of quantities (a row) that are distinct from another set of quantities. The values in the row represent a difference or transformation from some other row. This general use of the term vector should not be confused with the geometric definition of a vector representing a distance and direction in three dimensional space.

$$\text{Irradiated Shape} = \begin{matrix} U \\ V \end{matrix} \begin{bmatrix} 3.5 & 0.0 & -1.0 & -1.0 & -1.5 & 0.0 \\ -1.75 & 4.25 & .5 & 0.0 & .75 & -3.75 \end{bmatrix}$$

Matrix multiplication to determine the irradiated area is performed in two steps. First, the bottom row vector is multiplied by a diagonal matrix as shown in Fig. 9. By definition the diagonal matrix will be a square matrix having an equal number of rows and columns. The number of rows and columns is determined by the number of elements in the row vector it must be multiplied by. Each element in the V-row vector is multiplied by the corresponding element in each row of the diagonal matrix. The products are then added by row to produce a new column vector.

The second step is to multiply this column vector by the remaining row vector from the original set of point coordinates (the U-row vector). This is done by multiplying each element in the column vector by the corresponding element in the row vector and then summing the products. The resulting value is a scalar quality representing the area bounded by the U, V vector chain shown in Fig. 8. In architectural terms it is the area of the window that is receiving direct solar radiation for the time period displayed in the sunshot view (Fig. 5). This information along with the total collector area is used to calculate instantaneous solar gain or to compute average monthly gains using the method given by Utzinger and Klein.[2]

## 3. CONCLUSIONS

A vector algebraic procedure for determining the area of polygons has been explained. The use of the procedure to compute the irradiated area of collector surfaces in building has also been presented. Computer generated pictures showing how the method is employed by the SOLTST subroutine provide a graphic example of the operation of this technique. The vector computer graphic approach has several significant advantages over alternative methods for computing solar gains.

a. Windows and shading devices of any size, shape or orientation

## irradiated shape

$$\begin{bmatrix} 3.5 & 0.0 & -1.0 & -1.0 & -1.5 & 0.0 \\ -1.75 & 4.25 & .5 & 0.0 & .75 & -3.75 \end{bmatrix}$$

## step 1

$$\begin{bmatrix} -1.75 & 4.25 & .5 & 0.0 & .75 & -3.75 \end{bmatrix} \quad \begin{bmatrix} \frac{1}{2} & 0 & 0 & 0 & 0 & 0 \\ 1 & \frac{1}{2} & 0 & 0 & 0 & 0 \\ 1 & 1 & \frac{1}{2} & 0 & 0 & 0 \\ 1 & 1 & 1 & \frac{1}{2} & 0 & 0 \\ 1 & 1 & 1 & 1 & \frac{1}{2} & 0 \\ 1 & 1 & 1 & 1 & 1 & \frac{1}{2} \end{bmatrix}$$

$$\begin{aligned}
(\tfrac{1}{2} \times -1.75) + (0 \times 4.25) + (0 \times .5) + (0 \times 0) + (0 \times .75) + (0 \times -3.75) &= -.875 \\
(1 \times -1.75) + (\tfrac{1}{2} \times 4.25) + (0 \times .5) + (0 \times 0) + (0 \times .75) + (0 \times -3.75) &= .375 \\
(1 \times -1.75) + (1 \times 4.25) + (\tfrac{1}{2} \times .5) + (0 \times 0) + (0 \times .75) + (0 \times -3.75) &= 2.75 \\
(1 \times -1.75) + (1 \times 4.25) + (1 \times .5) + (\tfrac{1}{2} \times 0) + (0 \times .75) + (0 \times -3.75) &= 3.0 \\
(1 \times -1.75) + (1 \times 4.25) + (1 \times .5) + (1 \times 0) + (\tfrac{1}{2} \times .75) + (0 \times -3.75) &= 3.375 \\
(1 \times -1.75) + (1 \times 4.25) + (1 \times .5) + (1 \times 0) + (1 \times .75) + (\tfrac{1}{2} \times -3.75) &= 1.875
\end{aligned}$$

## step 2

$$\begin{bmatrix} 3.5 & 0.0 & -1.0 & -1.0 & -1.5 & 0.0 \end{bmatrix} \quad \begin{bmatrix} -.875 \\ .375 \\ 2.75 \\ 3.0 \\ 3.375 \\ 1.875 \end{bmatrix}$$

$$\begin{aligned}
3.5 \times -.875 &= 3.0625 \\
0.0 \times .375 &= 0.0 \\
-1.0 \times 2.75 &= -2.75 \\
-1.0 \times 3.0 &= -3.0 \\
-1.5 \times 3.375 &= -5.0625 \\
0.0 \times 1.875 &= 0.0 \\
\hline
\textbf{irradiated area} &= -13.873
\end{aligned}$$

Fig. 9. Matrix multiplication to determine the irradiated area of the window shown in Figure 5.

can be modeled through standard vector algebraic procedures. Even the most complex designs do not represent special cases in this method.

b. The effect of shading from adjacent objects or buildings is easily modeled regardless of the distance and angular relationship between a window and the object or objects shading it.

c. The incorporation of the method as a subroutine in more general computer graphic programs fosters an appropriate relationship between architectural design and passive solar considerations. A designer, working at a computer graphic terminal, can study the visual and formal implications of the shape of a design alternative from any viewing angle desired. The vector procedures described above can then be employed to instantaneously compute the solar gains of the building. The use of interactive "change" commands provided in many computer graphic programs, allows for quick reiteration of design solutions and recalculation of solar performance.

The design issues noted above are three areas where the vector computer graphic procedure has the potential to significantly improve existing solar design methods. As research and development continues, it is anticipated that this approach will have far-ranging consequences in the field of passive solar design.

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# MICROPAS, AN ANNUAL HOURLY HEATING AND COOLING BUILDING SIMULATION FOR MICROCOMPUTERS

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## ABSTRACT

This paper discusses the development, capabilities, and use of a new building design tool named MICROPAS. MICROPAS, initially developed under contract with the State of California Office of Appropiate Technology to document compliance with the new residential building energy standards in California, brings sophisticated annual hour-by-hour heating and cooling simulation analysis capabilities for passive solar and conventional buildings to microcomputers. By simulating a reduced number of hours per year and taking advantage of the dedicated use of microcomputers, MICROPAS maintains reasonable computer run-times and accuracy while incorporating the ease of use typical of today's microcomputer software.

## 1. INTRODUCTION

In recent years the use of computer programs has become a popular method of calculating the energy performance for all types of buildings. The currently available programs use a wide variety of modeling techniques from detailed hourly heating and cooling simulations to simplified techniques such as bin or degree-day methods. Some of these programs can analyze only conventional buildings while others can also analyze the energy conserving passive or active solar features of a building design. The computer hardware required to use these tools cover the range of available hardware from programmable hand held calculators for simplified techniques or general nodal simulations of limited time duration, to main-frame computers for full-year hourly simulations.

Also during these years of the development and acceptance of computer programs for building energy analysis, small microcomputers have matured into powerful yet inexpensive office management and analysis tools. The increased power and availability of microcomputers have now made detailed microcomputer based building energy analysis programs possible.

With these two events in mind and a third event, the implementation of revised residential building energy standards in California, the MICROPAS development project was begun at the State of California Office of Appropriate Technology by project manager David Hansen.

The goal of the MICROPAS project was to provide the seed money to develop a sophisticated microcomputer based design tool to the building designer that was capable of modeling the heating and cooling performance of many of the popular energy conserving and passive solar building designs, and also be capable of documenting compliance with the new standards in California. After a survey of available techniques, hourly simulation was selected because it is the only technique capable of this level of modeling flexibility, while maintaining reasonable performance predictions with a minimum of assumptions.

Hand in hand with the need for flexible yet detailed modeling capabilities, the MICROPAS program needed to be easy to use by building design professionals, not just experienced computer users. Much of the development effort of MICROPAS went into making it easy to use and well documented.

## 2. MODELING CAPABILITIES

The MICROPAS program has been designed to provide detailed energy analysis capabilities on microcomputers. The program is capable of modeling building design features such as multiple building zones, opaque and glazed surfaces of arbitrary orientation, a variety of thermal masses, and space conditioning systems systems on an hourly, daily, and annual basis.

### 2.1 Multiple Building Zones

Many buildings can be analyzed using a single building zone. However, there are often situations where the zone temperatures are different enough to require the use of more

detailed multi-zone modeling. This might be the case for buildings with an attached sunspace or a two story building. To accommodate this situation, MICROPAS models up to three complete building zones. Each building zone can have its own floor area, internal gain, infiltration, solar gain, envelope characteristics, thermal masses, space conditioning systems, and thermostat settings. The individual zones may be connected to other building zones or ambient conditions by masses, opaque surfaces, glazed surfaces, or ventilation.

### 2.2 Opaque Surfaces

MICROPAS can model twenty opaque surfaces such walls, roofs, floors, and doors. Each opaque surface is described by an arbitrary area, U-value, azimuth, tilt, and solar absorptivity. MICROPAS calculates heat flows due to both conduction with ambient conditions and solar gain absorbed by the exterior surface on an hourly basis.

### 2.3 Glazed Surfaces

Twenty glazed surfaces can be modeled by MICROPAS. Each glazing may have its own unique area, U-value, azimuth, tilt, number of panes, and shading devices. Possible shading devices include simple overhangs, shade screen, insulating shutters, and hourly shading schedules to model obstructions such as other buildings or trees.

The solar calculations, such as sun position, glazing transmission as a function of orientation, and shading due to overhangs, are done on an hourly basis by MICROPAS. The resulting calculated transmitted solar radiation is then applied to any thermal mass or building zone as specified by the user.

### 2.4 Thermal Mass

MICROPAS can model five thermal masses such as slabs, interior and exterior mass walls, Trombe walls, and water walls. Two mass models are provided--an isothermal model suitable for modeling high conductivity mass such as water, and a nodal model suitable for modeling concretes and other solid materials. For maximum flexibility, the surface conditions, location, and mass materials are specified by the user. This allows the mass surfaces to be placed in any building zone, between zones, connected to the ground, or connected to outside temperature and solar conditions.

### 2.5 Space Conditioning

The heating and cooling equipment of a building is modeled using seasonal efficiencies and maximum rated capacities. Up to three different heating and cooling systems can be incorporated into one model, one for each building zone. Fuel and electricity costs are input to estimate annual space conditioning costs. For heating and cooling systems with duct work, a duct loss fraction may be included. Latent cooling loads may also be included as a fraction of the sensible cooling load.

Both fan-forced and natural ventilation systems can be modeled between ambient and inside or between two building zones. The natural ventilation algorithms, based on those found in ASHRAE (1), include ventilation due to both wind and/or thermal stack effect. Air-to-air heat exchangers with a constant fan flow rate and power consumption can be modeled for air exchange between ambient and inside air.

### 2.6 Thermostat Systems

Each building zone may have its own thermostat system. The thermostat settings consist of six temperatures, the heating, cooling, and desired setpoints; and the the heating cooling, and desired setbacks. The heating and cooling temperatures control the activation of the heating and cooling systems, respectively. The desired temperature is the temperature which MICROPAS attempts to reach using ventilation from other zones or ambient conditions. Setback scheduling, which may include multiple setbacks, is accomplished using an hourly schedule. Different schedules may be used for heating and cooling seasons.

## 3. MODELING TECHNIQUES

The MICROPAS simulation program is based on the California Energy Commission version of CALPAS1 (2), a main-frame hourly simulation program designed to simulate the heating and sensible cooling performance of conventional, direct-gain, and mass-wall buildings. Numerous enhancements to this model were made in the process of developing MICROPAS. Two of the most important enhancements are the capability to handle multiple building zones and the use of statistically reduced weather data from full-year weather tapes.

### 3.1 General Technique

MICROPAS uses an approximate calculation sequence in which the current hour's zone air temperatures, exclusive of heating, cooling, or ventilation, are calculated using the sum of the instantaneous heat flows. Included are heat flows due to conduction, convection, insolation, infiltration, and internal gain.

Heating, cooling, and ventilation is controlled in the following manner. Once the temperature based on the heat flows has been calculated, MICROPAS looks to see if the zone is at the desired temperature. If the

desired temperature can be reached by using ventilation, either from another zone such as a sunspace, or from outside, then the ventilation system is turned on until the desired temperature is reached. If the heating or cooling available from ventilation is not sufficient to keep the zone temperature within its thermostat setpoints, then the heating or cooling system will be activated. When the heating or cooling load exceeds the capacity of the specified system, then the zone temperature will float above or below the setpoint.

After the current room temperature is determined, the storage mass temperatures are updated. For short time constant internal mass, such as sheetrock or furniture, the heat capacity is combined with that of the room air. For high conductivity internal mass, such as water storage, a isothermal model is used to update the temperature. For storage masses with finite conductivity, such as concretes, MICROPAS uses a nodal model.

The MICROPAS simulation is always in one of two modes during a given simulation day: the heating mode, in which the passive and backup systems are operated with the intent to provide heating for the building; or the cooling mode, where the intent is to provide cooling for the building. Many MICROPAS variables--such as shading factors, thermostat systems, and internal gain schedules--are entered in pairs, one for the heating season and one for the cooling season.

The simulation mode is determined daily in one of three ways. In the first scheme, used by default, the program is in heating mode if the average daily temperature is less than or equal 18.3 °C (65 °F), and in the cooling mode when the average daily temperature is above 18.3 °C (65 °F). Under the second scheme, the user may select a switch mode temperature between -17.8 °C (0 °F) and 65.6 °C (150 °F). The third scheme allows the user to specify the mode on a seasonal basis.

### 3.2 Reduced Weather Data

One of the key features of MICROPAS is the use of reduced weather data. Reducing the weather data is necessary to better meet the speed and disk storage requirements of today's microcomputers.

Several goals were set to determine how the weather data were to be reduced for MICROPAS. First, the run time for a MICROPAS simulation on a typical microcomputer had to be reasonable, between ten minutes and a half hour. Secondly, the weather data files had to be a reasonable size for microcomputers. But most importantly, the reduced weather data scheme had to maintain reasonable accuracy. Two approaches were considered--using monthly average daily data on a monthly basis and using some form of real hourly weather data reduced from the nationally available weather tapes.

After a series of tests simulating one average day a month, it was determined that this approach did not yield results comparable to full-year simulations. Eventually, a reduced weather data scheme using real hourly weather data were selected because it afforded the best accuracy while retaining the flavor of real weather events.

The reduced weather data is selected from the annual hourly weather tapes. The year is divided into six seasons (WINTER, WINTER/SPRING,SPRING/SUMMER, SUMMER, and SUMMER/FALL). For each season, seven consecutive days are statistically selected to represent the weather for the whole season. A seven day period was chosen to allow for eventual weekday/weekend scheduling in the MICROPAS model. These weekly periods were selected using a modified routine developed by researchers at the National Bureau of Standards (3).

Each of the seasons average two months in length. Because of the wide variation in local weather patterns, the amount of weather data an individual MICROPAS season represents varies somewhat from location to location. To compensate for this variation, the seasons are weighted according to the number of days they represent to determine the annual performance.

In addition to these six seasons, two peak seasons (PEAK HEATING and PEAK COOLING), which contain the weeks of the year with the most extreme weather conditions, can be simulated to provide information concerning peak building performance or preliminary sizing of heating and cooling systems.

## 4. PERFORMANCE PREDICTIONS

To demonstrate the energy performance predictions of MICROPAS using reduced weather data, a series of comparison runs between MICROPAS and other programs using full-year weather data were run. Two comparisons are presented here. The first comparison is between MICROPAS and MICROPAS using full-year weather data for a variety of building types. The second comparison is between MICROPAS and the CALPAS3 minicomputer program (4). The CALPAS3 program, like MICROPAS, was derived from the CALPAS1 computer code which has become widely accepted in both the private and regulatory sectors of the California building industry.

For the first comparison, eight different building types were run for Sacramento on MICROPAS, one using reduced weather data and

one using full-year weather data. The eight buildings include a typical single family tract house with some passive solar features, a multi-family cluster complex (common walls), a multi-family apartment complex (common walls, floors, and ceilings), a single family home built to the old California standards (similar to ASHRAE 90-75 standards), a high mass passive solar single family house, a single family house with an attached sunspace, a small one zone commercial building with tilt-up concrete walls, and a three zone commercial building with wood frame construction.

The results of the comparison are presented in the bar chart in Fig. 1. The agreement between the reduced and full-year weather data is quite good, demonstrating the accuracy of the reduced weather data strategy selected for MICROPAS. The percent difference is -0.16% for heating, -0.45% for cooling, with an overall difference of -0.31%.

Note that in both Figs. 1 and 2, the electrical energy used for cooling (heating is assumed to be gas) has been adjusted to reflect the amount of energy consumed at the source power plant by multiplying the electrical energy used by three. This accounts for the inefficiency of electricity generation and transmission, and reflects the relative dollar costs of electricity to gas fuels in many areas.

The second comparison, shown in Fig. 2, consists of MICROPAS and CALPAS3 runs for eight locations across the United States modeling the single family tract house with some passive solar features used in the first comparison. The trends predicted by the two programs are the same, but the percent difference is larger than in the first comparison, -2.3% for heating, -13.7% for cooling, with a total difference of -5.4%. Still, the agreement between the two programs is good when differences between the models, such as the control of heating, cooling, and

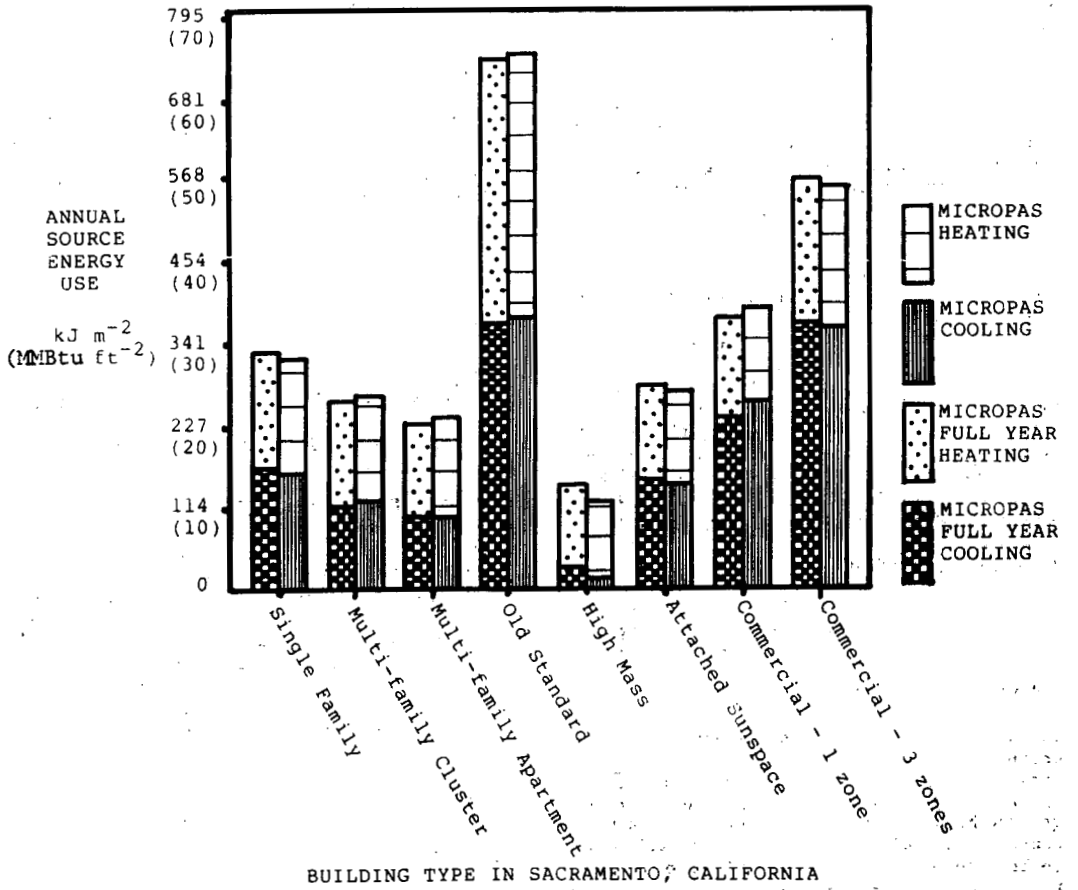



Fig. 1. Sensitivity to Building Type.

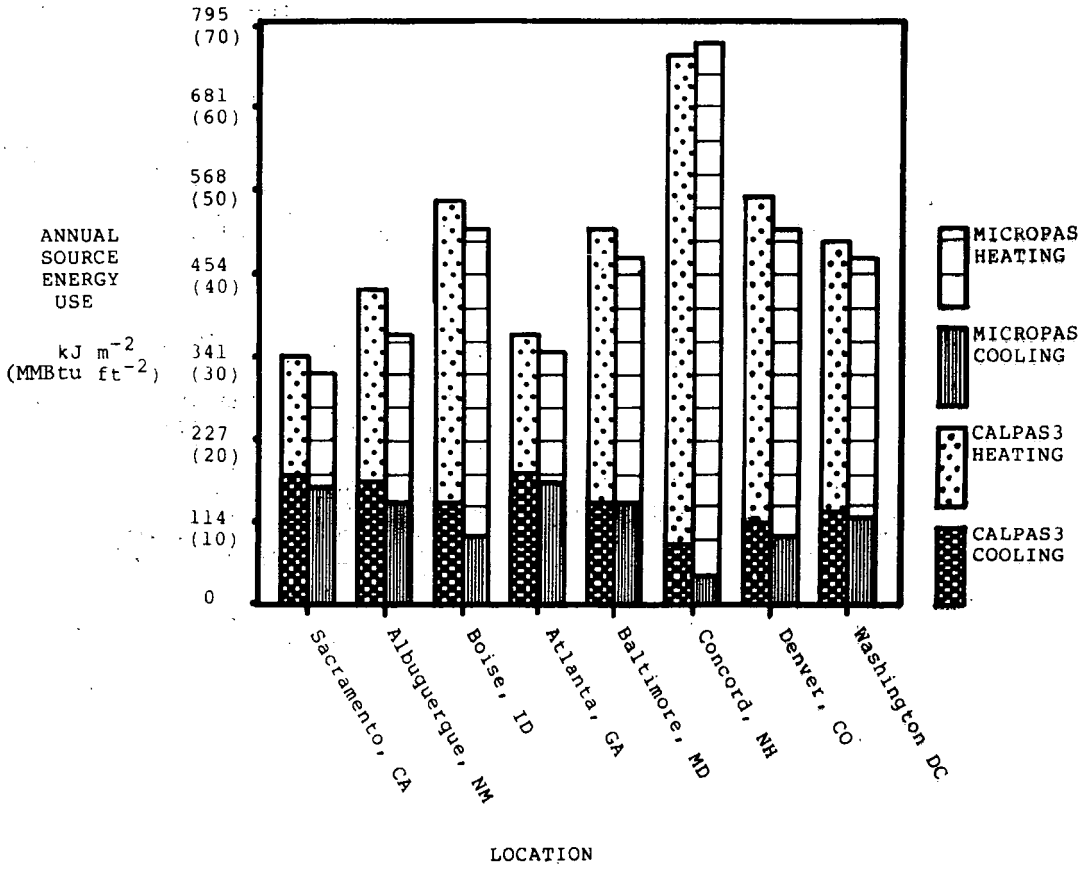



Fig. 2. Sensitivity to Building Location.

ventilation and the use of reduced weather data, are considered.

## 5. USING MICROPAS

One of the major design goals of the MICROPAS development project was to make the program easy to use by design professionals. To meet this goal, considerable time and effort went into the design and implementation of the user features of the program--the interactive input, the input data organization, and the structure of the outputs available from MICROPAS.

Documentation is another key area which required significant development resources. The MICROPAS User's Manual, 270 pages in length, was written to provide detailed information on how to prepare inputs for the program as well as how to use the program.

### 5.1 Interactive Input

The MICROPAS program has extensive interactive input which handles all aspects of data entry and program running. This includes management of disk storage resources such as directories, listing, and erasing files. MICROPAS stores all data files on disk, so reruns with modified data are easily to accomplished.

The interaction between the user and MICROPAS is entirely through the use of menus, consisting of menu items and a prompt line. The user selects the desired item and enters the corresponding number on the prompt line. Error checking is performed on all entries. The checking takes several forms depending on the type of value being input. For numeric values, the program checks to see that the input is a legal value within a certain range. For text entries, MICROPAS checks to

see that only legal characters have been entered for a specified length.

### 5.2 Inputs

The inputs to the MICROPAS model have been conveniently divided into eight groups--CONTROL, ZONE, OPAQUE SURFACE, GLAZED SURFACE, INTER-ZONE, MASS, SYSTEMS, and SCHEDULE DATA. Dividing the inputs into small easy to understand groups aids the user in preparing inputs. A further aid to preparing inputs is that the data input format displayed on the screen is identical to the format available on paper, such as blank data forms.

### 5.3 Outputs

MICROPAS output has been designed to provide the designer clear and concise energy performance information about the proposed design. Three types of output are available--summary, tabular, and graphical. Each of the outputs are designed for standard paper.

The summary output provides an annual summary of the building energy performance and costs. It has been designed to summarize both the performance of the building, such as the annual heating and cooling loads, and important building design parameters, such as floor areas and glazing areas.

The tabular output displays all numbers relevant to the performance of a building on an hourly, daily, seasonal, and annual basis. Tabular output available, as selected by the user, includes temperatures, heat flows, solar gain, infiltration, internal gain, ventilation, heating and cooling loads, and heating and cooling energy use. Additionally, a table of peak conditions may be requested which shows the minimum and maximum values for ambient conditions, zone temperatures, and zone heating and cooling loads.

The graphical output is provided to aid in the interpretation of the hourly temperatures produced by MICROPAS. Hourly temperatures plotted include the ambient, ground, all zone, and all mass temperatures. The graphs are compatible with standard typewriter characters so that the graphs may be listed on any printer or video screen--no special graphic capabilities are required.

### 5.4 Microcomputer Compatibility

MICROPAS can be used under two of the most popular operating systems on today's microcomputers--the eight bit CP/M™ and the sixteen bit MS-DOS™ (similar as PC-DOS™ used on the IBM Personal Computer) operating systems. Most microcomputers available can run under one of these operating systems, including those from IBM, DEC, Hewlett Packard, Radio Shack, Apple, and many others.

Typical run times for a MICROPAS simulation vary with the microcomputer system used. For a one zone, one mass building, MICROPAS takes about ten minutes to run on an IBM Personal Computer, twenty minutes on a typical CP/M microcomputer, and twenty-five minutes on an Apple II with a CP/M card. More complex models require additional time.

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# QUIKPAS: A MICROCOMPUTER BASED TOOL FOR PASSIVE SOLAR DESIGN

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## ABSTRACT

Recently a microcomputer version of CALPAS 1 known as MICROPAS has been developed by the State of California. This paper describes an enhanced version of MICROPAS which we are calling QUIKPAS. This program uses the core algorythms of MICROPAS but the input and output sections have been restructured to facilitate user friendliness. The program was developed around a set of full screen input menus, where design parameters can easily be created, stored, replaced or changed to determine the effects of design alternatives. At any time during the input process the designer can ask for help if any entry is not understood; thus, program documentation is available on the screen, not just in a support manual. The program output, like the input, is menu driven so that the designer can select only that part of the output that is of interest. Various output features can be combined (in spreadsheet fashion) to create user defined tabular or graphic output displays. Future developments that will further increase the program's power and usefulness to the designer are also discussed.

## 1. INTRODUCTION

Many early design decisions significantly affect the thermal performance of buildings. A clear understanding of the impact of these design decisions is an essential prerequisite to serious passive solar design. In addition, many designers have found that the speed and flexibility of any design tool often encourages their attempts to make modifications, which significantly improves the design under study. Unfortunately, many of the procedures that have been developed for predicting the thermal performance of buildings tend to be either inflexible, incomplete, overly complex or involve long periods of expensive design time. Such procedures can be divided into two main bodies, those using a correlation approach (such as the Solar Load Ratio - SLR - method) and those using a simulation approach (such as CALPAS, BLAST or DOE-2).

Correlation methods typically seek to identify one or more important parameters and then, by using detailed computer simulation, attempt to empirically correlate these parameters with the monthly fraction of the heating load being supplied by the sun. Such methods are usually easy to learn and use, cheap (requiring no more equipment than a handheld calculator), and give relatively quick results (typically 15-30 minutes). The main disadvantage of the correlation approach is its lack of flexibility. If the building under consideration has characteristics that differ from the original correlation assumptions, then results will not be very applicable. As a result correlation methods are not suitable for studying many different types of construction. In addition, correlation methods tend only to predict a building's heating requirements and neglect important design information like cooling, peak load conditions and temperature profiles.

Simulation methods overcome many of the limitations of correlation techniques by providing a mathematical model for analyzing the dynamic behavior of a specific building in response to selected weather data. The weather is usually interpreted as a set of irregular time-dependent functions which can be represented either on a small (one day - 24 hours) or larger (annual - 8760 hours) time scale. The thermal capacitance of the building is represented mathematically by either a transfer function or thermal network type of equation. Unlike the correlation approach, simulation is flexible enough to allow for almost any type of construction, as well as allowing the designer access to numerous aspects of a building's thermal performance (heating and cooling requirements, peak load conditions, temperature profiles, etc.). However simulation (especially annual hourly simulation) requires the use of large computers, which are cumbersome and expensive to use. Most design firms cannot afford to own the hardware necessary to run these programs, so they must rent time from a time-sharing facility. This almost always leads to a batch type input which can be very intimidating and confusing to most designers. As a result, simulation has tended to be used more as an analytical tool than as

a design tool - it has been used mainly after completion of the building design rather than during the design process.

The advent of the microcomputer presents the opportunity to combine the best qualities of both methods: the accuracy and flexibility of simulation and the speed and economy of correlation methods. In addition, the microcomputer can be easier and quicker to use than either of the previously available methods because of the microcomputer's tremendous capacity to be user-friendly. Such a feature is a direct result of the ability of the microcomputer to be programmed using an interactive approach. Large computers have been prevented from using such features because of the high cost of computer and connect time necessary for the interactive appraoch. Unlike large main-frame computers or time-sharing facilities, microcomputers are completely self-contained (often no larger than a typewriter), highly accessible and relatively simple to operate. They have become commonplace in the home, school, and office, where they are performing functions like word processing and accounting. Their low cost (usually less than $5000) makes them very affordable to design firms which are traditionally small in size.

With these issues in mind, the authors were excited to hear (in April 1982) that California's Office of Appropriate Technology had funded the development of MICROPAS, a public domain simulation program for microcomputers.[1] MICROPAS is based on the California's Energy Commission's hourly simulation program called CALPAS 1, a public domain main-frame computer program.[2] CALPAS 1 and its subsequent versions are generally well respected and have been used extensively in the passive solar design and research communities. MICROPAS was tailored to efficiently operate on a microcomputer by statistically compressing hourly weather data to represent weather patterns for an entire year. These compressed weather data are reduced from an annual hourly weather tape to six weeks of representative seasonal data and two weeks of peak occurrences by means of a program developed by the National Bureau of Standards. MICROPAS has been shown to give results comparable to CALPAS 1 and has been certified for use under the new California Residential Building Standard. However, upon receiving our copy of MICROPAS (in December 1982) we found it somewhat difficult to use. For example, to create a new building description, the designer must use the "Return" key in excess of one hundred times. In addition, much of the program's input and output has been organized to address compliance with California's energy standard which tended to limit MICROPAS's application in other locations. Further discouraging news came in January when we learned that California's new Governor, in one of his first official acts, had eliminated the Office of Appropriate Technology. Thus, with little or no public support of MICROPAS and the enhancements that would have evolved in time, we decided to attempt to make modifications to the program ourselves.[3]

## 2. PROGRAM DESCRIPTION

QUIKPAS, the enhanced version of MICROPAS, uses the same core algorythms that are in MICROPAS but the input and output sections have been restructured to facilitate user friendliness, hopefully resulting in an easier program to use. QUIKPAS is capable of modeling most conventional, passive solar and natural cooling design strategies and is flexible enough to include new design strategies as they develop. Currently the program simulates a building of up to three independent thermal zones. Each zone can be described with an individual thermostat and can have up to ten exterior walls, thirty exterior windows, and three types of thermal mass. Internal gains within each zone can be varied on an hourly basis. Windows can be oriented in any direction or tilt and include overhangs, thermal shutters and/or sun screens. In addition, windows are described as part of the walls, which allows for easy modification of glass area (simply change the glass area and the wall area that the glass is in will automatically be corrected).

QUIKPAS is capable of modeling a variety of HVAC equipment using seasonal efficiency or EER as input, whereas ventilation is modeled by varying either the fan flow rate for forced ventilation, inlet/outlet areas or stack effects for natural ventilation. QUIKPAS also has a highly flexible series of thermostat options which can vary heating, cooling and ventilation setpoint and setback as many times of the day as needed.

### 2.1 Input

To perform an analysis of a building, a designer would first describe a new building (or edit a description of an existing building). To do this, the designer selects the appropriate aspects of the building that is to be modeled from the "Building Description Options" menu (see Figure 1). This menu is divided into three parts: Zone Description, Component Description, and Interzone Surface and Ventilation Description. QUIKPAS initially comes with a library of components (e.g., different types of glass, thermal mass, etc.), however a designer can add, subtract, or change any of the various components as desired while describing the building. These components are then used to describe the zones of the building (e.g., a window will use a previously described glazing type, overhang, or shutter). This approach allows the designer to change any one part of the building description without having to redescribe any other components.

Although QUIKPAS can accept over two hundred variables, one could actually run the program with a minimum of sixteen entries. A full screen editor aids the designer by entering only the necessary data (marked with an asterisk "*") or as much data as desired. For example, each wall requires three entries (name, area, and azimuth) but the designer can enter up to nineteen other variables to describe a wide variety of wall and window combinations (see Figure 2). Default values for every item not having an asterisk are displayed so that they can be accepted by doing nothing or changed if desired. Many of the default values are assigned during initialization of the program so that they can reflect the state-of-the-art of construction practices in one locale or the preference of a particular designer (e.g., a designer in New England might choose a default of R-19 for a wall, whereas a designer in the southwest might perfer R-11).

Every item is tested to insure that an acceptable value has been entered so that any input errors will be detected when they are entered and not during the simulation run. If at any time the designer is uncertain about the meaning of a particular input or what the program will accept, he or she can ask for help or for a list of valid entries. These features facilitate the entry of unfamiliar information by making program documentation immediately available on the screen so that the designer need not search through the support manual for individual input descriptions.

### 2.2 Output

After a simulation has been run, the designer has available a great deal of information, which he or she may or may not want to see presented. The program output, like the input is menu driven so that the designer can select only that part of the output that is of interest (see Figure 3). The output menu has been divided into four categories, they are: annual report, seasonal reports, daily reports, and hourly reports. The annual report is a summary of climatic conditions, heating and cooling loads, energy consumption, and energy cost of the entire building for one year. The seasonal reports are broken down into six divisions: peak conditions, total building, climate, zone, mass and temperature. Daily and hourly reports include all of those in the seasonal reports, except for peak conditions, and are based on days and hours instead of seasons.

The outputmenu is manipulated by the space bar, which moves a highlight over each option. The user can select any option by simply pressing the enter key (carriage return). If daily or hourly reports are chosen, the program asks which season is to be covered. Once selection has been completed the desired report is shown on the screen (see Figure 4) and consists of a title, a menu, and a table. The latter is actually a window (looking into a larger table) which can be moved around, by pressing the cursor keys, to expose other areas (columns) of the larger table. The menu allows changing the order of the columns as well as arithmetic operations between two columns or between a column and a constant. New columns can be created and labeled by the user. The bottom row of the table contains totals or averages (whichever is significant) of each column. Another menu option will plot, one or more columns on one axis versus time (by season, day, or hour depending on the report). The fourth option will list all of the columns either on the printer or onto a file. The List option will include all data regardless of whether or not they are visible. The Quit option will send the user back to the report selection menu, where he or she can choose a different report, or exit the program.

## 3. HARDWARE CONSIDERATIONS

This version of QUIKPAS operates on an IBM PC microcomputer. The program is written in basic and uses several machine language utilities. Currently, 128K of RAM is required, as are two disk drives using double-sided double density floppy disks. Hardcopy output is produced on an Epson dot matrix printer, though any printer compatible with the PC can be used. We chose this equipment for developement to test the usefulness of typical microcomputers, as opposed to specialized, more expensive equipment. A future version of QUIKPAS will utilize the PC's optional color graphics, which will be written in such a manner that a designer without such capabilities can still use the program.

## 4. FUTURE DEVELOPMENTS

QUIKPAS is still very much in the developmental stages. This version has basically the same computational capabilities as MICROPAS. There are currently several significant limitations in the capabilities of both programs and work will be continuing to increase their power and usefulness.

Currently, QUIKPAS can simulate only three independent thermal zones, which need to be increased to make the program more flexible in the modeling of the larger building type. In addition, present HVAC options would have to be expanded in order for QUIKPAS to be able to accurately handle the large building. Along these lines we are considering borrowing several HVAC subroutines from a recently released public domain microcomputer program which is based on ASHRAE TC 4.7's Simplified Energy Calculation Procedure.(4)

Another limitation of both MICROPAS and QUIKPAS is the non-availability of compressed weather data for locations other than California. The authors are in the process of

```
QUIK-PAS      BUILDING:  DEMO          A  1  ZONE BUILDING

                    BUILDING DESCRIPTION OPTIONS

     ZONE DESCRIPTION                    COMPONENT DESCRIPTION

 *1) BUILDING GENERAL INFORMATION         9) GLASS TYPES
 *2) ZONE GENERAL INFORMATION            10) SHUTTERS
 *3) EXTERIOR WALLS AND WINDOWS          11) OVERHANGS
  4) ROOF                                12) SHADES
  5) INFILTRATION                        13) THERMAL MASS MATERIALS
  6) THERMAL MASS                        14) HVAC TYPES
  7) INTERNAL GAINS                      15) THERMOSTATS
  8) HVAC AND THERMOSTAT SYSTEMS

  0) FINISHED ZONE DESCRIPTION           16) INTERZONE SURFACES
  CTRL F) FINISHED BUILDING DESCRIPTION  17) INTERZONE VENTILATION SYSTEMS

  ZONE TO DESCRIBE IS NUMBER: 1
  SELECT DESCRIPTION OPTION:  3
```

Fig. 1. "Building Description Options" menu.

```
QUIK-PAS      BUILDING:  DEMO          ZONE #  1: MAINZONE

  EXTERIOR WALL AND WINDOW DESCRIPTION

 *NAME:              SOUTH
 *TOTAL AREA:        1000          SQ.FT.
 *AZIMUTH:           0             DEGREES
  TILT:              90            DEGREES
  R-VALUE:           19
  WALL TYPE:         FRAME
  ABSORPTANCE:       0.5

 NUMBER OF WINDOWS IN WALL:  1                    SOLAR GAIN DISTRIBUTION

 WINDOW NUMBER:      1                        MASS   HEATING FRACTION  COOLING FRACTION
 AREA:               200           SQ.FT.
 GLASS TYPE:         DBLPANE      ZONE AIR:          0.2                  0.2
 SHUTTER:            NONE         SLAB:              0.5                  0.6
 OVERHANG:           NONE         WALL:              0.3                  0.2
 SHADING:            NONE
```

Fig. 2. "Exterior Wall and Window Description" menu.

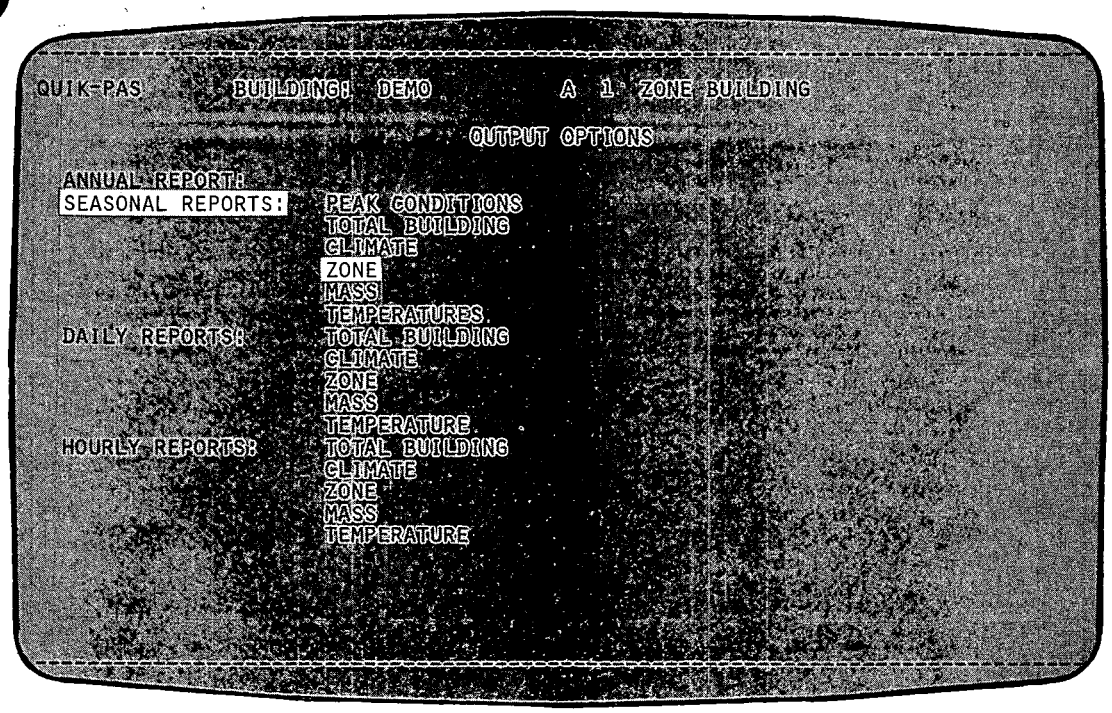



Fig. 3. "Output Options" menu.

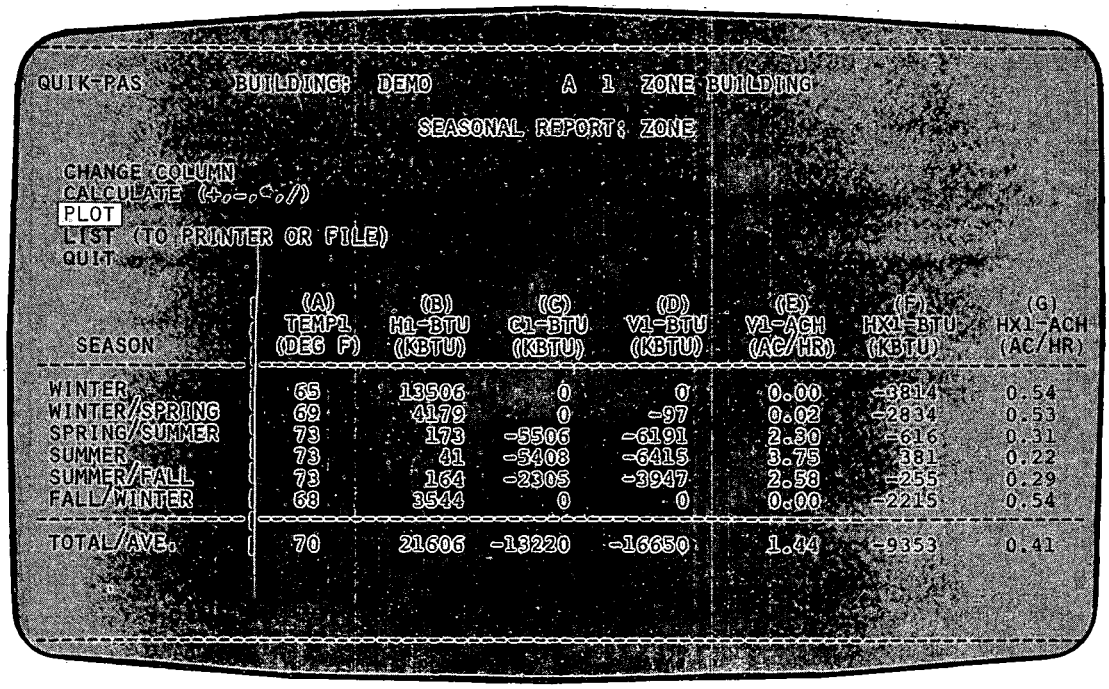



Fig. 4. Typical Output Report.

compressing weather data for a number of U.S. cities using the NBS program (which was included in the original MICROPAS package sent from California). We plan to use the recently generated Weather Year for Energy Calculation (WYEC) tapes[5] rather than the typically used Test Reference Year (TRY) or Typical Meteorological Year (TMY) tapes. This is because we have found that the WYEC data best represent long term mean temperature and solar radiation as well as being geographically well distributed. WYEC tapes presently cover 22 U.S. cities and are about to be expanded to cover 51 cities (five of which will be in Canada).

Finally, the authors are extremely interested in combining a thermal program such as QUIKPAS with a daylighting program such as Microlite.[6] Since only with the simultaneous investigation of thermal and daylighting concerns can a designer begin to understand many of the important qualitative issues associated with passive solar design.

## 5. GENERAL COMMENTS

We view QUIKPAS as an important step in our exploration of microcomputers for energy analysis. If the microcomputer is to be effective, it has to provide the designer with not only quantitative information, but with a deep understanding of how the energy use of a building is determined by design decisions. In this spirit, it is our feeling that QUIKPAS, like the original MICROPAS, must be placed within the public domain. To achieve this end, funding is presently being sought for the documentation of QUIKPAS. This documentation will include both program and weather disks, detailed user instructions as well as several worked examples and will be available at reproduction cost to any user.

## 6. ACKNOWLEDGEMENTS

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# NEW PROGRAMS FOR COMPUTER AIDED DESIGN

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## ABSTRACT

The use of two public-domain computer programs, CALPAS 1A and MICROPAS 1.0, to predict energy consumption of buildings is discussed. CALPAS 1A is compared with its earlier versions, and validation results with actual monitored homes are presented. Both programs are used in design and building energy standard compliance with California's Residential Building Energy Regulations.

## 1. INTRODUCTION

The advent of relatively inexpensive yet powerful minicomputers and microcomputers has produced widespread acceptance of computer aided design (CAD). This paper discusses two programs, CALPAS 1A and MICROPAS 1.0 which are used by the California Energy Commission to conduct energy performance studies, and used by builders and architects to do CAD and show compliance with California's 1982 residential building energy standards. Both are public domain computer programs. CALPAS 1A is an hour-by-hour simulation program which requires a main frame or minicomputer . MICROPAS, on the other hand, is designed to run on a microcomputer and uses statistically reduced weather data. Both of these programs are excellent design tools which can accurately analyze most residential or small commercial buildings. The advancements to CALPAS 1, which led to CALPAS 1A, are discussed and validation results are presented.

## 2. ADVANCEMENTS TO CALPAS 1

The essential differences between CALPAS 1A and its earlier versions in addition to an improved output format are:

i. CALPAS 1A calculates the hourly transmissivity values of the glazing and applies the inputted shading coefficient to calculate the solar gain. CALPAS 1 used two seasonal average values for the whole year for both glazing and devices. With the CALPAS 1A method, the user only has to input the number of lights of glass and the shading coefficient of any external shading device.

ii. CALPAS 1A treats each of four glazings which are 90° to each other as a separate entity in terms of transmissivity, shading coefficient, overhang, window height and U-values. Wall U-values are also treated separately for each of four orientations. These enhancements allow more user flexibility and accuracy.

iii. A new feature which CALPAS 1A can model that CALPAS 1 could not is skylights. CALPAS 1A can model up to four skylights having any area, tilt, orientation, transmissivity, or shading coefficient.

iv. Lastly, the floor and roof areas are entered as separate inputs which allow CALPAS 1A to model buildings with different floor and ceiling areas, e.g., a two story building.

## 3. VALIDATION OF CALPAS 1A

### 3.1 Description of Building and Environment

In order to test the validity of CALPAS 1A two houses in California were extensively monitored for more than a year by Sukhbir Mahajan, et al., of California State University, Sacramento. The results of the test from the monitoring are compared to CALPAS 1A simulation runs. Table 1 shows the major solar and conservation features of each house. Both houses are located in Rio Linda, a suburb just north of Sacramento. The Sacramento Valley is characterized by clear skies from April to October with relatively dry hot days and dry cool nights. The rest of the year is cool (0-10°C minimums) with about 50 to 75 centimeters (20 to 30 inches) of rain and extended periods of overcast and foggy weather.

TABLE 1

HOUSE PARAMETERS

| | Solar House | Conservation House |
|---|---|---|
| Floor Area | 113 $m^2$ (1215 $ft^2$) | 111 $m^2$ (1199 $ft^2$) |
| Glazing Area (% of Floor Area) | 19.8% | 13.3% |
| Glazing Type | Double Light | Double Light |
| Ceiling Insulation | R 30 | R 30 |
| Wall Insulation | R 16 | R 16 |
| Slab Insulation | R 7 | R 7 |
| Shading | None | None |
| Thermal Shutters | R 6 | None |
| Thermal Mass | 100 $m^2$ (1075 $ft^2$) | None |
| Air Changes per Hour (ACH) | 0.5 ACH* | 0.5 ACH* |
| Heating System Type | Gas Furnace (wall unit) | Gas Furnace (central) |
| Cooling System Type | None | Air Conditioner |

*The houses were tighter, but occupant use generally does not allow air exchange rate to fall below 0.5 ACH.

The first house, the solar house, is a passive solar design with extensive thermal mass and a north-south orientation in terms of glazing. A small gas wall furnace provided the backup heating. There was no mechanical cooling--all the cooling was done by natural ventilation. The Valley receives cool prevailing winds from the Pacific Ocean during the night. This cooled the house at night when the windows and vents were open and during the day heavy insulation in the walls and ceiling kept the heat out. The extensive thermal mass helped to keep both the summer and winter indoor conditions comfortable.

The second house, the conservation house, has a variety of conservation features such as thick wall and ceiling insulation and tight infiltration control, but little thermal mass. The solar tempering features include a north-south glazing orientation and a carpeted slab floor. This house has a central forced-air natural gas heating system and a central refrigeration unit for cooling. Again, like the solar house, this house benefitted from the cool night breezes from the south which allowed a relatively small load for the air conditioner.

### 3.2 Results

Table 2 and Figures 1 and 2 show the measured thermal performance of the solar house and the computer simulation in terms of heating load and inside temperature. Except for March, the solar house simulation was within 15 percent of the monitored values.

Table 2 and Figures 3 and 4 show the measured thermal performance of the conservation house and the computer simulation in terms of heating load and inside temperature. No monthly record was kept of the cooling load to compare with the computer simulation, but the total simulated load was only 10 percent more than the actual consumption.

### 3.3 Conclusion

The solar house simulation had closer correlation to the measured values but the thermal performance of both houses were closely predicted by CALPAS 1A. The weather data used to do the simulation were average year data normalized by the monthly averages measured at the actual sites. The

TABLE 2

COMPARISON OF MONTHLY HEATING
LOAD AND INDOOR AIR TEMPERATURES

| | MONTHLY HEATING LOAD (kWh) | | | | INDOOR TEMPERATURE (°C) | | | |
|---|---|---|---|---|---|---|---|---|
| | Solar House | | Conservation House | | Solar House | | Conservation House | |
| | Measured | CALPAS 1A | Measured | CALPAS 1A | Measured | CALPAS 1A | Measured | CALPAS 1A |
| JAN | 1,161 | 1,260 | 1,181 | 959 | 20.6 | 20.6 | 21.9 | 21.9 |
| FEB | 812 | 758 | 516 | 523 | 20.7 | 20.7 | 22.0 | 22.0 |
| MAR | 844 | 710 | 639 | 567 | 21.1 | 21.1 | 21.2 | 21.2 |
| APR | 484 | 434 | 384 | 443 | 20.7 | 21.2 | 21.3 | 21.6 |
| MAY | -- | -- | -- | -- | 21.7 | 22.6 | 23.1 | 20.9 |
| JUN | -- | -- | -- | -- | 21.7 | 23.1 | 23.2 | 21.4 |
| JUL | -- | -- | -- | -- | 24.0 | 26.1 | 24.0 | 22.6 |
| AUG | -- | -- | -- | -- | 23.4 | 25.4 | 25.9 | 22.7 |
| SEP | -- | -- | -- | -- | 22.8 | 23.8 | 25.2 | 21.8 |
| OCT | -- | -- | 278 | 287 | 21.8 | 21.1 | 22.7 | 22.8 |
| NOV | 460 | 491 | 308 | 377 | 21.1 | 21.2 | 21.0 | 21.2 |
| DEC | 900 | 787 | 768 | 739 | 21.2 | 21.2 | 21.8 | 21.8 |

| | Conservation House | |
|---|---|---|
| | Measured | CALPAS 1A |
| TOTAL COOLING LOAD (kWh) | 1,235 | 1,360 |

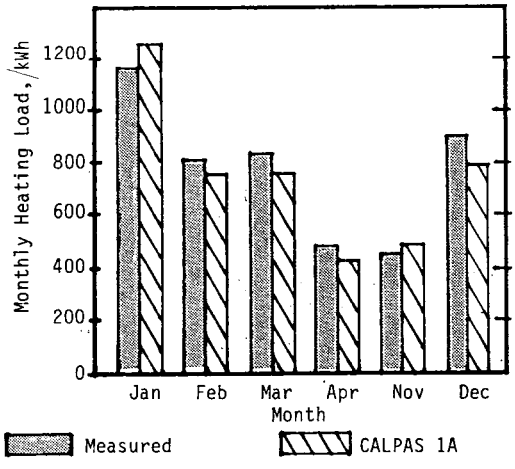



Fig. 1. Monthly Heating Load of Solar House.

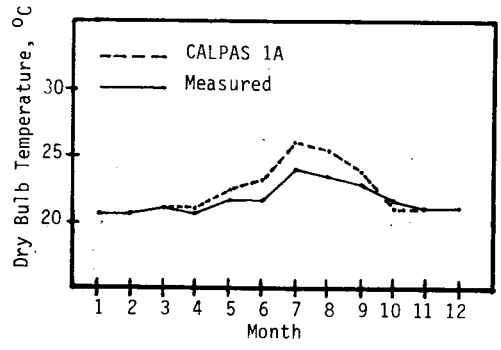



Fig. 2. Average Monthly Indoor Air Temperature of Solar House.

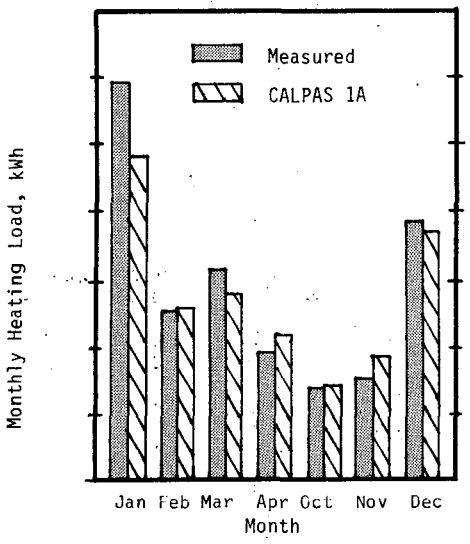



Figure 3. Monthly Heating Load of Conservation House.

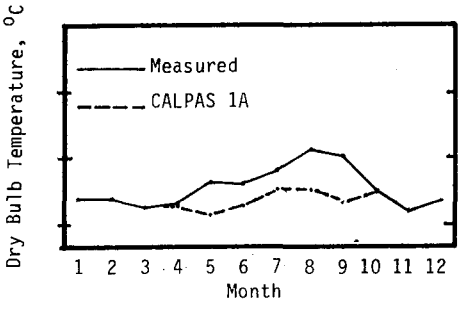



Figure 4. Average Monthly Indoor Air Temperature of Conservation House.

most difficult parameters to model and measure are the internal load and its schedule. They are such strong functions of occupant behavior that precise data is nearly impossible to acquire. Another possible source of error is venting. CALPAS 1A assumes automatic optimum venting, depending on environmental conditions. The occupants may not have responded optimally to the environment. The cooling temperature setpoint was generally set above 27°C (80°F) but no record was kept of the exact setpoints.

## 4. MICROPAS 1.0

MICROPAS 1.0 is another computer program which is used by the California Energy Commission and others to predict the energy consumption of buildings. The essential difference between it and CALPAS 1A is that MICROPAS uses statistically reduced weather data, allowing it to run on microcomputers. The year is divided into six seasons and each season is simulated by seven consecutive days. Thus, MICROPAS calculates 1,008 hours of data and statistically expands them to a full year instead of calculating 8,760 hours individually. Another major difference is that MICROPAS can model three separate thermal zones in a building as compared to only one zone for CALPAS 1A. MICROPAS, written in BASIC, is also much more user friendly than CALPAS 1A which is written in FORTRAN.

## 5. ACKNOWLEDGEMENTS

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# SURVEY OF DESIGN TOOLS FOR PASSIVE AND HYBRID LOW ENERGY BUILDINGS

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## ABSTRACT

A survey of design tools for Passive and Hybrid Low Energy Buildings has been undertaken as part of the International Energy Agency (IEA), Solar Heating and Cooling Program. A total of 164 design tools have been surveyed. The design tools have been categorized in various ways. The need for further design tools development for certain application has been identified.

## 1. INTRODUCTION

It has been the desire of the building design community to be able to predict accurately and rapidly a building's future. energy requirements while it is being designed. The manner in which active and passive solar systems perform and interact with building's performance complicates this prediction procedure substantially. Many people around the world have been working diligently in recent years trying to describe mathematically this complex behavior. The result of this effort has been a proliferation of design and analysis tools of varying complexity and accuracy. It is difficult for the design community to know of the availability of these various tools. It is even more difficult for them to evaluate their effectiveness and suitability for a particular use in the design process.

A survey of the design tools for Passive and Hybrid Low Energy Buildings was undertaken as part of the International Energy Agency (IEA) Solar Heating and Cooling Program. Information on the availability of various design tools was collected from 15 countries participating in the IEA Task.

A standard survey form was sent to the design tool developers in the participating countries. The main criterion of the survey was to collect information about the design tools which can be used by building design professionals for decision making during various stages of the building design process. Only those design tools which are likely to be used by the building design professionals were considered. Calculation methods suitable only for researchers were not considered.

With the information obtained from the surveys, the design tools were categorized in various manners so that designers can select a tool for their particular application depending on their requirement. The detailed results of the survey have been reported in the IEA document "Design Tool Survey - Passive and Hybrid Low Energy Buildings," December, 1982.

A few important results of the survey are described below.

## 2. RESULTS OF THE SURVEY

The surveys received from the design tools developers were analyzed and later categorized in a number of ways. Some of the important variables analyzed are described below.

### 2.1 Design Tools by Countries

A total of 164 surveys were received from seven countries. Table 1 shows the design tools reported from various countries. The design tools requiring mainframe computers, microcomputers, programmable calculators and manual methods are shown separately. It is seen from Table 1 that of the total 164 design tools, 118 were from the United States. A majority of the tools from the U. S. are for use with microcomputers.

### 2.2 Design Tools By the Intended Users

The design tools were categorized by the intended users, i.e. Architects, Engineers, Technicians, Builders, etc. Table 2 shows the number of design tools that are suitable

for each user and the type of machine required for the design tool. Since many tools can be used by more than one user type, the numbers in Table 2 may not add to the total of 164 design tools. It is seen from Table 2 that for the architects and engineers, the numbers of design tools available requiring various equipment are fairly uniformly distributed between all major equipment type, i.e. mainframe computer, microcomputer, etc. For technicians and builders, most design tools use manual methods.

### 2.3 Design Tools by Application - Heating, Cooling, Lighting, Service Hot Water

The design tools suitable for various applications are shown in Figure 1 and Figure 2. It is seen from Figure 1 that the majority of the design tools will calculate heating energy requirements, and very few of them would calculate the energy requirements for lighting and miscellaneous (pumps, blowers, etc.) Figure 2 shows that most of the design tools are to be used for residential and small commercial buildings, and there are a few which can be used for large commercial buildings. It is interesting to see from Figure 2 that in the residential and small building category, only about one-half of the design tools calculate the cooling energy requirements, while in the large commercial buildings category, almost all of the tools will calculate the cooling energy requirements.

### 2.4 Design Tools for Active Solar Energy Systems

The design tools suitable for active solar energy systems are shown in Table 3. It is seen from Table 2 that most of the design tools require mainframe computers. Of the total of 164 design tools, 48 are suitable for active solar energy systems. Of the 48, about 13 are for programmable calculators and only 4 are the manual methods. The design tools for active solar energy systems use various algorithms. Most of the design tools use the F-chart method. Most mainframe computers use component-based simulation, while most programmable calculators use the F-chart method. Figure 3 shows that of the total of 48 design tools for active solar, 23 use F-chart and 15 use component-based simulation. Figure 4 shows the design tools requiring various types of machines, and the algorithms used.

### 2.5 Design Tools for Passive Solar Energy Systems

The design tools suitable for use with passive solar energy systems are shown in Table 4. The table shows the algorithms used by the design tools and the type of machine required. Out of a total of 164 design tools surveyed, 91 can be used for passive solar calculations. It is seen from Table 4 that the solar load ratio (SLR) method is by far the most commonly used algorithm by the microcomputers, programmable calculators and the manual methods. The thermal network method is the most commonly used method by the mainframe computers.

### 2.6 Design Tools for the Calculation of Underground Loads

Of the total number of 164 design tools surveyed, 18 were suitable for calculating underground loads. Figure 5 shows percentage of the total design tools suitable for underground load calculations, which require various machines. It is seen that most of the design tools require a mainframe computer. There is no design tool which could be used to calculate underground loads with programmable calculators.

### 2.7 Design Tools by Applications to the Phases of Building Design

All the design tools, by application to the phases of building design, are shown in Figure 6. It is seen that the majority of the design tools are applicable for schematic design and design development. Figure 6 also shows some design tools suitable for research. Although the design tools suitable for research only were not considered, some of the design tools considered could also be used for research. Table 5 shows the design tools for various stages of building design and the machine required. It is seen from Table 5 that the number of design tools requiring programmable calculators and manual methods is large for the predesign and schematic phases. For other stages of building design, the number of tools for programmable calculators and manual methods is less. Since many design tools are suitable for more than one phase of building design, the numbers in Table 5 may not add up to 164 (the total number of design tools surveyed).

### 2.8 Design Tools by Building Category

The design tools by the building category and the machine required are shown in Figure 7. It is seen that out of a total of 164 design tools, 38 (23%) require a microcomputer and are suitable for residential and small commercial buildings, while 28 (17%) require mainframe computers and are suitable for large commercial buildings. It is also seen that from the total of 164 design tools, 123 are for use

with residential and small commercial buildings and 41 are for large commercial buildings.

## 3. COMMENTS

The result of this survey has shown the following:

3.1 There are few design tools available to be used with programmable calculators.

3.2 There are a considerable number of design tools using manual methods.

3.3 Only a few design tools calculate energy use by lighting and miscellaneous equipment. Most of the tools that calculate these categories of loads are the mainframe computer programs, with a few using microcomputers.

3.4 The tools which can be used to calculate cooling energy use require mainframe or microcomputers. There are very few simplified tools for the calculation of cooling energy requirements.

3.5 There are a considerable number of tools to calculate the energy requirements for various uses, of residential and small commercial buildings. For large commercial buildings, fewer design tools are available.

3.6 For the calculation of active solar energy systems, the majority of the design tools use F-chart method, and are, therefore, suitable for residences only. Most of the component-based simulations require mainframe computers. The only means to calculate the solar energy system performance for the commercial building so far is to use a mainframe computer. No simplified method exists for calculating the active solar system performance for space cooling.

3.7 The two most widely used methods for passive solar heating systems performance are Solar Load Ratio (SLR) and Thermal Network. Only a few design tools use SLR method for mainframe computers, while a majority of design tools for other machines use the SLR method. Most of the methods used by simplified design tools for passive solar were developed for residential use. There is no simplified method for calculating the performance of passive solar systems for commercial buildings. At the present time only mainframe computers can be used for this purpose.

3.8 There are virtually no simplified design tools for the calculation of underground loads. Only a few mainframe computer tools are available.

3.9 Simplified design tools for the calculation of energy saving due to the use of daylighting do not exist.

3.10 There appears to be a shortage of design tools for various phases of building design for large commercial buildings.

3.11 Very little information was available on the validation effort for various design tools. Only a few design tools seem to have been validated to a reasonable extent.

3.12 The design tools for use with microcomputers have been developed for all types of computers, using various kinds of operating systems. Portability seems to be a problem.

## 4. ACKNOWLEDGMENT

The authors wish to acknowledge the support provided by the various task leaders in the IEA participating countries. Thanks are due Dr. Fred Morse of the United States Department of Energy for valuable suggestions. The assistance provided by Mr. Alvin Sain of Burt Hill Kosar Rittelmann Associates in preparing the survey form is greatly appreciated. Thanks are also due various design tool developers for their cooperation in this survey. The authors wish to thank Ms. Tammy McGaughey for typing this manuscript.

## 5. NOMENCLATURE

| | |
|---|---|
| AVDY | Average Day |
| CBS | Component Based Simulation |
| CLG | Cooling |
| DEDV | Design Development Stage |
| DHW | Domestic/Service Hot Water |
| FCHT | F-Chart |
| HTG | Heating |
| IEA | International Energy Agency |
| LTG | Lighting |
| MC | Microcomputer |
| MF | Mainframe Computer |
| MIS | Miscellaneous |
| MN | Manual Method |
| OTHR | Other |
| PC | Programmable Calculator |
| POSV | Post Design Services |
| PRDG | Pre-Design Stage |
| RESP | Response Factor |
| RSCH | Research |
| R/LC | Residential/Large Commercial |
| R/SC | Residential/Small Commercial |
| SCHM | Schematic Design Stage |
| SLR | Solar Load Ratio |
| THNW | Thermal Network |

TABLE 1. DESIGN TOOLS BY COUNTRIES* AND THE MAJOR EQUIPMENT

| Participating Countries | Mainframe Computers (MF) No. of Tools | Microcomputers (MC) No. of Tools | Programmable Calculators (PC) No. of Tools | Manual Methods (MN) No. of Tools |
|---|---|---|---|---|
| Canada | 4 | 3 | 0 | 3 |
| Denmark | 0 | 1 | 1 | 0 |
| Italy | 1 | 1 | 0 | 4 |
| Netherlands | 2 | 1 | 0 | 1 |
| Norway | 1 | 1 | 1 | 1 |
| Switzerland | 7 | 4 | 5 | 5 |
| U.S.A. | 36 | 39 | 24 | 19 |
| TOTAL | 51 | 50 | 30 | 33 |

Total Number of Design Tools = 164

* Only the countries responding to the survey are shown here

TABLE 2. DESIGN TOOLS BY INTENDED USERS AND MAJOR EQUIPMENT

| Intended Users | Mainframe Computers (MF) No. of Tools | Microcomputers (MC) No. of Tools | Programmable Calculators (PC) No. of Tools | Manual Methods (MN) No. of Tools |
|---|---|---|---|---|
| Architects | 40 | 44 | 29 | 30 |
| Engineers | 46 | 48 | 30 | 30 |
| Technicians | 12 | 19 | 8 | 18 |
| Builders | 13 | 11 | 3 | 14 |

TABLE 3. DESIGN TOOLS FOR ACTIVE SOLAR ENERGY SYSTEMS, BY THE TYPE OF MAJOR EQUIPMENT AND CALCULATION METHOD

| Algorithms for Active Solar Energy Systems | Mainframe Computers (MF) No. of Tools | Microcomputers (MC) No. of Tools | Programmable Calculators (PC) No. of Tools | Manual Methods (MN) No. of Tools |
|---|---|---|---|---|
| F-Chart | 4 | 5 | 11 | 3 |
| Component Based Simulation | 14 | 1 | 0 | 0 |
| Average Day | 0 | 2 | 0 | 0 |
| Others | 4 | 1 | 2 | 1 |
| TOTAL | 22 | 9 | 13 | 4 |

TABLE 4. DESIGN TOOLS FOR PASSIVE SOLAR ENERGY SYSTEMS, BY THE TYPE OF MAJOR EQUIPMENT

| Algorithms for Passive Solar Energy Systems | Mainframe Computers (MF) No. of Tools | Microcomputers (MC) No. of Tools | Programmable Calculators (PC) No. of Tools | Manual Methods (MN) No. of Tools |
|---|---|---|---|---|
| Solar Load Ratio | 1 | 11 | 11 | 14 |
| Thermal Network | 14 | 7 | 4 | 0 |
| Response Factor | 4 | 3 | 0 | 0 |
| Others | 9 | 6 | 2 | 5 |
| TOTAL | 28 | 27 | 17 | 19 |

TABLE 5. DESIGN TOOLS BY APPLICATION TO THE PHASE OF BUILDING DESIGN AND THE MAJOR EQUIPMENT

Total number of design tools = 164

| Type of Major Equipment | Pre-Design Phase (PRDG) No. of Tools | Schematics Phase (SCHM) No. of Tools | Design Development Phase (DEDV) No. of Tools | Post Design Services (POSV) No. of Tools | Research (RSCH) No. of Tools |
|---|---|---|---|---|---|
| Mainframe Computers | 17 | 30 | 37 | 19 | 17 |
| Microcomputers | 25 | 38 | 26 | 11 | 5 |
| Programmable Calculator | 20 | 28 | 9 | 2 | 0 |
| Manual Methods | 23 | 21 | 15 | 5 | 3 |

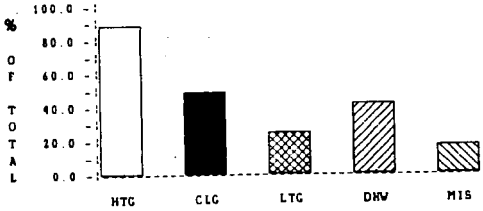



Fig. 1. Design Tools Categorized by the Application for Energy Calculations

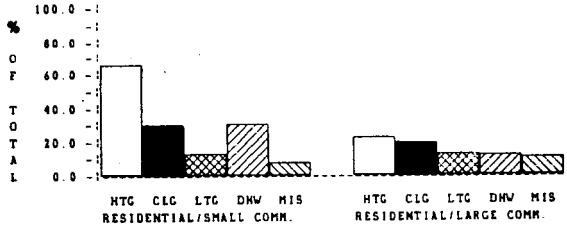



Fig. 2. Design Tools Categorized by the Application and the Building Type

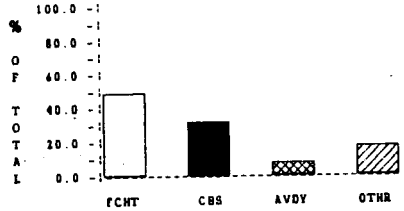



Fig. 3. Design Tools Categorized by the Algorithms Used for Active Solar Energy Systems

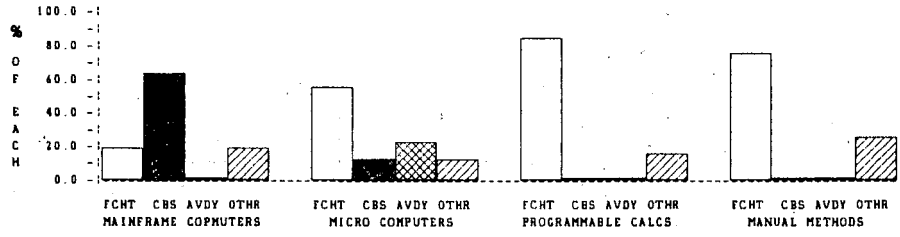



Fig. 4. Designs Tools for the Calculation of Active Solar Energy Systems, Categorized by Machine Type and the Algorithm Used.

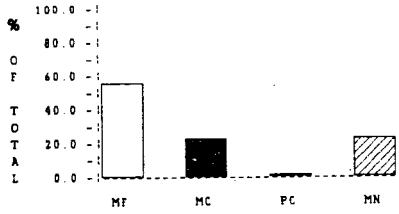



Fig. 5. Design Tools for the Calculation of Underground Loads Categorized by the Machine Required

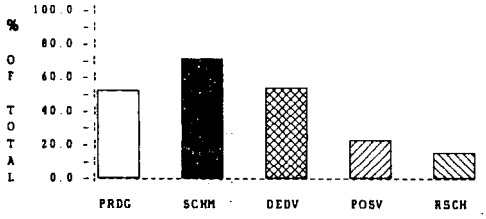



Fig. 6. Design Tools Categorized by Application to the Phases of Building Design

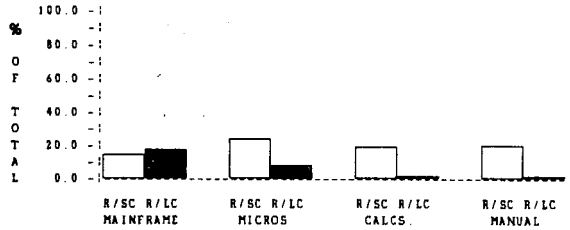



Fig. 7. Design Tools Categorized by the Building Type and the Machine Required

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# THE RESIDENTIAL ENERGY MANUAL: AN EXAMPLE OF USE AND COMPARISON OF RESULTS TO DETAILED COMPUTER SIMULATION

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## ABSTRACT

This paper discusses the application of the Residential Energy Manual (REM) heating calculation procedure to design problems and compares the REM Method results to BLAST simulations. The background, technical basis and calculation procedure are briefly described. The use of the REM Method is shown on a 1,600 square foot passive solar home located in Denver, Colorado. Comparison is made between the REM Method and the BLAST simulation values.

## 1. INTRODUCTION

The Residential Energy Manual (REM) is a flexible, accurate and easy to use residential energy design tool developed to serve the needs of homebuilders, home designers and consumers.(1) The REM evaluates both *heating and cooling building performance* for the continuum of residential and building energy design - conventional, suntempered, passive and superinsulated. Also, the basic REM approach is applicable to both new and *retrofit single and multi-family construction.*

The REM is organized into two major sections: (1) design/construction guidelines and (2) calculation procedures. The first section provides the needed background to familiarize the homebuilder with energy-efficient design principles and techniques. It identifies those techniques providing the greatest energy savings and includes a procedure for combining energy saving strategies. It presents and describes universal and location specific design guidelines and rules-of-thumb that the homebuilder can use to develop a new design or modify an existing design. Critical construction details are included so that an energy efficient design can be turned into a practical reality.

The second section presents the calculation procedures used to estimate accurately the home's annual heating and cooling energy consumption and size mechanical equipment. The procedures allow for the integrated treatment of energy conservation and passive solar design features, calculates heating and cooling loads and includes the effects of arbitrary amounts of thermal mass, ventilation and shading strategies, multiple window orientation, movable insulation, internal gains, thermal zoning and mechanical system efficiency.

The REM has been developed to be a true design and analysis tool - supplying basic information that allows the homebuilder and home designer to understand the form and performance implications of various options as they are conceived. The design/construction guidelines provide sufficient quantitative and qualitative information to allow the homebuilder to develop a near-optimum design solution for both new and retrofit applications without the need of calculations. Only when the design is almost completely specified are the calculation procedures needed and then used to show compliance with local energy codes, size mechanical equipment, establish an energy rating index or to modify the building design to achieve improvement in *energy performance.* The heating and cooling calculation procedures have been organized within the REM to complement the design/construction guidelines not replace them. In practice, the REM user should *first consider the design/construction* guidelines and then, if necessary, use the calculation procedures. However, for analyzing an existing home, a single pass through the calculation procedures would be an appropriate *first step before considering* any retrofit design alternatives.

## 2. DESCRIPTION OF REM CALCULATION PROCEDURES

The REM heating and cooling calulation procedures are based on "load curves" in which the building load coefficient for each curve is held constant over variations in solar aperture area and internal gains.* This approach eliminates the need

*The enlarged solar aperture area posseses an R-value equal to the wall it replaces.

to establish fixed assumptions of a reference building such as number or type of glazing panes, mass to glass area ratio and so on. For the REM Heating Calculation Procedure these load curves are used to produce a Utilization Table for specific geographic locations. The Utilization Table expresses the fraction of solar and internal gains used in offsetting auxiliary heating energy consumption. Also, it indicates the maximum potential auxiliary heat reduction achieved by adding thermal mass above the "free mass" (drywall, furniture, furnishings, etc.) present in all residences. For each geographic location, separate tables representing component heat loads, solar gains and internal gains provide seasonal values to be entered into the Utilization Table.

The REM Cooling Calculation Procedure uses an "Overload Table" to express the cooling loads generated by envelope conductive gains, window solar gains and internal gains. The effects of shading, ventilation and thermal mass are included in the procedure. Geographic specific tables for component loads, solar and internal gains have been developed for determing cooling season performance.

## 2.1 REM Heating Calculation Procedure

Eleven steps are involved in using the REM Heating calculation procedure to determine building energy consumption. These steps are organized by a number of precalculation worksheets and the Heating Calculation Sheet (HCS) (Figure 1).

1 Calculate Component Loads and Heating Load Index. A thermostat setpoint must be established. Use of night setback is considered as a modifier to the total building heating load further in the procedure. Next, component areas for walls, roof, floor, doors, windows and volume are taken off the architectural drawings. Net area/volume are entered on the HCS and appropriate heat load factors are selected from the component load tables (Figures 2 and 3). Individual component heat loads are summed to obtain total component loads and divided by house plan area to determine the Heating Load Index.

2 Calculate Internal Gains. From the Internal Gains Table select appropriate values and enter on HCS. (Figure 4.)

3 Calculate Solar Gains. Calculate window area by orientation and type (double or triple glazing). Select heating season solar gain contribution from Solar Gain Table (Figure 5) and enter on HCS. Adjust for shading and calculate total solar gains.

4 Calculate Gain Index. Add one-half of the internal gains to the solar gains and divide by the house plan area to determine the Gain Index.

5 Determine Base Utilization Factor. Enter Utilization Table (Figure 6) with Heating Load Index and Gain Index to obtain appropriate Utilization Factor and Mass Utilization Increment Factor.

6 Determine Thermal Mass Scaling Factor. Establish Mass Thickness Factor and design Mass Scaling Factor from Tables (not shown). Multiply the two to obtain Mass Scaling Factor and enter on HCS.

7 Calculate Thermal Mass Utilization Factor. Multiply Mass Scaling Factor and Mass Utilization Increment Factor to obtain Thermal Mass Utilization Factor. This is the amount of energy consumption reduction achieved by the use of thermal mass in the design.

8 Determine Overall Utilization Factor. Add Thermal Mass Utilization Factor to Base Utilization Factor to obtain Net Utilization Factor.

9 Calculate Utilized Gains and Heating Load. Multiply the Net Utilization Factor by the total solar and one half internal gains to obtain Utilized Gains. Subtract Utilized Gains plus one half internal gains from Total Component Loads to obtain the Heating Load.

10 Adjust Heating Load. Calculate heat savings for movable insulation and thermostat night setback from worksheets and Savings Factor Tables and enter on HCS.

11 Calculate Auxiliary Heating Energy Consumption. Subtract "Heat Savings" from Heating Load to obtain Modified Heating Load. Divide Modified Heating Load by Mechanical System Efficiency to obtain auxiliary heating energy consumption.

All that is needed to make these calculations is a four function calculator. If a change is made in any input value (R-value of insulation), it is a simple matter to enter the change and redo the calculation.

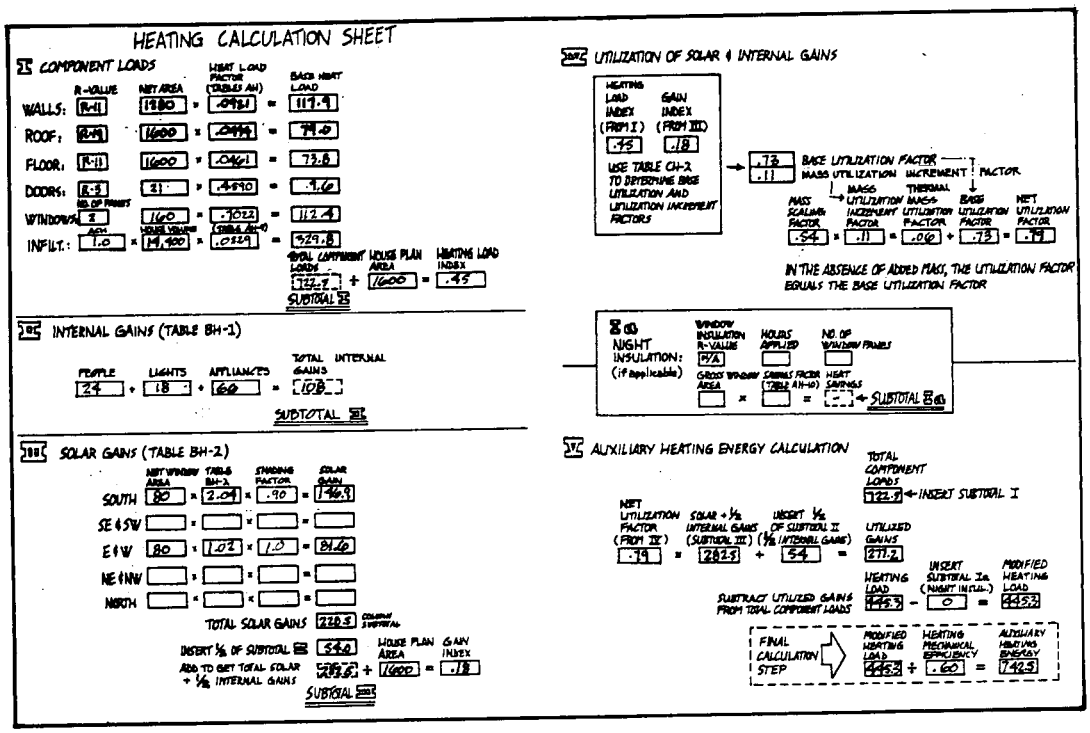



Fig. 1. Heating Calculation Sheet (HCS)

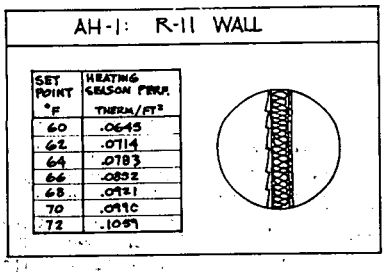



Fig. 3. Component Load Table

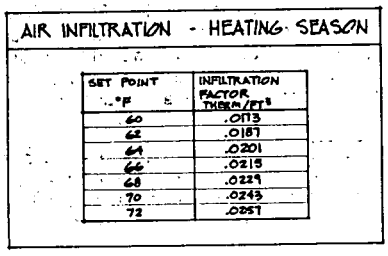



Fig. 2. Component Load Table

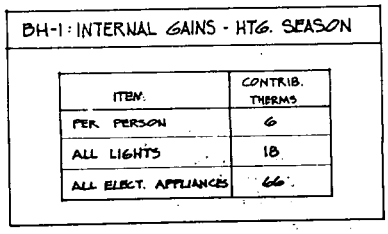



Fig. 4. Internal Gains Table

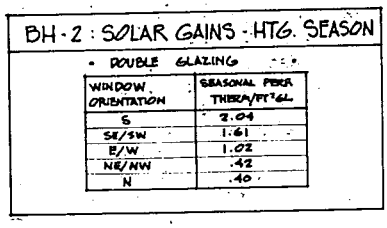



Fig. 5. Solar Gain Table

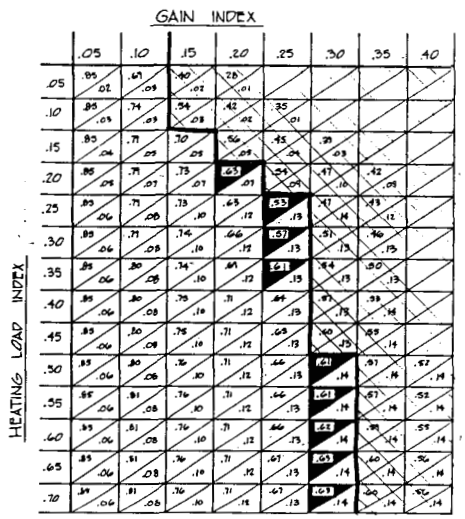



Fig. 6. Utilization Table for Denver

## 2.2 REM Cooling Calculation Procedure

For many U.S. cities, such as Denver, there is essentially no cooling load. Ironically, however, the inappropriate use of large solar aperture can create an otherwise non-existent cooling load. It is unnecessary to calculate cooling in these cities. The heating Utilization Table (Figure 6) indicates glazing levels (in cross hatched area) that, if exceeded, will produce a cooling load. On the same table, the darkened triangular areas denote levels of glazing that require additional thermal mass, above the free mass embedded in the table to minimize overheating during the heating season. This use of mass to prevent winter cooling is augmented by occasional venting for "free" cooling. The white areas on the Utilization Table indicate no cooling issue but assume 50% shading of summer sun and appropriate venting through open windows or use of a whole house fan.

For climates with no or little cooling loads proper use of the REM design/construction guidelines and a judicious use of the Utilization Table will yield a balanced year-round house design. On the other hand, cities such as Phoenix, Miami or Atlanta that have an extended overheated period, require the calculation of a cooling load. The cooling calculation procedure relies on an Overload Table. It is beyond the scope of this paper to describe the cooling calculation procedure in any detail. However, it is instructive to note that it is simplified by our analytical findings that variations in insulation and infiltration levels (except for humid climates) have a negligible to small effect on cooling performance.

Also, cooling load curves are remarkably linear compared to heating load curves. The primary cooling performance determinants are solar gains, ground coupling, ventilation, interior thermal mass, internal gains and exterior color, roughly in that order.

The REM cooling calculation procedure will be the subject of a future technical paper.

## 3. EXAMPLE OF REM METHOD USE

To illustrate the ease of using the REM Calculation Method, a simple test building is analyzed. The key design parameters are listed in Table 1. Example Heating Calculation Sheet (HCS) is shown in Figure 1.

TABLE 1. TEST BUILDING DESIGN PARAMETERS

| | |
|---|---|
| Location: | Denver, Colorado |
| Floor Area: | 1,600 square feet |
| Volume: | 14,400 cubic feet |
| Wall Insulation: | R-11 |
| Ceiling Insulation: | R-19 |
| Floor Insulation: (over crawl space) | R-11 |
| Window Size and Orientation: | |
| S - 80 square feet | |
| E - 40 square feet | |
| W - 40 square feet | |
| N - 0 square feet | |
| No. of Panes: | 2 |
| Infiltration Rate: | 1 ACH |
| No. of Occupants: | 4 |
| Thermal Mass: | 400 square feet 4" brick interior walls in direct gain spaces |

The area take offs for exterior walls, windows, doors, thermal mass area and so on are done on a precalculation worksheet (not shown). These values are then entered on the Heating Calculation Sheet (HCS). The appropriate heat load factors, solar gain and shading factors, internal gain values are entered on the HCS. Base component heat loads, internal gains and solar gains are calculated. Next, the Heating Load Index and Solar Gains Index are calculated and used to enter the Utilization Table. From the Utilization Table, the Base Utilization Factor and Mass Utilization Increment Factors are

*Rigorous parametric analysis has substantiated this procedure of incorporating internal gains. The error band is within a few percent using this approach. In general, less than 100% of solar and internal gains are utilized in offsetting auxiliary energy because such gains raise average room temperatures and increase heat losses.

selected and entered on the HCS. The Net Utilization is calculated. To calculate the Utilized Gains (to offset heating energy), the Net Utilization Factor is multiplied by the sum of solar gains plus one half internal gains and added to one half the internal gains.* The Heating Load is determined by subtracting the Utilized Gains from the Total Component Loads. This base Heating Load can be modified to account for movable insulation and thermostat night setback. As the final calculation step, mechanical heating system efficiency is considered and total Auxiliary Heating Energy established.

One advantageous feature of the REM method is the transparency of the calculation variables. That is, one can see the magnitude of one parameter to another and immediately see the effect of individual changes on overall auxiliary energy consumption. One will also note that the method is applicable to all types of design whether massive, passively driven, superinsulated or combinations of each. At present, the REM's passive solar capabilities are limited to direct gain systems. However, extension to sunspaces and Trombe walls is being developed and will add little or no complexity to the overall method.

The scope of this paper has been limited to dealing with Denver, Colorado. However, our previous and ongoing research on REM has shown that the general methodology is applicable to all climates. A unique finding with regard to utilization has demonstrated that perhaps only five or six Utilization Tables will be necessary to address the whole United States. However, separate component tables for each climate region are necessary, although their development has been streamlined through a generalized mathematical approach.

## 4. HANDLING INTERIOR ZONES WITH REM

Every design whether superinsulated, highly passive, or some combination in between, has to deal (to various degrees) with distributing passive solar gains from warm to cool rooms during the heating season. Therefore, the REM Design/Construction Guidelines provide the user with the necessary information to balance passive solar gains by window sizing on a room by room basis, make judicious use of heat conduction and convection through partition walls and open doorways, and to augment natural heat flows with properly sized blowers when necessary. Often one may want to size a solar aperture to

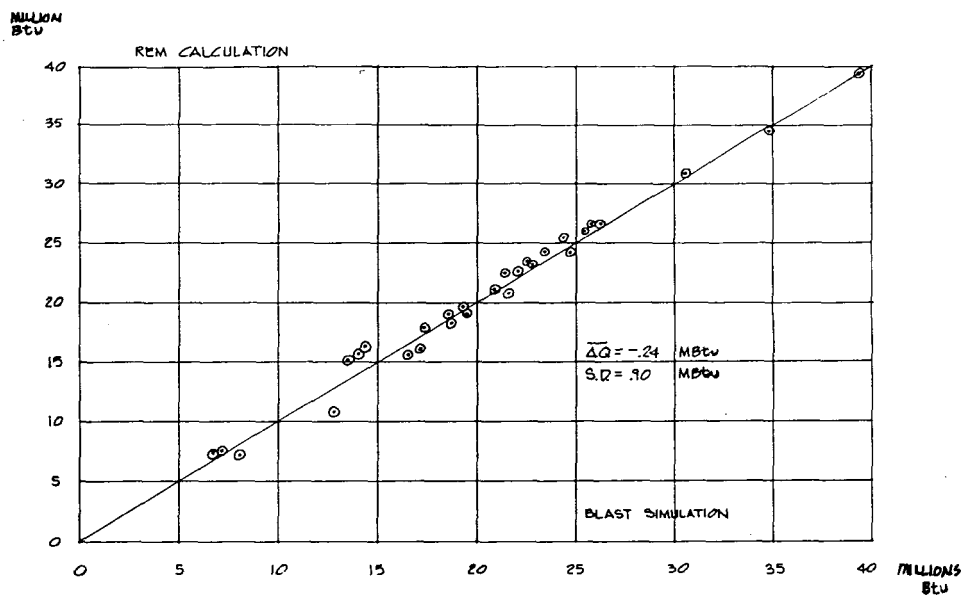



Fig. 7. Comparison of REM Hand Calculations to BLAST Simulations.

serve two or more zones. A direct gain room (or sunspace) may be designed to supply heat to itself and adjacent rooms otherwise isolated from passive solar energy (e.g., north rooms). The REM contains guidelines and simplified mathematical formulas for executing such a design properly.

Similar issues are encountered in the cooling season. However, in the summer one does not want to distribute solar gains, but to take advantage of cool rooms and to maximize shading whenever possible. Also, it is often a subtle matter to design a house for natural or whole house ventilation because of the way zones interact with one another. The REM handles these design issues with appropriate rules-of-thumb and guidelines.

The Heating and Cooling Calculation Procedures deal with a house as one zone, with the assumption that the user has explored and fully utilized the REM guidelines to address the interior zoning thermal questions.

## 5. SOFTWARE VERIFICATION OF REM METHOD

Figure 7 shows a comparison of the REM hand calculations and BLAST (Building Load Analysis System Thermodynamics) simulations for 32 house cases. Each point represents a house with a different combination of window area and orientation, levels of thermal mass and insulation and infiltration values. The figure shows excellent agreement between the hand calculations and the BLAST computer program. Thus, the present means of verification is a software-software comparison. We intend to compare REM predictions to measured data in the near future. The software-software comparison results shown in Figure 7 were completed during an early development phase of the REM calculation procedures. Since this time, the method has been improved and reflects recent advances in computer simulation using the BLAST and SERI/RES programs. We expect the next round of verification studies to show even greater accuracy then these already excellent results. This verification effort will be described in a forthcoming technical paper.

## 6. CONCLUSIONS

We have shown a residential energy calculation method that is extremely easy to use, flexible, comprehensive and accurate. It unifies residential energy performance prediction by its ability to analyze conventional, suntempered, passive solar and superinsulated designed, heating and cooling energy requirements and new and retrofit applications. We hope to complete its development shortly and make it available to the U.S. homebuilding industry.

## 6. REFERENCES

(1) R. G. Derickson and M. J. Holtz, The Residential Energy Manual (REM), International Solar Architecture Conference, Cannes, France December 1982.

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# A DESIGN PROCEDURE TO SIZE WINDOWS FOR NATURALLY VENTILATED ROOMS

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## Abstract

A step-by-step procedure for sizing inlet and outlet window areas for naturally ventilated rooms is presented. The procedure sizes windows to obtain a desired airflow (cfm) in cross-ventilated rooms for a given wind speed and direction. It accounts for the effects of architectural projections, neighboring buildings, terrain type and insect screening. The procedure has been verified against airflow measurements in a full-scale residence.

## 1. INTRODUCTION

This paper presents a simple procedure for sizing inlet and outlet window (aperture) areas in cross-ventilated rooms in naturally ventilated buildings. In cross-ventilated rooms, the airflow is primarily a result of the mean wind pressure differences acting across the windward inlet and the leeward outlet. The procedure is for rooms with one effective inlet and one effective outlet, i.e., all the inlet windows are assumed to experience identical positive pressures and all outlet windows to experience identical suction (negative) pressures.

The airflow in such rooms can be expressed as

$$CFM = (A).(CD).(W).\sqrt{PD}; \text{ where} \qquad (1)$$

CFM = Airflow in cubic feet per minute (CFM)

A = Effective window area (sq. ft.)

$= A_o A_i / \sqrt{A_o^2 + A_i^2}$ Where $A_o$, $A_i$ are open outlet and inlet areas, respectively

CD = Discharge coefficient of opening (assumed) 0.64

W = External wind speed at 10 meters in feet per minute (fpm)

PD = Pressure difference coefficient acting across the inlet and outlet, nondimensionalized with respect to exterior windspeed at 10 meters (dimensionless).

The airflow equation is patterned after Aynsley (1). The discharge coefficient value of 0.64 is for typical small-window openings that take up less than 20% of the wall area and that are located in the middle of the wall. For large openings and airflow equations involving a series of openings (but no flow branching) see Aynsley[1]. For airflow involving multiple windows and significant flow branching see Walton[2] or Vickery[3].

The major difficulty in using equation (1) is in estimating the pressure difference coefficient PD. PD is given by

$$PD = WPC - LPC; \text{ where} \qquad (2)$$

WPC = Windward Pressure Coefficient
LPC = Leeward Pressure Coefficient

Surface pressure coefficients have been measured by civil engineers for structural wind load calculations[4,5]. The effect of neighboring buildings on pressure coefficients has been investigated by Lee[6]. These measurements were made primarily for structural calculations and emphasized peak loads at critical points of a building. Pressure coefficient data with an emphasis on natural ventilation have been obtained by Aynsley[7] and, recently, as part of studies by Cermak [8] and Vickery[9]. All of these pressure data are for solid buildings. Recent investigations by Vickery[9] have shown that the effect of small apertures (less than 20% of wall space) on solid-building pressure data is not significant if the apertures are in the walls. However, roof level outlets -- even small ones -- can have significant effects, and airflows in such situations can be much smaller than those computed on the basis of solid-body pressure coefficients.

## 2. SIZING PROCEDURE

In the following, a sizing form and accompanying tables are presented. The pressure data given in Table 1 are synthesized from Cermak[8] and Vickery[9]. Table 2 data are from Lee[6] and Aynsley[7]. The terrain correction factors (Table 3) are based on wind speed variation with height for standard terrains[10], and the nighttime wind speed factors have been obtained by analyzing hourly weather data for Orlando. This analysis indicated that the ratio of nighttime average wind speed to 24-hour average wind speed is 0.75. The porosity factors (Table 4) for screen and window types is based on estimated geometric reductions in aperture area.

This form is designed to size windows in one room. For sizing windows in multiple rooms of a house, the calculations need to be repeated for each room. Major inputs of this procedure are design air change rates and weather conditions. A value of 30 airchanges per hour is recommended as a design goal for low-mass residences. This airchange level is to be attained at the monthly average wind speed and direction. Monthly data are available form NOAA (11). The selection of the design month is subjective and in humid climates depends on the maximum tolerable humidity levels. For house designs in Florida, May seems to be a reasonable design month.

## 3. VERIFICATION

The procedure given here has been verified against airflow measurements in a conventional three-bedroom, two-bath slab-on-grade single-story house located at the Florida Solar Energy Center. Figure 1 shows the plan view of this 1214 $ft^2$. house. For these experiments, the top sashes of all eight double-hung windows are opened. Figure 1 also shows the open area of all the windows in square feet. In addition, the windows are screened with a 60 percent porosity insect screen.

The airflows were measured with a multiroom $SF_6$ sampling technique. With the windows closed, a small amount (approximately 1 cc) of $SF_6$ was injected into the return-air duct of the forced-air system and the air-system fan was operated for one hour to obtain thorough mixing of the $SF_6$ in the house. Then, after turning off the mechanical systems fan, initial gas samples were taken at four locations -- the living room (LR), master bedroom (MBR), and bedrooms 1 and 2 (BR1, BR2). The windows were then opened for five minutes for ventilating and then closed. Final samples from each room were taken five minutes after window closure.

The air change in each room is given by

$$ACPH = \ln (C_i/C_f)/\Delta t; \text{ where,} \qquad (3)$$

ACPH = Air change rate per hour

$C_i$, $C_f$ = Initial and final $SF_6$ concentrations

$\Delta t$ = Time windows were open in hours.

The outside wind speed and direction at the 10-meter level were measured and averaged for the time the windows were open. The results are presented in Table 5. Note the variations in airflow rates from room to room. Since the present theory cannot account for multiple airflow paths, an average house airflow was computed by weighting the room airflows by their individual volumes. Thus the average airchange was calculated as

$$AV. = 0.5 \times LR + 0.25 \times MBR + 0.125 \times (BR1 + BR2) \qquad (4)$$

Table 6 compares the measured average airflows computed from eq. (4) with predicted values. It is seen that the predicted values are always lower. This is believed to be due to the effect of wind turbulence. Wind turbulence tends to promote ventilation. Therefore, the fact that the present procedure underpredicts ventilation is considered satisfactory for design purposes. The predicted values were arrived at as follows:

For easterly winds (WD10 = 87), the garage acts as a wing wall making windows W7 and W8 inlets (see Fig.1). From note 2 of Table 1 the windward pressure coefficient (WPC) is +0.40. The same WPC is applicable for the other inlet, W6, as seen from the 0 degrees entry for surface" a" in Table 1. The leeward pressure coefficients (LPC) are different for the different outlets -- for W3, W4, W5 it is -0.25 and for W1 and W2 it is -0.4. Considering the larger total areas of the south windows, an area weighted average LPC of -0.32 is used for calculations.

For WD10 = 140 the 45 degree wind angle values of Table 1 are used. W3 through W6 are inlets in this case with a WPC = +0.25, and the remaining windows are outlets with an LPC = -0.45. WD10 = 152 results in a wind angle of 62 degrees on the east wall of the house. Using the 67.5 degree wind-angle column it is noted that W6 (in wall surface "a") is a weak outlet. W3, W4, and W5 are inlets with a WPC = +0.3. W1 and W2 are outlets with an LPC = -0.55 and W7 and W8 are outlets with an LPC = -0.4. As an approximation, an area weighted average LPC = -0.42 is used for the calculations.

Since the house is a type 1 house for Table 2 and since there is negligible upwind wind shadowing from neighboring buildings, the PCCF of Table 2 is 1.0. The terrain correction factor of Table 3 is 1.0 since the 10-meter wind speeds were measured on site. The CFMs were then calculated from eq.1 and multiplied by 0.6 to account for screen porosity. The CFMs then are converted to air changes per hour using a house volume of 9300 cubic feet. The calculations are summarized in Table 7.

## 4. CONCLUSIONS

An experimentally verified procedure for sizing windows in cross-ventilated rooms has been presented. The procedure is found to be conservative in that it predicts airflow rates 7 percent to 18 percent lower than measured. This is considered satisfactory for design purposes.

## 5. ACKNOWLEDGEMENTS

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Available for about 300 U.S. Cities from
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Federal Building
Asheville, NC 28801

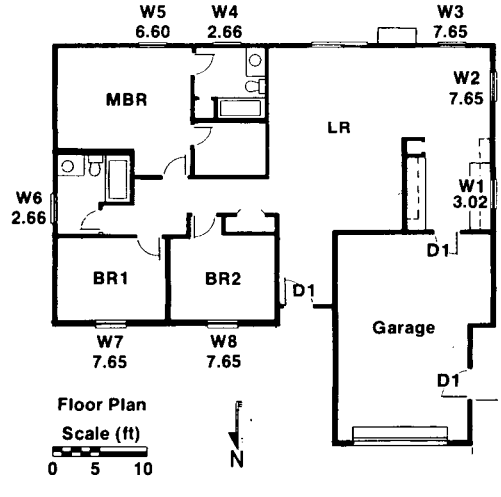



Fig. 1. The FSEC PV House used for ventilation experiments. Open window areas in $ft^2$ indicated below each window.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

## FORM FOR CALCULATING WINDOW AREAS FOR CROSS VENTILATED ROOMS

1. Room volume, V = Floor area x ceiling ht = _____ $ft^3$

2. Required airchange rate per hour, ACPH = _____

3. Required airflow rate, CFM

   CFM = V x ACPH/60 = _____ cfm

4. Building location = _____ (city)
   Design month = _____ (month)

5. Wind speed for month, WS = _____ mph

6. Prevailing wind direction for month, WD = _____

7. Incidence angle on windward face, $\alpha$ = _____ deg.
   (From site plan and prevailing wind direction)

8. From Table 1 determine
   8a. Windward pressure coefficient, WPC = _____
   8b. Leeward pressure coefficient, LPC = _____

9. Pressure coefficient differential, PCD

   PCD = WPC - LPC = _____

10. For the surrounding neighborhood and the proposed building type determine from Table 2 the pressure coefficient correction factor, PCCF = _____

11. Calculate revised pressure coefficient differential PD

    PD = PCD (Step 9) x PCCF (Step 10) = _____

12. Obtain terrain correction factor, TCF from Table 3 = _____

13. Compute revised meteorological wind speed in feet per minute, W

    $W = \underset{\text{Step 5}}{WS} \times \underset{\text{Step 12}}{TCF} \times 88$ = _____ fpm

14. Calculate required open effective window area, A as

    $A = \frac{1.56\ CFM}{W\sqrt{PD}} = \frac{1.56 \times \text{Step 3}}{\text{Step 13} \times \sqrt{\text{Step 11}}}$ = _____ sq. ft

15. Select an open inlet area, $A_i$ greater than A. Note: If equal inlet and outlet area are desired $A_i = 1.41A$ = _____ sq. ft

16. Calculate open outlet area, $A_o$

    $A_o = \frac{A.A_i}{\sqrt{(A_i^2 - A^2)}}$ = _____ sq. ft

    Step 15, Step 14

17. Increase open areas calculated above for blockage due to insert screens, partially open windows etc.

    Find Porosity Factor (PF) from Table 4 PF = _____

18. Calculate TOTAL (not open) inlet and outlet window areas, $TA_i$, $TA_o$

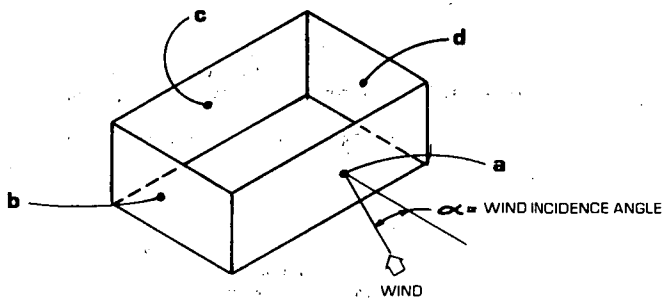
    $TA_i = A_i/PF$ = _____ sq. ft

    Steps 15&17

    $TA_o = A_o/PF$ = _____ sq. ft

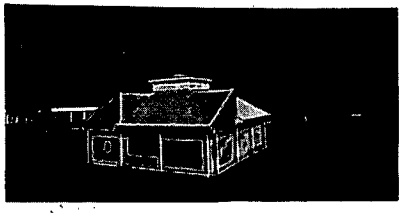
    Steps 16&17

TABLE 1. Typical Surface Average Pressure Coefficients on the Walls of a Residential Scale Building




| Wind angle | Building Wall Surface Pressure Coefficients, PC at Surfaces | | | |
|---|---|---|---|---|
| α | a | b | c | d |
| 0 | +0.40 | -0.40 | -0.25 | -0.40 |
| 22.5 | +0.40 | -0.06 | -0.4 | -0.60 |
| 45 | +0.25 | +0.25 | -0.45 | -0.45 |
| 67.5 | -0.06 | +0.3 | -0.55 | -0.40 |
| 90 | -0.40 | +0.40 | -0.40 | -0.25 |

Source - Colorado State University wind tunnel tests on a 1:25 scale model of the Florida Solar Energy Center Passive Cooling Laboratory



Notes: Recommended Pressure Coefficient, PC values for other apertures are

1. Inlet with wingwall assist, PC = +0.40
2. Outlet with wingwall assist, PC = -0.25
3. Roof outlets (e.g. venturi type), PC = -0.30

TABLE 2. Pressure Coefficient Correction Factor PCCF

Wall height of typical upwind buildings, h = _____ft

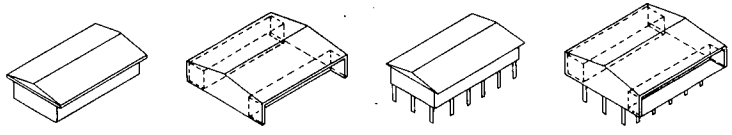
Gap between proposed building and adjacentupwind building, g = _____ft

Ratio g/h = _____

| Ratio g/h | PCCF for building types 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 0 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 0.17 | 0.24 | 0.23 | 0.31 |
| 2 | 0.40 | 0.57 | 0.54 | 0.72 |
| 3 | 0.59 | 0.83 | 0.79 | 1.06 |
| 4 | 0.73 | 1.03 | 0.98 | 1.32 |
| 5 | 0.87 | 1.23 | 1.17 | 1.57 |
| 6 or more | 1.0 | 1.41 | 1.34 | 1.80 |

Building Description

1. Common one story building on ground, or lower floor of two story building.
2. One story building with extended eaves and wingwalls.
3. Building elevated on stilts or second floor of common building.
4. Type 2 building elevated on stilts or second floor with extended eaves and wingwalls.




**BUILDING TYPES**

**SOURCE: AYNSLEY**

Table 3. Terrain Correction Factor for Wind Speed, TCF

| Terrain Type | TCF 24 hr ventilation | TCF Night-only ventilation |
|---|---|---|
| 1. Oceanfront or >3 miles water in front | 1.3 | 0.98 |
| 2. Flatlands with isolated wall separated buildings (e.g., farmhouse) | 1.00 | 0.75 |
| 3. Rural or suburban | 0.85 | 0.64 |
| 4. Urban or industrial | 0.67 | 0.50 |
| 5. Center of large city | 0.47 | 0.35 |

Table 4. Porosity Factors, PF

a) Insect screening, IPF

| | Screen type | Typical IPF |
|---|---|---|
| i. | No screen | 1.00 |
| ii. | Bronze, 14 wires/inch | 0.80 |
| iii. | Fiberglass, 18 wires/inch | 0.60 |

b) Window Porosity, WPF

| | Window Type | Typical WPF |
|---|---|---|
| i. | Single or double hung | 0.40 |
| ii. | Awning, Hopper, Jalousie or Projection which swivel open on a horizontal pivot | 0.60 |
| iii. | Casement. | Varies depending on fixed sash amount. Need to measure porosity |

Porosity Factor, PF = IPF x WPF = _____

Note: Above WPF s assume that interior drapes or shades will not be blocking any wind.

Table 5. Measured Natural Ventilation Airflow

| WD10 | WS10 (mph) | Airchanges/hr in LR | MBR | BR1 | BR2 |
|---|---|---|---|---|---|
| 87 | 5.6 | 17.1 | 14.5 | 22.6 | 31.8 |
| 140 | 9.7 | 18.1 | 46.0 | 37.4 | 36.2 |
| 152 | 7.1 | 17.9 | 36.0 | 26.8 | 31.9 |

WD10 - Wind direction at 10 m degrees from north, i.e. 90 means easterly winds 135 is southeasterly winds etc.

WS10 - Wind speed at 10m, mph.

Table 6. Comparison of Measured and Predicted Average Airflow (Airchanges/hr)

| WD10 | WS10 | Expt | Theory | Diff |
|---|---|---|---|---|
| 87 | 5.6 | 19.0 | 15.6 | 17.9% |
| 140 | 9.7 | 29.8 | 27.7 | 7.0% |
| 152 | 7.1 | 23.3 | 19.1 | 18.0% |

Table 7. Summary of Natural Ventilation Calculations (see eq. 1 for symbols)

| WD10 | PD | $A_i$ | $A_o$ | A | CD | W | CFM |
|---|---|---|---|---|---|---|---|
| 87 | 0.72 | 18.0 | 27.6 | 15.08 | 0.64 | 493 | 4037 |
| 140 | 0.70 | 19.6 | 26.0 | 15.65 | 0.64 | 854 | 7157 |
| 152 | 0.72 | 16.9 | 28.7 | 14.55 | 0.64 | 625 | 4938 |

Airchanges/hr = CFM x 0.6 (porosity) x 60 (min/hr)/9300 (volume)

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# SOLAR AND INTERNAL GAIN ADJUSTMENTS IN CALCULATION OF ENERGY CONSERVATION SAVINGS

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## ABSTRACT

Heating degree days are often used as a climatic measure in building energy calculations. To account for the effects of solar and internal gains, degree days at a lower base temperature are sometimes used, or the number of degree days is adjusted downward by a degree-day correction factor. In this paper, we present a theoretical derivation which demonstrates that ASHRAE $C_d$ factors are not the appropriate correction factors for calculation of energy savings from envelope conservation measures. The results of this derivation can be used to develop new correction factors appropriate for savings calculations.

## 1. INTRODUCTION

A large number of home energy audits have been completed by utilities across the country; these programs are continuing and expanding to include multifamily and commercial buildings. In these audits, energy savings are typically calculated by simplified procedures, many of which are derived from the Residential Conservation Service (RCS) model audit (1). At SERI, we have worked on verification of portions of the RCS model audit by comparison with hourly simulations. In the course of these verification efforts, we have investigated the use of degree-day correction factors in energy savings calculations and building load calculations. The term "energy savings" refers to a reduction in heating "load," and the important distinction is that "savings" are calculated as a difference. The focus of this paper is on savings calculations; some aspects of load calculations are discussed to demonstrate and support our conclusions regarding savings calculations, but many related issues regarding load calculations are beyond the scope of this paper and are mentioned only briefly. This paper is based on degree-day theory, and simplified methods are said to be "inappropriate" or "in error" relative to the more detailed version of the theory (see discussion of the variable-base degree-day method in Section 3.) We have found problems when the $C_d$ factor from the modified degree-day method for load calculations has been inappropriately used for savings calculations.

## 2. THE MODIFIED DEGREE-DAY METHOD

In the ASHRAE modified degree-day method (2), annual building heating loads are calculated as:

$$Q = 24(UA)(HDD_{65})C_d \,, \qquad [1]$$

where

$Q$ = annual heating load

$UA$ = overall building heat-loss coefficient

$HDD_{65}$ = annual heating degree days to base temperature 18.3°C (65°F)

$C_d$ = degree-day correction factor.

The $C_d$ factor in Eq. 1 is needed primarily because degree days are used to a 18.3°C (65°F) base temperature (3), a value based on work done in the 1930s when the degree-day method was originally developed. For modern residential buildings, lower base temperatures should be used because of better insulation, higher internal gains, and lower thermostat settings. Because degree-day data were not available for lower base temperatures until recently (2), the $C_d$ factor was introduced in the modified degree-day method. $C_d$ is a multiplier, generally less than 1.0, which modifies $HDD_{65}$ to a smaller number of degree days, thereby approximating the effect of a lower base temperature. Appropriate base temperatures are a function of building characteristics and use. The ASHRAE $C_d$ factors, however, are given only as a function of climate. Therefore, the $C_d$ factors include assumptions of average building characteristics and use, and Eq. 1 will be in error for buildings that do not match the $C_d$ assumptions.

### 2.1 The $C_d$ Factor in Energy Savings Calculations

According to Eq. 1, the heating loads before and after the application of a conservation measure can be calculated using the following two equations:

$$Q_1 = 24(UA_1)(HDD_{65})C_d \qquad [2]$$

and

$$Q_2 = 24(UA_2)(HDD_{65})C_d\,, \qquad [3]$$

where

$Q_1$ = annual heating load before retrofit

$Q_2$ = annual heating load after retrofit

$UA_1$ = building heat-loss coefficient before retrofit

$UA_2$ = building heat-loss coefficient after retrofit.

The energy savings from a particular conservation measure are equal to the difference between heating loads before and after retrofit. It seems logical that the difference, $Q_1 - Q_2$, can be calculated by subtracting Eq. 3 from Eq. 2, and that the result should be

$$\Delta Q = 24(UA_1 - UA_2)(HDD_{65})C_d\,, \qquad [4]$$

where

$\Delta Q$ = annual energy savings due to retrofit

$UA_1$ = component heat-loss coefficient before retrofit

$UA_2$ = component heat-loss coefficient after retrofit.

Note that only component UA values for the retrofit measure remain, because the other UA values, which are equal before and after retrofit, have been cancelled out.

Even though Eq. 4 appears to be a reasonable extension of Eq. 1 based on the above derivation, a more detailed analysis presented in the following section shows that this is not the case. The approximate nature of the heating loads calculated in Eqs. 2 and 3 will cause large errors when savings are calculated as the difference in Eq. 4. Even if the $C_d$ factor is accepted as a reasonable approximation in Eq. 1, the use of $C_d$ in Eq. 4 is not theoretically correct.

## 3. THE VARIABLE-BASE DEGREE-DAY METHOD

The variable-base degree-day (VBDD) method involves determining the appropriate number of degree days for a specific building in a given climate (2). Predictions of annual heating loads based on the VBDD method have been shown to compare well with results from hourly simulation programs (4). The VBDD method is applied by first determining the balance-point temperature $T_b$ for a particular building. $T_b$ is defined as the outdoor temperature above which heating is not required on the average, because heat losses are balanced by internal and solar gains. $T_b$ can be calculated as:

$$T_b = T_{set} - (I + S)/UA\,, \qquad [5]$$

where

$T_b$ = balance-point temperature

$T_{set}$ = thermostat set point temperature

I = average hourly utilizable internal gains

S = average hourly utilizable solar gains.

Heating loads are assumed to be proportional to degree days to a base temperature equal to the balance-point temperature. Then according to the VBDD method, building heating loads are calculated as:

$$Q = 24(UA)(HDD_{T_b})\,, \qquad [6]$$

where

$HDD_{T_b}$ = the heating degree days to base temperature $T_b$.

The VBDD method does not explicitly account for hour-to-hour or day-to-day variability of solar or internal gains, nor the degree of coincidence of gains with hourly heating loads. Consequently, there is some uncertainty as to the proper determination of average utilizable solar and internal gains. The effect of solar gains is accounted for more explicitly in various passive solar calculation methods. The issue of coincidence is addressed in the concept of sol-air heating degree days recently developed by Erbs et al. (5). The utilizability of solar gains including the effect of thermal mass is addressed in correlation-based techniques such as the solar-load-ratio method (6) and the unutilizability method (7). Energy savings due to a particular conservation measure can be calculated by use of these passive solar methods to calculate heating loads before and after retrofit. In this paper, we discuss degree-day correction factors to be used in a simple, one-step approach and the applicability of this method to certain types of buildings.

Figure 1 shows heating degree days plotted as a function of balance-point temperature, based on TMY and ersatz TMY data (8) for Altanta, Denver, and Madison. The data have been fitted by using the following quadratic expression:

$$HDD_{T_b} = A + B(T_b) + C(T_b)^2\,, \qquad [7]$$

where A, B, and C are location-dependent constants.

### 3.1 $C_v$ Factors from the VBDD Method

To demonstrate the effects of degree-day correction factors on the calculation of loads and savings, we define $C_v$ factors to be building-specific $C_d$ factors calculated according to the VBDD method. The new correction factor can be defined as:

$$C_v = HDD_{T_b}/HDD_{65} \qquad [8]$$

or

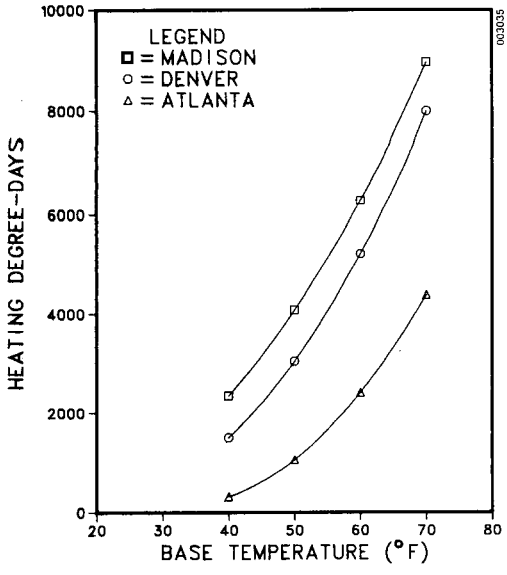



**Fig. 1. Heating Degree-Days as a Function of Base Temperature**

$$C_v = [A + B(T_b) + C(T_b)^2]/HDD_{65}\,, \qquad [9]$$

where $C_v$ is the heating degree-day correction factor according to the VBDD method.

Thus, annual heating loads can be accurately determined for a building using the following modification of Eq. 1:

$$Q = 24(UA)(HDD_{65})C_v\,. \qquad [10]$$

The energy savings from a conservation measure can be calculated by taking the difference between the calculated loads before and after the retrofit:

$$Q_1 = 24(UA_1)(HDD_{65})C_{v_1} \qquad [11]$$

and

$$Q_2 = 24(UA_2)(HDD_{65})C_{v_2}\,, \qquad [12]$$

where

$C_{v_1}$ = VBDD heating degree-day correction factor before retrofit

$C_{v_2}$ = VBDD heating degree-day correction factor after retrofit.

Therefore, the annual energy savings from the conservation measure are:

$$\Delta Q = 24[(UA_2)C_{v_2} - (UA_1)C_{v_1}]HDD_{65}\,. \qquad [13]$$

Eq. 13 allows the calculation of energy savings according to VBDD theory. However, this equation can be developed further into a simpler method that loses little in accuracy.

## 4. THE $C_s$ FACTOR

Based on Eq. 13, a new factor, $C_s$, will be derived for use in Eq. 4 in place of $C_d$.

Inserting $C_s$ for $C_d$ in Eq. 4 gives:

$$\Delta Q = 24(UA_2 - UA_1)(HDD_{65})C_s\,, \qquad [14]$$

and combining Eq. 14 with Eq. 13 gives:

$$C_s = [(UA_2)C_{v_2} - (UA_1)C_{v_1}]/(UA_2 - UA_1)\,. \qquad [15]$$

This equation, which results from VBDD theory, shows that $C_s$ is not equal to any single value of $C_v$, nor is it an average of $C_v$ values before and after a retrofit measure. Combining Eqs. 5, 9, and 15 gives:

$$C_s = (HDD_{T_{set}}/HDD_{65}) - C(I + S)^2/(UA_1)(UA_2)(HDD_{65})\,. \qquad [16]$$

The first term in this equation merely converts from a base temperature of 18.3°C (65°F) to the heating set-point temperature. The second term is a second-order adjustment, which is the result of the nonlinearity of heating degree days as a function of base temperature. It should be noted that as the UA values become large, or the I + S values become small, the value of $C_s$ approaches $HDD_{T_{set}}/HDD_{65}$.

The differences between $C_s$ and $C_v$ are shown in Fig. 2. According to the VBDD method, heating load is a function of overall building UA, as given in Eq. 6. The result is the solid curve in Fig. 2, assuming internal gains equal to 646 W (2208 Btu/h) and average solar gains equal to 880 W (3000 Btu/h). According to the modified degree-day method, the heating load is directly proportional to overall building UA. For a building-specific $C_v$ factor (Eq. 10), the result is the dashed straight line in Fig. 2, but the heating load is correct only at the point where the straight line intersects the curve, i.e. when UA = $UA_1$. A similar condition holds for Eq. 11, and the dotted line in Fig. 2 is the result. The energy savings for a change from $UA_1$ to $UA_2$ are given by the vertical distance between point 1 and point 2. This vertical distance can be determined by multiplying $(UA_1 - UA_2)$ by the slope of a line connecting the two points. The $C_s$ factor is defined so that $24(HDD_{65})C_s$ equals the slope of a line between the two points. For the modified degree-day method, the slope of the line will not match the slope of the VBDD curve, even if the intersection is approximately correct; i.e., $C_d$ is not the correct factor for calculating energy savings, even if the value of $C_d$ is approximately correct for calculating heating loads.

## 5. COMPARISON OF DEGREE-DAY CORRECTION FACTORS

In Figs. 3 through 5, $C_d$, $C_v$, and $C_s$ factors are plotted as functions of overall building UA for three locations. The ASHRAE $C_d$ factors have a single value for each location and are, therefore,

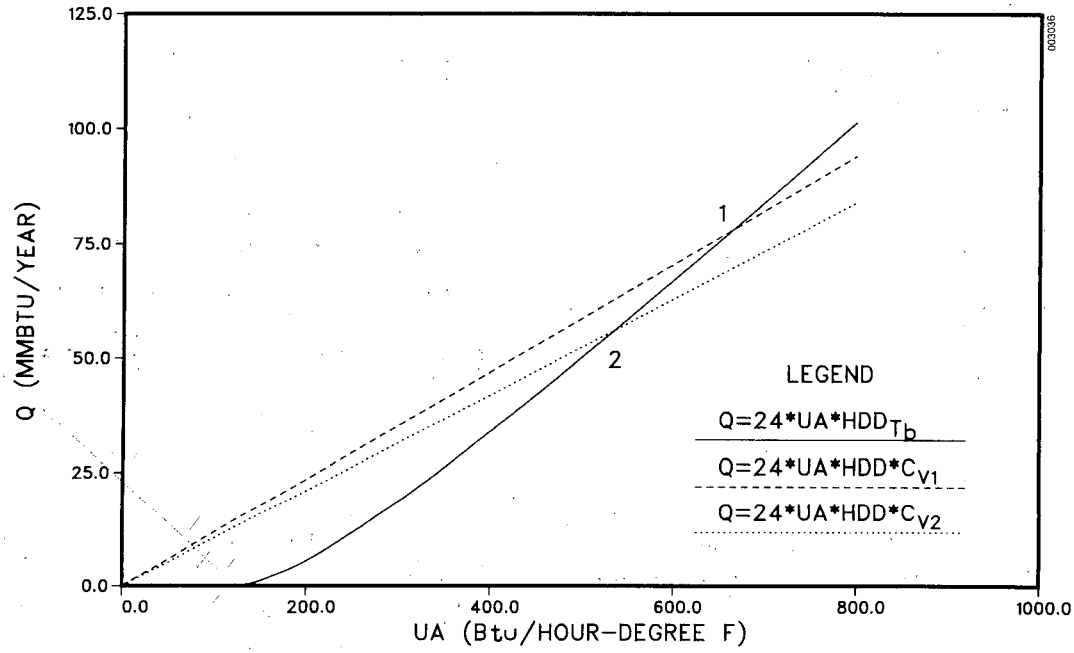



**Fig. 2. Annual Heating Load as a Function of Building UA**

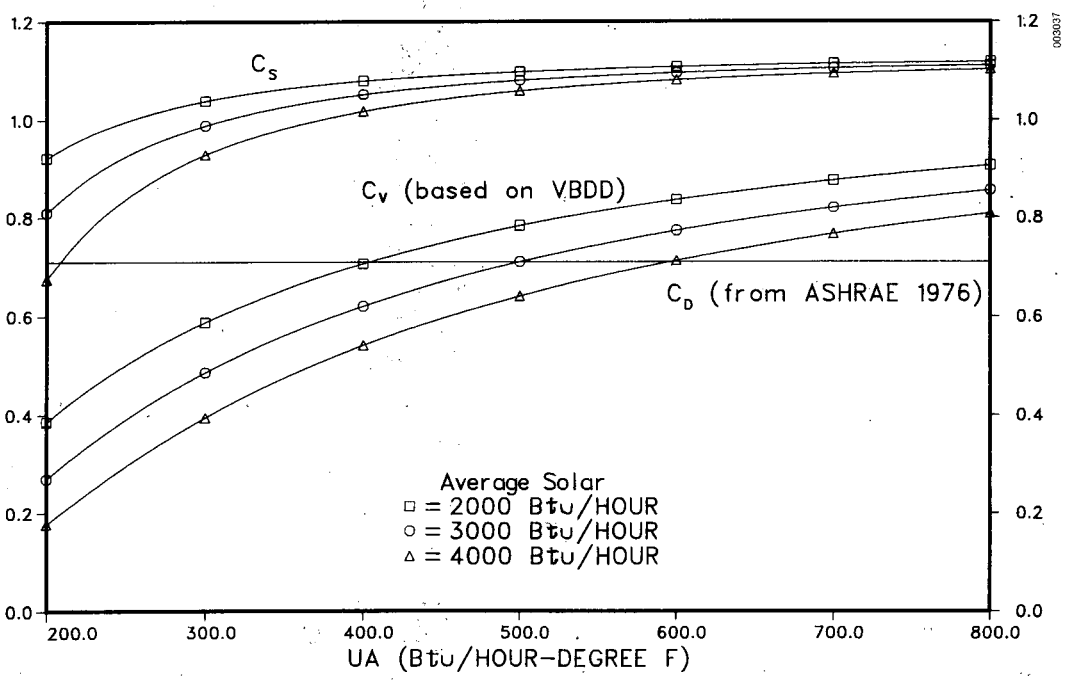



**Fig. 3. Degree-Day Correction Factors (Denver, CO): $C_d$ and $C_v$ for Calculating Loads and $C_s$ for Calculating Savings**

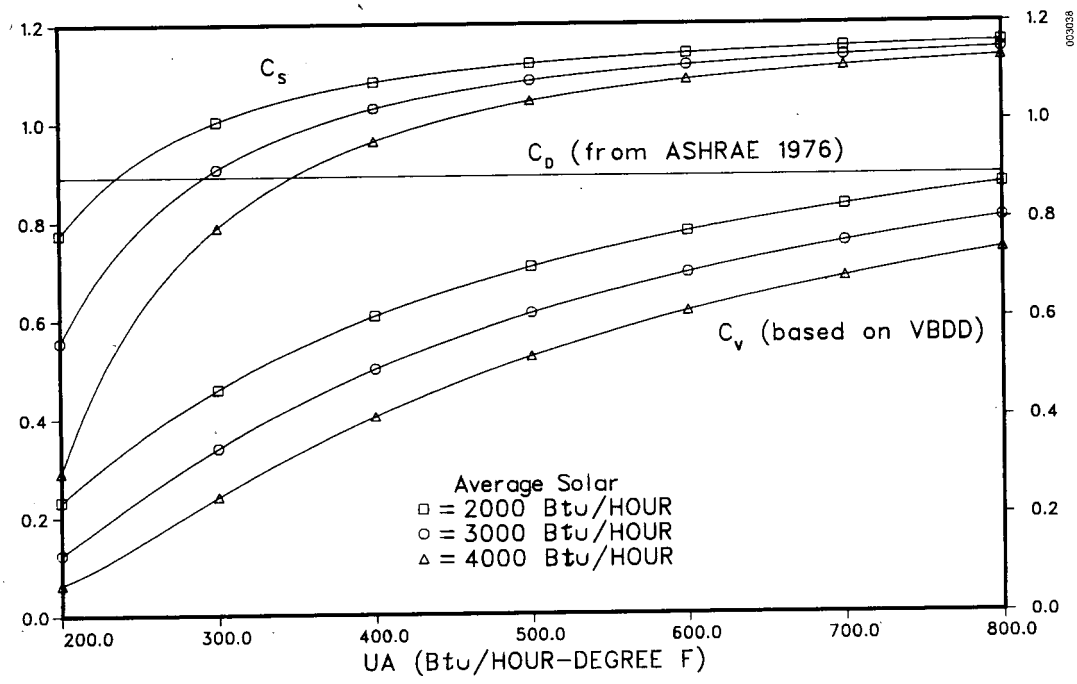



**Fig. 4.** Degree-Day Correction Factors (Atlanta, GA): $C_d$ and $C_v$ for Calculating Loads and $C_s$ for Calculating Savings

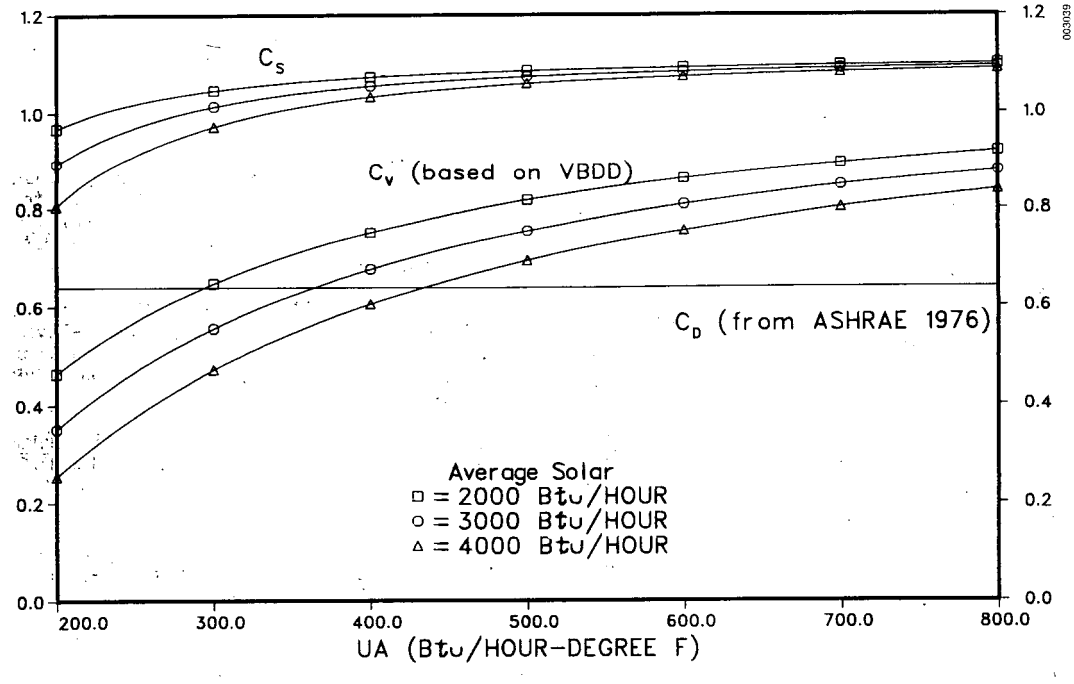



**Fig. 5.** Degree-Day Correction Factors (Madison, WI): $C_d$ and $C_v$ for Calculating Loads and $C_s$ for Calculating Savings

shown as horizontal lines. The building- and climate-specific $C_v$ factors (from VBDD) were calculated according to Eq. 9. The values for $C_s$ were calculated according to Eq. 16. The $C_s$ values assume a 20% difference between $UA_1$ and $UA_2$ and are plotted as a function of the average of $UA_1$ and $UA_2$. It can be shown that reasonable deviations from these assumptions will result in only slightly different values for $C_s$. Both $C_v$ and $C_s$ are plotted for three levels of average utilizable solar gains and a constant value for internal gains of 646 W (2208 Btu/h).

Comparison of the $C_d$ factors with the $C_v$ factors for the three locations presented in Figs. 3 through 5 shows that if the building UA is large, then use of the standard ASHRAE $C_d$ factor will underpredict heating loads compared to the VBDD method (except in Atlanta). Conversely, if the UA is small, then use of the standard ASHRAE $C_d$ factor will overpredict heating loads compared to the VBDD method. For each location, there is only a single UA value for which the ASHRAE $C_d$ factor is equal to the VBDD $C_v$ factor for a given level of solar gain. Assuming average solar gain of 880 W (3000 Btu/h) for Denver and 590 W (2000 Btu/h) for Madison and Atlanta, then the $C_d$ factor is equal to the $C_v$ factor when the UA is approximately 49, 65, and 81 W/°C (300, 500, and 800 Btu/h °F) for Madison, Denver, and Atlanta, respectively. That is, the $C_d$ factors correspond to building insulation levels that are relatively good, average, and poor in Madison, Denver, and Atlanta, respectively. This conclusion is based on a preliminary analysis with approximations for solar gains and assumptions for internal gains. The trend, however, is as expected and is consistent with development of the modified degree-day method.

Comparison of the $C_s$ factors with the $C_d$ factors for the three locations presented in Figs. 3 through 5 shows that the use of $C_d$ factors will underpredict energy savings in most cases. For buildings with overall UA values above a certain threshold and with internal and solar gains within the range represented on the figures, the values for $C_s$ do not vary by more than 10%, and $C_d$ factors will underpredict energy savings by approximately 42%, 37%, and 23% in Madison, Denver, and Atlanta, respectively. The threshold UA values are approximately 49, 65, and 81 W/°C (300, 400, and 500 Btu/h °F) for Madison, Denver, and Atlanta, respectively. For such buildings, constant $C_s$ factors can be presented in tabular form similar to the ASHRAE $C_d$ factors and used directly in the modified degree-day method. This approach will be valid for most existing single-family detached residences. For other buildings that are highly insulated or have exceptionally high levels of internal or solar gains, $C_s$ factors (and $C_d$ factors) could be developed as functions of location, overall UA, solar gains, and internal gains, and presented in graphical form.

## 6. CONCLUSIONS

The ASHRAE $C_d$ degree-day correction factors were developed for load calculations. The use of these $C_d$ factors in savings calculations is theoretically incorrect and produces results that underpredict energy savings by 23%-42% for typical, existing single-family detached residences in a range of climates.

New heating degree-day correction factors specifically for savings calculations, $C_s$ factors, can be developed based on the results presented in this paper. These factors, based on the variable-base degree-day method, avoid the theoretical problems of the $C_d$ factors and can be derived in a form that is directly usable in the ASHRAE modified degree-day method.

## 7. ACKNOWLEDGEMENTS

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# CONSERVATION AND SOLAR GUIDELINES*

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## ABSTRACT

Guidelines are given for selecting R-values and infiltration levels and determining the size of the solar collection area for passive solar buildings. The guidelines are based on balancing the incremental cost/benefit of conservation and passive solar strategies. Tables are given for 90 cities in the US and the results are also displayed on maps. An example is included.

## 1. INTRODUCTION

During the last few years, a conclusion has been expressed repeatedly: good passive solar design involves a balance of conservation and solar gains, and the proper balance depends on the climate. This conclusion is independently reached by cost/benefit studies using computer models and by practitioners designing and building across the country. By conservation we mean added insulation and decreased air infiltration to reduce the gross heating energy required to maintain winter comfort. By passive solar we mean adding south windows, Trombe walls, or sunspaces to supply some of this gross heat. The net heat required by the building is the gross heat minus the solar savings. Conservation makes the passive solar system's job easier; likewise, passive solar reduces the need for auxiliary heat well below levels attainable by conservation alone. Good thermal design consists of achieving a proper balance of these two strategies.

The purpose of this paper is to present a quantitative but simple set of guidelines for balancing conservation and solar that takes proper account of the solar and weather characteristics of each location. The guidelines are not a substitute for thermal evaluation later in the design process, but do provide a reasonable starting point for schematic design. They are applicable to residential buildings and small commercial buildings having residential levels of internal gains (30-60 Btu/ft$^2$ per day).

The two guidelines will be presented first; an explanation of their development follows.

## 2. GUIDELINE 1. CONSERVATION LEVELS

Recommended levels of insulation and building airtightness can be computed based on a conservation factor (CF). Two suggested levels of CF, corresponding to two different projected fuel costs, are given in Table 1 for 90 cities. Unless conditions indicate otherwise, use the CF values corresponding to high fuel cost as a starting point.

Use the following formulas to compute guidance values for insulation and airtightness levels.

$$R_{wall} = 14 \cdot CF$$
$$R_{ceiling} = 22 \cdot CF$$
$$R_{perimeter} = 13 \cdot CF - 5$$
$$R_{basement} = 16 \cdot CF - 8$$
$$N_{E,W,N} = 1.7 \cdot CF$$
$$ACH = 0.42/CF$$

Based on guidance resulting from these formulas, select practical, buildable conservation levels as a starting point for the design, trying for the most part to stay within 20% of the guidance. For windows choose the closest integer value.

$R_{wall}$ and $R_{ceiling}$ are the overall R-values (h $^oF$ ft$^2$/Btu) of the opaque wall and ceiling insulation, accounting for the series effect of all air layers and materials, including the attic air space, if any.

$R_{perimeter}$, which refers to slab-on-grade construction, is the R-value of insulation

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TABLE 1. GUIDELINE VALUES OF CONSERVATION FACTOR, LOAD COLLECTOR RATIO, AND SOLAR SAVINGS FRACTION

| | Low Fuel Cost | | | High Fuel Cost | | |
|---|---|---|---|---|---|---|
| | CF | LCR | SSF(%) | CF | LCR | SSF(%) |
| BIRMINGHAM, ALABAMA | .95 | 117 | 31 | 1.19 | 41 | 58 |
| PHOENIX, ARIZONA | .70 | 123 | 53 | .83 | 66 | 74 |
| WINSLOW, ARIZONA | 1.13 | 46 | 57 | 1.35 | 25 | 75 |
| LITTLE ROCK, ARKANSAS | 1.04 | 97 | 31 | 1.30 | 34 | 59 |
| FRESNO, CALIFORNIA | .91 | 108 | 39 | 1.12 | 47 | 60 |
| LOS ANGELES, CA | .70 | 96 | 70 | .81 | 61 | 84 |
| RED BLUFF, CALIFORNIA | .92 | 116 | 34 | 1.14 | 47 | 58 |
| SACRAMENTO, CA | .93 | 102 | 40 | 1.15 | 46 | 60 |
| SAN FRANCISCO, CA | .89 | 70 | 64 | 1.04 | 42 | 78 |
| COLORADO SPRINGS, CO | 1.30 | 33 | 60 | 1.55 | 18 | 78 |
| DENVER, COLORADO | 1.27 | 36 | 57 | 1.52 | 19 | 76 |
| GRAND JUNCTION, CO | 1.27 | 45 | 47 | 1.56 | 21 | 69 |
| HARTFORD, CONNECTICUT | 1.42 | 137 | 13 | 1.88 | 36 | 29 |
| WILMINGTON, DELAWARE | 1.25 | 90 | 23 | 1.62 | 28 | 47 |
| WASHINGTON, DC | 1.26 | 97 | 21 | 1.64 | 30 | 45 |
| APALACHICOLA, FLORIDA | .69 | 173 | 39 | .82 | 74 | 65 |
| ORLANDO, FLORIDA | .50 | 272 | 46 | .59 | 134 | 70 |
| ATLANTA, GEORGIA | 1.00 | 101 | 32 | 1.24 | 37 | 59 |
| BOISE, IDAHO | 1.31 | 64 | 33 | 1.67 | 28 | 51 |
| CHICAGO, ILLINOIS | 1.39 | 121 | 15 | 1.83 | 34 | 32 |
| SPRINGFIELD, ILLINOIS | 1.32 | 98 | 19 | 1.73 | 28 | 42 |
| EVANSVILLE, INDIANA | 1.21 | 121 | 19 | 1.58 | 34 | 42 |
| INDIANAPOLIS, INDIANA | 1.33 | 158 | 12 | 1.76 | 40 | 30 |
| BURLINGTON, IOWA | 1.39 | 91 | 19 | 1.82 | 27 | 41 |
| MASON CITY, IOWA | 1.56 | 81 | 18 | 2.07 | 25 | 36 |
| DODGE CITY, KANSAS | 1.21 | 49 | 45 | 1.49 | 22 | 69 |
| LEXINGTON, KENTUCKY | 1.23 | 131 | 17 | 1.60 | 35 | 39 |
| LAKE CHARLES, LA | .72 | 219 | 28 | .89 | 73 | 57 |
| NEW ORLEANS, LA | .70 | 176 | 36 | .85 | 71 | 64 |
| CARIBOU, MAINE | 1.72 | 92 | 14 | 2.29 | 33 | 25 |
| PORTLAND, MAINE | 1.52 | 103 | 15 | 2.02 | 32 | 30 |
| BALTIMORE, MARYLAND | 1.23 | 92 | 24 | 1.58 | 29 | 48 |
| BOSTON, MASSACHUSETTS | 1.33 | 113 | 17 | 1.75 | 32 | 37 |
| DETROIT, MICHIGAN | 1.40 | 168 | 11 | 1.85 | 47 | 24 |
| TRAVERSE CITY, MI | 1.54 | 191 | 8 | 2.04 | 63 | 16 |
| INT. FALLS, MINNESOTA | 1.80 | 148 | 8 | 2.39 | 59 | 14 |
| MINNEAPOLIS, MN | 1.60 | 126 | 11 | 2.13 | 39 | 23 |
| JACKSON, MISSISSIPPI | .86 | 133 | 32 | 1.06 | 48 | 60 |
| COLUMBIA, MISSOURI | 1.26 | 97 | 21 | 1.64 | 28 | 46 |
| KANSAS CITY, MISSOURI | 1.29 | 80 | 25 | 1.67 | 25 | 50 |
| SAINT LOUIS, MISSOURI | 1.22 | 97 | 23 | 1.58 | 29 | 48 |
| BILLINGS, MONTANA | 1.47 | 57 | 29 | 1.91 | 22 | 48 |
| DILLON, MONTANA | 1.55 | 41 | 37 | 1.98 | 18 | 55 |
| GREAT FALLS, MONTANA | 1.51 | 64 | 25 | 1.97 | 26 | 41 |
| OMAHA, NEBRASKA | 1.43 | 72 | 23 | 1.87 | 22 | 47 |
| NORTH PLATTE, NEBRASKA | 1.41 | 44 | 39 | 1.77 | 18 | 62 |
| ELY, NEVADA | 1.41 | 30 | 59 | 1.70 | 16 | 76 |
| LAS VEGAS, NEVADA | .86 | 80 | 55 | 1.02 | 43 | 75 |
| RENO, NEVADA | 1.23 | 38 | 60 | 1.47 | 21 | 77 |
| CONCORD, NEW HAMPSHIRE | 1.51 | 123 | 12 | 2.01 | 36 | 27 |
| NEWARK, NEW JERSEY | 1.27 | 99 | 21 | 1.65 | 29 | 44 |
| ALBUQUERQUE, NM | 1.08 | 48 | 58 | 1.29 | 26 | 77 |
| LOS ALAMOS, NM | 1.29 | 33 | 61 | 1.53 | 18 | 79 |
| ALBANY, NEW YORK | 1.47 | 160 | 10 | 1.95 | 42 | 24 |
| BINGHAMTON, NEW YORK | 1.50 | 269 | 6 | 1.99 | 70 | 15 |
| BUFFALO, NEW YORK | 1.47 | 261 | 7 | 1.94 | 70 | 15 |
| NEW YORK (CENTRAL) | 1.25 | 146 | 15 | 1.64 | 37 | 36 |
| ASHEVILLE, NC | 1.14 | 67 | 38 | 1.42 | 27 | 63 |
| RALEIGH, NORTH CAROLINA | 1.06 | 88 | 33 | 1.32 | 33 | 59 |
| BISMARCK, NORTH DAKOTA | 1.67 | 82 | 16 | 2.22 | 29 | 29 |
| CLEVELAND, OHIO | 1.39 | 231 | 8 | 1.84 | 62 | 19 |
| COLUMBUS, OHIO | 1.34 | 184 | 11 | 1.78 | 46 | 26 |
| OKLAHOMA CITY, OK | 1.07 | 77 | 37 | 1.33 | 30 | 64 |
| MEDFORD, OREGON | 1.22 | 90 | 27 | 1.56 | 38 | 43 |
| NORTH BEND, OREGON | 1.11 | 55 | 53 | 1.35 | 29 | 69 |
| PORTLAND, OREGON | 1.21 | 120 | 21 | 1.55 | 46 | 36 |
| PHILADELPHIA, PA | 1.25 | 103 | 20 | 1.62 | 30 | 44 |
| PITTSBURGH, PA | 1.37 | 208 | 9 | 1.81 | 54 | 22 |
| PROVIDENCE, RI | 1.37 | 92 | 19 | 1.79 | 28 | 40 |
| CHARLESTON, SC | .84 | 129 | 35 | 1.03 | 51 | 62 |
| RAPID CITY, SD | 1.48 | 52 | 31 | 1.90 | 20 | 52 |
| SIOUX FALLS, SD | 1.56 | 83 | 18 | 2.07 | 26 | 35 |
| MEMPHIS, TENNESSEE | 1.02 | 117 | 27 | 1.29 | 37 | 55 |
| NASHVILLE, TENNESSEE | 1.10 | 147 | 18 | 1.42 | 39 | 44 |
| AMARILLO, TEXAS | 1.08 | 52 | 54 | 1.30 | 26 | 75 |
| CORPUS CHRISTI, TEXAS | .58 | 260 | 35 | .70 | 108 | 62 |
| DALLAS, TEXAS | .87 | 118 | 35 | 1.06 | 46 | 63 |
| EL PASO, TEXAS | .88 | 74 | 58 | 1.04 | 40 | 77 |
| SAN ANGELO, TEXAS | .84 | 103 | 44 | 1.01 | 47 | 69 |
| BRYCE CANYON, UTAH | 1.49 | 24 | 65 | 1.77 | 14 | 80 |
| SALT LAKE CITY, UTAH | 1.31 | 50 | 41 | 1.64 | 22 | 61 |
| BURLINGTON, VERMONT | 1.56 | 229 | 7 | 2.08 | 64 | 15 |
| NORFOLK, VIRGINIA | 1.05 | 85 | 34 | 1.31 | 33 | 60 |
| ROANOKE, VIRGINIA | 1.16 | 78 | 31 | 1.47 | 28 | 57 |
| SEATTLE, WASHINGTON | 1.25 | 112 | 22 | 1.60 | 48 | 35 |
| SPOKANE, WASHINGTON | 1.44 | 109 | 17 | 1.88 | 44 | 28 |
| CHARLESTON, WV | 1.21 | 169 | 14 | 1.58 | 42 | 34 |
| GREEN BAY, WISCONSIN | 1.58 | 110 | 13 | 2.10 | 37 | 25 |
| MADISON, WISCONSIN | 1.55 | 95 | 16 | 2.05 | 30 | 31 |
| CASPER, WYOMING | 1.44 | 34 | 50 | 1.78 | 16 | 70 |

added to the outside of foundation walls or under the slab perimeter. Normally this is rigid insulation installed below grade against foundation walls down to the footing or 2 feet wide under the slab. For a floor built over a crawl space, use either the floor insulation R-value for the frame floor or the perimeter insulation value outside the stem wall down to the footings.

$R_{basement}$ refers to a heated basement and is the R-value of the insulation outside the exterior basement walls extending 4 feet below grade. Use 1/2 this R-value from 4 feet below grade down to the top of the basement-wall footings. Use this same strategy for fully bermed walls.

$N_{E,W,N}$ refers to the number of window glazings to be used on east, west, and north windows. However, if this number exceeds 3, consider using either double glazing combined with movable insulation or using a low-conduction glazing with U-value less than 0.3 Btu/h $^{o}$F ft$^2$.

ACH refers to the effective air changes per hour resulting from natural infiltration and forced ventilation; it is the sum of the natural infiltration and the non-heat-recovered portion of the forced ventilation. If a heat recovery unit is used for forced ventilation, the non-heat-recovered portion is equal to

$$\left(\begin{array}{c}\text{heat recovery}\\ 1 - \text{effectiveness}\\ \text{factor}\end{array}\right) \cdot ACH_{forced}$$

If the guidance value is less than ACH = 0.5 air changes per hour, forced ventilation is recommended using a heat recovery unit to maintain adequate indoor-air quality. For commercial applications or situations with unusually high sources of indoor-air pollution, higher ventilation levels may be required.

## 3. GUIDELINE 2. PASSIVE SOLAR GLAZING AREA

The primary solar parameter of the building is the load collector ratio, LCR. This is defined as follows:

$$LCR = \frac{NLC}{A_p}$$

where NLC is the net load coefficient, excluding losses through the solar wall (Btu/$^{o}$F day), and $A_p$ is the projected area of the solar wall glazing, ft$^2$. See Ref. 1 or 2 for a more complete definition of these terms. (NLC is the same as BLC in Ref. 2.)

Recommended values of LCR are given in Table 1; however, to use these values, an estimate of NLC must somehow be obtained. NLC depends on the conservation level achieved. If the recommendations of Guideline 1 have been followed, NLC can be computed approximately as follows:

$$NLC = \frac{GF \cdot A_f}{CF}$$

where GF is a geometry factor that accounts for the relative dimensions of the building and $A_f$ is the gross floor area. Suggested values of GF are given in Table 2.

TABLE 2

GEOMETRY FACTOR, GF

| Floor Area | Number of Stories 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1000 | 7.3 | | | |
| 1500 | 6.5 | 6.7 | | |
| 3000 | 5.4 | 5.4 | 5.7 | |
| 5000 | 4.9 | 4.7 | 4.9 | 5.1 |
| 10000 | 4.3 | 4.0 | 4.0 | 4.2 |
| 20000 | 3.9 | 3.5 | 3.5 | 3.5 |

The projected area, $A_p$, can now be determined as follows:

$$A_p = \frac{NLC}{LCR}$$

As a starting point for design, the combined projected area of all passive system types should be within 20% of this value. The recommendation is independent of the choice of passive system type or types.

## 4. BACK-UP HEAT

At this point, a very rough estimate of annual auxiliary heat, $Q_{aux}$, can be obtained from the relation

$$Q_{aux} = DD \cdot NLC \cdot (1 - SSF)$$

where DD is the degree days for the location and SSF is the solar savings fraction.

SSF values will depend on system type. Values of SSF for reference design SSD1, a semienclosed sunspace with 50$^{o}$ sloped glazing (see Ref. 1 or 2) are given in Table 1. For other passive system types, refer to the LCR tables in Appendix F of Ref. 2.

## 5. EXAMPLE

Determine conservation and solar guidelines for a 1500 $ft^2$ house in Denver, Colorado.

Table I values, using high fuel cost, are

CF = 1.52
LCR = 19
SSF = 0.76

Therefore, guidance values are as follows:

| | | Recommended Range |
|---|---|---|
| $R_{wall}$ | = 14 x 1.52 = 21 | 17 to 25 |
| $R_{ceiling}$ | = 22 x 1.52 = 33 | 27 to 40 |
| $R_{perimeter}$ | = 13 x 1.52 - 5 = 15 | 12 to 18 |
| $R_{basement}$ | = 16 x 1.52 - 8 = 16 | 13 to 19 |
| $N_{E,W,N}$ | = 1.7 x 1.52 = 2.6 | 2 or 3 |
| ACH | = 0.42/1.52 = 0.28 | 0.22 to 0.34 |

For a 1500 $ft^2$, single-story building,

GF = 6.5, from Table 2

Therefore, if the conservation guidance is followed,

NLC = 6.5 x 1500/1.52 = 6410 Btu/$^oF$ day

$A_p$ = 6410/19 = 340 $ft^2$

For Denver, the degree days (base 65$^oF$) are 6018. Therefore,

$Q_{aux}$ = 6018 x 6410 x (1 - 0.76) = 9.2 million Btu/year

All these estimates, of course, are subject to updating as the design proceeds. However, they do give valuable guidance for beginning the design.

## 6. MAPS

Maps of CF, LCR, and SSF (for a semienclosed sunspace) based on values at 219 locations are given in Figs. 1-3.

## 7. BASIS FOR THE GUIDELINES

Table 1 has been developed based on balancing the incremental cost/benefit of conservation and solar strategies as outlined in Refs. 2 and 3. Each case in Table 1 represents an economic life-cycle cost optimum for each city for identical assumed fuel costs and financial parameters. Thus the table shows how the optimum mix varies with climate.

To obtain simple guidelines, assumed values have been used for the incremental cost of passive solar aperture, conservation improvements, the cost of heat, the escalation rate of the cost of heat, and the fixed charge rate. Note, however, that the guidelines depend on cost ratios and, thus, will not change with inflation if all costs escalate proportionally. The "high fuel cost" column in Table 1 is intended to represent the cost of electric resistance heat in much of the US (about 6.5¢/kWh in 1983 dollars); the "low fuel cost" column is based on one-half of the high fuel cost.

The formula for NLC is based on the premise that conservation levels will be set based on the conservation guidelines. If different conservation levels are used, $A_p$ should be based on a realistic estimate of NLC and the recommended value of LCR.

The guidelines are based on heating-season performance only. Nevertheless, summer cooling should also be a major concern to the designer, especially in the hotter areas of the nation. The first strategy should always be a good defense. This consists primarily of avoiding solar gains in the summer through effective window placement and shading. Deciduous trees are particularly effective to the east and west of the building but should not be used in the south 120$^o$ sector. Various passive cooling strategies can also be used. Most importantly, care should be taken to insure that the passive heating system does not exacerbate the cooling load. Full shading may be warranted in some areas; several studies have indicated that unless this is done, diffuse solar gains alone will significantly add to the cooling load. Preliminary results from studies by McFarland and Jones at Los Alamos indicate that Trombe walls and water walls result in the least cooling load, sunspaces are next (depending on glazing slope), and direct gain usually results in the greatest cooling load. Sloped glazing should probably be avoided (or well shaded in the summer) on sunspaces in the warmest climates. East and west sunspace glazing should be minimized in all locations, and adequate summer venting capability should be provided.

## 8. COST ASSUMPTIONS

As shown in Ref. 3, a global optimum is achieved when D = a/h,

where D = d(SSF)/d(1/LCR), (derivative of SSF with respect to 1/LCR),

a = incremental cost of the passive system, dollars per $ft^2$ of projected area,

h = CH • FF • DD/FCR,

CH = current cost of heat delivered to the building, $/Btu,

FF = levelization factor (see Ref. 4), dimensionless, and

FCR = fixed charge rate (see Ref. 4), $yr^{-1}$.

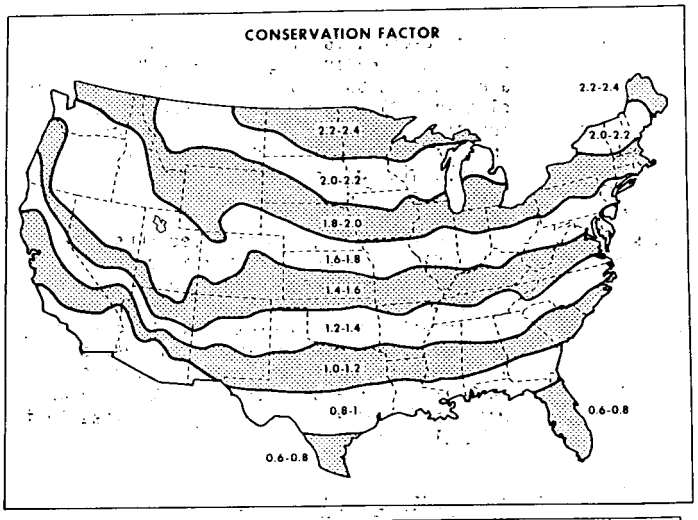



Fig. 1. Guideline values of the conservation factor (CF).

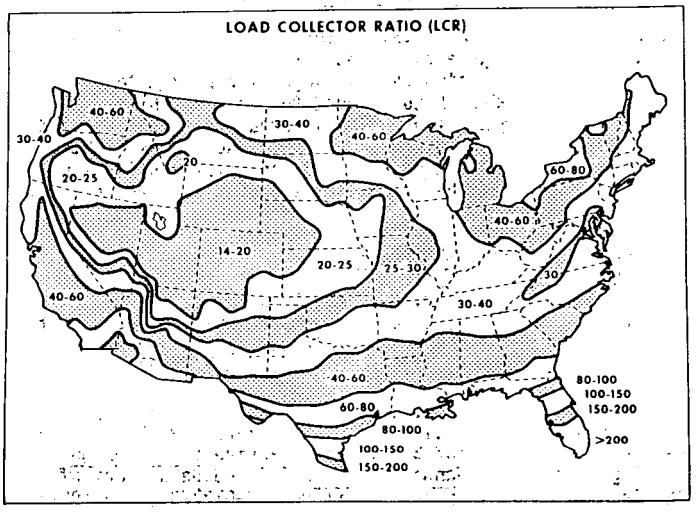



Fig. 2. Guideline values of the load collector ratio (LCR).

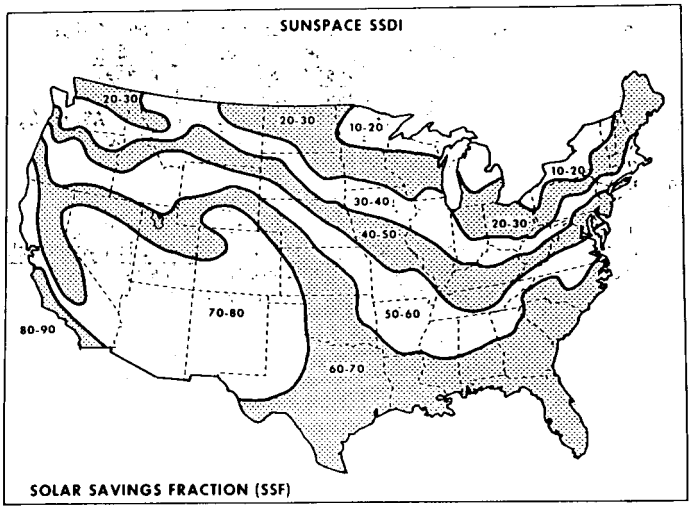



Fig. 3. Solar savings fractions for the guideline values of LCR for a semienclosed sunspace with 50° sloped glazing (reference design SSD1).

SSF was determined using the solar load ratio method.

A complete development of the equation for GF, the geometry factor, cannot be given here because of space limitations. It follows from the equations in Ref. 3.

Table 1 was developed by specifying passive system type SSD1 and then finding values of LCR such that the following values of D would result:

| | |
|---|---|
| high fuel cost | D = 30,000/DD |
| low fuel cost | D = 60,000/DD |

Because D = a/h = (a · FCR)/(CH · FF · DD), this implies the following ratios:

| | |
|---|---|
| high fuel cost | (a · FCR)/(CH · FF) = 30,000 |
| low fuel cost | (a · FCR)/(CH · FF) = 60,000 |

Values for CF, LCR, and SSF in Table 1 correspond to any values of a, FCR, CH, and FF that satisfy these conditions. One particular set of values is as follows:

a = \$10/ft$^2$
FCR = 0.1 yr$^{-1}$
CH = \$22.22/MMBtu (high heat cost)
CH = \$11.11/MMBtu (low heat cost)
FF = 1.5

Obviously many other choices could have been made that would satisfy the equation for D.

The following incremental conservation costs were used:

| | | |
|---|---|---|
| wall insulation | 0.05 | \$/R-ft$^2$ |
| ceiling insulation | 0.03 | \$/R-ft$^2$ |
| perimeter insulation | 0.25 | \$/R-lineal ft |
| basement insulation | 0.50 | \$/R-lineal ft |
| E,W,N windows | 4.00 | \$/glazing |
| infiltration reduction | 0.0312 | \$/HAC-ft$^3$ |

where HAC = 1/ACH represents the hours per air change.

## 9. COMMENTS REGARDING PASSIVE SYSTEM SELECTION

The rationale for choosing the semienclosed sunspace system, SSD1, for developing Table 1 is based on observing the nature of the results. The LCR values that are obtained for the high fuel cost case are reasonably close to the overheating limit in US cities where winter overheating might be a problem and are close to buildable limits in cold, sunny climates. They lie between results obtained for other systems. Thus, the criteria used in developing Table 1 are reasonably compatible with other criteria that might have been used instead.

The double glazed, semienclosed sunspace system SSD1 is a good performer throughout US climates without requiring night insulation (although performance is considerably improved with night insulation). Whereas we desired to avoid requiring night insulation in developing a general guideline, night insulation (or a selective surface on a water wall or Trombe wall) may well be advisable in cold climates.

## 10. BASE TEMPERATURE CALCULATION

The base temperature used for calculating degree days needed to develop Table 1 was adjusted over a range of approximately 55-67°F to account for internal heat generation. The internal heat rate assumed is 47 Btu/day per ft$^2$ of house, as might be associated with a residential application, and the thermostat setpoint assumed is 70°F.

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# DEVELOPMENT OF AN INEXPENSIVE PASSIVE SOLAR SIMULATION TECHNIQUE USING SMALL-SCALE MODELS

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## ABSTRACT

In order to investigate the thermal simulation of a full-sized passive solar building using scale models, a simplified large test unit (6'x6'x7' inside dimensions) was used as a base line in testing the adequacy of the scaling factors, and several test units of half and quarter-scale were used. Various types of passive solar systems -- including direct gain, water wall, thermosiphon air collector systems, moveable insulation and multi-zone were used.

## 1. INTRODUCTION

In a passive solar energy design, it is important to be able to simulate the thermal performance of the building under design in order to identify the appropriateness of the design for given conditions. Up to now, many passive solar buildings have been designed and built without the simulation prior to the final construction, hoping the system will match one's expectations. At the present time there are no simple ways to simulate the thermal performance of the building except with simple generic types of one room passive solar house designs which can be simulated by the computer or with a hand-held calculator. However, when the design becomes complicated or the systems that are introduced are innovative new systems, it is extremely difficult to simulate the system using generic types of simple passive computer simulations.

For example, south facing rooms are much warmer than north facing rooms in most passive solar buildings, and upper space in a two story open space is much warmer than lower space due to temperature stratification. These multi-zone thermal responses will play important roles in thermal comfort, and it would be an over-simplification to treat a single space with one average temperature as in a generic type of one-room passive solar computer simulation. In architectural education and practice, it would be very useful if the designer were able to manipulate the passive system design in order to achieve an optimum thermal performance under a given condition. Therefore, it would be useful if one can use a physical model to simulate the localized building performance. This physical model located on the particular site will minimize the undesirable variables of the dynamics of surrounding environments for the simulation. Micro-site analyses in relation to thermal impacts on the building performance can be easily achieved by using physical modeling techniques.

The objective of this research is to investigate various types of passive solar systems, in order to demonstrate the feasibility of the simulation technique by using scaled physical models.

## 2. DIRECT COMPARATIVE THERMAL SCALE MODELING TECHNIQUE (Independent from time scaling)

In heat transfers through building envelopes, the most dominant mode is conduction heat transmission. The next most important is convection heat transmission. Due to the small temperature difference between the exterior surface temperature, the radiation heat exchange can be neglected, especially if the wall is well insulated. Since the conduction heat transmission is the most dominant mode, one should establish mathematical scaling factors based on the theory of conduction heat transmission prior to an experimental test.

Due to the temperature fluctuation in most passive solar systems, it is reasonable to allow some acceptable level of error in a simulation of a passive solar energy performance. Therefore, other modes of convection and radiation heat transmission can be lumped together with conduction heat transmission, although the scaling is independent from one another, to establish an overall scaling factor since the most dominant mode is conduction heat transmission.

Two types of energy have been used for the experimental test presented in this study: (1) external solar radiation; and (2) an an internal heat source using light bulbs. This indoor laboratory test was performed in

order to achieve a preliminary test result prior to the outdoor test. External heat sources can be achieved by allowing solar radiation through a south-facing glazed area (Northern hemisphere). By conducting experimental tests on identical micro-site conditions for a number of test boxes (Fig. 1), the external influence such as wind, rain, snow, sol-air temperature and ground reflection are somewhat controlled.

## 2.1 Shape Factor

Area Ratio (Conduction heat transmission through the wall): According to the basic principles of a one way conduction heat loss through a wall, the amount of heat loss through a wall is directly proportional to the temperature difference ($\Delta T$) between indoor and outdoor, surface area, and heat transmission coefficient. If one maintained an identical heat transmission coefficient (U) and temperature difference ($\Delta T$), the total heat loss through a wall (Q) is directly proportional to the wall surface area (A). Therefore, if one provided an identical ratio of UA and Q for both prototype and scaled unit, one will be able to maintain identical $\Delta T$ assuming one uses identical wall section details including both opaque and transparency walls. Since the most dominant mode is conduction heat transmission, the conduction heat transmission through the wall can be used as a base for the heat loss calculation.

Volumetric Ratio (air mass ratio): The volumetric ratios between a prototype and a half-scale unit is eight to one (8:1). A prototype unit therefore holds twice as much air volume as a half-scaled unit if one uses a surface area ratio of 4:1 as a base for a heat loss calculation. However, volumetric considerations do not play an important part in thermal scaling due to the small thermal mass value in air volume, and fortunately in most passive solar buildings we expect a reasonable amount of thermal mass inside the space.

Edge and Corner Ratio (edges and corner heat loss): The linear edge ratio between a prototype and a half-scaled unit is two to one (2:1), and corner ratio is one to one (1:1). Therefore, a scaled unit will lose twice as much heat through the corners if one uses a surface area ratio (4:1) as a base for heat loss calculation (Fig. 2). One of the reasons why the smaller unit loses more heat than the prototype can be explained by these edge and corner factors.

Radiation Heat Exchange: According to the radiation heat transfer theory, the quantity of energy leaving a surface as radiant heat is directly proportional to the surface area, and this surface area relationship is identical to the relationship of surface area heat loss by conduction. As long as one maintains identical geometry for both prototype and scaled-unit, the night sky radiation impact will be directly proportional to the surface area. Therefore, radiation impact on the scaling can be eliminated if one maintained an identical geometric shape.

## 2.2 Thermal Mass Scaling Factor

Convective Heat Transfer: According to the theory of heat transfer by convection, the amount of heat transfer by convection ($Q_c$) is directly proportional the the surface area (A). Therefore, if one used identical wall details for both a prototype and scaled-unit, there will be no scaling factor in the thermal mass of the wall due to the identical area relation of both conduction and convection if one used the conductive surface area ratio as a base for a heat loss calculation.

Internal Energy of the Mass: According to the theory, the internal energy of the mass is directly proportional to the volume. Therefore, if one used identical thermal mass (wall details) and thickness, the volume of the thermal mass is directly proportional to the wall surface area. Other isolated types of thermal mass should be scaled in such a way that a volumetric ratio of the thermal mass is identical to the surface area of the thermal mass.

## 2.3 Natural Convection Scaling Factor

Thermosiphon Opening Area Ratio: The air flow rate (Q) due to the thermosiphon action is proportional to the square root of the product of height (h) and the temperature difference ($\Delta T$) between the two zones. According to the theory of thermosiphon, if one scaled the air flow rate (Q) based on the conduction surface area ratio in order to balance the energy ratio between the prototype and scaled unit, the opening area ratio of the prototype and scaled ($A_1:A_2$) is $2S:\sqrt{S}$ where the S is equal to the ratio of the scale of the prototype and the scaled unit. For example, for a scale ratio of 2:1, one could use a 2x2: $\sqrt{2}$ opening area ratio, and for a scale ratio of 4:1, one could use a 2x4:$\sqrt{4}$ opening area ratio. (See Figure 4 for the test results.)

Mixing Velocity of the Air: According to the theory of natural convection, the mixing velocity (V mix) of the air is directly proportional to the heat transferred by convection (Q) and the mixing velocity (V mix) is proportional to the square root temperature difference ($\Delta T$), distances (L) and the force of gravity (g). Therefore, the ratio of mixing velocity of the prototype and scaled unit ($V_1$mix:$V_2$mix) is $\sqrt{S}$:1 where the S is to the ratio of the scale of the prototype and the scaled unit. As an example, the prototype unit will have $\sqrt{2}$ times more mixing velocity than the half-scale unit due to the ratio of the height. This mixing velocity

ratio difference explains, in part, why more temperature stratification occurs in smaller scale models.

## 3. STANDARD TEST BOX DESIGN

One 6'x'6'x7' (inside dimension) prototype, six 3'x'3'x3'-6" half-scale test boxes, and four 1'-6"x1'6"x1'-9" quarter-scale test boxes were constructed by a manufacturing company to control the craftmanship and materials.

In order to reduce direct conductive heat transmission through the wall, no structural framing members have been used. Instead, 4-inch rigid urethane insulation was laminated to one-fourth inch waffle boards (see the details in Fig. 3). All the finishes, including painting (white exterior gloss to minimize sol-air temperature impact) and caulking, have been carefully applied in order to reduce undesirable variables of thermal performance in each box. The shading effects of glazing mullions have been carefully calculated to maintain the identical ratio of the surface area (inside dimension) over the south facing glazed area to satisfy the geometric scaling factors.

## 4. TEST RESULT

All tests were done under identical micro-climate and site conditions at the Building Technology Laboratory of The University of Michigan. Both direct and indirect gain passive solar systems were tested under dynamic natural environmental conditions. Five types of direct gain systems including multi-zone passive systems, and one type of indirect (thermosiphon air collector) were tested.

According to the test results of the direct gain passive system, the thermal mass played an important role in scaling. Direct gain with thermal mass type A (one gallon water container) showed clearly that the mean error was +1% in the MA (half-scale) box, and ±5% in the SA (quarter-scale unit). However, direct gain with less mass showed that the mean error air temperature was ±4% in the MA (half-scale), and ±7% in the SA (quarter scale) box.

Convective heat distribution systems (thermosiphon action between the two zones) with thermal mass type A (one gallon water container) were tested during the period of January 14, 1981, to February 2, 1981. According to the test results, one could expect a ±2% mean error in both front (south facing) and rear zones in a half scale box, and a ±7% mean error in both front and rear zones in a quarter-scale with 1 to .5 opening ratios between a scaled box. In all, one could expect a 1% to 2% mean error in a half-scale and 5% to 8% mean error in the quarter-scale. According to the analysis, during a clear day, one could expect a higher percentage mean error and low percentages during cloudy days and nights.

For a direct gain water wall with a thermal mass type B (17 gallon water tank), one could expect less than a 2% mean error in air temperature, less than a 1% mean error in the water temperature, and more than a 30% mean error in the air temperature stratification in the half-scale box (Fig. 4 & 5).

Four types of opening area ratios were tested, and the test results showed that $4:\sqrt{2}$ opening ratio between the prototype and half-scale unit fits the best. (See Thermosiphon Opening Area Ratio.) However, slight changes in the opening area ratio will not have much impact in overall thermal performance. According to the test results, opening ratios between 4:1 to $4:\sqrt{2}$ were acceptable for the convective heat distribution scaling (Fig. 6).

## 5. CONCLUSION

### 5.1 Summary

This research has shown that small-scale models can be used as predictive tools for the more complex passive solar systems now in common use. The test results showed that the half-scale models were adequate within 3% and the quarter-scale models were adequate within 8% for each of the passive solar applications. Important factors in this direct comparative thermal scale modeling technique have been identified:

1. Interior thermal mass has played a significant impact in thermal scaling in the aspect of time lag. The difficulty in scaling volumetric air mass ratio can be overcome by introducing thermal mass.

2. The edge and corner heat loss ratio difference has played an important role in scaling due to the transition from a two dimensional heat transfer into a three dimensional heat transfer. Statistical analyses of the data can be used to establish adjustment factors.

3. The temperature stratification (temperature gradation) due to the scaling has been identified that the smaller the model the more temperature stratification exists.

4. The time scaling variable can be eliminated in both conductive and convective scaling if one satisfied the scaling factors as discussed.

5. Convective heat distribution systems from one space to the next by natural convection can be simulated using a small scale model by providing an appropriate opening area ratio between the prototype and scale model while maintaining identical time lag between the prototype and scaled model. The opening area ratio has been identified.

## 5.2 Discussion

These initial test results have accomplished an essential logical step that is required prior to simulating a full-scale passive solar building. All the analyses of the test results suggest that thermal scale-modeling is quite feasible to simulate the thermal performance of full-sized passive buildings which have thermal features more complex than those reported in this study. This study has only scratched the surface of this subject area. More rigorous studies of these aspects can lead to more successful scale modeling techniques for dealing with complicated passive solar building systems.


## 6. ACKNOWLEDGEMENT

I am thankful to have had access to the facilities and staff of the Building Technology Laboratory at the College of Architecture and Urban Planning of The University of Michigan. I wish to thank the members of my doctoral committee, Professors W. A. Oberdick, N. Barnett, H. Borkin, W. J. Yang and R. Metcalf for their enthusiastic support of the project and their patience and guidance.


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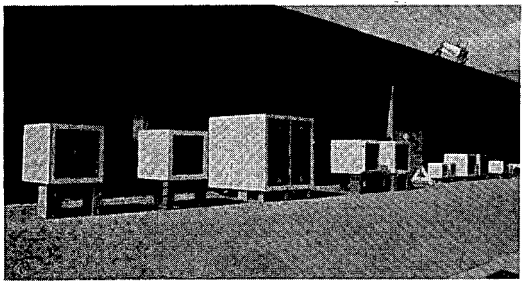



Fig. 1. Outdoor test site: Building Technology Laboratory, University of Michigan, Ann Arbor, Michigan, USA

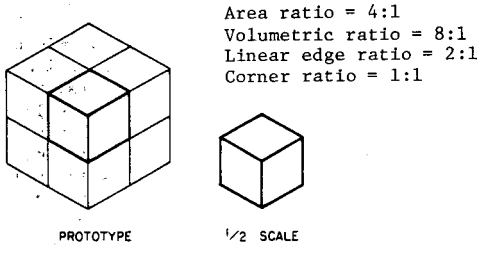



Fig. 2. Shape Factors: Geometric Relationships

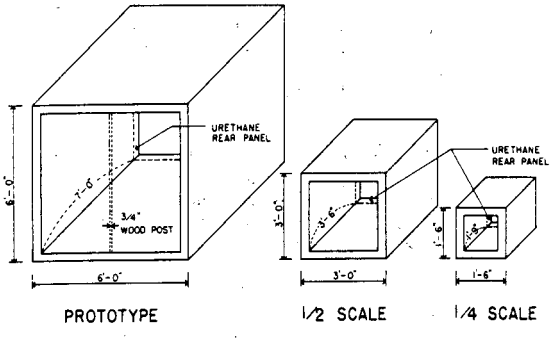
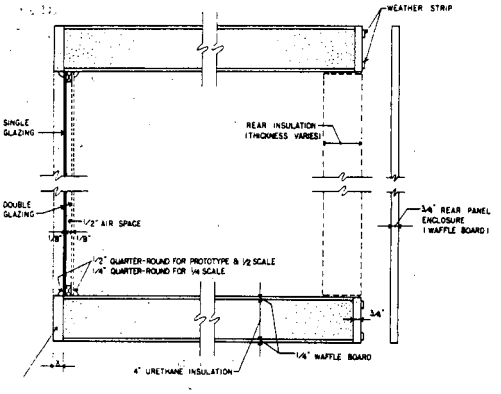
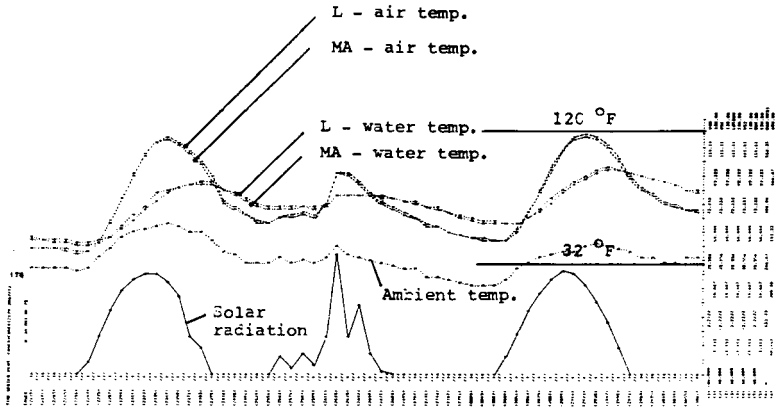
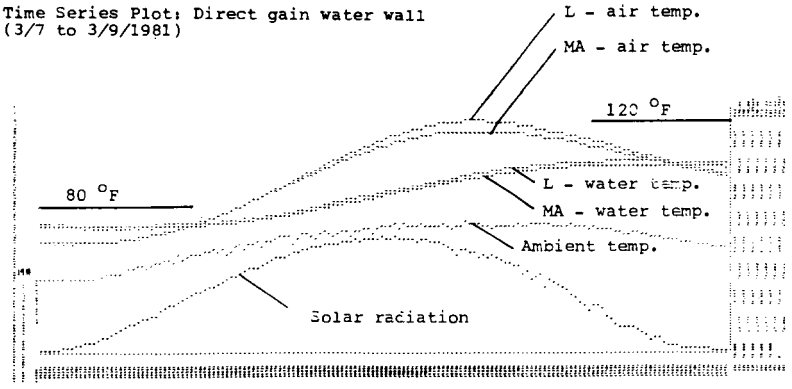



Fig. 3. Standard Test Box Design Details






Time Series Plot: Direct gain water wall
(3/7 to 3/9/1981)




Time Series Plot: Direct gain water wall
(date: 4/1/81)

Fig. 4. Time Series Plot: Direct Gain Water Wall System

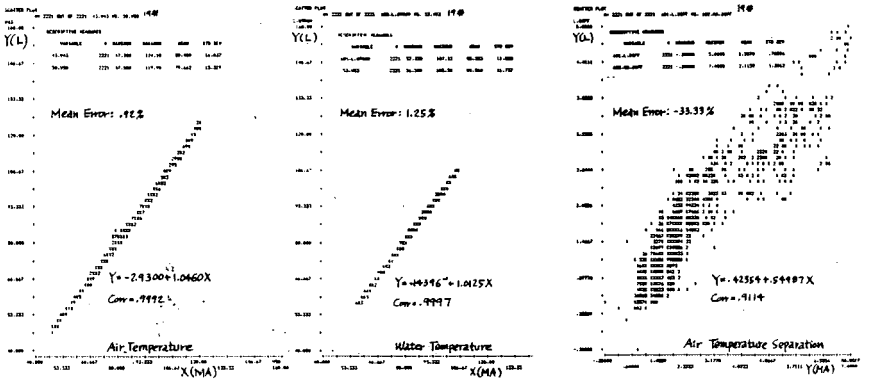
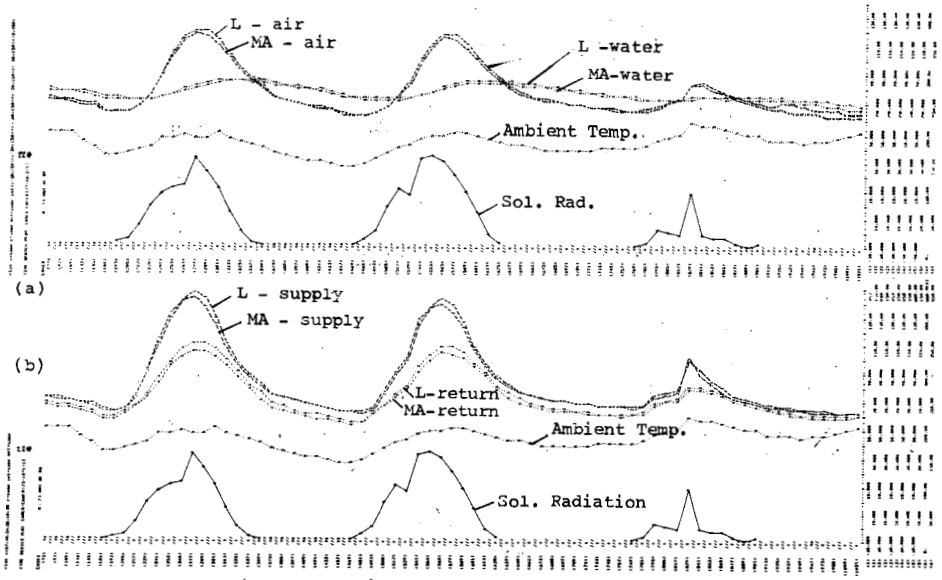
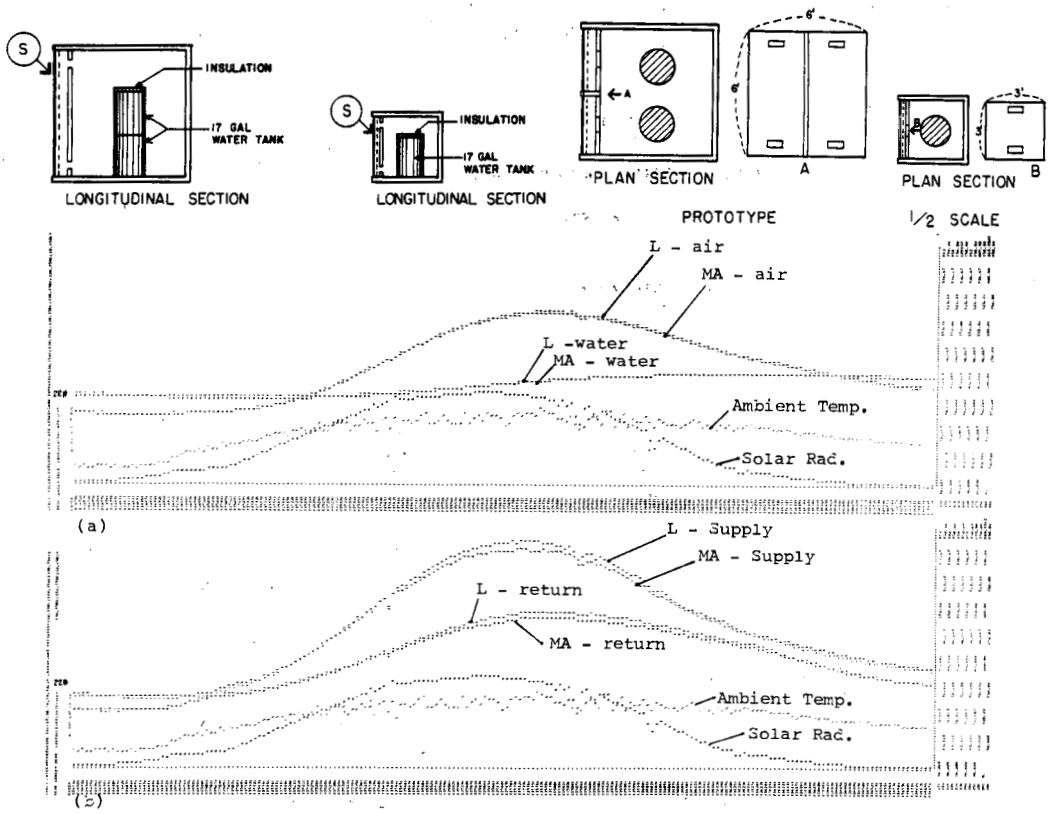



Fig. 5. Scatter Plots: Regression and Correlation Analyses




Time Series Plot: Indirect gain thermosiphon air collector (4/20 to 4/22/81)




Time Series Plot: Indirect gain thermosiphon air collector
(date: 5/2/81)

Fig. 6. Time Series Plot: Thermosiphon air collector system with $4:\sqrt{2}$ opening area ratio for a scale of 2:1 ratio

# DAYLIGHTING


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# A GRAPHICAL METHOD FOR DETERMINING INTERFLECTED DAYLIGHT IN CLEAR CLIMATES

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## ABSTRACT

This report presents an extension of the daylight factor method of analysis that includes a graphical method for determining interflected light in clear climates. The interflected component of daylight, called the internal reflectance component (IRC), has been determined for overcast skies in research performed in the United Kingdom. The technique developed by the Building Research Establishment in the United Kingdom is based on determining an average IRC for a given room or space. Using a daylight availability model developed at SERI (1), we established a similar average IRC analysis technique for clear skies. The results of applying the SERI daylight availability model suggest that a critical element in determining the IRC under clear sky conditions is the ratio of global to diffuse (G/d) illuminance on a horizontal surface. This graphical technique for determining clear sky IRC values is expected to enhance the accuracy of daylighting system design by simplifying the format used in clear sky computation.

## 1. INTRODUCTION

The amount of daylight received in buildings can be expressed as the percentage ratio of indoor illuminance. This ratio is called the daylight factor (DF) and is computed as

$$DF\ (\%) = E_i/E_e \times 100\ , \qquad [1]$$

where:

$E_i$ = interior illuminance
$E_e$ = exterior illuminance

This value depends on the sky conditions; the size, shape, and position of the aperture; and, in the case of clear skies, the location of the sun relative to the aperture.

Using the daylight factor method we can calculate the three components of the daylight reaching any reference point in a room:

- The sky component (SC)--the light received directly from the sky.
- The external reflectance component (ERC)--light received after reflection from buildings and other external surfaces, including a direct view of the ground.
- The internal reflectance component (IRC)--the light reflected from surfaces inside the room and an indirect view of the ground.

These components are calculated separately and added to determine the daylight factor:

$$DF\ (\%) = SC + ERC + IRC\ . \qquad [2]$$

Corrections for interior room maintenance, glazing material, dirt, and reductions for framing around the aperture can be added to Eq. 2 as follows:

$$DF = \left[SC + ERC + (M)(IRC)\right](D)(F)(G)\ , \qquad [3]$$

where:

M = interior maintenance factor

D = dirt on glass factor

F = framing factor

G = glazing factor, for other than clear glass.

The average IRC is defined as the IRC at the midpoint of the room. This value is often used during the early stages of the building design process to predict daylight penetration into a building. The average IRC does not vary a great deal with respect to the view factor of an aperture from a specific station point in a room. Because it does not vary, graphical design aids can be used to determine the average IRC.

## 2. ESTIMATING INTERFLECTED LIGHT IN BUILDINGS

### 2.1 The BRS Interflection Formula

The Building Research Station (BRS) interflection formula was developed to estimate interflected light and can be determined from the equation:

$$IRC_{avg} = \frac{(T)(W)}{A(1 - R)} \left(C_1 R_{fw} + C_2 R_{cw}\right) \quad [4]$$

where:

T = transmission of the glazing in the visible spectrum

W = area of glazing

A = total area of the ceiling, floors, and walls including the glazing

R = average reflectance of the ceiling, walls, floor, and aperture

$C_1$ = aperture configuration factor equivalent due to the light incident on the aperture from above the horizontal at the midheight of the aperture

$R_{fw}$ = average reflectance of the floor and those parts of the walls below the midheight of the aperture (excluding the aperture and aperture wall)

$C_2$ = aperture configuration factor equivalent due to light incident on the aperture from below the horizontal at the midheight of the aperture

$R_{cw}$ = average reflectance of the ceiling and those parts of the walls above the midheight of the aperture (excluding the aperture and aperture wall).

The difference between clear and overcast conditions in the application of Eq. 4 lies in the configuration factors, which vary depending on the sky condition. $C_1$ and $C_2$ values for the BRS interflection equation are shown in Tables 1 and 2.

### 2.2 LBL Interflection Formula

Research at the Lawrence Berkeley Laboratories (LBL) (2) developed an equation, similar to Eq. 1, to compute an average internal reflectance component for clear sky conditions. However, because direct illuminance is contributing illumination to the ground, $C_1$ and $C_2$ are calculated differently than in the BRS interflection formula. The $C_1$ factors for a clear day are illustrated in Table 3.

**Table 1.** Aperture **Configuration Factor Equivalent $C_1$ for Overcast Skies**

| Angle of Obstruction* (deg) | $C_1$ |
|---|---|
| No obstruction | 39 |
| 10 | 35 |
| 20 | 31 |
| 30 | 25 |
| 40 | 20 |
| 50 | 14 |
| 60 | 10 |
| 70 | 7 |
| 80 | 5 |

*Measured above the midheight of the aperture at the center of the room.

**Table 2.** Aperture **Configuration Factor Equivalent $C_2$ for Overcast Skies**

| Average Ground Reflectivity (%) | $C_2$ |
|---|---|
| 10 | 5 |
| 20 | 10 |
| 30 | 15 |
| 40 | 20 |
| 50 | 25 |
| 60 | 30 |
| 70 | 35 |
| 80 | 40 |

**Table 3. Aperture Configuration Factor Equivalent $C_1$ for Clear Skies**

| Solar Altitude (deg) | Aperture Azimuth with Respect to the Sun | | | | |
|---|---|---|---|---|---|
| | 0 deg | 45 deg | 90 deg | 135 deg | 180 deg |
| 10 | 68 | 65 | 50 | 35 | 32 |
| 20 | 72 | 67 | 50 | 33 | 28 |
| 30 | 73 | 70 | 50 | 30 | 27 |
| 40 | 74 | 69 | 50 | 31 | 26 |
| 50 | 73 | 68 | 50 | 32 | 27 |
| 60 | 70 | 66 | 50 | 34 | 30 |
| 70 | 66 | 62 | 50 | 38 | 34 |
| 80 | 59 | 56 | 50 | 44 | 41 |
| 90 | 50 | 50 | 50 | 50 | 50 |

The $C_2$ coefficient is determined from the equation:

$$C_2 = \frac{(E_{DH,c} + E_{dH,c})(R_g)(F_g)}{E_{dh,c}} \times 100 \ , \quad [5]$$

where:

$E_{DH,c}$ = direct illuminance on a horizontal plane, clear sky

$E_{dH,c}$ = diffuse illuminance on a horizontal plane, clear sky

$R_g$ = ground reflectivity

$F_g$ = surface-to-ground configuration factor (0.5 for a vertical aperture and 1.0 for a horizontal aperture).

Because the direct plus the diffuse illuminance falling on a horizontal plane equals the total (global) illuminance $E_{GH,c}$ on a horizontal plane, Eq. 5 can be rewritten to reflect a global-to-diffuse ratio (G/d), an average ground reflectivity of 0.2 (20%), and a configuration factor of 0.5 for vertical surfaces:

$$C_2 = (G/d)(0.2)(0.5)(100)$$
$$= G/d \times 10 \ . \quad [6]$$

## 3. Graphical Techniques to Determine the Average Internal Reflectance Component

### 3.1 BRS Nomograms

BRS nomograms offer a comprehensive method for computing the average IRC in spaces, although their precision is not as great as the equations from which they were derived. Because of their ease of use, the nomograms provide probably the most useful method of calculation for the majority of cases. A BRS nomogram is shown in Fig. 1.

### 3.2 SERI Clear-Sky Nomograms

The development of clear sky nomograms requires the establishment of local specific illuminance data to calculate the $C_1$ configuration factor using Eq. 6.

Since daylighting represents an instantaneous use of the available resource, the availability of daylight over the entire day (dawn to dusk) is not as critical as the availability during the operating schedule of the building. Some typical operating schedules, which we call standard work years, are shown in Table 4.

A review of daylighting availability data for 12 standard work years indicates that the G/d ratio for most locales falls between 4:1 and 7:1. Therefore, constructing an IRC nomogram based on 4:1 and 7:1 ratios allows us to calculate the clear sky IRC under varying conditions by interpolating between the scales to determine intermediate values.

The average IRC under a clear sky depends on the orientation of the aperture. Therefore, we have established five (0, 45, 90, 135, 180) clear-sky IRC nomograms for each 10 deg of solar altitude with the exception of a 90-deg angle, for which only one nomogram is needed. This results in a total of 41 nomograms. Figure 2 illustrates a sample nomogram for a solar altitude of 40 deg and an aperture azimuth of 0 deg from the sun.

To determine the $IRC_{avg}$ with the clear sky nomogram, assume that the aperture to total surface area ratio (W:A) is 0.076, the average room reflectivity (R) is 42%, the G/d ratio is 5:1, and the aperture azimuth with respect to the sun is 0 deg for a solar altitude of 40 deg. Mark the W:A on the A scale and the R-value on the B scale. Draw a straight line between A and B, which will pass through the two (4:1 and 7:1) C scales as shown in Fig. 2. The $IRC_{avg}$ from the 4:1 scale is 5.0%, and from the 7:1 scale, 6.5%. Using the straight line, interpolate between these values the $IRC_{avg}$ when the G/d is 5:1, which would be 5.5%.

## CONCLUSIONS

The SERI clear sky IRC nomograms provide the lighting designer a simple manual technique to determine the internal reflectance component. The nomograms can be used with the MIT clear sky protractors (3) to determine the daylight factor at any given reference point in a space.

This graphical technique for determining clear sky IRC values is expected to enhance the accuracy of daylighting system design by simplifying the format used in clear sky computations and thereby allowing the lighting design professional to analyze daylighting systems during the earliest phases of the building design process.

## ACKNOWLEDGMENTS

The authors would like to thank the U.S. Department of Energy, Systems Research Branch, Passive and Hybrid Solar Heat Technologies for funding the research.

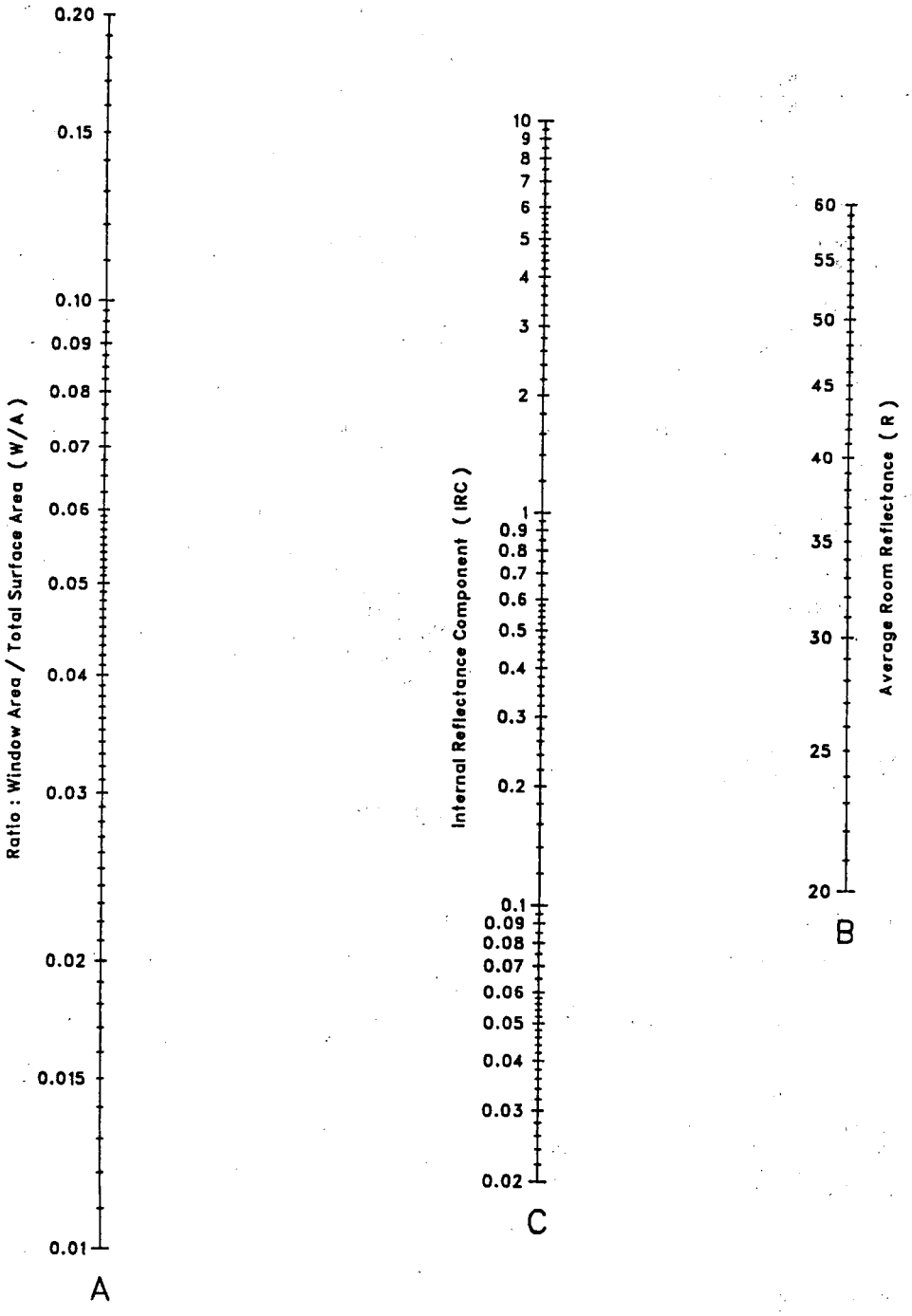



Figure 1. Nomogram for Figuring Average Internally Reflected Component of Daylight Factor.

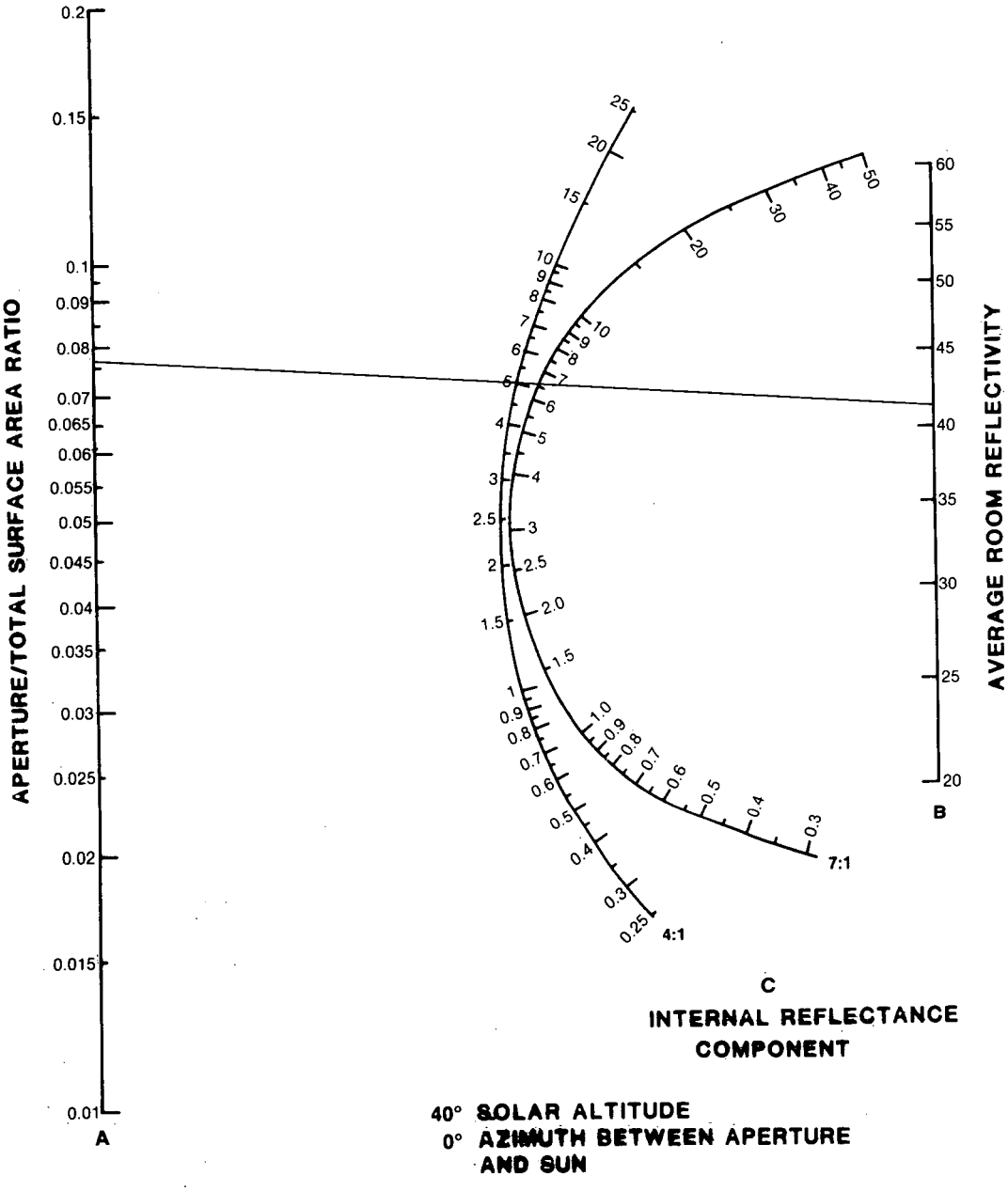



**Figure 2.** Sample of a Nomogram for Figuring Average Internally Reflected Component of Daylight Factor for Clear Skies.

**Table 4. Standard Work Years**

| | | |
|---|---|---|
| 0700-1600 hours | 0800-1600 hours | 0900-1600 hours |
| 0700-1700 hours | 0800-1700 hours | 0900-1700 hours |
| 0700-1800 hours | 0800-1800 hours | 0900-1800 hours |
| 0700-1900 hours | 0800-1900 hours | 0900-1900 hours |

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# DAYLIGHTING: A GENERAL ECONOMIC AND ENERGY-SAVING ANALYSIS

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## ABSTRACT

The energy and economic benefits available from daylighting depend upon several variables including glazing amount, glazing shading coefficient, and daylight penetration and level. In work performed for the California Energy Commission's Nonresidential Building Standards Development Project, AREA conducted an analysis of daylighting in office buildings to determine energy savings, economic benefits and life cycle costs.

The goal of the analysis was to quantify the benefits and costs of daylighting within an office environment. Calculations were made for each of three California climate regions (Fresno, San Diego, and Oakland) with various shading coefficients and amounts of glazing. The results consist of a set of benefit-to-cost ratios for two different artificial lighting levels. Also presented are a series of graphs for three climate regions in California. Each graph displays building energy use as a function of shading coefficient, daylighting contribution, and amount of glass. These results can be used by the designer to evaluate energy and economic trade-offs for daylighting and glazing options in the preliminary phases of the design process.

## 1. INTRODUCTION

Daylighting is one of the most effective options available to a designer for reducing building energy consumption. As most office buildings are designed with exterior glazing, the energy impact of windows can be reduced by utilizing the solar radiation to offset space lighting needs. However, as with all conservation measures, the blind application of daylighting can result in increased life cycle costs. Thus, the designer needs some guidelines during predesign and early schematic design to effectively implement and integrate daylighting into the building design. Faced with trade-offs on glass type, glass amount, artificial lighting levels, and daylight requirements, the designer often selects parameters without being able to assess the impacts of interactions among them. For a given glass type and amount, a selected lighting level may minimize daylight contribution and render that concept ineffective with negative life cycle benefits. This paper presents a series of graphs which can be utilized by the designer to understand the impacts of daylighting and evaluate interactions among various design parameters.

## 2. METHODOLOGY

For this analysis, a building model was developed with the following characteristics:

- 2 story office building
- 63 feet x 158 feet x 22 feet
- building long axis north/south
- rooms are 25 $ft^2$, 8 ft ceiling
- top of glass 7 feet above floor
- lighting levels of 3.1 $W/ft^2$ and 1.5 $W/ft^2$

A total description of the engineering assumptions used in the modeling of this office building can be found in References 1 and 2.

Daylighting levels were calculated using the Quicklite computer program. Footcandle levels were analyzed at a point 9 feet in from the window, centered between the side walls, and on a workplane 2.5 feet above the floor. Sill heights were varied depending upon the amount of glass, but in all cases the top of the window remained 7 feet above the floor. Windows were modeled as strips 15 feet in length extending across the exterior wall of a 15 foot square room. Glass amounts were calculated based on a percentage of the total exterior wall surface area. Thus, for a glass amount of 30%, the window was 15 foot wide by 3.3 feet high with the sill 3.7 feet above the floor.

Footcandle levels were determined with sun angles based on September 21; this was

identified as an equivalent average day for an annual calculation. Levels were calculated for 9 am, noon, and 3 pm for both clear and cloudy days. Justification of this approach and a more detailed description of the methodology can be found in Reference 3.

Once the footcandle contribution from daylight was calculated, it was applied to the prescribed lighting levels within the office. Excess light above that required in the space was ignored so the maximum contribution from daylight was equal to the minimum footcandle requirements of the space. The clear and cloudy day contributions were extended to an annual basis by weighting the footcandle contributions by the number of clear and cloudy days at the location under consideration. This allowed the calculation of a daylight reduction factor which could be applied to the lighting profiles detailed in DOE-2.1A.

To provide reduced energy consumption, a daylight control system is required. For each perimeter office, it was assumed that there would be a controller which sensed the light level at the workplane and adjusted the artificial lighting levels accordingly. To avoid fluctuations and fluttering in fluorescent lights, the system was set to accept a maximum contribution of 50 percent from daylight. Thus, the daylight reduction factors were adjusted accordingly before being applied to the DOE-2.1A lighting profiles.

After the lighting profiles were corrected for daylight contribution, the energy consumption of the building with the specified glazing type and amount was determined using DOE-2.1A. Runs were made for three California climate zones (Fresno, Oakland, and San Diego). The climate in Fresno requires both heating and cooling with an average January temperature of 45°F and an average July temperature of 81°F. In this climate, with a substantial number of clear days in the summer, daylighting should have maximum potential for cost effective energy conservation. In Oakland, while both heating and cooling are required, cooling can normally be supplied via an economizer so the benefit from daylighting is reduced (cooling is cheap). The San Diego climate is more benign than the other two requiring little heating or cooling depending upon the building's internal loads. With slightly higher summertime temperatures than Oakland, daylighting can effectively reduce some of the excess cooling load and thus play a more important role in San Diego.

This method of using Quicklite in conjunction with DOE-2.1A has been verified against results using DOE-2.1B which handles both daylighting and energy calculations. Results of the cross-verification runs indicated that the combination of DOE-2.1A and Quicklite produced energy consumptions within 5 percent of those calculated by the more sophisticated algorithms in DOE-2.1B.

Using the results of the DOE-2.1A runs, the life cycle costs for each of the different glazing types and amounts were calculated using the SOLFIN2A computer program with a base case of 30% clear glass without daylight controllers. The economic analysis included the differences in glazing costs (by area and shading coefficient), the cost of daylighting controls including maintenance and replacement costs based upon useful life, and the dollar savings from reduced energy consumption. Life cycle cost and benefits are then used to calculate a benefit to cost (B/C) ratio for each measures. This allows the user to identify those options which are cost effective (i.e., B/C greater than 1) over the life of the building.

## 3. ECONOMIC RESULTS

Figure 1 shows the benefit-to-cost (B/C) ratios for daylighting options in Fresno as applied to a building with two different lighting levels. For the high level of 3.1 Watts per square foot, daylighting seems to be cost effective regardless of glass type or amount. B/C ratios for clear glass decrease more rapidly than for other types since it takes a smaller amount of clear glass to achieve the maximum daylight contribution level. Thus, additional amounts of glass only add solar gain which must be removed by cooling. This is also true of the other glass types, except these have lower shading coefficients and thus admit less sun for the same increase in glass amount.

For the lower lighting level of 1.5 W/ft$^2$, the slopes of the curves for the three glass types remain the same with clear glass having the steepest slope. In fact, the slopes for clear glass and absorbing glass at 1.5 W/ft$^2$ are identical to those at 3.1 W/ft$^2$. This indicates that beyond 20%, additional amounts of glazing provide no additional daylighting benefit but incur the same solar liability regardless of the connected artificial lighting load. Also, since there is less artificial load to be displaced, only small percentages of clear and absorbing glass have benefit-to-cost ratios greater than one. Thus, in a building with small connected lighting loads, the designer should include only as much glass as necessary to satisfy client constraints. Higher percentages of glass are economically acceptable only when the shading coefficient is reduced.

The results of this economic analysis seem to provide the following guidelines to designers who are trying to provide cost effective,

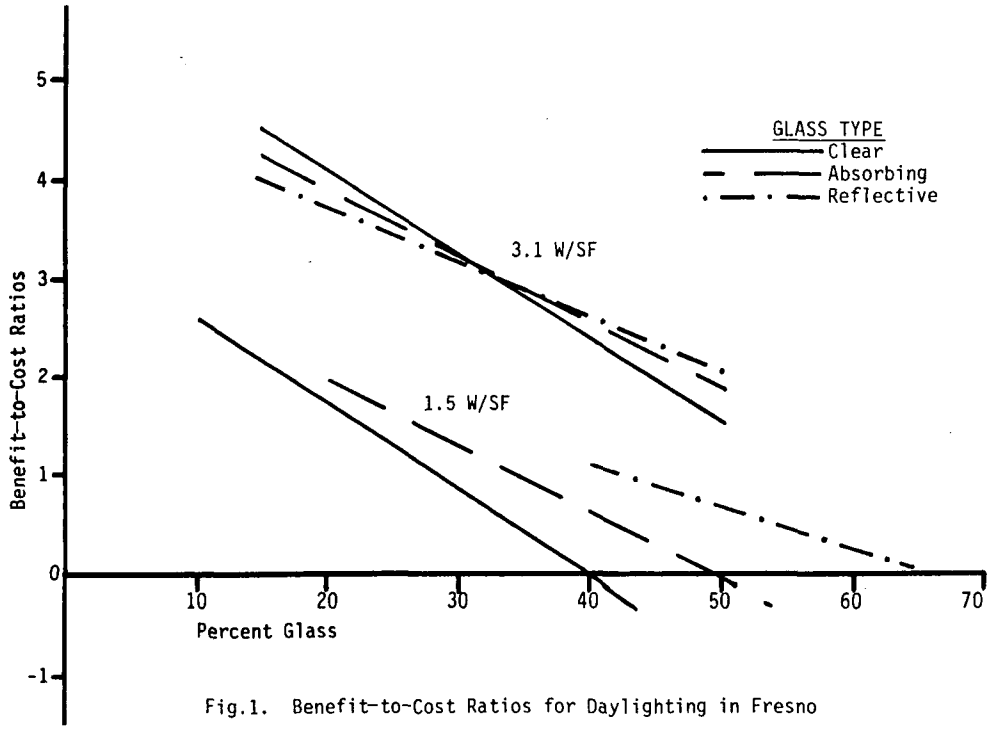



Fig.1. Benefit-to-Cost Ratios for Daylighting in Fresno

energy conserving office buildings.

- In buildings with a relatively high connected lighting load (greater than 2 W/SF), utilization of daylighting controllers with any type or amount of glass appears to be cost effective over the building life.

- In buildings with lower connected lighting loads (less than 2 W/ft$^2$ utilization of daylighting controllers is usually cost effective. However, the use of increased amounts of glass to provide additional daylighting is not cost effective beyond percentages which provide maximum daylight contribution. These percentages appear to be around 15% for clear glass and 25% for absorbing glass in the Fresno climate. These will vary by climate, but in general remain low in all regions since minimum light levels in office areas are relatively low compared to footcandles provided by daylight.

## 4. ENERGY RESULTS

To provide a better understanding of the interactions among daylight, glass amount, and shading coefficient, energy analyses for various combinations of those parameters were performed in the three California climate zones. As the economic analysis has indicated, the sizing and shading coefficient issues become more complex at lower lighting levels Figure 2 shows the results of the energy analysis parametrics for the building model in Fresno with a connected lighting load of 1.5 W/ft$^2$.

One of the interesting features of the daylighting curves in Figure 2 is the knees or breaks in the clear and absorbing glass curves. These break-points represent the amount of glass where daylighting is providing maximum contribution based on the control scheme assumed. Glass percentages beyond the knee only result in increasing solar loads and no additional lighting load reduction. Although these break-points shown as sharply defined, in fact they are actually gradual curves connecting the two segments. The knees occur at a glass percentage which provides maximum daylight through south and east windows in the morning, south, east and west windows at noon, and south and west windows in the afternoon. The gradual curve is due to the addition of daylight through north windows as the glass percentage increases above the knee.

The conclusion which can be drawn from these curves is that daylighting can be effectively done with very small amounts of glass assuming window placement is high enough to provide penetration into the rooms. Thus, it is not necessary and not economical to add large amounts of glass for daylighting.

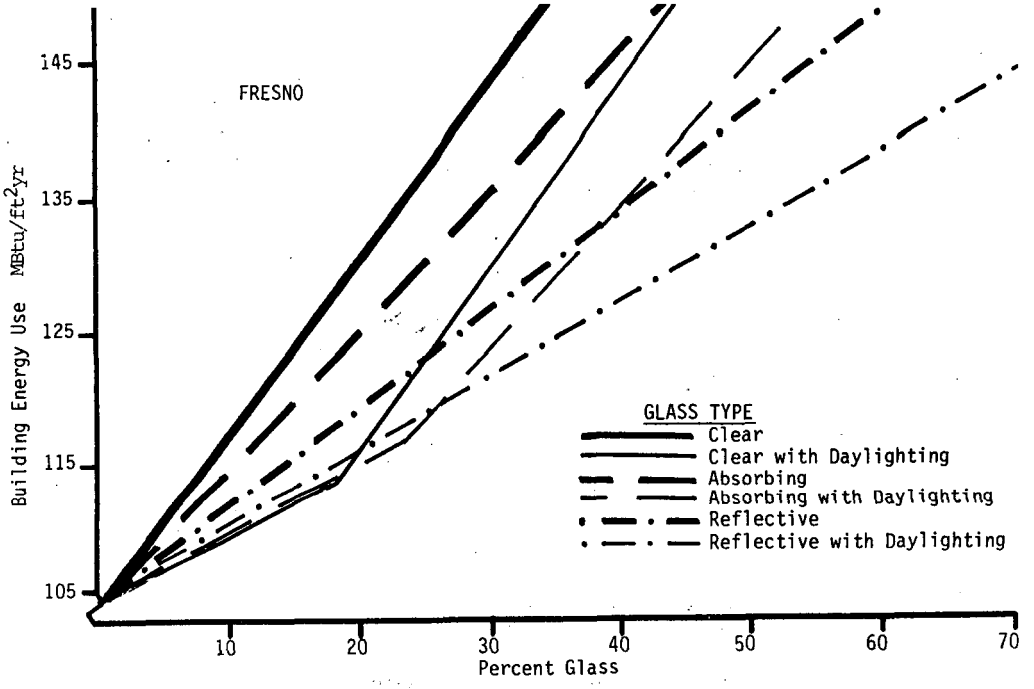



Fig. 2. Building Energy Use Versus Glass Type and Amount

Since all three daylighting curves have approximately the same slopes on those segments prior to the knee, there appears to be a common physical cause for the energy consumption due to glass amount. Even though the shading coefficients are significantly different, the common slope indicates that solar gain is the driving force in energy consumption. The clear glass allows more solar gain than does reflective, but it also puts then gain to good use in providing daylight. Thus, up to the knee point for clear glass, all glass types with daylighting are effectively equal in energy consumption impact; trade-offs can then be made on the basis of costs and aesthetics.

Figure 3 shows the set of glass parametric energy analysis curves for Oakland. The conclusions reached from these curves are the same as those specified for Fresno. The cloudiness of Oakland is reflected in the more gradual slopes of all the curves. As there is less annual solar gain for a given size of glazing, windows in Oakland represent less cooling energy consumption than in Fresno. Since the Oakland climate is cloudier, the knees of the curves occur at higher glass percentages than in Fresno, but all three glass types still have the same slope.

San Diego represents a climate that is between those of Fresno and Oakland in terms of daylight potential (see Figure 4). Again, the slopes of the curves represent the daylight potential of the climate in relation to the other regions.

## 5. SUMMARY

Once drawn, a set of daylighting curves and benefit-to-cost ratios for a given climate will allow the designer to identify the economic and energy impacts of different combinations of glass type, glass amount, and daylight potential. For example, if a building in Fresno is to meet an energy budget of 135 MBtu/ft$^2$yr. then the designer can use 30% absorbing glass without daylighting controllers, or 34% clear glass with daylighting, or any other combination with an energy use below the specified level. This allows the designer to satisfy client constraints on aesthetics and glass amount while still providing a cost effective energy conserving design.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

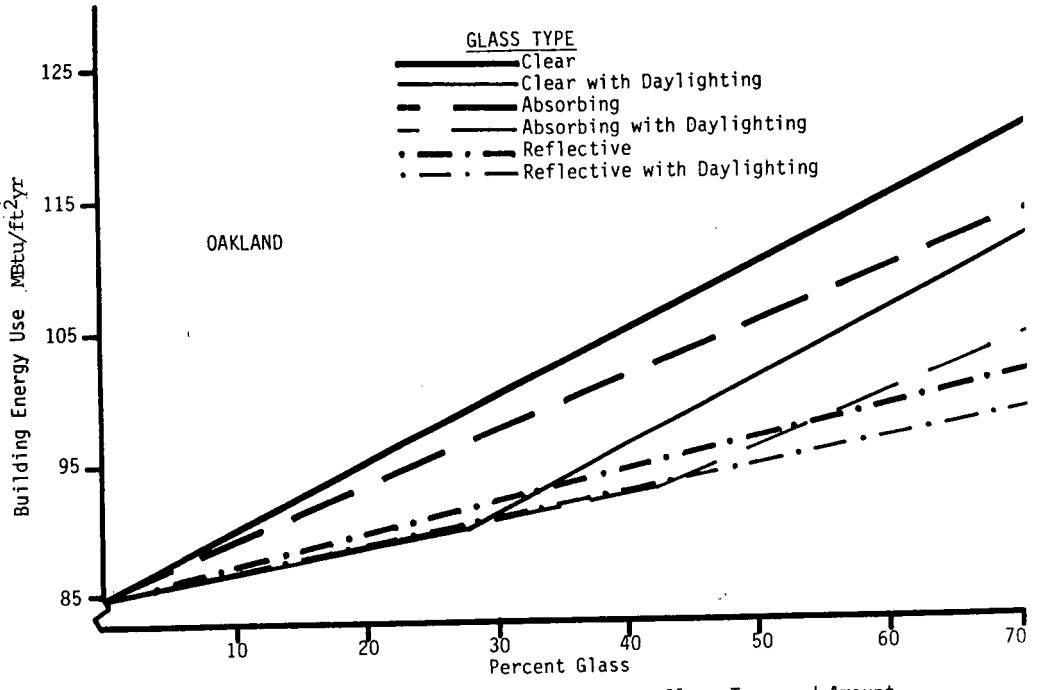



Fig. 3. Building Energy Use Versus Glass Type and Amount.

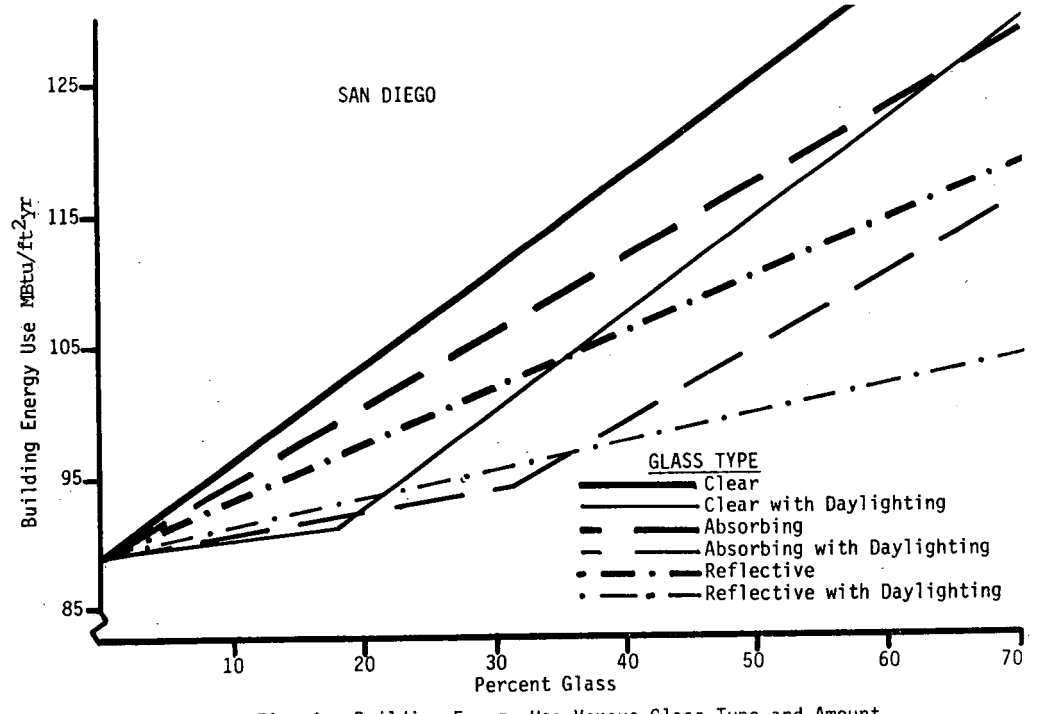



Fig. 4. Building Energy Use Versus Glass Type and Amount.

## 6. ACKNOWLEDGEMENT

The information presented in this paper resulted from work performed by the authors under contract to the California Energy Commission.

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# RELATIVE CONTRIBUTIONS OF BEAM, SKY AND GROUND COMPONENTS TO DIFFUSELY REFLECTED SUNLIGHT ILLUMINANCE IN PHYSICAL MODELS

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## ABSTRACT

By correctly positioning and tilting a physical model, solar altitudes and azimuths can be simulated. This provides a quantitative tool for measuring the interior illumination performance of a building design which uses diffusely reflected sunlight as it's primary illumination strategy. The tilting of the model, however, exposes the glazing to artificial sky and ground components of different luminances. Since the beam radiation contribution (80.7%) dominates the interior illuminance, only a relatively small and insignificant error is introduced. The tilted physical model is a valid simulation tool for predicting interior illuminance from diffusely reflected sunlight under clear sky conditions.

## 1. INTRODUCTION

The crux of daylight illuminance research has concentrated on the use of the diffuse sky vault as the primary source of illuminance. In England, the Building Research Station has developed a method of calculating diffuse skylight illuminance of a building under overcast sky conditions (1). Others, particularly in the United States, have completed research to provide methods for calculating diffuse sky illuminance in buildings under clear sky conditions (2). However, these methods deal only with daylighting techniques which purposefully exclude direct sunlight from the interior of the building.

Due to the relatively low level of luminance of the sky, large areas of north facing glazing are needed to admit sufficient illuminance. North glazing, which is necessary to exclude direct sunlight, is a victim to excessive heat loss, making these illumination strategies undesirable for energy conserving buildings.

On the other hand some passive solar heated buildings purposefully introduce large amounts of direct sunlight into the building. This strategy supplies heat to the building, but glare is often a problem if visual tasks are to be carried out in the space. Again much research has been conducted to allow calculation of hte amount of heat gained from the sunlight (3).

An alternative daylight illumination technique which has been effectively employed recently by some architects is diffusely reflected direct sunlight illumination (4). By properly reflecting and diffusing sunlight introduced through relatively smaller glazing areas faced south, high quality glare free illumination can be accomplished. This strategy combines the advantages of high quality daylighting with those of passive solar heating and cooling (5). While this technique holds great promise for energy conservation, little has been done towards developing quantitative methods for estimating illumination performance. This paper attempts to help fill this void. Presently some work is also being carried out in this area at the Solar Energy Research Institute under the direction of Claude Robbins.

Due to the computational complexities involved in theoretical modeling of diffuse sun reflections, physical models are frequently used instead. The physics of illumination are such that light behaves exactly the same way in a model as it does in a full scale building, provided the model ia built to scale (6). Physical modeling estimation is done by tilting the model to artificial positions in order to simulate solar altitudes and azimuths for different times of the year. This tilting of the model correctly simulates the effects of the beam radiation, but distorts the ground and sky components contributions.

## 2. RESEARCH OBJECTIVES

The objective of this experiment is to determine the relative error introduced by tilting the physical model, thereby distorting the illuminance contributions of the diffuse sky vault and ground reflectance. A physical model will be used to provide verification of the appropriateness of using a tilted model to simulate illuminance by diffusely reflected

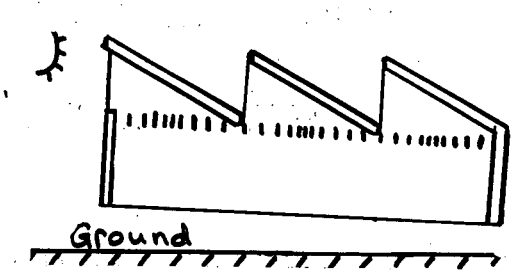
sunlight for various times of the year. By running a series of experiments which block different components of the total illuminance-beam,sky and ground reflectance, the experimenters can determine the relative contributions to the interior illuminance of the model. Then by rotating the model 180 degrees about the axis of the sun the same relative solar altitude and azimuth can be simulated, but different ground and sky components contributions will result. By comparison of the upright and inverted model data the effects of the artificial sky and ground position and proportion can be determined. The experimenters hope to verify that the errors introduced by this artificial positioning are small and can be ignored when diffusely reflected sunlight is the primary illumination strategy.

## 3. EXPERIMENTAL PROCEDURE

The model used was a scale model of the Mt. Airy Library in North Carolina (J. Peays with consultation from Edward Mazria). It was built with a removable roof and placed on a tiltable stand in an asphalt parking lot. Glazing was not included in the model but its effect could be accounted for mathematically for most glazing materials. The experiments were all performed on the same day under clear sky conditions.

The model was tilted to reduce the relative solar altitude to 27 degrees and the stand was aligned with the sun to make the relative azimuth 0 degrees - simulating noon conditions for December 21 at 40 degrees north latitude. Measurements were taken of the total solar radiation in the plane of the roof using a Lambda-Licor pyranometer and a Hewlett Packard Multimeter digital voltmeter. Then the illumination in the plane of the roof, the plane of the glazing aperature and at three interior locations were measured using a Photo Research Litemate 500 hand held digital photometer. These same measurements were then taken with the beam radiation shielded, the ground reflectance shielded, and beam radiation and ground reflectance shielded.

A total of four experiments were performed including the one described above, the same measurements were taken for each experiment. The other three experiments were the December 21 sun angle simulation with the model rotated 180 degrees about the axis of the sun (inverted model), a noon June 21 sun angle simulation (relative altitude 73, relative azimuth 0) and an inverted model experiment for the June 21 sun angles. The first set of measurements, for which all components of the illuminance contributed to the interior illuminance, was used as a total reference case. Throughout the experiments the position of the table and the tilt were checked and




Fig, 1. Winter case, upright model

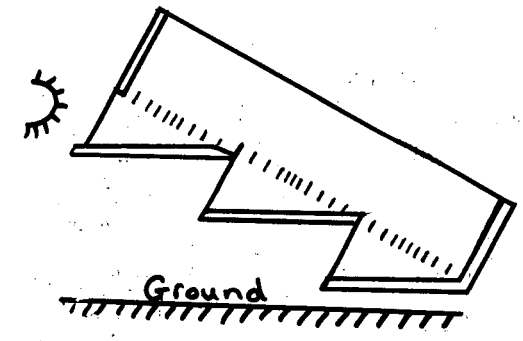



Fig. 2. Winter case, inverted model

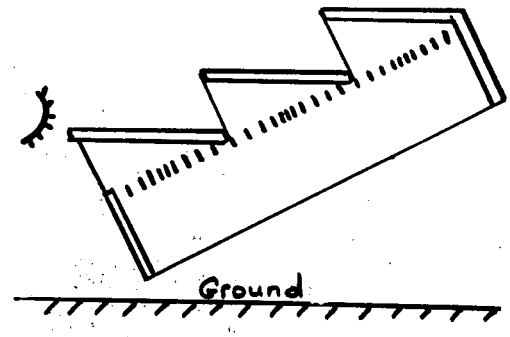



Fig. 3. Summer case, upright model

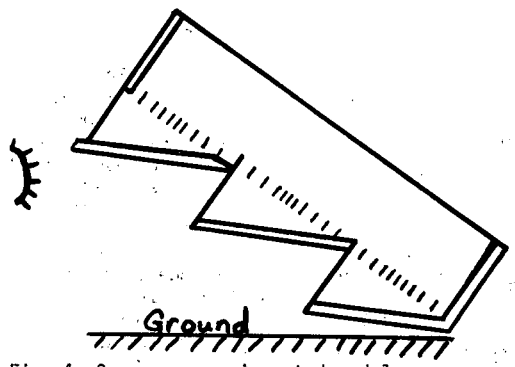



Fig. 4. Summer case, inverted model

TABLE 1. DATA

Winter case (relative solar altitude = 27°)

| Measurement | Total | | Block Beam | | Block Beam & Ground | Block Ground |
|---|---|---|---|---|---|---|
| | Upright | Inverted | Upright | Inverted | | |
| Interior Illuminance (ft cd) | | | | | | |
| Front | 1556 | 1580 | 325 | 276 | 237 | 1524 |
| Center | 1577 | 1672 | 328 | 244 | 252 | 1553 |
| Rear | 1567 | 1524 | 321 | 231 | 249 | 1534 |
| Total Solar Radiation (plane of roof) | | | | | | |
| MBtu/ft$^2$ | 604 | 572 | 395 | 354 | 389 | 604 |
| Exterior Illuminance (ft cd) | | | | | | |
| Plane of roof | 3820 | 3694 | 1299 | 995 | 1224 | 3820 |
| Plane of glazing | 7286* | 8218* | 1719 | 1901 | 1373 | 6956 |
| Summer Case (relative solar altitude = 73°) | | | | | | |
| Interior Illumination (ft cd) | | | | | | |
| Front | 852 | 885 | 197 | 191 | 166 | 726 |
| Center | 1009 | 1080 | 208 | 205 | 182 | 903 |
| Rear | 1002 | 1057 | 197 | 193 | 182 | 932 |
| Total Solar Radiation (plane of roof) | | | | | | |
| MBtu/ft$^2$ | 655 | 604 | 421 | 373 | 414 | 655 |
| Exterior Illumination (ft cd) | | | | | | |
| Plane of roof | 9096 | 10060 | 2089 | 1970 | 2034 | 9098 |
| Plane of glazing | 2922* | 2457* | 1070 | 1160 | 794 | 2243 |

* Interior illuminance does not follow illuminance in plane of glazing due to differences in sky luminance in clear sky conditions. The sky is much brighter close to the sun, but this sky luminance does not influence interior illuminance significantly (7).

adjusted as needed to maintain the relative azimuth at 0 degrees and the desired relative altitude.

All results were then normalized to the middle of the data using correction factors ranging from 0.95 to 1.05. The data was then used for comparison to determine the magnitude and significance of the error involved in using a tiltable model to simulate diffusely reflected illuminance performance for different solar altitudes.

## 4. CONCLUSIONS

The interior illuminance of the model is a function of four main factors. These are the amount of light present in the plane of the glazing, the amount of light present in the plane of the roof, the luminance of the roof and the illuminance gradient across the plane of the glazing. The experimenters have concluded that the amount of light in the plane of the glazing is the dominant factor of interior illuminance.

The beam radiation component contributes the great majority of the interior illuminance accounting for a mean of 80.7% over the four experiments, with a standard deveation of 5.8%. The beam contribution is 2% greater in the winter case than the summer case. The beam contributes 3.2% more of the interior illuminance in the inverted model than in the upright model.

The diffuse sky vault contributed a mean of 17.1% of the interior illuminance with a standard deviation of 2.8%. The remaining 2.2% is the mean contribution of the ground reflectance. The difference between mean

summer and winter sky vault contributions is only 2.9%.

By comparing the upright model to the inverted model it is found that in the winter case the beam contributes 5% more to interior illuminance in the inverted model than the upright model. In the summer case the beam contributes only 1.5% more to the inverted model than the upright model. Since the upright and inverted orientations are exposed to radically different portions and amounts of the sky and ground the experimenters can conclude that tilting of a model to artificial positions can correctly simulate year round diffusely reflected sunlight illumination performance with a relative error of less than 10%. This error is small enough in magnitude to be considered insignificant in total interior illuminance results. This conclusion is valid for testing under clear sky conditions. Further testing must be carried out to determine the effects of other sky conditions on physical model simulation of diffusely reflected sunlight illumination strategies.

The experimenters have found it will be helpful in further research to take more luminance readings from different parts of the sky as well as the ground and the roof of the model. An assumption which must be verified is that the effects of the glazing will be constant throughout the experiments, this is yet unproven.

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## 6. ACKNOWLEDGEMENTS


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# DEVELOPMENT OF AN INTEGRATED DAYLIGHTING DESIGN METHODOLOGY

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## ABSTRACT

This paper describes six daylighting calculation procedures that the author has been involved in developing over the last several years. They include: sky vault projection, tabular, graphic, protractor, programmable calculator, and microcomputer procedures. After analyzing each, the author finds that they all lack important qualities that would encourage their successful integration into the daylighting design process. A counter model is then proposed where the daylighting procedure becomes part of a learning experience which can integrate with the design process in a natural way and where the designer can exercise his of her knowledge and experience.

## 1. INTRODUCTION

> ". . . whenever we treat [day]lighting in purely physical, quantitative terms . . . we must constantly sit back and think where our calculations are leading us. If they lead us to a design that common sense and experience tell us will be disliked, there is no choice but to . . . reject [them]"
>
> Ralph Hopkinson, Architectural Physics: Lighting, H.M.S.O., London, 1963, pp. 28.

After spending the last several years developing some half-dozen daylighting design tools and writing some two-dozen papers on the subject I recently managed to find some time to reflect on Professor Hopkinson's quote. Upon inspection, I found myself rejecting the bulk of my own work at least as far as my original intentions were concerned. Since making this discovery, I increasingly find it difficult to write papers or give presentations that continue to propagandize the use of design tools that I rarely use in my own design practice. Thus, I would like to take this opportunity to begin to shift my emphasis away from a deterministic toward a more pedagogical approach to daylighting design. I hope no one interprets the comments that I am about to make as being patronizing or condescending to those still working in the tradition that I have since abandoned. My hope here is to be able to share with you some of what I have learned and the direction that my work is now taking.

## 2. MY PAST ACTIVITIES

Like all good researchers I embarked on my activities in daylighting by extensively surveying the literature. From this survey I found that previous procedures for calculating the effects of daylight can be divided into two main bodies, those using the Lumen method,[1] and those using the daylight factor method.[2] The lumen method, which is primarily used in the United States, is based on a series of physical model measurements conducted in Texas in the early 1950's the results of which were used in developing a correlation coefficient approach. This method can consider both overcast and clear sky conditions, however, like many correlation techniques the lumen method has a number of serious limitations which have been created by the original set of correlation assumptions. The daylight factor method, which was developed in Britain and recommended by the CIE (Commission Internationale de l'Eclairage), is primarily used in Europe, where design tools such as sky vault projections, tables, graphs and protractors have been developed for the determination of daylighting at various stages of the design process. Unlike the lumen method, the daylight factor method is derived from first principles and for this reason is a much more rigorious approach. Unfortunately, up until this time the daylight factor method was applicable only for overcast skies. Thus, I decided to build my daylighting research activities on the wealth of British daylighting research by making the daylight factor method relevant to the United States (where the clear sky is a significant condition) by expanding it to cover the clear sky condition.

### 2.1 Sky Vault Projection Procedure[3,4]

The sky vault projection procedure (see

Figure 1) was based on the Waldram diagram which was developed in Britain in the 1920's The Waldram diagram is a rectangular projection that represents a half-hemisphere of the sky. On this diagram a grid of equal solid angles were drawn with the luminance of each solid angle determined by the CIE Clear Sky formula. Sky vault diagrams were derived for every $10^{o}$ of solar altitude (9 in total) in this manner. A window outline (in the case of Figure 1, for a window $40^{o}$ high, $30^{o}$ to the right and $50^{o}$ to the left of a reference point that is at the ▲ mark) is then plotted on the sky vault diagram grid, where the solid curve lines represent the horizontal edges of the window while the vertical edges of the window are drawn as vertical lines. With the window outline complete, the sky component can now be determined, by summing the values contained within the outline. Thus, the sky component for the window outlined in Figure 1 would be 6.4%.

## 2.2 Tabular Procedure[4]

Although the sky vault diagram can be applied to a wide range of circumstances, their construction tends to be tedious. Therefore, it became necessary to evolve a technique for more rapid estimation of the sky component. This was done by obtaining sky components for various window configurations from the sky vault diagram and recording them on tables (see Figure 2). Then by knowing (a) the effective height H of the window above the reference plane, (b) the effective width left and right of the window on each side of a line extended from the reference plane normal to the plane of the window and (c) the distance D from the reference point to the plane of the window, the sky component can determined. Using the same conditions as were used in Figure 1, the values for H/D ($40^{o}$)=.8, $W_r/D$ ($30^{o}$)=.6 and $W_l/D$ ($50^{o}$)=1.2 are calculated. The dash lines indicate how the tables are to be read; the sky component for the portion of window to the right and to the left must be determined separately and were found to be 2.0% and 4.4% respectively. Thus the sky component for the entire window is 6.4%, the same as was previously determined by the sky vault procedure.

## 2.3 Graphic Procedure[3,4]

The tabular procedure was somewhat complicated by the large numbers of tables that were needed; however, by plotting these tables on graphs (see Figure 3) the number of tables could be significantly reduced. Graphs for every $45^{o}$ in orientation of window wall to solar azimuth (8 graphs for every $10^{o}$ of solar altitude) were derived in this manner. The sky component is then found in the same way as in the tabular procedure, by knowing the H/D, $W_r/D$ and $W_l/D$ ratios. Using the same conditions as were used in the two previous procedures, the sky component can be determined. The dash lines indicate how the graphs are to be read; the sky component for the right and left portions of the window were determined separately and again found to be 2.0% and 4.4% respectively. Thus the sky component for the entire window is the same as in the previous examples.

## 2.4 Protractor Procedure[5,6]

The protractor procedure that was developed (see Figure 4) closely parallels a series of protractors that were developed in 1946 by the British Building Research Station for calculating daylight from overcast skies. Building on this and my previous work (the protractors are just another way of plotting the previously generated tabular data), a series of clear sky protractors were developed for use with various window orientations and solar altitudes. Each protractor is comprised of two semi-circular scales which are centered over the reference point on both plan and section and sight lines are drawn to the edges of the window. Values are then derived from where these lines intersect the appropriate scale. The values from each scale are then multiplied in order to get the corrected sky component. The sky component is found by centering the upper scale of the protractor over the reference point in section and reading the intersection of the sight line, which in our case ($40^{o}$ high window) would be 9.0%. The lower scale which corrects the upper value, is then centered over the reference point in plan with its base on a line parallel to the window. A semi-circle is then drawn on this scale corresponding to the average angle of elevation of the window ($20^{o}$). The intersection of the sight lines to the right and left edges of the window with the semi-circle are read to be .23 and .48 respectively. These values are then added together and multiplied by the uncorrected sky component (9.0%) in order to arrive at the corrected sky component of ((.23 + .48) 9.0) = 6.4%. Again the sky component works out to be the same as in the previous examples.

## 2.5 Programmable Calculator Procedure[7,8]

Up until now my daylighting activities could be characterized as expanding on the British daylighting tradition; however, by the late 1970's advances in microelectronics opened up the possibilities of introducing daylighting calculation procedures into devices such as programmable hand calculators (see Figure 5). This process was facilitated by the fact that the daylight factor method was based on a first principle approach, which allowed for easy conversion into programmable hand calculators. The program called Quicklite was designed to combine the low cost and ease of operation of the simplified hand procedures with the speed, flexibility and accuracy of the large-scale computer models. The output

compares well with the previously presented procedures, however the length of this paper precludes, showing an example. Of all the daylighting procedures with which I have been involved, Quicklite has had the most widespread use.

### 2.6 Microcomputer Procedure [9,10]

As microcomputers began to emerge in the early 1980s it became necessary to adapt Quicklite to run on these machines. Thus an enhanced version of Quicklite for microcomputers called Microlite (see Figure 6) was developed. The program was developed around a set of input and output menus that attempted to be sensitive to the designer's needs. The input was organized so that design parameters can be easily created, stored, replaced or changed to determine the effects of various design alternatives. The output from the program offers several formats in the familiar architectural representation of plan, section, and parallel projection as well as the standard tabular format. The graphic capabilities that the microcomputer offers brought to this calculation procedure a power that had not been present in any of the previously discussed procedures. Microlite was made available at a slight cost (cost of the disk and manual) to any user, and in the year since it has been released over two hundred copies have been requested.

## 3. REFLECTIONS ON MY ACTIVITIES

No matter how elegant or refined these procedures may or may not be, for me the ultimate test has been their validity to the design process. Under close examination I have found that these procedures have integrated poorly with the design process. So poorly in fact, that I don't even use them in my own practice. I guess my training as an architect has made me my toughest critic, because I view design very differently than many of my daylighting research colleagues who have not had a design background. For me, design requires the embracing of all aspects of the problem immediately, where gaps in knowledge exist they must be solved in an ad hoc manner with insight and experience. A designer can not wait to have these gaps filled by an analytical effort at least during the design process itself.

In the numerous attempts I have made to apply these procedures in practice, I have found my designs being forced in directions that I did not want them to go. As a designer I was beginning to rely more upon the predictive capabilities of these procedures than on the wealth of experience that I had gathered in my years as a designer. As a result, I began having less than an overall feel for the design process. Design started to become a reductionist process - each design element had to be dealt with separately, calculated and checked against some standard. Such an approach tended to stop or freeze the iterative nature of the design process by producing a series of fragmented answers which do not lend themselves to maintaining an integrated approach to design. Design was becoming analysis rather than an activity I once believed was more akin to riding a bicycle. It must be remembered that all of this was being experienced by someone who was intimately involved in the development of the procedures he was testing and who you would think would have had some control over the process. I shudder to think what would have been the case if a designer unfamiliar with many of the assumptions underlying these procedures, had attempted to test them. The question I must now ask is, has my work done more to harm the cause of daylighting than to help it?

## 4. ALL IS NOT LOST

Although I do not use these procedures in my own practice, nor do I recommend them for use by anyone for design purposes, I did find the process of developing them quite enlightening. The process of developing these procedures has allowed me the opportunity to internalize many of the principles of daylighting. So I've come to think of them not as design tools but as educational tools, because they are useful not for making a design but a designer. The process I call internalization is closely akin to what many designers might call intuition. In its simplest form, internalization is a learning process that allows a designer to learn about the problem under consideration in such a manner as to transcend the problem; the problem solution becomes second nature to the designer - like learning to ride a bicycle.

I have discussed this experience with a number of designers and almost to the last they have acknowledged a similar experience. However, I have found that designers have extreme difficulty in making explicit these shared experiences to a wider audience.

### 4.1 Development of an Internalization Aid

If the process of development of these daylighting procedures has been an important learning experience for me as a designer, then could such an experience be communicated to other? Teaching at M.I.T.'s Department of Architecture offers me the opportunity to organize a course around the testing of such a hypothesis. Thus for the last two years I've taught a course in daylighting which is non-traditional in the sense it is not a support course (run in support of a design studio) nor a technology course, but rather an intensive case study of my daylighting experiences. The objective of which is to

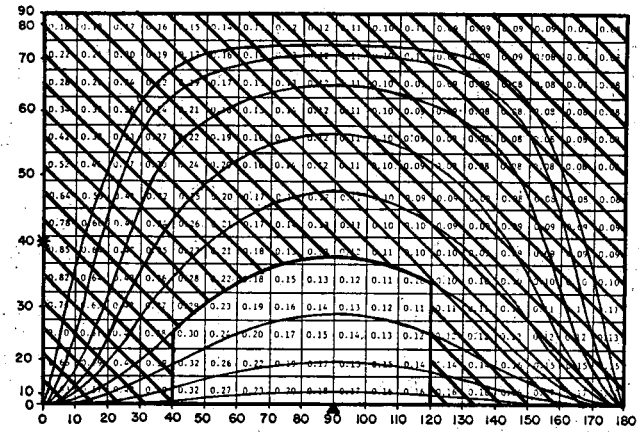


Fig. 1. Sky Vault Projection Procedure

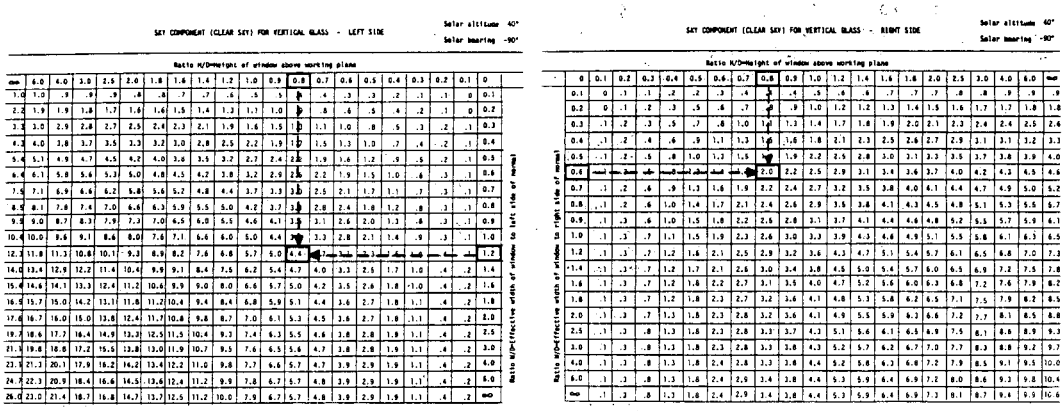


Fig. 2. Tabular Procedure

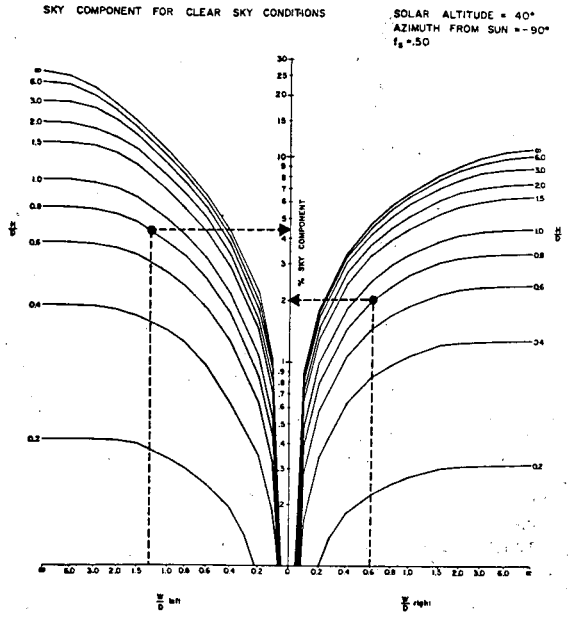



Fig. 3. Graphic Procedure

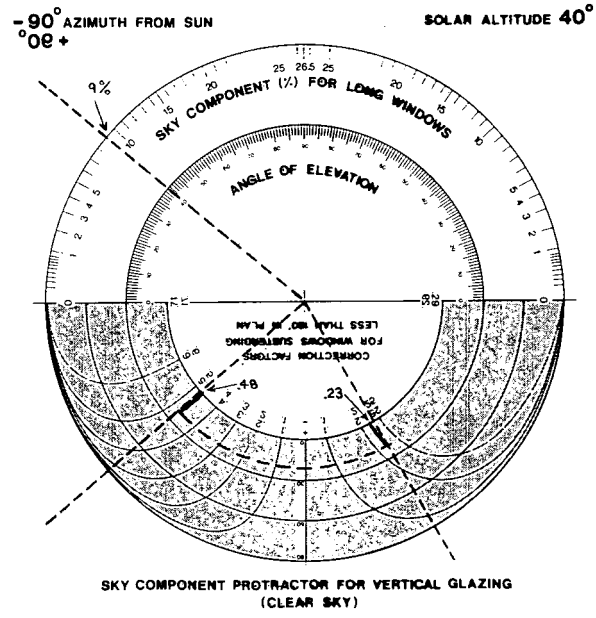



Fig. 4. Protractor Procedure

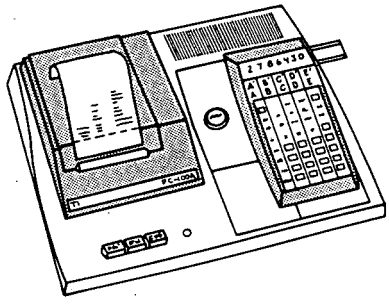


Fig. 5. Programmable Hand Calculator Procedure

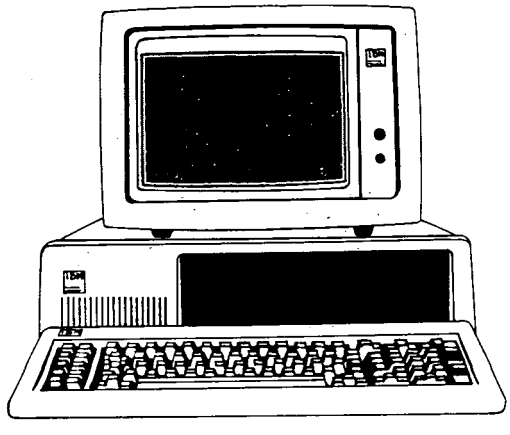


Fig. 6. Microcomputer Procedure

simulate in a small way the process of internalization that I went through.

In this course I try to show that a designer will always be confronted with unknowns, that the design problems will always be changing as the designer's knowledge increases, and that no design tool will be able to solve all the issues at hand. If the designer is not careful he or she can easily fall into the trap of becoming too dependent on these tools. Since no design tool will ever adequately represent the understanding of the problem that designers possess, they must be able to construct their own learning aids. Their effort should be aimed at the construction of "rule-of-thumb" or "ad hoc" models - models which are based on common sense and experience. In class, hypothetical problems are posed and ad hoc models are constructed. From such exercises we have found that ad hoc models should have the following properties:

1. They should accurately model what they are being used to measure, ever if the results of the measurement provide only a gross pictures.
2. They should be understandable, so that the user knows what he or she is measuring and how the result is obtained.
3. They should be pedagogically useful, providing the user with a steadily greater comprehension of the underlying principles of the phenomena he or she is measuring.
4. They should be simple, concentrating on the most important variables and capable of use by persons without special knowledge.
5. They should be accessible to the designer at various stages of problem solution, and be capable of giving different levels of information.
6. They should be dispensable, once the principles inherent in them (or the qualities that result from their use) are mastered by the designer.

Such properties help the designer go beyond the reductionist qualities that the previously outlined procedures had. Their use would allow the designer to proceed in any sequence, making use of information as needed - as required by the nature of the design problem encountered and not by an externally imposed logic. The most important point within this progression is what I call the test for adandonment, where the designer can exercise his of her own knowledge and experience by testing their understanding of the issues under consideration. Once passing this test the designer can abandon that particular ad hoc model.

## 5. CONCLUSION

Experience has shown me that ad hoc models are a refreshing approach to the present state of calculation practices which neglects to encourage the designer to exercise his or her knowledge and experience. I hope that the evolution I have described here will help provide stronger impetus to explore the use of an ad hoc approach. This evolution will inevitably continue; my future work and hopefully the work of others will tell how significant the issues I have raised here are and how we can better understand the design process.

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# INFLATABLE STRUCTURE IN DAYLIGHTING RESEARCH

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## ABSTRACT

The purpose of the proposed research project is to evaluate daylighting characteristics of a variety of window and skylight configurations useful in architectural design. The proposed studies will be quantitative in nature. The subjective nature of user responses to environmental conditions are equally important in terms of user satisfaction. The need to summarize both quantitative and qualitative data is recognized in the structure of this research.

In examining natural lighting through the use of architectural models, the direct sunlight characteristics are readily simulated. Diffuse daylighting studies require the use of a heliodome configuration which is typically a costly, bulky structure with significant maintenance difficulties. This project examines the potential use of an inflatable fabric structure to examine the diffuse lighting characteristics of architectural models. It will compare the simulated and natural diffuse lighting of each prototype model as well as the direct and diffuse daylighting differences.

Other research goals include an evaluation of the practicality and convenience of inflatable structures in daylighting research and instruction. It will also identify how readily such demountable structures can be made available for research or instructional purposes.

## 1. OBJECTIVES

The purpose of this research project is to evaluate the daylighting characteristics of a variety of window and skylight configurations which may be useful in the design of commercial, institutional, and residential structures.

In order to inform designers of the relative benefit of each of several configurations it is necessary to provide comparative analysis through ranges of configuration alternatives and for a variety of daylighting conditions.

The proposed studies will be quantitative in nature. The results are expected also to be instructive as to the subjective nature of user responses to environmental conditions. The need to summarize both quantitative and qualitative data is recognized in the structure of this project.

In order to evaluate these fenestration configurations in terms of equivalent sphere illumination, the practicality of an inflatable structure for this phase of daylighting research is examined. Another intention of the study is to demonstrate that such inflatable structures are easily erected, used and demounted and, consequently, can readily be made available for research or instructional purposes.

## 2. JUSTIFICATION

Since the invention of the incandescent lamp, each re-examination of task lighting requirements has produced a prescriptive increase in illumination levels. Gradually, quantity displaced quality as a design criterion until lighting accounted for 20% or more of energy use in offices. The increases in fuel cost since 1973 have reawakened designers' interest in the use of daylight as a means to reduce energy consumption. That goal is now an accepted design imperative.

As thermal loads are reduced the lighting fraction of energy use could become even more significant. Yet, few architectural designers appear to be knowledgeable about the use of daylight in commercial, institutional, and industrial structures. The challenge is to provide appropriate evaluative criteria and design guides for increased use of daylighting. The use of daylighting introduced in conjunction with

passive solar energy collection constitutes a special case of this same problem.

## 3. REVIEW OF LITERATURE

The architectural modeling of daylighting alternatives is possible because the physics of light allows scale reductions without any change in physical properties or response characteristics. With wavelengths of less than 1 micrometer[1] the essential problem is the accuracy of the physical features of the model,[2] particularly such features as surface reflectivity, window and skylight configurations and lighting control devices.

Because of the relatively smaller potential for saving energy in residential applications, current emphasis of funded research activity is upon schools, commercial and institutional installations.[3]

Between World War II and the "Energy Crisis" the interest in daylighting diminished with the introduction of the relatively economical and efficient fluorescent lamp.

Few designers are equipped by experience to design with daylight in mind. The efficacy of such designs usually requires manipulation of structure, mechanical systems and economic constraints in mutually contradictory ways. But certainly, "Daylighting can be used in a variety of ways for a variety of purposes and, properly used, can conserve energy in most circumstances, while at the same time adding measurably to peoples' satisfaction with, and appreciation of, their living and working environments."[4] Research will provide information which can make the design opportunities and alternatives more explicit. Climatic differences will cause more or less emphasis to be placed upon direct sunlight conditions. Since cloudy conditions represent the minimum case for effective daylighting, equivalent sphere illumination characteristics are among the essential considerations for such experimentation.

> The physics of illumination is such that light behaves exactly the same way in a model as it does in a full-scale building. If the scale model is a duplicate of the full-scale building in all respects and it is tested under identical sky conditions, the results in the model will be identical to those of the full-scale building. The feasibility of using models for daylighting studies had been well established by scientists in this country and in Europe.
>
> Model simulation may be conducted under an actual sky or in a simulated sky where conditions can be held constant. A number of successful attempts have been made to develop simulated skies for use with models, notably at Texas A & M College in the 1950s, and in England, Europe, and Australia. The simulated sky provides opportunity for model tests under non-varying sky conditions, which is a great advantage. Unfortunately, such are too costly except for institutions such as universities and research laboratories. Simulated skies are presently in use in America at Virginia Polytechnic Institute and State University, Blacksburg; at the University of Washington, Seattle; and at the University of California at Berkeley, and for those who have access to these facilities, their use can be quite beneficial.[5]
>
> B.H. Evans, AIA

Among spheriod tensile, structures where the only external force on the hemisphere is that of gravity, membrane forces are induced in reaction to a pressure applied normal to its surface and are proportional to its curvature. Due to the symmetry of form the membrane tensile forces counteract the axial force of gravity. The meridional membrane forces at a given level (or latitude) are constant and proportioned to the radius defining the hoop curve at that level. For a spherical segment smaller or equal to a hemisphere the meridional membrane forces are also constant under horizontally projected loading. It is noted that for a spherical segment greater than a hemisphere the increasing meridional forces approach infinity as the shape approaches a sphere.

## 4. METHODOLOGY

In examining natural lighting through the use of architectural models, the direct sunlight characteristics are readily simulated with spotlight and heliodon table. Diffuse daylighting studies require the use of a heliodome configuration which is typically a costly, bulky structure with significant space and maintenance implications. Evans describes the impracticality of dome configurations for all but the most research oriented of institutions. This research examines the use of an inflatable fabric structure to evaluate the diffuse lighting characteristics of fenestration configurations in architectural models as measured by remote sensing devices. As verification we

also compare the simulated and natural diffuse lighting of significant prototype models as well as the direct and diffuse daylighting differences.

By modeling techniques, the study examines a more or less typical room at 1/16 full size. Other room configurations will be examined as preliminary results warrant. Different combinations of fenestration and/or skylights are examined with distributed instrumentation for simultaneous measurement at 12 locations and 3 instrument heights of 0, 30, and 60 in. The data are plotted initially by means of a micro-computer graphic program which provides isotrophic mapping of illumination intensities. Later data runs will be plotted by means of the SASS Graph computer program, which promises a greater variety of graphic interpretation modes. Data series will be compared for a single configuration at different latitudes, dates and time of day for direct sunlight. Other data will be used to examine different configurations under the identical combinations of environmental conditions.

Each configuration will also be examined under direct and diffuse daylighting conditions. Direct lighting studies are accomplished with a 1000W quartz spot light and a helidon table constructed by John Weidt Associates. The adjustable table has proven to be within 1/2 a degree of the calculated values for the same hour, date and latitude.

The inflatable heliodome is constructed of white rip-stop sailcloth which is translucent under ordinary conditions. This structure is 16 feet in diameter and includes an integral drum segment 30 in. high. Inflation of the structure is accomplished by materials salvaged from an air handling unit, consisting of a fractional horse power 120V motor and a belt driven 8 x 16 in. squirrel cage fan. This arrangement delivers 600 cfm. When connected to the dome air inlet it delivers 490 cfm.

The cloth inlet funnel is in the form of a 12 x 12 in. trunk flared to a 24 x 24 in. opening into the dome. Using round cardboard tubes to restrict air flow, the dome remained inflated when a 5 in. diameter tube limited the flow to 180 cfm and when a 3 in. diameter tube limited the flow to 70 cfm. The maximum rate of flow in every case was measured at approximately 1400 fpm.

The changes in delivered air quantities seem to have little effect on the pressure differences measured between inside and outside the dome. The pressure difference in every case is less than one pound per square foot ($\pm 0.75$ lb/ft$^2$).

Portable lighting, consisting of 24 ER120W lamps mounted on individual bases with appropriate shielding, provides the internal illumination. Inflation develops the dome's hemispherical shape for data runs. A simple lightweight secondary structure supports the cloth during the longer set up intervals.

The spotlights were originally mounted on boards in banks of six. Each lamp was provided with 45° shielding placed in the vertical position around the perimeter, the lamps did not provide the necessary 3.1/zenith:horizon distribution. Tilting each bank to point to the apex of the helisphere produced a 2.5:1 ratio of light distribution. Finally, black broadcloth was added to the inside of the drum portion of the helidome. Ratios of 4:1 were readily obtained as a result of this alteration.

The desired lighting distribution inside the dome is more readily obtained with swivel mounted lamps in raised positions. However, they are obtainable with shielded, swivel mounted fixtures set on the floor around the perimeter if light reflections below the horizon line are reduced to a minimum either by shielding or addition of flat black material below the horizon line.

With the fixtures described above, the peak illumination is in the 20-30 fc range. Additional studies are currently underway to evaluate use of multiple 1000W quartz floodlighting fixtures.

In determining the dome configuration the hemisphere shape was selected on the basis of conventional wisdom. The structural characteristics of the drum portion were successfully ignored.

The instrumentation for this project includes a "Megatron" Architectural Model Luxmeter, Simpson Model 408 illumination level meter and a Li-Cor photoelectric photometer and recorder.

Remote sensors were mounted on pegs at the same diameter projecting through the floor of the model. The model was raised or lowered over the pegs for simulated readings at floor (0 in.), table (30 in.) and eye (60 in.) levels. Each configuration was examined for direct sunlight conditions for various latitudes, dates and hours. ESI conditions were also examined for each configuration.

## 5. PRELIMINARY FINDINGS

The initial studies have focused upon seeing and the visibility criteria for a) visual acuity, b) contrast sensitivity, c) brightness differences and d) veiling reflections.

Time available for seeing is not a consideration at this stage of the project development.

Date: December 21st Hour: 8 am
Height of Sensors: 0 inches

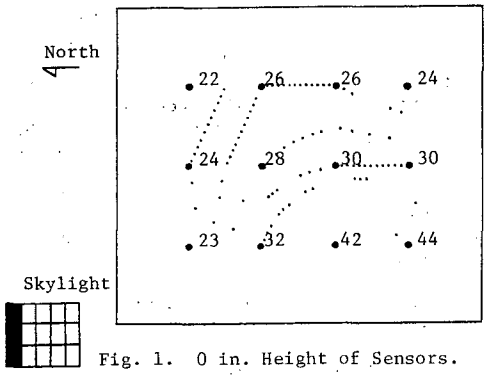



Fig. 1. 0 in. Height of Sensors.

Date: December 21st Hour: 8 am
Height of Sensors: 30 inches

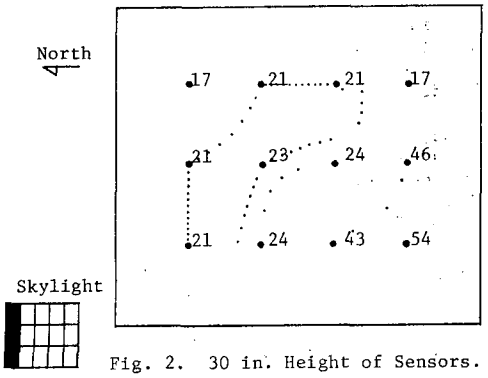



Fig. 2. 30 in. Height of Sensors.

The most uniform daylighting levels have been achieved by south facing skylight monitors which illuminate walls opposite south facing window walls. Skylights which illuminate the full width of such walls perform disproportionately better. For this configuration daylighting levels are most uniform at the highest measured elevations above floor level.

Date: December 21st Hour: 8 am
Height of Sensors: 60 inches

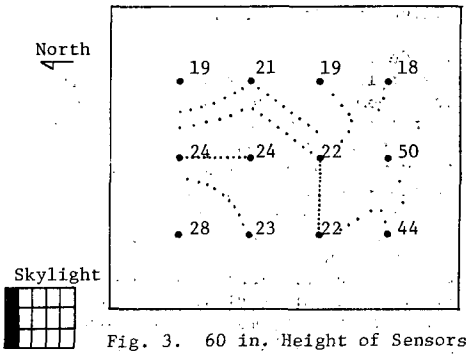



Fig. 3. 60 in. Height of Sensors.

The dome has proven to be easily inflated. The dome has not been provided with facilities for continuous access. It does seem readily obtainable.

## 6. CONCLUSIONS AND RECOMMENDATIONS

The inflatable heliodome is a practical device for conducting daylighting research and instruction. Test results are consistent and useful.

Further evaluation and refinement are warranted.

The development of comprehensible analysis and conceptual guidelines is a reasonable expectation.

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# INDIRECT SUNLIGHTING AND SKYLIGHTING: Strategies Used by Alvar Aalto

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## ABSTRACT

A conceptual framework is presented for designer understanding of daylight illumination strategies that utilize large white surfaces as light "sources". LUMINANCE x APPARENT SIZE is proposed as a simplified conceptual design framework. A series of strategies by the Finnish architect Alvar Aalto that employ white surfaces as light sources is discussed using photographs and matching line drawings from several libraries in Europe and the United States. This paper is derived from a forthcoming book by the author to be published by Van Nostrand Reinhold.

## 1. THINKING ABOUT LIGHT

In order to understand daylighting in general, (and Aalto buildings in particular), it is necessary for the designer to have a conceptual frame of reference.

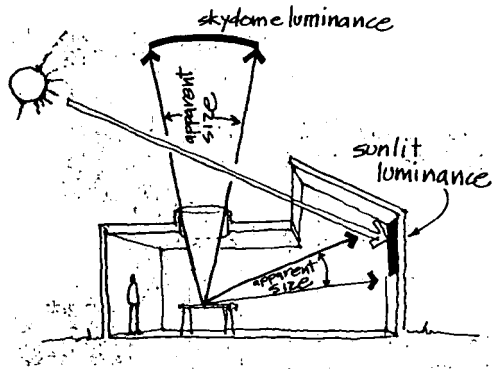



Fig. 1. LUMINANCE x APPARENT SIZE Conceptual Framework - Well suited for considering illumination from distributed sources and diffuse paths.

Consider illumination as what can be "seen" by the TARGET. The basis for this approach is that the amount of light at the TARGET is the result of exposure to all of the bright and dim surfaces within the view of that TARGET. More specifically, the light contributed to the target is the product of the LUMINANCE (measured brightness) of a particular source times its APPARENT SIZE as viewed from the receiver. It should be noted that this is an oversimplification if the RECEIVER is a flat plane. Because of the "cosine effect" oblique light does not contribute as much illumination on a plane as does perpendicular light. Moore (1982) has presented a discussion of this approach.

Because daylighting typically employs distributed SOURCES (skyvault) and diffusing PATHS (translucent glazing and white reflective surfaces), this LUMINANCE x APPARENT SIZE method will be used for subsequent discussion. While this method might be unfamiliar to architects, it is widely accepted as the numerical basis for analyzing daylighting and radiation heat transfer.

## 2. LESSONS FROM AALTO'S LIBRARIES

A matte white surface illuminated by a primary source (i.e., sunlight or skylight) is luminous and can be considered by the designer as distributed light source (similar to a fluorescent fixture) for illuminating a building interior. Aalto made extensive uses of white reflectors as secondary source "fixtures".

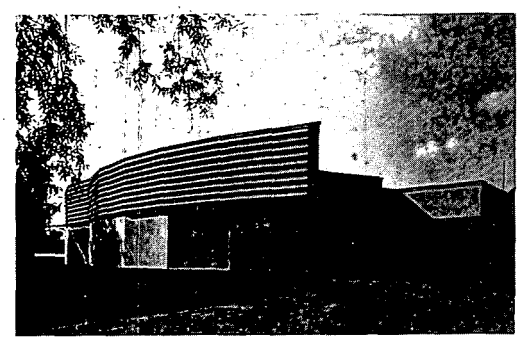


Fig. 2. Seinajoki Library.

The public library in Seinajoki, Finland is a rich source of examples of his integration of these reflectors into the architectural form of the building. The large, high, south window has clear glazing, with horizontal, diagonal exterior louvers. The louvers are white on both sides with a cut-off angle of 45 degrees. At angles higher than 45 degrees, no sunlight or skylight penetrates directly, but is instead reflected twice by the parallel louvers. As a result, the high window performs like a translucent diffuser to high light sources. Its large area adequately illuminates the reading areas from above the field of view of the reader. The result is generous illumination evenly distributed, little cosine reduction, and minimal glare because of the high source location.

At angles below the 45 degree cut-off angle, direct skylight (and in the winter, direct sunlight) enters directly. Most of the direct sunlight strikes the lower part of the large, curved reflective "light scoop". The lower portion of this scoop has a high luminance level (due to its orientation relative to the window). This bright surface becomes the principle source for the vertical book stacks along the exterior wall. Note the large apparent size of the scoop as "seen" from the stack.

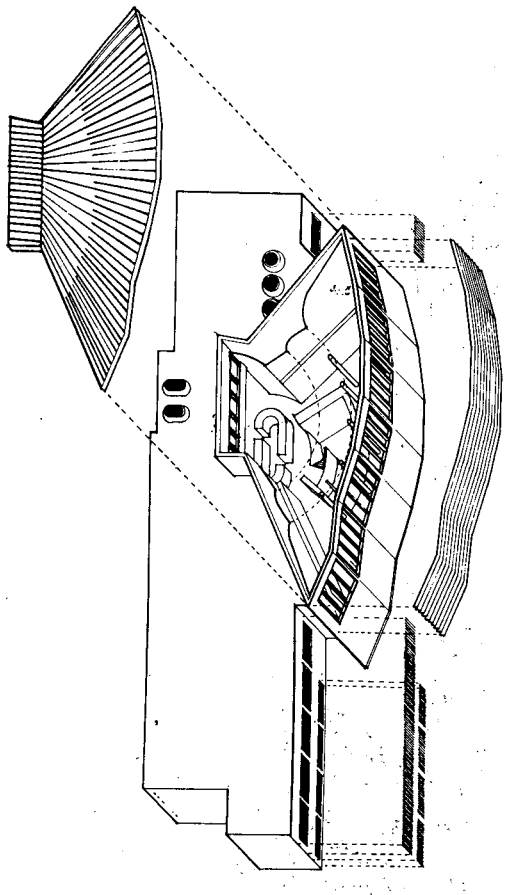
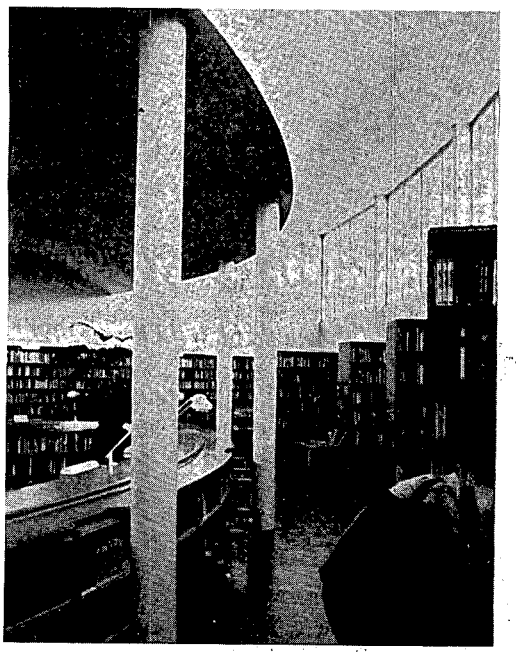


Fig. 3. Seinajoki Library, Exploded Axonometric.



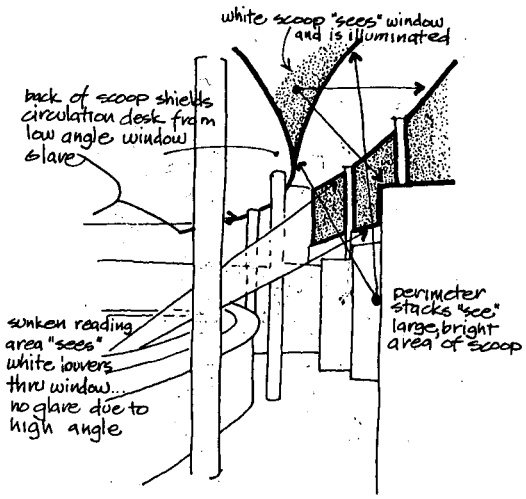


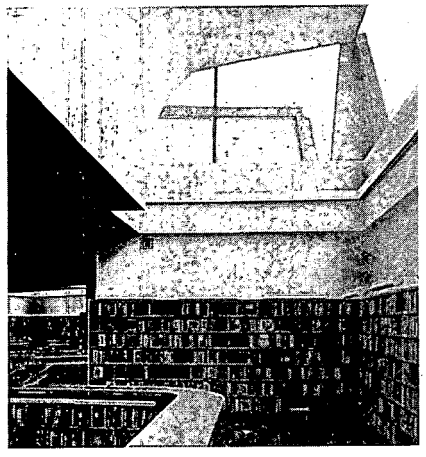

Fig. 4. Seinajoki Library, Interior showing Light Scoop (with explanation).

The top of the scoop receives light reflected from both the lower part of the scoop as well as the top to the louvers and exterior ground. The exterior wall (below the window and above the stacks) receives light from the lower part of the scoop. While both the upper scoop and his wall portion in turn contribute to the general illumination of the room, their luminance is important in reducing the brightness contrast around the window.

The sunken reading area "sees" two large, bright secondary sources: the high, south window and the north clerestory. The sunken location places both sources high, reducing the cosine reduction from both sources onto a horizontal reading plane, while keeping them above the reader's field-of-view to reduce glare.

Most Aalto libraries employ a sunken study area located in the center of the main library space. This creates a strong spatial focus. It also allows stacks to be located in the center without blocking visual control from the circulation desk. In those libraries where light is admitted only from the perimeter, the sunken floor configuration keeps the high side light above the field of view of the reader, while reducing the cosine reduction of illumination on reading tables.

Aalto's largest public library is located in Rovaniemi, Finland. The fan-shaped plan is segmented with separated sunken reading areas. Each is defined and illuminated by a light scoop and high window on three sides. The backs of the light scoops also receive diffuse daylight as well as low-angle morning direct summer sunlight. The result is a relatively uneven distribution of illumination with the greatest amounts occurring at each sunken reading area. Like the Seinajoki Library, the Rovaniemi bottom of the scoops act as eyebrows, preventing glare (i.e., large amounts of bright sky visible at low viewing angles) at the centralized circulation desk. This is achieved at the expense of deep light penetration from the high perimeter windows.



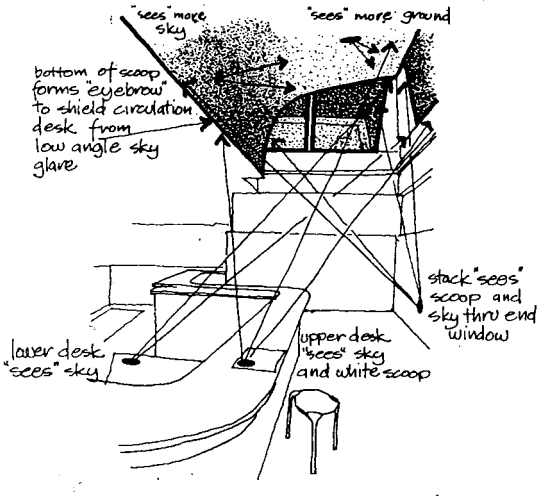



Fig. 6. Rovaniemi Library, Interior (with explanation), showing typical bay with sunken reading area, high window and light scoop.

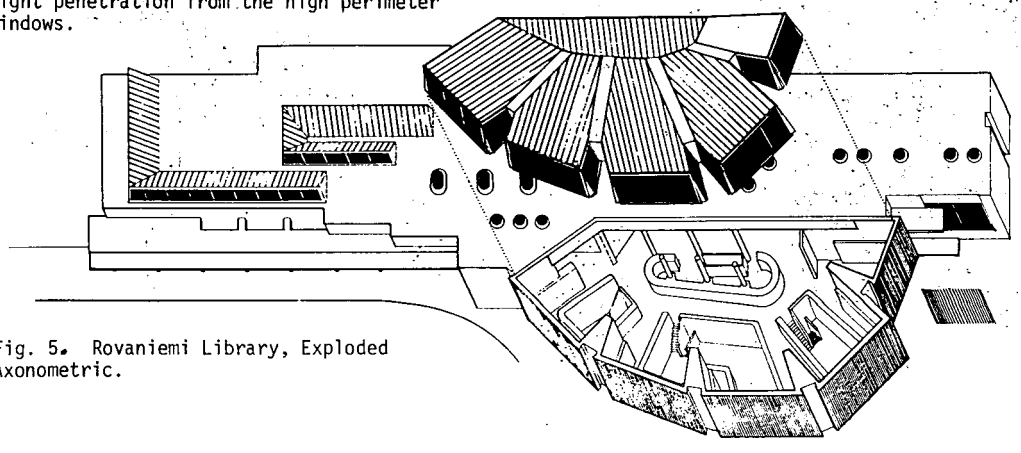


Fig. 5. Rovaniemi Library, Exploded Axonometric.

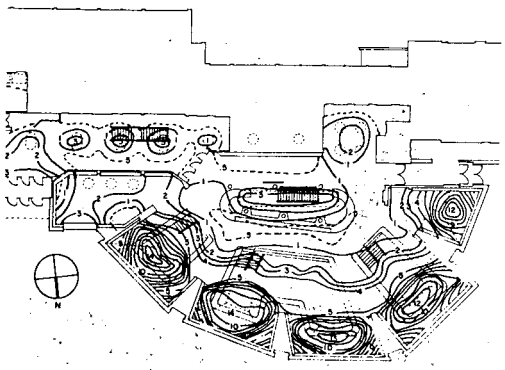
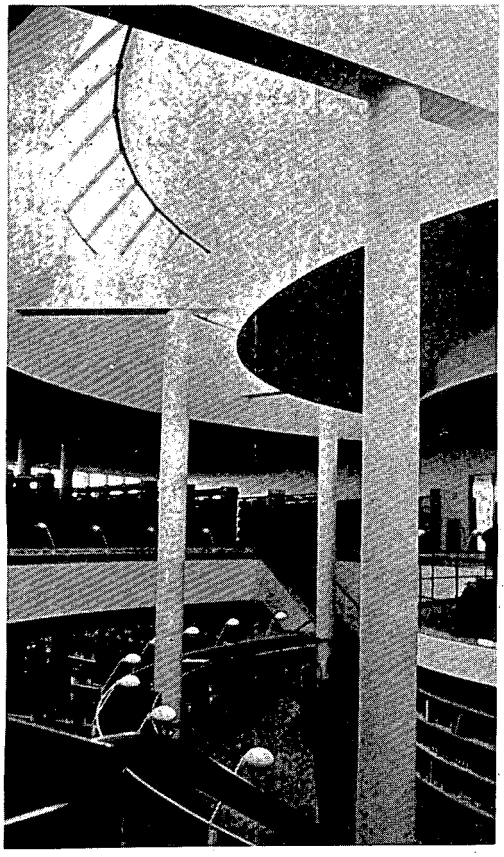


Fig. 7. Rovaniemi Library, Plan with Isolux Contours (percent of exterior horizontal illumination, excluding direct sunlight). The levels of greatest illumination are concentrated in the sunken reading areas.

The last library to be designed by Aalto is located at Mount Angel Abbey, a Benedictine Monestary near Portland, Oregon. Using a fan-shaped plan, light is introduced over the center reading area by a north-facing,



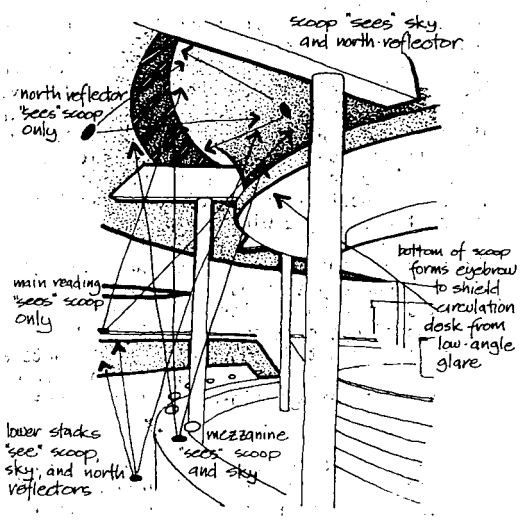
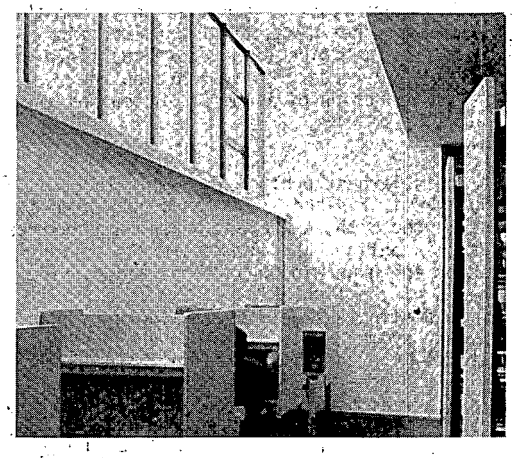



Fig. 8. Mount Angel Library, Interior (with explanation).



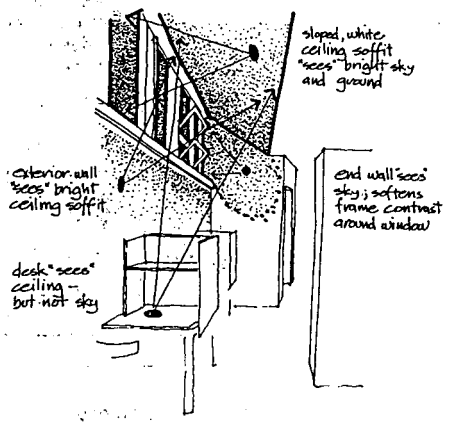
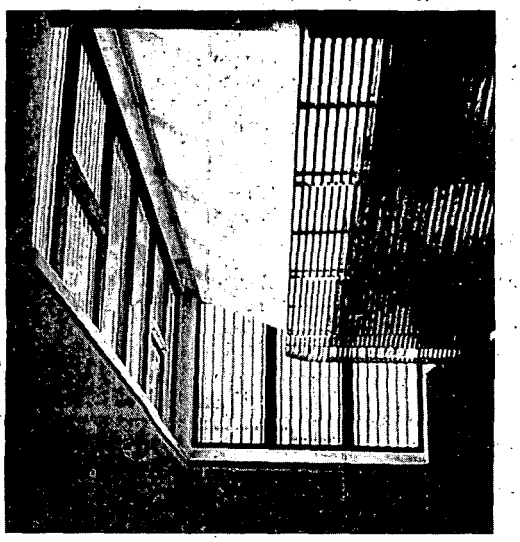



Fig. 9. Mount Angel Library, interior (with explanation).

crescent-shaped roof monitor, with a white "scoop" behind clear glazing sloped about 60 degrees. The sectional profile is shallow allowing direct sky illumination in one direction and reflection from the scoop in the opposite. This provides generous illumination to the reading stations surrounding the sunken mezzanine crescent and the mezzanine level itself. In addition, adequate light penetrates down past the mezzanine into the basement open stack area to allow selection of books.



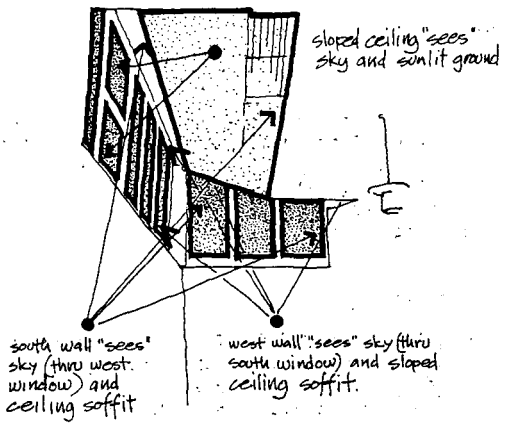



Fig. 10. Mount Angel Library, High North Window (with explanation).
Both the sloped soffit and the perpendicular end wall receive light directly from the north sky vault. Their brightness reduces contrast with the sky visible through the window. In addition, the soffit illuminates the carrels below (which receives little direct skylight) and the wall below the window (again to reduce brightness contrast with the sky).

On the main level, stacks radiate out from this center light chamber, allowing visual control from the circulation desk. At the perimeter of the main level, open carrels are illuminated from above by high window light which is reflected from the sloped ceiling. This straight "scoop" also washes the wall below the window to reduce the brightness contrast of the sky seen through the windows. A similar sloped ceiling is positioned above corner windows in the small lecture room. In addition to light reflected by the sloped ceiling, each lower wall is washed from the adjacent perpendicular window.

## 3. AALTO BUILDINGS IN PERSPECTIVE

After visiting numerous Aalto buildings, and making detailed illuminance measurements in the six major libraries, this author remains impressed with the breadth and richness of his architectural and illumination vocabulary. In most cases, the two are inseparable. It is easy to be awed by his buildings (and his reputation) and to dismiss them as somewhat mystical creations of a gifted genius. There is a temptation to directly transpose these strategies to the design of contemporary buildings.

This is unwise. Not only were most of Aalto's solutions heavily influenced by local (typically overcast, northerly) daylight environments, they were designed during a time of abundant energy. Little regard seems to have been given to problems of excessive heat loss (or gain). For contemporary architects designing in an environment of clearer skies and much higher relative energy costs, probably the single most valuable principle to be gleaned from Aalto is the use of white surfaces as diffuse, secondary illumination sources. This principle must now be adapted to the preferred use of sunlight (instead of diffuse skylight) to allow smaller glazing areas. The south facing roof monitor (with suitable reflective baffles) for top lighting and the "light shelf" for side lighting are two adaptations of secondary source reflective diffusers to our high sun angles and present energy costs.

## 4. CONCLUSIONS

The following are design strategies based on Aalto's buildings, but modified for application in U.S. climates and present energy costs:

a) MAXIMIZE SOUTHERN EXPOSURE.
Direct sunlight is easily controlled. Even under overcast conditions, this is the direction of greatest sky luminance, and glass areas can be reduced proportionally.

b) IN MULTI-STORY BUILDINGS, USE NARROW PLANS TO MINIMIZE DISTANCES TO PERIMETER LIGHT.

c) USE SUNLIT WHITE SURFACES AS SECONDARY LIGHT SOURCES. Position these for (1) maximum exposure to the primary source, and (2) maximum apparent size from the receiving location. This translates to positioning the white reflector approximately as though it were a mirror.

d) POSITION DIFFUSE SOURCES (either white reflectors or the sky as "seen" through a window) AS HIGH AS PRACTICAL: 45 degree above the horizontal allows equal illumination of both horizontal and vertical surfaces while causing relatively little "cosine" reduction on either. This high location also reduces glare by positioning the bright source above the normal field of view.

e) USE WIDE, HORIZONTAL SOURCES in preference to narrow, vertical ones for more even distribution.

f) USE VERTICAL GLAZING. Sloped and horizontal glazings are difficult to shade during summer months. South vertical glass receives more winter and less summer sunlight.

g) EXTERIOR SUN CONTROL DEVICES ARE PREFERABLE TO INTERIOR in order to reduce solar heat gain, especially in internally load-dominated commercial buildings.

h) SUN CONTROL DEVICES SHOULD BE REFLECTIVE (white or mirror) to increase their brightness. This increases their potential as secondary illumination sources while reducing brightness contrast with the visible sky.

i) USE VERTICAL LOUVERS TO CONTROL SUNLIGHT ON EAST, WEST, AND (if necessary) NORTH GLASS. On east and west locations, angle the louvers toward the north to admit north skylight while excluding morning and afternoon direct sunlight. If the louvers are white, they become secondary sources by reflecting (and thus diffusing) direct sunlight twice before entering.

j) USE AUTOMATIC, PHOTO-CELL CONTROLLED ELECTRIC LIGHTING. No daylighting system will save energy unless electric lighting is automatically controlled. Manual controls have repeatably been found unreliable.

k) USE EXTERIOR HORIZONTAL REFLECTORS BELOW HIGH WINDOWS, CLERESTORIES, AND MONITORS TO REFLECT LIGHT ONTO WHITE CEILINGS. This is an important strategy for converting the ceiling into a secondary source as well as reducing contrast with the sky. Avoid ceiling obstructions parallel to the glazing (such as beams) that reduce deep penetration of ceiling penetration. Keep these surfaces above eye level to avoid glare to occupants (e.g. locate light shelves on sidewalls above 7'-0").

l) SURROUND WINDOWS WITH "SOFT FRAMES". Use deep openings so that the surfaces surrounding the window receive skylight, and thus reduce sky brightness contrast. Extend windows to touch adjacent perpendicular walls. In addition to directly reducing brightness contrast at these points, the perpendicular wall reflects light back onto the wall below the window. Slope the soffit up to receive skylight for the same reason.

m) ADMIT CONTROLLED SHAFTS OF SUNLIGHT INTO NON-CRITICAL AREAS. These add movement and sparkle to the interior.

n) PROVIDE CONVENIENT BLACKOUT CONTROLS FOR DAYLIGHTED LECTURE SPACES. If these spaces cannot be easily controlled for audio-visual purposes, they will be left dark by the occupants. Several lecture skylights and monitors, designed by Aalto prior to the present widespread use of slide projectors, have been permanently sealed off by the occupants.

o) UTILIZE "BORROWED LIGHT" TO ILLUMINATE INTERIOR LOCATIONS.
Minimize opaque obstructions parallel to the glazing. Use glass partitions where required for sound isolation (translucent where required for privacy).

## 5. ACKNOWLEDGEMENTS

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# DAYLIGHTING ANALYSIS FOR AN EARTH COVERED OFFICE BUILDING IN SACRAMENTO, CALIFORNIA*

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## ABSTRACT

In order to assess daylighting performance and analyze anticipated energy savings during the design process, scale models were constructed to study three key areas: (1) typical light court, (2) subterranean commons, and (3) multilevel north-facing lightwell. Following completion of the building in late 1982, on-site measurement data were obtained to compare the actual results with those obtained through modeling during design.

Site conditions, at the time measurements were taken, were very close to the minimum design sky assumed for the model studies. Although some configuration and surface treatment changes were made on the constructed building, a remarkable degree of correlation between actual and simulated building performance is clearly demonstrated. The performance measures include both actual lighting levels and distribution penetration patterns. Thus, energy savings anticipated from the validated model studies might be reasonably expected to occur during actual building operation as well.



Fig. 1 .Aerial View of Sacramento Office Building Looking North.

## 1. PROJECT DESCRIPTION

Daylighting was a predominant energy conservation feature in the design of this earth covered California State Office Building which won the National Energy Design Competition in 1977. The project later received the Owens Corning Energy Conservation Award as well (1-4).

The Sacramento Office Building, Site No. 3, was occupied in January 1983. The project

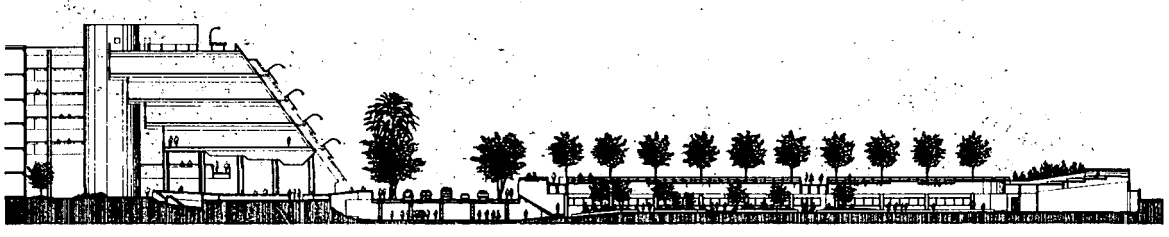


Fig. 2. Longitudinal Section Showing Multilevel North Lightwell and Subterranean Office Level.

* This paper is based on a presentation given at the International Conference on Earth Sheltered Buildings conducted in Sydney, Australia, in August 1983.



Fig. 3. View Looking South in Subterranean Commons.

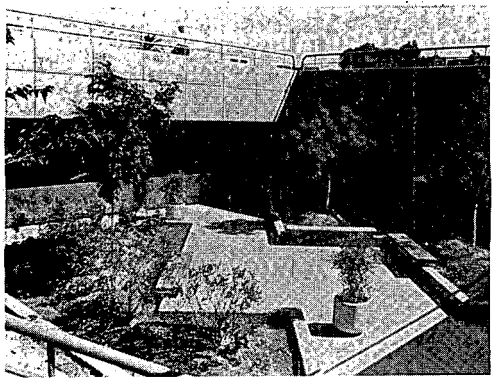


Fig. 4. External View of Subterranean Light Court.

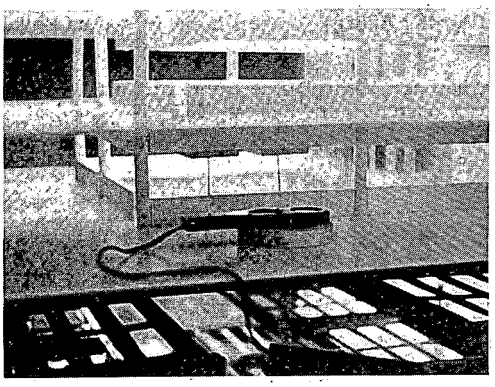


Fig. 5. Daylight Model of Subterranean Light Court.

covers a block-and-a-half site which is just three blocks from the State Capitol Building. The aerial view of the building in Figure 1 indicates that more than two-thirds of the site contains earth covered office space.

The far north end of the site contains a multi-level daylighted office structure, which supports an array of concentrating solar collectors on one side and forms a large entry lightwell with the existing building on the other side. The longitudinal section in Figure 2 shows this large north lightwell and the subterranean office level. Figure 3 is a view looking south in the subterranean commons circulation spine in the earth covered office area. A series of light courts, shown in Figure 4, project down into the subterranean offices to admit daylight, provide an exterior view, and allow access and egress for the occupants. The project was designed by The Benham Group with headquarters in Oklahoma City. The authors were both members of the original design team.

## 2. MODELING APPROACH

The procedure described herein for evaluating the performance of daylighting prior to construction is based on analyses of models built to a scale 1/24 of full size. An artificial diffuse sky condition without benefit of direct sun effects was simulated in each case.

Daylight factor contours and profiles were developed utilizing the ratio of interior levels measured in the models compared to actual simulated "exterior" levels. With the developed daylight factor contours, and an evaluation of actual sky conditions at the project site, expected interior daylight levels can be predicted at the conceptual stage for a project (5-8).

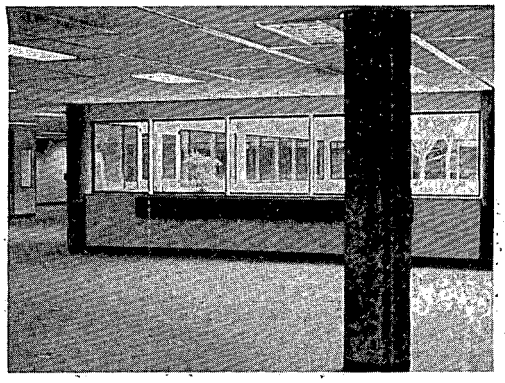


Fig. 6. Constructed Interior Showing Subterranean Light Court.

Foam-core board models were constructed for each typical daylighted configuration. Model finish materials were modified throughout the measurement process, primarily for selected exterior treatments including landscaping. However, the effects of interior furnishings and partial height partitions were also assessed. Interior surfaces were constantly maintained at an all-white treatment mode.

A photograph of the daylight model utilized to simulate the subterranean light courts is shown in Figure 5. In Figure 6, a view of the final constructed interior is provided.

## 3. AS-BUILT CHARACTERISTICS

The design goal was to obtain a typical daylight factor of about 2.5 at a penetration distance of 5 meters (15 ft) from the window wall. Except for some weeks during the winter, this level of perimeter daylighting would provide at least half of the task lighting needed much of the time. The level of installed interior electric lighting is about 27 watts/$m^2$ (2.5 w/$ft^2$).

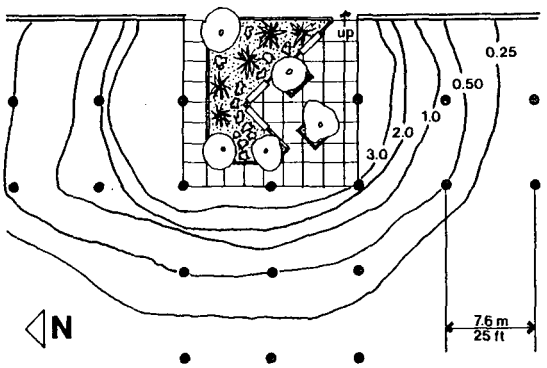
Modeling studies suggested a number of design features to be provided in order to achieve sufficient penetration of the 2.5 daylight factor contour. For example, a white stucco exterior and a perimeter band of concrete paving were appropriate for the light court areas. Less than half of the court area could be of low-reflectance materials like grass and low shrubs. The use of large trees should be restricted to the street entry portions of the courts.

The ceiling height is maintained at 3 meters (9 ft) with close to 90 percent reflectance; the overhang soffit is at a slightly higher elevation. The use of desk-height interior partitions would not seriously affect the daylighting unless placed fairly close to the exterior walls. However, the use of cabinet-height partitions anywhere would drastically affect natural lighting distribution throughout the space, and thus should be avoided, except in deep interior spaces where electric lighting would always be used.

## 4. DAYLIGHTING PERFORMANCE

Daylight factor measurements were obtained on-site for the southeast and southwest light courts and along the column line connecting these two courts. All measurements were made at mid-day in early December just prior to occupancy; all electric lighting was turned off.

The daylight factor contours were similar for both light courts - measurements for the southeast court are shown on the plan in Figure 7. In Figure 8, the on-site measurements are




Daylight Factor in Percent

Fig. 7. Daylight Distribution Contours at Subterranean Light Court.

shown in profile, including levels measured next to the subterranean commons. In addition, Figure 8 shows results of preliminary model test data for the light court. For a penetration distrance of up to about 4 meters the model data seems to bracket the actual on-site performance rather well. Beyond that distance, the model data tends to over-estimate actual performance, possibly due to the use of high model reflectances throughout.

Daylight distribution in the multilevel north lightwell is shown in Figure 9. A view looking west in this north lightwell is provided in Figure 10. Measurements at the north side of the sloped multilevel structure are in very close agreement with the pre-construction modeling results. In the center of the lightwell, on-site measurements were made from the bridge walkways, while the model values were obtained with the probe held in the center of the open space - well away from the bridge. Thus, the recorded differences between those two sets of readings is quite understandable. All measurements in this north lightwell were made in mid-afternoon, to assure that direct sun effects would not be present in the lightwell space. All on-site measurements on the south side of the sloping structure were obtained in a manner which excluded possible direct sun effects through a probe-shading technique.

A series of electric lighting levels were also measured deep in the interior of the new office areas. In general, these levels were about equal to the levels already experienced in previous quarters of the new occupants.

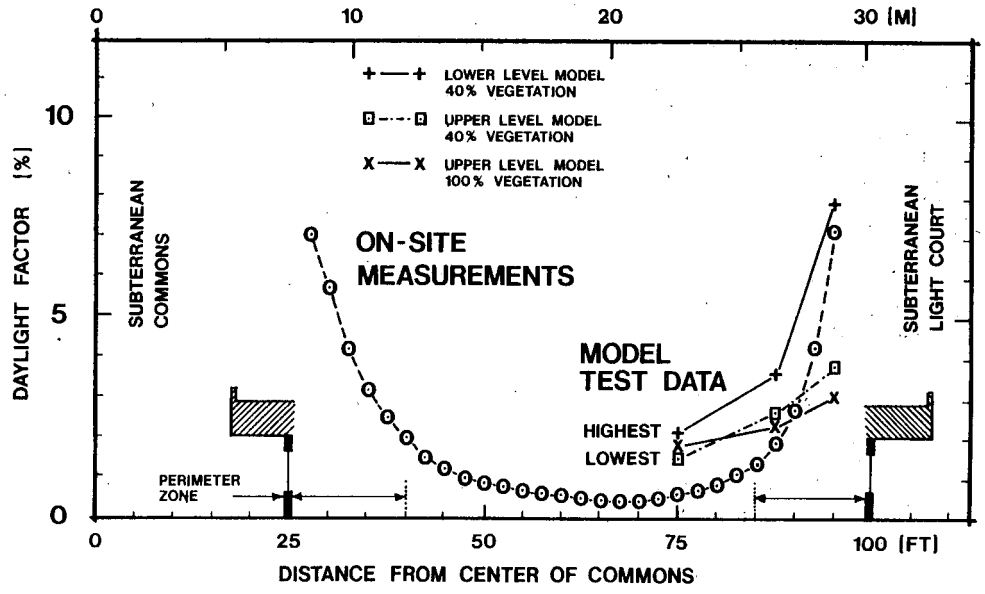



Fig. 8. Daylight Distribution Profile through Subterranean Offices.

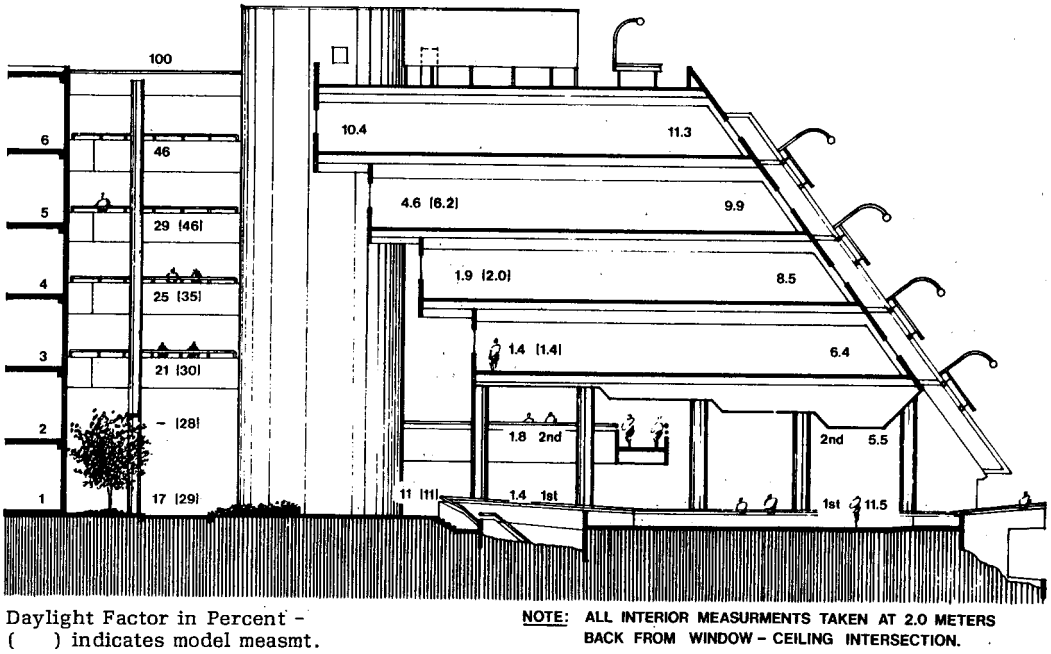



Fig. 9. Daylight Distribution in Multilevel North Lightwell.

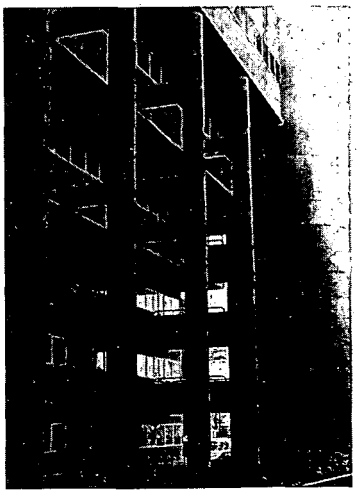


Fig. 10. View Looking West in Multilevel North Lightwell.

## 5. ENERGY SAVINGS

In order to capitalize on the energy savings aspects of daylighting, a series of photocells is located in each light court/lightwell. With the use of a programmable lighting controller, these photocells trigger the cut-off of one, two, or all three lamps in each fixture according to the level of daylighting available at any given time. The performance of this particular system can only be determined after an extended period of occupancy has transpired. A photograph of the programmable lighting controller console is shown in Figure 11.

A preliminary pre-construction study of energy savings due to daylighting on this project has been previously published, with assessment techniques subsequently analyzed (9, 10). That study offered several outcomes depending upon how percent energy savings is determined. If one-half of all perimeter lights are turned off, a figure of 20 percent savings would occur during one hour of a clear day for the entire building complex area. With an overall annual appraisal, the calculated savings was about 9 percent on the most conservative basis. This latter figure might be suggested as an actual estimate of occupant utilization.

Using a non-conservative approach, actual annual savings might be placed at more than 20 percent, while possible potential savings might be estimated at double this amount. The real annual energy savings under actual occupancy conditions can be readily assessed on-site quite easily with the programmable lighting controller system already installed. Hopefully, such information will provide a more certain basis for energy savings expectations due to properly engineered daylighting design.



Fig. 11. Programmable Lighting Controller System.

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# "LIGHT PLENUM" CONCEPT IN OFFICE BUILDING DESIGN

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## ABSTRACT

Through the use of modelling, the "Light Plenum" concept was investigated to determine daylighting patterns in office building design. This concept is merely an extension of the light shelf application, or an enlargement of the conventional mechanical plenum to form a light trap. The trapped light reflected within the plenum is transmitted into the office space through a translucent ceiling pattern integrated with the electrical lighting system.

Under sky conditions for the Pacific Northwest, the recorded results taken at Pullman, Washington indicate that the translucent ceiling with daylighting controls will allow adequate, uniform task lighting levels. This daylight contribution for task lighting could allow a significant reduction in electrical lighting demands in office building design.

## 1. INTRODUCTION

Some familiarity is assumed with building designs that utilize complex configurations and high-tech materials in an attempt to enhance daylight contribution. The plenum concept is a simple approach to receive more daylight into task spaces without a great deal of building distortion. The objective is to demonstrate that the "Light Plenum" will provide adequate lighting levels in certain (40 ft and narrower) rooms. This can be achieved by overhead, daylight penetration, solar control and ventilation control at the air plenum between each floor level as shown in Fig. 1.

Generally, most conventional, long-span office building designs accommodate the structural and mechanical systems between the floor and ceiling creating a plenum. With proper spacing and alignment of the structure, and with placement of the mechanical network within the plenum, this space could also serve as a light trap (Fig. 2). The plenum used in this study is six feet deep at the light shelf with an eight-foot ceiling, then changes to a four-foot plenum depth with a ten-foot ceiling. The intent is to get maximum solar exposure above the ceiling without increasing the overall floor-to-floor height dramatically. Consequently, by increasing the typical floor-to-floor height by two to three feet, the plenum becomes a vehicle for light penetration and a means for air ventilation.

## 2. CONCEPT

Light rays, either direct or diffuse, enter the plenum above the office space from a light shelf over the viewing window at the building's southern exposure. The daylight is reflected throughout the plenum by means of flat reflective surfaces; no curved surfaces or tracking devices are employed. This "Light Plenum" concept reduces glare and ceiling problems because soft light enters from above at ceiling level through diffusing lenses. With the aid of louvers at the side windows and at the plenum, a degree of uniform illumination can be maintained.

## 3. TESTING

### 3.1. Modelling

An important step in this study was to determine the lighting pattern and illuminance level facilitated by the perforated ceiling below the light plenum at the work surface (2.5ft above the floor). Because most open landscape office plans rely on informal placement of furniture, equipment and privacy partitions on carpeted floors, little reflectance should be anticipated from the floor. Therefore, only the tenant walls or major partitions at 40'-0" on center were considered in terms of shading and reflectance on the work surface.

A four-story office building with an atrium and south and north solar exposure was modelled. At 3/4 in. = 1 ft scale only a 40' x 40' southern space of the building was monitored under clear and cloudy sky condi-

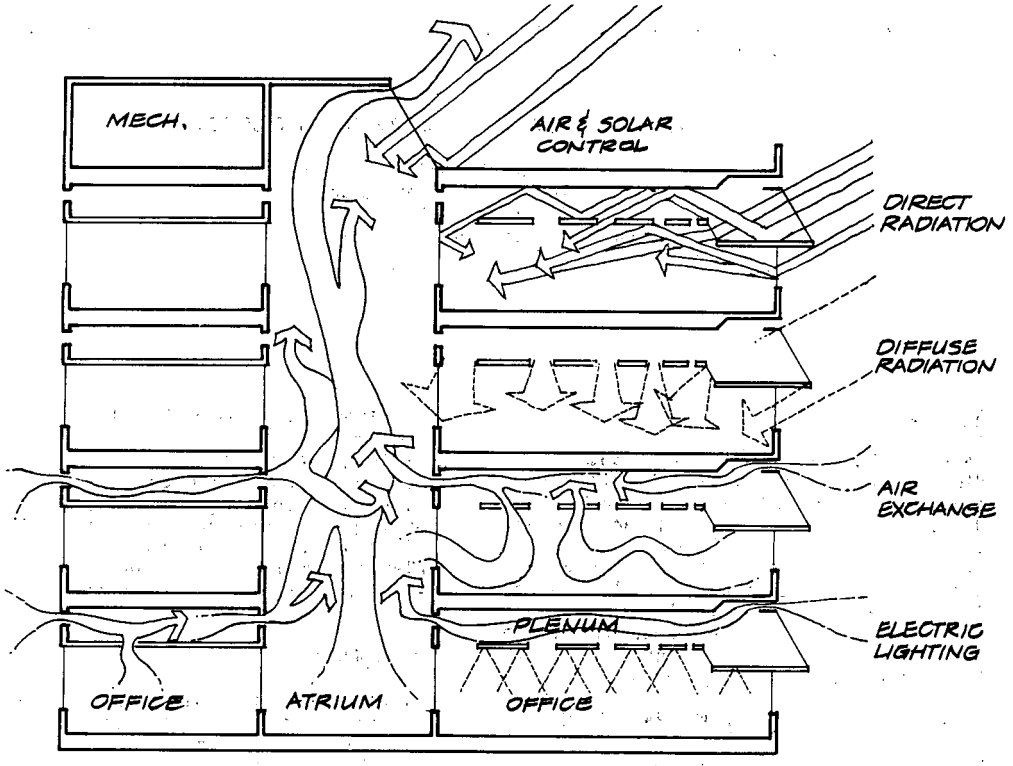



Fig. 1. Section of Office Building with Solar Control at Envelope, Atrium and Plenum.

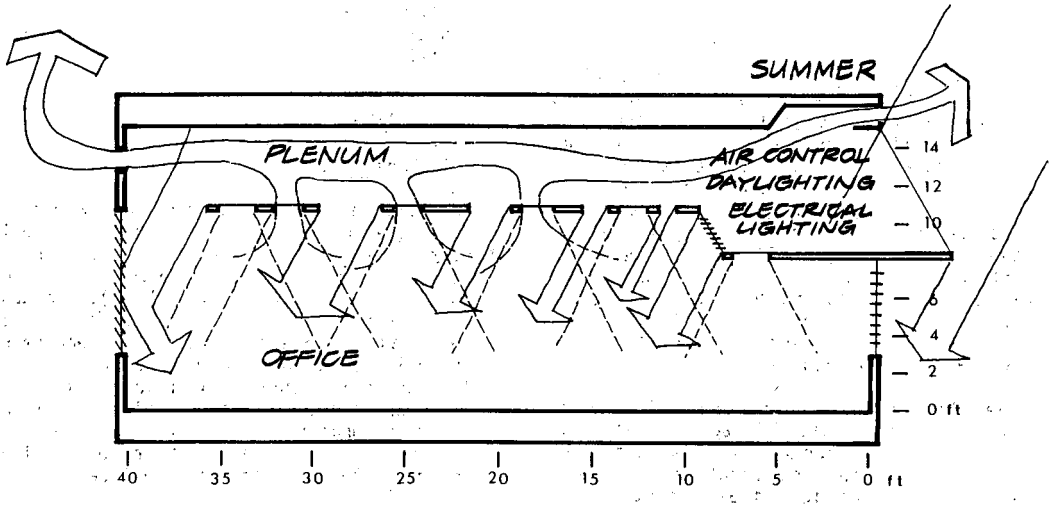



Fig. 2. Section of Office Space (40'x40') with Integrated Daylighting, Electric Lighting and Ventilation at Ceiling.

tions for the Spokane/Pullman, Washington region. The section of the space had an 8 ft ceiling extending 6 ft from the south window, then a 10 ft ceiling extending 34 ft to the atrium for an office width of 40 ft and a length of 40 ft.

There was no attempt to use highly polished, reflected surfaces in the model. A 70% reflectance was achieved at the shelf, plenum, and office walls. The office ceiling had a 30% reflectance and the floor a 13% reflectance. Ground reflectance was recorded at 21% for a concrete surface.

The daylight transmittance for the plenum at the south elevation was 87% for clear glass placed at a 60-degree angle. At the ceiling, the acrylic lenses had a daylight transmittance of 84%. Glazing was not used in the north and south window openings.

### 3.2 Procedure

In order to simulate the seasonal solar conditions, the model was oriented in azimuth and altitude to achieve the desired sun angles from 0900 to 1500. By utilizing this method, there is a degree of inaccuracy in regard to ground surface reflectance, and actual atmospheric composition. However, the intent of the study was to determine lighting patterns within the space, not light quality.

A Gossen Panlux electronic footcandle meter was used to record light intensity in footcandles at the ground, the light shelf, and at the work surface within the space. Direct normal radiation and illumination at the side windows were not recorded.

Because the intent was to study the plenum, the side windows were secondary in importance as sources for daylight contribution. However, adjustable louvers at the windows and at the plenum were employed to control glare and light penetration during daily and seasonal solar changes (Fig. 2). With this control, excessive light at the south window or glaring low altitude rays could be directed and diffused more evenly throughout the space.

Three different perforated ceiling patterns were studied: A, B, and C (see Fig. 3). The area of the perforated ceiling increased proportionately to the back of the room in order to emit more illumination in the low light level area (north).

Therefore, to really understand the performance of the plenum and each ceiling type, the light within the space was recorded with side windows and without side windows. After the light patterns were identified by the rays passing through the ceiling, the side windows were throttled to emit light, mainly to control the light characteristics in the room. This control determined the overall additive daylight contribution.

### 3.3 Results

In this initial study, the three ceiling patterns, A, B, and C, all performed well, with Type B performing, overall, slightly better than the other two. However, no pattern was significantly superior over the other on a yearly basis.

Under clear and cloudy skies, for all seasons, the light level at the back of the room (North), 40 ft from the south elevation was above 75 ft candles.

Winter conditions with clear skies posed a problem because of the low altitude angles sending direct light on select diffusers, while other diffusers experienced less intense reflected light. This situation created low and high illumination levels within the space with a high illumination level at the south window (Fig. 4).

Summer conditions with clear skies and high altitude angles allowed the rays to reflect several times within the plenum before entering the space allowing for a fairly even distribution of illumination (Fig. 5).

Autumn conditions with clear skies allowed relatively deep penetration into the plenum without the erratic illumination levels experienced in the winter (Fig. 6).

## 4. CONCLUSION

With the reliance only on daylighting from the "Light Plenum" and louvered south window, the illumination level for all seasons under cloudy skies was above 75 footcandles within the office space.

The uniformity of the light distribution was determined most dramatically by the diffuse nature of the sky conditions and the altitude of the sun. All ceiling patterns (A, B, and C) had diffuse ceiling lenses at the interior walls, which increased in area to the north, thus allowing good light distribution, regardless of azimuth angle. This was possible because the shadow areas created by the partition walls (East and West) were patterned in accordance with the ceiling lenses. Therefore, even at large solar azimuth angles with low solar altitude angles, the plenum responded as a light trap with illumination selectively escaping to needed low lumen areas.

Consequently, the "Light Plenum" concept appears to be quite feasible in office building application, where north lighting is not always available and the space does

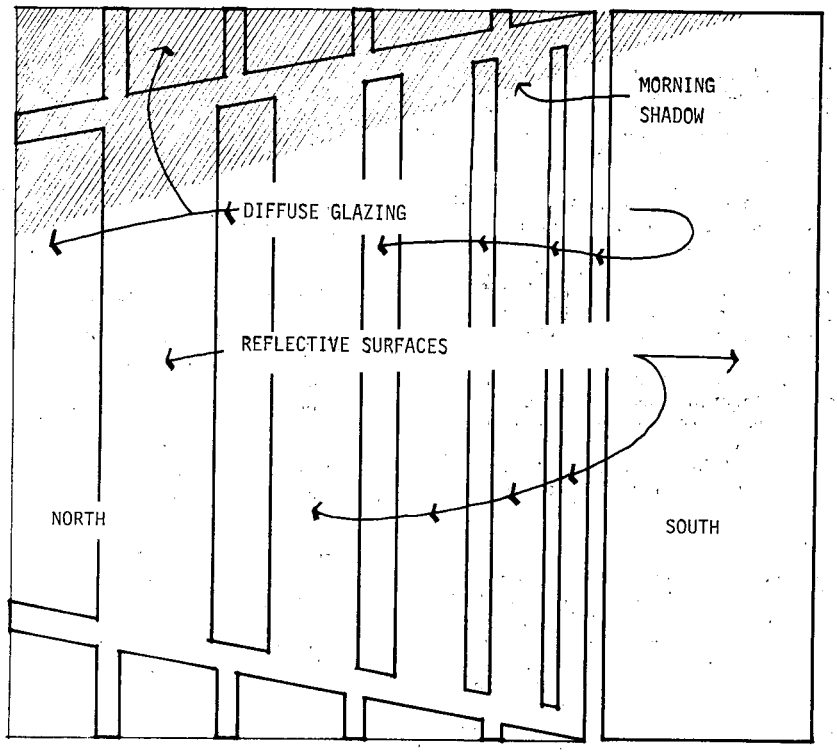



Fig. 3. One of Three Ceiling Patterns, Type A with Diffuse Glazing.

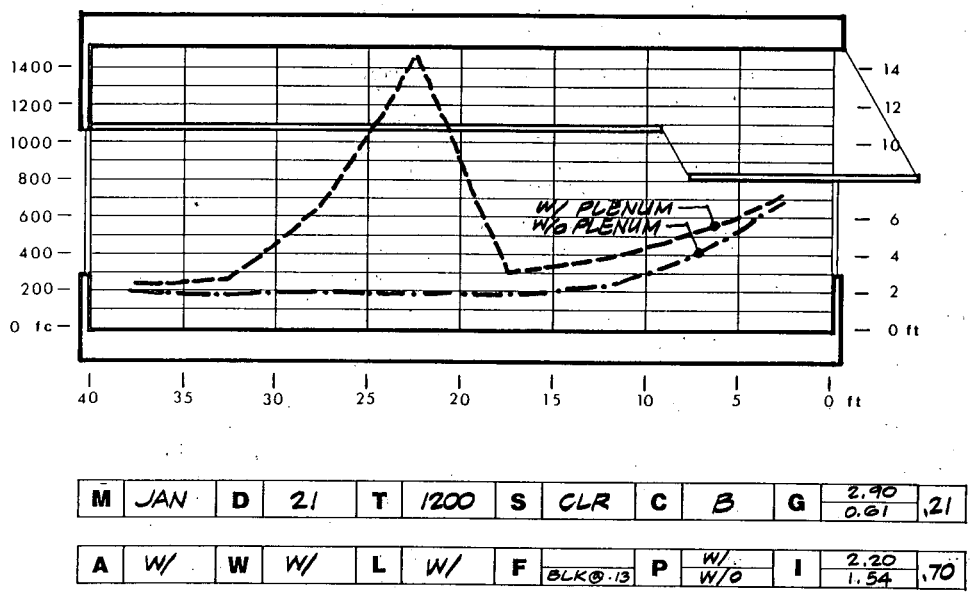
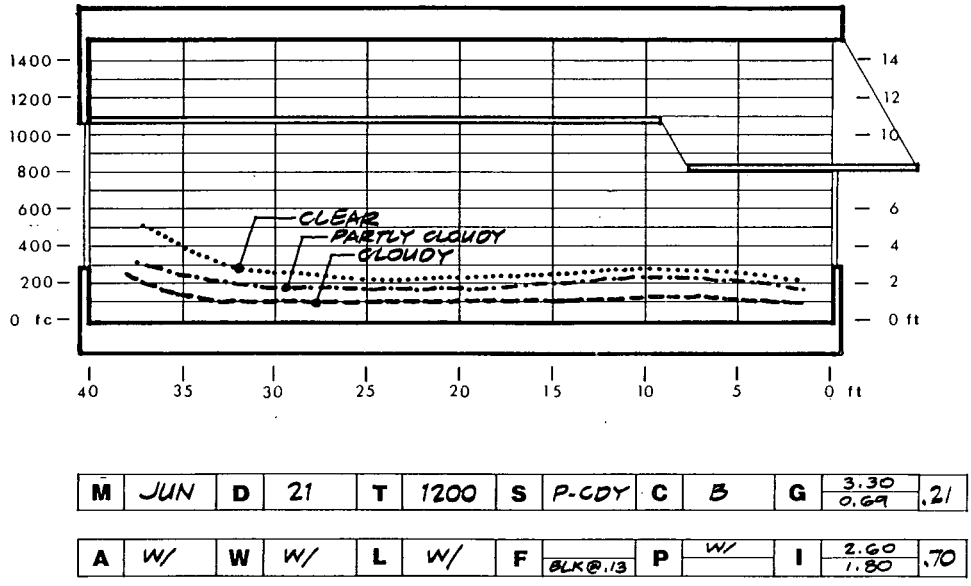
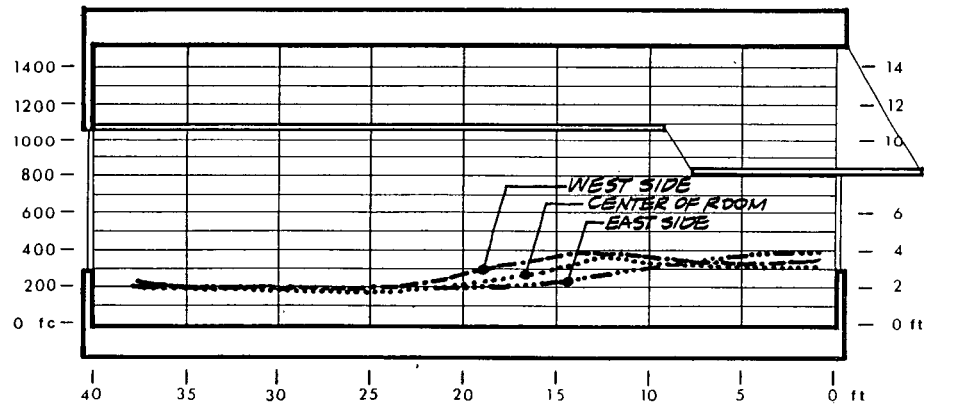



Fig. 4. Type B Ceiling: Winter at 1200 with Clear Skies, Side Windows and Operable Plenum Glazing.




| M | JUN | D | 21 | T | 1200 | S | P-CDY | C | B | G | 3.30 / 0.69 | .21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | W/ | W | W/ | L | W/ | F | BLK@.13 | P | W/ | I | 2.60 / 1.80 | .70 |

Fig. 5. Type B Ceiling: Summer at 1200 with Varied Sky Conditions and Side Windows.




| M | SEP | D | 21 | T | 0900 | S | CLR | C | B | G | 3.30 / 0.69 | .21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | W/ | W | W/ | L | W/ | F | BLK@.13 | P | W/ | I | 2.60 / 1.80 | .70 |

Fig. 6. Type B Ceiling: Autumn at 0900 with Clear Skies and Side Windows.

not exceed 40 feet in width. The testing of the model indicates lighting levels are actually higher than necessary for general office tasks, thus requiring controls. It is assumed that a savings could be realized in the electrical lighting requirements, but saving must be considered along with lighting sensors, integrated lamps, solar and air control and increased cost in higher floor-to-floor levels.

## 5. ACKNOWLEDGMENTS

This study was made possible by a grant from the Washington Water Power Company. The author gratefully acknowledges Leslie Vierra for her design expertise, Greg Lambier for his computations and computer analysis, and Wayne Williams for his delineation and presentation assistance.

## 6. NOMENCLATURE

- A Atrium, north, with or without
- C Ceiling type A, B, or C
- D Day
- F Floor, color and reflectance
- G Sky illumination on the ground/light given off by the ground = reflectance
- I Sky illumination on the shelf/light given off by the shelf = reflectance
- L Louver control at south window, with or without
- M Month
- P Plenum opening at ceiling, with or without
- S Sky condition, clear, partly cloudy, cloudy
- T Time, hours
- W Window, south, with or without

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# DAYLIGHTING IMPACTS OF FENESTRATION CONTROLS

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## ABSTRACT

The California Energy Commission under a legislative mandate established and periodically updates energy efficiency standards for new buildings. Performance standards in Btu/ft$^2$-yr as well as prescriptive standards are being developed.

Daylighting impacts were calculated using Quicklite for typical office characteristics. Although Quicklite as well as manual calculations can be modified for horizontal shading devices (i.e., equivalent room concept), vertical fenestration controls such as fins can not be easily modelled.

To access the daylighting impacts of commonly used fenestration control systems, physical model testing was conducted in the Sky Simulator at Lawrence Berkeley Laboratory. Four common control strategies were selected through recommendations from a Professional Advisory Group (PAG) representing the interests of the A I A , ASHRAE, IES, and other industry groups. These devices include vertical fins with two reflectances ( $\rho$ =.88, $\rho$ =.67), an overhang and a light shelf design with clear glass above and heat absorbing glass below the light shelf.

Each of these strategies were tested parametrically with scaled models. Solar altitudes were set at 30°, 50°, and 70°. Sky conditions also varied including both overcast and clear conditions to cover most of the variables impacting daylight performance.

The result of this parametric analysis is a set of coefficients by which common fenestration controls reduce daylight in a generic office space. These coefficients will aid the designer in selecting the most suitable fenestration control.

## 1. INTRODUCTION

The California Energy Commission (CEC), working under the legislative mandate of the Public Resources Code, Section 25402 and 25612, is developing energy efficiency standards for new nonresidential buildings. The standards are being developed in cooperation with the state's building community and are slated for adoption by the CEC in 1983 and 1984. Expected to go into effect statewide one year thereafter as an upgrade of the current Title 24 energy requirements, the standards will call for the cost-effective use of energy conservation and passive solar energy measures in new commercial and governmental buildings.

Many estimates have placed the potential for saving energy in nonresidential buildings at well over 50% of current levels. Although these energy savings can be realized at a real savings in dollars over the useful lives of most contemporary buildings, several factors have tended to work against the design and construction of highly efficient new buildings. These include a general lack of knowledge about energy saving design techniques and analysis tools, a shortage of time and financial resources during the design and construction phases, and a lack of interest among building designers and owners in the potential for dollar and energy savings.

Technical engineering assumptions[1] and policy directions for development work have been guided primarily by the input of a Professional Advisory Group (PAG). The group consists of 40 members representing interests of organizations such as ASHRAE, AIA, IES, utilities, contractors, manufacturers, and state agencies.

By law, the process must be evidentiary--that is; all decisions must be proven technically, with support evidence acceptable to and documented for a court of law.

Early in the project, lighting was identified as the primary opportunity for energy conservation. In a 3048 $m^2$ (10,000 $ft^2$) base case low-rise office building, modeled with engineering assumptions based on the 1977 California energy standards, lighting and its impact in cooling accounted for 45% of total annual energy consumption. Benefit cost analysis was used to rank a series of available, reliable, and enforceable energy conservation measures. Since it involved a decrease in building capital costs, the reduction of lighting power densities was the single most cost effective energy conservation measure for a lowrise office building. Additionally, daylighting with automatic lighting controls reduced energy use in perimeter zones by 40% and proved to be cost effective.

The methods by which the reduced lighting power levels from daylight could be achieved and the impact of fenestration controls raised several analysis issues. Although the development of computer programs for the prediction of daylight illumination levels in a space is increasing, architects and designers, by necessity, must compromise[2] with respect to most current design tools.

These design tools can be used at various stages of the design process because of the difference in capabilities of the methods. If a general knowledge of illumination levels is needed for uncomplicated spaces, simple computer models such as Quicklite[3] may be sufficient. Quicklite is the program the CEC used for much of the analysis work required during the standards development process as well as DOE 2.1B. Although Quicklite, as well as other manual calculation methods, can be modified for simple overhangs with the equivalent room concept,[4] other fenestration controls can not be easily modelled.

The intent of this paper is to discuss the procedures and results for testing the Quicklite outputs with the results of measured physical models and the daylighting impacts of fenestration controls which were applied to the generic office space.

## 2. EXPERIMENTAL DESIGN

To study the daylighting impacts of commonly used fenestration control systems, a physical model 1 in. = 1 ft was built based on recommendations from the PAG. A 4.57 m (15 ft) by 4.57 m (15 ft) room with a 2.44 m (8 ft) floor to ceiling height was modelled.[5] The window ran the full width of the room (4.57 m 15 ft ) along a single outside wall and had a sill height of 0.76 m (2.5 ft) above the finished floor. The ceiling reflectance was 80%, the walls 50%, the floor and the ground 20%. A section taken through this generic office space is shown in Figure 1.

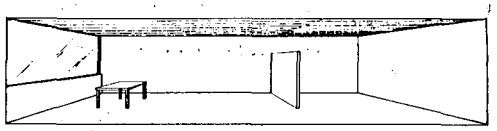


Fig. 1. Generic Office Space.

Nine reference points were modelled parallel to the fenestration area in rows of three. The reference points were always 0.762 m (2.5 ft) above the finished floor.

Three common control strategies were selected based on PAG comments. These devices include fixed 45° vertical fins, with two reflectances ($\rho$=0.88, $\rho$=0.67), and an overhang. Two light shelf designs were also tested with clear glass above and heat-absorbing glass below the light shelf. One utilized a 0.61 m (2 ft) light shelf outside with a 74% reflectance only. The second light shelf extended 0.46 m (1.5 ft) inside the space with a reflectance of 80% and 0.61 m (2 ft) outside the light shelf with a reflectance of 74% and 40%.

A base room was also modelled without any control. These control strategies are shown in Figure 2.

Each of these strategies were tested parametrically in the Sky Simulator[6] under overcast and clear conditions. The solar altitudes were set at 30°, 50°, and 70° to cover most of the conditions impacting daylight performance.

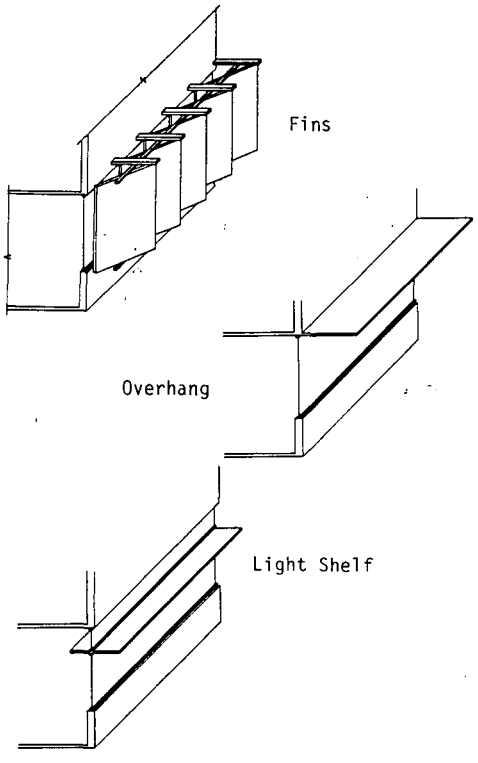



Fig. 2. Fenestration Controls Tested.

## 3. THEORETICAL CONSIDERATIONS

Quicklite will calculate either a footcandle level or daylight factor (D.F.). We will be using the daylight factor which is defined as the ratio between the daylight illumination at a point in an interior space and the simultaneous exterior illumination available on a horizontal surface from an unobstructed sky, excluding direct sunlight. The Daylight Factor is expressed as a percentage. For each reference point of every physical model parametric test, the Daylight Factor was also calculated using a Quicklite.

Scaled physical models have been used by designers for qualitative and quantitative problem-solving. Models can be tested outdoors under real sky conditions or indoors under a controlled simulated sky luminance distribution. For the daylighting parametric analysis it was necessary to compare model measurements for various sky conditions as well as different fenestration systems. Real sky conditions are difficult to reproduce for consistency. The Sky Simulator at Lawrence Berkeley Laboratory has the capability of reproducing the C.I.E. overcast as well as clear sky luminance distributions. These are the same distributions which are used in most computer models and can be used to validate computer codes.[7]

To determine the coefficient of the various fenestration controls, the following equation was implemented:

$$a_1 = b_1/b \times a \qquad [1]$$

where: $a_1$ = coefficient for fenestration control
$a$ = Quicklite calculated Daylight Factor with no fenestration control
$b_1$ = physical scaled model Daylight Factor with a fenestration control
$b$ = physical scaled model Daylight Factor with no fenestration control

## 4. DISCUSSION OF RESULTS

The parametric runs which were calculated by Quicklite were compared with the model measurements from the Sky Simulator. Figures 3-6 show the agreement of the results under the sky conditions tested.

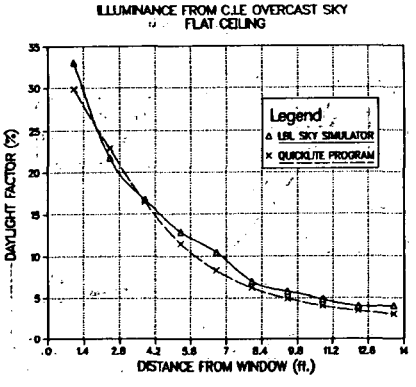



Fig. 3. Illuminance from C.I.E. Overcast Sky.

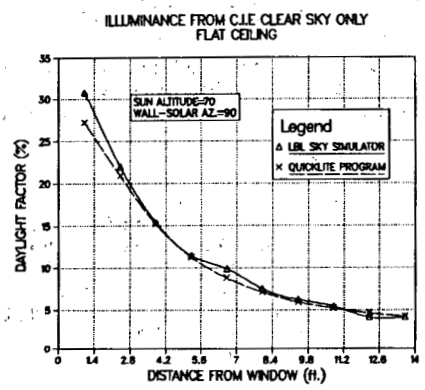



Fig. 4. Illuminance From C.I.E. Clear Sky, Solar Altitude--70°.

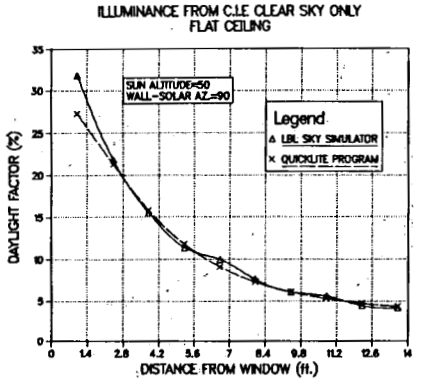



Fig. 5. Illuminance From C.I.E. Clear Sky, Solar Altitude--50°.

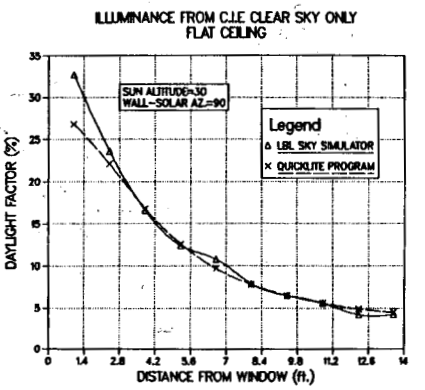



Fig. 6. Illuminance From C.I.E. Clear Sky, Solar Altitude--30°.

Based on the agreement of the results of Quicklite and the Sky Simulator, a set of coefficients were developed by which common fenestration control systems (see Fig. 2) could be designed and the resulting daylight in a generic office space evaluated. These coefficients will aid the designer not only in selecting the fenestration control system, but also allow him to design an interior space more suitable to the occupant. For this purpose, three daylight zones were selected within the generic office space. Zone 1 is 1.52 m (5 ft) from the window; Zone 2 is 3.05 m (10 ft) from the window area; and lastly, Zone 3 is 4.57 m (15 ft) from the window area.

Tables 1, 2, and 3 list the coefficients ($a_1$) for overcast and clear sky conditions for the three zones. Table 1 represents the window area as the percent of glazing area which is shaded and two fin conditions with a reflectance equal to 88% and 67%. Table 1 is for overcast conditions.

Table 2 lists the coefficients ($a_1$) for the 45° vertical fins for three solar altitudes with reflectances of 88% and 67%. These values are for clear sky conditions for either east or west orientations. Table 3 lists the coefficients for the light shelf conditions at 30°, 50°, and 70° solar altitudes. The

light shelf characteristics are described as A, B, and C, which correspond to:

A = 0.61 m (2 ft) exterior light shelf with a surface reflectance of 74%.

B = 0.46 m (1.5 ft) interior light shelf with a surface reflectance of 80%, and a 0.61 m (2 ft) exterior light shelf with a surface reflectance of 74%.

C = 0.46 m (1.5 ft) interior light shelf with a surface reflectance of 80%, and a 0.61 m (2 ft) exterior light shelf with a surface reflectance of 40%.

All light shelf values were determined with a 0.46 m (1.5 ft) light of clear glass above the light shelf and a 1.22 m (4 ft) light of heat absorbing glass below.

TABLE 1. FENESTRATION CONTROL COEFFICIENTS FOR OVERCAST SKIES.

| | Zone 1 | Zone 2 | Zone 3 | 3 Zone Average |
|---|---|---|---|---|
| 100% Shaded Window | 0.658 | 0.706 | 0.750 | 0.705* |
| Vertical Fin Reflectance=88% | 0.503 | 0.534 | 0.525 | 0.521 |
| Vertical Fin Reflectance=67% | 0.410 | 0.431 | 0.425 | 0.422 |

* A 100% shaded window under overcast conditions will reduce the D.F. about 30%.

TABLE 2. FENESTRATION CONTROL COEFFICIENTS FOR VERTICAL FINS; CLEAR SKY CONDITIONS--EAST OR WEST ORIENTATION.

| Solar Alt. | Fin Reflect. | Zone 1 | Zone 2 | Zone 3 | 3 Zone Average |
|---|---|---|---|---|---|
| 30 | 0.88 | 0.565 | 0.555 | 0.575 | 0.565 |
| 30 | 0.67 | 0.496 | 0.476 | 0.475 | 0.482 |
| 50 | 0.88 | 0.491 | 0.442 | 0.418 | 0.450 |
| 50 | 0.67 | 0.429 | 0.377 | 0.348 | 0.385 |
| 70 | 0.88 | 0.536 | 0.482 | 0.487 | 0.502 |
| 70 | 0.67 | 0.490 | 0.430 | 0.414 | 0.445 |

TABLE 3. FENESTRATION CONTROL COEFFICIENTS FOR LIGHT SHELVES; CLEAR SKY CONDITION.

| Solar Alt. | Light Shelf Type | Zone 1 | Zone 2 | Zone 3 | 3 Zone Average |
|---|---|---|---|---|---|
| 30 | A | 0.532 | 0.538 | 0.571 | 0.547 |
| 50 | A | 0.508 | 0.559 | 0.571 | 0.546 |
| 70 | A | 0.486 | 0.500 | 0.536 | 0.507 |
| 30 | B | 0.475 | 0.507 | 0.547 | 0.510 |
| 50 | B | 0.517 | 0.559 | 0.571 | 0.549 |
| 70 | B | 0.504 | 0.532 | 0.560 | 0.532 |
| 30 | C | 0.435 | 0.492 | 0.523 | 0.483 |
| 50 | C | 0.491 | 0.542 | 0.547 | 0.527 |
| 70 | C | 0.495 | 0.532 | 0.560 | 0.529 |

In order to determine the interior illumination levels and the impact of fenestration controls, the following formula would be used:

$$DL = A.I. \times D.F. \times C.F.C. \qquad [2]$$

where: D.L. = Daylight Level (foot-candles or lux)
A.I. = Available Illumination
D.F. = Daylight Factor
C.F. = Coefficient for fenestration control

The results of this study show the impact of the various fenestration controls are generally uniform across the space (perpendicular to the window). There exists some discrepancies at lower solar altitudes where deeper penetration occurs as one would expect. There also is more inter-reflection with the fenestration control surfaces and in some cases with the back wall. Since the values were close for the three zones, an average value was calculated and is listed in the last column of the tables.

The fin application did not have an even distribution across the space parallel to the window as one would expect. For the overhang and light shelf designs, we found about a 10% variation in illumination parallel to the window from the center of the room to the side wall.

To summarize the results for the generic office space considered, the following "rules of thumb" about daylighting impacts of fenestration controls may be deduced:

- Under overcast conditions, an overhang calculated to fully shade the generic window will reduce the Daylight Factor about 30%.

- Under overcast conditions, 45° vertical fins reduce the Daylight Factor 48%-58% depending on the fins reflectance.

- Under clear conditions, 45° vertical fins reduce the Daylight Factor about 53% depending on the fins reflectance and solar altitude.

- Under clear conditions, the light shelf will reduce the Daylight Factor about 47%.

Further research is being conducted to test additional shading coefficients of utilization for various fenestration controls and solar altitudes.

## 4. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support from: Stephen Selkowitz, John Schade, Bill Pennington, Mickey Horn, and Nader Sharabionlou.

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# THE NEGLECTED HALF OF COMMERCIAL DAYLIGHTING DESIGN REPORTING: SELECTING THE CONTROLS, FIXTURES, BULBS, AND BALLASTS

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## ABSTRACT

An overview is provided of those features of electric lighting controls, lighting fixtures, bulbs and ballasts that are of practical relavance to the daylighting designer. Particular emphasis is placed on daylight controlled dimming, and on the frequent practical necessity for limiting the amount of dimming to 50% or less in the interest of economy and of permitting the utilization of a wider spectrum of available illumination schemes and hardware. Advantages of the use of dimmers independent of the complementing of daylighting are stressed. The effectiveness of air-return ceiling-mounted luminaires on lighting fixture heat collection and on bulb luminosity is presented. The status of fluorescent bulb and ballast technology is briefly reviewed, and the matching of bulbs to ballasts and to dimmers is discussed. The importance of a working knowledge of these practical concepts by the designer is emphasized.

## 1. INTRODUCTION

A great deal of excellent work has been reported in the theory and practice of designing for daylighting in commercial buildings (1). Complicated analysis approaches are being simplified to cookbook or nomograph form for easier use by the design professional, and are being made available in software for the microcomputer user. Yet there continues to be relatively little discussion in the same literature regarding the practical realities of designing compatible ancillary electric lighting systems.

The space limitation of this particular report requires that I narrow the scope of this topic considerably, and just offer some practical observations and guidelines for early consideration by the daylighting designer. I focus on some specific considerations pertinent to the selection of the lighting controls, lighting fixtures, bulbs and ballasts. I stress controls and luminaires, but I also touch on bulb and ballast selection in its relevance to other system parameters.

At the minimum I should like to point out the importance of careful selection of the lighting and electrical components, based upon specific integrated design goals, as opposed either to the frequent procedure of simply leaving this as a chore for the illumination engineer or electrical contractor, or to the placing of too much emphasis on just the daylighting aspect of the completed design.

## 2. LIGHTING SYSTEM DESIGN

The design of an electric lighting system for a daylit commercial building can be pursued as an eight-step process:

a. Decide upon the electric lighting system philosophy (Direct? Indirect? High-level ambient? Low-level ambient plus task? Energy-saving? How important is color rendition?);

b. Decide upon the target lighting levels;

c. Identify a lighting control philosophy appropriate to the daylight performance of the building and select controls that meet both operational and cost objectives;

d. Lay out a lighting plan appropriate to the design philosophy and to the desired lighting levels;

e. Select the lighting fixtures appropriate to the lighting philosophy, layout, targeted illumination levels, and integrated thermal and electric design criteria;

f. Select bulbs by desired color, appropriate intensity (lumens), energy consumption (if relevant), and compatibility with the fixtures and controls;

g. Select ballasts appropriate to the selected bulbs and lighting controls;

h. Calculate results to verify targeted illumination levels. Whereas simple estimates (e.g., by the zonal cavity method) are neces-

sary to proceed with steps d, e and f above, a computer mapping of the actual illumination distribution is really necessary at this stage. (Luminaire manufacturers and their representatives readily offer this computer service for direct lighting, if in-house computer capability is not available.)

The actual design process is not quite so sequentially tidy as this list would suggest, for it often requires a fair amount of back-and-forth iteration before a best compromise to all desired parameters is achieved.

## 3. SOME CONSIDERATIONS OF LIGHTING SYSTEM COMPONENT SELECTION

### 3.1 Controls

It is generally agreed that no amount of provision for convenient manual switching, even for 50% light reduction, will result in useful energy savings. For this to be accomplished, the operations must be automatic.

The role of daylighting in determining the type of automatic control to be selected is discussed in a very useful article by Sain (2). Two of the illustrations from that Reference are reproduced here, as this paper's Figs. 1 and 2.

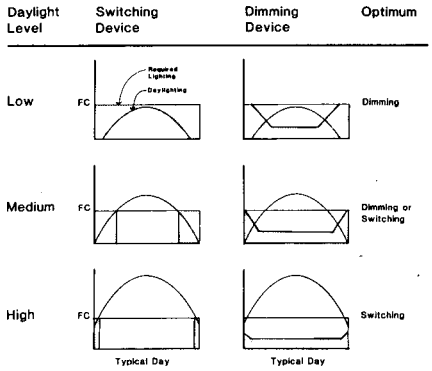



Fig. 1. Appropriate controls for various daylighting levels (2).

In particular, Fig. 1 demonstrates that the available daylight level during a "typical day" can determine whether one should utilize switching, or dimming, controls. Fig. 2 reveals more descriptively how the different types of controls operate, and qualitatively what the combined daylight + electric lighting results will yield during the course of a day. But many other factors must also be considered by the designer in selecting the automatic lighting controls. For example, the unavoidable illumination discontinuities from switching lights off when available daylighting achieves working levels can be annoying to the users of those lights, leading to momentary perceptions of insufficient lighting by the rather slow adjustment of the eye to lower light levels (as opposed to the more rapid eye adjustment to increasing light levels). Furthermore, Lam notes that "...the addition of some artificial illumination is usually desirable anyway to counteract the gloomy daylight color quality." (3)

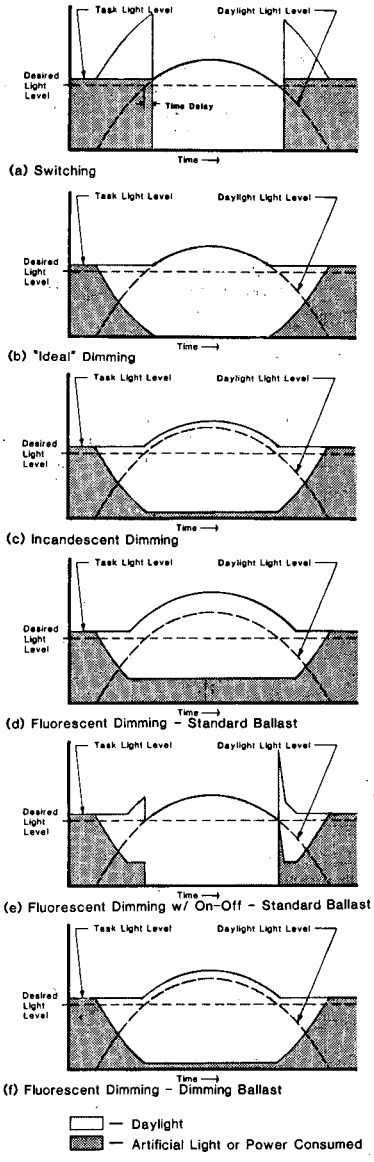



Fig. 2. Operation and illumination results of various control device strategies (2).

The physics of the lights themselves, the actual use schedule of the building and of the individual work spaces, and even the utility pricing policy, should also be determinants the selection of automatic controls, all in

addition to the requirements imposed by daylighting.

For example, fluorescent bulbs "age" significantly during their lifetimes, with a corresponding reduction in bulb lumens by 20% to 35% out near the end of the typical 20,000 hour life of the bulb. To compensate for this, the lighting designer utilizes "maintenance" values for average bulb + luminaire output in the design calculations, forcing the well-known and energy-wasteful overlighting condition of newly installed or relamped lighting systems. A continuous dimming system operating in a "closed loop" mode (with the photocell viewing the interior environment of combined daylight and electric light) can be set initially to provide an illumination level either equal to the "maintained" level or, better, to the even lower later aged value of the bulbs, in order to maintain both constant and adequate lighting levels at all times.

The disadvantage of this from the perspective of daylight-induced energy savings is that the daylight-caused dimming will be relatively less early on in the bulb lifetime for the less expensive dimming systems with fixed lower dimming thresholds of about 50% of full output. As the bulbs "age", the dimmers will cause the system to use more energy in order to maintain the selected lumen output under conditions of no daylight, but then will reduce in proportionately greater amounts in response to daylight. While this introduces a difficulty in energy-savings calculations, the practical energy-saving benefits of this additional function ("lumen maintenance") of a dimming control are extremely important for both designer and user.

Yet another nondaylight-induced advantage of dimming capability is that a partially dimmed (e.g., 50%) level can be selected with the aid of an inexpensive timer as a night "setback" level to reduce energy costs during cleaning or security periods. Of course, this can also be accomplished with programmed switching control of 50% of the luminaires, or of 50% of the bulbs within the luminaires (at least with 4-bulb fixtures). On the other hand, such programming of a dimming control by a central building energy management system can also permit the shedding of lighting loads by dimming to limit demand to below some critical utility billing point during periods of system peak load demand. This can have important economic consequences in those areas where peak-demand pricing, or time-of-day pricing, are important elements in utility billing structures, and is certainly more acceptable to users than a forced reduction in lighting load by switching.

Of potentially great energy significance is the combination of continuous dimming plus ultrasonic "occupancy sensor" switching (the lights are switched off by a motion sensor whenever the office is not occupied, and automatically switched back on when the occupant returns). People don't stay in their offices, and yet they don't turn lights off when they expect to return momentarily. Additional electric energy savings of the order of 45% have been demonstrated in private offices in major commercial buildings from automatic occupancy sensor switching (4).

Costs of commercially available dimming systems vary widely, with two such units, both of which utilize the attractive time-modulation approach to the dimming of fluorescent bulbs with standard ballasts, differing by a factor of three in cost, yet apparently (to this writer, at least) featuring equal performance and reliability. And cost differences of up to 600% exist between full dimming systems using electronic dimming ballasts, which can safely take standard bulbs down to 10% or less lumen output, and partial dimming systems which operate through standard ballasts, and which can safely take standard bulbs down to about 50% lumen output.

The cost-effectiveness of the expensive full dimming system can well be difficult to justify purely on energy-saving grounds, whereas the cost-effectiveness of the reasonably inexpensive 50% dimming, standard ballast system is always indisputable, yielding paybacks typically 1½ to 3 years, without the benefit of tax credits, and based purely on the savings of lighting energy, to less than 1 year with additional allowances for savings of building cooling energy. (Particularly noteworthy in the low cost category is the system offered by Enertron of Baltimore, Maryland.)

An important criterion for the cost-effective selection of the dimming control is the effectiveness of the daylighting. Computer studies examining reasonably "conventional" office buildings (for example, with heat reflecting glass and no overhangs, and up to 50% drape coverage) demonstrate that about 50% dimming is both a reasonable maximum expectation, as well as a value that is attained for a major part of the day in the perimeter zones in all building directional quadrants (4), suggesting a major energy conservation market for the less expensive dimming approach with standard ballasts.

The bulb manufacturers do not make this easy for the dimming system specifiers, for they will not warrantee any bulbs under conditions of dimming. The argument is advanced by them that the responsibility lies with the manufacturer of the dimming equipment. Presumably, if the dimmer manufacturers have fully tested the dimmer + bulb system, then that system may be used, but still only with the dimmer fabricator providing warranty assurance. This is causing cautious endorsement by the dimmer manufacturers, usually based on full-life (20,000 bulb burn-hour) testing. And it is

still causing some difficulties in the field, for laboratory testing, under controlled environmental conditions, does not duplicate actual conditions of use, e.g., with return-air luminaires (see Section 3.2 of this paper) or under drafty conditions that can affect bulb stability.

It is both the author's opinion and experience that the lighting designer can safely utilize off-the-shelf full dimming systems with electronic dimming ballasts and standard F40 fluorescent bulbs up to nearly 100% dimming, and also safely use off-the-shelf dimming systems with either standard or energy-saving ballasts and 40-watt F40 bulbs up to 50% dimming, or the 34 to 35 watt bulbs with matched ballasts to 30% to 35% dimming. The end energy result of either of the latter two cases is nearly the same. (The dimming range with standard ballasts is extended down to perhaps as low as 20% lumen output with slimline bulbs, which do not have cathode filaments.)

To go beyond this to "extended range" dimmers with energy-saving bulb/ballast combinations is to move out of the realm of security at this time. Nevertheless the field is moving fast, and these stipulations will probably soon prove to have been overly cautious. Cost-effective dimming as an important lighting design tool is here to stay.

### 3.2 Luminaires

The common lighting contractor or electrical engineer "rules of thumb" for the relationship between artificial illumination and energy-use is that 4 watts per square foot will yield 100 footcandles at work height, 3 watts per square foot will yield 75 footcandles, and 2 watts per square foot will yield 50 footcandles. These rules persist, even though today's highly efficient luminaires, bulbs and ballasts permit these values to be halved. Indeed, it is now common to achieve better than 50 footcandles at task height in commercial offices at 1 watt per square foot with direct lighting from ceiling-mounted luminaires, or 30 footcandles at one watt per square foot with indirect fluorescent ambient lighting, and a fraction of a watt for supplementary task lighting. The remainder of this particular brief discussion will focus on ceiling-mounted "louvred troffer" luminaires.

The key to luminaire efficiency is to have a design that both permits the light to escape from the luminaire itself (the "efficiency") and to be evenly distributed below. In addition, an important criterion for the design of energy-efficient lighting systems is to allow the eye to relax, so as not to have to compensate for glare or brightness contrasts, such as with our commonplace office ceiling full of brightly glowing plastic light lenses. Accordingly, when viewed from a shallow angle (that is, from some distance to the side), the light should appear to be cut off, so that the ceiling is visually "quiet". (The official way of describing this is to speak of a high "Visual Comfort Probability", or VCP.)

These attractive characteristics are all accomplished to varying degrees by the metal "parabolic" lenses and plastic parabolic curved "cube louvre" lenses. The former are the most energy-efficient, with luminaire efficiencies that can exceed 70%, while the latter suffer a comparative loss in efficiency of 30% or more when compared to the parabolics (depending on cube dimension--the larger the cube, the higher the efficiency). But the cube louvres also feature a sharper angular cutoff, ($45^{\circ}$, as opposed to $60^{\circ}$ for the parabolics), and hence a higher value for the VCP.

Keene Lighting has developed a metal parabolic louvre with smaller cells, to provide some of the VCP advantage of the cubed louvre at the higher efficiency of the metal parabolics, utilizing brushed aluminum rather than specular surfaces, to reduce glare and enhance diffusion. This is offered in both 60-cell and 78-cell versions for 2 x 4ft air handling troffers. While the number of bulbs in the fixture strongly influences the efficiency in a parabolic, the 60-cube is in general more efficient than the 78-cube. In this author's opinion, they are both more attractive than the deep-cell parabolics.

Cube-louvred lighting truly appears "dark" and avoids the row of bright reflections in desk-mounted video screens. The metal parabolics show a nonglaring "glow" at each fixture location, yielding more visual consistency to the ceiling. Both types of fixtures unfortunately are very bright when viewed from within the illumination fields. The cube-louvred lights appear to leap out of the dark ceiling as one passes below.

Especially pertinent to this paper is the unsymmetrical distribution of light from both cube-louvred and parabolic-louvred luminaires with reference to the long axis of the fixture. The light is cast farther to the sides (perpendicular to the fixture axis). The placement of desks perpendicular to both cube- and parabolic-louvred lights will provide more intense and more even lighting distribution across the work area, while at the same time causing the desk user to be at a viewing angle parallel to the fixture axis, and hence subject to less visual glare. Since daylighting requires that the desks be oriented perpendicular to the windows, this uniquely prescribes that the cube- and parabolic-louvred lights are to be oriented with their long axes parallel to the window wall.

Since the reduction of thermal loads in a building is a major objective of daylighting designs, it is very important to be able to remove lighting fixture heat and either rein-

troduce it more efficiently into the building in winter, or reject it in summer. Toward this end, the parabolic- and cube-louvred luminaires are advantageous to use, as they are simply open, allowing return air to be drawn easily up though the troffer, carrying with it a significant amount of light and ballast heat into a negative pressure plenum or return air duct. But end-ducted troffers for air-return with plastic lenses are now also commonplace.

Fig. 3 provides heat transfer measurements on three-lamp and four-lamp 2 x 4 ft luminaires by Keene (top two graphs, related to the shown section view of the luminaire), as well as on a two-lamp 1 x 4 ft luminaire, also by Keene (section drawing not shown) (5). "Balancing" the return air through the luminaire can clearly be a very important part of the integrated thermal and electric design of a building.

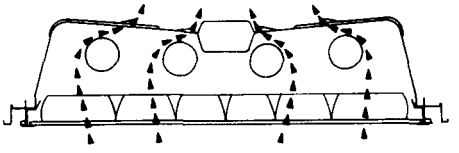
The important influence of return air extracted through the luminaire on relative light output of the bulbs, as shown in the top graph of Fig. 3, is also apparent. Equally important is a similar improvement in performance, as well as on lifetime, of the ballast, when cooled by the return air.

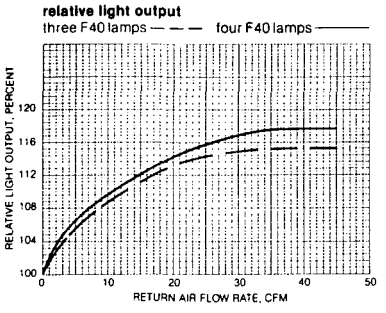
### 3.3 Bulbs and Ballasts

To complete the daylight-supporting (or complementing) electric light system one wants bulbs with high lumen output at low input energy, accurate color rendition across the spectrum (it is the user's choice if it is to have a "cold", "warm", or "daylight-like" quality), with long lifetimes, and with dimming capability. In support of these one wants ballasts with low losses (near unity ballast factors), closely matched to the bulbs. To date, this full set of simultaneous requirements has not been attained, but the recent improvements in bulbs and ballasts has been dramatic. A brief sketch of this trend is offered in the following.

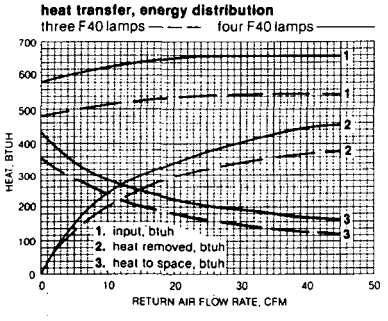
The useful efficiency of a bulb is in its lumens/Watt (l/W) output rating. This has been in the range of up to 80 with standard cool white or warm white fluorescent bulbs, but suffered considerably from attempts to develop "full spectrum" (1/W of 55) or "daylight" (1/W of 65) bulbs. The 2nd-generation Supersaver (or Wattmiser) bulbs increased this to about 85 l/W, and 3rd-generation lite-White bulbs (General Electric, Sylvania, Westinghouse, Norelco) has taken this figure to over 90 l/W, but with fairly limited color balance.

Attempts to improve the color rendition of fluorescent bulbs has led to the "Deluxe" series, where the red end of the spectrum is enhanced, but the inefficiency of both eye and phosphor at that end usually causes a disproportionate loss in bulb energy efficiency. This has been overcome with the introduction of new fluorescent bulbs with rare earth phosphors and a very high "Color Rendering Index", producing an extremely pleasing reflected color quality (e.g.,the Sylvania Royal White--this author's favorite), but very expensive.






All performance data on the 2' x 4' luminaire is based on a maintained room temperature of 75°F. Air performance tests were conducted in accordance with Air Diffusion Council (ADC) air diffusing trolfer heat removal test code TC-66.



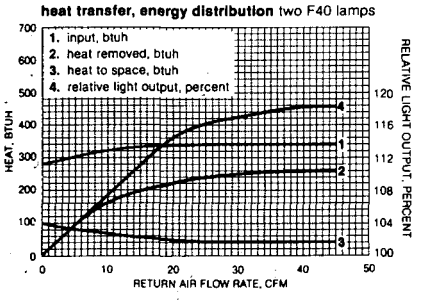




Fig. 3. Heat transfer and relative light output in two return-air luminaires with three bulb configurations (5).

What we might term the "4th-generation" in fluorescent bulbs is the new "Octic" series of 1 in (rather than the customary 1½ in) diameter bulbs with high (better than 90) lumens/watt values and really excellent color rendition (e.g., Sylvania "Octron", Westinghouse "Octolume", and others). The costs are also very competitive with the earlier energy-efficient bulbs.

Where the conflict arises--and hence the pertinence to this particular paper--is in the unfortunate tendency of the more energy-efficient bulbs to be much more sensitive. They are designed to operate at full light output, and they are much more temperature sensitive. The important temperature sensitivity of fluorescent bulbs can be utilized to the designer's advantage by keeping them cooler than their rated parameters (see Fig. 3, top graph) with return-air luminaires, thereby realizing an important gain in footcandles for a given energy input, but if the bulb flickers or blows out this ceases to be an advantage(!). This is a partial explanation of why the bulb manufacturers will not rate the energy-efficient bulbs for dimming. The possibility of cathode degradation (coating) at lower cathode voltages is another aspect of their concern. (This has been observed in deep dimming of energy-saving fluorescent bulbs.)

I indicated earlier that experience seems to be proving that up to 35% dimming is permissible with the 2nd generation, and possibly 3rd generation, of energy-efficient bulbs, but the fine new Octic bulbs should, unfortunately, not be dimmed at all. I'm not even certain that they should be used in return-air luminaires with high cooling air flow rates. Of course, if one expects a lighting system to be dimmed down to nearly off most of the daylit time, then the initial energy rating of the bulb/ballast combination is of little significance. Standard bulbs with electronic dimming ballasts may be used for this purpose.

There is little opportunity left in this paper to remark on ballasts, other than to note that ballasts are being produced (by Advance, Universal, General Electric, and others) with considerably greater energy efficiency than the old "add 20% for the ballast wattage" rule-of-thumb, and ballasts have also been produced to match each generation of bulbs as it appeared. The evidence points to the "safest" suggestion that bulb and ballast should be well matched: standard bulb with standard ballast, and energy-saving bulb with energy-saving ballast. Both ballast and bulb manufacturers tend to argue against this conservatism with present-day units, and approve the mixing of types in both new and "relamping" circumstances (excluding the 1in.Octic bulbs, which must be used with low-current ballasts). I do not feel that the evidence yet supports this freedom, and suggest continuing caution by the designer, especially in relamping. The safest "mixing" at this point would be to use standard bulbs with energy-saving ballasts, but the reverse can cause ballast temperature elevation that can negate the savings of the lower-wattage bulbs after a year or two of operation.

## 4. CONCLUSION

The diversity of electronic dimmers, lighting fixtures, bulbs and ballasts now available, and their continuing improvement, offers a fine opportunity for the daylighting designer to deliver a "complete" energy-efficient product to the client. But the integration of daylight with the electric and thermal operation of the building requires that all components work harmoniously, toward the unified goals of reliable, energy-efficient performance, with an enhancement of environmental quality for the building user. The daylighting designer must expect to stay current with the practical realities of the ancillary equipment that must be specified.

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# THE IMPACT OF FENESTRATION ON ENERGY USE AND PEAK LOADS IN DAYLIGHTED COMMERCIAL BUILDINGS

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## ABSTRACT

Effective utilization of daylight is one of several design strategies that promise to provide substantial energy savings for commercial buildings. Despite the revived interest in the field, there are very few occupied buildings for which performance data verify the magnitude and cause of real savings. In order to optimize costs it is first necessary to understand building performance in sufficient detail to assess the contradictory component impacts. This can be done most effectively using an hour-by-hour energy analysis model, in this case DOE-2.1B

This paper reports conclusions of an extensive series of computer analyses in two climates to determine the energy use and demand impacts of fenestration in commercial buildings. Particular attention is paid to the tradeoffs involved in using fenestration to daylight perimeter zones. The study includes the effects of climate, orientation, window area, U-value, shading coefficient, visible transmittance, lighting power density, and lighting control strategy.

## INTRODUCTION

In commercial buildings, fenestration design is a major determinant of energy requirements for space conditioning. Using daylight effectively will greatly reduce electric lighting requirements and associated thermal loads. Fenestration's influence on total energy performance involves a complex interaction among the fenestration's thermal and optical characteristics and other building parameters within the context of climate and orientation.

When efficient energy utilization first became a national concern, it was suggested that reducing fenestration was the appropriate response to reducing energy use. This simplistic response is frequently incorrect, but definitive performance data that include potential daylighting benefits are not available to guide architectural solutions.

Defining these benefits has been a slow process for several reasons. First, the problem is inherently complex and is linked to many aspects of commercial building performance. Second, until recently the large computer models used for energy analysis were unable to model daylighting effects accurately. There is little or no operating experience; nor are there measured performance data, on fenestration's net thermal performance, and even less information on daylighting effects. In order to understand fully the energy conservation and economic benefits of daylighting, it is necessary to consider energy consumption, thermal performance, and peak electrical demand.

Detailed data on peak electrical demands are necessary to completely analyze the cost benefits of daylight-responsive electric lighting systems and to accurately determine total electrical costs. Reducing both consumption charges and demand should provide substantial operating savings.

The studies discussed here focus on improving the understanding of the relationship between fenestration parameters and 1) electric lighting reductions due to daylighting, 2) thermal loads both with and without daylighting, and 3) the impact of daylighting strategies on building electrical demand. This will help us develop the functional interrelationships from which future cost/benefit studies can be made. This paper summarizes results of several recent studies that have examined portions of the problem in greater detail (1,2,3).

## METHODOLOGY

In order to study the effects of fenestration on building energy performance, a representative five-zone commercial office module was designed. This module consists of four identical perimeter zones, each 4.8 m (15 ft) deep, surrounding a square common core zone. The ceiling and floor were modeled as adiabatic surfaces. The overall envelope thermal conductance was held constant in order to

isolate solar gain and daylighting effects. Thus when glazing area or glazing U-value was changed, the wall U-value was adjusted to maintain a constant overall envelope conductance. After basic performance patterns were established, the overall conductance was varied over a representative range. Fenestration characteristics were varied by changing number of panes of glazing, glazing area, visible transmittance, shading coefficient, and exterior shading. As base-case conditions, we assumed that occupant requirements for thermal and visual comfort result in the use of drapes or shades for any hour in which transmitted direct solar radiation exceeds 63 $W/m^2$ (20 Btu/hr $ft^2$), or any hour in which window luminance produces a glare index greater than 20. The interior shading device reduces solar heat gain by 40% and visible transmittance by 65%.

Electric lighting power density was varied from 13 to 34 $W/m^2$ (1.2 to 3.2 $W/ft^2$) based on a design illuminance of 538 lux (50 fc). We examined the effects of stepped switching and continuous dimming in response to daylight. A continuous dimming system dims from 100% light output with 100% power to 0% light output with 10% residual power.

The DOE-2.1B building energy analysis program used as the modeling tool incorporates a daylighting model that calculates hourly interior daylight illuminance for each zone of a building based on architectural design and hourly weather data (4,5). The primary analysis was completed for five climates that range from cooling-dominated (Lake Charles, Louisiana) to heating-dominated (Madison, Wisconsin). Total plant energy consumption was calculated for the entire five-zone module; however, in order to examine the effects of orientation, we studied zone-by-zone requirements based on zone-level coil loads. The interactions among various HVAC systems and building envelope characteristics can be important, but were not a primary issue in this study.

## RESULTS

### Energy Usage

The numerous parametric runs we completed provide a data base that demonstrates the complexity of daylighting energy analysis relative to our primary concerns--climate, orientation, and fenestration--along with other physical and operational building parameters. To simplify interpretation of results, we define a new term, effective aperture, which is the product of the ratio of glass area to floor-to-ceiling wall area times visible transmittance (or, when appropriate, shading coefficient).

The dimming system is continuously responsive to variations in daylight level and maximizes the benefit from low daylight levels. The simple stepped system reduces electric lighting power only when daylight exceeds the design criteria and provides all required lighting; at zero electric light output there is zero power consumption. Thus the step-switching system is most effective at high interior daylight levels, where it outperforms the continuous dimming system with low-level losses; step switching is least effective in situations in which low daylight levels provide only a fraction of desired illuminance.

The principal effect of daylighting is to reduce electric lighting usage. As the effective aperture increases, electrical consumption for lighting first drops off sharply then levels off in all climates. For a given effective aperture, the fractional savings depend on the design illuminance level lighting power density and the lighting control strategy. Figure 1 illustrates the change in fractional lighting energy savings as a function of effective aperture for three design illuminance values with a stepped system. For small aperture areas the savings are not linear with respect to design illuminance level. For larger aperture areas the shape of the curves indicates that daylighting becomes saturated and further savings not possible.

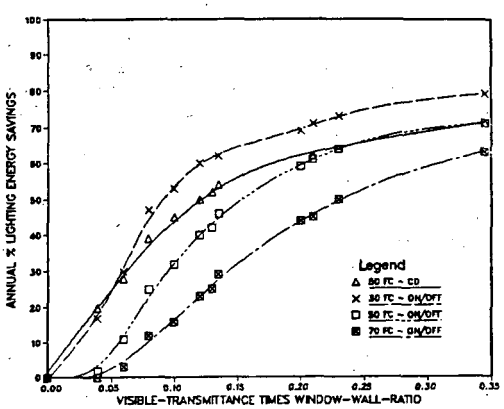



Fig. 1. Lighting energy savings as a function of effective aperture. Madison: 1.7 $W/ft^2$.

The choice of lighting control strategy has several consequences. Figure 2 illustrates lighting energy consumption in Madison with a dimming control and a stepped control both set to 538 lux (50 fc). For small apertures, the dimming control always outperforms the stepped system because for many hours the available daylight is below the control set-point, allowing partial savings with the dimming system but none with the switched control. As the aperture increases, the difference between the two is reduced. Eventually

the switched system outperforms the dimming system because of the dimming system's low-end operating characteristics. This pattern appears in all climates and orientations.

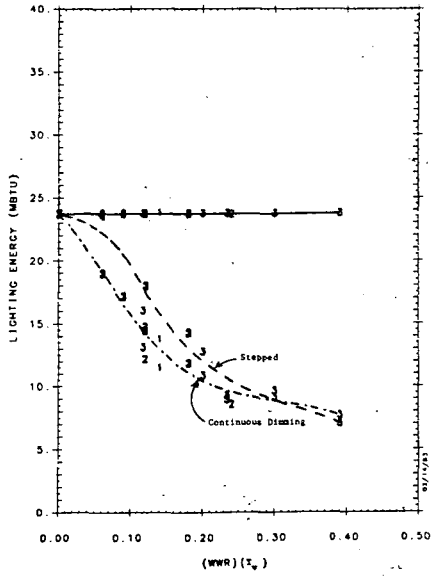



Fig. 2. Lighting energy use as a function of effective aperture. Madison: 1.7 W/ft$^2$.

Total electric lighting energy savings can be substantial. Approximately 50 to 80% of electric lighting in the perimeter can readily be saved. Note, however, that the savings saturate at moderate effective apertures of 0.2 to 0.3. This suggests that for a 538-lux (50-fc) setpoint, a 50% glazed wall with 50% transmittance or a 30% glazed wall with 80% transmittance will provide most of the possible daylighting savings in a typical perimeter zone. Walls that are fully glazed from a 0.8 m- (30 in.-) high sill to ceiling have 71% glazing and would provide most of the potential savings with a transmittance as low as 30%. These moderately-transmitting products may also reduce discomfort from glare. However, the highly reflective architectural glasses in common use, which have 8 to 14% daylight transmittance, provide substantially lower daylighting savings. These glazings emphasize sun and glare control at the expense of daylight transmittance. Note that if the design illuminance level was lowered to 323 lux (30 fc), a level that might be used for ambient lighting only, savings in all the above cases would increase, notably with the very low-transmittance glazings.

During winter months, the balance point of a zone shifts when the electric lighting is reduced and additional heating energy is consumed. The magnitude of the heating load increase depends on orientation. The worst case occurs in a north zone, which can show a 25% increase for large effective apertures. However, for the south zones the increase can be much smaller, about 5%. This is because the solar gain that was useless when the electric lights were on is now available to offset part of the increased heating load. In the summer, reduced electric lighting diminishes cooling loads. An overall picture of total zone energy consumption as a function of orientation, glazing parameters, and lighting load is shown in Fig. 3, which presents total energy results for a south zone in Madison for two different lighting loads: 12.9 and 23.7 W/m$^2$ (1.2 and 2.2 W/ft$^2$). The solid curves (for the nondaylighted cases) rise monotonically for all effective apertures. We show curves for the two daylighted cases, one for continuous dimming, and one for step switching. The continuous dimming system outperforms step switching for small effective apertures, but the curves cross and change relative positions for larger apertures.

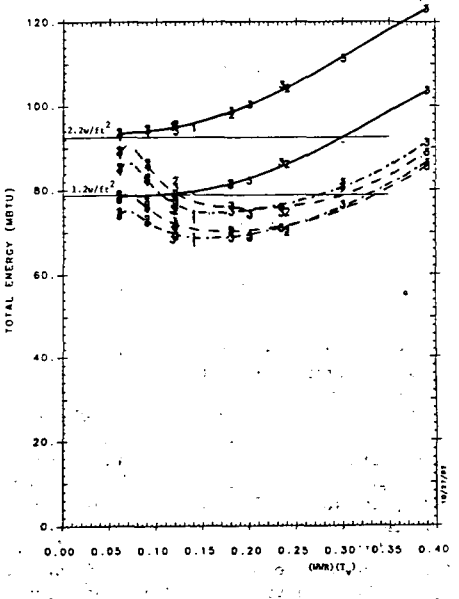



Fig. 3. Annual energy requirement as a function of effective aperture. Madison: south zone.

For this south orientation an optimum effective aperture is reached, after which total energy consumption increases, dominated by the rising cooling load. In this case there is a more obvious tradeoff between cooling and daylighting, and the optimum solution is more sensitive to installed lighting power. For 23.7 W/m$^2$ (2.2 W/ft$^2$) installed lighting load, the optimum effective aperture ranges between approximately 0.12 and 0.22. However, even at the largest value studied

(approximately 0.4), the consumption with daylighting just equals that of an opaque insulated wall. If we drop to an installed lighting load of 12.9 W/m$^2$ (1.2 W/ft$^2$) on the south zone, the optimum shifts somewhat to smaller effective apertures and is less broad. In addition, the energy requirement in the daylighted case now equals that of an opaque wall for an effective aperture of 0.33 and exceeds it for greater aperture values. A comparison between north and south zone performance shows that the relative differences are small up to an effective aperture of 0.15 - 0.2 for the nondaylighted case, after which the south zone's total energy requirement rises steeply relative to the north's. This occurs even though heating requirements are reduced more rapidly in the south zone as effective aperture increases, results entirely from the large increase in cooling requirements.

Figure 3 also shows that the slope of the increase in energy consumption generally rises faster for the nondaylighted cases than for the daylighted cases through the range of interest. This rise indicates 1) that daylighting effectively reduces electric lighting consumption, and 2) daylighting's thermal impact is proportionally less than electric lighting's. However, for more efficient electric lighting systems with low installed power densities, the two curves are essentially parallel. This suggests that daylighting's contribution to cooling load is approximately the same as electric lighting's, which is to be expected with electric lighting of comparable efficacy.

This result challenges the popular belief that daylighting strategies always produce a lower cooling load than electric lighting. While the nominal efficacy of daylight as luminous flux (100 - 130 lumens/watt) is substantially higher than the efficacy typical of fluorescent lamps (60 - 90 lumens/watt), an "effective annual efficacy" for daylighting can be estimated in much the same way that lighting system efficacy can be calculated. The equivalent value for electric lighting is about 40 lumens per watt, which is obtained by dividing the design illuminance value (538 lux or 50 fc) by the installed power density (12.9 W/m$^2$ or 1.2 W/ft$^2$). The equivalent instantaneous value for a daylighted case could be calculated and then averaged over a year, but we observe that, for the specific power density at which the slopes of the curves are similar, the "effective annual efficacy" of the daylighted system must just equal that of the electric system, which can be readily calculated. This occurs at about 16.1 W/m$^2$ (1.5 W/ft$^2$), resulting in an efficacy of about 33 lumens/watt for daylight, far lower than the source characteristics. This is due primarily to variation in daylight intensity with time and to non-uniform distribution in the daylighted room.

Peak Analysis

Unless electricity is the primary heat source in a cold climate, electrical consumption in office buildings typically peaks during summer months when cooling requirements are at a maximum. In this study heating was supplied with a gas-fired boiler and cooling was provided with an open centrifugal chiller. Therefore, the conclusions of this study are limited to summer peaking. Results might change if a heat-pump system was used.

Figure 4 shows that daylight from moderate-to-large effective apertures can reduce total building peak demand by 14-15% in Madison, compared to a nondaylighted building with identical glazing when the electric lighting is 18.3 W/m$^2$ (1.7 W/ft$^2$) (compare curves B and D). In this case the daylighted perimeter floor space is only 37% of the total. The fraction of total building peak demand saved will vary with the perimeter/core ratio.

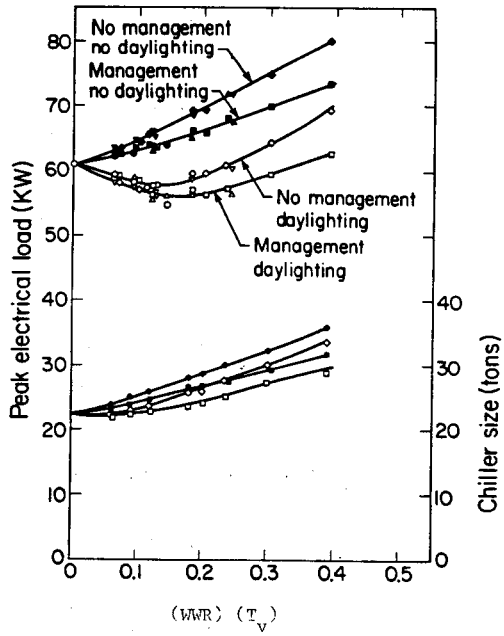



Fig. 4. Peak load and chiller size as a function of effective aperture. Madison: 1.7 W/ft$^2$.

A plot of required chiller size as a function of effective aperture is included in Fig. 4. Chiller size increases continuously with effective aperture even in the daylighted cases. This pattern contrasts with the peak load patterns, which show an intermediate value of effective aperture for the minimum peak loads. The data for Madison indicate that the incremental chiller savings due to reduced lighting loads occur at low aperture

values and remain constant, while the incremental adverse impact of solar gain continues to increase as aperture size increases. These results emphasize the importance of control of solar gain if daylighting is to be successfully utilized to control peak demand.

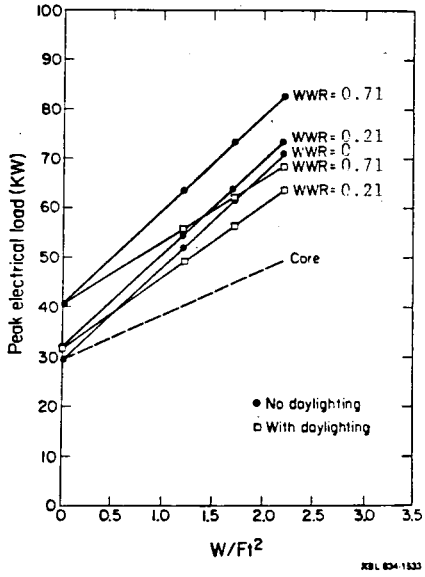



Fig. 5. Peak load as a function of lighting power density. Madison: $T_v$ = 0.69.

The results described above also depend on installed lighting power density. When the installed electric lighting is very efficient, daylighting without window management requires a larger chiller than window management without daylighting. When installed electric lighting power density is above 21.5 $W/m^2$ (2.0 $W/ft^2$), daylighting is always beneficial in terms of chiller size. Chiller size is approximately linearly dependent on electric lighting level regardless of daylighting and window management, although the rate of increase will vary with the conservation strategies utilized.

Peak electrical demand as a function of installed electric lighting power density for Madison is shown in Fig. 5. Changes in installed lighting power are assumed to represent hardware changes that increase or decrease luminous efficacy. In all cases the illuminance design criterion remains 538 lux (50 fc). For the nondaylighted cases, including a building having no windows, the relationship between peak demand and electric lighting power is linear and the plots for different values of window area or shading coefficient are parallel. However, for daylighted cases, the relationship between peak and lighting load becomes more complex.

In Madison the three nondaylighted cases (solid lines) represent glazing areas of 0%, 21%, and 71%, respectively. These have essentially the same slope. The value includes the cooling impact of lighting as well as the effect of operating schedules. These schedules assume that 90% of the installed lighting power is operating during most daytime hours. These values represent results for core and perimeter zones combined. If we examine results from the perimeter zone alone, we find that, at peak conditions with small windows (August 31, 3 pm), the electric lighting is operating at about 30% power. For large windows, the lighting is operating at its lowest limit, 10% power. All the peak demands plotted in Fig. 5 (both daylighted and nondaylighted) occurred between 3 and 5 pm on August 31.

## SUMMARY AND CONCLUSIONS

Daylighting is potentially an important design and conservation strategy in nonresidential buildings. Results from an hour-by-hour simulation model that accounts for daylighting impacts help refine our understanding of this complex subject. An extensive set of parametric analyses for a simple office module in several climates suggests the following generalizations:

1. Increasing window area and/or transmittance to increase daylighting savings reaches a point beyond which total energy consumption increases due to greater cooling loads.
2. Control of solar gain is vital if daylighting strategies are to provide net energy benefits.
3. Managed windows without daylighting controls may require less energy than unmanaged windows with daylighting.
4. Daylighting may not always be a "cooler" light source than fluorescent lighting--the conditions under which this statement holds true depend on the details of window management and installed lighting power.
5. Daylighting strategies provide peak demand management opportunties, but the results are climate-sensitive.
6. Daylighted buildings may have lower total peak electrical demand, but may require larger cooling systems than non-daylighted buildings with smaller windows.
7. Installed lighting power and the lighting control system characteristics are major factors in determining the real value of daylighting strategies.
8. Most of the conclusions above are sensitive to climate, orientation, and other building modeling assumptions.

While we believe that these results represent the most comprehensive perspective to date on this subject, we remind the reader that there are still very few measured building data to

verify simulation results. Changes in base-case conditions and operating assumptions may also modify some conclusions.

Our work continues to extend these results to include a broader range of fenestration designs. Further development of the DOE-2 model to allow analysis of other architectural solutions (e.g., light shelves, atria) is in progress and is described in Ref. 6. We believe that the regression techniques that we used (3) to simplify the representation of a large data set could also be used to convert our data set to a simple, yet powerful, design tool (7). We are also working on experimental projects to provide the quantitative data required to build confidence in the algorithms used in the simulation models (8), and have begun to collect detailed performance data in several innovative daylighted buildings.

ACKNOWLEDGEMENT

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# THE DAYLIGHT SOLAR VENT: FLEXIBLE DESIGN

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## ABSTRACT

This paper presents the Daylight Solar Vent (DSV), a concept by which daylighting, solar heating, and ventilation are provided within one flexible system. The intent is to make use of available solar energy to provide ventilation and illumination as well as space heat. Conservation and super insulated houses requiring less than 8 Btu/ft$^2$DD are, by definition, well designed for the cold season when energy efficiency may be the primary design consideration. However, daylighting and ventilation, design considerations that increase in relative importance during the warmer seasons, are all too often sacrificed in narrowly focused design. The DSV concept provides daylighting, ventilation, and solar heating with the flexibility for building occupants to modify the system as solar fluctuates and seasons change. This system is conceived with the Pacific Northwest in mind, although the concept is applicable to most climates.

This system provides daylighting/direct solar heat, isolated gain solar heat, or thermal stack summer ventilation. Three primary moving parts allow the system to be converted from one mode to another.

1. A large thermal shutter controls the amount of daylighting.
2. A thermal damper at the top of the stack, when open, allows the system to ventilate as a thermal stack.
3. With the fan activated, and the damper and shutter closed, the system is an isolated gain solar heating system.

Combinations of these functions may also be used. With both the shutter and damper open, the system provides daylighting and thermal stack ventilation. With the shutter open, the damper closed and the fan on, the system is a direct gain/isolated gain solar heating system.

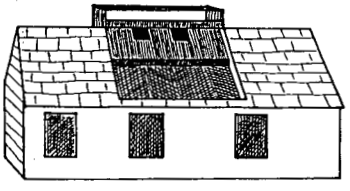


Fig. 1. DSV Applied to Residence

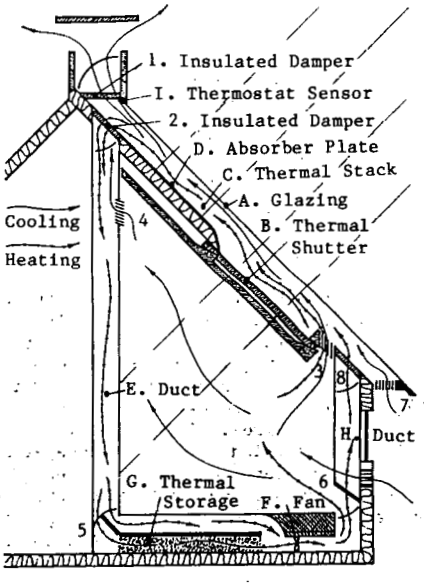



Fig. 2. DSV Components and Airflow

## 1. DESIGN PARAMETERS

The major considerations resulting in the conception of the Daylight Solar Vent have been the following:

Daylighting. The provision of maximum natural light for daylighting and solar gain was the primary motivating force in the conception of the DSV. The esthetic of abundant natural light is important in this part of the country, which is known for its long dark winters.

Conservation/economics. The conservation of energy required for heating, lighting and ventilation is desirable, both from the perspective of the individual homeowner and society at large.

Solar heating. There are economic, esthetic and health incentives for taking advantage of this naturally available energy form. It is desirable to have the flexibility to make use of solar as direct gain or as isolated gain for charging up storage.

Simplicity/flexibility. To minimize the number of separate systems necessary in the structure, it is desirable to have several systems combined into one. The system must be flexible so that separate functions may be performed in various combinations.

## 2. APPLICATION

The DSV is applicable to cathedral ceilings in residential use or commercial/industrial facilities with sloped roofs and open ceilings. It may be retrofitted, but is likely to be most cost effective in new construction. The example used in this paper is a building with a cathedral ceiling and a mass wall dividing the building east to west. Massive construction is preferred so that potentially excessive diurnal temperature swings may be evened out.

Roof slope must be at an appropriate angle to allow insolation to penetrate effectively for direct gain and indirect gain solar heating. For the project example, a roof slope of 45° is assumed. At this slope, the solar gain during the coldest months is not significantly less than the maximum. This angle is more appropriate for daylighting than a steeper angle as the building interior has an increased view of the skydome, and therefore more even illumination. In addition, illumination from above is less of a potential glare problem than side illumination.

The DSV daylighting, solar heating and ventilating concept could be applied to single story buildings or to the top stories of multilevel factories and commercial buildings. Buildings on a long east/west axis could have multiple systems along the south roof. Buildings on a north/south axis could use multiple systems on a sawtooth roof design.

In order to provide abundant daylighting, it is necessary to have a large area of glazing. Large areas of glazing may be assets or liabilities, depending on conditions. Reducing glazing disadvantages while maintaining advantages usually requires added system complexity. A thermal shutter, manual or automatic controls, dampers, or daylight tempering louvres add complexity to the DSV. In each application of the DSV, the level of amenity/complexity can be determined only after balancing many factors. Use of the DSV is appropriate if the life-cycle benefits of avoided lighting, heating, ventilation and cooling energy costs, and the perceived esthetic, psychological and health values outweight the total lifetime costs of system installation, maintenance, operational complexity, and potential ultraviolet degradation of interior furnishings.

## 3. SYSTEM COMPONENTS

The primary components of the DSV, as labeled in Figure 2, are as follows:

(A) A transparent or translucent glazing is necessary to allow solar penetration for daylighting and solar heating.
(B) The thermal shutter allows control of daylighting, solar gain and thermal loss. It can be constructed of common building and insulating materials. It may be automatically or manually operated with lines and pulleys. It rolls along straight tracks on standard garage door wheels.
(C) The thermal stack is glazed on the south face. The peak opening is designed in such a manner that winds from any direction will increase the circulation.
(D) A highly absorptive plate is located in the thermal stack.
(E) This ducting is the passageway for delivery of solar heated air to the conditioned space, the thermal storage, or both. When in the ventilating mode, exhaust air may rise up through this duct and be exhausted through the peak of the thermal stack.
(F) The fan pulls air from duct E through the thermal storage medium or through the storage bypass duct.
(G) The storage medium would typically be small washed rocks, .75-1.5 in. in diameter. It is important to size the thermal storage medium appropriately for each application.
(H) Air leaving the fan passes to the conditioned space or back up to the solar collector, depending on damper position.
(I) A thermostat sensor is placed in the top of the thermal stack to control fan operation and, possibly, some dampers.

In the example illustrated in Figure 2, seven dampers are placed in the air handling system to allow control of heating and cooling. These dampers may be manually controlled in smaller systems or activated by thermostats in larger systems. In most applications, the DSV system would be connected to a backup heating and/or cooling system. The dampers

perform the following functions:

(1) This damper, an insulated panel at the top of the thermal stack, controls the stack function--open for venting, closed direct and/or indirect gain solar heating.
(2) Damper 2 controls the airflow in duct E and is insulated to prevent heat loss during cold periods when solar heat is not being collected.
(3) This damper controls the airflow from the conditioned space to the lower part of the solar collector. This damper may also be insulated.
(4) When open and in the ventilating mode, this damper allows air to flow from the peak of the conditioned space to the outside via the thermal stack. When open and in the thermal storage heating mode, this damper allows air to flow back down duct E to the thermal storage.
(5) This damper directs the airflow through either the thermal storage or the bypass duct around the storage. In larger systems of greater complexity, controls may orient this damper in a fractional position to allow some heat to be stored and the remainder to be ducted directly to the conditioned space.
This strategy would also allow temperature control of the air delivered to the conditioned space.
(6) This damper channels the air to either the conditioned space or the duct return to the DSV collector.
(7) When open, this damper allows outside air into the bottom of the DSV collector to allow summer ventilation of the collector when conditioned air is not being circulated through it.
(8) An insulated damper may be added at the top of duct H to prevent heat loss in extremely cold climates.

## 4. OPERATING MODES AND CONTROL LOGIC

An effective DSV may be large, small, simple or complex. The DSV example presented in this paper is of medium control complexity. Four primary factors determine the degree of control required by a system:

Conditioned Space Requirements. The particular use of a space determines how critically environmental conditions of light, heat, humidity and air changes must be controlled.

Size. What percentage of facility needs will be provided by the system? A small supplemental system will not have as great potential to markedly change the interior environment as a large system. Critical control is therefore not as necessary for supplemental systems.

Structural Mass. Air temperatures in a heavy mass building will not fluctuate as greatly, given the variable solar gain input of the DSV, as air temperatures of a building of light construction. All else being equal, required control complexity and sophistication would therefore be less in a building of greater mass.

Weather Conditions. The variability and severity of particular weather conditions must be considered when sizing and designing controls for the DSV.

There are seven primary operational modes of the Daylight Solar Vent. The following is an aggregate summary of the shutter position, fan activity, and damper positions for each mode.

| | |
|---|---|
| Shutter open, shutter closed | BO, BC |
| Fan on, fan off | Fon, Foff |
| Damper 1 open, Damper 3 closed | 1O, 3C |

A. Daylighting. Direct gain and indirect gain heat interior space.
BO, Fon, 1C, 2O, 3O, 4O, 5O, 6O, 7C

B. Daylighting. Direct gain to heat space and to charge storage. Indirect gain to charge storage.
BO, Fon, 1C, 2O, 3O, 4O, 5C, 6O, 7C

C. Daylighting or no daylighting. Heating of interior space with storage.
BO or BC, Fon, 1C, 2C, 3C, 4O, 5C, 6O, 7C

D. Daylighting. Ventilation using the thermal stack.
BO, Foff, 1O, 2O, 3O, 4O, 5O, 6O, 7O.

E. No daylighting. Increased ventilation using thermal stack.
BC, Foff, 1O, 2O, 3O, 4O, 5O, 6O, 7O.

F. Nighttime cooling of space and storage so storage may be used for daytime cooling.
BO, Fon, 1O, 2O, 3O, 4O, 5C, 6O, 7C.

G. No daylighting. Daytime cooling using storage.
BC, Fon, 1O, 2C, 3C, 4O, 5C, 6O, 7O.

The following is a sequential description of how the DSV would be operated during daily and seasonal weather fluctuations.

Winter: Clear and cold sunny morning--operational mode A. The interior space is cool and could use some heating. The thermal shutter is opened, providing daylighting and direct gain heat. The fan is activated manually or automatically by a thermostat sensor in the thermal stack. Heat is drawn through the collector, the thermal stack and the space, and then ducted to the space that requires heat.

Heated space reaches desired temperature--operational mode B. At this point, damper 5 is closed so that heated air is directed

through the storage medium, charging it with heat. If the air returning to the space from the storage is either too cool or warm, dampers 6, 3 and 4 can be closed to separate the storage heating air loop from the conditioned space. If more heat than is provided by the direct gain alone is needed during the day, the dampers may be changed back to mode A as needed. If the sky is clear and the temperature mild, the direct gain aperture may cause overheating. When this occurs, the shutter may be partially closed, decreasing the direct gain while increasing the size of the indirect gain solar collector and increasing the amount of heat going to storage.

Winter, day or night: heavy clouds, cold--operational mode C. In this mode, the DSV provides neither daylighting nor solar gain. Heat is provided to the interior space by circulating air through the storage. If the storage is exhausted, then a backup heating system must be used. The fan is controlled by a thermostat located in the heated space.

Spring, summer or fall: sunny; ventilation using thermal stack--operational mode D. This mode has a passive control. As the solar intensity rises, increasing the unwanted direct gain of the daylighting, the thermal stack increases the frequency of interior space air changes. If interior temperatures are still too high, the shutter may be partially closed, increasing the ventilation generated by the thermal stack and decreasing the direct solar gain to the interior.

Summer: Clear and warm; no daylighting; maximum ventilation using thermal stack--operational mode E. In this mode, the shutter is closed and all dampers are open. The fan is off.

Summer heat wave, night: Temperature usually below 70°F in Pacific Northwest--operational mode F. In this mode, the interior space and the storage are cooled. The storage may then be used for daytime cooling. The interior air is ventilated through the collector/stack. The storage is cooled by drawing outside air through it.

Summer heat wave, daytime: Temperature 80°F+ --operational mode G. During heat wave conditions, the shutter is closed to prevent extreme overheating. Ventilation to the outside is kept ata minimum so that the interior temperature may be kept lower. Interior air is circulated through the night cooled storage to provide cooling.

## 5. PERFORMANCE OF THE DSV

It is not within the scope of this general conceptual presentation to analyze in detail solar heating or daylighting performance. Analysis of the thermal stack ventilation capability is provided, however. Certain daylighting and solar heating control strategies deserve note. To increase daylight control, a double glazed window could be placed in the thermal shutter. To control direct sunlight, light colored horizontal louvres, rotating on the east/west axis, would diffuse the light and reflect a portion of it off the north wall. The isolated gain portion of the solar collector should be of a similar design to the most efficient (40-50%) solar air collectors. As in any solar heating system, ducting and heat storage should be as efficient as possible.

### 5.1 Ventilation Performance

In the Pacific Northwest during the summer and a good portion of the spring and fall, such a sizable daylighting aperture requires more than the usual ventilation rate to prevent building overheating. On a clear warm day the excess heat of direct gain is ducted to storage as in mode B. Once the storage medium is saturated, the building operator may begin dumping heat to the exterior, knowing that the storage will provide heat during subsequent cool weather. The size of the thermal stack relative to the direct gain aperture should be large enough to provide sufficient ventilation cooling during hot sunny midsummer conditions. If it is assumed that interior or exterior shading or sun tempering devices will be used, the daylighting aperture may be somewhat larger.

### 5.1a Building Stabilization Temperature

In the following calculations, the total building heat gains and losses will be compared during a sunny one-hour period to determine the building stabilization temperature. In the sunny condition, the building temperature will rise above ambient because of the solar gain. As the temperature rises, the envelope and thermal stack heat losses increase. The inside temperature will stop rising when the rate of total building heat loss equals the rate of total building heat gain. This is the building stabilization temperature.

Assumptions. For these first calculations, it is assumed that the area of the daylight aperture and the thermal stack are equal. No shading devices are used. The time is mid-day in July with an ambient temperature of 75°F. The solar intensity is 250 Btu/ft$^2$ on a 45° slope and 165 Btu/ft$^2$ on a vertical surface. The building used as an example is shown in Figure 3.

The building solar gains are figured:

Daylighting aperture:
112 ft$^2$ x .76 transm. x 250 Btu/ft$^2$hr
= 21280 Btu/hr (6234.0 W)

Windows:
60 ft$^2$ x .76 x 165 = 7524 Btu/hr (2204.5 W)

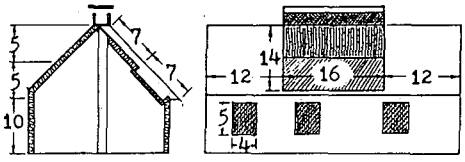



Fig. 3. Assumed Building Dimensions

Roof: It is assumed that the roof is a neutral color of medium absorptivity, such that the temperature of the roof is approximately 120°F. Assuming the interior temperature to be 7°F above the ambient 75°F (as is later concluded in these calculations), the temperature differences between the inside and outside of the cathedral ceiling roof is 120-(75+7) = 30°F. This results in the following heat gain for the south facing roof.

336 $ft^2$ x .025 Btu/$ft^2$°F x 38°F
= 319 Btu/hr (93.5 W)

Walls: It is assumed that the south facing wall is a light color. This factor plus the fact that the sun is not as concentrated on a vertical surface would result in a surface temperature of no more than 95°F. The temperature difference between interior and ambient is 95-(75+7) = 13°F. The heat gain resulting from the south wall is therefore:

340 $ft^2$ x .05 Btu/$ft^2$°F x 13°F
= 221 Btu/hr (64.7 W)

Typical building internal gains are:

30,000 Btu/day ÷ 24 hr = 1250 Btu/hr

The sum of these gains is:

21,280 + 7524 + 319 + 221 + 1250
= 30,594 Btu/hr (8964 W)

The combined envelope heat loss for the north roof; north, east and west walls; floor; windows and daylighting aperature; and infiltration is:

14 Btu/hr°F +50 + 40 + 136 + 216
= 456 Btu/hr°F (240.5 W/°C)

The building heat losses due to the thermal stack ventilation are now calculated. Air velocity in the thermal stack is determined in the following calculation.

$$V = [(gL_V(T_H-T_A)T_A^{-1})x(fsd^{-1}+1)^{-1}x2]^{1/2}$$

$$V = [(32.2 \times 5(555 - 535)535^{-1}) \times ((.03 \times 7 \times 4.5^{-1}) +1)^{-1} \times 2]^{1/2}$$

V = 3.39 ft/sec thermal stack air velocity

In this example, $L_V$ equals 5'. It is assumed that the average temperature in the stack is 20°F greater than the ambient 75°F. The stack length, s, equals 7'.

Using this velocity and the size of the upper stack opening, the $ft^3$/min (CFM) is figured:

3.39 ft/sec x 16 $ft^2$ x 60 sec/min=3256 CFM

The hourly ventilation heat loss per F° difference between interior and ambient temperature is calculated:

3256 CFM x .018 Btu/$ft^3$°F x 60 min/hr
= 3516 Btu/hr°F (1854 W/°C)

The sum of the hourly building envelope heat loss and the hourly ventilation heat loss is:

456 Btu/hr°F + 3516 Btu/hr°F
= 3972 Btu/hr°F (2095 W/°C)

The building stabilization temperature, where heat losses are equal to heat gains, may now be figured:

30594 Btu/hr ÷ 3972 Btu/hr°F
= 7.7°F (4.28°C)

75°F ambient + 7.7°F = 82.7°F (28.2°C)

Clearly, 82.7°F is not within a typical comfort range. During such warm spells it is most appropriate to reduce solar gains by shading direct gain apertures. The important information acquired from the previous calculations is that even during the sunniest weather the indoor temperature will not be greater than about 8°F above ambient. Seattle's monthly temperature averages are: March 44.1, April 48.7, May 54.9, June 59.8, July 64.5, August 63.8, September 59.6, October 52.2, and November 44.6. Only when it is sunny and the ambient temperature is 72°F or greater will it be possible for interior temperatures to rise above 80°F.

### 5.1b Building Stabilization Temperature

Assumptions. In these calculations it is assumed that the daylighting aperture and windows are covered with materials that reflect 50 percent of the sun's energy back out through the glazing. This is still abundant daylighting during sunny weather. However, the total building solar gains are reduced from 30,594 Btu/hr to 16,192 Btu/hr (4744.2 W). The temperature and insolation conditions remain the same. The new stabilization temperature, barely in the comfort range, is 4.1°F (2.28°C) above ambient -- 79.1°F (26.2°C).

### 5.1c Building Stabilization Temperature

Assumptions. 50 percent shading of daylighting aperture and windows. Thermal shutters closed 50 percent, increasing the ventilation of the thermal stack.

Building solar gain:

Roof, walls and internal gain:
319 Btu/hr + 221 Btu/hr +1250 Btu/hr
= 1790 Btu/hr (524.5 W)

Daylighting aperture and windows--50% shaded:

[(21,280 Btu/hr ÷ 2) + 7524 Btu/hr] ÷ 2
= 9082 Btu/hr (2661 W)

Total gains = 10,872 Btu/hr (3185.5 W)

Building heat losses:

Envelope losses = 456 Btu/hr°F (240 W/°C)

Thermal stack ventilation losses: With the shutter half closed, three factors of the formula are affected. $L_V$, the vertical distance between the upper and lower stack openings, is increased to 7.5 feet. Variable s, the stack length, is increased from 7 to 10.5 feet. The head factor of 1 is increased to 1.2. This is due to the slight irregularity of air flow created by the lip where the shutter meets the upper edge of the shutter cavity.

$$V = [(32.2 \times 7.5\ (555 - 535)\ 535\text{-}1) \times ((.03 \times 10.5 \times 2\text{-}1) + 1.2)\text{-}1 \times 2]1/2$$
$$V = 3.65 \text{ ft/sec}$$

CFM = 3504 (99.22 $m^3$/min)
Btu/hr°F = 3784 (1995 W/°C)

Total building losses:
456 + 3784 = 4240 Btu/hr°F (2236 W/°C)

Building balance temperature
10,872 Btu/hr ÷ 4240 Btu/hr°F
= 2.56°F (1.42°C)

75°F ambient + 2.56°F = 77.6°F (25.3°C)

Clearly, the appropriate strategy for preventing summertime overheating is to reduce the amount of direct sunlight entering the building. The calculations do show the significant ventilation capability of the thermal stack. Therefore, buildings with the DSV are able to have higher daylighting levels while maintaining comfortable temperatures. In the Pacific Northwest, the DSV could be in the full daylighting mode for much of the year because of the cool mild climate. The thermal shutter would only need to be used during very cold cloudy days in winter, winter nights, and hot sunny summer days.

## 6. VARIED APPROACHES TO USE OF THE DSV CONCEPT

The DSV example used in this paper is one straightforward application of the concept. However, numerous variations on the theme are possible, enabling the concept to be considered in a wide variety of design approaches. The daylighting aperture need not be located only in the lower portion of the DSV. Constructing part of the upper thermal stack as a daylighting aperture would allow deeper daylight penetration into the building. Multiple smaller DSVs may be more appropriate than fewer large DSVs in long buildings or where a more even distribution of light is needed. The DSV may be applied having the greatest dimension in either width or length. Where the roof does not provide sufficient vertical distance between the upper and lower stack openings, the stack may be extended upward above the roof. In extending a stack, the airflow may be bent to travel vertically, but not without increasing the head loss factor to a certain extent.

The DSV is a dynamic system, having positive and negative potential. It is crucial to carefully match the diverse system capabilities with the varying needs of building occupants.

## 7. NOMENCLATURE

g = gravitational force: 32.2 ft/$sec^2$
$L_V$ = vertical distance between upper and lower thermal stack openings.
$T_H$ = The average temperature inside of the thermal stack.
$T_A$ = The ambient temperature.
f = Friction factor. Using the Reynold's formula, this was determined to be 0.03.
s = The length of the thermal stack.
d = The diameter of the thermal stack, assuming a cylindrical shape. In this example of a 16 $ft^2$ thermal stack section, the diameter of a cylinder with an equal cross sectional area is 4.51 ft.
l = Head loss. This number increases as irregularities or bends are introduced into the thermal stack.
ADR= Air Density Ratio.
ACH= Air Changes per Hour.

## 8. ACKNOWLEDGEMENTS

I wish to thank Dr. John Bodoia of the school of Mechanical Engineering, University of Washington, for his formulation of the thermal stack equation and invaluable instruction involving thermal stack ventilation. The criticism and comments provided by Ralph Minor, Larry Palmiter, Evan Brown and Terry Egnor are also much appreciated.

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# A REVIEW AND ANALYSIS OF 24 DAYLIGHTING SOLUTIONS

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## ABSTRACT

Twenty-four daylighting models were designed and built by the graduate studio in energy conscious design at Arizona State University under the direction of Professor Jeffrey Cook. Each scale model represents a 9.1 x 12.2 m (30 x 40ft) office space. The models were displayed at the 1983 International Daylighting Conference; however, no documentation was presented. This paper explores the assumptions and specifics of each design in an effort to expand the library of daylighting designs available to architects and designers.

## 1. INTRODUCTION

As part of their studies, the Graduate Energy Design students at Arizona State University concentrated several weeks on the subject of daylighting in architecture. Under the direction of Professor Jeffrey Cook, the eight students built 24 models, which they presented at the 1983 International Daylighting Conference in Phoenix, Arizona.

Through the group's studies (and a guest lecture by Professor Ben Evans), it was agreed that scale modelling is the only technique that allows the designer to visualize and experience interior space as well as to evaluate a design's luminous performance. These characteristics make it a unique tool for qualitative as well as quantitative explorations and observations. The students had no previous experience with this type of modelling. All of their designs result from a creative approach rather than from scientific calculations; thus, all are unique.

As a handbill describing the exhibit noted: " Perceiving daylight is subjective, just as these models must be perceived by you and your eye. Yet there are certain strategies in daylighting that are true for all solutions: handle it delicately, soften it, filter it, bounce it, use it as if it were spreadable-- put a layer of daylight of equally good quality all over the space."

The designers avoided direct solar gain, glare, considered brightness ratios, contrast (quality), and attempted to distribute the daylight as evenly as possible throughout the 9.1 x 12.2 m (30x40 ft) scale models (quantity). A view to the outside was also desired, to fulfill the biological and psychological needs of the occupants. Professor Cook encouraged the students to design their models as "daylighting fixtures".

## 2. WHY DAYLIGHT?

Each of the models was tested with a light meter for brightness levels at nine grid points within each space, at a scaled height of 76 cm (30 in.). The readings were taken at two times of day for each model, and the results were overall surprisingly consistent. The solid line in Figure 4 represents the general illumination level in the base case, or open model (Figs.2,3). This was built as a 9.1 m (30 ft) deep control with a 76 cm (30 in.) window sill, open (glazed) to the ceiling. This is a simplified configuration of most buildings designed without studied consideration for the energy saving potential of daylight. Near the window, the illumination level, brightness ratio, and contrast are too high for visual comfort. If there is direct sunlight inside, it would be too warm for thermal comfort as well. Consequently, curtains and blinds are often closed, thus darkening the center zone (which would have been closest to the optimum), and eliminating almost all day-

light from the already dark back zone. On come the electric lights.
The dashed line in Figure 4 represents the general performance of all of the modelled solutions. Brightness ratios, glare, and contrast are softened, and the illumination levels are more uniform throughout. The curtains can then be opened, and the electric lights dimmed or turned off, allowing healthier, better color-rendering, free daylight to illuminate the space. Daylight is cooler than electric lights, and lost heat can be replaced by more conventional and economical means when required. Well designed daylighting is therefore advantageous in any climate.

## 3. THE EXHIBIT

To best experience these models at the Daylighting Conference, the class designed and built a 3.7 m (12 ft) high walk-through pavilion on an open roof terrace at the conference hotel (Figure 1). Viewing ports cut to allow full view of each model interior provided viewers first hand experience with the quality and quantity of light in each solution. Scaled cross-section drawings and graphic data were presented outside the pavilion, below the facade of each model.



Fig.1. ASU Daylighting Pavilion northwest corner.

In order to best examine the range of daylighting problems, the group was divided into 3 north side, 2 east-west, 2 south, and one base case, which was tested for all orientations (northern hemisphere conventions). Each model was then designed exclusively for its particular orientation.

## 4. SOLUTIONS

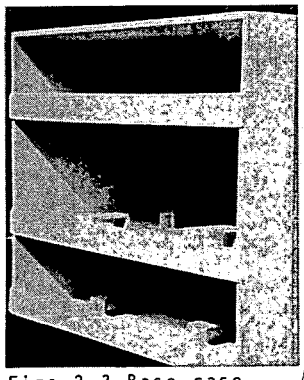
The base case model consisted of three stacked 9.1 x 12.2 m (30 x 40 ft) office spaces, painted white, all with a 76 cm (30 in.) window sill scross the full 12.2 m width. The ceiling height on the first and third floors was 2.9 m (9.5 ft), while the middle floor was 4.3 m (14 ft') high. The 1.3 cm (½ in.) plywood models were built at a scale of 1:16 (3/4"=1'-0"). Wooden desks, 76 cm (30 in.) high were included in each model for visual scale. Design changes were restricted to the interior, one window facade, and for the third floor only, also the roof.

### 4.1 North

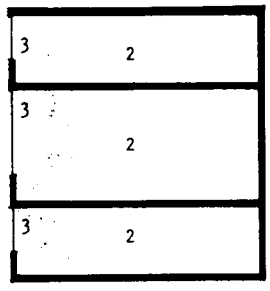
North light is generally considered cool and bluish. Though more constant than the other orientations, the available illumination levels are lower, since the direct sun only hits the north side a fraction of the year.

Model A (Figs.5,6,7) gets around the shortcomings of north light with a series of heliostats which track the direct sunlight from over the building, reflecting it off of a parabolic reflector and down to other reflectors, which bounce it deep into each office space. Additional reflectors ensure that any available light striking the structure is reflected into the rooms. On the first floor, the reflectors outside the window sill proved simple but effective for bouncing light deep into the back of the room. The second and third floors used a suspended ceiling system, while the roof consisted of rows of reverse curved reflectors angled to reflect but diffuse all direct (south) light as well as admit north light. Panels spaced perpendicular to these rows were calculated to eliminate direct gain from morning and afternoon sun. Though not a requirement of each design, all those in Model A also provide a large mechanical chase below each window sill.

Model B (Figs.8,9,10) uses a different approach for each floor. The first floor uses a curved group of small reflective louvers, angled to reduce the view of the upper sky to increase the visual comfort and bounce available light deeper into the space. The semicircular sill provides a smooth visual transition from the bright window to the darker interior levels. The second floor used a thin cloth interior diffuser to soften and deepen the light penetration. This was coupled with a screen overhang to filter the view of the sky and the light near the window, while also bouncing some light into the space. Similar to



Figs.2,3. Base case



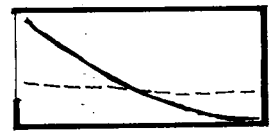
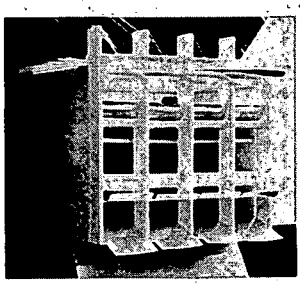
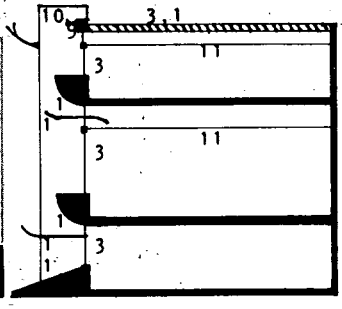
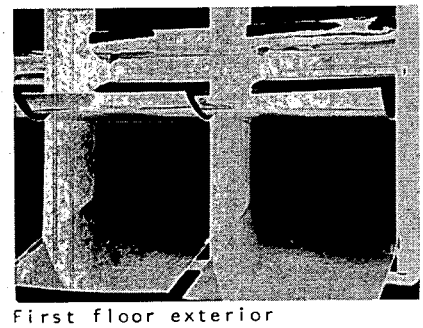



Fig.4 Illumination patterns



Figs.5,6,7. Model A

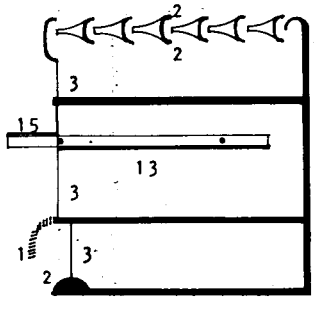


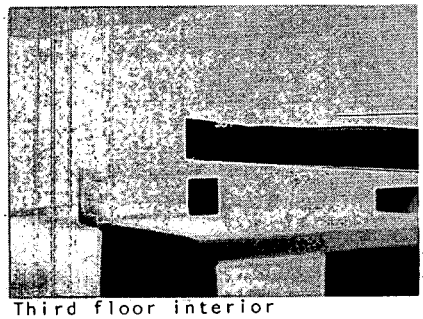



First floor exterior

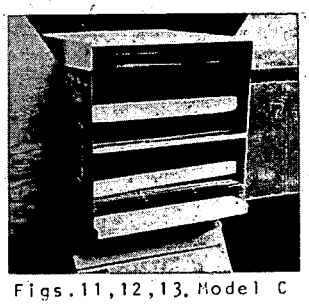


Figs.8,9,10. Model B

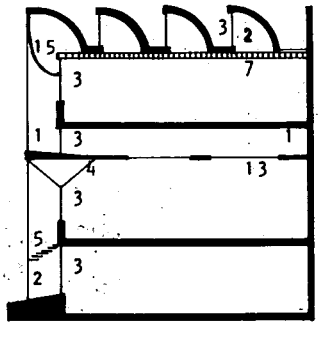


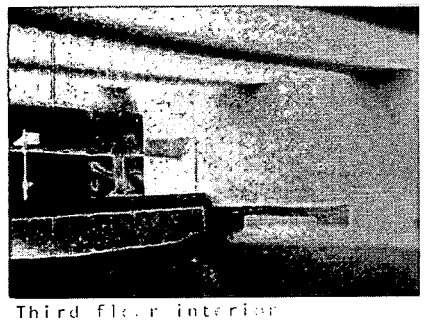



Third floor interior



Figs.11,12,13. Model C

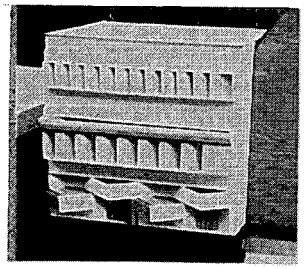


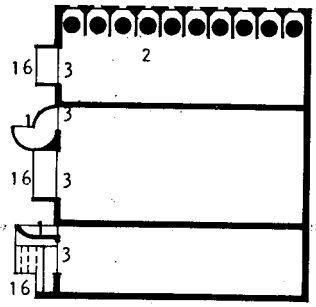
Third floor interior

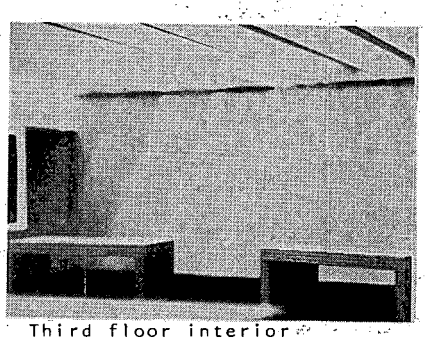
LEGEND:

1. Highly reflective surface
2. White finish
3. Clear glass
4. Tinted glass
5. Louvers
6. Vertical fins
7. Egg crate louvers
8. Sloped sill

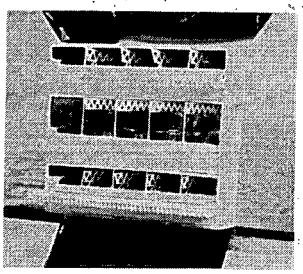


Figs.14,15,16. Model D

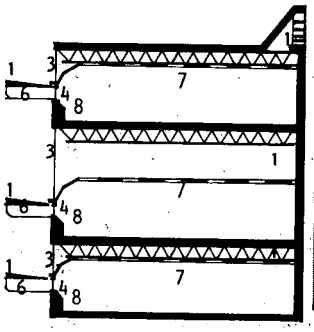


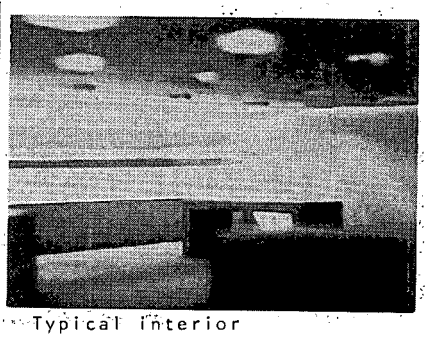



Third floor interior

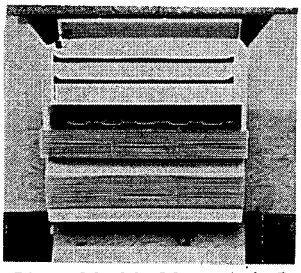


Figs.17,18,19. Model E

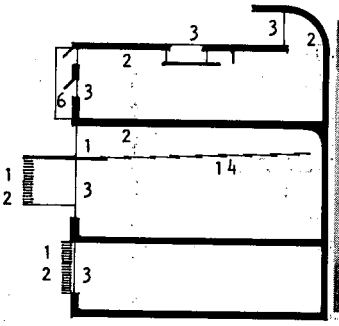


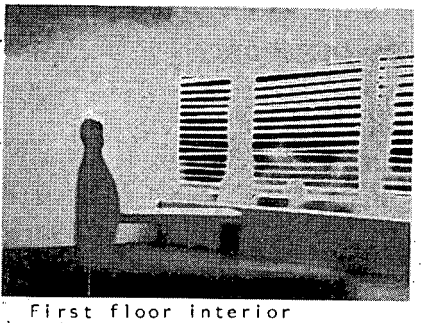



Typical interior

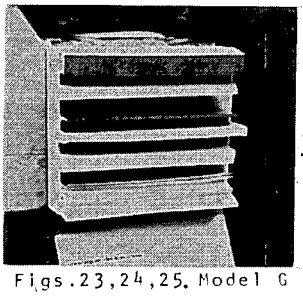


Figs.20,21,22. Model F

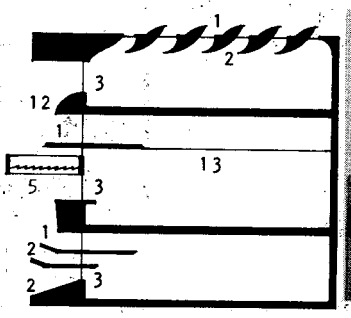


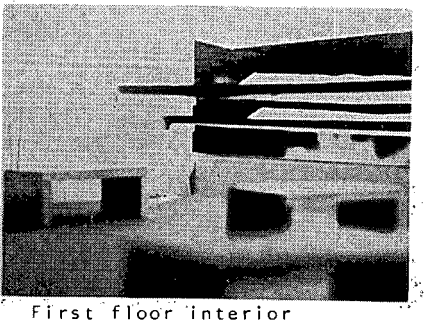



First floor interior



Figs.23,24,25. Model G



First floor interior

9. Parabolic mirror
10. Heliostat
11. Diffuse material
12. Matte finish
13. Fabric
14. Staggered circular ceiling
15. Screening
16. Northwest angled vertical fins

Model A, the roof also takes advantage of direct sun, and the third floor was very brightly daylit.

Model C (Figs.11,12,13) uses the same principles discussed under Models A&B, but in all new ways. On the first floor, there is another sloped exterior sill, but not as steep as in Model A, and white here. Again are the upper louvers, here in wood, to reduce the lighting level near the window and bounce it back further into the room. They also filter the view to the bright upper sky.
The second floor uses clear viewing glass with the angled glass tinted for visual comfort. The upper glass is clear over the reflective overhang. The ceiling here has a reflective surfaced upper plenum to minimize the absorbed light and maximize that going through the cloth diffusers.
The third floor uses a gently hanging screen as a visual transition and filter with a standard egg-crate ceiling diffuser. Large north facing clerestories provide very even, diffuse light to the entire floor.

4.2 East/West

The east and west building orientations are here considered together since the angles of the sun are symmetrical about solar south. These orientations are generally considered least desirable, as most of the day they receive only diffuse light, while during several hours, the rays get very low in altitude, shining deeply into the rooms. In order to avoid this direct gain and glare, then, vertical fins and overhangs must be incorporated. The models in the exhibit were designed for the west side of the pavilion.

Model D (Figs.14,15,16) uses many large vertical northwest oriented fins with overhangs. Turning the fins north of due west allows greater fin spacing, shorter overhangs, or both. The first floor uses the 45 degree fin orientation to create a series of staggered window bays. The lower bays use vertical wood louvers to shield the direct gain and glare while providing diffuse light near the windows and a view to the outside. The upper bays have a highly reflective surface to help bounce light deep into the room. While the quantity of light in the back of this room is rather low, the quality of light overall is much improved over that in the base case. The second floor uses wider fins with greater spacing and two reverse curved reflectors for the length of the window. The third floor uses a bank of vertical fins similar to that on the second floor. These fins are thinner, however, and therefore closer together. The toplighting here is an array of large white cylinders which act as light diffusers and mechanical or electrical chases.

Model E (Figs.17,18,19) uses a very different approach for the west wall situation. All three floors use the same concept and configuration, but with minor changes to each, for comparison. This design minimizes the tinted lower viewing glass in order to increase the clear glass for daylight above. In order to maximize this upper aperture, exposed white open web joists were chosen while all other ceiling plenum surfaces were covered with a highly reflective material. In theory, any light entering this "mirrored box" would be continually reflected and thus be uniformly distributed over the entire ceiling. Below, in the conditioned space, square diffusers were spaced in the ceiling just as electric lights would be. A thin strip was also cut into the perimeter as a wall wash feature. The large overhang and closely spaced vertical fins keep direct gain and glare from the room by reflecting it into the light plenum. Additionally, the window head and sill were splayed to reduce the high contrast between the walls and tinted window glass (not shown in Fig.19). The third floor also incorporates an east facing clerestory to increase the morning light level in the space.
The effect is a very even light distribution throughout the spaces. While the first floor light level was lower in the back of the room than the other floors, this is believed to have been caused more by shade from the second floor overhang than by the lower ceiling plenum.

4.3 South

South orientations have the greatest exposure to direct sun. On this side, rooms can be protected from solar gain with some form of horizontal overhang. Unlike diffuse light, direct light rays can be focused, or reflected where desired. Glare, however, is especially acute on the south side.

Model F (Figs.20,21,22) begins the first floor with essentially a venetian blind configuration with the upper surfaces of each blade highly reflective. The second floor uses a

similar arrangement with a form of a light shelf above. Inside the space, the light shelf becomes a triangle of staggered overlapping reflective disks which (in plan view) resemble the scales of a fish. This shelf bounces light to the back of the room while at the ceiling, pleasant diffuse light peeks out from between each circle. This ceiling is another example of the influence of creativity in daylight design. The third floor uses two angled overhangs, which allow them to be much shorter than if they had been horizontal. Thin floor to ceiling windows at the end walls are shielded by angled vertical louvers to keep direct sun out of the room, but allow light to splash onto the wall certain times of the day. Overhead is a skylight with a diffusing shelf below it, while a clerestory with protective overhang lights the back of the room. All three of these floors were rather well lit throughout; moreover, the upper floor was brightest at the back of the room, under the balcony.

Model G (Figs.23,24,25) begins the first floor with a double light shelf carefully calculated to eliminate all direct gain while bouncing light deep into the room. The large sloped lower sill also bounces light into the space. A view to the outside is ensured, but the bright upper sky is blocked from view. The second floor uses a louvered overhang to filter the light coming in near the windows with an upper shelf to bounce the light deep within. A cloth diffuser continues the plane of this shelf to soften and distribute the light. The third floor uses top lighting with rows of sweeping curved bands, highly reflective on top to bounce the light in, but with a softer white where visible inside. The large overhang blocks the direct sun while the curved sill eases the contrast between inside and out. All three models also displayed a very uniform light distribution across the rooms. In addition, these designs included space for mechanical chases along the facade, and emphasized the importance of color in design.

## 5. CONCLUSIONS

This paper has explored the rationale behind each of the twenty-four daylighting models built by the Graduate Energy Design students at Arizona State University for the 1983 International Daylighting Conference. The students, under Professor Jeffrey Cook, stressed a creative approach to daylighting design, rather than one based on calculations. A firm understanding of the properties of light, comfort, climate, solar angles, and the economic and energy implications of daylight are primary factors in the success of daylighting design. The exhibit emphasized the importance of the quality of light through scale modelling and observation

## 6. ACKNOWLEDGEMENT

Pavilion & base case- Joe Martinolich
Models: A- Eugenio Vergara
B- Siglinde Kaiser
C- Mamoon-Ur-Rashid
D- Benedito de Castro
E- Kurt M. Neubek
F- Manfred Trappenberg
G- Monique de los Rios
Photographs- Eugenio Vergara
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# LENS-GUIDE VIEWING SYSTEMS: AN INNOVATIVE USE OF DAYLIGHTING AT THE UNIVERSITY OF NEW MEXICO, SCHOOL OF ARCHITECTURE AND PLANNING

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Albuquerque, New Mexico 87131

## ABSTRACT

An optical, lens-guide viewing system has been constructed at the University of New Mexico, School of Architecture and Planning. Entirely passive, the system transmits a real time image of the Sandia Mountains through a series of lenses and mirrors into an interior design studio. The project design was modified from a system developed by M. A. Duguay and G. D. Aumiller of Bell Laboratories. The major problem to overcome was understanding the boundaries of the beam of light carrying the image in order to penetrate the building within the constraints of structure and existing use of space.

Although the lens-guide concept did not originate at UNM, this project applies a natural lighting concept which has been largely ignored in solar design--that of transmitting information. Lens-guides could be used in passive, inter-office visual communication systems, as windows providing psychologically needed contact with the outdoors, or for purposes as yet not conceived.

## 1. INTRODUCTION

As passive solar design advances beyond the infant, experimental stages, concern with greater diversity in design applications must become more important. Such concern is essential for resource conservation to become integrated into every aspect of our technologically interdependent society. This requires more than technical innovation; it requires that new inventions become widely obtainable products which have their own place in the market. This fundamental principle applies to all passive solar design. The lens-guide, optical viewing system described in this paper demonstrates an existing but little known technology which has tremendous potential for development in the field of passive solar/daylighting design.

## 2. PROJECT DESCRIPTION

A lens guide is a window which transmits a visual image over some distance in space. The system at UNM provides a view of the nearby urban campus with its backdrop of the 3,200 meter high Sandia Mountains from within an isolated, interior studio in the School of Architecture and Planning. The system utilizes four lenses and two mirrors. The image is captured from a second-story roof, turned downward and projected through a 46 cm (18 in.) hole in the roof, then turned horizontally and projected onto the eyes of people passing by. The system provides visual relief and a sense of connection to the outside world in an otherwise monotonously lighted space.

## 3. INITIAL DESIGN PHASE

The UNM project was started in fall of 1982 as an offshoot of a beamed sunlighting project. The sunlighting system, started the previous fall, involved a student designed heliostat which traced the daily path of the sun and projected a beam of full-spectrum sunlight into the interior entrance lobby of the Architecture building. For this purpose, a hole was cut through the roof and through a second-story studio to the interior lobby. Because the steel joists of roof and second-level floor are perpendicular, the finished opening through both structures was limited to 46 cm. A 46.92 cm (18 x 36 in) hole was cut and framed from roof to second-floor level with the intent of providing additional sunlighting for model or daylighting studies in the second-floor studio.

A change in the intended use of this extra daylighting space was inspired by an article in Applied Optics, "Transmission of 3-D Images by Means of Lens-Guides," by M. A. Duguay and G. D. Aumiller (1). Duguay and Aumiller, presently at Bell Laboratories in Holmdel, New Jersey, suggested that a

high-quality three dimensional image could be transmitted with simple lens-guides, similar to those used in medical endoscopes. Their initial research was with the use of lens-guides to transmit images within buildings. This "optical television" resulted in images of a quality high enough to read fine print at a distance equivalent to three stories. Although their experimentation focused on viewing objects or persons at a relatively close distance to the end of the lens system, they suggested that modified lens-guides could be constructed for viewing distant objects, for example for seeing a view of the outdoors from interior rooms.

### 3.1 Experimentation and Prototype Development

Based on the available chase space and an estimate of appropriate focal lengths, two large fresnel lenses were acquired. Two additional lenses were borrowed from Michael Duguay at Bell Labs in order to set up a trial system. Moveable stands for holding the lenses were constructed and were set up in different configurations in the foyer of the Architecture School. It was found that for projecting long-distance images the spacing of lenses based on the close-up image, interior building projection system did not work. One problem was that our lenses had different focal lengths; another was that the focusing point of the image changed as the object became more distant, which of course affected the propogation of the image through the entire system. A satisfactory configuration of the lenses was reached--after simple trial-and-error experimentation. An observer at 3-4 meters from the final lens would see its 61 cm. diameter filled with an image of whatever objects were 4 meters or more in front of the first lens in the series. Refinements in image clarity were found to be possible with minor movement in the first lens, which also changed the angle of view of the final image. Changing the focal length of the first lens by adding one inch of water in front of it also had the effect of improving image quality. We determined that the best optical quality lens should be placed first in the series to produce the sharpest final image.

In the controlled setting of the foyer of the Architecture School, it was possible to use a small laser to align the system. With this capability for fine tuning, a high level of accuracy in alignment could be achieved. A surprising aspect of the system resulting from this accuracy was the remarkable three-dimensionality in image appearance; an arm projected toward the first lens, for example, would appear to come out of the viewing lens. This excellent 3-D quality, according to Duguay and Aumiller, is a function of precise alignment of the optical axis of the lenses, the viewer, and the object viewed. The Bell researchers also suggest that clarity and depth are enhanced because light entering the eye goes through every other lens only over tiny regions roughly the size of the human iris, thus those portions of the system act as high f/number lenses.

## 4. FINAL DESIGN AND CONSTRUCTION

The linear lens arrangement in the controlled setting of the Architecture building foyer had to be modified by the realities of constructing the final system. The lenses borrowed from Dr. Duguay needed to be replaced by permanent lenses, and the arrangement had to fit the existing roof opening and room configuration. Purchase was negotiated for two 46 cm. diameter plastic plano convex lenses of 1.49 m. focal length from Applied Products Corporation of Horsham, Pennsylvania. These complemented the two 61X91 cm, 1.32 m. focal length fresnel lenses purchased earlier. We also received a valuable gift from Applied Products Corporation, a 33X69 cm. rectangular plano convex lens of 2.13 meter focal length which had been chipped slightly following manufacture. Several large surplus mirrors had been obtained for the sunlighting project indirectly from the Sandia Labs Solar Power Tower project. Two of these thin-surface glass, laminated mirrors were cut for the lens-guide project. Total cost of materials was a little under $500.

The entire experimentation phase that had been undertaken with the linear configuration had to be repeated with the new lenses. Initially, a right side up, clear image could not be obtained using both fresnel lenses. The previous success was eventually replicated, however, this required utilizing the 33X69 cm. rectangular lens as the final viewing lens. This cut down the total viewing area. After refinements in spacing, mirrors were added to turn the image and cardboard apertures were constructed to test the boundaries of the image-carrying beam of light. By utilizing the cardboard apertures, an approximation of the image boundaries was determined which satisfied the limits of the existing chase. The length of the final four lens array, however, was too long for the established distance between the second floor viewing area and the enclosure on the roof which housed the secondary mirror of the heliostat and provided thermal closure. This problem was solved by modifying the design to include an extension stand to hold the first imaging lens about 2.5 m. away from the thermal enclosure on the roof. A horizontal diagram of the final spacing and image transmittal is shown in Fig. 1. (shown on following page).

### 4.1 Construction

Construction of the lens-guide system was

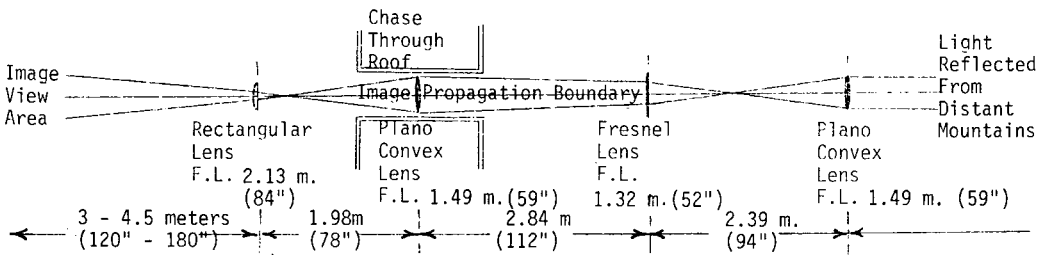



Fig. 1. Lens-guide, linear dimensions.
University of New Mexico, School of Architecture and Planning.

complicated by several factors. First, in order to achieve the desired view (the Sandia Mountains as opposed to the neon strip of East Central Avenue), the system had to be pointed 35-40 degrees east of due north. The rectangular hole in the roof was oriented on a north-south axis. Because the heliostat system occupied the southern half of the opening, the partition separating the beam of light from the heliostat interfered with full use of the lens system hole at the required angle of view. The solution was a compromise; a mirror was cut which fit the compound angle of 45 degrees in the vertical plane (to turn the image downward) and 35-40 degrees in the horizontal plane (to capture the view). Although the turn was satisfactorily accomplished, some portion of the total possible view was lost. Another unanticipated problem was the danger of fire produced by the sun shining through the extended lens on the roof. At certain times of the day, focused sunlight was sufficiently concentrated to ignite wood or other flammable materials. This problem was solved by constructing a lightweight shell above and along the southern exposure of the path between the extended lens and the second relay lens which was mounted in the thermal enclosure. This shell had to be perforated and securely anchored to resist Albuquerque's powerful winds.

As constructed in the UNM building housing the School of Architecture and Planning, the lens-guide viewer is quite striking in appearance and seems to cause surprise and fascination in viewers who come upon it for the first time. As a person tops the stairs leading to the second-floor design studio, a glimpse of bright sunlight and outside activity captures one's attention. The 33X69 cm. TV-like viewer is mounted above eye height beyond a small partition wall defining the studio space. It alternately brings brilliant sunlight, the warm hues of sunset on the mountains, or the night lights of the city into view from the interior of the studio. The natural colors and the quality of image indicate that this is not an electronically reproduced image, but most convincing is the fact that by moving your viewing position within the imaging cone one can see a slightly different viewing area. This phenomenon appears to cause a realization in viewers that the image is a real-time view and not an electronic reproduction. A diagram of the UNM reproduction is shown in Fig. 2. (shown on following page).

## 5. APPLICATIONS OF LENS-GUIDES

The importance of the experimental lens-guide viewer at the UNM School of Architecture and Planning is as a demonstration of a concept with tremendous creative and practical application in the fields of resource-conserving architecture and environmental design. The ultimate use of lens-guide systems remains in the hands of future designers; however, suggestions can be offered for further research in areas with psychological need for visual contact with the outside or with the need for free, uninterrupted viewing.

The low cost of construction and the positive user response to the UNM prototype indicate that lens-guide "windows" could have many applications in office environments, universities, or other institutions. Perhaps underground housing or building complexes are the most obvious application of the concept. Prisons offer another area with potential for beneficial use of lens-guide windows.

The inter-office applications of lens guides, initially explored by Duguay and Aumiller, also offer many possibilities. Real-time, face-to-face contact, observation of restricted areas, or observation of difficult-to-access mechanical equipment are a few possible uses of lens guides. Lens guides could open up a variety of options in architectural programming.

Aesthetics or quality of environmental concerns offer additional areas with possible lens guide uses. For example, in the hands

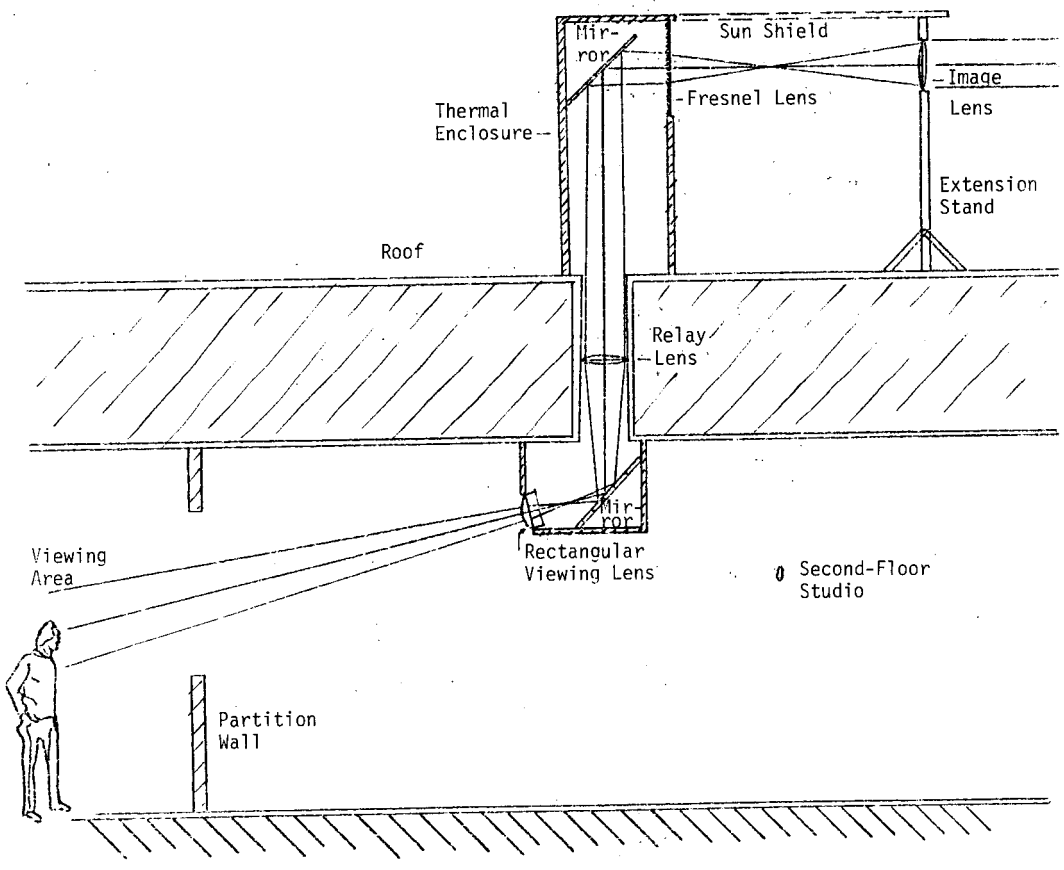



Fig. 2. UNM Lens-guide Viewing Window.

of a creative interior designer, the lens-guide window could enhance the sensory stimuli of a fine restaurant. Aesthetic applications also could be appropriate in the home by bringing landscape architecture to interior spaces.

In sum, lens guides appear to have a great deal of potential for enriching the design field and conserving energy. This technology is an application of daylighting which has been largely ignored--that of transmitting information. The clarity and 3-dimensional quality of lens guides can be compromised by dust and by imperfections in lens alignment, but the visual impact remains a strong stimulus to the imagination. The UNM project has been a pioneering effort at a low-cost application of an affordable technology, however, it has also demonstrated unexpected and potentially significant aesthetic and psychological benefits. The authors of this paper invite optical engineers, architects, industrial designers, and home builders to refine this tool and to develop widespread applications.

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# HEATING SEASON RESULTS FROM THE BONNEVILLE POWER ADMINISTRATION CLASS B PASSIVE SOLAR MONITORING PROGRAM

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## ABSTRACT

Thermal performance monitoring results for the 1982/83 heating season from sixteen passive solar houses located in the Pacific Northwest are presented. Use is made of the SERI Class B monitoring methodology. Design effectiveness implications of the data, and comparison with design tool predictions are discussed. The houses are located in Portland, Oregon, and Spokane, Washington. They were designed under the Bonneville Power Administration's Solar Homebuilders Program.

## 1. INTRODUCTION

In compliance with the Pacific Northwest Electrical Power Planning and Conservation Act of 1980 (P.L. 96-501), the Bonneville Power Administration (BPA) has been operating a number of conservation programs and studies. Under the BPA Solar Homebuilders Program, sixteen new passive solar houses are being monitored using the SERI Class B methodology and equipment (1). This program was closely modelled after the SERI Denver Metro Program. Monitoring results for the period of October 1982 through March 1983 for those houses are summarized in this paper.

## 2. DESCRIPTION OF THE HOUSES

The sixteen passive solar houses monitored were constructed in the spring and summer of 1982, six in Hillsboro, Oregon, and ten in Spokane, Washington. The houses are contiguous at both sites. One house in Spokane was not monitored (because no agreement could be reached with the homeowner) and an adjacent house not constructed under the program was monitored in Hillsboro.

Characteristics of the houses are summarized Table 1. Average floor area was 147 $m^2$, or somewhat smaller than the surrounding houses, and average sales price was $87,000 or $590 per $m^2$. This reflects both the market for which they were designed and an effort, especially on the part of the designers, to achieve low energy consumption. In floor plan, they are relatively compact, open designs with generally three bedrooms and two baths.

### 2.1 Construction

All the houses are conventional wood frame designs. Most houses in Hillsboro have crawl spaces, and most in Spokane have unheated basements, with most having at least partial attics. In style, the houses vary from mildly solar tract designs to moderately solar, custom designs. Average cost of the solar and extra conservation features as reported by the builders was $3000.

### 2.2 Conservation

Energy conservation was emphasized by BPA during design review as a prerequisite to the passive solar design. Average overall heat loss coefficient for the houses was 0.17 $kW°C^{-1}$ or 1.2 X $10^{-3}$ $kW\ °C^{-1}M^{-2}$ normalized to floor area as measured by electric coheating as specified in (1). This compares to 1.7 to 2.3 X $10^{-3}$ $kW°C^{-1}M^{-2}$ for houses meeting local building codes (Oregon).

These low levels were achieved in large part by air infiltration reductions. Average leakage area for the houses was 480 $cm^2$, or 3.3 $cm^2\ M^{-2}$ (averaged from two blower door tests per house) and average estimated seasonal air exchange rates were 0.29 ACH using analysis specified in (2). Most houses had 2x6, R-19 walls, many with insulated sheathing, and R-38 ceilings. All were double-glazed, and many had hollow metal insulated doors, and an air lock entrance. Careful attention was paid to caulking and weatherstripping.

## 2.3 Heating Systems

All but one house in Hillsboro was electrically heated and all but one house in Spokane was gas heated, reflecting local fuel prices and practices. The gas furnaces were mostly high efficiency models (although not condensing) and all were moderately oversized; the average estimated ratio of design heat load to furnace output was 0.35. Following standard practice in Spokane, furnaces were located in basements with ducts taped but not insulated, and in most cases, with no floor insulation between house and basement. This practice, designed to prevent freezing temperatures in basements, resulted in relatively low (measured) overall heating system efficiencies; an average of 0.46 for gas furnaces.

## 2.4 Passive Solar

In solar design, ten of the sixteen houses incorporated sunspaces, two incorporated masonry storage walls, and four used direct gain only. The popularity of sunspaces was due in part to perceived sale appeal by the builders. Adequate mass and properly sized glazing areas were emphasized by BPA during design review. The average ratio of directly illuminated, exposed thermal mass area to aperture area achieved was approximately 1.5.

Most of the sunspace designs incorporated a transfer fan to move heat into the living zone, and some incorporated exhaust fans for summer overheating. Natural ventilation was emphasized in design review, but was not always deemed practical by the builders. Both manual and automatic fan controls were utilized, but as discussed below, transfer of heat from sunspaces was not particularly efficient.

# 3. MONITORING METHODOLOGY

Use has been made in this program of the SERI Class B passive solar monitoring methodology and equipment as specified in (1) with several minor modifications. An extension of the methodology was made in order to estimate energy savings attributable to conservation and passive solar features employed. This information, while not unambiguous, is required for purchase of conservation savings by BPA as a power acquisition. Such acquisitions form the basis of BPA's conservation activities.

## 3.1 Class B Monitoring

Class B monitoring makes use of a microprocessor-based data acquisition system (DAS) temporarily wired into each house with ten to twenty standardized channels of continuous input. A number of thermal calibrations are also prescribed, as well as standardized data reduction software centered around a one zone heating energy balance for the building. This data reduction is performed by the DAS in real time and printed to paper tape for a quick approximate check of house and DAS operation. It is also performed more carefully with a modest time delay in a central processing facility and reported monthly to builders and homeowners in standardized form. This data management strategy minimizes ambiguous and missing data through rapid and thorough data analysis. Details of the Class B measurements, calibrations, and analysis are fully specified in (1).

Institutional arrangements are often as important as experimental technique in monitoring building performance. In this program, a formal agreement was signed with each homeowner to permit access and regulate distribution of the data. A fee of $300 was also paid to homeowners to compensate for nuisance and for not burning wood for the duration of the monitoring. (Twelve of the sixteen houses had and would have used wood stoves without this arrangement.)

For unoccupied houses, (four of sixteen houses were unoccupied for the entire monitoring period, and an additional four for part of the period) heating systems were left operating in a normal mode with thermostats set to 65 °F. Water heaters and some lights were also left on.

## 3.2 Energy Balance

Class B analysis is centered around determination of a monthly one-zone heating energy balance for the living zone of the house (heated floor area). This balance can be expressed as:

$$Q_l = Q_a + Q_i + Q_p \qquad (1)$$

Where:

$Q_l = L\int(T_i - T_o)dt$ = Monthly overall heat loss from the living zone

$Q_a = \eta E_a$ = Monthly heat delivered to the living zone by the auxiliary heating system

$Q_i$ = Internal heat gains delivered to the living zone (lights, metabolic, and appliance corrected for heat loss outside the living zone)

$Q_p$ = Solar and other heat gains delivered to the living zone not accounted for in $Q_a$ and $Q_i$

and

L = Measured overall heat loss coefficient (wind corrected monthly)

$T_i$ = Spatial (UA weighted) average living zone temperature

$T_o$ = Outside temperature

$\eta$ = Measured heating system delivery efficiency (constant)

$E_a$ = Measured heating system input energy

This energy balance methodology is discussed more fully in (1).

As a check on the basic energy balance, $Q_s$, the monthly solar radiation transmitted through the total aperture glazing was also calculated. Measured vertical solar radiation incident upon the major aperture of each house was used (aperture as defined in (3)), and an average transmittance of 0.8 was assumed.

For most direct gain buildings, agreement between $Q_p$ and $Q_s$ to within 15% for most months of the heating season is possible. For storage wall and sunspace houses, this discrepancy will be larger and can be used as an indication of system efficiency.

## 4. MONITORING RESULTS

Monitoring equipment was installed during the summer of 1982, and data collection began in October. This paper reports heating season results (October, 1982 through March, 1983). Average data recovery for this period was 92% (range 57% to 100%) of possible channel hours. To generate monthly performance parameters from incomplete data sets, all totals were scaled by the ratio of possible to actual channel hours. (Average quantities were not scaled). This procedure is not very accurate for such fluctuating quantities as solar radiation and heating energy for monthly data recovery fractions less than about 70%. Such cases amounted to 7% of the available months, and these months have been included in performance averages. Monitoring will be continued through September, 1983, in order to assess summer performance.

### 4.1 Occupancy Related Performance

Figures 1, 2, and 3 display observed variation for occupied houses in two occupancy-related performance factors, per capita internal gains, and average inside temperature. The observed distribution of monthly average daily per capita internal gain is shown in Figure 1. The monthly internal gains are related to family size, although the sample size is too small here to determine a correlation, and are quite consistent at a particular house. The observed daily average per capita internal gain of 35±12 MJ/day-capita is somewhat higher than conventional estimates (20 MJ/day-capita). This may be due to the small average family size of 2.2, and the relatively high socioeconomic level of the families.

The observed variation in monthly average spatial average living zone temperature is displayed in Figure 2. Not all occupants used night setback. Only one home maintained some zones significantly colder than average. The overall average was 19 ± 2 °C.

### 4.2 Energy Balance

Table 2 summarizes the relative sources of space heating energy for the monitoring period for occupied houses. On an average, internal gains and auxiliary heating made up slightly over one third of the heating requirements each. Total available solar energy over the monitoring period (transmitted through aperture glazing) was on an average, about equal to total heating load ($Q_l$). The average passive solar contribution (24%) was perhaps twice or three times that for average energy conserving houses in the Pacific Northwest.

### 4.3 Solar Performance

The energy terms discussed above, $Q_p$ and $Q_s$, can be used to estimate how effectively the available solar energy was used for space heating. In particular, from Eqn. 1, the auxiliary heating energy, $Q_a$, is bounded by $Q_{a,max.} = Q_l - Q_i$ ($Q_p = 0$, no utilization of available solar energy) and $Q_{a,min.} = Q_l - Q_i - Q_s$ ($Q_p = Q_s$, full utilization of available solar energy). The actual auxiliary heating energy would be expected to be between these two limits ($Q_p \geq 0$). Due to thermal losses and venting of excess solar gain, monthly $Q_a$ would not be expected to be as low as $Q_{a,min.}$, especially for low thermal mass cases and especially for fall and spring months. The "utilization", $Q_p/Q_s$, is one measure of these effects.

In order to separate system thermal efficiency from overall solar utilization,

the USDOE Volume 3, Methodology (3) was used to estimate performance under optimum design and operation conditions. For these calculations, measured values of degree days, insolation, and $Q_i$ were used. Monthly BLC's were derived from measured L and measured $T_i$ was used for $T_{set}$. Correlations were chosen from the 94 standard system types without modification by sensitivity factors. The predicted monthly auxiliary heating is denoted $Q_{a,SLR}$. Results of this analysis are summarized in Figure 3, which displays auxiliary heating parameters averaged over all houses. Table 3 displays the average over all houses and by system type of the utilization, $Q_p/Q_s$, where $Q_p$ and $Q_s$ have been summed per house over the monitoring period. It can be seen that the average utilization was less than that predicted for ideal conditions (0.4 as compared to 0.5), and that sunspaces seemed to have significantly more inefficiencies than direct gain systems (0.28 as compared to 0.51). (Too few storage walls were available for a meaningful average).

This performance variation by system type is also evident in Table 4 which summarizes predicted and actual auxiliary heating summed over the monitoring period. Agreement is good for direct gain, but sunspace auxiliary heating is underestimated significantly.

## 5. Discussion

A number of implications can be drawn from the above performance results. It should be noted that the 1982/83 heating season was relatively mild; 65°F degree days were 10% below normal in both Hillsboro and Spokane, and the horizontal insolation was 20% high in Hillsboro and 10% high in Spokane for the period.

### 5.1 Sources of Error

The analysis outlined above is based upon a number of assumptions which introduce, in general, more uncertainty than the less significant instrumentation and data reduction errors. Some of the most important are outlined here.

The energy balance calculated for each house makes use of several one-time measurements, or thermal calibrations. The overall loss coefficient, L, has been approximately corrected for variations due to wind on a monthly average basis by modifying measured infiltration parameters. Nonlinear wind effects and other variations such as ground coupling will introduce additional error. Furnace delivery efficiency, $\eta$, is assumed constant for the monitoring period, but part load and basement temperature variations will introduce error. Additionally, although both of these measurements were made with the house well stabilized for a number of days prior to the test (1), and no monotonic variation in $T_i$ was allowed, long time constant storage transients could have been undetected. This is particularly true for basement houses. The resulting error in L and $\eta$ are probably on average in the range of 5% to 20% .

The internal gains, $Q_{int.}$, have been estimated from overall energy consumption corrected for various appliance and occupant effects (1). Treatment of dryer and water heater space heat gains, motor power factor, dehumidifier COP, spa latent heat, and average occupancy, introduce errors probably also in the range of 5% to 20% of $Q_{int}$.

It should also be noted that the utilization parameter, $Q_p/Q_s$, is somewhat ambiguous, because $Q_p$ is a subtractive term which includes aperture solar gains, as well as non-aperture solar gains, sol-air effects, and errors in $Q_l$, $Q_a$, and $Q_i$. Comparison of $Q_a$ and $Q_{a,SLR}$ can, however, still be made in order to investigate system efficiency.

### 5.2 Sources of Non-Ideal Performance

On average, the difference between average $Q_a$ and $Q_{a,SLR}$ was significant only for sunspace designs, and was apparently due to poor utilization of available solar energy (Tables 3 and 4, and Figure 3). This was very likely due to poor heat transport to the living zone. Several principal reasons are discussed briefly here.

For sunspace designs, some transfer fan arrangement was specified by designers typically using automatic controls. These fans were not always correctly, or even completely installed by the HVAC contractor. This was apparently due to unfamiliarity with the systems and poor supervision by builders, and in some cases was not corrected until well into the heating season.

Many systems incorporated the transfer fan controls and/or ducting into the back-up HVAC system. This resulted in thermal comfort problems, because the sunspace air was, in general, too cool for delivery at furnace flow speeds. Several such systems had to be disabled. Also, excess thermal losses occured due to use of HVAC ducting to deliver sunspace air long distances.

Finally, occupants were not adequately instructed by builders and designers in sunspace operation, including use of manual vents, and fan controls. Although most did become familiar with system operation during the heating season, operation was somewhat unreliable (particularly opening night insulation, closing doors and turning off fans to the living zone). This seems to be due to unfamiliarity, more than lack of interest or effort.

### 5.3 Data Availability

The above heating season analysis is not intended to be complete or thorough, and additional analysis is underway by BPA. The data are available for analysis by other investigators (including hourly data, monthly performance factors, and complete house descriptions), and we would welcome such a collaboration.

## 6. REFERENCES:


1. Frey, D. et al; "Installation Manual for the SERI Class B Passive Solar Data Acquisition System", SERI/TR-254-1671, November, 1982.

2. Grimsrud, D. et al; "Infiltration Measurements in Audit and Retrofit Program"; LBL-12221.

3. Balcomb, J. et al; "Passive Solar Design Handbook, Volume 3, USDOE, 1983.


TABLE 1: HOUSE CHARACTERISTICS

| Sites | No. Sites | No.Occ'd Sites | Fl.Area ($m^2$) | Price $10^3$ $ | Aper. ($m^2$) | Type DG | Type TW | Type SS | Total UA (kW/°C) | Lkg.Area ($cm^2$) | Inf'n Rate (ACh) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hillsboro, Oregon | 7 | 3 | 137 | 92 | 16 | 3 | 1 | 3 | 0.17 | 425 | 0.32 |
| Spokane, Wash | 9 | 9 | 154 | 86 | 24 | 1 | 1 | 7 | 0.18 | 523 | 0.27 |
| All sites | 16 | 12 | 147 | 89 | 21 | 4 | 2 | 10 | 0.17 | 480 | 0.29 |

TABLE 2. AVERAGE HEATING SEASON ENERGY BALANCE*

| Site | $Q_a/Q_l$ | $Q_i/Q_l$ | $Q_p/Q_l$ | $Q_s/Q_l$ |
|---|---|---|---|---|
| Hillsboro | 0.42 | 0.34 | 0.24 | 0.93 |
| Spokane | 0.35 | 0.40 | 0.25 | 0.91 |
| All Houses | 0.39 | 0.37 | 0.24 | 0.92 |

*Occupied houses only, energy terms summed over heating season

TABLE 3. AVERAGE HEATING SEASON UTILIZATION*

| System Type | $\frac{Q_p}{Q_s}$ Average | $\frac{Q_p}{Q_s}$ Std.Dev. | $\frac{Q_l-Q_i-Q_{a,SLR}}{Q_s}$ Average | $\frac{Q_l-Q_i-Q_{a,SLR}}{Q_s}$ Std.Dev. |
|---|---|---|---|---|
| Direct Gain | 0.75 | 0.27 | 0.53 | 0.63 |
| Sunspace | 0.28 | 0.14 | 0.51 | 0.11 |
| All Houses | 0.40 | 0.26 | 0.50 | 0.20 |

* Energy terms summed over heating season.

TABLE 4. AVERAGE HEATING SEASON AUXILLIARY HEATING

| System Type | $Q_a$ (MJ) Average | $Q_a$ (MJ) Std.Dev. | $Q_{a,SLR}$ (MJ) Average | $Q_{a,SLR}$ (MJ) Std.Dev. |
|---|---|---|---|---|
| Direct Gain | 14 | 8 | 14 | 6 |
| Sunspace | 20 | 8 | 11 | 8 |
| All houses | 18 | 8 | 12 | 8 |

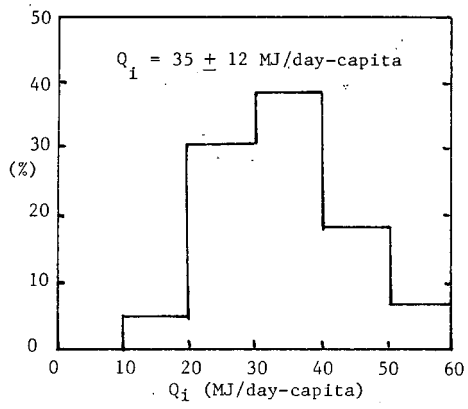



Fig. 1. Variation in Monthly Average Daily Internal Gains.

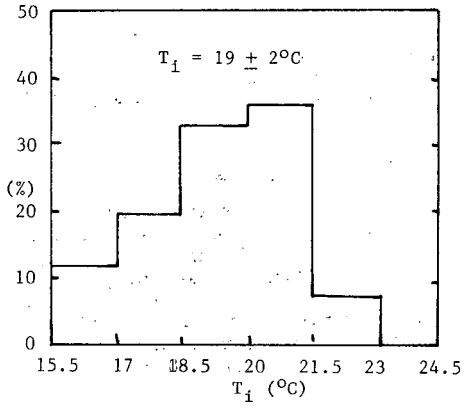



Fig.2. Variation in Monthly Average Indoor Temperature.

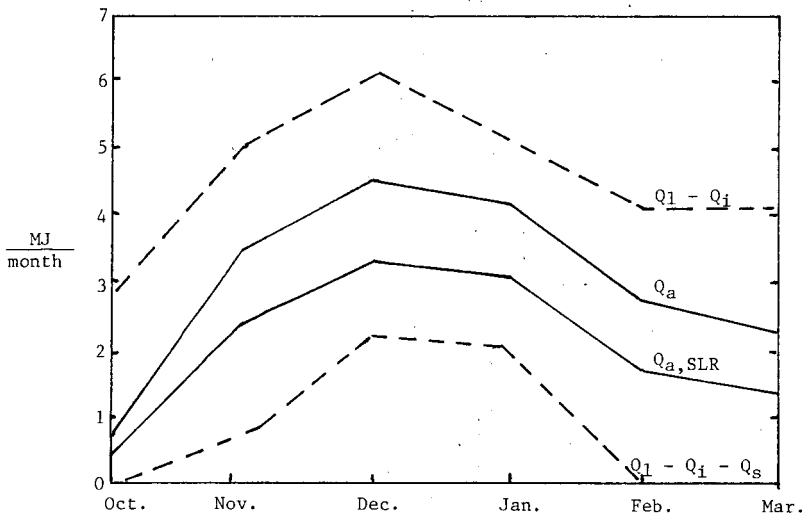



Fig. 3. Monthly Auxiliary Heating; Measured, Predicted, and Bounded.

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# INSTRUMENTATION AND DATA ANALYSIS FOR BUILDING ENERGY MONITORING

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## ABSTRACT

This paper relates the result of our efforts, spanning several years, toward the goal of making low cost and meaningful thermal measurements on buildings. Experimental pitfalls are illustrated with examples and suggestions for better experimental procedures are given. A data acquisition system using a powerful portable microcomputer in conjunction with compact data acquisition modules is discussed.

This paper also discusses real time data analysis methods that may prove useful for short-term performance monitoring. Results of some data using recursive, digital filtering algorithms are presented. These algorithms when programmed on the computer (which can sense and respond in real-time in the physical world using the data I/O modules) form a system with an order of artificial intelligence. The goal of this intelligent system is to form an Energy Signature for the building. The Energy Signature consists of several equivalent thermal parameters of the building which form an energy signature characterizing the building.

## 1. INTRODUCTION

To some the notion that we need to instrument buildings to understand and quantify their thermal performance must seem a foolish waste of time. Our magazines and books concerned with solar design are filled with elaborate descriptions of "how it works", complete with colored drawings showing red heat-arrows wiggling through vents in Trombe walls to escape blue cold-arrows, etc.. This powerful combination of artistry and sophistry can leave us with a conviction that there is little left to be learned.

Experience shows the thermal behavior of a building is a composite resulting from the interaction of a large number of subtle and interrelated thermal mechanisms. The intuitive "descriptions" are often just misleading fantasies. The scientific documentation and delineation of the mechanism presents a nontrivial task in measurement and interpretation.

My work in the area of instrumenting buildings for thermal characterization has only spanned a few years. (1-4) During this time I have had the opportunity to make a lot of mistakes in my programs and to observe a lot of mistakes in other programs. Many of these mistakes can be anticipated and avoided if we maintain a balanced view of the experimental process.

Personal interests, preferences and orientation tend to distort the experimental process. The theoretician hopes the experiment will produce data to verify his pet model. The instrumentation hardware specialist may focus on cute ways to measure things. The project manager wants a thick final report to show his boss. All of the people (or functions) are a necessary part of the experimental process. Experimental failures result when one of these separate interests, functions or orientations dominate the experiment.

## 2. EXAMPLES OF EXPERIMENTAL PITFALLS

(1) Only a few months ago I heard a presentation of results of a building thermal performance monitoring program. The speaker expressed pride in the fact that their print-out of monitoring data was 4 meters high! They were measuring over 100 transducer channels. The presentation of results was a plot of daily auxiliary energy versus degree-days which could have been made by a 12 gauge shotgun at 10m. The minicomputer found a straight line through these points having a correlation coefficient of 0.42 and everyone was apparently pleased with the results.

The instrumentation in this experiment was very powerful and apparently carefully calibrated and maintained. The analysis model was woefully inadequate and this led to results having little information.

(2) Another building research project used a quality data logger to measure 113 transducer channels. Data tapes had been collected (but not analyzed) for 4 months when an intermittent electronic problem was noticed. Internal elec-

trical gains were not being measured and the building was regularly ventilated with a fan that was not instrumented. These two "unknowns" were major features (15 to 35%) of the building energy balance.

The instrumentation hardware was adequate in this case but it was not properly maintained and was not used to measure all the important variables. Better experiment design and equipment maintenance would have enormously increased the significance of this effort.

(3) I observed another monitoring effort conducted by a respected national solar data monitoring group. This experiment was well formulated and the instrumentation hardware and software was excellent. The temperature transducer "measuring ambient air temperature" was mounted near the mouth of a building air vent, on the west side of the building in direct sunlight. A plate was soldered to the transducer making it a better solar collector! Fluid temperature probes were mounted to the surface of the pipes and their readings were erratic. These probes were jiggled around until the readings "seemed reasonable".

The installation of the transducers in this short-term experiment was less than optimum. This produced uncertainties in the results. The "portable" instrumentation system occupied several crates weighing over 200 kg. It was a centralized (rather than distributed) data acquisition system. Two trained technicians spent 4 days installing over 150m of wire to set up the test and one day in removing the instrumentation. Two days of data were collected. A similar effort on another building produced no usable data.

(4) I visited four different projects located around the country where dozens of solar DHW systems had been instrumented with heat meters for performance monitoring. Inspection of the installations coupled with elementary cross-checking of the data showed that at least 80% of the data were worthless. The basic faults were related to equipment failures and improper installation. The participants in the program lacked an appreciation of the art of successful measurement.

(5) Three years ago I was analyzing data on a small building incorporating active air collectors. Specific data on the collectors showed they were leaking badly and were not contributing significant solar heat to the building. The hourly heat balances clearly showed errors when the sun was shining. I had overlooked the fact that the south facing glazed area was nearly equal to the collector area. The analysis model was modified to include direct solar gain through the windows and the hourly heat balances improved dramatically.

These examples are included to illustrate the types of problems that occur during experimental projects. Some of these problems can be avoided.

## 3. REVIEW OF EXPERIMENTAL PROCESS

The goal of an experimental measurement program is to provide answers to questions that cannot be economically or accurately answered in any other way. A "good" experiment will provide answers having adequate accuracy at a minimum cost. The milestones for the execution of an experiment are INSTRUMENTATION, DATA, MODEL and RESULTS and a report on the elements of an experiment will often be presented in this order. It is important to recognize that milestones during the design phase of the experiment occur in exactly the opposite sequence, Figure 1.

The first step in the Design Phase is to decide what we want to know at the end of the experiment; what RESULTS are needed. We then select or devise a conceptual model representing the system and establish what input data must be measured to produce the output results. This is a difficult and crucial step in the experimental design procedure. If the MODEL and DATA are well defined the INSTRUMENTATION requirements are clearly specified.

The first step in the Execution phase is to calibrate and install the measuring and recording instruments. DATA are collected over a suitable time-period. These are then processed using the analysis MODEL. RESULTS and their expected errors are then summarized.

If the experiment was well designed and executed the errors will be within the allowed range, the new information and results are reported and the job is done. The process seldom runs this smoothly and often we must loop back to some earlier step and re-do the experiment; perhaps returning to the beginning.

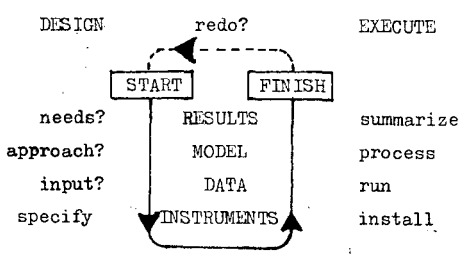



Fig. 1. Experimental Process Model.

## 4. IMPROVING THE EXPERIMENT

### 4.1 Experiment Design

It is impossible to over emphasize the importance of the design phase. This begins with a clear definition of the final results desired and the maximum inaccuracy that can be tolerated.

Next is the evolution of a process model and its associated input data. This activity includes questions like; "How simple can the model be?", "What effects can we ignore?", "What is the error in the result for the worst possible combination of input error?" The value of this analysis is to establish whether there is a significant probability of success, before investing time and money in the actual experiment. Errors are discussed further in the following section on Signals and Noise.

### 4.2 Instrumentation

The steady progress in microelectronics technology has resulted in the availability of cheap and powerful computers and accurate data acquisition equipment. Economic considerations demand the use of these machines for most experiments.

An example of a system suitable for many building monitoring tasks is shown in Figure 2. A portable microcomputer controls the data acquisition, storage, display and processing. A wide range of transducers can be connected directly to the data acquisition modules. The computer communicates with the modules using a digital code carried by a single cable. These modules are located near the transducers to minimize wiring. The system can be expanded by adding more modules as required. One or two modules are adequate for many energy monitoring jobs on small buildings. The whole system costs around $2,000 and can be carried in a brief case. This system is currently being used to control and log data from a side-by-side solar DHW experiment.

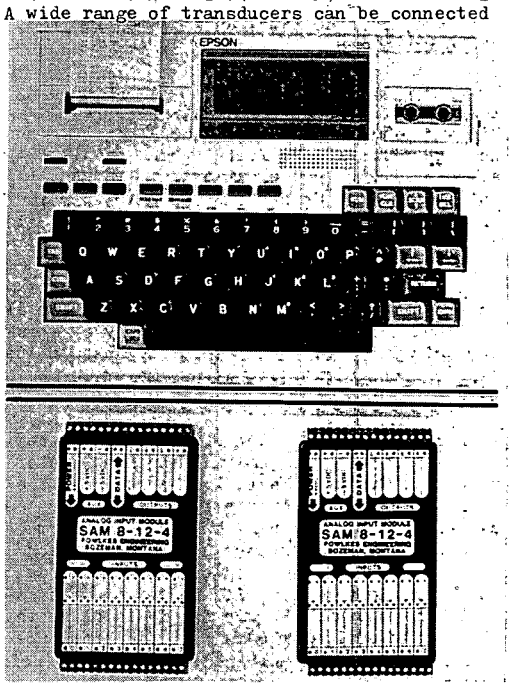



Fig. 2. Portable Data Acquisition System.

Once the data requirements are defined the data acquisition system specifications are easily determined. The crucial considerations in selecting hardware are accuracy, reliability, cost and ease of use. The installation and calibration of the transducers are of utmost importance. The examples of pitfalls given earlier in this paper are not unique. The success of the experiment can be ruined if you are not really measuring what you think you are measuring.

### 4.3 Data Processing and Results

If the experiment has been properly planned you already know what to do with the data as it comes in. It is a good idea to start processing the data as soon as possible. There are two motivations for doing this; (a) it is fun to see if the experiment is working and to find out the initial results. (b) if the experiment is not working you will want to revise it before generating a pile of useless data.

## 5. SIGNALS AND NOISE

Thermal monitoring experiments are usually aimed at measuring some component of energy gain or loss. It is often impossible to specifically measure the component of interest in a real building. The building thermal response is a composite reflecting the interactions of many thermal inputs, outputs and storage effects. Table 1 lists nominal values for 14 identifiable (at least in concept) heat exchange components for a "hypothetical" residence. This data explains why simple energy analyses using limited data such as fuel bills and a simple conductive model often yield results so noisy that general conclusion are impossible.

Assume we have a simple experiment consisting of an electric heater in a small test cell with constant inside and outside temperature. We plot energy input versus $\Delta T$ for a range of values and get a nice straight line. The results show little scatter because we have good control over the important variables.

Now assume that a lab assistant enters the test room several times a day, uses the heater to boil water for coffee, sits and reads his newspaper and opens the window if he feels too hot.

TABLE 1.

NOMINAL DAILY HEAT EXCHANGES, MJ

Heat into Space is Positive

| Description | Winter | Spring/Fall |
|---|---|---|
| Envelope Conductive | -450 | -150 |
| Infiltration, stack | -100 | -40 |
| *Infiltration, stack | -10 | -2 |
| Infiltration, wind | -45 | -15 |
| *Infiltration, wind | -5 | -3 |
| Furnace heat | 400 | 35 |
| *Humidifier | 15 | 5 |
| Electrical dissipation | 120 | 100 |
| *Bathing, Cooking | 20 | 20 |
| Solar gain, windows | 80 | 80 |
| Sol-air effects | ±30 | ±30 |
| Stored heat | ±50 | ±40 |
| Mechanical venting | -20 | -20 |
| *Mechanical venting | -5 | -10 |
| Occupant effects, unknowns | ±30 | ±30 |

*Latent heat exchanges

We now innocently plot our data and the points are scattered all over the page.

The point of this simple example is to illustrate the inevitable noise that enters any experiment. The noise in the hypothetical experiment is a real physical event that we can't control or maybe do not conceive. It is due to a mismatch or a poor fit between our model of the process and whatever is going on out there.

A second type of noise is related to faulty instruments. In principal we can deal with these problems more effectively. Our concepts of properties are better defined and the instruments are simpler systems complete with calibration standards, trouble shooting hints and repair procedures.

## 6. DATA PROCESSING TECHNIQUES

### 6.1 Batch Processing

Many experiments are analyzed using a procedure that may be described as batch processing. The data logger, over some interval of time, produces a "batch" of data. This batch of data is transferred to a computer and statistical algorithms such as linear regression are used to find the "best" values which fit an a priori process model.

This approach is depicted graphically in Figure 3. The model of the parameter represented by the data has a value that is constant with time. The data is scattered due to random noise in the measurements and random noise due to approximations inherent in the simplified process model. The true signal having a value of 100 was corrupted by adding a random value (noise) having a range of ±50.) The best fit to the model is a line passing through 100.

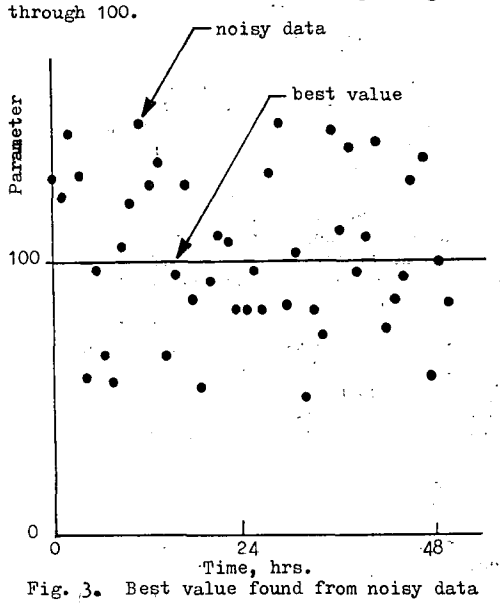



Fig. 3. Best value found from noisy data after test.

### 6.2 Real Time Processing

We have been experimenting with real-time processing of building data. Since a computer is already part of the system it is possible to write programs to keep a running summary of the data, in real time, as it comes in from the sensors.

There are numerous algorithms for processing real-time data. These methods referred to as "digital filters, stochasistic algorithms, recursive filters, observers," etc. Basic to all algorithms is the notion of a current estimate of the true value and rules for improving this estimate in response to new data coming in.

We usually input a starting value, our best estimates before the first data point. We also input information about how noisy we think the data will be. This basically adjusts the gain or sensitivity of the estimator to new data.

To illustrate this general idea we take the example data set and imagine the response of an estimator that reacts to the new data one point at a time. We give it a starting value of zero out of playfulness. We could formulate a "fickle estimator" that assumes each new data point is the true value. The graph of the history of the fickle estimator's estimate is shown in Figure 4. It is clear that the fickle estimator doesn't learn from experience and does not help us filter out the noise.

For contrast we could formulate a hypothetical

"conservative estimator" and give him a starting value. As the data comes in the conservative estimator slowly and sluggishly responds to the data, Figure 4. Given a sufficient time the conservative estimator may converge on the true value.

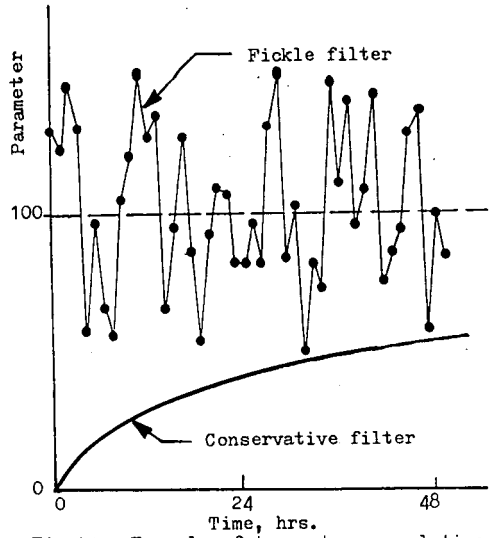



Fig. 4. Example of two extreme real-time estimators or filters.

Neither of these estimators or filters appears very helpful for finding a best value in a short time. Fortunately much mathematical work has been done to develop smarter and more optimal estimators or filters. (5) A good example of an optimal filter is the Kalman filter developed in the 1960s (6).

### 6.3 Smarter Filters

The Kalman filter "catches on" to the trend of the data and can find the best value rather quickly. At each new data point it reevaluates it's current gain or sensitivity and thus, in a sense, learns from experience to make better estimates. As it approaches the best value it becomes insensitive or conservative and starts to ignore the noisy data. (We have "warned" the filter about the noise in our formulation of the problem.) Another property of the Kalman filter is that it eventually finds the same best value that we would find by processing a batch of data using standard regression methods.

A computer simulation of the response of a Kalman filter to our noisy test data set is shown graphically in Figure 5. Note that after only 15 data points it is within 5% of the true value. After 20 points it is locked in on the true value and never varies more than $\pm$ 1%.

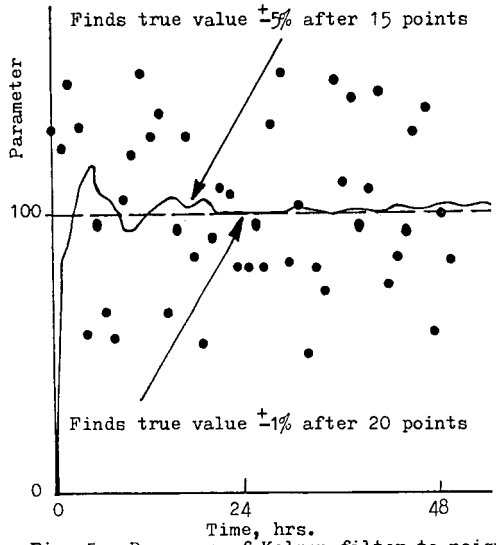



Fig. 5. Response of Kalman filter to noisy data.

## 7. APPLYING REAL-TIME PROCESSING

We have applied the method of real-time filtering or estimation to processing building thermal response data. An energy balance equation for the building is formulated in terms of unknown coefficients and measured driving forces. The coefficients are terms like overall envelope conduction factor, equivalent solar aperature, equivalent thermal mass, etc. This set of coefficients forms an Energy Signature for the building. (7,8) The measured driven forces are temperatures, solar radiation, electricity entering the building, etc.

Each coefficient is given a "reasonable" starting value. At each stage of the process, the new data is fed into the energy balance equation and the error or imbalance is determined. The error is partitioned and each coefficient is adjusted in the direction of smaller error according to a filter algorithm.

Table 2 shows the behavior of a Kalman filter using hourly raw data from a building we monitored three years ago. A simple 5 element model was used to represent the building and the filter parameters were fairly crude. The first part of the table shows the results after 24 and 48 hours when the filter was given "good" starting values. The second part shows the estimates resulting from "poor" starting values. For comparison we have shown the values we derived after analyzing 10 weeks of hourly data.

The remarkable fact is how quickly these crude filters approach the long term values. These data suggest that if the proper filters were

included within the data acquisition program results could be made available, in real-time at the site. The computing power required is easily within the capability of the system shown in Figure 2. Further work is needed to test the adequacy of the thermal model and to study the response of different filters.

TABLE 2.

FILTER RESPONSE TO REAL DATA

| TIME | BUILDING U | FURNACE OUTPUT | ELECTRIC RECOVERY | SOLAR RECOVERY |
|---|---|---|---|---|
| hrs. | MJ/°C-hr | MJ/hr | MJ/MJ | MJ/MJ/m$^2$ |
| 0 | .67 | 18 | .9 | 2.4 |
| 24 | .66 | 20 | .8 | 2.2 |
| 48 | .61 | 23 | .9 | 2.2 |
| 0 | .46 | 28 | 1.0 | 2.8 |
| 24 | .61 | 21 | .7 | 2.7 |
| 48 | .62 | 22 | .7 | 2.7 |
| Reference | .67 | 22 | .8 | 2.4 |

## 8. CONCLUSIONS

In this paper I have reviewed some of the problems and pitfalls surrounding the topic of thermal performance measurements of buildings. The effectiveness of this type of work can be improved by careful experimental design and appropriate selection of instrumentation. The combination of cheap, portable, computing power and advanced real-time analysis methods point to a possible avenue for greatly improving our ability to diagnose the thermal behavior of buildings.

## 9. ACKNOWLEDGEMENTS

The observations reported in this paper are based on experience gained while instrumenting buildings for the Department of Energy and the Montana Department of Natural Resources. The instruments and real-time analysis application were developed by Fowlkes Engineering. Sharon Kleingartner is acknowledged for typing and editing this manuscript.

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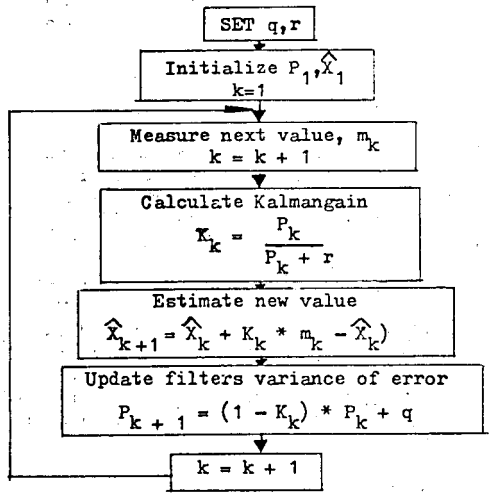
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## APPENDIX 1: KALMAN FILTER




q,r – expected noise, variance
P – error covariance
X – estimate of parameter

Fig. A-1. Flow chart showing Kalman algorithm for estimating parameter based on real-time data. See References (5,6) for complete discussion and derivation.

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# MEASURED PERFORMANCE OF 50 PASSIVE SOLAR RESIDENCES IN THE UNITED STATES

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## ABSTRACT

This paper summarizes the thermal performance of 50 passive solar residences in a variety of U.S. locations. These buildings were monitored as part of the Solar Energy Research Institute (SERI) Residential Class B Passive Solar Performance Monitoring Program.

The paper describes the monitoring and performance evaluation methods and presents the overall heating season performance of the buildings in graphical form. We draw some general conclusions from these results and discuss the validity of extrapolating such conclusions to passive solar buildings overall.

## 1. INTRODUCTION

The SERI Residential Class B Passive Solar Performance Monitoring Program is a low-cost program that evaluates the thermal performance of selected residential buildings throughout the country (1). The goal of this program is to provide a consistent measure of the thermal performance of different types of passive buildings in different climates. Instrumentation is limited to that needed to calculate the monthly building energy balance, separating passive solar heating from the other building energy flows. Thermal storage and other individual components are not monitored, and no attempt is made to determine a building's thermal processes in detail.

Instrumentation began in 1981. At that time, SERI was to coordinate the national program, and the Regional Solar Energy Centers (RSECs) were to oversee the operation of the monitored sites in their regions. More than 60 buildings were instrumented to some degree. However, the regional centers closed at the end of 1981, and SERI assumed the supervision of as many of the sites as possible. We assembled sufficient 1981-1982 data to summarize the performance of 40 buildings (2). In addition, we plan to provide the research community with more detailed monthly performance calculations, hourly raw measurement values, and complete site handbooks that describe the buildings and measurements in more detail.

Also, we instrumented 40 buildings for the 1982-1983 heating and cooling seasons, ten of which are included in this paper. The complete results from these buildings will be available in late 1983, along with comparisons between measured performance results and monthly design tool predictions.

## 2. PERFORMANCE EVALUATION APPROACH

The Class B program features on-site data processing using a standardized microprocessor data acquisition system (DAS). The DAS collects up to 22 continuous measurements every 15 seconds and processes these values in the microprocessor. The system is programmed to calculate daily and monthly performance factors in real time and print them on a daily basis. These real-time computations include the major building energy flows, weather variables, and the other basic monthly performance factors required in the Class B program. With proper DAS programming and operation, these factors, which are the basis of this paper, can be taken directly from the DAS, requiring off-site computation only for statistical data analysis.

The system also produces magnetic data storage tapes that contain hourly averages of the raw continuous measurements. The raw data tapes and the monthly performance factor summaries are transcribed into the SERI computer system for archiving and further analysis. If necessary, the monthly summaries are corrected for any programming errors. If this is impossible, the hourly data are used to calculate the summaries. The hourly data have many potential applications, such as graphic data presentations and statistical building characterization.

Building thermal performance calculations are based on a monthly building energy balance. The energy balance is calculated for a single control-volume that includes the air of the living zone, defined as conditioned space and space that always remains within 10°F (6°C) of conditioned space temperature. This usually excludes attics and garages and includes basements and sunspaces only when the space is conditioned.

The energy balance has four components: a heat-loss component and three gains—auxiliary heat, internal heat, and passive heat. The passive heat used by the building is found by subtracting the measured heat delivered to the building by auxiliary and internal sources from the building heat loss, calculated from measured temperature difference. The passive heat includes the effects of all passive heat gains and losses, not just the direct solar gain through the south-facing glazing. Other passive energy flows include solar gains through east and west windows, solar absorption by walls and roofs, thermal buffering by sunspaces, thermal storage mass effects, and additional infiltration and venting caused by the occupants. Direct measurement of all these energy flows would be difficult and is beyond the scope of the Class B program.

Living zone heat loss is the product of the living zone heat-loss coefficient and the measured indoor-outdoor temperature difference. The indoor temperature is the average of several living zone temperatures, measured at locations that represent the building's major heat loss areas. The heat loss coefficient is measured using electric coheating (3) and is adjusted for infiltration effects, based on pressurization and tracer-gas infiltration measurement (4,5). The building heat-loss coefficient, along with other building and heating system characteristics, is stored in the DAS computer software to be used during the real-time data reduction. Details of the coheating procedure and other measurement techniques are included in the installation manual for the Class B program (6).

## 3. SUMMARY OF RESULTS

Figure 1 shows the overall heating season performance for 50 buildings in the Class B program. Each bar represents the total building heating load divided into passive, auxiliary, and internal heating components. The energy quantities are normalized per unit floor area and degree-day (based on measured indoor-outdoor temperature difference). The buildings are ordered from left to right according to total purchased heating energy (auxiliary plus internal). We will use this value as a building performance index (BPI). At the top of each bar, the south glazing to floor area ratio and passive system types are indicated (DG = direct gain, SS = sunspace, TW = Trombe wall, WW = water wall). We refer to the ratio of the passive heating component to the total heating load as the passive heating ratio (PHR).

The buildings are identified by a three-letter site code. The first two letters denote the region of the country, and the third letter denotes the specific building in the region (DM=Denver, MA=Mid-America, NE=Northeast, SS=South, WS=California). An additional site code prefix, MB, identifies buildings in the SERI Passive Solar Manufactured Buildings Program (MBA is in Denver, MBB is in Wisconsin, and MBD is in North Dakota). Figure 2 shows the location of each building.

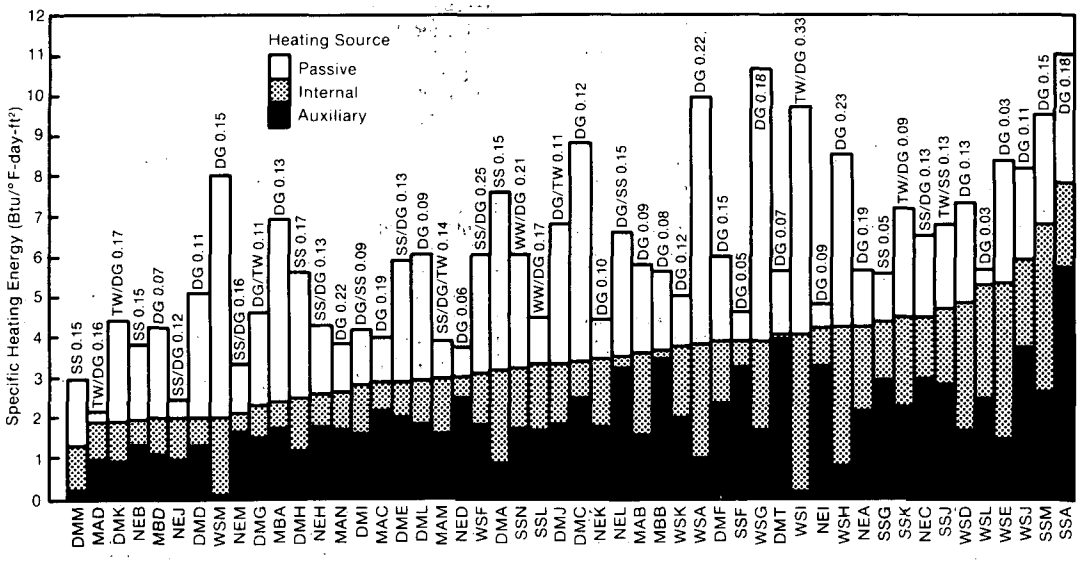



**Fig. 1. Heating Season Energy Summaries for 50 Monitored Buildings**

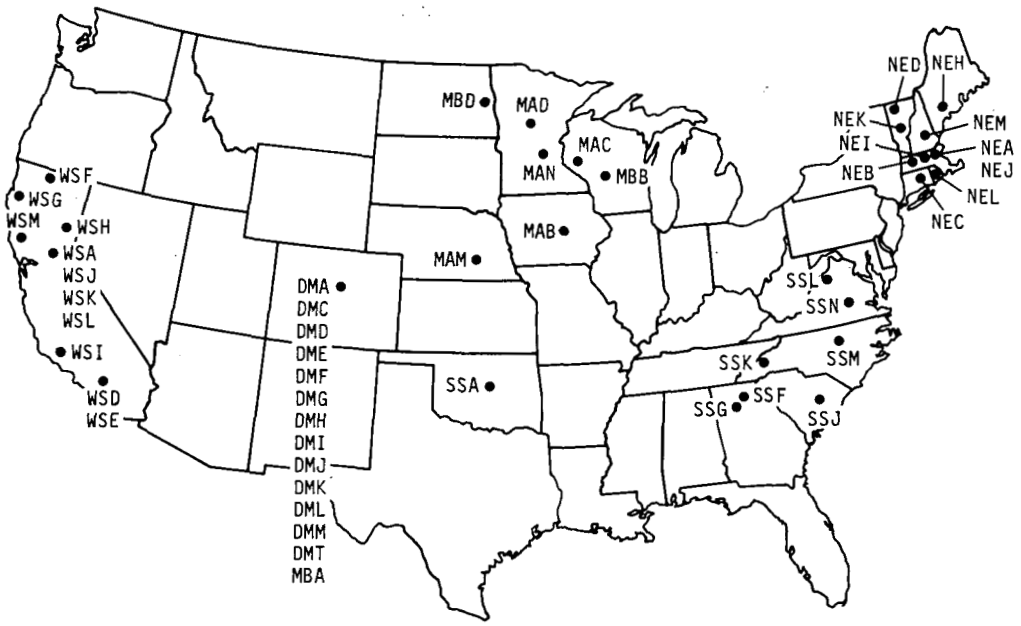



**Fig. 2. Class B Site Locations**

The 50 sites included in this report represent a wide variation in building and passive system size, configuration, and operation. The thermal performance of these buildings also varies a great deal. Much of the practical relevance of the results presented here lies in the study of the individual building summaries. However, some general observations can be made regarding the overall performance of the monitored buildings.

The following conclusions are based on interpretations of the results in Fig. 1 and a simple statistical analysis of the results. The statistical approach involves averaging the results and grouping them according to various categories, such as passive system type and geographical region. The statistical results are shown in Table 1 for 48 sites and in Table 2 for several categories of buildings. Sites WSE and WSL were eliminated from the sample because they were included in the program as nonsolar comparison buildings (7).

First, these buildings have low auxiliary heating needs. Figure 1 shows that the auxiliary heating is generally less than 3 Btu/°F-day-ft$^2$ (60 kJ/°C-day-m$^2$) with an average of 1.9 Btu/°F-day-ft$^2$ (38 kJ/°C-day-m$^2$). Conventional buildings typically use from 6-12 Btu/°F-day-ft$^2$ (120-240 kJ/°C-day-m$^2$), and the proposed Building Energy Performance Standard would allow 4 Btu/°F-day-ft$^2$ (80 kJ/°C-day-m$^2$). We will not, however, attempt to calculate an energy savings comparison in relation to a standard nonsolar building. The basis of

**Table 1. Statistics of Key Variables**

| Variable | Mean | Standard Deviation |
|---|---|---|
| Inside temperature [°F(°C)] | 67.56 (19.76) | 3.09 (1.72) |
| Monitored days | 127 | 31.5 |
| Passive heating fraction | 0.393 | 0.159 |
| Building performance index [Btu/°F-day-ft$^2$ (kJ/°C-day-m$^2$)] | 3.469 (70.86) | 1.270 (25.94) |

Note: Number of homes in sample: 48

such comparisons is inherently arbitrary and the results are subject to one's assumptions of what is standard. Swisher and Cowing (2) present sufficient information to allow the reader to make any desired comparisons. The average BPI, which includes internal heat, was 3.5 Btu/°F-day-ft$^2$ (70 kJ/°C-day-m$^2$), indicating that internal heating was nearly equal to auxiliary heating on the average.

Second, the energy saving effects of insulation and weatherization are critical. Modest solar designs

**Table 2. Thermal Performance Mean Estimates by Category**

| Category | Number in Sample | BPI Btu/°F-day-ft² (kJ/°C-day-m²) | | PHF | Incident Radiation Btu/day-ft² (kJ/day-m²) | |
|---|---|---|---|---|---|---|
| System type | | | | | | |
| Direct gain | 29 | 3.76 | (76.8) | 0.395 | — | |
| Sunspace | 11 | 2.76 | (56.4) | 0.383 | — | |
| Mass wall | 5 | 3.45 | (70.5) | 0.393 | — | |
| Water wall | 2 | 3.38 | (69.0) | 0.335 | — | |
| Hybrid | 1 | 3.17 | (64.8) | 0.587 | — | |
| Location | | | | | | |
| Denver | 14 | 2.85 | (58.2) | 0.501 | 1320 | (14,980) |
| New England | 10 | 3.19 | (65.2) | 0.287 | 875 | (9,930) |
| Midwest | 7 | 2.80 | (57.2) | 0.323 | 913 | (10,360) |
| South | 8 | 4.89 | (99.9) | 0.287 | 5611 | (6,370) |
| California | 9 | 4.00 | (81.7) | 0.493 | 891 | (10,110) |
| Night Insulation | | | | | | |
| Yes | 20 | 3.48 | (71.1) | 0.406 | — | |
| No | 28 | 3.46 | (70.7) | 0.385 | — | |

on very tight buildings generally use less heat than more ambitious solar designs on very leaky buildings, and low heat losses will increase the fraction of the heating load met by the solar components. Figure 1 shows that the largest purchased energy users (right side of the graph) have relatively high total heating loads; and with the exception of a few very heavily solar-driven buildings in Denver, Colo., and Northern California, the buildings with higher heat-loss coefficients required more purchased heat. Some of the smallest purchased energy users (left side of the graph) were buildings in the Northeast that had moderate passive heating and very low heat-loss coefficients.

Third, the solar performance is variable. From the data collected so far from the largest sample yet of passive solar houses monitored in a consistent manner, we can say that the passive solar systems contribute a statistically significant portion (39%) of the total heating load, or 55% of the net heating load (total load minus internal heat). Figure 1 shows several buildings with large passive heating contributions, but this does not necessarily translate into energy savings. While many heavily glazed buildings perform well in terms of auxiliary heat (e.g., sites DMK, DMM, NEB, NEM, WSM), some are disappointing (e.g., sites NEA, SSA, SSM, WSJ).

Fourth, it appears that the habits of the building's occupants in using the building are critical to passive system performance. This especially applies to the use of operable components such as insulation, sunspace doors, and vents. There was no significant statistical difference in either the BPI or PHF for houses with night insulation and those without (see Table 2). In reviewing the operation of the individual buildings, we found that most of the buildings with disappointing performance had a problem with operable components or occupant participation. There are several reasons for this. In some cases, the occupants were simply inattentive. Some automatic components, such as thermostatically controlled fans, did not operate properly. Several occupants, however, ignored operable components because the components were not sufficiently simple or convenient to use. This indicates that designers should continue to improve the simplicity and convenience of manual components and emphasize reliability in selecting automatic components.

Fifth, none of the basic passive system types (direct gain, sunspace, and thermal storage wall) had significantly better or worse overall performance. It is interesting to note that several of the sunspace designs used very little purchased heat, but did not have an especially large passive heating contribution. This points out the advantage of using a sunspace for a thermal buffer, for reducing heat losses, as well as for a solar energy collection device.

Sixth, performance varied significantly by location. The PHF means for California and Denver were significantly different (at the 95% confidence level) from the means for the other regions. As expected, the solar contributions were larger in the West. The differences in measured incident radiation, shown in Table 2, accounted for some of this difference. The BPI means for California and the south were significantly higher than those for the colder regions. There are three reasons for this: (1) the buildings in the colder regions tend to be more heavily insulated; (2) there tends to be more venting of internal heat in the warmer regions; and (3) the degree-day normalization may introduce a slight bias in favor of the colder climates.

Seventh, the passive solar houses are comfortable, with an average indoor temperature of 67.6°F (19.8°C). The time-averaged temperature of each site ranged from 54°-73°F (12°-23°C).

## 4. CONCLUSION

The estimated mean BPI of 3.469 Btu/°F-day-ft$^2$ (70.86 kJ/°C-day-m$^2$) has a 95% confidence interval of ±0.363 Btu/°F-day-ft$^2$ (7.41 kJ/°C-day-m$^2$). Thus, given the assumptions that the monitored houses are representative of the population of passive solar houses and that the measured BPI values are not consistently biased, then with a 5% risk of error the true mean BPI is within ±10.5% of the estimated mean. Work is in process to determine the validity of the above two assumptions regarding the representativeness of the monitored houses and the extent of any bias in the individual BPI estimates. No obvious sources of bias in the BPI estimates have been uncovered as yet. Lack of information about the number, characteristics, and location of the general population of passive solar houses has made a test of representativeness of the monitored houses difficult.

The 50 buildings in this sample clearly show that passive solar design can achieve very low purchased energy usage in all regions of the country. These results also show that solar performance can be improved further, especially with regard to operable components such as movable insulation.

## 5. ACKNOWLEDGMENTS

We thank Blair Hamilton, Don Frey, Michael Holtz, Mark McKinstry, Ralph Beckman, Jim Boswell, Tom Cowing, George Yeagle, and all the other people who have contributed to the Class B Program. This work was sponsored by the U.S. Department of Energy, Division of Passive and Hybrid Solar Heat Technologies.

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# THE MASSACHUSETTS MULTI-FAMILY PASSIVE SOLAR PROGRAM: A COMPARISON OF MONITORING DATA TO DESIGN TOOL PREDICTIONS

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## ABSTRACT

The Massachusetts Executive Office of Energy Resources, (EOER) through its Multi-Family Passive Solar Program, (MFPS) has provided design and technical assistance, and funded construction, for solar heating and conservation measures affecting more than 750 apartments at 30 different sites in the Commonwealth.

Four sites from the program are monitored as part of the Solar Energy Research Institute (SERI) Level B Program. This paper describes the simulation and monitoring design for one of the apartments in Braintree, Massachusetts, presents performance data collected during the 1982-83 heating season in graphic and tabular form, compares measurements to predictions, and describes analysis of the data to calibrate computer simulation models used for design.

## 1. THE MFPS PROGRAM AND THE LEVEL B MONITORING PROGRAM

### 1.1 The MFPS Program

The MFPS Program was conceived at the Massachusetts EOER in 1979 to initiate the practice of passive solar design in multi-family buildings in the Commonwealth, identify both problems and the potential for passive solar in real building programs and facilitate a transition to passive solar design as standard practice during a period of rising energy prices.

The program's staff act as energy consultants (providing design and technical assistance to architects for housing for the elderly financed by the Commonwealth), administer grants for construction, and monitor performance after occupancy.

Design and technical assistance was partially funded by the U.S. Department of Energy, (DOE) through the Northeast Solar Energy Center. Apartments are built by Local Housing Authorities and the Commonwealth's Executive Office of Communities and Development, (EOCD) with funding for solar and conservation from Massachusetts Energy Bonds under The Alternative Energy Property Program. Performance monitoring is partially funded by DOE.

The program is described in more detail in Publications 1-7.

### 1.2 Level B Monitoring Program

The Braintree monitoring site is one of many in SERI's Level B Monitoring Program sponsored by DOE. This program has as its purpose the evaluation of the thermal performance of a wide variety of passive solar residences throughout the U.S. To date, over 90 sites have been instrumented, and well over 725 complete months of data have been collected in the program. The aims, methods, and some preliminary results have been published elsewhere [1,2,3] and the methods will be only summarized here.

Low-cost microprocessor-based data acquisition systems are used in the program. Sensors are installed to measure appropriate temperatures, solar radiation, auxiliary and domestic hot water energy, and total electrical power. Measurements are stored every hour on cassette magnetic tapes. Certain other measurements are made to determine heat loss coefficients, infiltration rates, furnace efficiencies, and other needed parameters.

A heat balance approach is applied whereby it is assumed that the living zone heat loss is met by the sum of the solar contribution, the auxiliary heating energy delivered to the space, and the internal gains.

## 2. THE BRAINTREE MFPS PROJECT

The Braintree MFPS project was one of the earliest and most ambitious projects from the first phase of the MFPS program. The design was developed largely without access to currently available design tools (Volume II of the Passive Solar Design Handbook was published in January 1980; construction began in July). The design was subjected to the analysis described below after construction began. The Braintree design is not presented here as a model to be emulated, but as an early experiment which has been both extensively analyzed and monitored for a reasonable period of time.

The Braintree MFPS project apartments each have about 46 $ft^2$ of direct gain and about about 104 $ft^2$ of stagnating tripleglazed Trombe wall on a 520 $ft^2$ apartment. The project has been described in more detail in Publications 3, 5 and 7.

## 3. THERMAL PERFORMANCE ANALYSIS

Thermal performance for the Braintree MFPS project had been predicted with several design tools using substantially identical inputs. In addition TSWING simulations were performed with model inputs based on monthly data.

### 3.1 Simulation Model Design

The BLAST model is a complex hour-by-hour simulation code [4]. The FCHART/SLR code is based on the SLR method [5]. TEASOL and TSWING are two of a variety of packaged nodal network simulation models designed to provide short-term temperature profiles for solar-heated buildings. Many approximations and assumptions are made during both the design and the use of these abstract models of building performance; results may not be replicable. Differences between TEASOL and TSWING, and their limitations, are discussed below. The nodal network used for both the TSWING and TEASOL simulations is shown in Figure 1.

### 3.2 Monitoring Strategies

One representative unit in the Braintree MFPS complex was chosen to be monitored at the Level B. Seven other nearby units had electric watt hour meters installed (courtesy of Commonwealth Energy) for comparison purposes to see how typical the monitored unit was in total energy consumed.

The sensors and their locations in and around the first floor apartment are indicated in Figure 2. Total electrical power into the apartment is measured with a pulse-initiating watt hour meter. The electric domestic hot water heater is on a separate circuit monitored with an amp probe. The hot water system is shared by four apartments, so the hot water energy for the monitored apartment is estimated to be one-fourth of the total energy. Auxiliary heating is provided by electric radiant ceilings in both the living room and bedroom and a resistance heater is in the bathroom. Current probes and voltage readings are used to monitor the power to the heaters. Trombe wall temperatures are taken at two depths approximately midway between the floor and ceiling: 0.875 inches and 4.5 inches from the interior surface. In addition, the temperature of the air between the trombe wall and glazing is measured approximately six inches from the top of the cavity.

A key parameter needed for the energy balance estimates and for a general measure of overall thermal efficiency was the heat loss coefficient. For the purpose of defining a heat loss coefficient and for energy balance estimating, the apartment was treated as a single thermal zone. Two buffer zones were the hall and the upstairs apartment. The hall air temperature was monitored. The apartments were well insulated from each other, and it was assumed that the air temperature of the upstairs apartment was reasonably close to that of the monitored apartment. The concrete slab under the monitored apartment was uninsulated, but the perimeter footings were well-insulated.

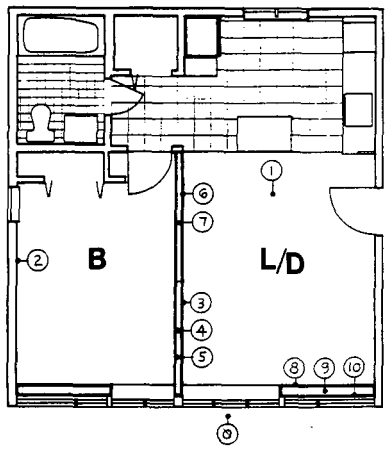
## 4. CALIBRATION OF THE SIMULATION MODEL

A series of TSWING simulations were run to compare both load and temperature predictions to the monitoring data. Comparative runs were performed for three cases described below.

Each of the three cases was run for 2 representative days from the monitoring period: January 8 and April 2, 1983. The particular days were chosen to correspond closely with weather for particular days in the TEASOL runs. January 8 was a sunny winter day with typical electric use properties and thermostat setpoint. April 2 was a sunny day during a period when the apartment was unoccupied and the thermostat was at a lower setting.

### 4.1 Case 1 Simulation

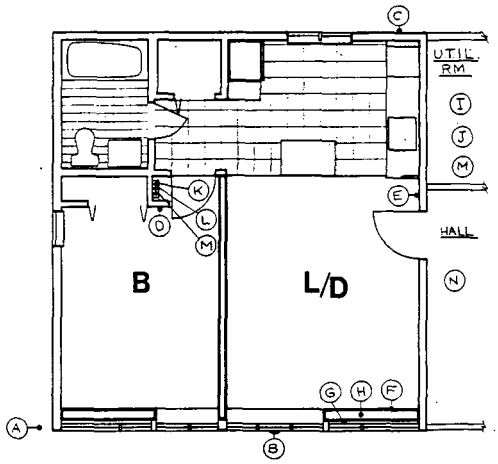
A comparison between TSWING and TEASOL was made with identical inputs based on pre-construction data. The major difference in inputs between TEASOL and TSWING was that TEASOL has a solar radiation subroutine that




NODE LOCATION

0 Outside Air
1 Room Air and Ceiling
2 Light Weight Room Mass
3 Direct Gain Mass Wall "Surface"
4 Direct Gain Mass Wall "Middle"
5 Direct Gain Mass Wall "Interior"
6 Interior Mass Wall "Surface"
7 Interior Mass Wall "Interior"
8 Trombe Wall "Interior Surface"
9 Trombe Wall "Middle"
10 Trombe Wall "Exterior Surface"

FIGURE 1 NODE LOCATIONS




SENSOR PARAMETER

A Horizontal Radiation
B Vertical Radiation
C Ambient Temperature
D Bedroom Temperature
E Living Room-Kitchen Temperature
F Trombe Interior Surface Temp.
G Air Between-Trombe & Glazing Temp.
H Trombe Wall Middle Temperature
I Total Electrical-Power to Apt.
J Voltage
K Auxillary Heat-Electric Current
L Bathroom Heater-Electric Current
M DHW Electric Current
N Entrance Hallway Temperature

FIGURE 2 SENSOR LOCATIONS

calculated transmission reflectance and absorbtance for glazing systems at any orientation; TSWING uses average values.

TEASOL allows for night setbacks while TSWING requires separate runs each time the thermostat is changed. In our TSWING runs we did not credit north and west windows with solar gains. Neither model limits the rate of auxiliary output, to simulate a reasonably sized heating system. The TSWING run includes a ground conductance since the monitored apartment is on ground level while TEASOL simulated a 2nd floor apartment.

4.2 Case 2 Simulation

Actual outside temperature and solar radiation from monitored data were used as inputs for TSWING simulations.

4.3 Case 3 Simulation

Case 3 is identical to case 2 except that monitored thermostat setpoints and internal gains were also input. The models are very sensitive to these occupant effects. The elderly appear to use thermostats as on-off switches and seem to prefer room temperatures averaging roughly 75°F.

The total electrical use for the other metered first floor apartments was within 10% of the monitored apartment usage. The second floor apartments used approximately 8 kWh/day less than the 1st floor apartments for the period 12-15-82 through 3-16-83.

A common complaint in ground floor apartments (slab on grade w/2in. perim. insulation) is cold floors. This might explain why 1st floor apartments used more electricity. Besides ground loss, the mean radiant temp-

erature would be lower and there would be a comfort need to turn up thermostats.

Accuracy of temperature predictions was quantified by calculating the root mean square temperature differences for three critical nodes for each of the simulations. (See Fig. 5 ).

### 4.4 Heat Loss Coefficient Estimates

The heat loss coefficient was estimated from monitoring data for periods of time before and during which the interior temperatures and Trombe wall temperatures were reasonably stable and no solar gains were present. Three different time periods were found suitable when the temperature difference between inside and outside was between 40 and 50 °F. The result of dividing the average hourly measured energy input by the average temperature difference between the inside and outside was 131 Btu/F-hr, similar to an ASHRAE-type calculation of 137 Btu/F-hr used for the simulations.

The infiltration component of the heat loss coefficient was estimated on the basis of a tracer gas test [6]. The infiltration rate at the time of the test was estimated at 0.23 air changes per hour (ACH). The average temperature difference was higher than the heating season average of 34°F that can be estimated by dividing the number of degree (7200) by the numbers of days in the heating season (212). The daily average wind speed recorded at a nearby weather station (10.9 mph) was near the normal average for the heating season. Thus, it appears that the 0.23 ACH can be used as a slightly conservative initial estimate of the heating season average.

Because the above parameters were in agreement with estimates no additional comparative simulation model runs were performed.

### 4.5 Sensitivity Analysis

There were a number of nodal network design considerations for the Braintree model. Whether to put all interior mass with the air node, how many nodes to put in the Trombe, whether to include a glass node for the glazing outside the trombe, whether an average daily solar transmission is reasonable or if hourly radiation accounting for varying transmission must be used.

In a number of sensitivity runs two of these variables showed significant effects. Doubling the number of Trombe nodes showed slightly better temperature profile agreement with the monitored output. Hour by hour input of the transmitted solar radiation substantially improved agreement in the April simulations. Therefore, all April simulations are based on hourly radiation input.

## 5. RESULTS

Monthly and annual auxiliary heating load predictions are compared to monitoring data for 1982-83 in Table 1.

Figure 5 plots the root mean square difference between simulated and monitored temperatures at the outside of the Trombe walls (10), the inside surface (8), and in the living room (1) for Cases 1, 2 and 3. Figures 3 and 4 plot hourly temperature profiles for cases 1 and 3.

Note that TEASOL and TSWING are in good agreement in Case 1, that the simulation is very sensitive to thermostat setpoint, and that while temperature predictions improved on average from Case 1 to Case 3, not all predictions improved in all cases, particularly for January when the apartment was occupied.

TSWING and TEASOL auxiliary loads for the January day were 23,500 Btu and 27,200 Btu respectively, for Case 1. The TSWING load for Case 3 was 59,300 Btu., similar to the monitored load of 56,170 Btu. The April load was very small for all cases.

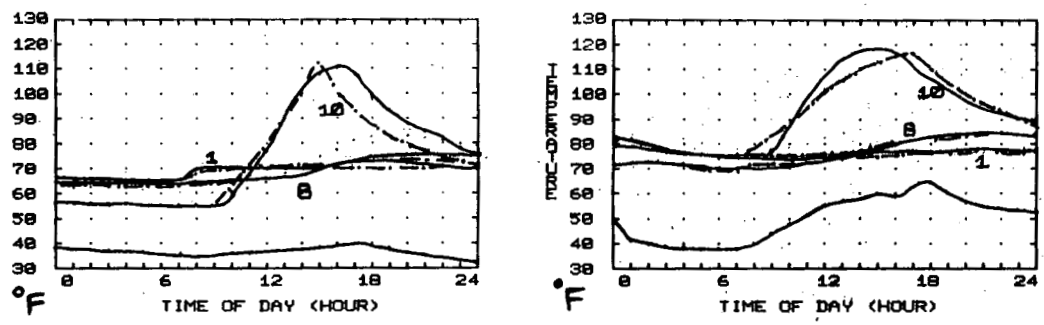
TABLE 1.
Comparison of Performance Predictions

(Auxiliary Heating Energy (MMBtu))

| Month | TEASOL | F-Chart SLR | BLAST | Monitor |
|---|---|---|---|---|
| JAN. | 1.6 | 1.32 | 1.60 | 2.70 |
| FEB. | .9 | .93 | .90 | 2.16 |
| MAR. | .8 | .65 | .94 | 1.40 |
| APR. | .3 | .17 | .32 | 0.77 |
| MAY | .1 | 0 | .17 | 0.96 |
| JUN. | 0 | 0 | .02 | ---- |
| JUL. | 0 | 0 | 0 | ---- |
| AUG. | 0 | 0 | 0 | ---- |
| SEP. | 0 | 0 | .02 | ---- |
| OCT. | .1 | 0 | .1 | ---- |
| NOV. | .5 | .36 | .5 | ---- |
| DEC. | 1.4 | 1.15 | 1.31 | 2.74 |
| TOTAL | 5.7 | 4.58 | 5.88 | 12.06** |

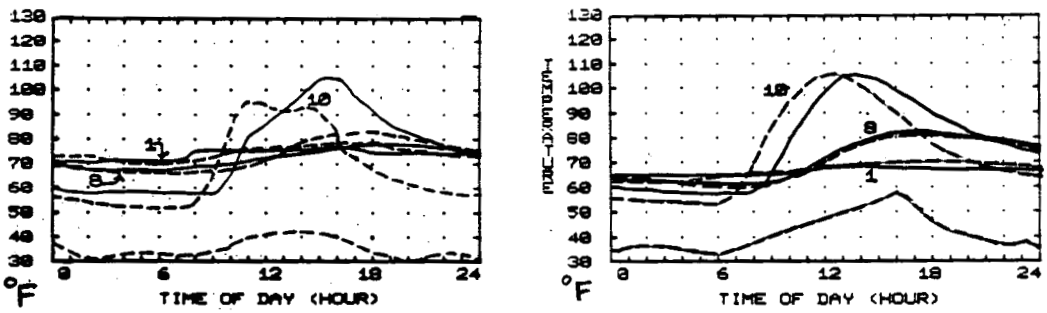
"----" Data not available

** Extrapolated



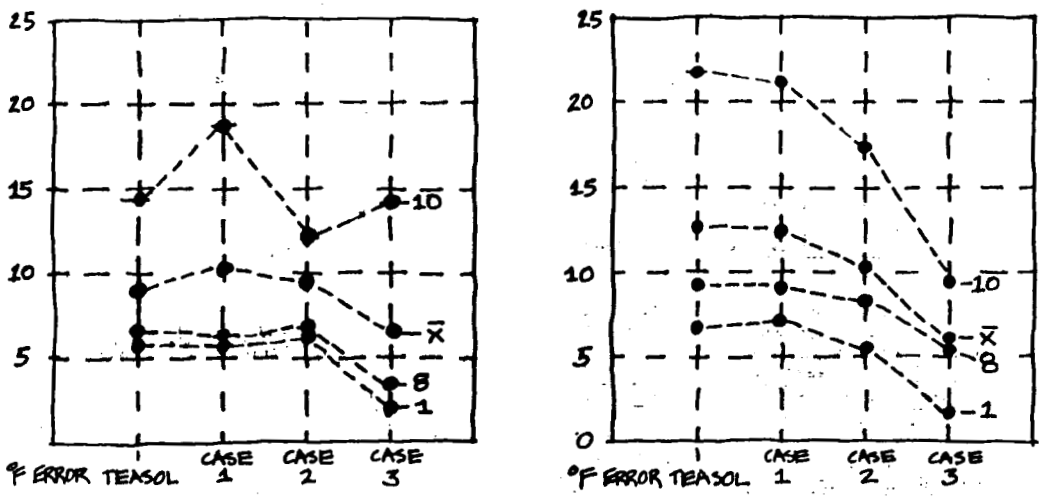

JANUARY APRIL

Figure 3. Comparison of TSWING (———) and TEASOL (—·—·) temperatures, Case 1.




JANUARY APRIL

Figure 4. Comparison of TSWING (———) and Monitoring data (– – – –), Case 3.




JANUARY APRIL

Figure 5. Root Mean Square Differences of Temperature Profiles, Compared to Monitoring data.

## 6. CONCLUSIONS

The simulation model results agree reasonably well with each other for monthly auxiliary energy values, but they do not agree with the monitored results. However, when estimates based on monitoring data were used as inputs to a simple nodal network model, temperatures were predicted that were reasonably close to monitored data.

From this analysis and other experience the authors conclude that even very simple nodal network simulation models can predict temperature profiles reasonably accurately, given correct inputs.

The usefulness of nodal network simulations as design tools is limited, however, by their sensitivity to input parameters about which the designer may have only limited information, such as occupant behavior. Passive solar building designs need not be changed in minor ways (such as small changes in solar apertures or thermal mass), based on output from such simulations; however, output from large numbers of simulations can have real value by providing information about the designs' sensitivity to critical variables. Such sensitivity analysis can lead to more robust and resilient designs for passive solar heated buildings.

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## 9. CREDITS


Special thanks to Marlene Hoey and Alan Predella of the Braintree Housing Authority, Alice Wilson who lives in the monitored apartment, and Linda Sutliff, of MEOER, who tirelessly reminded us that all of this was paid for with her tax dollars. Thanks also to Carol Stone, Ruth Nee and James Guertin for their last second typing.


Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# PERFORMANCE OF PASSIVE SOLAR AND ENERGY CONSERVING HOUSES IN CALIFORNIA - CLASS B MONITORING

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## ABSTRACT

Nine passive solar and two conservation houses in various California climates were monitored for a period of one year starting in July 1981. The two conservation houses were located next to passive solar houses for convenient comparison of performance. The Solar Energy Research Institute (SERI) Class B data collection methodology and instrumentation, modified to meet California needs, were used. This included continuous data collection with data stored hourly on cassette tape and processed daily, weekly and monthly on paper tape. In addition to the continuous data, one time measurements were made on each house to determine the building loss coefficient, infiltration rates and furnace efficiency.

The hourly data on cassette tape were transferred to disc and then used to analyze the thermal performance of each house. The solar contributions were obtained subtractively and comfort levels maintained are indicated by monthly plots of extreme, and binned inside and outside temperatures. The overall performance for each house is presented and compared to an equivalent non-solar house. In the two cases where solar and conservation houses are nearby, these performances are also compared.

## 1. INTRODUCTION

For the past several years there has been intense interest in the measurement and prediction of the performance of passive solar houses. Despite this effort little reliable field data are available and the validity of the predicted performance from a wide variety of computer codes are still being questioned[1]. In order to partially fill this gap the California Energy Commission supported the collection and analysis of one year of performance data on eleven houses in California[2]. This paper is a final report on that work.

During the planning stages of this work SERI began an effort to organize national data collection activities by promulgated three data collection strategies; Class A (heavily instrumented research sites), Class B (instrumented occupied houses) and Class C (survey and billing data). Shown in Table 1 is a brief description of the eleven sites that were monitored using the SERI Class B strategy.

## 2. INSTRUMENTATION

The Aeolian Kinetics PDL-24 data logger and sensors were used for collecting and processing the data as specified by the SERI Class B Installation Manual[3]. The outside temperature and several inside temperatures were measured using the Analog Devices AD590 sensor mounted in double radiation shields. The horizontal and vertical insolation were measured using Li-Cor silicon pyranometers. Continuous wind measurements were made using a pulsing anemometer. The total electrical energy was monitored with a pulse initiating watt-hour meter and all major electrical appliances outside the living space were current-clamped. The total natural gas used was measured with a specially designed pulse initiating gas meter. And finally several types of on/off sensors were used to determine the status of doors, windows, drapes, furnace burners, ventilation fans, etc. Typically a total of 19 sensors were used in each house.

## 3. DATA COLLECTION

The PDL-24 logger has a general purpose microcomputer and is programmable in BASIC. Under the guidance of SERI, Aeolian Kinetics has developed the software to handle data collection on magnetic tape. The user must supply the sensor parameters. The logger automatically samples each sensor every 15 seconds accumulating or averaging and the values recorded on magnetic tape at the end of each hour. This is referred to as the hourly data. A typical sample is given in Table 2. The user also developes a function

TABLE 1. CLASS B SITE DESCRIPTION

| Site | Passive Solar Type | Living Area ($ft^2$) | South Aperture ($ft^2$) | Climate Zone |
|---|---|---|---|---|
| Truckee Solar House | Direct Gain | 1158 | 271 | Cold-Mountain CTZ 16† |
| Yreka Solar House | Sunspace | 1375 | 258 | Cold-North Inland CTZ 11 |
| Eureka Solar House | Direct Gain | 2094 | 367 | North Coastal CTZ 1 |
| Sebastopol Solar House | Direct Gain | 1493 | 228 | North Bay-Coastal CTZ 2 |
| Santa Barbara Solar House | Trombe Wall | 842 | 198 | Mild-South Coastal CTZ 6 |
| Colton Solar House | Direct Gain* | 1664 | 207 | Warm-South Inland CTZ 10 |
| Colton Conservation House | N/A | 1660 | 50 | Warm-South Inland CTZ 10 |
| Rio Linda Conservation House | N/A | 1199 | 40 | Moderate-Central Valley CTZ 12 |
| Rio Linda Solar House | Direct Gain | 1215 | 135 | Moderate-Central Valley CTZ 12 |
| Sacramento Solar Condominium | Direct Gain* | 1420 | 170 | Moderate-Central Valley CTZ 12 |
| Davis Solar Duplex | Direct Gain* | 1273 | 255 | Moderate-Central Valley CTZ 12 |

* Passive Solar Design contest winners  † California Thermal Zones

program in BASIC which takes the reading from the sensors every 15 seconds and processes as many as 20 different functions. A typical list of these functions from the Sebastopol Solar House is also given in Table 2. These function values are printed out on paper tape at the end of each day, week and month. Copies of all of the information and the hourly data on nine track tape is being archived at the California Energy Commission and at SERI.

In addition to these continuously accumulated and processed data, a series of "one time measurements" required for the heat flow analysis were also made on each house. These included, the infiltration rate, the building loss coefficient, burner flow rates and delivery efficiency of the furnace.

## 4. ANALYSIS AND RESULTS

The large amount of data collected on each of the eleven houses have been used to obtain three performance indicators:

- the total auxiliary energy used for heating and the percentage of the gross load met by solar energy.
- the comparison of the measured performance to that of an equivalent non-solar house.
- the comfort level maintained in the house.

Before the above indicators were calculated, however, a number of checks were run to test for consistency of the data. One of the first steps was to plot the hourly data from various sensors for three to five day periods during Winter and Summer months to check for the reasonableness of the data. As an example shown in Figure 1 are plots of four sensors from the Santa Barbara house for two clear days followed by a cloudy day in January. This plot illustrates how the Trombe wall passive solar system responses to solar inputs, the charging and discharging of the thermal mass, and occupant activities. For example the peaks on the inside temperature plot are first due to solar gain and then due to occupant activities such as cooking and use of appliances. As expected the heat pulse through the Trombe wall arrives about 8 hours after the peak solar gain. The transition from the two sunny days to the cloudy day shows clearly the exponential decay of the Trombe wall thermal mass temperature. Other qualitative plots which are used in this way are the daily max-min temperature plots and the interior "binned" temperature bar graphs. With this level of information a good picture of how the house was operated and a qualitative understanding of the performance is possible.

A second check on the consistency of the data was accomplished through a trial daily and monthly heat balance across the house envelope using the equation:

$$Q_{balance} = Q_{cond} + Q_{infil} + Q_{int} + Q_{solar} + Q_{aux} + Q_{vent} + Q_{storage}$$

If all heat flow were accurately measured, $Q_{balance}$ should be zero. Of course it is generally not and so $Q_{balance}$ represents the

TABLE 2. TYPICAL LIST OF FUNCTIONS PRINTED OUT AT THE END OF EACH DAY, WEEK, AND MONTH AND THE HOURLY DATA RECORDED ON MAGNETIC TAPE

| Function Definitions | Units |
|---|---|
| Energy used by water heater | Watt hrs |
| Energy to heaters | Watt hrs |
| Internal heat gain when $T_{in} > T_{out}$ | Btu |
| Energy to guest house and water pump | Watt hrs |
| Internal heat gains | Btu |
| Heat lost thru conduction and air infiltration | Btu |
| Heat lost thru venting of doors | Btu |
| Total solar insolation on horizontal surface | $Btu/ft^2$ |
| Total solar insolation on vertical surface | $Btu/ft^2$ |
| Energy to jacuzzi and solar pump | Watt hrs |
| Energy to clothes dryer | Watt hrs |
| Heat lost thru cond. & infil. when $T_{in} > T_{out}$ | Btu |
| Total electrical energy purchased | Watt hrs |
| Heat balance of house | Btu |
| Average wind speed | MPH |
| Average inside temperature | $^oF$ |
| Average outside temperature | $^oF$ |
| Average sunspace temperature | $^oF$ |
| Average thermal mass temperature | $^oF$ |
| Max inside temp/time it occured | $^oF$ |
| Max outside temp/time it occured | $^oF$ |
| Max sunspace temp/time it occured | $^oF$ |
| Max thermal mass temp/time it occured | $^oF$ |
| Min inside temp/time it occured | $^oF$ |
| Min outside temp/time it occured | $^oF$ |
| Min sunspace temp/time it occured | $^oF$ |
| Min thermal mass temp/time it occured | $^oF$ |
| Maximum 5 minute electric power consumption | Watts |
| Time it occured (0:00 PST) | |

| Sensor | Units |
|---|---|
| Insolation on horizontal surface | $Btu/ft^2/hr$ |
| Insolation on south vertical surface | $Btu/ft^2/hr$ |
| Outside temperature | $^oF$ |
| Living room temperature | $^oF$ |
| Kitchen/Office temperature | $^oF$ |
| Master bedroom temperature | $^oF$ |
| Sunspace temperature | $^oF$ |
| Thermal mass temperature | $^oF$ |
| Total electrical energy | Watt Hrs |
| Electric heater current | AC Amperes |
| Water heater current | AC Amperes |
| Wind speed | MPH |
| Water pump current | AC Amperes |
| Jacuzzi and pump current | AC Amperes |
| Clothes dryer (on time) | Hours |
| Front door (closed time) | Hours |

error or uncertainty of measuring the various heat flows. Also $Q_{vent}$ and $Q_{storage}$ cannot be estimated very well and so in most cases were lumped with $Q_{balance}$ on the left side of the equation as an unknown term which should generally be small. In this equation $Q_{solar}$ is calculated by the additive method using measured insolation. Energy balances of this kind done on each site for several months typically would give balances within 10% of the gross load ($Q_{cond} + Q_{infil}$) for the month. On occasion a balance would exceed this 10% and no reasonable explanation could be found in the data available.

Shown in Table 3 is the auxiliary heating energy delivered to each house for the entire heating season and solar energy utilized in terms of the percent solar of the gross load. In this case the useful solar energy is calculated subtractively using:

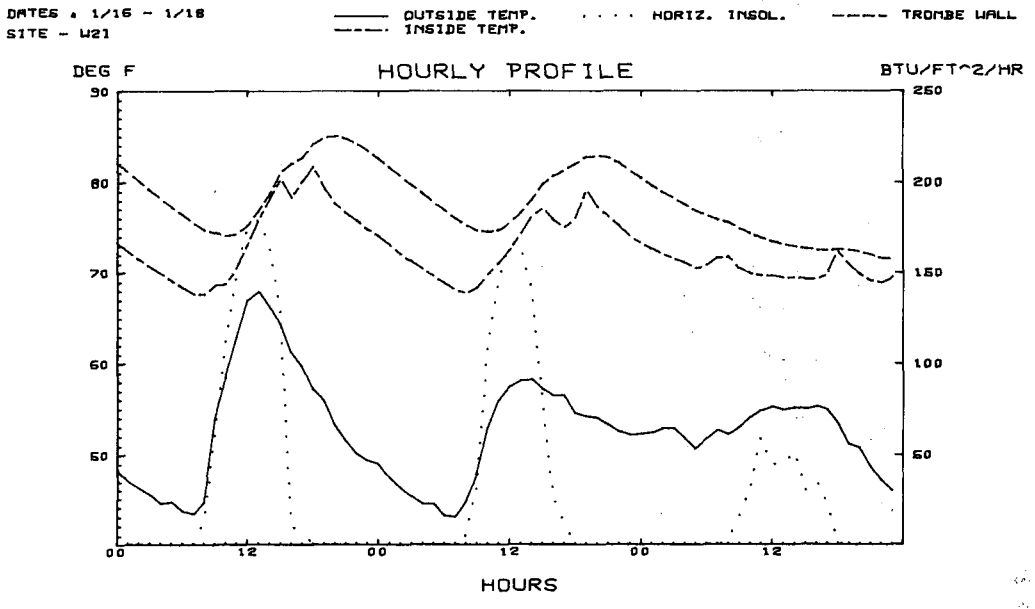



Fig. 1. Hour-by-hour plot of four sensors in the Santa Barbara Trombe Wall house.

$$Q_{solar} = Q_{cond} + Q_{infil} - Q_{int} - Q_{aux}$$

It is assumed that $Q_{solar}$ includes any vented energy and that storage effects are small over the period of a month. The Eureka and Sebastopol houses which are both located in the northern California Coastal climate had the highest percent solar, both near 70%. This is largely due to the need in this climate for some heating the year round and so the performance during the Fall and Spring when there is an abundance of clear weather improves dramatically. The solar houses in Truckee and Yreka, which experience a cold mountain climate, also performed quite well with over 50% of the gross load provided by solar gain. The houses that performed the poorest are in the warmer climates and in the Central Valley where during the peak heating months a significant number of days are foggy and overcast. The one exception to this is the Davis solar duplex which "got by" on very little auxiliary energy due mainly to the occupants letting the interior temperature swing down to 60°F during the cloudy periods.

Another way to gauge the performace of the passive solar house for heating is to compare the auxiliary energy delivered to that of an equivalent non-solar house. The non-solar house was taken to be the same as the solar house in construction, orientation, operation, and weather except the solar features are removed and glazing area set at 16% of the floor area and redistributed equally to the four sides of the house. Infiltration and internal gains are kept the same but the thermal mass is removed and the slab floor is covered with a carpet. The hourly data taken on the solar house was then used directly to determine the performance of the non-solar house. With this comparison the lifestyle effects which can be significant in effecting performance are minimized and the savings due to just the solar features are clearly indicated.

Shown in Table 3 are the results of the comparison giving the auxiliary heating energy required by the equivalent non-solar house and the energy savings. In general there is a direct correlation of the energy savings and the percent solar of gross load. A significant amount of energy was saved in the Sebastopol, Eureka, Yreka, Truckee and Davis solar houses. In the more mild climates and where the winters are quite cloudy and overcast the savings are considerably smaller, e.g., in the Santa Barbara house the savings is 6.5 MMBtu for the entire heating season or about $30 worth of natural gas used in the small wall furnace.

The corresponding results for the cooling season cannot be quantified to the same

TABLE 3. ENERGY SAVINGS FOR THE HEATING SEASON BASED ONLY ON AUXILIARY ENERGY

| Site Location in California | Auxiliary Heating Energy delivered to House (MMBtu) | Solar % of Gross Load | Heating Energy Required by an Equivalent non-solar House (MMBtu) | Energy Savings (MMBtu) |
|---|---|---|---|---|
| Truckee | 5.6 | 52 | 16.6 | 11.0 |
| Yreka | 12.9 | 52 | 27.3 | 14.4 |
| Eureka | 11.7 | 69 | 49.4 | 37.7 |
| Sebastopol | 0.4 | 68 | 15.9 | 15.5 |
| Santa Barbara | 0.4 | 58 | 6.9 | 6.5 |
| Colton | 3.2 | 34 | 9.0 | 5.8 |
| Rio Linda | 15.9 | 30 | 19.5 | 3.6 |
| Sacramento | 9.0 | 25 | 14.0 | 5.0 |
| Davis | 3.9 | 61 | 20.9 | 17.0 |
| Rio Linda Conservation | 12.8 | - | - | - |
| Colton Conservation | 5.3 | - | - | - |

degree as heating for two reasons. First, only one of the solar houses monitored has mechanical cooling while the other eight use nighttime ventilation. and second with the limited instrumentation available in the Class B monitoring it is not possible to determine a cooling load for the house and to follow the various heat flows while the house is open for venting. To quantify the cooling effectiveness of passive solar houses is a much more difficult problem and not possible with any meaningful accuracy with Class B data. As a result, rather than using the energy required for cooling as a measure of performance, it is necessary to use the comfort maintained.

Since only one of the solar houses used a thermostat setpoint strategy the thermal comfort as indicated by interior temperatures maintained during the winter and summer becomes an important measure of performance. One common criticism of passive solar houses is that they are often too cold in the winter and too hot in the summer. This to some degree was true in most of the solar houses in this study. Shown in Figure 2 are plots of typical extreme temperatures maintained in this case in the Davis solar house during December and August, which illustrates the above statements. Taking the comfort zone as 65°F to 80°F it is clear that the inside temperature was often outside these limits. This is an attempt by the homeowners to minimize the use of auxiliary energy and to take full advantage of solar gain and thermal mass effects. As evident from Figure 2 when the days were clear in December the interior temperature responded to solar gain and rose into the high seventies. However, during the extended cloudy period the maximum interior temperature was around 65°F even with the use of some auxiliary heating energy. In August when all the days are clear the large conductive gain was difficult to manage and the house went above 80°F on almost every day. However, with the cool nights, which are prevalent in most areas in California, nighttime ventilation was very effective in cooling the house down quickly to the 65°F range.

In general the solar houses followed the above temperature performance. During the heating season they performed very well on clear days but during cloudy periods operated in the 60-65°F range. Thermal mass had very little affect beyond 24 hours in maintaining interior temperature during these cloudy periods and its function needs to be evaluated much closer for California climates. On the other hand most of the homeowners agreed that when the house temperatures were in the 65°F range the comfort was acceptable. This is partly due to their own bias but also can be attributed to the low infiltration rates, the brightness in the houses even on cloudy days, and the radiation effects of thermal mass. During the cooling season with the usual clear sunny hot California weather the solar house would leave the comfort zone and go above 80°F on many days. Because of the low humidity, most of the homeowners did not see this as a problem in part due to the expectation of cool nights for sleeping.

## 5. CONCLUSIONS

In general all of the solar houses saved energy and performed about as expected for heating.

Some overall conclusions are:

- For well insulated conservation houses in mild climates any passive solar system added to meet heating load must be designed very carefully so as not to degrade the conservation features.
- The major thermal mass effects have a time constant of at most 24 hours. Thermal

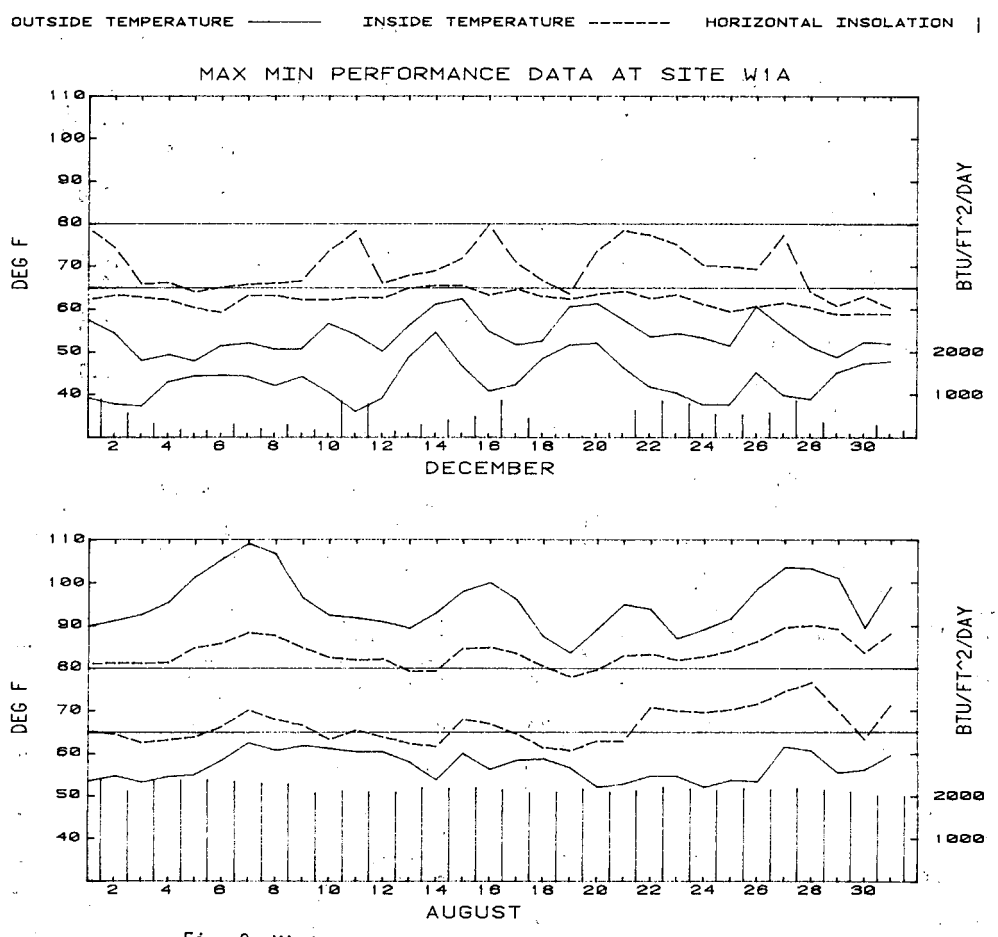



Fig. 2. Min/Max Temperature data for Davis Solar House for the months of December, 1981 and August, 1982

mass does tend to moderate indoor temperatures, but only for about one day.

- Climates which require some heating year round, namely those on the North coast of California, performed the best according to the results. The houses in the colder climates (mountains in California) also performed quite well. Solar houses in more mild climates did save energy but in most cases not a significant amount when compared to conservation houses.
- Solar house must be allowed to swing in temperature significantly in order to take full advantage of storage effects. This implies letting the house swing out of the comfort zone on most days for a few hours.
- Solar features if not managed properly lose the potential savings in winter and are a liability in the summer. Large direct gain apertures in the mild but often overcast winters and the hot but clear summers in California should be questioned.

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# ONE TIME MEASUREMENT OF THE INFILTRATION RATE AND CONDUCTIVE LOSS COEFFICIENT FOR HOUSES IN CALIFORNIA - CLASS B SITES

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## ABSTRACT

In this paper the measurements of infiltration in residential structures using tracer gas ($SF_6$) and blower door techniques are compared. Careful measurements using both techniques were made in eleven energy conserving and passive solar houses in California. During all the measurements, the weather conditions were monitored continuously. Using the data from the blower door measurements, the wind induced and stack induced parameters are calculated. These parameters are then used to calculate the infiltration rates for weather conditions under which tracer gas measurements were The agreement of blower door predictions and experimental tracer gas results are quite good.

Our results suggest that one should use the blower door methodology for infiltration measurements. The latter has the advantage of giving the instantaneous infiltration rates once the wind speed and the temperature difference between inside and outside is known.

In addition the house conductive loss coefficient was measured using the method of electric co-heating. These results are compared with the standard ASHRAE calculation of the same quantity.

## 1. INTRODUCTION

As part of the SERI Class B monitoring procedures to determine the performance of a passive solar building, it is necessary to make two important one time measurements, the infiltration rate and the conduction loss coefficient of the envelope. The reason these measurements are so important is that the useful solar gain is calculated subtractively using

$$Q_{solar} = Q_{gross\ load} - Q_{int} - Q_{aux}$$

where

$$Q_{gross\ load} = (U_{Acond} + U_{Ainfil})(T_{in} - T_{out})$$

In the Class B methodology the internal gains ($Q_{int}$) and the auxiliary energy ($Q_{aux}$) are measured directly with various sensors and are considered to be known quite well as are the inside and outside temperatures. To complete the calculation for the useful solar gain ($Q_{solar}$), the conduction loss coefficient, $U_{Acond}$, and the infiltration loss coefficient, $U_{Ainfil}$, need to be measured. The process developed as part of the Class B project in California follows quite closely the SERI Instruction Manual(1) but also includes several significant changes. This process and the results for eleven houses monitored for a year in California are presented in this paper.

## 2. INFILTRATION MEASUREMENT

One method often used to measure the air infiltration rate in buildings is the tracer gas technique. In this technique and the one used in this study a small amount of relatively inert gas such as $SF_6$ is introduced into the living space of the building. It is allowed to mix for several hours and then air samples are taken approximately one hour apart. These samples are then analyzed to determine the concentration of the tracer gas. From the rate of decay in concentration the number of air exchanges per hour (ACH) is calculated. By repeating this procedure every month a reasonable estimate of the seasonal infiltration rates can be obtained.

It is important to understand that the tracer gas method gives an instantaneous infiltration rate for the weather conditions that existed at the time the samples were taken. If it was particularly calm or windy or the difference in outdoor and indoor temperatures was extreme, then the ACH will be quite different from the typical value for the month. This limitation of the tracer gas method may introduce sizeable error when the results are used to do monthly performance evaluation and also when predicting hour-by-hour heat loads. In principle, one can monitor the infiltration continuously using the tracer gas technique.

However, this approach would be very costly and impractical for an occupied house.

More recently, another methodology for measuring air infiltration has been developed(2). This methodology, often referred to as the "blower door" method, includes mounting a large reversible fan in one of the door openings and using it to pressurize and then depressurize the house up to 0.2 inches of water. While under pressure smoke sticks are used to identify the major cracks in the envelope. Following this, a careful measurement is made of the flow rate of air in and out of the house as a function of pressure drop across the envelope. This data are then used to calculate two coefficients; one related to the temperature drop across the envelope or the stack induced infiltration (B) and the second for the wind induced air infiltration (C). In equation form the heat loss per hour due to infiltration is given by:

$$Q_{infil} = \Delta T \sqrt{B^2 \Delta T + C^2 V^2} \qquad (1)$$

where:

$U_{Ainfil} = \sqrt{B^2 \Delta T + C^2 V^2}$
$\Delta T = (T_{in} - T_{out})$ in $^oF$
B = "stack" induced coefficient in BTU/hr/$^oF^{3/2}$
C = "wind induced coefficient in BTU/hr/$^oF$/MPH
V = wind speed in MPH

It is assumed here that air flow or infiltration varies with the square root of the induced pressure difference which is set up by each of these effects. The effective leakage area of the envelope is the key parameter which is calculated from the blower door data of pressure drop versus flow rate caused by the fan at different RPM. The B and C coefficients are directly proportional to the leakage area and related to terrain constants by way of two empirical equations developed by Sherman's Group at LBL. This method was recently accepted as an ASTM test procedure and field tested by Barbara Sholl Wagner(3) also at LBL.

Once the B and C coefficients are known, the infiltration rate for most other weather conditions can be determined using Equation (1). For example in this monitoring project the wind velocity and the temperature drop across the envelope were measured allowing the instantaneous air infiltration rate to be calculated. As a check, this methodology was used to predict the ACH for weather conditions under which the tracer gas measurements were made with quite good agreement between the two methods.

## 3. INFILTRATION RESULTS

The results of the tracer gas field measurements on the eleven houses are given in Table 1 along with the temperature drop across the house envelope ($\Delta T$) and the wind velocity (V) for the 2-3 hour period of the measurement. At five of the sites the wind

TABLE 1. RESULTS OF TRACER GAS DETERMINATION OF ACH MADE SOON AFTER THE DATA LOGGER WAS INSTALLED AT THE ELEVEN CLASS B HOUSES

| Site | Floor Area ($ft^2$) | Volume ($ft^3$) | $\Delta T$ ($^oF$) | V (MPH) | ACH |
|---|---|---|---|---|---|
| Truckee House (H) | 1158 | 11832 | 9 | (5) | .51 |
| Yreka House (F) | 1375 | 16087 | 5 | (4) | .15 |
| Eureka House (G) | 2094 | 22000 | 7 | (0) | .21 |
| Sebastopol House (M) | 1493 | 13937 | - | - | - |
| Santa Barbara House (I) | 842 | 7574 | 26 | (3) | .74 |
| Colton Solar House (D) | 1664 | 14900 | 21 | 4 | .24 |
| Colton Conservation House (E) | 1660 | 13280 | 21 | 5 | .32 |
| Rio Linda Solar House (J) | 1215 | 11850 | 19 | 1 | .17 |
| Rio Linda Conservation House (L) | 1199 | 9935 | 16 | 6 | .38 |
| Sacramento Condominium (K) | 1420 | 11400 | 3 | 0 | .11 |
| Davis Duplex (A) | 1273 | 10783 | 7 | (6) | .60 |

velocity was not monitored (shown in parenthesis), however, estimates were made of the magnitude during the measurement and confirmed at nearby weather stations. The wind velocity used in Equation (1) was that measured or estimated at the roof level of the house and with the anemometer on the side of the house with the prevailing winds. This value is typically a factor of 2-3 lower than that reported by the Weather Bureau where the wind velocity is measured at 10 meters.

The infiltration rates vary from 0.74 ACH for the Santa Barbara house down to 0.11 ACH for the Sacramento Condominium. Most of the sites have relatively low values since considerable care was given to reduce leakage area during construction. Also, the two or three lowest values of ACH correspond to periods when the two driving forces for infiltration, $\Delta T$ and wind velocity were small. When the infiltration rate drops below 0.2 ACH, the uncertainty in the value can go as high as 20-30%.

Listed in Table 2 are the infiltration rates determined using the blower door methodology for the same eleven houses. First the effective leakage area, A, is calculated for each house using the blower door data. This value of A is then used to calculate the two coefficients B and C. These coefficients can then be used in Equation (1) to determine the infiltration rate for different values of $\Delta T$ and V.

Also listed in Table 2 are predictions of the infiltration rate for the weather conditions at the time the tracer gas measurements were made. This provides a convenient check of the blower door method. From the results it is clear that at least for this sample of houses the two methods agree quite well. For seven of the houses the difference is within $\pm$ 15%. The largest deviations generally occur for those sites with very small infiltration rates which also have the greatest uncertainty in the absolute value. The results of the two methods are plotted in Fig. 1.

Even though further work needs to be done to verify this methodology it appears that with a single blower door measurement the instantaneous infiltration rate in houses can be determined. In monitoring projects like Class B work having available the instantaneous infiltration rate has improved the accuracy and ease of interpretation of the thermal performance data.

## 4. BUILDING CONDUCTION LOSS COEFFICIENT MEASUREMENT

There are several methods available to determine the heat loss coefficient of a house. A direct approach, one developed by Sonderegger et. al. at LBL(4), is to use electric co-heating. In this approach small electric portable heaters were placed in the major living zones throughout the house the day before or the morning of the test and their separate thermostats set so as to maintain the "equilibrium" temperature of the room. Prior to this, the homeowners were asked to use their backup system to keep the house above 70°F, although this was not always possible. Also most of the homeowners did not have a normal thermostat setpoint and only used their auxiliary heating systems when they absolutely had to. This made it difficult to duplicate normal building operation with the electric heaters. The data acquisition system was set to print out average temperatures and total energy uses every half hour. For most houses thermometers were attached to the surface of the thermal masses and readings were taken every hour. Care was also taken to minimize solar gain on the day prior to the test and during the data collection period. This was done when needed by blocking the aperture with a makeshift cover. Periodically during the day adjustments were made to the thermostats based on the 30 minute temperature averages printed out by the logger in an attempt to stabilize the air and mass temperatures. The actual test period was usually from 7 pm to 7 am the next morning. During this period, the families complained of it being too hot in the house, but did not feel it necessary to move out for the night.

From the co-heating data the energy entering the house during each two hour period was calculated ($Q_{total}$). This included the electrical energy input by the electric heaters, electrical energy used by appliances inside the conditioned space, and the energy input (250 Btu/hr/person) from the body heat of the occupants. The blower door data and measured temperatures, and wind speeds were used to calculate the infiltration heat loss for each of the two hour periods using Equation (1). Since infiltration heat loss is not a linear function of $\Delta T$, a linear regression done on total energy to calculate the $U_A$ value will give rise to inconsistencies. For this reason the infiltration heat loss ($Q_{infil}$), the nonlinear term, is first subtracted out. The resulting heat balance is:

$$Q_{net}(t) = Q_{total}(t) - Q_{infil}(t) \qquad (2)$$
$$U_{Acond}\Delta T(t) + M\,\Delta T'$$

where M is the participating thermal mass and $\Delta T'$ is the estimated change in temperature of the thermal mass. Ideally $\Delta T'$ should be zero but this was not always the case and so this correction was included in the calculation. A linear regression analysis was then done for the twelve hour

TABLE 2. RESULTS OF THE DETERMINATION OF THE INFILTRATION RATES (ACH) OF THE ELEVEN CLASS B SITES USING THE BLOWER DOOR METHODOLOGY. ALSO INCLUDED ARE THE PREDICTIONS OF THE ACH VALUE USING THE B AND C COEFFICIENTS AND THE WEATHER CONDITIONS WHEN THE TRACER GAS MEASUREMENTS WERE MADE.

| Site | Floor Area ($ft^2$) | leakage Area ($ft^2$) | $\Delta T$ ($^oF$) | V (MPH) | B * | C ** | ACH | Blower Door Prediction of Tracer Gas Results ACH | % Diff. |
|---|---|---|---|---|---|---|---|---|---|
| Truckee | 1158 | 637 | 25 | 1 | 16.2 | 14.6 | .39 | .41 | 7 |
| Yreka | 1375 | 297 | 28 | 0 | 8.2 | 7.9 | .15 | .15 | 0 |
| Eureka | 2094 | 1025 | 19 | 0 | 31.8 | 17.4 | .34 | .21 | 0 |
| Sebastopol | 1493 | 640 | 15 | 8 | 18.7 | 14.2 | .54 | - | - |
| Santa Barbara | 842 | 650 | 23 | 4 | 17.2 | 11.7 | .69 | .69 | 7 |
| Colton Solar | 1664 | 662 | 26 | 3 | 11.4 | 13.5 | .27 | .27 | 13 |
| Colton Conservation | 1660 | 603 | 21 | 5 | 10.8 | 13.3 | .35 | .35 | 9 |
| Rio Linda Solar | 1215 | 615 | 13 | 0 | 10.7 | 10.1 | .18 | .22 | 29 |
| Rio Linda Conservation | 1199 | 463 | 15 | 7 | 8.3 | 8.6 | .38 | .38 | 0 |
| Sacramento | 1420 | 452 | 21 | 0 | 10.7 | 8.1 | .24 | .08 | 27 |
| Davis | 1273 | 690 | 10 | 1 | 18.9 | 18.4 | .30 | .59 | 2 |

* $Btu/Hr^oF^{3/2}$

** $Btu/Hr^oF \cdot MPH$

TABLE 3. RESULTS OF CO-HEATING MEASUREMENT OF THE BUILDING LOSS COEFFICIENT AND FURNACE EFFICIENCY TESTS

| Site | $U_A$(cond) ASHRAE ($Btu/hr^oF$) | $U_A$(cond) Co-heating ($Btu/hr^oF$) | Diff. (%) | M ($Btu/^oF$) | Infiltration Average* (ACH) | $U_A$(infil) Average ($Btu/hr^oF$) | Furnace Efficiency (%) |
|---|---|---|---|---|---|---|---|
| Truckee | 398 | 313 | +27 | 2679 | .39 | 101 | NA |
| Yreka | 377 | 306 | +23 | 7186 | .15 | 55 | NA |
| Eureka | 706 | 805 | -12 | 7505 | .34 | 193 | NA |
| Sebastopol | 535 | 419 | +28 | 11271 | .54 | 107 | NA |
| Santa Barbara | 387 | 312 | +24 | 11898 | .34 | 90 | 68 |
| Colton Solar | 529 | 524 | +1 | 1932 | .26 | 63 | NA |
| Colton Conservation | 580 | 523 | +11 | 6872 | .35 | 124 | 65 |
| Rio Linda Solar | 345 | 366 | -6 | 4108 | .18 | 59 | 33(64)** |
| Rio Linda Conservation | 292 | 293 | 0 | 3108 | .38 | 53 | 41 |
| Sacramento | 280 | 284 | -1 | 2189 | .24 | 55 | NA |
| Davis | 418 | 459 | -9 | 3139 | .32 | 115 | 48 |

* Average infiltration for the twelve hour period of the Co-heating tests. The weather is different for each site and, therefore, the infiltration values are not comparable.

** New efficiency determined after furnace adjusted (1-20-82)

period to determine the best values of $U_{Acond}$ and M.

The two hour time interval was chosen since heat flows and storage effects are not really steady state. The characteristic response time of 1/2 to 1 in. of concrete or of a heat pulse travelling through a standard wall is 1-2 hours. Thus a two hour time interval provides a more realistic averaging time. However, some mass effects in the house have much longer time constants and add uncertainty to the results.

## 5. CONDUCTION COEFFICIENT RESULTS

Since co-heating had to wait until the winter months, the building conductive loss coefficient $U_{Acond}$ was first calculated using the standard ASHRAE method. The parameters needed to make this calculation were taken from the architectural drawings for each site. The results of the ASHRAE calculation for each house are listed in Table 3. Even though considerable care was taken in making these calculations and a site check made of all construction details, all of the usual uncertainties associated with ASHRAE values of $U_{Acond}$ are probably present here. Further the ASHRAE value is usually considered to be a maximum value to be used for design and sizing of heating and cooling systems.

Also listed in Table 3 are the values of $U_{Acond}$ and M (participating thermal mass) extracted from the regression analysis of the twelve hours of co-heating data. These values fit the experimental data with a standard deviation generally less than 8% indicating an accuracy of better than 16%. The two main problems encountered while making the measurements and contributing to this error were the inability to get a large enough $\Delta T$ across the envelope in many of the mild California Climates and the difficulty of holding constant temperatures in the houses with the electric heaters for the twelve hour period. In several cases the $\Delta T$ across the house envelope was less than 20°F rather than 30°F, the recommended minimum value, resulting in smaller energy gains and losses and, therefore, greater percent uncertainties. Also a drop of even a degree or two in the thermal mass surface temperature makes the more tenuous mass correction term in Equation (2) quite large relative to the conduction loss term and again increases the uncertainty of the results.

One check of the consistency of the $U_{Acond}$ values determined using the co-heating method is to compare them to the corresponding ASHRAE values. Shown in Fig. 2 is a plot of the two values indicating quite good agreement. Also listed in Table 3 is the percent difference between the two values with the co-heating value assumed to be the more accurate. Only four of the houses have values outside what might be considered reasonable agreement and these four houses have ASHRAE values that are high by over 20%. This was not unexpected, but why only four of the sites have higher values is not clear.

A second check of the $U_{Acond}$ values calculated from the co-heating data is to do monthly heat balances with the values for each house using the hourly data. Over a period of a month most mass effects will cancel out due to charging and discharging, eliminating this problem with the co-heating data were mass effects during the twelve hour period were larger than desired. Generally the overall balances were within ± 10% of the total load for most of the sites indicating that the values of $U_{Acond}$ presented in this section are quite good.

## 6. CONCLUSION

Even though further testing needs to be done to verify both of these measurements, it is clear that by perfecting them and developing specific procedures on how to carry them out would greatly simplify and add to the accuracy of any future monitoring of occupied buildings. Research work on this matter should be funded before any additional funds are made available for monitoring.

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

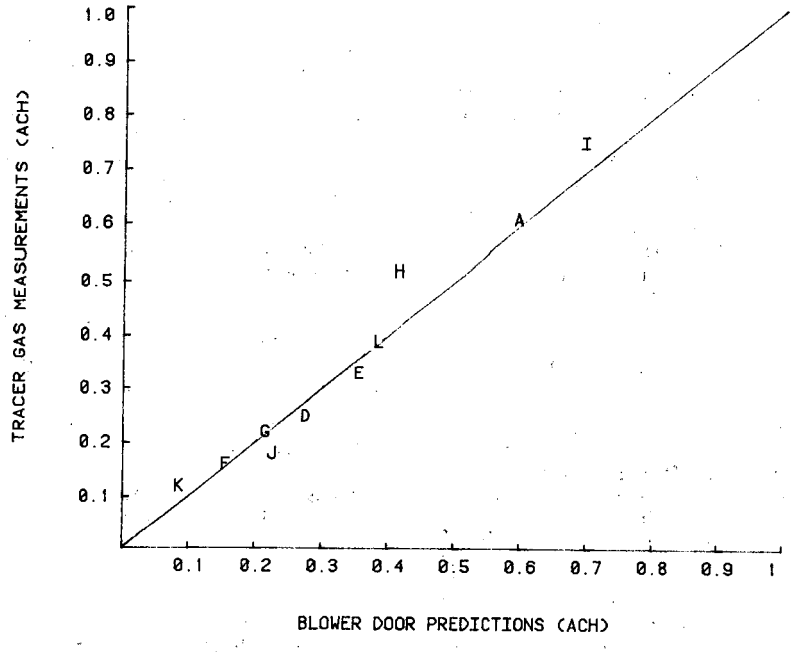



Fig. 1. Comparison of the Infiltration Rate (ACH) in the Eleven Class B Houses Using the Tracer Gas Measurements and the Blower Door Methodology. Refer to Table 1 for Site Code Identification.

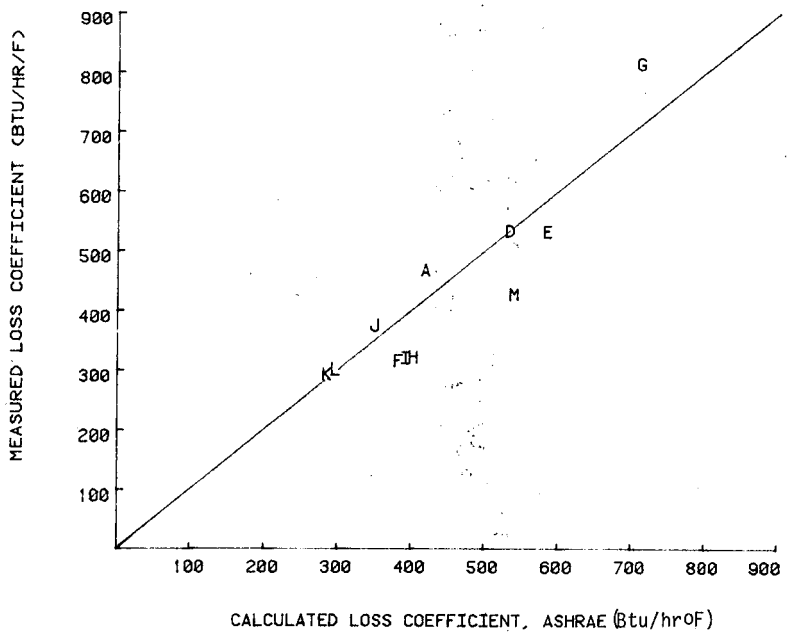



Fig. 2. Comparison of the Building Loss Coefficient ($U_A$) as Determined Using the Standard ASHRAE Method and Measured Using Electric Co-Heating. Refer to Table 1 for Site Code Identification.

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# THE HODGES RESIDENCE: FOUR YEARS OF MONITORING PERFORMANCE AND OCCUPANT REACTIONS

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## ABSTRACT

The Hodges Residence, an award-winning 2200 square foot superinsulated direct gain passive solar home in Ames, Iowa, has been occupied and monitored for four winters and three summers. It has served as Iowa State University's de facto passive solar research home, with particular emphasis on studying the effects of variations in operation. Thermal performance results are given for different seasons, with and without the use of night insulation, using only off-peak heating, with deliberate natural ventilation during wintertime, and so forth. Psychological impacts on the occupants are also described, with emphasis on temperature swings, glare, indoor air quality, and the use of a masonry floor. Reactions of visitors are also reported.

## 1. INTRODUCTION

The Hodges Residence is an earth-sheltered superinsulated direct gain passive solar home in Ames, Iowa (latitude 42.0°N). The architect was David A. Block, A.I.A., who is professor of architecture at Iowa State University. The passive solar system was designed by him and Laurent Hodges, professor of physics at Iowa State University. The design of the home was one of the winners in the 1978 National Passive Solar Residential Design Competition sponsored by the U.S. Department of Housing and Urban Development. The home was recently featured in Passive Solar Architecture - Logic and Beauty: 35 Outstanding Houses Across the United States by David Wright and Dennis A. Andrejko (New York: Van Nostrand Reinhold, 1982).

The home is on two levels, each with a floor area of 1100 square feet (44 feet long E-W and 25 feet deep N-S, interior dimensions). The floor between the two levels coincides with the natural ground level of the site, which was initially flat. The ground was scooped out on the south side (and used for berming on the other three sides) to expose 5 feet of glass on the lower level; this glass starts 3 feet above the bottom (floor) of the lower level. There are 8 feet of glass on the upper level.

North of the upper level is a 500 square foot garage-storage area which extends the whole length of the house, serving as a buffer. There is berming on the north, east and west sides of the house. The lower level is completely below ground except for the 5 foot glass exposure on the south side. The home is earth-sheltered in the sense that over half its exterior envelope is underground or bermed.

The upper level is very open and serves as the daytime living area; it includes living room, dining room, family room, kitchen, pantry, and bathroom, with only the last two rooms actually separated off by walls. The lower level includes three bedrooms, one bath, a darkroom, and storage and utility areas. The bedrooms were located on the lower level for tornado protection and summer coolness.

To lend architectural interest to the home, an arch was added near the front of the home and the stair tower was allowed to protrude out of the south wall. These features have no energy significance and indeed slightly degrade the thermal performance of the home.

The home has no north windows and only a few east and west windows, which are partly shaded in summer by the arch. There are a total of about 40 $m^2$ (440 $ft^2$) of south glass, consisting of double-pane tempered window glass, both fixed and sliding glass doors.

The primary thermal storage in the home is the floor between the two levels. It consists of 8-inch-thick concrete cored slabs topped by 2 inches of exposed aggregate, for a total mass of about 40 metric tons. The cores in the floor run N-S and serve as the return ducts to the auxiliary natural gas furnace; on sunny days the furnace fan can

then be used to help transfer solar heat into the floor. Since the upper surface of this floor is mostly uncovered (only a few area rugs are used on it), and since the lower surface has only a thin plaster texture on it (giving the appearance of an ordinary ceiling), this slab floor is a source of radiant heat to both levels. In addition to this floor, there is a considerable amount of thermal storage on the lower level, which has 8-inch poured concrete walls and a 4-inch slab floor.

The home was superinsulated. The ceiling has 12 inches of fiberglass insulation and is approximately R-40. The lower level concrete walls are insulated outside with 3 inches of extruded polystyrene rigid insulation. The upper level east and west walls (which support some berming) are 2x8 walls insulated to about R-30. The upper level north wall (to the garage) is a 2x4 wall with rigid insulation added to make it about R-20. There is a continuous vapor barrier.

The exterior is an "edible landscape" with many types of berries, fruit trees, garden vegetables, and both perennial and annual flowers. (There are also beehives, so the flowers count as edible.)

The Hodges Residence has been occupied by a family of four (two adults and two children) since late September,1979. Records of energy consumption and performance were kept using minimum-maximum thermometers and meters. The natural gas furnace and the water heater both have gas meters to record their consumption, and a special electric meter records the electrical energy consumption of the blowers associated with the forced air system of the home. In addition, the utilities' outdoor gas and electric meters record total consumption. Finally, wood burned in the fireplace is weighed. The fireplace is in the family room, on the north wall, with its masonry extending into the garage-storage area. The fireplace has glass doors and uses outside combustion air.

## 2. THERMAL PERFORMANCE: HEATING

Testing during the first winter established the fact that this home remained comfortable even when the indoor air temperature fell below 65°F, presumably because of the high mean radiant temperature in the home from all the non-glass surfaces. Consequently, the usual operation of the home has been to set the thermostat (for the auxiliary natural gas furnace) at 65°F. Occasionally, during warm sunny periods, the indoor air temperature rose to 80°F or more, at which point windows or sliding glass doors would be opened to ventilate excess heat.

Although the home is very open, and there is good air circulation between the two levels, there was some temperature stratification in the home, with the upper level generally being a few degrees warmer in winter and up to about 5 C° (9 F°) warmer in summer. This was expected and was taken into account in the design of the home. The bedrooms were located on the lower level because it was cooler year-round.

### 2.1 Performance in 1979-80 Heating Season

Table 1 shows the energy consumption in the home recorded during the first year, from October 1, 1979, through September 30, 1980. During the first winter, no night insulation was used on the glass in a study of how the home behaved without night insulation. The winter was a comparatively mild one, but also cloudier than average. For the months of September through May there were 3591 C°-days (18.3°C base) (6463 F°-days to 65°F base) compared to the long-term average of 3769 C°-days (6785 F°-days). Solar radiation on a horizontal surface was about 30 percent below average in January and about 15 percent low in December and February.

The total heat input to the home from the auxiliary heating sources (furnace and fireplace) was 26.2 GJ (24.85 million Btu), estimating 70 percent of the furnace consumption and 30 percent of the fireplace consumption as actually delivered to the home. The cost of the auxiliary heat was $85 for the natural gas and nothing for the scrap wood, but a fairer figure would be about $100 for natural gas and the natural gas equivalent of the wood energy contribution.

Note that over the full year (as in all other years) the furnace required less energy than the water heater.

### 2.2 Performance in 1980-81 Heating Season

Night insulation was used on the south glass during the 1980-81 heating season, and some permanent insulation was placed over most of the small amount of east and west glazing. The movable insulation consisted of one- to two-inch-thick panels of Klegecell (a rigid polyvinyl chloride foam manufactured by the American Klegecell Corporation of Grapevine, Texas). These panels were cut to fit the large glazing areas of the home and covered by a fabric decorated by Linda Hodges to form a large mural when in place. This insulation was installed over about 90 percent of the south glazing between 5 and 6 p.m. nightly and removed between 7 and 8 a.m. Removal and installation each took about 10 minutes, and never became a burden (they generally coincided with the morning and evening news). During the day the panels were stored in spaces designed for them on each level.

TABLE 1. ENERGY CONSUMPTION IN HODGES RESIDENCE, 1979-1980.

| Month | Electricity (kWh) | | | Natural Gas (CCF) | | | | Wood |
|---|---|---|---|---|---|---|---|---|
| | Fans | Other | Total | Furnace | W. Htr. | Other | Total | (pounds) |
| Oct. 1979 | 0.8 | 617.8 | 618.6 | 0.1 | 30.6 | 10.3 | 41.0 | 0 |
| Nov. | 25.7 | 656.4 | 682.1 | 12.5 | 28.2 | 15.7 | 56.4 | 0 |
| Dec. | 126.6 | 729.4 | 856.0 | 43.7 | 30.2 | 13.1 | 87.0 | 176 |
| Jan. 1980 | 209.9 | 705.3 | 915.2 | 115.0 | 33.3 | 14.7 | 163.0 | 329 |
| Feb. | 136.1 | 565.2 | 701.3 | 80.0 | 29.8 | 10.0 | 119.8 | 251 |
| Mar. | 129.1 | 563.6 | 692.7 | 45.3 | 32.5 | 10.2 | 88.0 | 362 |
| Apr. | 29.4 | 577.9 | 607.3 | 7.7 | 32.6 | 8.7 | 49.0 | 176 |
| May | 5.4 | 550.4 | 555.8 | 0 | 33.6 | 7.4 | 41.0 | 0 |
| June | 31.6 | 531.7 | 563.3 | 0 | 21.8 | 5.4 | 27.2 | 0 |
| July | 126.6 | 727.3 | 853.9 | 0 | 25.0 | 6.4 | 31.4 | 0 |
| Aug. | 1.7 | 648.3 | 650.0 | 0 | 25.2 | 8.5 | 33.7 | 0 |
| Sept. | 0 | 571.6 | 571.6 | 0 | 25.1 | 9.6 | 34.7 | 0 |
| Total | 822.9 | 7444.9 | 8267.8 | 304.3 | 347.9 | 120.0 | 772.2 | 1294 |

TABLE 2. ENERGY CONSUMPTION IN HODGES RESIDENCE, 1980-1981.

| Month | Electricity (kWh) | | | Natural Gas (CCF) | | | | Wood |
|---|---|---|---|---|---|---|---|---|
| | Fans | Other | Total | Furnace | W. Htr. | Other | Total | (pounds) |
| Oct. 1980 | 18.6 | 623.3 | 641.9 | 0 | 30.2 | 10.7 | 40.9 | 17 |
| Nov. | 37.5 | 598.6 | 636.1 | 0 | 28.2 | 10.8 | 39.0 | 44 |
| Dec. | 74.6 | 652.6 | 727.2 | 34.2 | 31.1 | 13.8 | 79.1 | 374 |
| Jan. 1981 | 84.6 | 602.9 | 687.5 | 31.0 | 31.4 | 12.2 | 74.6 | 122 |
| Feb. | 78.7 | 549.8 | 628.5 | 35.8 | 30.8 | 10.0 | 76.6 | 200 |
| Mar. | 21.9 | 563.6 | 585.5 | 2.2 | 33.5 | 9.8 | 45.5 | 24 |
| Apr. | 1.6 | 622.0 | 623.6 | 0 | 27.4 | 9.3 | 36.7 | 24 |
| May | 2.3 | 581.7 | 584.0 | 0 | 26.3 | 10.0 | 36.3 | 0 |
| June | 4.7 | 581.7 | 586.4 | 0 | 18.0 | 6.8 | 24.8 | 0 |
| July | 4.7 | 638.1 | 642.8 | 0 | 19.3 | 8.2 | 27.5 | 0 |
| Aug. | 0 | 679.2 | 679.2 | 0 | 22.7 | 7.0 | 29.7 | 0 |
| Sept. | 0 | 577.2 | 577.2 | 0 | 20.3 | 9.0 | 29.3 | 0 |
| Total | 329.2 | 7270.7 | 7599.9 | 103.2 | 319.2 | 117.6 | 540.0 | 805 |

TABLE 3. ENERGY CONSUMPTION IN HODGES RESIDENCE, 1981-1982.

| Month | Electricity (kWh) | | | Natural Gas (CCF) | | | | Wood |
|---|---|---|---|---|---|---|---|---|
| | Fans | Other | Total | Furnace | W. Htr. | Other | Total | (pounds) |
| Oct. 1981 | 7.9 | 620.7 | 628.6 | 0 | 18.6 | 10.7 | 29.3 | 25 |
| Nov. | 24.0 | 637.0 | 661.0 | 5.4 | 24.7 | 11.8 | 41.9 | 65 |
| Dec. | 66.0 | 711.2 | 777.2 | 29.2 | 26.0 | 14.1 | 69.3 | 287 |
| Jan. 1982 | 119.5 | 678.5 | 798.0 | 84.7 | 28.4 | 16.1 | 129.2 | 379 |
| Feb. | 53.2 | 620.8 | 674.0 | 40.8 | 28.2 | 12.8 | 81.8 | 68 |
| Mar. | 44.6 | 657.3 | 701.9 | 31.7 | 30.5 | 12.0 | 74.2 | 24 |
| Apr. | 13.8 | 599.6 | 613.4 | 10.0 | 28.3 | 10.1 | 48.4 | 0 |
| May | 0 | 680.7 | 680.7 | 0 | 26.0 | 10.8 | 36.8 | 0 |
| June | 0 | 631.5 | 631.5 | 0 | 22.2 | 9.3 | 31.5 | 0 |
| July | 0 | 714.5 | 714.5 | 0 | 16.1 | 9.0 | 25.1 | 0 |
| Aug. | 68.2 | 720.9 | 789.1 | 0 | 14.8 | 6.6 | 21.4 | 0 |
| Sept. | 0 | 624.9 | 624.9 | 0 | 16.6 | 9.5 | 26.1 | 0 |
| Total | 397.2 | 7897.6 | 8294.8 | 201.8 | 280.4 | 133.0 | 615.0 | 848 |

The 1980-81 heating season was mild but cloudy. For the months of September through May, there were only 3284 $C^{o}$-days (5912 $F^{o}$-days), 13 percent below average. Solar radiation on a horizontal surface averaged 30, 10, and 13 percent below the long-term averages for the months of December, January, and February. The total heat input to the home from auxiliary sources was only 9.8 GJ (9.25 million Btu). The cost of auxiliary heat (including the natural gas equivalent of the wood burned) was only $45.

## 2.3 Performance in 1981-82 Heating Season

Table 3 shows the energy consumption for the third year of occupancy. The 1981-82 heating season was generally regarded as very severe, although the total heating degree-days from September through May,

TABLE 4. ENERGY CONSUMPTION IN HODGES RESIDENCE, 1982-1983.

| Month | Electricity (kWh) | | | Natural Gas (CCF) | | | | Wood |
|---|---|---|---|---|---|---|---|---|
| | Fans | Other | Total | Furnace | W. Htr. | Other | Total | (pounds) |
| Oct. 1982 | 0 | 633.0 | 633.0 | 0 | 22.5 | 9.9 | 32.4 | 0 |
| Nov. | 40.2 | 649.6 | 689.8 | 31.0 | 25.8 | 9.5 | 68.3 | 0 |
| Dec. | 68.6 | 695.6 | 764.2 | 56.5 | 28.8 | 9.7 | 95.0 | 0 |
| Jan. 1983 | 99.7 | 702.5 | 802.2 | 83.7 | 31.4 | 10.0 | 125.1 | 0 |
| Feb. | 69.7 | 637.1 | 706.8 | 54.6 | 30.3 | 11.0 | 95.9 | 0 |
| Mar. | 94.9 | 675.9 | 770.8 | 56.4 | 30.5 | 10.5 | 97.4 | 0 |
| Apr. | 42.4 | 794.6 | 837.0 | 41.6 | 27.0 | 11.3 | 79.9 | 0 |
| May | 4.6 | 663.0 | 667.6 | 0 | 30.0 | 11.5 | 41.5 | 0 |
| Total* | 488.3 | 8143.1 | 8631.4 | 323.8 | 296.0 | 117.8 | 739.6 | 0 |

* 12-month period, June 1982 through May 1983.

3946 $C^{o}$-days (7102 $F^{o}$-days), was only 5 percent above normal. However, January had 973 $C^{o}$-days (1751 $F^{o}$-days), 26 percent above normal, and was characterized by several consecutive weekends of harsh ground blizzards; coming after two mild winters, this probably accounted for the impression of a terribly severe winter. For the third year in a row, the mid-winter months were cloudy.

Night insulation was used again during the 1981-82 heating season. The total auxiliary heat delivered to the home totaled 17.4 GJ (16.5 million Btu). The cost of auxiliary heating (again counting the natural gas equivalent of the wood burned) was $105 for the whole heating season. The highest natural gas bill (January) was $57 for a 34-day period; this covered furnace heat, water heater, cooking and drying for a family of four.

### 2.4 Performance in 1982-83 Heating Season

During the 1982-83 heating season, a major change in operation was tried. Almost every day, the home was given a good flushing out by natural ventilation. The upstairs and downstairs sliding glass doors on the south side were opened part way for periods ranging from just a few minutes on cloudy days to as much as two hours on sunny days. This was done to see if increased natural ventilation would seriously affect thermal performance. As it happened, the winter was exceptionally cloudy every month from November through April. As a result, auxiliary energy consumption was up significantly for two reasons: increased air infiltration and decreased insolation. Table 4 shows the monthly energy consumption. Table 5 shows the results of measurements of solar radiation taken by a silicon sensor (Solar Data Model 81B, calibrated against an Eppley PSP pyranometer) through vertical south-facing double-pane glass (one of the windows of the home) during the 1981-82 and 1982-83 heating seasons. Since even the first of these winters was cloudier than average, the second winter was (hopefully) about as cloudy a winter as will ever occur.

The auxiliary heating requirement for the 1982-83 heating season was 23.9 GJ (22.6 million Btu), considerably more than in the 1981-82 season despite a smaller number of heating degree-days (3516 $C^{o}$-days or 6328 $F^{o}$-days from September through May).

### 2.5 Use of Off-Peak Auxiliary Energy

Although energy conservation receives more attention than power conservation, the latter is extremely important, especially for electric utilities. An electric utility's power plant capacity is determined by its peak demand load, which usually occurs on hot summer afternoons when the air conditioning load is high, but can occur in winter for some utilities. Utilities have been experimenting with seasonal and time-of-use pricing in order to encourage the shift of energy consumption from on-peak to off-peak times, the same strategy employed by telephone companies. The typical time-of-use pricing by electric utilities allows very low rates (often 30 to 40 percent of on-peak rates) during off-peak periods, which are usually evening hours and weekends. As an example, Iowa Electric Light and Power (which serves customers around but not in Ames) defines on-peak as 7 a.m. to 8 p.m. Mondays through Saturdays and off-peak as the rest of the week, billing customers who agree to time-of-use rates at 125 percent of the usual rate for on-peak consumption and only 50 percent of the usual rate for off-peak consumption.

TABLE 5. AVERAGE DAILY INSOLATION (IN $MJ/m^2$) RECEIVED THROUGH SOUTH-FACING DOUBLE-PANE WINDOWS IN AMES, IOWA.

| | 1981-82 | 1982-83 |
|---|---|---|
| November | 7.0 | 5.6 |
| December | 7.3 | 5.2 |
| January | 8.2 | 5.8 |
| February | 9.1 | 5.8 |
| March | 6.9 | 5.0 |
| Average | 7.7 | 5.5 |

TABLE 6. HOME HEATING REQUIREMENT AND HOME HEATING INDEX OF THE HODGES RESIDENCE

| Month | Heat from Electricity | Heat from Natural Gas | Heat from Wood | Total Heat | Degree-days | HHR | HHI |
|---|---|---|---|---|---|---|---|
| Dec. 1979 | 2.92 MBtu | 6.27 MBtu | 0.40 MBtu | 9.59 MBtu | 1148.5 | 8350 | 3.80 |
| Jan. 1980 | 3.12 | 11.75 | 0.74 | 15.61 | 1402 | 11134 | 5.06 |
| Feb. 1980 | 2.39 | 8.64 | 0.56 | 11.59 | 1367.5 | 8475 | 3.85 |
| Total | 8.43 | 26.66 | 1.70 | 36.79 | 3918 | 9390 | 4.27 |
| Dec. 1980 | 2.48 | 5.71 | 0.84 | 9.03 | 1392.5 | 6485 | 2.95 |
| Jan. 1981 | 2.35 | 5.38 | 0.28 | 8.00 | 1392 | 5747 | 2.61 |
| Feb. 1981 | 2.14 | 5.52 | 0.45 | 8.11 | 1120.5 | 7238 | 3.29 |
| Total | 6.97 | 16.60 | 1.57 | 25.14 | 3905 | 6438 | 2.93 |
| Dec. 1981 | 2.65 | 5.00 | 0.65 | 8.29 | 1424.5 | 5820 | 2.65 |
| Jan. 1982 | 2.72 | 9.32 | 0.85 | 12.89 | 1906.5 | 6761 | 3.07 |
| Feb. 1982 | 2.30 | 5.90 | 0.15 | 8.35 | 1362 | 6131 | 2.79 |
| Total | 7.67 | 20.22 | 1.65 | 29.54 | 4693 | 6294 | 2.86 |
| Dec. 1982 | 2.61 | 6.65 | 0 | 9.26 | 1229.5 | 7532 | 3.42 |
| Jan. 1983 | 2.74 | 8.59 | 0 | 11.33 | 1360.5 | 8328 | 3.79 |
| Feb. 1983 | 2.41 | 6.71 | 0 | 9.12 | 1101 | 8283 | 3.77 |
| Total | 7.76 | 21.95 | 0 | 29.71 | 3691 | 8049 | 3.66 |

Notes: MBtu = million Btu
Degree-days had base of 68°F in 1979-1980 and 70°F in the other seasons
HHR has units of Btu/degree-day Fahrenheit
HHI has units of Btu/degree-day-square-foot

Two significant energy needs of a home - heating and cooling - can be shifted at least partly into off-peak hours by the use of thermal storage mass. For example, the storage could be heated at night, when rates are lowest, and the heat allowed to enter the home during daytime hours, thereby reducing daytime heating. Some utilities sell thermal storage for this purpose; Iowa Electric markets an "Off-Peak Electric Furnace" using a large, well-insulated ceramic brick which is heated at night by electric resistance heating, then used as a heat source by day.

A home with considerable thermal mass on the interior should be able to use the mass naturally for this purpose. Since the Hodges Residence has considerable thermal mass with a large surface area, the concept was tested during the 1980-81 and 1981-82 heating seasons (a mild year and a colder-than-average year with a wicked January). The furnace was manually shut off at the thermostat each day at 7 a.m. (Sundays included) and kept off until 8 p.m. On a few occasions, when it was predicted that the following day would be both cold and cloudy, the thermostat was turned up (to 68°F) at night to store extra heat for the next day. This experiment was successful: no uncomfortable days were experienced, and indeed the other family members were not even aware of the daytime furnace shutoff. The combination of internal heat (cooking, appliances, etc.) and some solar gain even on cloudy days was sufficient to prevent the home from cooling down too much by day.

### 2.6. Home Heating Requirement and Home Heating Index

The overall energy performance of a home can best be expressed by the Home Heating Index and the Home Heating Requirement (1). Table 6 shows these quantities for the Hodges Residence during its four heating seasons. In the two years in which night insulation was used and insolation was somewhat below average (1980-81 and 1981-82) the Home Heating Index was 2.9 for the three coldest months averaged together. In the year in which night insulation was not used (1979-80) it was 4.3. In 1982-83, the cloudy year in which the home was ventilated during the winter, the Home Heating Index was 3.7. All of these numbers are very low, demonstrating the energy-efficiency of the home. In a completely ordinary winter, the Home Heating Index would be about 2.5.

### 2.7. Summer Performance

During the summer months the lower level of the home remains comfortably cool. At times a small electric fan has been used. There are few times when the temperature reaches as high as 80°F, and blankets are used in the bedrooms all but a few days of the year.

The upper level is warmer, but during the past two years there has been only one day on which it was uncomfortably warm. For this reason, air conditioning is not used. There are no overhangs or shading device used on the south glazing, yet measured solar gain is far smaller than in the winter months.

## 3. OCCUPANT REACTIONS

The Hodges Residence has proved extremely pleasant to live in, both in winter and in other months. The direct gain system provides excellent natural lighting to both levels, even on cloudy days. The ability to look outdoors and see the landscape, the weather, the clouds, the sky, and astronomical objects at night is marvelous. Glare is not a problem, probably for two reasons. First, the whole south wall is glazed and the sidewalls in the home are light-colored, so that there is not the harsh contrast that can occur in homes with only a small amount of glazing. Second, the interior design is such that even when the sun is low in the sky in winter, it will not be in the field of view of the occupants during their normal activities.

The temperature fluctuations in the home are not large, because of the large amount of thermal storage mass. On the very coldest nights of the winter the home only cools down about 10 $F^{o}$, and the daytime swings are not much larger. The home is normally maintained in the $65^{o}F$ - $80^{o}F$ range.

The masonry floor, which consists of 2 inches of exposed aggregate over the cored slabs, is very nice. Being somewhat uneven in texture and color, it does not show dirt, yet it is easy to clean with just a vacuum cleaner. For a family with two small children, it is far more practical than a carpeted floor, which we would not want to return to. The floor is not hard to walk on. (The kitchen has a rubber floor instead of the exposed aggregate.)

The indoor air quality appears to be good. The home was built using as little as possible in the way of particleboard, plastics, and other materials that might contribute pollutants to the air. The clothes dryer is vented to the exterior. The kitchen range has a filter vent which disperses the combustion products throughout the home so they do not concentrate in the kitchen area. The home has low air infiltration compared to conventional homes, but was not ruthlessly tightened. The experience of 1982-83, when there was extra ventilation, shows that it is possible in Iowa at least to have an energy-efficient home to which considerable fresh air is admitted.

With regard to indoor air quality, we have noticed that coming into the home from the outdoors, the interior never seems stale or musty, except in rare instances when, for example, something boiled over on the range. Yet in going outside, we have often noted a poorer air quality. This is particularly true on winter nights, when the foul smell of wood-burning systems is polluting the air.

There are many psychological benefits to living in a direct gain home, and these may well be worth more than the energy savings. In the middle of a cold Iowa winter, it is awfully nice to be able to "sunbathe" in the window on a cold but sunny day, watching the overcoated masses outdoors struggling against the elements.

## 4. VISITOR REACTIONS

Hundreds of persons have visited the home during tours or on other occasions. They are generally impressed by the aesthetics of a direct gain passive home, including the openness, the view, the warmth. Many favorable comments have been received from persons who have visited other solar homes in the area, particularly a well-known active solar home (the Iowa State University Energy Research House) and a nearby home which is more earth-sheltered than ours but has less passive solar glass. The $400 we have spent on auxiliary heating during the past four winters (counting the cost of the natural gas equivalent of the wood we've burned) impresses visitors, including some who have spent more than that for a single month, even with natural gas! It should be noted that this home, the first passive solar home in Iowa designed properly as such, has greatly assisted in demonstrating passive solar and superinsulation techniques to the state. Yet there are still occasional visitors who inquire, "This is a solar home? Where are your solar panels?"

## 5. ACKNOWLEDGEMENTS

I would like to acknowledge Dr. Richard Carlson for his solar radiation records kept for Ames, and K. Baker and the Iowa Energy Extension Service for the use of solar radiation monitoring equipment the past two years.

## 6. REFERENCE

(1) Hodges, L. et al. "The Home Heating Index," PROGRESS IN PASSIVE SOLAR ENERGY SYSTEMS 7: 125-130 (1982).

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# COMPARISON OF VERTICAL HIGH PERFORMANCE GLAZING TO SLOPED DOUBLE GLAZING WITH MOVABLE INSULATION

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## ABSTRACT

This paper compares the monitored performance of a passive solar home in Cincinnati, Ohio, before and after modification of the sunspace glazing system. The National Solar Data Network (NSDN) monitored Solargreen I from March 1980 through August 1981. During this period the sunspace consisted of 300 $ft^2$ of double glass at a $60^o$ tilt with "Window Quilt" movable insulation.

The NSDN resumed monitoring of Solargreen I after the sunspace was rebuilt in the fall of 1982 with 300 $ft^2$ of vertical, commercially available, quad-pane glazing and no movable insulation. The glazing system consists of two layers of 3M Sungain high transmission film suspended between two layers of glass. The glazing system has a manufacturer's specified U value of 0.26 and a transmittance of 0.63. The building, to which the sunspace is attached, was not changed.

This paper compares the performance of the sunspace system with $60^o$ sloped double glazing and movable insulation to the sunspace on the same building consisting of vertical quad-pane glazing with high transmission film and no movable insulation. Data for the two systems include transmittance of the glazing system, heat loss and net gain of the glazing system measured using a net radiometer and compared to UAΔT calculations, temperature swings in the sunspace, and overall building performance.

## 1. INTRODUCTION

The art of sunspace design is entering a new phase of development. In the years past, sunspace experts told us how to design sunspaces based on an "optimum design" generated by a computer simulation. The classic design is a $60^o$ sloped south wall with double glazing, movable insulation, and solid end walls. This design is now a standard in the prefab sunspace industry. After several years of experience with these computer-generated designs, designers and builders alike are realizing that this design has problems that the computer never told us about; like water leaks, glass fogging, and overheating, not to mention the fact that it just does not look right on a Cape Cod or a split-level house.

The sunspace as a home addition must be integrated with the style of the building. Vertical windows and walls are the norm and, therefore, look better on most houses. Sloped glass rarely looks like it fits. The nonsolar enthusiast or the basic American homeowner often thinks the commercial passive solar greenhouse or sunspace design with its $60^o$ sloped glass and solid end walls is odd, and they worry about how it looks tacked onto their house. Most people are primarily interested in adding to the living space of their home and secondly, saving energy. Therefore, the sunspace must be designed as a comfortable living space as well as an energy saver. The sunspace is a living place for people. The greenhouse, on the other hand, is a growing space for plants. The sunspace designer or homeowner must decide from the very beginning whether he wants a sunspace or a greenhouse (you cannot have both), because the two have very different design solutions.

The greenhouse design must meet the horticultural needs of plants: light, air, and water. Plants require both direct and diffuse light and, therefore, require overhead glass and glass end walls. Plants require lots of fresh air and, therefore, greenhouses must be ventilated even in winter. Plants also require a great deal of water and, therefore, the greenhouse environment is often very humid. The high humidity and constant evaporation of water in the greenhouse consume a great deal of energy. Therefore, greenhouses rarely have additional energy to share with the houses to which they are attached.

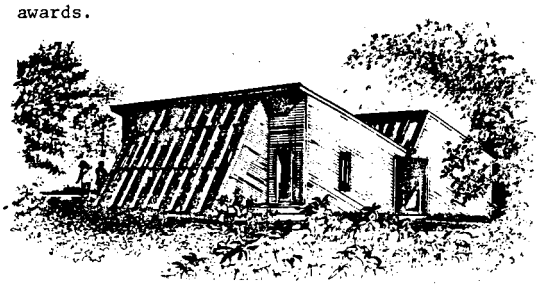
The sunspace must be designed to be comfortable for people. This means low temperature swings, low humidity, moderate light levels, warm in the winter and cool in the summer.

The new generation of sunspaces are doing away

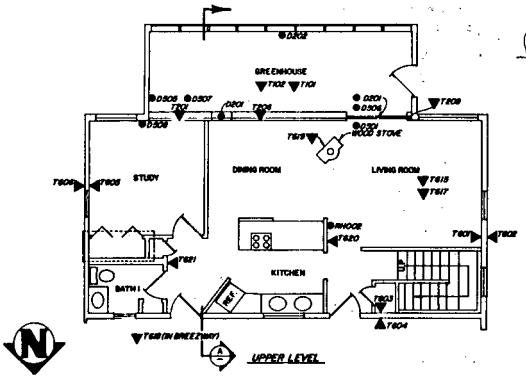
with sloped glazing and going to a vertical glazing system. The vertical glazing eliminates all the problems of leaks, overheating, and architectural integration, plus it costs less. Also, new glazings are coming on the market now that eliminate the need for movable insulation. A new generation of sunspaces is being designed based on years of field experience and the results of extensive monitoring and analysis.

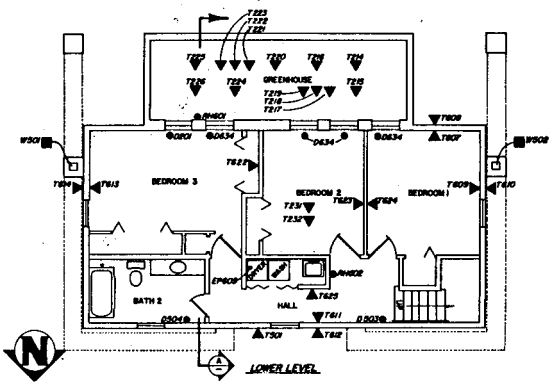
## 2. SOLARGREEN I

In 1979, Ray Baker built Solargreen I in Cincinnati, Ohio. At that time the building was praised for its "state of the art" passive solar sunspace design and the design won many awards.

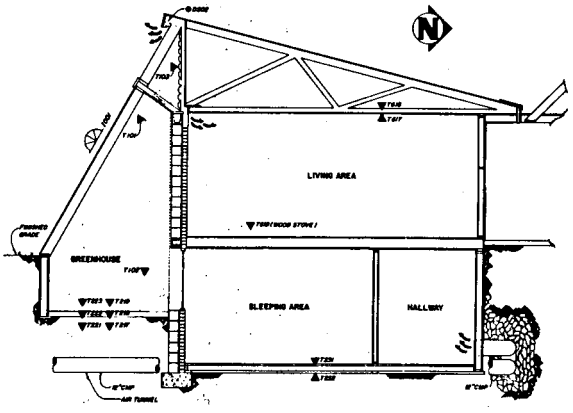


The home has three bedrooms and a bath on the lower level, and living room, dining room, kitchen, bath, and study on the upper level. The floor area is 1,600 square feet. The sunspace floor is four feet below grade and rises to the roof of the upper level. The bedrooms and upper level rooms have windows and doors that open into the sunspace.




The sunspace was glazed with 300 $ft^2$ of double-pane sealed insulating glass units. The glazing wall was tilted at $60^{\circ}$ and "Window Quilt" movable insulation was used to reduce heat loss from the glass. The end walls were solid and well insulated. A one-foot-thick concrete wall separated the sunspace and the living space and provided thermal storage. Additional thermal storage in the form of 20 phase-change thermal storage rods hung in front of the mass wall.




Solargreen I was monitored from 1980-1981 by Vitro Laboratories, for the Department of Energy under the National Solar Data Network (NSDN). The results of the monitoring showed the building to performed well with 55% of the building heat being provided by the sunspace, but numerous problems were also observed. Many of these problems seem to be common among sunspaces of this type.

- Overheating

  The sunspace overheated not only during the summer but also during the winter. During March and April 1981, the sunspace maximum temperature was 121°F. During the summer, the "Window Quilt" was drawn down in an attempt to prevent overheating, but the sunspace still reached temperatures well over 120°F. As a result, the house overheated.

- High Heat Loss

  The heat loss of the sloped glazing was much higher than expected due to clear night sky reradiation. A glazed attic space over the sunspace was monitored and found to drop below ambient temperatures by 5-10°F on cold clear nights.

- Thermal Stratification

  The upper level of the house and sunspace stayed very warm and often overheated. The auxiliary heat was rarely used in the upper level. On the other hand, the lower level remained cool and used the vast majority of the auxiliary heat delivered to the building. The heat distribution system was designed to thermosiphon from the sunspace to the house. The hot air from the sunspace collected in the upper level and the cool air settled to the lower level. The result was thermal stratification which always caused the upper level to be hotter than the lower level.

- Movable Insulation Problems

  The movable insulation caused constant problems. The primary problem was the edge seals. The weight of the curtain strains the edge seals and pulls them out. Even if the curtain can be hung so there is no strain on the edge seals, the constant wear on the edge of the curtain will cause it to wear out in only a few years. The curtain was operated regularly, but, even with prudent operation, the curtain was open to collect only 80% of the available solar radiation.

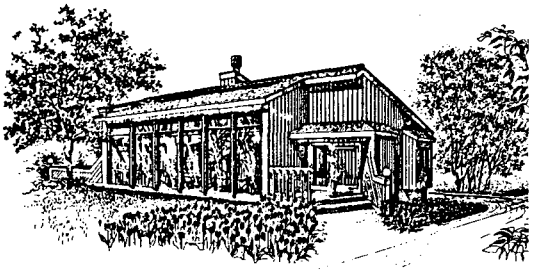
- Leakage

  The sloped insulated glass units were fogged after two years. This fogging is a typical problem with sloped glazing. The top layer of glass slips down over time and breaks the edge seals causing condensation between the glazing. Water leakage is also a problem with sloped glass systems. The seals require maintenance to maintain water tightness.

- High Initial Cost

  According to Mr. Baker, the sloped glazing system cost three times more to construct than the same area of vertical glass.

As a direct result of the close monitoring and performance analyses of Solargreen I by Vitro Laboratories, Solargreen I was redesigned. The new model is called Solargreen II. Solargreen II was built in Syracuse, New York, and has performed very well. Solargreen II was not monitored as extensively as Solargreen I, but the analyses of the utility bills showed a significant improvement over Solargreen I.



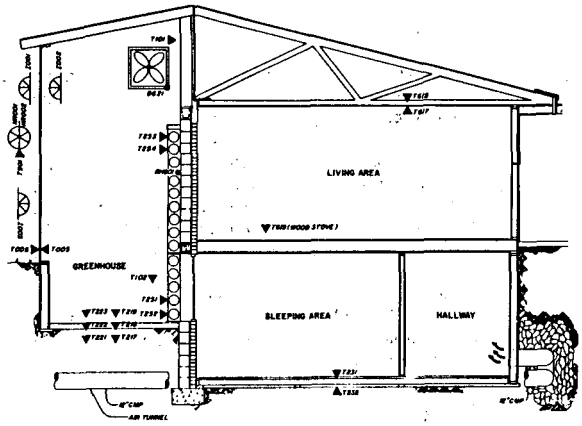
The heat load of Solargreen II was 0.99 Btu/DD·ft$^2$ as compared to 1.99 Btu/DD·ft$^2$ for Solargreen I.

The major difference between Solargreen I and Solargreen II is the use of vertical glazing instead of sloped glazing. A small fan was added to move hot air from the top of the sunspace to the lower level and prevented thermal stratification.

Solargreen II performed well in the summer and winter without overheating.

## 3. SOLARGREEN I MODIFIED

Based on the success of Solargreen II, Solargreen I was modified with vertical glazing. The new south wall of the new Solargreen I is approximately the same area as the previous sloped glazing but uses a new insulating glazing system developed by 3M and incorporated into Weather Shield windows. The new windows consist of four layers. The inside layer and the outside layer are ordinary window glass. The inside two layers are a very high transmission thin film developed by 3M called Sungain. The window is 1-3/4" thick and has a total solar transmittance of 63% with a U-factor of 0.26. The films are four mil, UV-protected polyester, coated with two invisible layers of antireflective material.




## 4. PERFORMANCE

Solargreen I with the new 3M glazing system has been monitored since January 1, 1983, under a cooperative effort between the 3M Sungain window project and the Department of Energy. The preliminary results are very encouraging. A comparison of the monitored performance was made of the sunspace net energy balance in four configurations: vertical double glazing with and without movable insulation, vertical quad glazing with Sungain film and sloped double glazing with movable insulation. The results are presented in Figure 1. The net gain (transmitted solar-glazing loss per square foot) of the sunspace at Solargreen I with 60° sloped double glazing and R-5 movable insulation was monitored from January 1, 1981, through June 1, 1981. Solargreen I with the Sungain film was monitored from January 1, 1983, through June 1, 1983.

The values for vertical double glass with and without movable insulation come from an NSDN site in Frederick, Maryland. All the values presented are normalized to the weather data from Solargreen I in Cincinnati, Ohio, from January 1, 1981, through June 1, 1981.

The monitored net gains and heating degree-days are plotted for the four configurations. The most obvious thing about this plot is how the 60° sloped system has the lowest net gain per square foot in January and the highest in April and May, while all the vertical systems have the highest net gain in January and the lowest in May. The 90° systems follow the slope of heating degree-days while the 60° system goes in the opposite direction. The quad-pane system with two layers of Sungain film had the highest net gains in January and February and the lowest in April and May. The next best performers were the vertical double glass with movable insulation and the vertical double glass without movable insulation.

The net gain of the Sungain system drops off in April when the heating degree-days also drop. This effect can be attributed to the seasonal change in transmittance of the glazing system.

Final assessment of the data collected at Solargreen I this past winter is not complete. However, preliminary analysis shows that the addition of the two layers of Sungain film does not significantly reduce the transmittance of the glazing system. In January and February the average transmittance of all three glazing systems were within a few percentage points of each other. Typical clear day transmittance of the quad-pane system at noon in January was 65%. Transmittance of the sloped double glass during the same period was 70%. In February the maximum transmittance measured was 62% for quad-pane and 68% for the sloped glazing. In March the transmittance was 58% and 67%, respectively.

The effect of vertical and sloped glazing on temperature swings is presented in Figure 2. Figure 2 is a plot of maximum, minimum, and average temperatures of the two systems. The 60° system had large temperature swings even using the movable insulation at night and on warm sunny days. The vertical glazed system maintained much smaller temperature swings with higher minimums and lower maximums.

## 5. CONCLUSIONS

Based on the monitoring and analysis of Solargreen I and other passive systems in the NSDN, two things seem clear. First, vertical glazing will probably perform better than sloped on an annual basis in most parts of the country. This performance is due to several factors:

- The transmittance of the vertical system is high in the winter and low in the summer, preventing overheating.
- Heat loss rate of sloped glazing is approximately 20% higher than for vertical glass, due to the direction of heat flow (heat flows up better than horizontally) and high night sky reradiation loss from the sloped system.

Other practical considerations which make vertical glazing preferable are:

- Vertical glazing costs less to install than sloped.
- Sloped glazing is prone to leakage.
- Seals around sealed glazing units break more readily on sloped applications and the glass fogs up.

- Vertical walls architecturally integrate better with most building styles.

The second conclusion is that the quad-pane system of two Sungain films between two layers of glass outperforms double glass with R-5 movable insulation in most parts of the country. This performance is due to:

- The net gains are higher in winter and lower in summer for the Sungain system.
- No maintenance or irregular operation of movable insulation.

The quad-pane glazing system with Sungain film costs less than double glazing with movable insulation. The average 34" x 76" double-pane patio door replacement panel costs about $70.00 or about $4.00 per square foot. The installed cost of "Window Quilt" in the Washington, DC area is about $7.00 per square foot. The total of glass and movable insulation is about $11.00 per square foot. The quad glazing with Sungain film can be purchased in 34" x 76" panels for $140.00 each or $7.78 per square foot. That represents a 30% savings in the cost of the sloped glazing system.

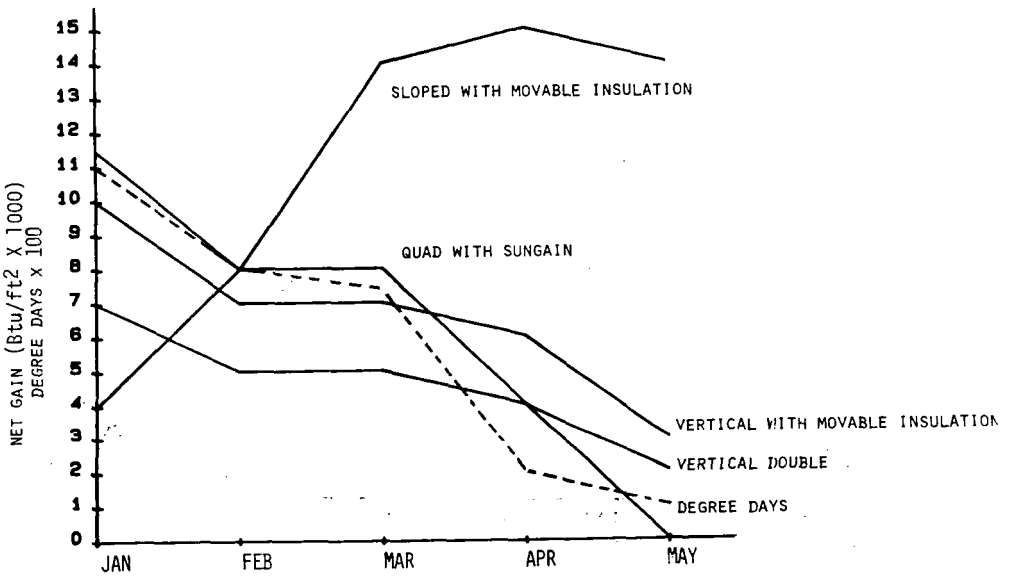



Fig. 1. Monitored Net Gain and Degree Days per Month.

## 6. REFERENCES


Solar Energy System Performance Evaluation Reports:

(1) Baker Construction, October 1980 - May 1981; SOLAR 1095-81/14.

(2) Rymark I and II, January 1981 - April 1981; SOLAR 1106-81/14 and SOLAR 1110-81/14.

(3) Rymark I and Rymark II and Rymark III; May 1981 - March 1982; SOLAR 1106-82/14 and SOLAR 1107-82/14 and SOLAR 1110-82/14.

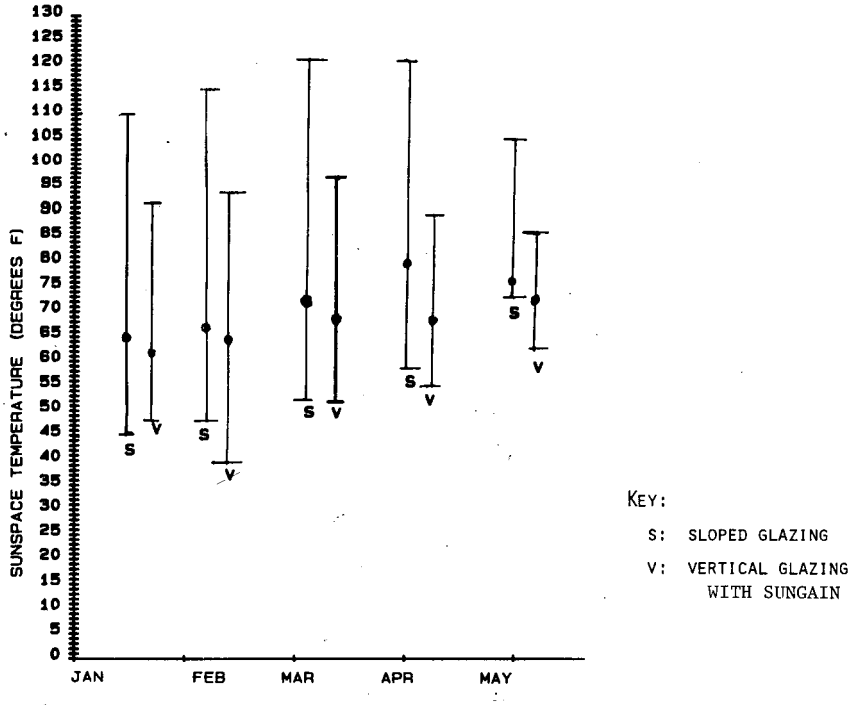



Fig. 2 Maximum and Minimum Sunspace Temperatures

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# LINEAR REGRESSION TECHNIQUES IN ANALYSIS OF THE BLOUIN SUPERINSULATED HOUSE*

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## ABSTRACT

Brookhaven National Laboratory, as part of its small building field validation program, gathered hourly data from the Blouin super-insulated house in South Royalton, Vermont, during March, April, and May, 1982. Least squares linear regression techniques came to be seen as one of the most valuable and powerful tools available for data analysis. Development of the models used and regression results obtained are presented for three major sub-systems of the house: the air-to-air heat exchanger system, the window and insulating shutter assemblies, and the building envelope.

## 1. INTRODUCTION

The first task in a bulding thermal performance monitoring project is the defining of the energy flows in the structure. This modeling effort can give the investigator the knowledge necessary to make observations about the thermal performance of the individual building components relative to the entire system. Integration and averaging techniques, manual iterations, and least-squares regression techniques have all been used for this purpose. In the subject project, least squares regression techniques were seen to have several advantages.

## 2. VENTILATION SYSTEM ANALYSIS

### 2.1 System Description

The ventilation system, consisting of air-to-air heat exchanger, fans, and duct system, is located in the basement. Insulated flexible supply and exhaust ducts, 8" diameter, connect to the heat exchanger and penetrate the west basement wall. Air is distributed from the heat exchanger to five diffusers on the upper floors and is exhausted from grills in the bathrooms and kitchen to the exchanger through an uninsulated flexible duct system. Supply and exhaust fans are activated on by a humidistat when the relative humidity in the living room approaches about 40%. Effectiveness of 0.62 for the heat exchanger unit was measured in the non-condensing mode.

### 2.2 Model

Heat loss from the building space due to the ventilation system is calculated hourly and assumed to be zero when the fans are idle. Hourly data for one week were examined, and the "effectiveness" of the ventilation system, including ducts, was calculated by the following equation:

$$EFF = (T_{fe} - T_{fl}) \times (T_{se} - T_{fe})^{-1} \qquad (1)$$

where:

EFF = heat exchanger system "effectiveness," including duct losses

$T_{fe}$ = temperature of fresh air entering the system

$T_{fl}$ = temperature of fresh air leaving the system

$T_{se}$ = temperature of stale air entering the system

The effectiveness was then plotted as a function of the outdoor air temperature. An upper bound was visually determined for the effectiveness of the operating system. During data analysis, the system was assumed to be shut off when this upper bound was exceeded.

### 2.3 Results

Results are shown in Figure 1. The clustered linear data represent times when the fans are operational. When the fans are idle, the calculated system effectiveness should approach 1.0, due to the effects of physical symmetry upon equation 1. Small air currents

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through the system after fan shut off account for the scatter seen in Figure 1. Duct heat gains and losses are responsible for the difference between the system effectiveness and heat exchanger effectiveness. The increase in effectiveness of the heat exchanger due to condensation (latent heat transfer) below about 35°F outdoor air temperature has no significant effect on the effectiveness of the total system. Calculations based on the effectiveness upper bound criteria are in excellent agreement with fan run times recorded by the home owner's elapsed-time recorder.

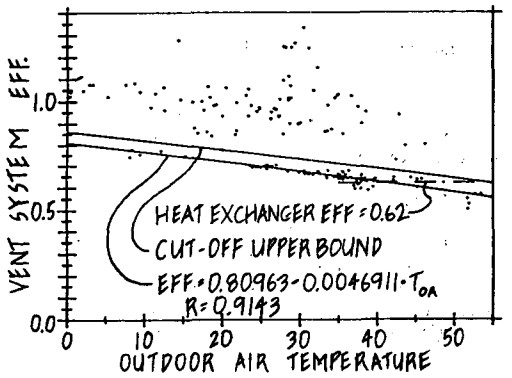



Fig. 1. Ventilation System Effectiveness.

## 3. WINDOW SYSTEM ANALYSIS

### 3.1 System Description

Moveable 1-1/4" thick urethane window insulation was fabricated for all the windows, which are double-hung, double glazed units. The north, east and west window insulation was in place the entire monitoring period. The insulation for the south windows was removed in the morning by the occupants before they left for work when a sunny day was anticipated, and replaced in the evening. Occupants were asked to remove or replace all south window insulation simultaneously so that each window would not have to be monitored. The occupants also kept a written record of the insulation status.

During data analysis energy conduction through the south window systems was calculated hourly as a function of the glazing thermal conductivity and movable insulation thermal conductivity and status. To allow determination of the latter two variables, a shielded thermocouple was installed centrally in the space between the glazing and the installed insulation in two different windows.

### 3.2 Data

Data sets for each of three window system operating conditions were assembled using the occupants written record as a guide.

1. Window insulation installed, no solar radiation (night), 84 records.

2. Window insulation installed, with solar radiation, 35 records.

3. Window insulation removed, with solar radiation, 41 records.

The variables found in each record are described in Table 1.

### 3.3 Models

Three separate models were created for analysis of the window system (Table 2). Each model is based upon a simple heat balance on the window system. Each was created specifically to be run on one of the three data sets.

Model W1, having only one independent variable, is the simplest of the three models. It was created for analysis of the window insulation installed R-value. In this model:

$$a_1 = R_{ins} \times (R_{glass} + R_{ins})^{-1} \qquad (2)$$

where:

$R_{ins}$ = window insulation thermal resistance

$R_{glass}$ = glass, muntons, and sash average thermal resistance.

By calculating a value for $R_{glass}$, using $a_1$ from the regression results, and rearranging equation 2, $R_{ins}$ may be calculated:

$$R_{ins} = a_1 \times (1 - a_1)^{-1} \times R_{glass}. \qquad (3)$$

Models W2 and W3 were created for determination of the window insulation status. $T_{sp}$ was predicted by rearranging both the model equations to the form:

$$T_{sp} = T_{in} - a_1 \times (T_{in-out}) - a_2 \times h \qquad (4)$$

The two values of $T_{sp}$ thus calculated are averaged. If $T_{sp}$ measured is on the same side of $T_{sp}$ average as $T_{sp}$ calculated from W2, then the insulation is assumed to be in place; if not the insulation is assumed to be removed.

### 3.4 Results

The results for all three models are presented in Table 3. Model W1 represents a very

TABLE 1. WINDOW ANALYSIS VARIABLES

| | |
|---|---|
| $x(1) = T_{out}$ | = outdoor temperature at end of hour, °F |
| $x(2) = T_{in}$ | = indoor air temperature at end of hour, °F |
| $x(3) = h_{ts}$ | = total solar radiation on vertical south surface, hourly total, Btu/ft$^2$ |
| $x(4) = T_{sp}$ | = temperature of sandwiched thermocouple at end of hour, °F |
| $x(5) = T_{in-sp}$ | = x(2) - x(4) |
| $x(6) = T_{in-out}$ | = x(2) - x(1) |

TABLE 2. WINDOW ANALYSIS MODELS

| MODEL I.D. | EQUATION |
|---|---|
| W1 | $X(5) = a_0 + a_1 \times X(6)$ |
| W2 | $X(5) = a_0 + a_1 \times X(6) + a_2 \times X(3)$ |
| W3 | $X(5) = a_0 + a_1 \times X(6) + a_2 \times X(3)$ |

NOTE: For all models $a_0 = 0$. The heat balance on the system indicates that a zero-intercept is appropriate.

TABLE 3. WINDOW ANALYSIS RESULTS

| MODEL I.D. | MULTIPLE R | MULTIPLE R-SQUARE | STD ERROR OF EST. | NO. OF DATA RECORDS | COEFFICIENT SYMBOL | COEFFICIENT VALUE | STD. ERROR | T | P(2TAIL) |
|---|---|---|---|---|---|---|---|---|---|
| W1 | 0.9991 | 0.9983 | 1.3071 | 84 | $a_1$ | 0.76500 | 0.00350 | 218.329 | 0.0000 |
| W2 | 0.9416 | 0.8865 | 10.4589 | 35 | $a_1$ | 0.66110 | 0.08229 | 8.034 | 0.0000 |
| | | | | | $a_2$ | 0.33421 | 0.02248 | 14.865 | 0.0000 |
| W3 | 0.9784 | 0.9572 | 2.8309 | 41 | $a_1$ | -0.10440 | 0.04389 | -2.379 | 0.0024 |
| | | | | | $a_2$ | 0.04321 | 0.00494 | 8.737 | 0.0000 |

close fit to the data. Substituting $R_{glass}$ = 2.02 ft$^2$·hr·°F·Btu$^{-1}$ (from table 4) and a 95% confidence interval 0.765 $\pm$ 1.96 x 0.00350 for $a_1$ into Equation 3, we get an $R_{ins}$ of 6.59 $\pm$ 0.24 hr·ft$^2$·°F·Btu$^{-1}$. A similar analysis for the other monitored window gives $R_{ins}$ = 6.28 $\pm$ 0.22 hr·ft$^2$·°F·Btu$^{-1}$. The average monitored $R_{tot}$ of 8.46 hr·ft$^2$·°F·Btu$^{-1}$ is 76% of the calculated value of 11.20 hr·ft$^2$·°F·Btu$^{-1}$.

Models W2 and W3, applied as previously described, did not give satisfactory agreement with the written record of window insulation operation. Note from Table 4 that the "standard error of estimate" (S.E.E.) of $T_{sp}$ is 10.5°F for model W2 and 2.8°F for model W3.

This can be taken into account by calculating a weighted average $T_{sp}$:

$$T_{sp} = (10.5 \times 2.8^{-1} \times T_{spw2} + T_{spw3}) \times (10.5 \times 2.8^{-1} + 1)^{-1} \quad (5)$$

Use of this value instead of the simple average as previously described gives excellent results with the written record of insulation operation.

## 4. ENVELOPE ANALYSIS

### 4.1 System Description

The building envelope is described in Table 4. Predicted values for the other building parameters will be presented in the "models" section.

TABLE 4. CACULATED HEAT LOSS

| | Calculated R-Value $hr \cdot ft^2 \cdot °F \cdot Btu^{-1}$ | Calculated U-Value $Btu \cdot (hr \cdot Ft^2 \cdot °F)^{-1}$ | AREA $ft^2$ | $\Delta T$ °F | HEAT LOSS W/SOUTH INSUL. Btu | HEAT LOSS W/O SOUTH INSUL. Btu | HEAT LOSS TO AMBIENT N,S WINDOWS Btu |
|---|---|---|---|---|---|---|---|
| Flat Ceiling | 56.7 | 0.0177 | 563 | 84 | 837 | 837 | 837 |
| Sloped Ceiling | 55.2 | 0.0181 | 347 | 84 | 528 | 528 | 528 |
| Floor to Bsmt. | 21.3 | 0.0469 | 820 | 15 | 577 | 577 | --- |
| Door to Bsmt. | 2.61 | 0.38 | 18 | 7 | 48 | 48 | --- |
| Stairwell to Bsmt. | 3.52 | 0.284 | 114 | 9 | 291 | 291 | --- |
| Walls | 40.7 | 0.0246 | 1019 | 84 | 2106 | 2106 | 2106 |
| Walls at Insul. Pockets | 31.0 | 0.0323 | 216 | 84 | 586 | 586 | 586 |
| Exterior Door | 2.5 | 0.40 | 20 | 84 | 672 | 672 | 672 |
| N,E,W, Windows (insul.) | 11.20 | 0.089 | 99 | 84 | 740 | 740 | 740 |
| So. Windows (insul.) | 11.20 | 0.089 | 99 | 84 | 740 | --- | --- |
| So. Windows (uninsul.) | 2.02 | 0.49 | 99 | 84 | --- | 4075 | --- |
| SUB-TOTAL | | | | | 7125 | 10460 | 5469 |
| Ventilation (1/2 air change/hr @ 0.7 heat rec. eff.) | | | | | 2643 | 2643 | |
| TOTAL | | | | | 9768 | 13103 | |

NOTE: These window areas include muntins and sash. Transparent south glazing totals 56 $ft^2$.

TABLE 5. ENVELOPE ANALYSIS VARIABLES

| | |
|---|---|
| X(1) = day number | = consecutive day number in year (not used in regression) |
| X(2) = $Q_{heat}$ | = heating equipment energy, daily total, Btu (measured) |
| X(3) = $Q_{app}$ | = appliance energy, daily total, Btu (measured) |
| X(4) = $Q_{dhw}$ | = domestic hot water heater energy, daily total Btu (measured) |
| X(5) = $h_{tot}$ | = solar radiation on south vertical surface, daily total, $Btu/ft^2$ (measured) |
| X(6) = $h_{open}$ | = solar radiation on south vertical surface with south window insulation removed, daily total, $Btu/ft^2$ (calculated) |
| X(7) = $Q_{vforce}$ | = forced ventilation heat loss, daily total, Btu (calculated) |
| X(8) = $Q_{union}$ | = net energy conducted out through south window system daily total, Btu (calculated using U-value from window regression analysis). |
| X(9) = $\Delta T_{in-out}$ | = weighted indoor average temperature - outdoor temperature, average daily, °F (calculated) |
| X(10) = $\sum_{i=1}^{24} (\Delta T_{in-out})$ | = buoyancy infiltration driver, daily total $°F^{1.5}$ (calculated) |
| X(11) = $Q_{heat} + Q_{app}$ | |
| X(12) = $Q_{heat} + Q_{app} - Q_{window}$ | |
| X(13) = $Q_{dhw} - 12,800$ | = domestic hot water heater energy in excess of jacket losses, daily total (calculated) |
| X(14) = $Q_{heat} + Q_{app} - Q_{window} - Q_{vforce}$ | |

TABLE 6. ENVELOPE ANALYSIS MODELS

| MODEL I.D | EQUATION |
|---|---|
| E1 | $X(11) = a_0 + a_1 \times X(9) + a_2 \times X(5)$ |
| E2 | $X(12) = a_0 + a_1 \times X(9) + a_2 \times X(6)$ |
| E3 | $X(14) = a_0 + a_1 \times X(9) + a_2 \times X(6)$ |
| E4 | $X(14) = a_0 + a_1 \times X(9) + a_2 \times X(6) + a_3 \times X(13)$ |
| E5 | $X(14) = a_0 + a_1 \times X(9) + a_2 \times X(6) + a_3 \times X(13) + a_4 \times X(10)$ |
| E6 | $X(14) = a_0 + a_1 \times X(9) + a_2 \times X(6) + a_3 \times X(13) + a_4 \times X(10) + a_5 \times X(5)$ |

TABLE 7. ENVELOPE ANALYSIS COEFFICIENTS

| COEFFICIENT | DESCRIPTION | PREDICTED VALUE |
|---|---|---|
| $a_0$ = | constant envelope losses - constant envelope gains | |
| = | $Q_{bsmt} - Q_{met}$ | = 7714 Btu·(day)$^{-1}$ |
| | $Q_{bsmt}$ = conduction thermal losses to 50°F basement | = 24314 Btu·(day)$^{-1}$ |
| | $Q_{met}$ = metabolic gains | = 16600 Btu·(day)$^{-1}$ |
| $a_1$ = | (heat transfer coefficient to ambient air temperature excluding south facing window system)·24 | = 1560 Btu·(24hr·°F)$^{-1}$ |
| = | when corrected for measured N,E,W Window U | = 1632 Btu·(24hr·°F)$^{-1}$ |
| $a_2$ = | (south window system $\tau \cdot \alpha \cdot A$ product)·(-1) | = - 33.6 ft$^2$ |
| | $\tau \cdot \alpha$ = (window glass average transmissivity)· (window system average absorptivity) | = 0.6 |
| | A = transparent south window area | = 56 ft$^2$ |
| $a_3$ = | (percent of $Q_{dhw}$ greater than jacket losses which displaces heating energy)·(-1) | = not predicted |
| $a_4$ = | stack natural infiltration $f_s \cdot A_t$ product | = not predicted |
| | $f_s$ = dimensionless building parameter | = not predicted |
| | $A_t$ = leakage area of house | = 0.14 ft$^2$ |
| $a_5$ = | sol-air multiplier for solar radiation incident on south-facing wall | = not predicted |

TABLE 8. ENVELOPE ANALYSIS RESULTS

| MODEL I.D. | MULTIPLE R | MULTIPLE R-SQUARE | STD ERROR OF EST. | NO. OF DATA RECORDS | COEFFICIENT SYMBOL | COEFFICIENT VALUE | STD. ERROR | T | P(2TAIL) |
|---|---|---|---|---|---|---|---|---|---|
| E1 | 0.7934 | 0.6295 | 15244.5781 | 29 | $a_0$ | 3716.87500 | | | |
| | | | | | $a_1$ | 2089.92529 | 338.77036 | 6.169 | 0.0000 |
| | | | | | $a_2$ | -12.25726 | 4.12114 | -2.974 | 0.0063 |
| E2 | 0.8260 | 0.6823 | 14992.2334 | 29 | $a_0$ | 1428.63281 | | | |
| | | | | | $a_1$ | 1763.82056 | 332.18921 | 5.310 | 0.0000 |
| | | | | | $a_2$ | -16.76041 | 3.29684 | -5.084 | 0.0000 |
| E3 | 0.8605 | 0.7405 | 13929.6826 | 29 | $a_0$ | -23915.10547 | | | |
| | | | | | $a_1$ | 2205.68848 | 308.64581 | 7.146 | 0.0000 |
| | | | | | $a_2$ | -14.01555 | 3.06318 | -4.575 | 0.0001 |
| E4 | 0.8755 | 0.7664 | 13476.5732 | 29 | $a_0$ | -41973.87109 | | | |
| | | | | | $a_1$ | 2334.28502 | 308.41309 | 7.569 | 0.0000 |
| | | | | | $a_2$ | -12.78334 | 3.05438 | -4.185 | 0.0003 |
| | | | | | $a_3$ | 0.51110 | 0.30666 | 1.667 | 0.1081 |
| E5 | 0.8826 | 0.7790 | | | | | | | |
| E6 | 0.8873 | 0.7872 | | | | | | | |

NOTE: X(9) and X(10) are so highly correlated with each other that the analysis program could not use them both in the same model. For E5 and E6, the program eliminated X(9), and the meaning of the resulting coefficients is difficult to interpret. $a_5$ in model E6 is not significant.

### 4.2 Data

All of the building envelope models described below were evaluated using the same data set, consisting of 29 days of daily totals or averages selected from the 60 full days of data. Days selected met the following criteria:

1. Weekdays (an attempt to reduce the variability of the metabolic and internal gains).

2. Days with a minimum hourly $\Delta T_{in-out}$ of 10°F (an attempt to eliminate days when windows were open).

These criteria are slightly different from those used in selecting records for analyses which have appeared earlier; these results are slightly different.

The data found in each daily record are described in Table 5. Data for wind speed, rate of natural infiltration, metabolic gains, and heat flux through building components are not available.

### 4.3 Models

All the models developed are based on a heat balance equation for the building envelope, and differ only in the number of variables which are explicitly accounted for. In this way the cumulative effect of each additional variable can be seen. Model E1, the SERI Class B model, is the simplest of all the models presented. Each successive model represents an attempt to explicitly account for another variable (Table 6).

Each regression coefficient represents a physical property of the building (Table 7). Differences between the predicted and regression properties can help in thermal analysis of the particular individual building component.

### 4.4 Results

Model E3 gives the best fit of any of the models for which all of the coefficients are significant ($T > 2$); therefore it is the best model presented (Table 8). Model E4 includes the effect of the domestic hot water entering the envelope, but the coefficient is not significant ($T < 2$), and is actually of the opposite sign (Table 7) of the predicted value. Apparently the different uses of domestic hot water contribute varying amounts of heat from the hot water to the living space with such wide variation that any meaningful average amount cannot be derived by regression.

Model E3. the best fit, results in three regression coefficients. $a_0$, the intercept equals -23915 Btu·day$^{-1}$, (Table 8) compared to the predicted value of +7714 Btu·day$^{-1}$ (Table 7). No valid explanation for the large difference has been found. The difference indicates that either the relatively constant gains to the house are greater than expected by 31629 Btu·day$^{-1}$ or equal to 290% of the predicted value, or that gains are greater and losses are smaller than predicted by some unknown amounts. Regression coefficient $a_1$, equal to (24 x UA), equals 2206 $\pm$ 1.96·(309)Btu·(24 hr·°F)$^{-1}$ for the 95% confidence interval (Table 8), compared to the corrected predicted value of 1632 Btu(24·hr·°F)$^{-1}$ (Table 7). The predicted value is within the 95% confidence interval for the regression result. The difference between the predicted and mean regression value would be reconciled by an average natural air infiltration of .12 air changes per hour (natural infiltration is not explicitly accounted for in this model). Regression coefficient $a_2$ equals -14.0 $\pm$ 1.96 x 3.06 ft$^2$, less than half of the predicted value of -33.6 ft$^2$. As for $a_0$, no valid explanation for the indicated reduced use of sunshine for heating has been found. It is interesting to note that regression coefficient $a_0$ increases gains to the house on average, while $a_2$ decreases gains to the house on average, relative to the predicted values. It is possible that the two variables interact in some unknown way.

## 5. CONCLUSIONS

Multiple linear regression techniques have greatly assisted evaluation of the Blouin superinsulated house. The ventilation and window systems are very well described by the regression models, and the system actual performance agrees well with predicted performance. The envelope models are not as easily interpreted, although the partial building UA found is reasonable compared with the predicted value using standard ASHRAE techniques.

## 6. ACKNOWLEGDEMENTS

The authors acknowledge the Blouin family for allowing their house to be monitored, Tony Whitehair at Central Vermont Public Service for supplying the printed electricity data, Wei-Yann Tsai of the Brookhaven National Laboratory Applied Math Department for assisting in regression analysis, and Sharon Zuhoski for processing the manuscript.

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# PERFORMANCE EVALUATION OF A THERMOSIPHON/BLOCKBED SYSTEM

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## ABSTRACT

This paper describes the performance of a thermosiphon air collector which was designed and built to heat the masonry floors of a residence in Santa Fe, New Mexico. The system uses ten different blockbeds, composed of concrete block on their sides, to transfer the heat to the floor above. Simple monitoring techniques were employed in February of 1983 to determine typical winter day performance of this passive solar heating system, and the results are evaluated in this paper along with recommendations for future systems.

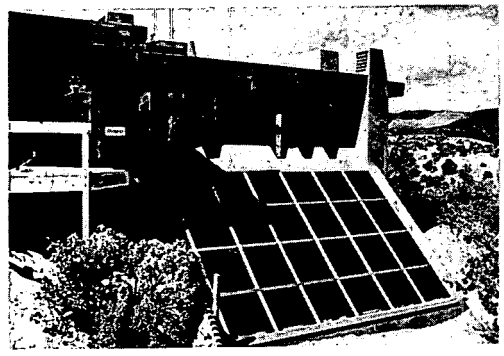


Fig. 1. Collector on finished house

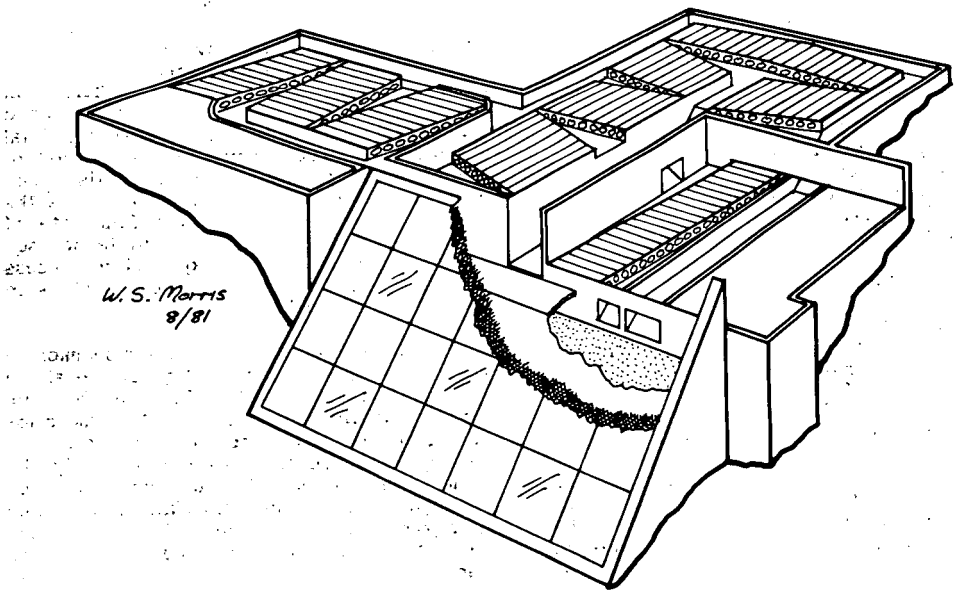



Fig. 2. Perspective of collector/blockbed system

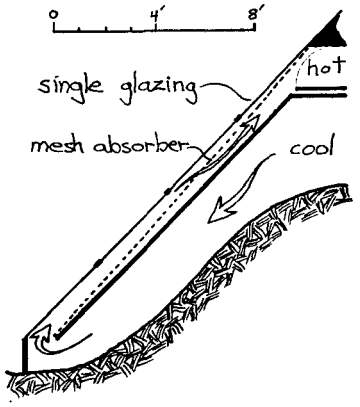



Fig. 3. Section thru Collector

## 1. DESCRIPTION OF SYSTEM

The residence for which this system was designed is an 1800 square foot adobe style house in Santa Fe, NM, designed and built by the Mark Jones Corp. in 1981. I acted as a consultant on the solar heating system during the design stages. Figure 1 is a photo showing the south face of the house and collector.

Figure 2 is a perspective drawing of the collector and blockbed storage which was designed to operate passively thru the principals of natural convection. An earlier system of this type which used rockbeds rather than blockbeds was monitored and proved to be an excellent performer[1]. This then was a second generation system designed to provide the same high performance at substantially lower costs.

The system consists of a simple site-built thermosiphon collector using a single low iron glass cover and five layers of expanded steel mesh placed at a diagonal to the hot air channel (Fig. 3). This type of diagonal mesh absorber has proved to be an excellent performer and is highly recommended in thermosiphon collectors.

Air in the collector is heated by the sun and rises naturally into the insulated hot air ducts which distribute it to the blockbeds under the floor of the living areas. Figure 4 shows the layout of these blockbeds which are composed of 8"x8"x16" concrete blocks on their sides so that the air can flow thru the hollow cores and, in the process, give up the solar heat. Figure 5 is a photo of these blockbeds under construction. Two inches of urethane insulation was placed under all the blockbeds. To increase the thermal mass each blockbed was covered with about 9 inches of riverrock and a 5 inch concrete slab was poured over the entire

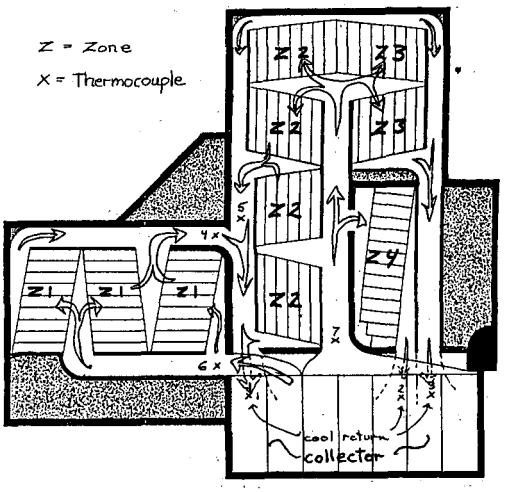



Fig. 4. Plan of blockbeds

floor. The finished floor is predominantly split paved brick although the western beds (zone 1) are covered with a hardwood floor over the slab.

There are two hot air outlets from the collector, one feeding the western beds at point 6 and the other at point 7 feeding all other beds. Once the air has travelled thru the blockbeds, it returns to the collector via three cool ducts (outlets at points 1, 2, and 3) to be reheated. The areas shaded with dots are floor areas with slab on grade (no blockbed).

The engineering of this system was initiated with several assumptions based on data from earlier systems and test units. The final design was then analyzed with standard HVAC calculations to insure that the total air pressure drops thru the system did not exceed the available pressure heads at an assumed temperature rise of 60°F across the collector and an assumed air flow rate of 2.35 standard cubic feet per minute per sq. ft. of collector. This engineering process is described for thermosiphon systems in general in an earlier paper[2].

In this particular design it was also important to insure even distribution of the air to the individual blockbeds. This can be done by varying the length of each bed to compensate for the difference in duct losses, so that the air pressure drop is virtually the same in the round trip loop thru any bed. The blockbed in zone 4 was under a sunken livingroom and from Figure 2 it can be seen that it was about 2 feet below the other beds. By making this a shorter bed and providing minimal ductwork we were able to overcome the pressure difference created by the 2 foot drop in height.

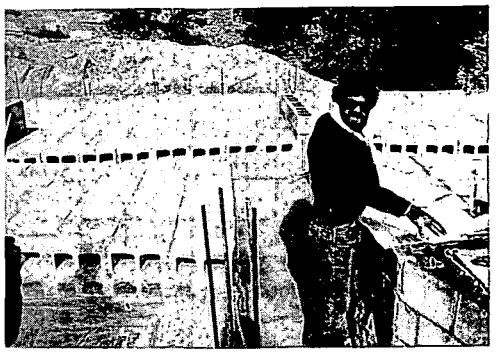


Fig. 5. Blockbeds under construction

Two dampers are located at the entrance to the two hot air ducts to prevent reverse thermosiphoning at night and to close off the house loop during summer months. These dampers are motorized with thermostatic controls; otherwise the system is entirely passive. Heat recovery into the house is by radiant floor heat.

The house itself is well insulated with a small amount of direct gain. Because it was inhabited at the time of the tests, no attempt was made to evaluate its thermal characteristics.

## 2. MONITORING

The system was monitored on February 15, 1983, to obtain an estimate of the thermal performance of the collector/ blockbed loop. This monitoring consisted of taking readings every one half hour between 10 a.m. and 2:30 p.m. of air flow rates and air temperatures.

Figure 4 shows the position of the thermocouple probes. Points 1, 2, and 3 monitored the air temperatures of the three separate cool air return ducts. Points 4 and 5 were periferal cool duct temperature probes. Points 6 and 7 measured the air temperature entering the two hot air ducts. Point #8 measured the outdoor temperature. A Doric Trendicator and type K thermocouple wire were used for all temperature readings.
Airflow rates were also measured every one half hour at the outlets of the cool return ducts (corresponding to points 1, 2, and 3). The measurements were made with a Hastings hot wire anomometer. Typically, six measurements were taken in an array across each outlet and the results averaged. In many instances, especially at point 1, there was considerable variation in flow velocity across the outlet, and I would estimate that the final average figure for air velocity is accurate to only ±15%.

A photovoltaic pyranometer with a strip chart recorder was used to record the incident solar radiation on the collector. Figure 6 shows the results in Btu/ft$^2$ hr.

February 15 was quite clear until about 10:00 a.m. when the testing started. High clouds reduced the insolation between 10:30 and 11:30, but the skies were clear between 11:45 a.m. and 2:15 p.m. Testing was stopped at 2:30 p.m. because of incoming cloud cover. The extended clear period during the middle of the day gave ample time to determine typical clear weather performance. It was a windy day, however, and this undoubtedly reduced performance somewhat over optimum conditions.

## 3. TEST RESULTS

From the raw test data, average airflows, collector inlet and outlet temperatures, and collector efficiencies were calculated. Figures 6 thru 9 are graphs of several values during the test period. As noted earlier, the accuracy of Figures 8 and 9 is limited by the accuracy of the air velocity readings, which I estimate to be within ±15% (i.e., 12:30 p.m. collector efficiency of 47% (Fig. 9) might be as low as 40% or as high as 54%.)

Because airflow rates and temperatures were taken at several different points, it was possible to divide the blockbeds into four separate zones (Fig. 4) and calculate the heat gain to each. Figure 10 shows the results in terms of heat gain per sq. ft. of blockbed per hour (total hourly gain into each zone divided by the number of sq. ft. of blockbed in that zone.)

## 4. DISCUSSION

Typical midday heat gains are in the neighborhood of 50,000 Btu/hr (total to blockbeds) and result in collector efficiencies of about 45%. This is really quite good. Well designed thermosiphon collectors of this type often yield midday efficiencies of about 50% or more, but the test day was quite windy, and this increases losses from the collector glazing, especially single glazing, and so reduces efficiencies.

Other factors that may contribute to these slightly lower efficiencies are air leaks in the system and obstructions in the air ducts. The access doors to the collector and the damper for summer venting had to be taped shut during the tests because of poor seals. The original design called for smooth unobstructed air ducts, but several pipes and other obstacles restrict the air flow in places.

The air flow appears to be quite good, staying above 2 scfm/sq. ft. of collector during peak hours. The delta T across the collector (TO-TI) is also very reasonable, staying about 58°F during midday. The original design of this system assumed an airflow of 2.35 scfm/ sq. ft. of collector and a delta T of 60°F, so the system performance is really extremely close to the design expectations.

The heat distribution to the various blockbeds, however, does not appear to be as even as originally planned. If we look at the Figure 10 we see that there is a wide variation in the amount of heat put into each blockbed.

Zone 1, which is under the master bedroom area, seems to be the worst performer in this regard, and this fact is reinforced by the occupants comments. To some extent this may be due to the fact that Zone 1 is fed primarily by only two sections of collector, whereas its area warrants more. The fact that this zone is covered by a wood floor may well contribute to the problem.

Zone 2 seems to be doing moderately well, while Zones 3 and 4 do much better than average. It should be noted that the calculations assume that the air exiting at point #3 (Fig. 4) comes only from Zone 3. In reality there is no physical barrier in the middle of the northern cool air plenum to prevent cool air from Zone 2 from moving into the cool return duct of Zone 3. Indeed there is a restriction in the Zone 2 cool air duct just north of point #5 which might encourage this. If this is happening, then the actual figures for heat gain into Zones 2 and 3 might be very similar.

Zone 4 seems to be doing very well. It appears that designing it as a short bed with minimum duct resistance worked well in overcoming its "sunken status."

The occupants have observed that the livingroom area, which extends over Zone 4 tends to be cooler than other parts of the house. This is to be expected in any case because the blockbed is quite small compared to the room. Since this room is the lowest point in the house, any cold air will tend to pool here. These problems were anticipated during the design, but there was no obvious solution.

Another point of interest is the return cool air temperatures, particularly at point #1 (Fig. 4). Generally this return air should stay between about 70°F and 80°F, but point #1 reaches close to 90°F at the end of the day. This could be caused by several things, including poor heat distribution within any given blockbed and/or inadequate heat transfer area in the blockbeds. Be-

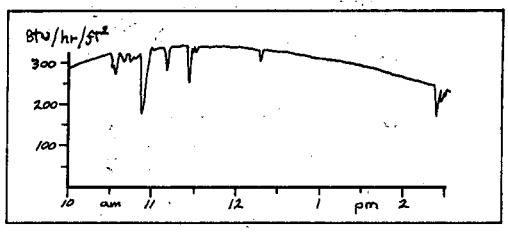



Fig. 6. Insolation on collector during test

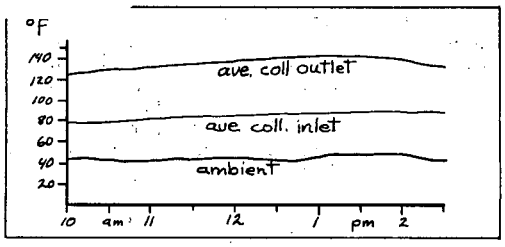



Fig. 7. Collector and ambient temperatures

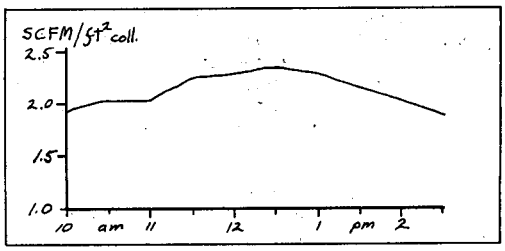



Fig. 8. Collector airflow rates

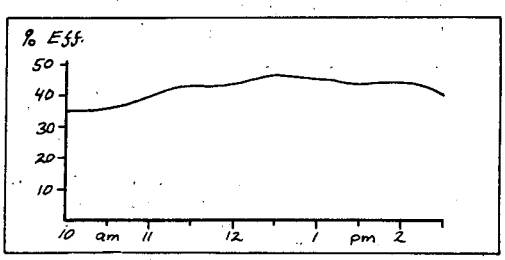



Fig. 9. Collector efficiencies

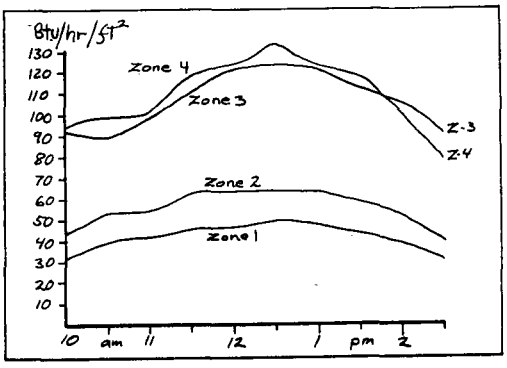



Fig. 10. Heat to blockbeds by zone

cause the blockbeds encompass only 692 sq. ft. total, the heat transfer area in the blockbeds turns out to be about 3.8 sq. ft. per sq. ft. of collector, which may be slightly low, thus contributing to these higher than normal return air temperatures. Although higher return air temperatures increase the overall system temperatures and decrease efficiencies, the problem in this case appears to be very minor and have only a small effect on net performance.

All in all the system appears to be functioning quite well. The only problem seems to be in the evenness of heat distribution to the various zones. This could possibly be corrected by restricting some of the ducts to encourage better flow to the areas that now have a problem (Zone 1); however, doing this will probably impair the overall performance. As long as no specific part of the house gets so hot as to need venting when at the same time other rooms still need heat, then all the heat produced by the systems is being used to advantage.

## 5. RECOMMENDATIONS FOR FUTURE SYSTEMS

While this particular thermosiphon floor heating system is doing well, there are several changes that I would recommend in future projects of this type.

1. Whenever possible, the collector glazing should be held entirely below the floor storage mass and ductwork. Not only will this increase the available pressure head and air flow rates, but if all collector channels (both hot and cool) are insulated, the collector will act as a thermal trap for cold air at night and the diurnal damping system should not be needed. As dampers are a real nuisance these self-damping designs are very desirable.

2. Most thermosiphon air collectors of this sort previously built have used single glazing. There is good reason to believe that double glazing, especially with low iron glass, is cost effective in all but the mildest climates.

3. In the system described here, river rock was used above the blockbeds to increase thermal mass. The blocks were set with gaps between them in hopes that some of the air would move up into the rock and thus have more transfer area to give up its heat. There is no real evidence that this is working, and retaining the rock was a bit of a problem. A thicker concrete slab would offer the same mass with better conduction and has indeed been used since with apparently good results. In any case, the designer should try for about 400 pounds of masonry per sq. ft. of collector to insure low temperature swings.

4. In cases where the original grade is very steep to the south it often makes sense to use precast hollow core slabs rather than blockbeds. This allows for a basement/ crawlspace area and makes the installation of the ductwork easier.

5. Although these floor heating systems can be designed to work with non-masonry floor finishes (carpet, hardwood, etc.) it is advantageous to use floor finishes having equal R values so that the heat conducts and radiates evenly from all floors.

6. Much simpler designs are possible than the one presented here. I have since worked on several systems that call for a long array of shorter collectors directly feeding a large rectangular blockbed (or cored slab) to the north. This can generally eliminate most ductwork and distribution problems and reduces expense.

## 6. ACKNOWLEDGEMENTS

This project was made possible by E.B.Hall.

## 7. REFERENCES

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2. W.S. Morris, Design Procedures for Thermosiphon Air Collectors. Proceedings of the Seventh National Passive Solar Conference. Knoxville, TN 6/82.

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# PERFORMANCE AND EVALUATION OF A PASSIVE SOLAR SUPERINSULATED RESIDENCE IN THE NORTHEAST

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## ABSTRACT

A large passive solar superinsulated house has been built in Lexington, MA, (42,4°NL, 6100°F · days) and energy use has been monitored for the 1982-83 heating system using a SERI Class B Passive Solar Data Acquisition System. The house was maintained at an approxmate average (and almost constant) temperature of 70°F, no window coverings of any sort were used, and the solar aperture of the house received approximately 52% of possible solation due to shading by leafless deciduous trees during the heating season. Under these conditions, the house used 0.89 Btu $°F^{-1}day^{-1}ft^{-2}$ living area of delivered auxiliary heat. The actual indoor-outdoor temperature difference was used in this calculation. Using base 65 degree days for 1982-83 from the Blue Hills weather station the result is 0.76 Btu $°F^{-1}day^{-1}ft^{-2}$ living area. If the 672 $ft^2$ 70°F basement is included the numbers become 0.82 and 0.70. At a cost of $ 0.70/therm the cost of the purchased fuel for space heating this large house was just under $100.

## 1. INTRODUCTION

A large, superinsulated, passive solar house has been constructed in Lexington, MA, a northern suburb of Boston, MA (42,4°NL, 6100°F days). Figure 1 shows a view of the south side of the house. The house was first designed to the owners' space and esthetic needs; then solar and energy saving features were integrated into the design. The house exterior was made compatible with New England vernacular frame housing to fit into an existing neighborhood (see ref. (2) for a "front" view). Although low energy use was a major consideration (the target was below $100(1982) for heating), low cost was a necessity. The house was to be buildable by a builder with no special training, and the house was to function well thermally without substantial management by the residents. The clients' desire for light and view ruled out building a superinsulated house with minimal windows. No more window area was to be used than that desired for light and view, yet this window area should also contribute to the house heating. No complicated and/or expensive HVAC equipment was to be used, and all thermal mass was to serve an architectural or structural purpose as well as a thermal one. A sunspace was desired. A 2200$ft^2$ (net) custom house (4 bedrooms and a study) that satisfied the above criteria was built for $46/$ft^2$ in an area where much less efficient houses cost $50 or $60/$ft^2$. (If the heated 672 $ft^2$ basement is included in the floor area, the cost drops to $35/$ft^2$.) The house was designed by a collaboration: Peter Bruckner (1) was primarily responsible for architectural design; and I was primarily responsible for overall energy design. The builder was Infinity Construction of Cambridge, MA. For more construction details and design considerations see reference (2).



Fig. 1. View from the South. The glazing for site-built active collectors for heating domestic hot water are visible on the roof.

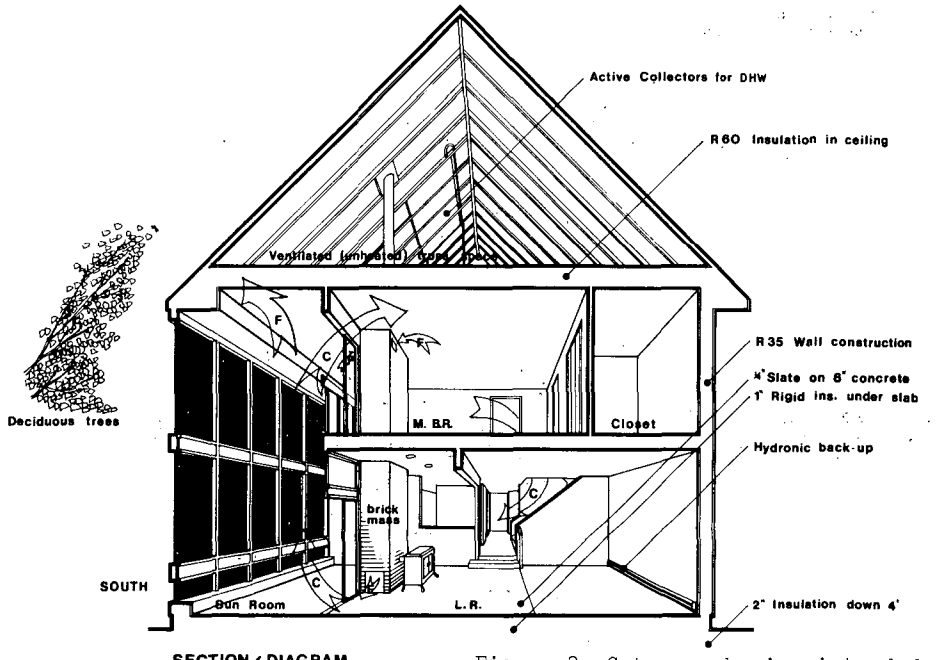



Fig 2. Cutaway showing intended thermal operation. See text for actual operation in 1982-83.

## 2. MONITORING EQUIPMENT AND DATA COLLECTION

The house has been monitored during the entire 1982-83 heating season using a SERI Class B Passive Solar Data Acquisition System.[3] For more information about the Class B program as well as results see reference (4). An Aeolian Kinetics PDL-24 Monitoring System is used to read and average data from the sensors every 30 seconds. Hourly data averages are stored on cassette tapes along with quantities of interest computed from the measured values. The following quantities are monitored at this house: horizontal insolation, actual vertical insolation on south facing windows, windspeed, outdoor temperature, three living space temperatures, basement temperature, sunspace temperature, electrical usage, boiler on-time, heat used for space heating, and air-to-air heat exchanger on-time.

## 3. MONITORING CONDITIONS

The house was designed to be thermally robust with good thermal performance under realistic worst case thermal conditions and these are exactly the conditions experienced during the past heating season. The indoor temperatures were kept high with an overall area weighted temperature average of 70.1°F for the house proper and an average basement temperature of 70.5°F. The coolest room was the master bedroom which averaged 68.1°F. The daily fluctuations were only a few degrees in the house proper and no night setback was used. No window coverings of any sort were used on the windows. The house was designed with triple glazing even to the south and with large areas of interior glass sheltered by the two story sunspace to allow good thermal performance without window coverings. It was thought however that inexpensive IR reflective privacy shades would be used. The average winter insolation on the south facing glass is only 52% of an unshaded site due to shading by mostly deciduous trees which will eventually be trimmed. During the winter of 1982-83 the Boston area experienced a heating season with approximately 15% less solation than average, with the least sunny April in history. However, the number of heating degree days were lower by 6%. In general only three people and a dog occupy this large house, with the people gone during working hours. The result is a low intrinsic heat contribution.

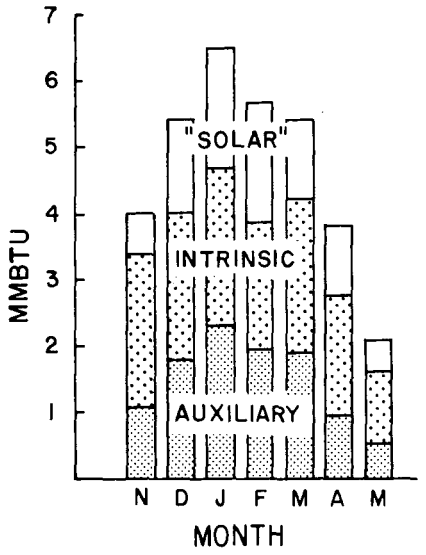



Fig 3. Measured 1982-83 results. Auxiliary is that heat delivered to the heated space. Intrinsic heat is that heat delivered from lights and appliances in the living space as well as a estimated contribution from domestic hot water, "Solar" is a derived quantity from a naive model explained in Section 4.

Figure 2 shows a cut-away that illustrates the optimal (and simple) thermal operation of the house. However, for the 82-83 heating season the following was true. The sunspace was isolated from the house largely because of the owners' sensitivity to a persistant odor of an exterior stain that should not have been used in the sunspace. As a result excess heat was not automatically removed from the top of the two story sunspace by means of a small fan and blown through an integral duct in the massive chimney and out into the living room. The natural convection path formed when a sliding door to the sunspace is opened on each floor was also not used. There is no woodstove in the house.

## 4. ACTUAL THERMAL PERFORMANCE AND ANALYSIS

In spite of the above conditions, the house has performed extremely well. During the 1982-83 heating season the house used only 0.89 Btu/DD/ft$^2$ of delivered auxiliary heat. The DD are °F-days calculated from the actual measured indoor-outdoor temperature difference from November through May. The area used was the 2200 ft$^2$ net living area of the house. This amount of delivered auxiliary heat corresponds to a purchased energy cost of approximately $100 a season for gas at $0.70 a therm. If the 672 ft$^2$ 70°F basement is included as heated area, then the number becomes 0.76 Btu/DD/ft$^2$. To allow comparisons with other houses, the delivered auxiliary heat is 0.83Btu/DD/ft$^2$ (0.70Btu/DD/ft$^2$ with basement) when 1982-83 base-65 degree-day data are used from the nearby Blue Hills weather station. The results compare favorably with the average of 2.66 Btu/DD/ft$^2$ for a large group of energy efficient Minnsota homes(6). Reference (6) claims the average new Minnesota home uses between 6 and 8 Btu/DD/ft$^2$ of delivered auxiliary energy.

Figure 3 shows the monthly deliverd auxiliary heat used during the past heating season. Also shown is the measured internal gain from purchased electrical energy for lights and appliances. The internal gain also contains a contribution for heat that remains in the living space as a result of hot water usage. The seasonal result for deliverd auxiliary heat and internal gains is 1.94 Btu/DD/ft$^2$ excluding the basement. The so called "solar" contribution in Figure 3 is a much less certain result. It was found by taking the measured heat loss of the house times the actual measured °F days for each month to compute a monthly load. The "solar" contribution is taken to be the load left after subtracting the measured auxiliary and internal delivered heat. The heat loss (UA) of the house was measured to be 232 Btu °F$^{-1}$ hr$^{-1}$. It was measured using portable electric heaters to keep the house at a constant temperature during a period of no solar gain. (See reference (2) for more details).

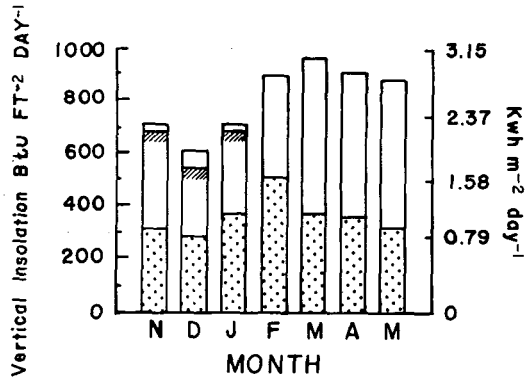



Fig 4. The Measured vertical insolation on the south wall of the house during 1982-83 is shown by dotted bars. The full height shows the Boston 30 year average while the shaded lines show measured vertical insolation in 1982-83 from the Northeast Residential Experimental Station in Concord, MA.

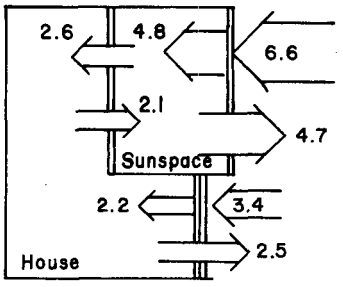



Fig 5. Total heat flows through the south windows and the sunspace during December, January, and February of 1982-83. All numbers are in MMBtu. See text for description of the calculation.

In this simple model no correction has been made for infiltration heat loss varying with weather conditions. Using this model we find the house required 32.9 MMBtu for the 1982-83 heating season of which "solar" supplies 7.7 MMBtu (24%), intrinsic heating 13.6 MMBtu (41%), and auxiliary heat 11.6 MMBtu (35%).

The simple model seems to make some sense if we examine the heat flows in the house. Consider the three coldest months December, January, and February. The model claims that 4.85 MMBtu came from solar heating. To see if this is reasonable we take a look at the measured insolation incident on the south solar aperture. During these months 33,292 Btu/ft$^2$ fell on the south glazing which is approximately 50% of that which would be incident on an unshaded site during the same period (see Figure 4 for more detailed insolation information). The average energy transmission through ordinary triple glazing is about .63 during these months while that through double is about .73 (6). Using the 101 ft$^2$ of south glass (30.2 ft$^2$ double, the rest triple) that is not part of the sunspace, we find 2.2 MMBtu make it into the house. The loss from the windows during these 3 months is about 2.6 MMBtu. Amazingly enough, the windows are just about lossless even without movable insulation and with all the shading during the coldest three months. In addition, the 198.3 ft$^2$ of sunspace glass allow about 4.8 MMBtu of the incident energy into the sunspace. If the model were right, 2.6 MMBtu would make it into the house. (This is 54% of the energy that gets into the sunspace.) Using the measured temperature differences and calculating the UA, we find that 2.1 MMBtu flow from the house to the sunspace for a net inward energy flow of .5 MMBtu. The sunspace is also breaking even during these coldest months even with 50% shading and no night insulation. Calculating the heat flow from the sunspace to outside by using measured temperature differences, we find 4.7 MMBtu which is consistent with all the other heat flows and shows the model to be a reasonable one. Figure 5 diagrams the calculated heat flows while Figure 6 shows monthly average temperatures from which the heat flows were calculated.

## 5. INFILTRATION MEASUREMENTS, HEAT EXCHANGER, AND AIR QUALITY

The natural infiltration of the house has been measured three different times. All measurements were made with the air-to-air heat exchanger off. Two measurements used a gas diffusion method where the change in concentration with time of an introduced gas sulfur hexafloride) measures the rate of air change in a straightforward manner. The first result, done the previous heating season, was 0.29 ACH(air changes per hour) while the second measurement found 0.31 ACH. During the first measurement the wind was estimated to be 5mph and the indoor-outdoor temperature difference was measured to be 33°F. In the second measurement the numbers were 1 mph (measured) and 40°F. The measured air infiltration rate seems reasonable although naively applying a 0.3 ACH to the whole heating season produces a somewhat higher total building load than seems actually to be the case. Since infiltration rates are in general a function of both the interior to exterior temperature difference and the wind speed, a more careful modeling may produce a different seasonal average infiltration from the measured numbers. A blower door measurement produced a result of 7.10 ACH at 50 pascals. An average of the 13 class B monitored buildings in the Northeast was 10.25 ACH. The relationship between the number of air changes at 50 pascals and an average air infiltration rate for a heating season is not straightforward. For more information on the blower door measurements and analysis in the class B study in the Northeast, see reference (5). An infiltration rate of 0.3 ACH does not indicate that this is an outstandingly

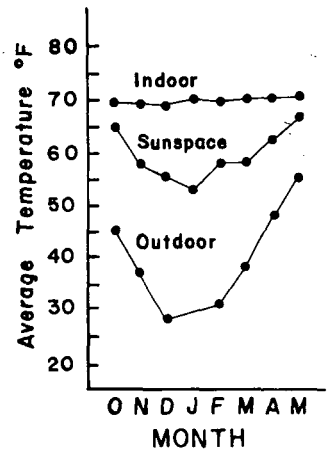



Fig 6. Monthly Average Temperatures During 1982-83.

tight house but probably represents a reasonable expectation for a house built by a standard contractor untrained in energy efficient houses. As of now, no effort has been made to correct sources of air infiltration after the fact. Two of the larger leaks in this house are the wooden sliding glass door directly to the outside and the ash cleanout cover on the chimney. No problems have been experienced with stuffiness, odors, or moisture in the house even when the air-to-air heat exchanger is not run for long periods of time. (The one exception, oil stain in the sunspace was described above) This result is not too surprising if the house has .3 ACH. The care taken in design to avoid interior air contaminants is described in reference (2), section 7.

## 6. SUMMER PERFORMANCE

The house remained comfortable with no overheating for the entire summer without the use of mechanical air conditioning. Even after three days of above 90°F weather the house did not overheat. If anything the owners thought it was sometimes too cool (remedied by opening more windows during the day). The house is well shaded by mature trees which are not the same trees causing the winter shading.

## 7. HOMEOWNER SATISFACTION

The owners are very satisfied with the house. The fact that the house requires no energy management pleases them. The house is quiet with no fan noise, and outside noises are greatly reduced by the wall and ceiling construction. The house is well lighted without glare and is always thermally comfortable with no overheating, moisture, or stuffiness problems. The ability to maintain the interior temperature at 70°F for about $100 a year is an asset. The coolness of the house in the summertime pleased and surprised them.

## 8. COMPARISON OF ACTUAL RESULTS WITH DESIGN CALCULATIONS

Using Sunpas (8)(software using Vol. III SLR correlations) and standard ASHRAE heat load calculations, the thermal performance of the house was predicted under many different circumstances both before and after the house was built. Some runs were made for no movable insulation and for no external shading, for 25% external shading, and 50% external shading. Infiltration was taken at .25 ACH and the guideline of 20,000 Btu/day/person for internal gains. (3.5 people were used due to regular weekend guests) The overall heat loss (UA) of the house was calculated to be 265 $Btu°F^{-1}\ hr^{-1}$. Boston 30 year average weather data was used. Figure 7 shows how well these more or less usual assumptions compare with the actual 1982-83 results. Most input numbers were very close to actual values. The average measured internal gains were 73,000 Btu/day compared to the 70,000 Btu/day actually used. The external shading factor was estimated at .5 and was measured at .52. The calculated UA, however, was 15% greater than the measured UA and is the cause of most disagreement. All in all, the estimated average usage is very close considering the difference is only about $25 of purchased fuel cost. (11.6 MMBtu measured vs a calculated value of 15.5 MMBtu of delivered auxiliary heat.) The calculated usage can of course be made extremely close to the actual value by using the measured UA, actual insolation, and measured degree days. For calculated auxiliary fuel usage for this house under ideal conditions, see reference 2, section 8.

## 9. CONCLUSIONS AND FUTURE PLANS

The house thermal performance has been excellent under difficult conditions. Passive solar and superinsulation with no complicated thermal systems (in this case not even mechanical air movement of any sort) do a marvelous job in New England and allow great design freedom in addition. Even with approximately 50% winter shading, the

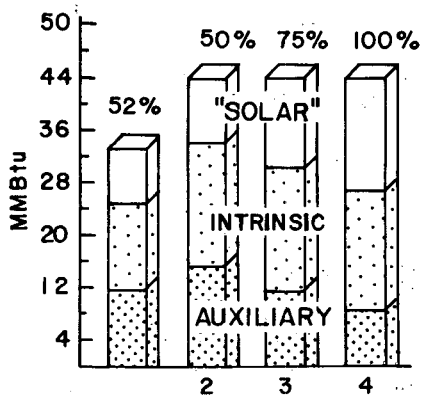



Fig. 7. Bar 1 shows the measured seasonal values for 1982-83 while bars 2 thru 4 show values predicted from actual design assumptions using the SLR method. Different levels of external shading (100% is no shading) are shown. The largest source of error is the heat loss calculation. See the text.

south windows and sunspace were approximately adiabatic in the three coldest months. It is hoped that trees producing the winter shading can be trimmed and IR reflective privacy shades installed by the next heating season and the thermal result measured.

## 10. ACKNOWLEDGEMENT

I would like to thank John Duffy for all of his careful work in data collection and reduction. It was a pleasure to collaborate with Peter Bruckner in the design of this house. Finally, I am very grateful to the owners who have willingly put up with intrusions due to the thermal monitoring.

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3. I am very grateful to John J. Duffy of J.J. Duffy and Assoc, 8 Orient St., Winchester, MA 01890. He is responsible for the SERI Class B Passive Solar Monitoring Program in the Northeast and has the primary responsibility for data collection and reduction. John should not, however, bear the burden of responsibility for the accuracy of the data, analysis and conclusions presented in this paper.

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# TWO YEARS EXPERIENCE: THERMAL PERFORMANCE AND OPERATING DATA OF THE FIRST GERMAN 2-STOREY GREENHOUSE RETROFIT IN KIEL-CITY, WEST GERMANY

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## ABSTRACT

The following paper describes the renovation of a single-family dwelling built in Kiel, West Germany, in 1951. Special consideration will be given to the passive solar planning criteria which are relatively new to West Germany. The paper discusses problems encountered in the planning, in acquiring approval from the proper authorities, and in the construction process itself. Heating-energy consumption preceding and following renovation as well as the thermal performance in the "Wintergarten" during different seasons will be shown. The measured results obtained have been evaluated and translated into planning suggestions for current house construction.

## 1. INTRODUCTION

The design, construction, and thermal performance of the "Wintergarten" has been known in Germany since the 16th century and could be found in the orangeries on noble estates and in the "Wintergartens" of the larger town houses during the 18th and 19th centuries; however, they cannot be found in the newer buildings of the past fifty years.



Fig.1. The Semm's residence before renovation

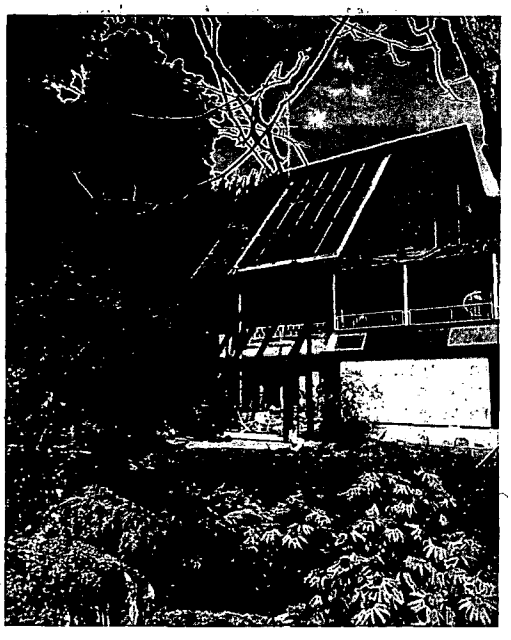


Fig.2. The Semm's residence after renovation

The "Wintergarten" was first rediscovered in Germany as a result of the energy debate, mainly influenced by American passive-solar-architectural concepts. The advantages and thermal performance of the "Wintergarten" throughout the year were long forgotten and therefore unavailable for planning. The vast array of design and construction solutions currently used reflect this lack of knowledge. "Wintergarten" have been built which are practically uninhabitable, since they are too hot in summer and too cold in winter. It is therefore essential to develop planning criteria which enable each architect to involve himself in solar architecture and to contribute to general energy saving. The data gathered at the Semm´s residence provide good insight into temperature fluctuations between seasons, into the question of energy saving possibilities, and into the influences different construction forms and materials necessary for the "Wintergarten" may have.

## 2. THE EXISTING BUILDING

The Semm's residence was built in 1951 according to the then prevalent guidelines for the construction of residential dwellings. Since saving measures were not considered important at the time, the demand for high construction quality was low and limited primarily to stability. As a result thousands of buildings built in this period were endowed with serious defects determined by the physical form itself. The exterior walls (36,5 cm solid sand lime bricks) were thoroughly soaked from an unbalanced annual humidity absorbtion. The wood-framed windows with single glaze needed to be replaced due to the massive energy waste. As a consequence of the site´s particularly windy location -50 meters above and directily on the Kiel Fjord - any windows that could be opened were to be avoided as much as possible. The old flat roof of concrete only had 2 cm of insulation and was not just overcome with age, it even leaked. Since the only usable remnant its soaked frame, the house had to be gutted, dried out, and then adapted to a new structural concept. Demolition and new construction would have been the only choice from an economic standpoint; however, the decision to renovate came from the owner on the basis of other considerations.

## 3. THE CONCEPT OF RENOVATION

The east, north, and west sides received insulation consisting of 12 cm semirigid fiberglass boards and a rain shield of large-format fiberglass plates on their facades. As many windows as possible were installed in the south side and the new window insulation contained a triple glaze. Since the owner desired additional living space, the old flat roof was replaced by a saddleback roof, which also permitted the installation of 25 sqm of sun collectors for the indoor swimming pool. The roof's insulation was set at a thickness of 22 cm. Special importance was placed on the installation of a tightly cemented vapor barrier, which above all made the walls windproof. On the south side a "Wintergarten" was built, covering two floors and a balcony. The "Wintergarten" has a ground surface of 36 sqm and a sun-exposed surface of approximately 65 sqm. The floor is brightly tiled, without insulation, and there is no sun protection.

## 4. ACQUIRING CONSTRUCTION PERMITS

The permit to build a house in Germany is given on the basis of a state construction law as well as a planning ordinance which regulates construction according to restrictions applicable locally. It is of fundamental concern that the new building blend into the pre-existing architectural environment. Since solar houses and collectors have not been seen much until recently, difficulties in acquiring permits still exist today. In smaller communities, building commissions consisting of local volunteers control the issuance of permits. In such cases the arbitrariness of local taste often plays a decisive role. The Semm´s residence was only approved after the presentation of comprehensive literature and photographic materials. However today, some four years later, building permints are as rule easier to obtain.

## 5. CONSTRUCTION PROCESS

The construction of energy-efficient houses demands considerable attention to detail in both the planning and constrution stages. During construction at the Semm´s the workers were observed to have little understandig of the need to follow handling and installation instructions accurately. The workers substituted professional carelessness for precision. The management was therefore required to supervise the workers progress on a day-to-day basis.

## 6. OPERATING DATA AND THERMAL PERFORMANCE

Measurements over a period of two years (including hottest summer in 36 years and the coldest winter in 18 years) gathered important data which not only illustrated the

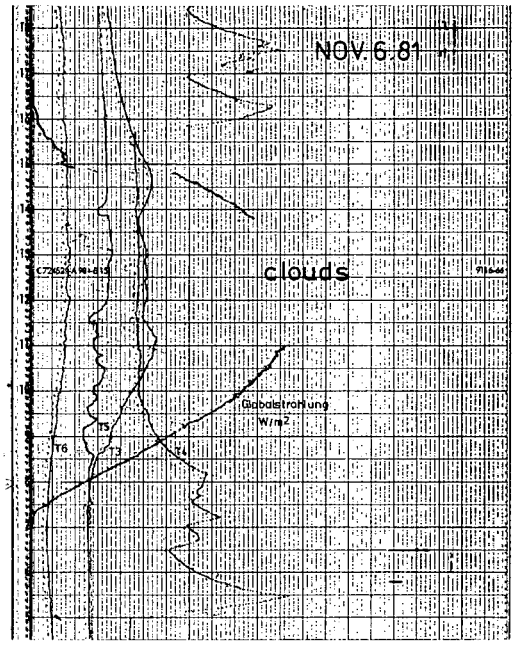



Fig. 3.
"Wintergarten" performance chart.

T6 = ambient temperature
T5 = temp.floor of Wintergarten
T3 = temp.top of Wintergarten
T4 = heating back-up system

Fig. 4.

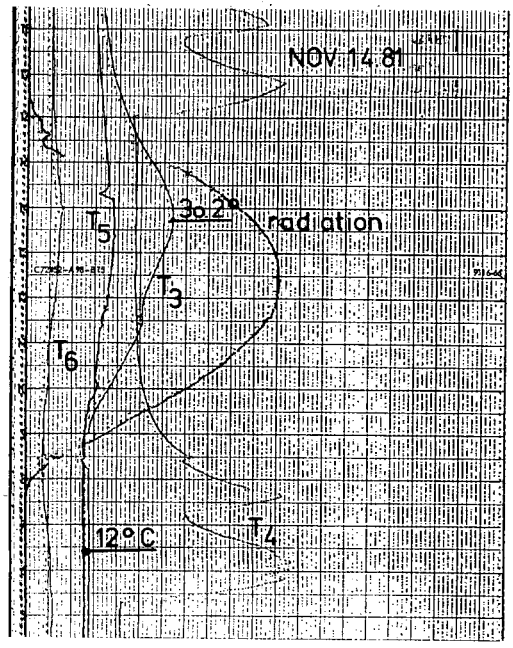





Fig. 5. Inside "Wintergarten"

Fig. 6. Inside "Wintergarten"



seasonal thermal performance on an annual basis, but also enabled conclusions to be drawn concerning planning and construction features for future installations. Fig.3 and Fig.4 show the sensitive interplay between individual temperatures recorded. With a practically stable outdoor temperature the sun allows for considerable heat accumulation, as discernable in the temperature increases indicated. Temperatures of up to 30°C in October-November and March-April (usually periods requiring heating) covered the daily heating requirement by practically 100%. Taken on an annual basis, the "Wintergarten" maintained an average daily temperature 10°C above the average outdoor temperature. As Fig.9 shows, the winter minimum and summer maximum temperatures are counter-balaced by the "Wintergarten's" storage mass. This problem is also rectified in that during the long winter frost periods the sun shines more than average. As outdoor temperatures increase in the summer, one naturally opens the doors of the "Wintergarten," enabling an air circulation which reduces the temperatures indoors. Statistically seen, Kiel-City enjoys only five summer days per year with temperatures over 25°C. As Fig.9 illustrates, the maximum temperature at the Semm's residence could always be held below 28°C, as measured at the top of the 2-story "Wintergarten". The temperature at the floor-level never climbed over 25°C. The lowest temperature was measured during the winter of 1981/1982, the coldest in Germany for over 18 years. With 24-hour frost for several consecutive days and -20°C outdoors, the "Wintergarten" produced a temperature measurement of + 6,3°C.

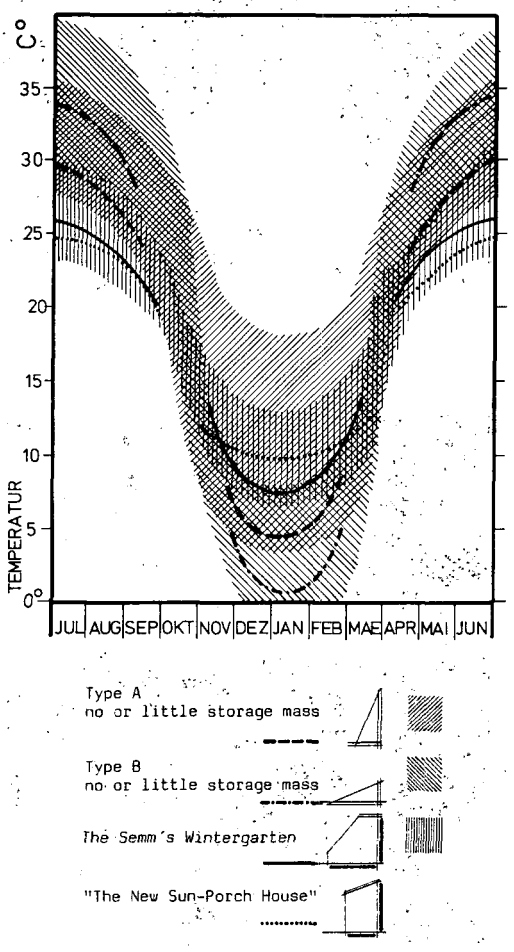
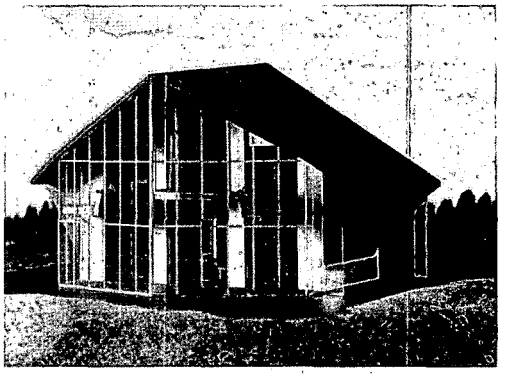



Fig. 7.

Assumed range of max. and min. temperatures and average daily temperatures at different "Wintergarten" designs and constructions.



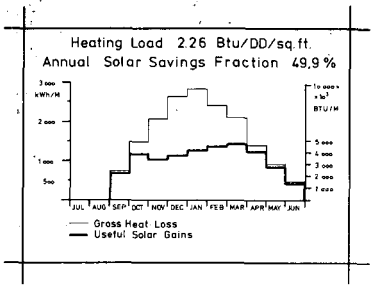
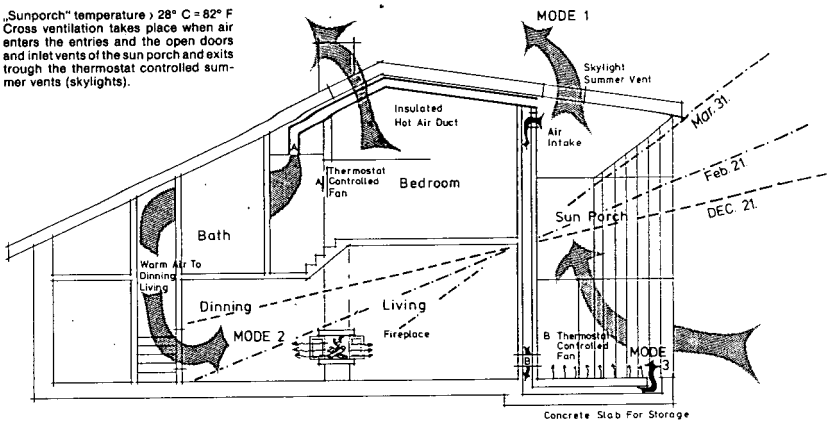



Fig.8.

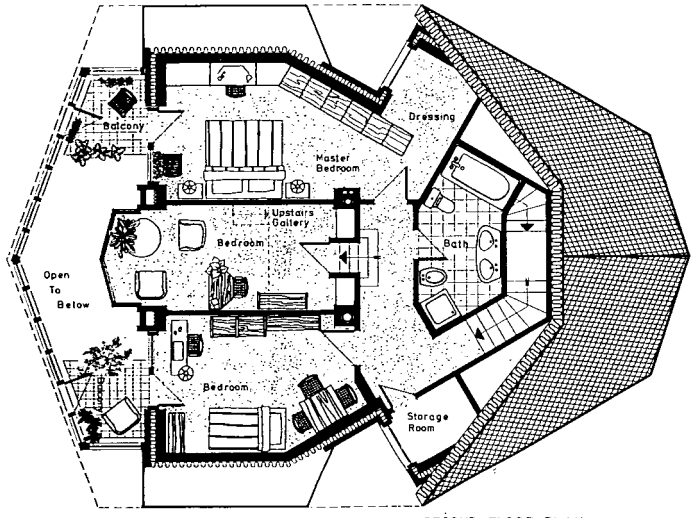
" The New Sun-Porch House " with the annual Solar Savings Fraction.

**Mode 1:** „Sunporch" temperature › 28° C = 82° F
Cross ventilation takes place when air enters the entries and the open doors and inlet vents of the sun porch and exits trough the thermostat controlled summer vents (skylights).

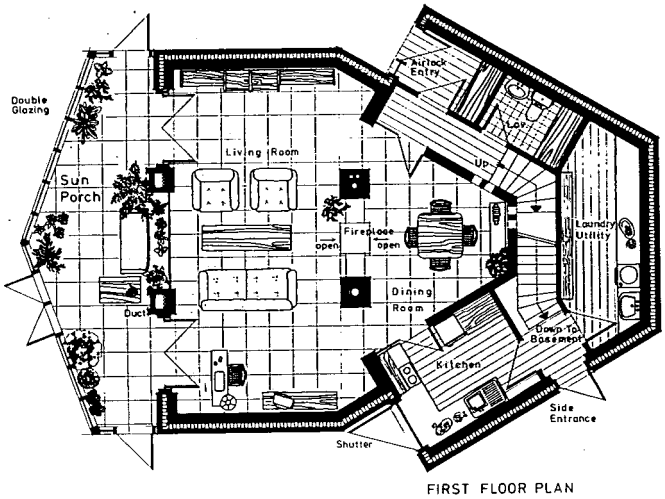



**Mode 2:** „Sunporch" temperature › 22° C = 72° F
Sunlight enters south glass and strikes mass areas on floor and walls of solid sand lime bricks. Even the dining room is in sun at noon from Nov. 1. to Jan. 31. The thermostat Controlled fan A supplies warm air to the rooms.

**Mode 3:** „Sunporch" temperature 14° C - 22° C / 57° F - 72° F
Fan B transfers warm air to the storage slab to balance the day-night temperature in the sun porch. Back up heat is provided by a gas furnace with an hot water heating system (European version). Further back up heat is provided by the fire-place in the middle of the house. The fire-place can be closed by glass doors for high efficiency heating.




SECOND FLOOR PLAN




FIRST FLOOR PLAN

# THE NEW SUN-PORCH HOUSE

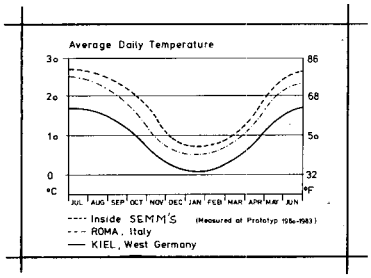



Fig. 9.

Inside temperature Semm's Wintergarten
Ambient temperature ROMA, Italy
Ambient temperature KIEL, West Germany

## 7. CONCLUSION

The measurements undertaken at the Semm's residence have proven the benefits of a "Wintergarten" in Germany for the first time in years. However, due to the vast number of measurements any attempt to incorporate our findings into this abstract was impossible. Nevertheless, the enrichment of the house dweller's living environment is unquestionable especially here in northern Germany where the sun rarly shines. The "Wintergarten" enables the coupling of house and garden, which is much sought today. Much as the "Wintergarten" serves as a border area between the house and nature; in its physical function it also performs as a buffer zone between higher and lower temperatures. As Fig. 7 shows, different designs and constructions exist, along with better or worse thermal performance results. The goal of our efforts should be an optimally balanced annual temperature curve which allows for bearable temperatures both in winter and summer. This is achievable if the following design elements are applied:

Vertically glazing
K-value 1,3 W/sqmK
Closed insulated roof

Floor storage mass instead
of seeded plant space;
Ceiling height over 5,0 m

It has not yet been possible to provide a finalized evaluation quantifying energy savings and gains. A new project, known as "The New Sun-Porch House" has been specifically designed to enable a finalized energy consumption analysis. This house, Fig.8,will be built in 1983 with the support of a grant from the German Ministry for Research and Technology ( BMFT ).

## 8. ACKNOWLEDGEMENTS

The author would like to express his gratitude to Mrs. R.Semm for hosting many people in her home during 1981/82; Prof. Dr.Dr.h.c.Kurt Semm for allowing a two year measurement, and Dr.A.Michel, Siemens Research Institute Erlangen, for providing the monitoring equipment and advice.

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# MEASURED TOTAL PERFORMANCE OF A SOLAR HOME USING CONCRETE MASONRY

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## ABSTRACT

The Roberts Home (Sundance I), located in Reston, Virginia, is a 214 square meter (2300 square foot) three level passive-hybrid solar residence using a single glazed, 62 $m^2$ (663 $ft^2$) Trombe wall with automated movable insulation and a 9.1 $m^2$ (98 $ft^2$) single sloped glazed sunspace. Concrete masonry comprises an inner core thermal mass, including an air-core hybrid storage system.

The winter building heat load was met by 52% passive solar heating, 12% auxiliary backup and 36% internal heat generation. The internal gains were high compared to other monitored buildings. The auxiliary heating thermal integrity was a low 17.77 kJ/ $m^2$ / HDD (0.86 Btu/ $ft^2$ /HDD).

Summer natural cooling using building design removed 99% of the measured sensible cooling load. The auxiliary heat pumps performed only 1% of the sensible cooling. High thermal mass, reflective movable insulation and night venting helped to keep the indoor comfort conditions very stable. The purchased cooling thermal integrity was 30.99 kJ/$m^2$ C DD (1.50 Btu/ $ft^2$ /CDD). Indoor comfort was achieved for 707 hours, while outdoor comfort occurred during 98 hours of 893 monitored cooling hours, during 1363 data hours in May through July 1982 despite 27% higher than expected cooling degree days.

Heating auxiliary electric cost 16$ per month (plus 1/3 cord of hardwood) and cooling cost 14$ per month, primarily for oscillating room fans. Costs were based on a $0.06/kWh electic rate.

These results are partly from work done at VITRO Laboratories, Silver Spring, MD; under contract DE-AC01-79CS30027.

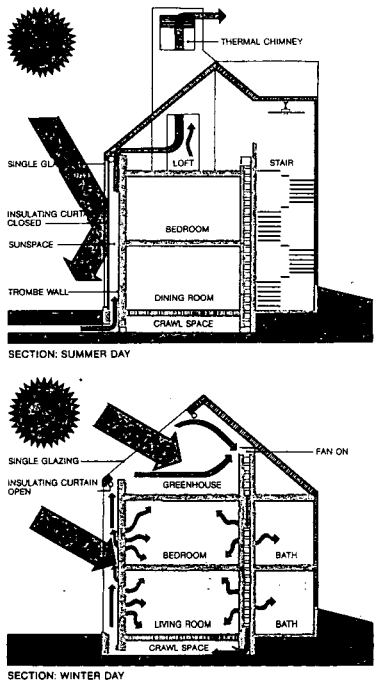



Fig. 1. Sundance I cross sections and seasonal modes.

## 1. INTRODUCTION

The Roberts Home (Sundance I) is an award winning passive/hybrid structure located outside Washington, DC, in Reston, Virginia. It was designed, constructed and is occupied by the architect, W. F. Roberts AIA.

### 1.1 Building Description

The solar system uses four primary elements integrated into the structure, shown in cross section in Figure 1. These drawings also show the seasonal operation of the solar system components used for space conditioning.

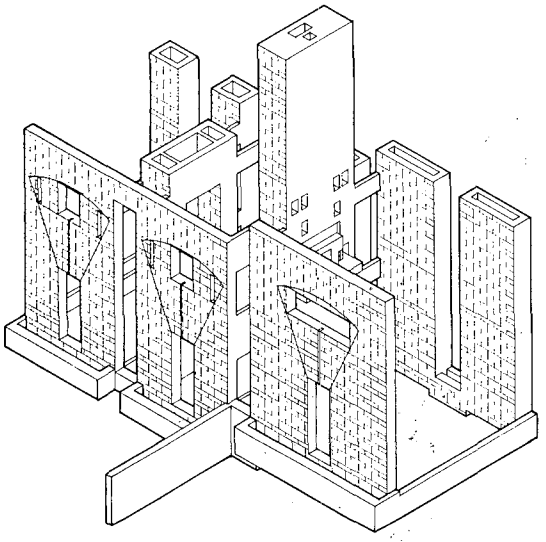


Fig. 2. Isometric showing concrete masonry thermal mass distribution.

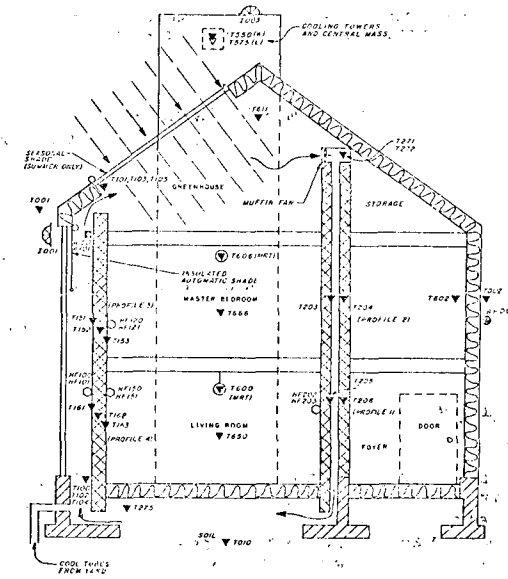



Fig. 3. Cross section showing sensors, Trombe wall and air-core wall system.

A 62 square meter (663 square foot) vented Trombe wall, with 6.35 mm (0.25 inch) single Plexiglass (TM) glazing employs a manufacturer rated Rsi 1.58 - 2.11 (R-9 - 12) automated movable insulation (MI) system with environmentally responsive controls, to protect the passive collector subsystem year around. The Trombe wall is of the vented type.

On the third level a 9.1 square meter (98 square foot) integrated sunspace collector with no MI, of 6.35 mm (0.25 inch) Plexiglass (TM) , is mounted at a 48 degree tilt to horizontal. It has a seasonally installed slatted exterior metal deck, used to reduce summer gain.

The concrete masonry thermal mass consists of a Trombe wall which contains 32,045 kg (71,140 lb ), a central core mass of 68,649 kg (152,400 lb ) and an air-core storage wall totaling 50,270 kg (111,600 lb ). The air-core energy balance is controlled by the use of a fan system on the upper level for hybrid solar heating. Careful study was made of all the mass in the building (Figure 2.) for proper sensor placement and software input data.

Some direct solar gains are provided by windows arranged to provide direct solar transmission when the movable insulation system is closed. The net area of additional south facing glazing provided is four square meters (43 square feet).

## 1.2 Conservation

Conservation is provided as follows. The envelope walls are insulated (outside the masonry) to Rsi 4.23 (R-24) and the roof sections are insulated to Rsi 5.63 (R-32). The perimeters are insulated to Rsi 1.76 (R-10). The floor on the lower level is insulated to Rsi 3.35 (R-19) to reduce heat loss to the crawl space which returns air from the air-core wall to the Trombe wall inlets. The concrete masonry inner shell is enclosed in insulation, shown to be good practice. Exterior insulated heavyweight buildings can perform better than steady-state predicitons. Air lock entrys are used on both front and rear doors. The home uses double glazed, insulated wood frame casement windows of the highest quality. Rigid insulating panels are inserted in north windows during winter to reduce losses.

## 2. INSTRUMENTATION

The sensor suite consisted of over 90 precision probes located throughout the structure to characterize its energy balance. This instrumentation is similar to the Class A program (1); however, co-heating and tracer gas infiltration measurements were never performed. Heat flux plates were installed to examine the relative magnitudes and directions of energy flux to and from the concrete masonry

Table 1. SPACE HEATING THERMAL PERFORMANCE

ROBERTS HOME
FEBRUARY 1982 THROUGH APRIL 1982

(All values in million Btu unless otherwise indicated)
(Btu = 1.055 kJ)

| MONTH | EMPIRICAL HEATING DEGREE-DAYS (F) (HDD) | BUILDING SOLAR FRACTION (%) (BHSFR) | BUILDING HEAT LOAD (BL) | CONDUCTION LOSSES (UA&T) (HLUA) | INFIL LOSSES (HI) | INTERNAL GAINS (HOTHER) | AUX ENERGY CONSUMED (HAT) | PASSIVE SOLAR ENERGY CONSUMED (HSEP) | EQUIPMENT HEATING LOAD (EHL) | EQUIPMENT SOLAR FRACTION (%) (EHSFR) |
|---|---|---|---|---|---|---|---|---|---|---|
| FEB | 729 | 46 | 11.2 | 8.10 | 3.08 | 3.64 | 2.43 | 5.12 | 7.54 | 68 |
| MAR | 649 | 50 | 10.5 | 7.74 | 2.73 | 4.07 | 1.15 | 5.24 | 6.39 | 85 |
| APR | 395 | 64 | 8.68 | 6.63 | 2.05 | 3.14 | 0.00 | 5.54 | 5.54 | 100 |
| TOTAL | 1,773 | - | 30.38 | 22.47 | 7.86 | 10.85 | 3.58 | 15.89 | 19.47 | - |
| AVERAGE | 591 | 52 | 10.1 | 7.49 | 2.62 | 3.62 | 1.19 | 5.30 | 6.49 | 82 |

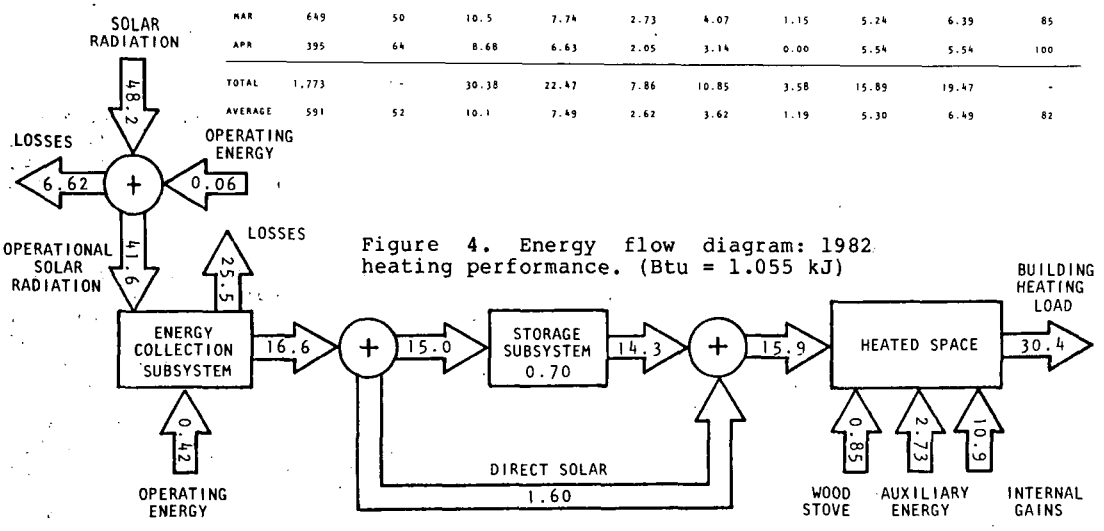



Figure 4. Energy flow diagram: 1982 heating performance. (Btu = 1.055 kJ)

mass. Weather sensors included both horizontal and vertical pyranometers, ambient temperatures on the north and south sides of the building, relative humidity and wind sensors. A cross section showing general sensor types and placement is shown in Figure 3.

The instrumentation of NSDN passive sites is described in a Comparative Report (2) and in each NSDN building's Solar Energy System Performance Evaluation (SESPE). A list of SESPEs is available (3).

## 3. ANALYSIS

The NSDN analysis was basically similar to that described by Spears (4). The heating season analysis was conducted using methods identical to those used to analyze buildings reported in Reference 2.

The cooling season analysis procedure was developed by the author and approved by VITRO, to measure the sensible heat flows into and out of the building during summer and track comfort parameters under measured outdoor weather conditions. An hourly calculation approach based on measured data was used to analyze the collector system energy balance. The difference between the collected solar value and the energy flow into storage was the energy vented from the collector subsystem by the cool tubes and thermal chimneys, without contributing to the building cooling load.

The total sensible cooling load equalled: solar energy transfer out of the storage, the operating energy for fans, the internal electric gains, auxiliary energy supplied to the heat pumps, and a radiant load factor (Qrad). Qrad was calculated based on a net radiant energy balance equation (5), after Federer. It is thought by the author to represent a fair approximation ( ± 12%) of the net radiant balance of building external materials. No data yet exist to support this assumption so the area remains open for investigation. Methods similar to those used by the author to measure the net radiant energy balance of the Trombe wall (6), could have been used, but were considered beyond the scope of the contract.

The ASHRAE standard (not modified) comfort envelope (7) was coded into the software to allow tracking of

summer hourly indoor versus outdoor comfort conditions. Statistical data profiles of temperature, relative humidity, window and movable insulation status conditions were analyzed to characterize better the performance of the building.

## 4. COLLECTION AND THERMAL STORAGE

The collector system operated well. Of the energy lost from the collection system, only 27% was by thermal losses. Of the total solar energy available to the collector system, 39% was uncollected. The ratio of net gains (collected minus glazing losses) to total insolation averaged 20%.

The Trombe wall performs well as a combined collector and storage device. Its efficiency averages 28% when the MI system is open. It is sand filled, and according to the data, this reduces its effectiveness somewhat. About 65% of the passive solar heating was supplied to the living space by the Trombe wall. For cooling, the Trombe wall net gains to insolaton ratio was reduced by control of the automated MI system to just 9.1% during May through July.

The concrete masonry thermal storage system is a key element in the good performance of this building. The concrete masonry mass is well distributed to allow radiative and convective heat transfer. The air-core rear wall is a hybrid sub-system which is charged by the operation of small fans. Passively collected solar heated air is forced down through the wall, giving up heat to the mass. The sunspace augments the function of the Trombe wall by furnishing extra solar energy to the air-core plenums. Its average transmittance was between 58 and 65%.

## 5. SPACE HEATING

Space heating performance monthly values are shown numerically in Table 1. The seasonal energy flows through the passive solar system are illustrated in Figure 4.

Daily temperature swings were small, below 4.4 °C (8 °F), due to the concrete masonry thermal mass. Average building temperature during winter was 17.8 °C (64 °F). Relative humidity was comfortable at 22 to 27%. The mass typically remained 1-3 °C warmer than the indoor air adding to comfort, shown by data from MRT black bulb temperature sensors.

Auxiliary electric baseboard heat contributed just 9%, or 2.88 Giga J (2.73 MM Btu) to the heat load of 32.07 Giga J (30.38 MM Btu) during February and March. April was 100% solar heated. Wood burning occurred infrequently in two masonry fireplaces. The use of 1/3 cord of hardwood contributed about 0.90 Giga J (0.85 MM Btu) to the space. The auxiliary heating thermal integrity was 17.77 kj/$M^2$/CHDD (0.86 Btu/$ft^2$/HHD).

## 6. SPACE COOLING

Monthly cooling thermal performance values are shown in Table 2. The energy flow diagram, Figure 5, illustrates the flows of energy into and out of the passive system.

There was a gross total of 10.38 Giga J (9.84 MM Btu) of solar heat gain from the passive solar collectors. Of this gain, 4.21 Giga J (3.99 MM Btu) were removed by cool tube venting of the Trombe wall - sunspace system before reaching the living space.

MI glazing control intentionally reduced the efficiency of the Trombe wall to just 13% in July. Cool tube venting helped prevent the Trombe wall mass from exceeding 23.9 °C (75 °F) during very hot weather, reducing the collector cooling penalty. Under 19% of the total insolation on the Trombe wall and sunspace glazings ever reached storage. Of the 6.17 Giga J (5.85 MM Btu) reaching storage, just 1.93 Giga J (1.83 MM Btu) are due to the Trombe wall; 4.24 Giga J (4.02 MM Btu) were contributed by the sunspace and direct gains.

The storage released 5.49 Giga J (5.20 MM Btu) into the living area and accumulated a net 0.75 Giga J (0.71 MM Btu), similar to in Winter. The temperature of storage increased from 19.4 °C (67 °F) in April to 24.4 °C (76 °F) in July. Qrad added 13.08 Giga J (12.4 MM Btu) to the building cooling load. Operating energy and internal gains added 2.33 Giga J (2.21 MM Btu) and 5.19 Giga J (4.92 MM Btu), respectively. Unavoided solar gains contributed 5.49 Giga J (5.20 MM Btu), and 0.03 Giga J (0.03 MM Btu) was added by the heat pump auxiliary. The total cooling load was 26.16 Giga J (24.80 MM Btu) of which 22.37 Giga J (21.20 MM Btu) was provided by "passive solar". The author thinks a better term is natural architectural cooling, or NAC in acronymeeze.

Table 2. SPACE COOLING THERMAL PERFORMANCE

ROBERTS HOME
MAY 1982 THROUGH JULY 1982

(All values in million Btu unless otherwise indicated)
(Btu = 1.055 kJ)

| MONTH | EMPIRICAL COOLING DEGREE-DAYS (#) (CDD) | PASSIVE COOLING SOLAR FRACTION (%) (CSFR) | BUILDING COOLING LOAD (CL) | EQUIPMENT COOLING LOAD (ECL) | CONDUCTION LOSSES (UAΔT) (HLDA) | NET SOLAR GAIN (NET_GAIN) | RADIANT COOLING NET LOAD (NET_RAD_GAIN) | INTERNAL GAINS (HOTHER) | AUXILIARY THERMAL (CAT) | PASSIVE SOLAR COOLING (CSEP) | STORAGE TEMP (°F) (TST) | BUILDING TEMP (°F) (TB) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MAY | 125 | 100 | 6.86 | 4.95 | 1.91 | 1.67 | 3.34 | 1.85 | 0.00 | 4.95 | 70 | 72 |
| JUN | 217 | 100 | 8.10 | 6.59 | 1.51 | 1.76 | 3.87 | 2.47 | 0.00 | 6.59 | 72 | 73 |
| JUL | 377 | 99 | 9.84 | 9.69 | 0.15 | 1.77 | 5.23 | 2.81 | 0.07 | 9.62 | 76 | 77 |
| TOTAL | 719 | - | 24.80 | 21.23 | 3.57 | 5.20 | 12.44 | 7.13 | 0.07 | 21.16 | - | - |
| AVERAGE | 240 | 100 | 8.27 | 7.08 | 1.19 | 1.73 | 4.15 | 2.38 | - | 7.05 | 73 | 74 |

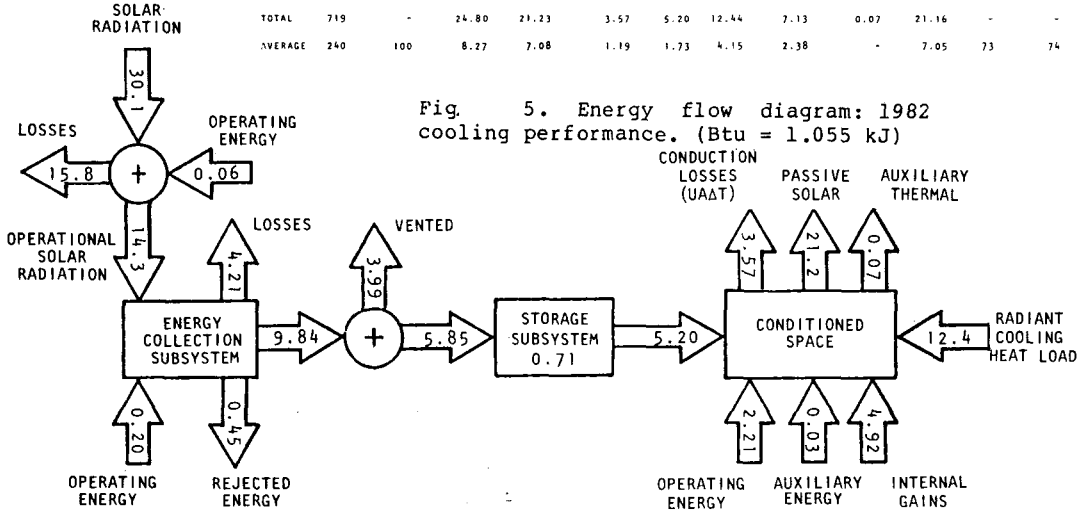



Fig. 5. Energy flow diagram: 1982 cooling performance. (Btu = 1.055 kJ)

The auxiliary cooling integrity (ACI) was 0.87 kJ/ $m^2$ /C DD (0.042 Btu/ $ft^2$ /CDD), and the base cooling coefficient (BCC) was 172.73 kJ/ $m^2$/CCDD (8.36 Btu/$ft^2$/CDD). BCC is the total sensible cooling load minus the solar gains, the solar unique operating energy and the conductive heat (UAdT) loss from the envelope. It is suggested that some standard NAC coefficients like these be developed to help compare building types.

Summer ASHRAE comfort was determined using special software. Of 1363 hours during May - July with available data (of 2208 hours total), 893 hours were cooling hours. Of the cooling hours, 707 hours were comfortable indoors while only 98 hours were comfortable outdoors. If the modified comfort envelope had been used, more comfortable hours would have counted.

The combination of the Trombe wall MI, sunspace glazing protection, cool tubes and thermal chimney venting, high mass and proper site design for the climate worked very well together.

Figure 6 shows side — by — side comparisons of June and July data-hour temperature profiles. These profiles are the result of statistical analysis of the entire valid hourly data sets for each variable. They represent a statistical composite day based on the bin-hourly behavior of the variable over the whole month. The stability provided by the concrete masonry thermal mass (CMU-MASS) is obvious. The indoor mass temperature swing is nearly an order of magnitude less than the outdoor swing. The mass clamps the building temperature very effectively.

Figure 7 shows the march of relative humidity (RH) over a seven month period, including data from August 1982. Winter values are low at 22% to 27%. Following spring, the RH values increase and track well, but remain about equal in net difference from month to month.

Figure 8 shows indoor versus outdoor bin-hourly RH profiles for June through August. An order of magnitude

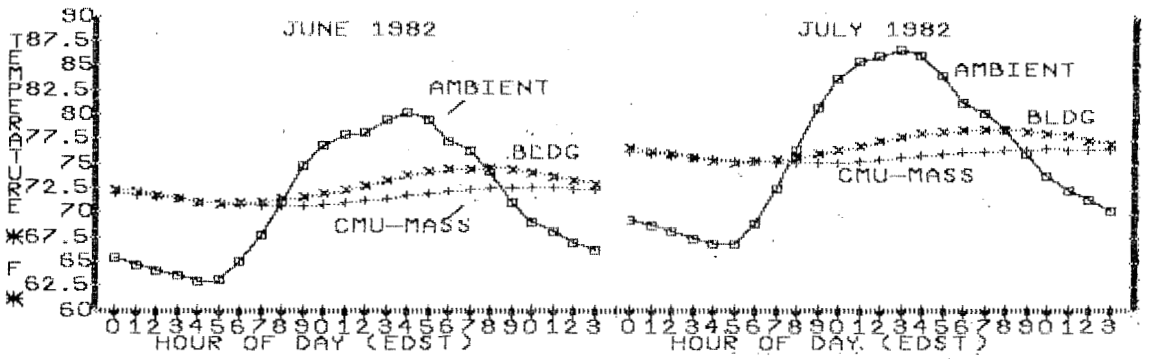



Fig. 6. Temperature bin-hourly profiles: June and July 1982.

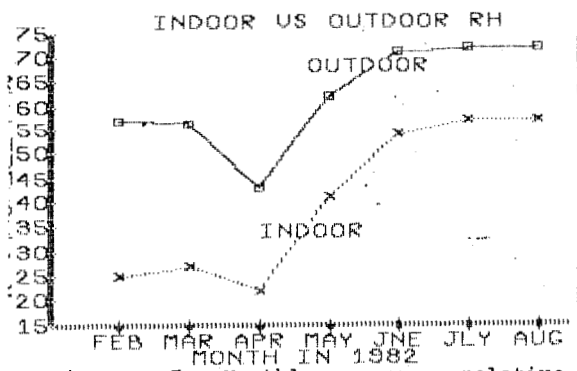



Fig. 7. Monthly average relative humidity values: June - August 1982.

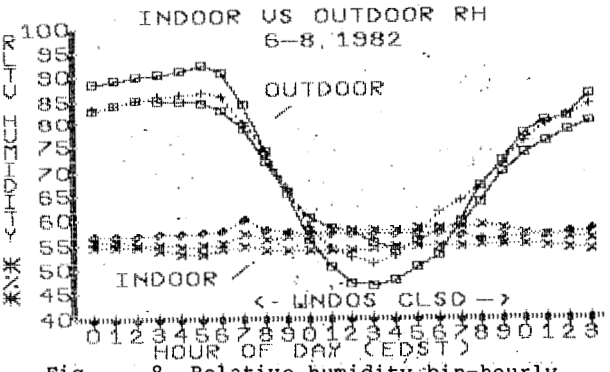



Fig. 8. Relative humidity bin-hourly profiles: June - August 1982.

difference in the net profile excursion of RH is observed for each month, similar to the mass effect that clamps indoor temperature. Some short term increases can be observed indoors during morning and evening from cooking and bathing. Despite night venting typically observed from 2100 to 0800 hours, high outdoor RH in air transiting and living space during the night created no obvious diurnal cycle. VTTRO checked out the RH sensors as fine on two occasions.

Possible hypotheses for these flat RH curves are: 1. water vapor exchange at the surface matrix of the concrete blocks which are not sealed or painted, 2. the solar gains to the mass and infiltration dry out the masonry via the thermal chimneys during the day, 3. cool tubes vent through the Trombe wall cavity to the thermal chimneys and so do not add moisture to living space.

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# HEAT DISTRIBUTION BY NATURAL CONVECTION*

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## ABSTRACT

Natural convection between spaces in a building can play a major role in energy transfer. Two situations are investigated: convection through a single doorway into a remote room and a convective loop in a two-story house with a south sunspace where a north stairway serves as the return path. A doorway-sizing equation is given for the single-door case. Detailed data are given from the monitoring of airflow in one two-story house, and summary data are given for five others. Observations on the nature of the airflow and design guidelines are presented.

## 1. INTRODUCTION

Natural convection can play a major role in distributing heat throughout passive solar buildings. Remote rooms can be effectively heated by air convection through a doorway that connects the remote room to a solar heated room. Experimental results from several buildings show typical daytime convective heat flow of 1000 to 2000 Btu/h driven by temperature differences of 3 to 5°F between rooms providing adequate heat for comfort. These results are in good agreement with a simple doorway correlation equation. Convection through single doorways was found to be the major mechanism for distribution of heat from the sunspace to the house in the Balcomb solar home, accounting for transfer of 16.3 million Btu during a 6-month winter period.[1] Analysis shows that the large swings in sunspace temperature aid in this exchange. Heat storage in the materials of room surfaces was also found to be quite important.

A more complex situation concerns internal convective loops that can play a vital role in distribution of solar heat. In a typical case, heat is convected from a sunspace through upper doorways or windows into the house, through hallways, down a stairway, and returns to the sunspace through doorways at the lower level. Several Santa Fe houses that have such loops have been monitored using smoke sticks, anemometers, and thermocouples; and the data have been analyzed to determine airflows and energy flows. The flow pattern is often found to be complex, involving a main loop and several subloops.

## 2. SIMPLE DOORWAY CONVECTION

Convection through a doorway at a point in time can be estimated from the following relation:[2]

$$Q = 4.6\, w \sqrt{(h\, \Delta T)^3} \quad , \qquad (1)$$

where $Q$ = convection heat flow, Btu/h,
$w$ = door width, ft,
$h$ = door height, ft, and
$\Delta T$ = room-to-room temperature difference, °F.

This relation can be used to determine the required door width needed to supply the heat losses from a remote room by using the same equation to describe average conditions. To do this we set Q equal to the 24-hour average heat loss of the room, in which case $\Delta T$ is the 24-hour average room-to-room temperature difference.

$$w = \frac{Q}{4.6 \sqrt{(h\, \Delta T)^3}} \quad . \qquad (2)$$

For example, if the average inside/outside temperature difference in January is 30°F and the loss coefficient of the room (UA) is 60 Btu/h, Q = 30 x 60 = 1800 Btu/h, average. If the maximum, tolerable, average $\Delta T$ from

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room-to-room is 4°F, the necessary width of a standard 6-ft 8-in. door is

$$w = \frac{1800}{4.6\sqrt{(6.67 \times 4)^3}} = 2.84 \text{ ft} = 34 \text{ in.}$$

Detailed numerical experiments were performed to determine the validity of the steady-state assumption under time-varying conditions using typical hourly room temperature and outside temperature measurements made in passive solar houses.[3] The conclusion of this investigation is that the $\Delta T$ given by Eq. 2 is quite close to the average room-to-room $\Delta T$ for cases of moderate room-temperature swing (for example, $\Delta T$ = 1.6°F, Q = 800 Btu/h, source room-temperature swing = 7°F.) However, if the source room-temperature swing is large, the equation tends to overpredict the average $\Delta T$. Thus, using Eq. 2 to size doorways is a conservative approach; the $\Delta T$ achieved will be equal to or less than the tolerance value desired.

## 3. NATURAL CONVECTIVE LOOPS

### 3.1. Discussion of Principles.

A convective loop, shown in Fig. 1, is between a two-story-high sunspace and the attached two-story house. One way to describe such a loop is as a "heat engine." Figure 2 shows this schematically. Heat is added in the south side of the loop, and the same amount of heat is withdrawn on the north side. Air flows around the loop because of the difference in densities between the south leg and the north leg. In fact, we can calculate the flow rate based on the difference in average temperatures between the two legs. It is also possible for heat to be removed along the top leg of the loop; this is particularly effective in driving the loop because it increases the average density

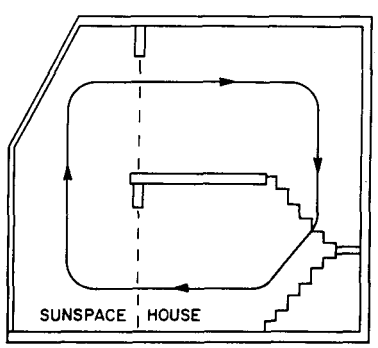



Fig. 1. Typical natural convective loop in a two-story house with a sunspace.

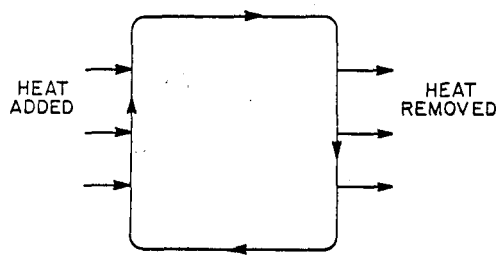



Fig. 2. "Heat engine" representation of a convective loop. The engine is the air motion, and the driving mechanism is heat added on one side and removed on the other.

along the vertical north leg. Lastly, it is possible for heat to be removed along the bottom return leg; this is not very effective in driving the loop because it does not contribute to the increased density in the north vertical leg.

This paper is not concerned with the double-envelope house concept, a special case that has been much debated. It is, instead, concerned solely with loops that involve normal architectural elements within a building, such as hallways, stairways, other rooms in the building, and doorways connecting these spaces.

### 3.2. Summary of Convective Loop Results.

Air velocity and temperature measurements have been made in six buildings that incorporate natural convective loops involving a sunspace and other architectural features. In most cases these loops are inadvertent; that is, they were not intentional or even perceived by the owner or designer. Measurements were made near midday during relatively sunny weather; a summary of these results for six houses is given in Table I. The results, which will be reported in detail in future Los Alamos reports, have been very encouraging, indicating large convective energy exchange.

### 3.3. La Vereda, Model 4 Results

Typical results, shown below for the third building in Table I, were gathered in a two-story house with a linear sunspace covering the entire south facade. The house is Model 4 in the La Vereda subdivision in Santa Fe, designed and built by Communico (Susan and Wayne Nichols). Floor plans are shown in Fig. 3. Although two-way airflow occurs in every doorway, the major flow is from the sunspace into the upper level through two double doors, [7] and [8]. About half of this flow returns to the sunspace through a door at midlevel, [1] (the house is

TABLE I

SUMMARY OF CONVECTION DATA MEASURED IN SIX HOUSES

| Sunspace Height | Sunspace Glazed Area | Sunspace-to-House | | | |
|---|---|---|---|---|---|
| | | Connecting Doorway Area | Typical $\Delta T$ | Total Airflow | Energy Transport by Convection |
| # of Stories | $ft^2$ | $ft^2$ | $^oF$ | CFM | Btu/h |
| 2 | 400 | 80 | 6 | 1680 | 17700 |
| 1 | 180 | 31 | 3 | 660 | 2430 |
| 2 | 410 | 114 | 5 | 2240 | 15500 |
| 2 | 570 | 49 | 10 | 1670 | 21100 |
| 1.5 | 310 | 64 | 4 | 1029 | 5110 |
| 2 | 210 | 82 | 4 | 1190 | 4870 |

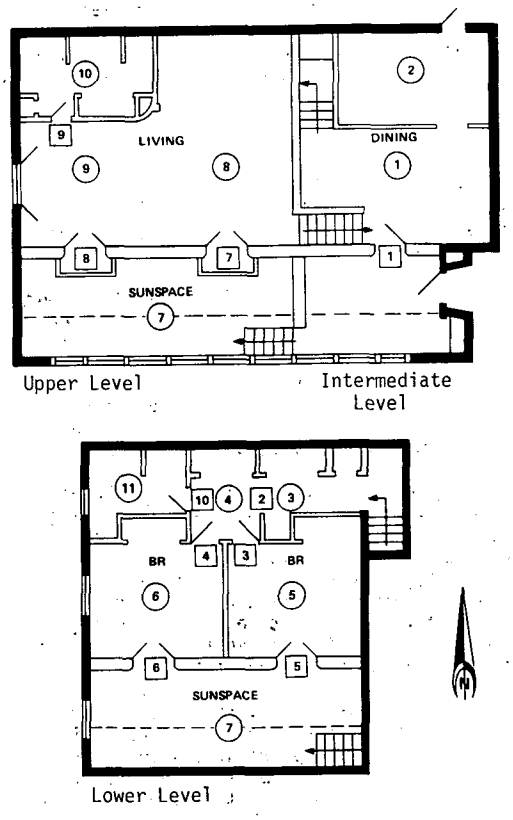



Fig. 3. Floor plans of La Vereda, Model 4. The west end is two-story; and the east, entry end is single story at an intermediate level. Arrows on stairs show traffic down. Circles refer to room numbers, and squares refer to aperture numbers.

split-level), and the remainder flows down a stairway and west along the downstairs hall, 2 , returning through two downstairs bedrooms, 5 and 6 .

Vertical air-velocity profiles were measured in each doorway, two examples of which are shown in Figs. 4 and 5. Volumetric airflows in each direction are calculated by integrating the velocity profiles for each doorway; the results are then adjusted to achieve the necessary overall mass balances for each zone, assuming no effect attributable to outside air infiltration. These adjustments are always within the range of air velocities measured.

Air temperature profiles were also measured, and energy flows are calculated by integrating the product of air velocity times temperature. Final results for the house are shown in Fig. 6, giving airflows, velocity-weighted average temperatures, and energy flows by natural convection.

### 3.4. Other Buildings

Data taken in other buildings have been analyzed in the same way to obtain the results in Table I. Some of the more interesting observations are as follows:

- In one house a 2 $ft^2$ laundry chute in the north part of the house provides a return air path for 183 cfm of air, helping to heat a remote north bathroom.
- In another house a series of 12 1-ft-diameter ducts were intentionally installed to provide a return air path to the sunspace. A combined airflow of 465 cfm was measured passing through these ducts compared with a return airflow of 1014 cfm through a single 27-in. door opening.
- In most, but not all, cases, two-way flow is observed in the apertures.

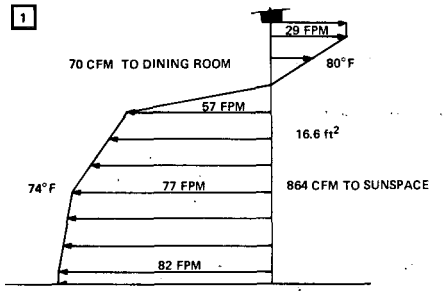



Fig. 4. Corrected velocity profile in aperture 1, located between the dining room and the sunspace.

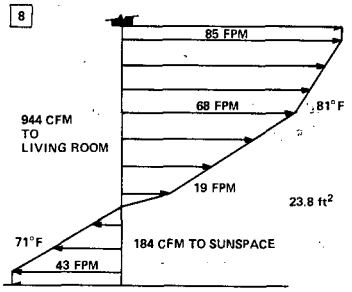



Fig. 5. Corrected velocity profile in aperture 8, located between the living room and the sunspace.

- Air stratification is pronounced in some buildings and almost nonexistent in others. This is not yet well understood.
- Warm airflow is generally across the ceiling and cold airflow along the floor, as expected.
- Different air streams do not seem to mix readily and, thus, flow to their destinations without interference. The warmest available air stream seems to flow to the coldest spot. Consequently, the airflow pattern seems to develop in a manner that will most nearly equalize the temperature distribution in the building.
- The zero-flow point in each doorway (the point where the flow velocity changes direction) is at about the same level in doorways that connect to the same large space, as expected.
- Small level changes, stepping down from north to south, help greatly in convective exchange, maintaining warmer north-room floor temperatures.
- Discomfort can be experienced in the evening if cool return air is channeled onto the feet of sitting people. This is observed in a house with a two-story Trombe wall forming the south side of the living room. Convection is driven up the Trombe wall and across the ceiling into upper-level bedrooms; air returning from these rooms collects on a balcony overlooking the living room; this cool air then funnels down the stairway and streams across the living room floor at high velocity. Floor-level perforations along the length of balcony that would allow the return air to spill into the living room at low velocity would have been a simple remedy.
- Air convection inside the Karen Terry direct-gain residence[4] was observed to be very small, with pronounced stratification. Solar gains are distributed uniformly through the building, and, therefore, there is little need to move heat horizontally and, thus, little convection.

### 3.5. Design Guidelines

Although the work described here is still in progress, certain design guidelines emerge clearly. It is evident that a major amount of heat can be distributed and stored inside a building by convection from a sunspace. The major driving mechanism for this convection is the heat engine, driven by solar heating on one side and heat removal on the opposite side (both by heat storage in walls and daytime heat losses). If the designer is fully aware of the principles involved, the design can benefit most from effective convective exchange.

The key design factor is proper layout of the building so that convective loops can operate effectively. This can usually be done without architectural compromise. In fact, in most cases studied, no conscious attempt to achieve a convective loop was made; it resulted, strictly in serendipitous fashion, from architectural considerations.

In designing for a convective loop, the designer should make multiple use of building elements as much as possible. Do not contrive a convective loop for its own sake but rather try to work it in with normal traffic flow. The following list gives design hints for one type of convective loop, starting with the source of heat and moving around in the same direction as the airflow.

- A sunspace makes an excellent heat source to drive the convective loop because high temperatures (80°F) are available in sunny weather. Because the flow velocity varies as the square root of the height, it is desirable to make the space as high as practical. A two-story building with a two-story sunspace has been found to work effectively; greater heights would probably work even better, although the tendency for temperature to stratify might be exacerbated. A dark-colored mass wall at the back of the sunspace will aid in absorbing the solar radiation and will heat the air as it rises.

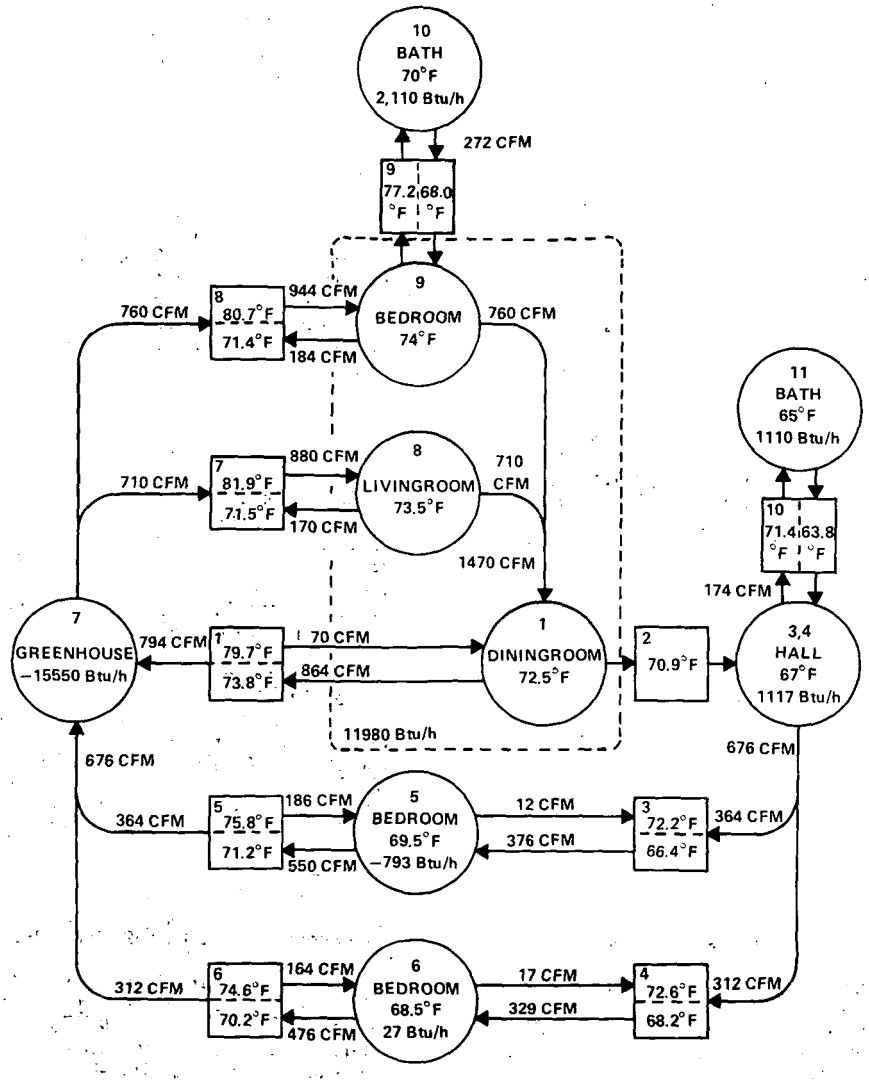



Fig. 6. Natural airflow diagram in La Vereda, Model 4, at 2:00 p.m., January 11, 1983, a sunny day. See Fig. 3 for identification numbers of rooms (circles) and apertures (squares). Airflow rates and velocity-weighted average temperatures are shown for each airflow direction for each aperture. Net energy flow rates are shown for the rooms, but note that rooms 1, 8, and 9 cannot be disaggregated so that the total energy deposited in the three rooms (11980 Btu/h) refers to the region enclosed by the dotted line. Room temperatures shown are ±1°F. Greenhouse temperatures ranged from 68°F near the floor to 82°F near the ceiling.

- Provide a large opening at the top of the sunspace for the air to enter the upper story. Doors are excellent for this purpose, although large operable windows can also be used. Doors are preferable because they are larger and are more apt to be opened during the day. A shallow balcony opening onto the top level of the sunspace is a popular design element. If vents at ceiling height are used, it is not necessary to close them during the night because closing openings at the return end will effectively shut off the loop.

- Provide for airflow across the upper level of the building from the south side to the north side. This is conveniently

achieved using a hallway, although other rooms can also be used.

- Provide for downflow of air in the north part of the house; a stairwell serves this purpose ideally. The fact that the air may have to bend around corners to get across the building, down the stairs, and into the lower portions of the building is of no great concern so long as the flow area is adequate. It is desirable for this path to be against the north wall both to increase the airflow and to assure that the convective loop can effectively supply the heat loss.

- Arrange for air return through the lower floor and back into the sunspace. Again, this might be through a hallway or simply across a room. It is essential to provide a doorway that can be closed in this portion of the path. This prevents cool air from the sunspace from flowing back into the building, tending to reverse the loop at night. Windows are not effective for this purpose because they will not allow cool floor-level air to return to the sunspace.

- Provide one or more level changes at the ground floor, stepping down from the north side of the house toward the south. This makes the floor level of the sunspace the lowest point in the loop so that cool air will drain to this spot. One or two steps should be sufficient. Elevate planting beds in the sunspace.

## 4. FUTURE WORK

- Measurements will be made over longer periods, perhaps for several days.

- The theory will be developed to allow quantitative prediction of convective exchange in complex situations. This will be reduced to algorithms for use in computer simulation models.

- Additional design guidelines, including quantitative estimation procedures, will be formulated and transferred to the design community.

## 5. ACKNOWLEDGMENT

We are grateful to the many people who allowed us to come into their homes and make measurements, to Richard Cottrell, Donald Neeper, Edward Mazria, and students at the University of Colorado for discussions regarding the concepts, and to Phillip Henshaw for his perceptions of airflow patterns.

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# MEASUREMENT-BASED CALCULATION OF INFILTRATION IN PASSIVE SOLAR PERFORMANCE EVALUATION

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## ABSTRACT

Low-cost, measurement-based techniques for calculation of infiltration as a variable in passive solar performance evaluation are suggested as an improvement over the use of an assumed constant air-change rate. Results of infiltration measurements and calculations are reported for 70 passive solar homes. Comparisons are made between two infiltration estimation techniques for 41 of these monitored buildings. The 50 Pascal air leakage rate of 67 of these buildings is compared to selected data on the leakage of non-solar buildings.

## 1. INTRODUCTION

Infiltration determination is a critical element of any residential passive solar performance evaluation. Continuous tracer-gas infiltration measurement techniques are available, but the cost of their use is prohibitive in most cases. Low-cost passive infiltration monitors are under development, but they are not yet commercially available. While these passive monitors may be an important tool for future passive solar performance evaluation, there is a significant lag-time before results are known, and they cannot provide useful information for short-term (hourly or daily) dynamic system analysis.

Because of these problems, and a general lack of understanding of infiltration, most previous low-level solar monitoring efforts have relied on a simplified approach to determining the infiltration component of heat loss, usually assuming it to be based on a constant air change rate. This approach can lead to significnt errors in performance results, particularly when the passive solar heating contribution is determined by the subtractive method. This can be illustrated by examining the impact of a constant air-change rate assumption on performance results from a typical monitored solar building. The example chosen is typical of the passive solar buildings monitored over the past two years using the standard "Class B" performance evaluation methodology [1]. In this methodology, the passive solar contribution to the heating load is determined by subtracting the internal gains and auxiliary heating from the gross heating load. Thus, any errors in the determination of the gross load are directly reflected in the passive heating term of the energy balance. Table 1 shows how the decision to treat infiltration as either an assumed constant value or as a variable can affect the value of passive solar heating. The example building has an assumed conductive heat loss rate of 130 W/°C, a volume of 425 m² and an effective leakage area of .057 m² . The columns computing infiltration as a constant assume an average .45 air change per hour while the columns computing infiltration as a variable use the calculation techniques described below. The results show significant variance in the determination of monthly passive heating. This paper presents two readily available and inexpensive techniques for determining infiltration as a variable. There is discussion regarding the accuracy of these techniques, and observations are presented on the infiltration levels found in the monitored homes.

TABLE 1. IMPACT OF CONSTANT AND VARIABLE INFILTRATION ASSUMPTIONS ON TYPICAL PASSIVE SOLAR PERFORMANCE DETERMINATION

| | OCTOBER | | JANUARY | |
|---|---|---|---|---|
| | assumed constant | variable | assumed constant | variable |
| average ambient temperature (°C) | 11.2 | 11.2 | 21.1 | 21.1 |
| average wind velocity | 4 | 4 | 6 | 6 |
| average degree-days (°C-days) | 227 | 227 | 604 | 604 |
| conduction heat loss (MJ) | 2549 | 2549 | 6784 | 6784 |
| infiltration heat loss (MJ) | 1273 | 1012 | 3387 | 4070 |
| total heat loss (MJ) | 3822 | 3561 | 10171 | 10854 |
| passive solar heating (MJ) | 1685 | 1424 | 1487 | 2170 |
| variance in value of passive heating | +18% | | -31% | |

## 2. THE HOMES

In a collaborative national effort coordinated by the Solar Energy Research Institute for the U.S. Department of Energy, 89 passive solar homes have been or are presently being monitored at the Class B level. They are located in Northeast (16 sites), Southeast (13 sites), Mid-America (12 sites), California (13 sites), Arizona (4 sites), Denver (15 sites), Portland (7 sites) and Spokane (9 sites). The homes vary widely in design, construction, size and occupancy. Most of the homes are recently built, and except for those in the Northeast, most are design competition winners and/or the subject of Federal, State or utility passive solar promotional programs. As a whole, they may be taken to be a reasonable representation of the current state of the art in passive solar construction. Further details on these homes and the results of the Class B performance evaluation program can be found elsewhere [1].

## 3. METHODS

When Class B monitoring of passive solar homes was first initiated, infiltration was assumed as a constant, lumped together with conduction heat loss in a single, overall heat loss coefficient. Based on early monitoring results and the realization of the potential errors discussed above, the methodology was modified to incorporate infiltration as a variable, based on short-term tests and calculations. Two short-term measurements were selected for use in the program: pressurization/depressurization testing to determine leakage characteristics of the homes and "bag sample" tracer gas measurements to measure natural infiltration at several different times during the monitoring period.

### 3.1 Pressurization/Depressurization Testing

83 of the Class B program sites were tested for leakage using a "blower door" to artificially pressurize and depressurize the house. This procedure has become increasingly common in the past several years and is well documented elsewhere [2]. While some researchers conduct only pressurization tests and some only depressurization, the procedure used here was to determine the leakage under both conditions and then compute averages of the two as the values to be reported and used in subsequent calculations. The "effective leakage area" is determined directly from this test, as is the air flow rate necessary to maintain a 50 Pascal (50 Pa) inside - outside pressure difference. This 50 Pa flow rate is normalized by the house volume to yield a flow rate in air changes per hour. 50 Pa is a much higher pressure than is experienced under average weather conditions, but the 50 Pa air-change rate is frequently used as a comparative index of building leakage. During pressurization tests, the leakage locations in each home were identified, usually with the aid of smoke guns or sticks for flow visualization.

While pressurization/depressurization tests were conducted by different people in different parts of the country, all followed certain standard procedures and all used Harmax or Gadzco blower doors.

### 3.2 Tracer-Gas Testing

At least one set of tracer-gas tests has been conducted at 64 of the Class B program sites, and most of these have been tested two or more times. The procedures used are those recommended by Grot [3]. In this procedure, a quantity of sulfur hexaflouride gas is introduced into the house to yield a concentration on the order of 100 parts per billion. Mixing is promoted by releasing the gas while walking through the house and by running any air circulation equipment found in the house. After at least one-half hour, a small hand pump is used to fill a sample bag while walking through the house. This procedure is repeated several times until three or four samples have been taken over several hours. The time of day, temperature difference, wind velocity and wind direction are noted for each sample. The samples taken in California were analyzed at California State University, Sacramento. All other samples were sent to the National Bureau of Standards (NBS) for analysis. At NBS. an automated system measured the concentration in each set of bags and determined the air-change rate as the constant in an exponential function fit to the concentration decay data.

### 3.3 Real-Time Infiltration Estimation

Using the results of pressurization/depressurization testing of the homes and the infiltration model proposed by Sherman and Grimsrud [4], monitoring at many of the Class B program sites was modified to incorporate real-time adjustment of the building heat loss as a function of infiltration variation. In addition to the effective leakage area, this model requires one-time determinations of the height of the structure, the local shielding of the structure and the partitioning of the total leakage area by location (the fraction in the floor, ceiling and walls). The other inputs to the model are the monitored values of wind velocity, average indoor temperature and ambient temperature. Because the Class B monitoring program uses an easily programmable data acquisition system, an equation for estimating real-time infiltration heat loss based on this model was programmed in:

$$L_i = 278\ C_p \cdot \rho \cdot A_o (f_s^{*2} \cdot \Delta T + f_w^{*2} \cdot W^2)^{\frac{1}{2}}$$

where $L_i$ = infiltration heat loss rate (W/°K)

$C_p$ = specific heat of air (MJ/kg-°K)

$\rho$ = density of air (kg/m³)

$A_o$ = leakage area (m²)

$\Delta T$ = inside - outside temp. diff. (°K)

and $f_s^*$ and $f_w^*$ are the reduced infiltration parameters defined in the Sherman and Grimsrud model for the stack and wind regimes, respectively.

## 4. RESULTS

The 50 Pa flow rates for 67 of the monitored homes are shown in Table 2, organized by regional location. Results are not included from five additional sites in the Southeast which the blower door used could not adequately pressurize. The mean 50 Pa flow for all 67 homes is 10.0 air changes per hour. These results show great variability in "airtightness" of the tested buildings and an overall higher level of leakage than expected. Passive solar buildings, designed to consume relatively low levels of purchased energy for space heating, have been expected to be substantially more airtight than other homes. However, a comparison to results of similar tests on other sets of homes does not support this expectation. Figure 1 compares the 50 Pa flow rates of the Class B homes to several other sets of homes tested in both the United States and Sweden, as summarized previously by Persily and Grot [5]. While most Class B homes

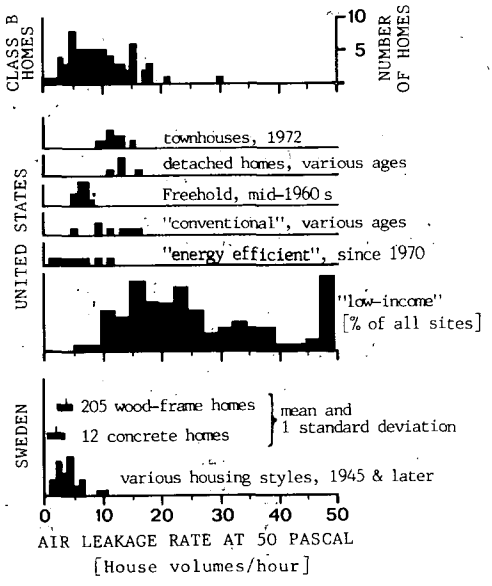



Fig. 1. Comparison of 50 Pa Air-Change Rates

are substantially tighter than the tested "low-income" homes in the U.S., they do not, on the whole, indicate leakage rates substantially different from the other tested U.S. homes. The reported Swedish homes are substantially tighter than the average Class B homes, and only three (4,5%) of the Class B homes are below the Swedish standard of 3 air changes per hour at 50 Pa.

TABLE 2. 50 Pa AIR CHANGE RATES OF MONITORED PASSIVE SOLAR HOMES

| NORTHEAST | | NORTHWEST | | SOUTHEAST | | MID-AMERICA | | CALIFORNIA | | DENVER | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NEE | 30.0 | SP8 | 18.2 | MBY | 18.8 | MAS | 14.7 | WSI | 15.0 | DMC | 21.6 |
| NEM | 18.6 | SP3 | 17.5 | MBG | 14.7 | MBB | 12.3 | WSG | 9.9 | DMJ | 17.9 |
| NEN | 10.6 | PO5 | 15.9 | SSK | 9.4 | MAI | 6.9 | WSA | 9.9 | DMH | 15.9 |
| NEB | 10.5 | PO2 | 15.9 | SSN | 5.5 | MAC | 6.6 | WSJ | 9.0 | DMA | 15.9 |
| NEL | 8.9 | PO3 | 15.1 | SSL | 4.4 | MAP | 6.4 | WSH | 8.9 | DMD | 13.8 |
| NEC | 8.4 | SP5 | 13.6 | | | MAD | 5.5 | WSK | 8.5 | DMF | 11.4 |
| NEH | 7.8 | PO6 | 13.6 | | | MAM | 5.3 | WSE | 7.9 | DML | 11.3 |
| NEJ | 7.1 | SP1 | 12.6 | | | MAN | 3.8 | WSD | 7.4 | MBA | 10.6 |
| NED | 6.0 | PO4 | 12.1 | | | MAA | 3.3 | WSL | 7.3 | DMI | 10.3 |
| NEI | 5.2 | SP6 | 11.3 | | | MBD | 3.0 | WSF | 5.6 | DMK | 10.0 |
| NEK | 5.0 | SP4 | 10.8 | | | MAB | 1.5 | | | DMG | 9.1 |
| | | SP0 | 8.7 | | | MAE | 1.0 | | | DMM | 5.2 |
| | | SP9 | 6.2 | | | | | | | DMN | 2.0 |
| | | PO7 | 5.5 | | | | | | | | |
| | | PO1 | 4.2 | | | | | | | | |
| | | SP2 | 4.2 | | | | | | | | |
| mean: | 10.7 | mean: | 11.6 | mean: | 10.5 | mean: | 5.8 | mean: | 8.9 | mean: | 11.9 |

The bag-sample type of tracer gas testing which was used on these homes only yields an infiltration rate for the time of the test. This value can differ substantially from longer term or average rates due to the dependence of infiltration on temperature difference and wind velocity. This test technique, however, can still be useful through the use of one of several techniques:

(1) conduct a test under selected average weather conditions for each month or season;

(2) conduct a large number of tests over the monitoring period and average the results;

(3) conduct a number of tests under different weather conditions to check or develop a site-specific infiltration model.

Because of cost limitations and the fact that most of these sites were located at some distance from the site operators, the first two options were not used in this program. While the target was at least four tracer gas tests for each site, under different weather conditions, this has been difficult due to budget limitations. To date, an average of only two tests have been conducted at each site, though some have had up to six.

The initial use of the results from these tests has been to compare tracer gas results with the model results described above. Figure 2 shows a comparison of tracer gas and model results for all sites where both tests were conducted. The model estimations are based on the wind speeds and inside - outside temperature differences which were noted for each tracer gas test. It is evident for the majority of points that the model estimations are higher than the tracer gas estimations. On the average, the model results are 0.13 air change per hour higher than the tracer gas results. The root mean squared error is 0.29 air change per hour, or 77% of the mean infiltration rate as estimated by the tracer gas testing. A regression with the gas test result as the dependent variable and the model result as the independent variable results in a slope of 0.49, an intercept of 0.13, a correlation coefficient of 0.68 and a standard error of 0.19. It appears there is both a substantial bias and a considerable random difference between the two methods.

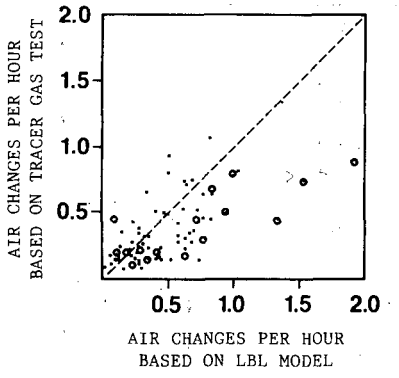



Fig. 2. Comparison of Tracer Gas Test and LBL Model Results

There is no obvious explanation of the discrepancies between the model and tracer gas results. Previous studies comparing tracer gas and model predictions have also been inconclusive. A similar bias, with model results consistently higher than tracer gas results, was found by Persily in measurements on 14 homes in New Jersey [6]. On the other hand, Sherman and Grimsrud [7] compared an average of three tracer gas measurements to model results for 15 houses of various ages, heights and locations, finding no pattern of relative overestimation or underestimation. Modera, Sherman and Grimsrud compared their model results to long-term measurements made in a portable test cell and in three unoccupied houses [8]. Again, no consistent bias in over- or underestimation was found. It should also be noted that the standard deviation of the ratio between model results and tracer gas results decreased from 66% to 19% in moving from one-hour to one-week values. Thus, the agreement appears to be better over the long term than the short term.

In the tracer gas tests, errors can be introduced from incomplete mixing of the gas in the house, the effect of occupants (if present), contamination of samples in the sampling equipment, and procedural errors (window left open, sample mislabelled, etc.).

In the model estimates it is also possible to identify the likely sources of error. The calibrations of some blower doors used have been questioned and are being investigated. The partitioning of leakage area according to location (floor, ceiling and wall) as well as the choice of local wind shielding values are certainly somewhat subjective. The determination of the "effective volume" (the volume of the house participating in infiltration) is difficult. For example, it is not always clear whether the volume of the basement should be included. This is another likely source of discrepancy which has yet to be investigated relative to these data. It was seldom possible to locate an anemometer in an ideal measurement location, and compromises made in this respect could also be a key source of error. It is also clear that wind direction can significantly affect infiltration, but wind direction is not accounted for in the model and was accordingly not monitored on any of the sites.

Examination of wind effects on the data presented in Figure 2 suggests that wind-

related error sources may be particularly significant in the comparison of model and tracer gas results. Shaw [8] has developed a model based on test measurements which divides infiltration into three types and treats each one separately: temperature-driven infiltration, wind-driven infiltration and combined wind- and temperature-driven infiltration. Shaw found wind to be a significant determinant of infiltration only when it was greater than 3.5 m/s. In Figure 2, the tests made when wind velocity was greater than 3.5 m/s are designated by open circle symbols. Almost all these points show a large overestimation resulting from the model relative to the tracer gas tests. A regression of wind velocity and the difference in results (tracer gas result minus model result) for each test yields a correlation coefficient of 0.26, while the correlation with temperature difference is insignificant.

Taking just the 16 tests where the reported wind velocity was greater than 3.5 m/s, the average difference between the tracer gas and model results is -0.30 air change per hour, with a variance of 0.22. Examining only the tests where reported wind velocity was less than 3.5 m/s, the average difference is -0.07 and the variance is 0.05. While these results appear to suggest a pattern, a "t" test indicates they are not statistically different from each other or from the results from all 55 tests. A linear regression of all the test data with wind less than 3.5 m/s results in a slope of .69, an intercept of .055, a correlation coefficient of .71 and a standard error of .19. This shows some improvement over the regression reported above for all test data.

This all suggests that some modification of procedures regarding wind velocity measurement or estimation of wind-driven infiltration in the model estimations may be appropriate. One approach which will be investigated in the future is the use of a number of tracer gas tests under different wind conditions to "back out" a site-specific value for $f_w^*$ in the model.

While the question of the discrepancies between the model and tracer gas results remains unresolved, the measurement-based model prediction technique has been used to modify heat loss values for 55 of the Class B monitored homes, using on-site measurements of wind velocity and temperature. While the potential errors in estimated infiltration are of continued concern, it has generally been found that the heat balance results from this treatment of infiltration as a variable are a significant improvement over the constant infiltration assumption. Figure 3 illustrates the significance of these estimated infiltration rates as part of the heat loss rate for each of these buildings. The percentage values next to each site code represent the fraction of the heat loss which is attributable to infiltration. These range from a low of 5% to a high of 69% with a mean of 28.7%.

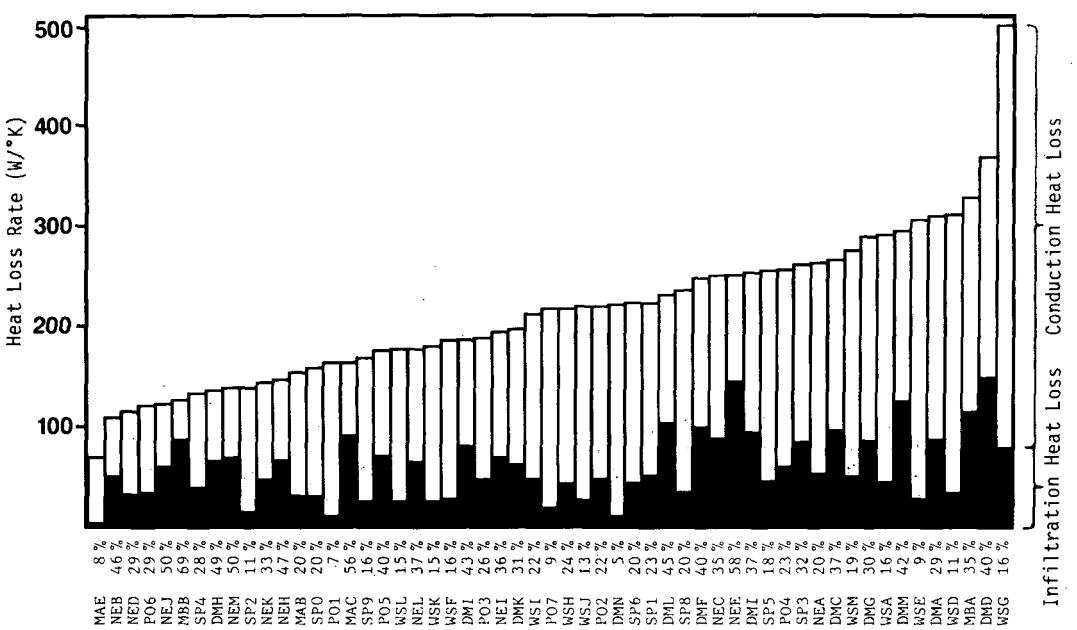



Fig. 3. Total Heat Loss Rate and Fraction Due to Infiltration in Monitored Homes

## 5. CONCLUSIONS

Pressurization tests of 67 passive solar homes show 50 Pa leakage rates ranging from 1.0 to 30.0 air changes per hour with a mean of 10.0. Based on an infiltration model which uses pressurization and depressurization test results together with monitored weather data, the infiltration in these homes was found to represent an average of 29% of the heating load. When infiltration is this significant a determinant of the load, its variability becomes significant. Infiltration will vary with weather on an hourly, daily and monthly basis, and load calculations (and resultant solar heating performance factors) can be significantly improved by treating infiltration as a weather-dependant variable instead of a constant.

The results of 71 bag-sample tracer gas tests were typically somewhat lower than model results for the test conditions. As a group, the tests conducted under high reported wind velocities showed a high degree of discrepancy between the two methods.

This set of passive solar homes shows both a high variability in infiltration rates and generally higher rates than were expected from houses which were designed to be energy-conserving. In a large number of the homes, the infiltration load alone is greater than the passive solar heating contribution. If the levels of airtightness exhibited in the tightest of these homes had been achieved in all of them, the typical loads would be substantially decreased, and the fraction of the gross load met by passive solar heating would be much higher. If this sample is at all representative of current passive solar home construction, much more attention deserves to be paid to saving energy through reducing infiltration.

## 6. ACKNOWLEDGEMENTS

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# CONSTRUCTION AND PRELIMINARY PERFORMANCE DATA ON TWO COMMERCIAL BUILDINGS WITH ACTIVE CHARGE/PASSIVE DISCHARGE SOLAR SYSTEMS

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## ABSTRACT

Two commercial buildings recently constructed in Las Cruces, New Mexico, incorporate low-cost active charge/passive discharge solar systems. The metal roofs of the buildings are used as solar collectors on sunny winter days; in each building, warm air from the space beneath the roof is blown through a rock bed underneath the concrete floor. Heat from the rock bed is transferred passively through the floor slab to the space above. In summer, air from the rock bed is circulated under the metal roof at nighttime to provide some cooling for the rock bed and for the building.

The construction of the buildings is described. Preliminary performance data are discussed; this indicates that the metal roofs provide a significant amount of heat in winter but that the cooling cycle is not operating efficiently.

## 1. INTRODUCTION

Active charge/passive discharge solar heating systems are gaining credence within the solar community as a viable alternative to systems which are strictly active or passive. These hybrid systems can supply energy at a lower cost than active systems and can operate more efficiently than passive systems (3, pp.14-18). Two commercial buildings recently constructed in Las Cruces, New Mexico, incorporate low cost systems of this type.

The Harrison building (most of which houses a retail carpet store) uses steel frame construction with ribbed metal cladding on the walls and the roof. It is 16,800 square feet in area, and 24 feet high in the center. A rock bed 21 inches deep (with rocks between 2 and 8 inches in diameter) lies under the concrete floor slab. The metal roof (with a bronze exterior finish) is used as a solar collector in winter. Air is drawn directly past the underside of the metal ribs, through a space created by draping vinyl-clad fiberglass insulation between the purlins and the roof. Three 3/4-horsepower blowers direct this warm air into the rock bed. Air is returned from the rock bed to the space between the inner and outer wall cladding through sections of standard downspouts. The space in the wall acts as the return air ducts to the roof collector.

The additional cost of the solar system was about $1 per square foot of floor area before federal and state tax credits, and about half that after tax credits. This amounts to about 3 percent of the total building costs (the building was completed about 3 years ago). Auxiliary heating with gas during the first winter of operation cost about $60 per month, compared with about $800 per month for a non-solar building of similar construction. These operating costs were verified when the solar system was switched off for about one month during the last winter while floor repairs were carried out. The thermal performance of the Harrison building has not yet been determined. Both the cooling and heating modes will be monitored during appropriate seasonal conditions in 1983.

The Southwestern Abstract and Title Company is a commerical structure housing office space heated by a closed loop active charge/passive discharge air solar system. The active portion of the system also utilizes a corrugated steel roof as an unglazed absorber. Collected energy is stored in a rock bed and passively distributed via radiation and convection.

Staff members of NMSEI have installed thermocouples in accessible portions of the Southwestern Abstract and Title Company system in an attempt to assess the thermal performance of the building. It is believed that this type of system utilizing the roof as an unglazed absorber and the floor as a

radiant distribution system holds great potential, particularly for areas with temperate heating seasons.

## 2. SYSTEM DESCRIPTION

The Southwestern Abstract and Title Company building reflects the style of old spanish architecture frequently seen in New Mexico. This is epitomized by the flat parapeted roof and the adobe colored stuccoed walls.

The building is composed of 8-inch grout filled concrete blocks with a 4-inch reinforced concrete slab on grade. The 6,900 cubic foot rock bed is under the entire slab to a depth of 18 inches. The rock bed and slab are thermally isolated from the footing with 1-inch rigid board insulation. The walls have exterior board insulation of 1-inch urethane, R-7.14, with a rough stucco finish. The interior finish on the concrete walls is gypsum board, which is also used on the 2 x 4 stud partitions.

The active portion of the system is characterized by the 4,800-square-foot, 24-gauge, dark brown corrugated steel roof which is the unglazed collecter. It is oriented on a northwest-southeast axis, 22° west of north, with a 5.5° slope to the southwest. The supporting roof members are 8-inch "Z" purlins which are in turn supported by 35#, 18-inch I-Beams. The flow channels of the roof collector are defined by the corrugations and 2-inch vinyl clad fiberglass duct wrap insulation which is draped over the "Z" purlin roof members.

The supply header for the roof collector is composed of two 8-inch, 14 gauge "C" purlins face to face, 8 inches apart. The header runs the entire length of the northeast and southwest walls for a total of 240 feet. The header is fed by multiple risers from the rock bed. These are 2-inch by 3-inch galvanized downspouts installed in the concrete block cells at approximately 4 feet on center (see Figure 1). The system has 22 risers in the northeast wall and 30 risers in the southwest wall.

The collector return header is an 8-inch by 36-inch site built duct composed of two "Z" purlins, the corrugated roof on top, and masonite underneath. This runs down the center of the roof the length of the building, 120 feet. The heated air returns to the rock bed via two 18-inch by 24-inch ducts, each containing a ½-horsepower centrifugal fan.

The 18-inch deep fan forced rock bed extends under the entire slab with rock approximately 2 to 8 inches in diameter. The thermal capacitance of the rock bed and concrete slab is about 43 Btu per square foot per °F. The hot air from the collector is distributed through the rock bed via two radial plenums constructed of 6-inch diameter, 1-inch by 1-inch wire mesh ducts. The arrangement of the multiple arms of the radial plenums feed all sections of the rock bed minimizing the airflow path through the rocks to 6 feet or less. The 2-inch by 3-inch galvanized risers are fed by a 6-inch diameter perimeter duct of 1-inch by 1-inch wire mesh which surrounds the rock bed (see Figure 2).

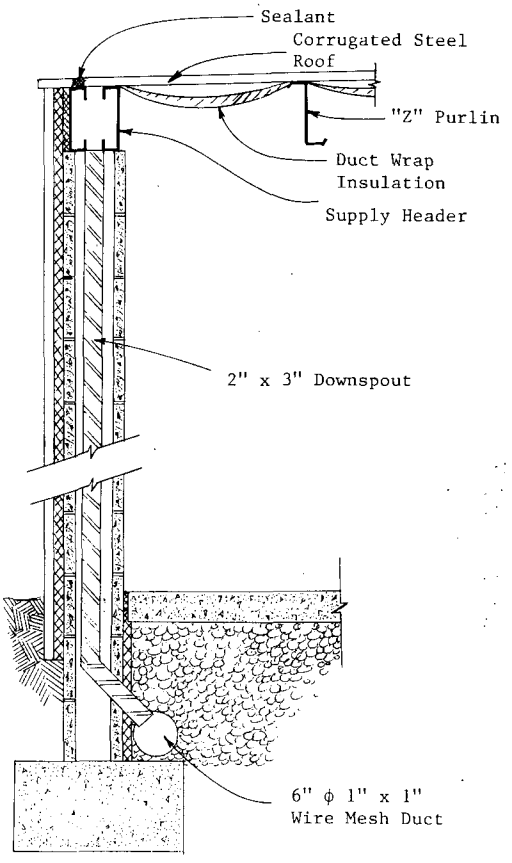



Fig. 1. Southwest Wall Cross Section.

Auxiliary heating for the building is supplied by two 150,000 Btu gas furnaces, distributed by the overhead air-conditioning ducts. Auxiliary cooling is supplied by two 5-ton refrigeration air-conditioning units.

The solar system controls are through two single set point thermostats, one for each fan. The collector return header has two low temperature limit switches, normally set at 68°.

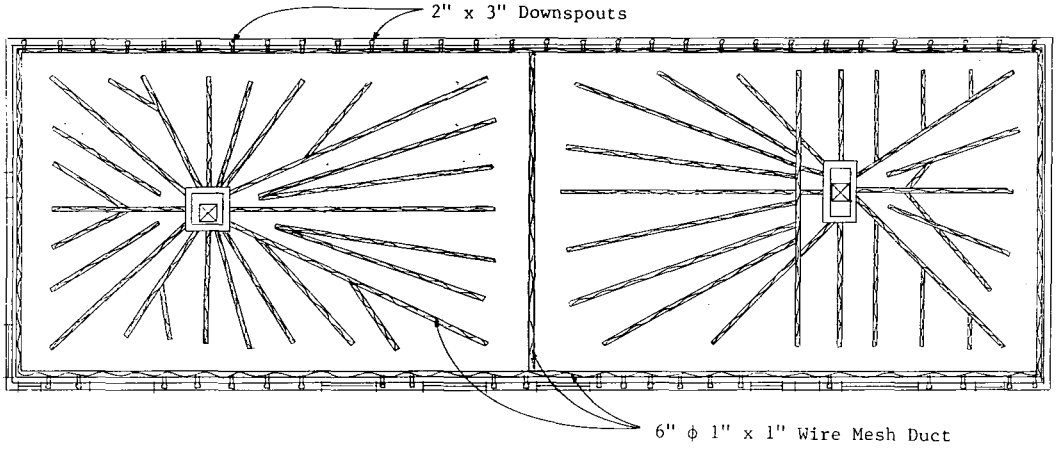



Fig. 2. Plan View of Rockbed.

## 3. SYSTEM PERFORMANCE

When the thermostats call for heat and the low temperature limit switches in the return header are not activated, the system starts the fans for solar collection. The combined flow rate of both fans is approximately 1,400 SCFM which is .29 SCFM per square foot of collector. It is a self balancing system with the two fans in parallel sharing the rock bed, and supply and return headers. The south fan operates at a flow rate which is 23 percent higher than the north fan. This is most likely due to a lower pressure drop in the southern half of the rock bed caused by the layout of the radial distribution ducts.

Monitoring on April 19, 1983, yielded performance data and the system efficiency across a narrow band of data points. At that time, the heating season in Las Cruces had ended which gave efficiencies at a stress factor ($\Delta T/I$) near zero (see equation 2).

The solar collection performance of the roof collector was determined in accordance with ASHRAE Standard 93-77, "Methods of Testing to Determine the Thermal Performance of Solar Collectors," with the following exceptions (1). The mass flow rate of the system was lower than recommended by ASHRAE Standard 93-77. Calculation of the air mass flow rate was determined by averaging four 16-point traverses in each duct with a hot wire anemometer. The data points are not symmetrical about solar noon. During the test, the collector inlet temperature remained essentially constant, due to the excellent heat transfer and large thermal capacitance of the rock bed. This fixed inlet temperature necessitated tests at lower levels of incident radiation in order to obtain a small spread on the data points. The determination of a collector time constant was not possible in accordance with ASHRAE Standard 93-77 due to the size of the collector. A time constant of 10 minutes was chosen for the performance monitoring. Tests at near normal incidence angles were impossible due to the fixed orientation and slope of the roof. Temperature measurements were conducted with Type K thermocouples and a digital thermometer.

The efficiency of the roof collector was determined by the following equation:

$$\eta = \frac{\dot{M} C_p (T_o - T_I)\, dt}{A_g I} \qquad [1]$$

where:

$\eta$ - collector efficiency

$\dot{M}$ - air mass flow rate, lbm $min^{-1}$

$C_p$ - specific heat of the air, Btu $lbm^{-1}$ $°F^{-1}$

$T_o$ - collector outlet temperature, °F

$T_I$ - collector inlet temperature, °F

dt - collector time constant, 10 minutes

$A_g$ - gross collector area, 2,400 square feet for the single duct calculations, 4,800 square feet for the combined north and south duct calculations

I - incident solar radiation recorded over the time constant, Btu $foot^{-2}$

The collector stress factor was determined by the following equation.

$$\frac{\Delta T}{I} = \frac{T_I - T_A}{I} \qquad [2]$$

$T_A$ - ambient temperature, °F

I - incident solar radiation, Btu hour$^{-1}$ foot$^{-2}$

In computing the stress factor for the total roof area, the following procedure was used. The system is self balancing due to the common rock bed and collector headers, consequently producing differing flow rates through the two fans, presumably caused by different pressure drops across the north and south ends of the system. The roof area served by each fan is unknown, therefore, an arithmetic mean was used.

The thermal performance of the system as monitored on April 19, 1983, is shown in Figure 1. These collector curves were computed using a least squares fit of the 10 sets of data points for the north duct, south duct, and for the total roof area with both ducts (see Figure 3).

The four data points of the north duct efficiency curve which lie to the left of the Y-axis occured in the afternoon when the ambient temperature exceeded the collector inlet temperature of the north end of the system. The system efficiency may not reflect a true operating intercept and slope due to the narrow spread on the data points and the low stress factor at which the system was tested. The low efficiency of this system is primarily due to the low flowrate, .29 SCFM per square foot of collector. An efficiency of this magnitude is not inconsistent with the results of controlled studies on unglazed collectors (4, pp. 4-14 to 4-19).

During the performance testing, the incident radiation on the roof varied from 332 Btu hour$^{-1}$ foot$^{-2}$ at 12:00 noon to 187 Btu hour$^{-1}$ foot$^{-2}$ square foot at 4:00 p.m., as recorded on an integrating Licor pyranometer on the plane of the roof. During the 50-minute period from 12:04 to 12:54, the system was collecting energy at a rate of 75,300 Btu per hour. During the 50-minute period from 3:14 to 4:04, the system was collecting energy at a rate of 51,400 Btu per hour. When the system is operating during the heating season, it is reasonable to assume that system gains will be of a lesser magnitude than the above figures due to a larger stress factor. Further testing during both the cooling and heating seasons will be undertaken in order to obtain an accurate analysis of the building thermal performance.

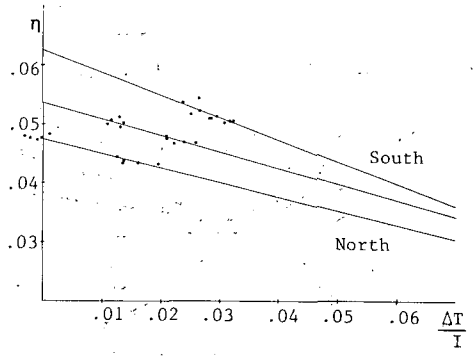



Fig. 3. System Efficiency Versus $\frac{T_I - T_A}{I}$.

The current owner is quite pleased with the performance of the collector in the heating mode. Auxiliary heating costs for this 4,800-square-foot structure for January, February, and March of 1983 totaled $163. These three months encompass over half of the heating degree day season.

TABLE 1. SYSTEM EFFICIENCY

| Time | North Duct η | North Duct ΔT/I | South Duct η | South Duct ΔT/I | Combined η | Combined ΔT/I |
|---|---|---|---|---|---|---|
| 12:04 - 12:14 | .0433 | .0195 | .0507 | .0323 | .0470 | .0259 |
| 12:14 - 12:24 | .0434 | .0161 | .0507 | .0316 | .0470 | .0239 |
| 12:24 - 12:34 | .0439 | .0136 | .0511 | .0284 | .0475 | .0210 |
| 12:34 - 12:44 | .0445 | .0124 | .0515 | .0293 | .0480 | .0209 |
| 12:44 - 12:54 | .0433 | .0135 | .0504 | .0308 | .0469 | .0221 |
| 3:14 - 3:24 | .0474 | -.0011 | .0539 | .0238 | .0507 | .0114 |
| 3:24 - 3:34 | .0483 | .0011 | .0524 | .0263 | .0504 | .0137 |
| 3:34 - 3:44 | .0479 | -.0004 | .0545 | .0264 | .0512 | .0130 |
| 3:44 - 3:54 | .0477 | -.0023 | .0511 | .0283 | .0494 | .0130 |
| 3:54 - 4:04 | .0481 | -.0032 | .0518 | .0250 | .0500 | .0109 |
| | $F_R\tau\alpha$ | .0475 | $F_R\tau\alpha$ | .0625 | $F_R\tau\alpha$ | .0537 |
| | $F_RUL$ | .2477 | $F_RUL$ | .3799 | $F_RUL$ | .2798 |

The cooling mode however, has not performed as designed. Nighttime operation during the cooling season should cool the rock bed via nocturnal radiation and convection from the roof collector. Unfortunately this has not occurred. The owner has stated that the building actually heats up during summertime night operation. The problem may be caused by the time lag in the diurnal temperature swing in the area between the roof and the suspended ceiling. This area contains the collector headers, the auxiliary heating and air-conditioning ducts, 6 inches of fiberglass insulation, lighting fixtures and wiring, plus a considerable number of structural steel roof members. The only insulation above this space to minimize overheating is the 2-inch duct wrap which acts as the back of the collector flow channel, and this is thermally short circuited where the roof is supported by the "Z" purlins. Daytime temperatures in this space can be quite high, in excess of 100°F in May. The heat stored in the structural steel roof members is released slowly at night, limiting the cooling performance of the system. Furthermore, the system has no timer which would enable it to be run only in the early morning hours before dawn. The system will be monitored during the 1983 cooling season in order to determine the exact nature of this problem.

## 4. CONCLUSION

The monitored thermal performance of this active charge/passive discharge system indicates that unglazed collectors can be a practical alternative for space heating in areas with moderate winter daytime temperatures. The low efficiency of this system does not preclude its use due to the low initial cost, large collector area, and dual function of the major components. Further studies are required during the heating season to fully assess its capability as a space heating system and during the cooling season to determine the cause of the poor performance in the cooling mode.

## 5. REFERENCES

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# PASSIVE SOLAR AND UTILITY LOAD MANAGEMENT : IMPLICATIONS FOR DESIGN PERFORMANCE GOALS AND TIME-OF-USE UTILITY RATES

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## ABSTRACT

This paper describes the interaction and economic impacts of various passive solar design features in a very low energy consuming single family residence which is served by experimental time-of-use (TOU) metering in an all-electric utility service area in North San Diego County.

The owner, an applied research engineer (formerly a Senior Specialist in the Solar Office of the California Energy Commission), and his wife, describe their experiences as the builder/owner/occupants. Their perspective of the techno-economic factors and occupant reactions are presented for the site selection, design and construction process.

Original Architect-Engineer (A-E) design development criteria and construction experiences are related. Various interdependencies among passive heating/ventilating techniques are discussed with respect to occupant comfort and satisfaction with design implementation.

Automatic data logging of thermal performance of different features has been undertaken, with preliminary results strongly indicating a positive relationship between the structure's thermal performance and reduction of peak demand upon utility reserves. Implications for load management, as well as direct conservation, are described with respect to the relationship between particularly low consumption passive solar dwellings and TOU rate structures.

## OWNER/BUILDER/OCCUPANT EXPERIENCE

The usual site considerations a custom-house owner weighs were supplemented by several unique features having a strong, positive influence on the passive solar design. Those key features are the location in a mild coastal valley, 9 miles east of the Pacific coastline in Oceanside, California (North San Diego County) providing good annual total solar radiation coupled with prevailing daytime coastal breezes sweeping up a south facing and view-oriented slope at the building site. It is further enhanced by a county regional park and wildlife preserve adjoining on the southern border or the two-acre site which ensures both solar access and a quiet country atmosphere with equestrian zoning.

Our familiarity with the principles in passive and active solar systems, the all-electric utility service constraints, and our desire for long-term economic operation coupled with comfortable living conditions all worked together to enable ourselves and the A-E team to get a good head start on the design process. Maximum retention of view, existing pine trees, accommodation for living area zone isolation, entertaining, etc., were all brought to bear on the siting and house design. Maximization of solar tax credits from both state and federal levels was treated thoroughly as a basic design requirement to ensure a sound investment strategy on the project. Although no plans for resale were specifically in mind, a practical and efficient design was dictated to accommodate good resale value if the requirement should arise.

The design process, from our point of view, turned out to be at times an emotional experience in that lifestyles were sometimes discovered, challenged, and redefined as one tries to balance pre-conceived impressions or desires with the real world of thermal and structural performance and cost trade-offs. The architect's role in guiding us through these decisions have, in retrospect, turned out to be as important as the execution of the working drawings and specifications package.

The construction phase dealt with two categories of added cost and complexity. The first category consisted of design features not part of conventional custom home construction features such as:

Trombe walls
Sun room/greenhouse
Bermed wall
Dedicated ventilation structure
Deck railing (low solar profile)
Isolated water storage (additional thermal mass)
Spa utilizing Trombe and thermosiphon for water heating.

The second category of added cost consisted of custom features requiring careful integration and consideration of cost impacts, but were justified by both aesthetic values and house thermal performance (including ventilation). They are:

Open beam ceiling (including drywall interface)
Angular layout of floor plan
Glazing
Skylights

Collectively, the problems encountered such as periodic plan and specifications discrepancies, material availability and substitutions, labor supervision and subcontract management, and cost control all culminated in both punishing and rewarding experiences. The end result of experiencing the comfortable and pleasant living environment with proven economical operation - and knowing these benefits are on-going and long-lasting makes the difficult period of implementation gradually fade away. There is certainly satisfaction of having gone through the process even if we wouldn't choose to repeat it, particularly in the exact same way. This end result would certainly have not been possible without the excellent conceptual design effort put out by the professional and dedicated team of architects and engineers.

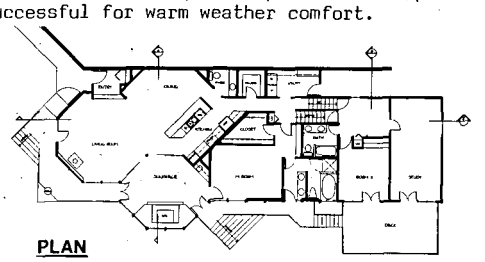
ARCHITECT-ENGINEER EXPERIENCE

The owner's design criteria included two major living zones and specifically emphasized overall energy conservation in conjunction with various, specific concepts of thermal storage and distribution. The primary design schematic effort involved a concerted process which emphasized the major benefits of "radiant" comfort over indirect thermal storage, and opportunities for direct ventilation. The schematic design responded to initial program requirements with specific East-West plan elongation in mind to take advantage of clear solar exposure, and to open the West and South-Westerly faces to the prevailing breezes. Investigations of local microclimate indicated relatively few peak weather events occured, and then mostly in overheated periods, (Easterly Santa Ana winds from the desert).

Preliminary thermal analysis was performed for the schematic design using the Berkeley Solar Group (BSG) Calpas 3.0 simulation program. Preliminary results indicated that a reasonably large amount of internal capacitance would be desirable even in the mild Transition Climatic Zone (between the ocean and coastal mountains.) Additional parametric runs indicated that a bermed, north wall could be effective, and that Trombe walls occupying wall area roughly equal to 25% of the floor area to be tempered could significantly level out internal temperature swings. Because of reasonably large direct-gain aperture (500 $ft^2$) venting appeared to always be useful. In response to this, a dedicated ventilator was designed for a high point above a flight of stairs with exhaust to the lea of the wind.

Final analysis showed that 52MMBtu/yr would be vented with a design heating load of 6.7 MMBtu/yr. Although additional mass could be used to store "wasted" heat, the predicted design load was already so low (92% passive) that no more effort appeared to be needed. However, we were concerned with the performance of the Trombe walls, since various programmatic changes had reduced their area. The ultimate design included 64 $ft^2$ vented and 220 $ft^2$ unvented Trombe walls, or 11% of the living area. The decision was made to improve their performance by adding a selective surface foil to drive up the wall temperature and act as an effective night insulator. (An R-9 value has been suggested by the manufacturer, Berry Solar Products). This Strategy has proven to be very successful as minimum sensible air temperatures measured next to the wall (mid-February, 1983) have not fallen below 71°F; simultaneous house return air and outside air temperatures were 68°F and 45°F respectively. This performance has resulted in a definite comfort increase over standard design structures, sinced no forced-air auxiliary heating has been required for morning warm-up through-out the winter heating season.

The natural ventilating scheme follows traditional guidelines for low inlet/high outlet. Internal traffic flow was arranged to also reduce the cross-sectional area of the flow pattern by approximately 75% to increase air velocity through the heat generating kitchen area. This technique has proved to be quite successful for warm weather comfort.



**PLAN**

The construction process was marred by different levels of workman experience and their expectations of assembly and detailing. Many unnecessary modifications could have been avoided if construction documents had been better understood as well as more understandable; it's probably unreasonable to expect "production" skills to coincide with "custom" detailing - especially if associated with "solar"!

It should also be noted that from a designer's standpoint, extensive documentation projecting thermal performance still has not resulted in our being able to significantly reduce costs for installed back-up, as local building departments have required full systems for this and other houses.

## TIME-OF-USE (TOU) ELECTRIC RATE STRCUTURE

The California Public Utilities Commission (CPUC) has determined that experimental work regarding TOU residential rates should be continued to better evaluate benefits to both consumers and utilities. Basically, these rates offer cost incentives and penalties to encourage both minimum energy use and a shift in time of demand. The local utility (SDG&E) began offering this rate structure last year, and to date, the Ottinger residence is the only operating service in the area to use the largest rate differential (DATOU), which requires various passive features to be included in the applicant's residence.

Within "lifeline" allowances, the DATOU rate schedule basically allows 60% savings over conventional all-electric rates for off-peak consumption, but penalizes on-peak consumption by 200% (See Fig. 1). Through a combination of various conservation features, and specifically the contribution from the Trombe walls, the Ottinger's have never used more that 100 kW on-peak/month, and have exceeded their life-line allowance only twice (and then in the first three months of occupancy). The literal "bottom-line" of Fig. 2 shows their average utility bill to be near $35/month, where the average bills for other new construction in the area run between $150-200/month.

In a previous paper, by Rob Taylor, P.E., of SDG&E ("Passive Solar Implications for Gas and Electric Utilities,"7th National Passive Conference) results from the Pala Passive Project (located just a few miles easterly of the Ottinger's) led to a conclusion that passive buildings generally do not benefit the utility from a load management standpoint except indirectly through conservation. Their experience with a Trombe wall test building, however, identified this one design strategy as remaining most constant in temperature of all tested. Further, it averaged 68°F with amplitude shifts of 6-7°F. Hence, with no real peak space conditioning demand, load management would benefit.

The data shown in Fig. 3 show, for five days in February, house return air averaging about 75°F , with a temperature range of 12-15°F.

UTILITY RATE AND BILL HISTORY FOR OTTINGER SOLAR HOUSE

| LINE ITEM | RATE HISTORY COMPARATIVE ANALYSIS DATOU vs OR | | | | |
|---|---|---|---|---|---|
| Rate Effective 5/10/82 | Domestic Assist Time of Use (DATOU) Peak = 11:00 A.M. - 8:00 P.M. M-F | | Domestic Residential (DR) (conventional all electric residential) | % Difference DATOU/DR | |
| 1. Customer Charge | $2.20 per month | | same | 0 | |
| 2. State Surcharge | $.00020/KWHR | | same | 0 | |
| 3. Lifeline Allowance | 490 KWHR 5/1 - 10/31<br>1040 KWHR 11/1 - 4/30 | | same | 0 | |
| 4. Below Lifeline Rate | OFF PEAK<br>$.05532/KWHR | ON PEAK<br>$.17858/KWHR | $.08990/KWHR | OFF PEAK<br>59 | ON PEAK<br>198.6 |
| 5. Above Lifeline Rate | $.08975/KWHR | $.21513/KWHR | $.12645/KWHR | 71 | 170.1 |
| Rate Effective 1/1/83 | | | | | |
| Items 1, 2 & 3 | No change from 5/10/82 except off peak hours reduced by disallowing holidays occuring on a Saturday from being credited on Friday usage. | | | | |
| 4. Below Lifeline Rate | OFF PEAK<br>$.06000/KWHR | ON PEAK<br>$.20474/KWHR | $.10258/KWHR | OFF PEAK<br>58.5 | ON PEAK<br>200 |
| 5. Above Lifeline Rate | $.09655/KWHR | $.24129/KWHR | $.13913/KWHR | 69.4 | 173.4 |
| Rate Effective 2/8/83 | | | | | |
| Items 1, 2 & 3 | No change from 5/10/82. | | | | |
| 4. Below Lifeline Rate | OFF PEAK<br>$.06005/KWHR<br>(+12.9%) | ON PEAK<br>$.20479/KWHR<br>(+14.7%) | $.10263/KWHR<br>(+14.2%) | OFF PEAK<br>58.5 | ON PEAK<br>199.5 |
| 5. Above Lifeline Rate | $.9660/KWHR<br>(+7.6%) | $.24134/KWHR<br>(+12.2%) | $.13918/KWHR<br>(+10.1%) | 69.4 | 173.4 |
| (+ %-2/8/83 5/10/82) | | | | | |

Fig. 1.

Close review of the data reveals two fairly compelling observations:

1. The lightweight sunspace performs much like a conventional structure where the rate of temperature change approximates ambient conditions. However, the mass of the floor and vented Trombes below the floor maintain indoor temperatures 15-20°F. above ambient conditions.
2. House air temperature falls at virtually the same rate as the Trombe walls, with minimum temperatures shifted noticeably forward in time, while never falling below the comfort zone.

## CONCLUSION

We believe that the Ottinger's low utility bills are due to a well tempered envelope and Trombe wall contributions that virtually eliminate on-peak heating for their all-electric home. Most power use is for appliances and pumping for DHW and spa use. Remaining power use falls largely within off-peak lifeline allowance (only 17% during on-peak hours).

The demand reduction for their 2500SF is equal to a single-user peak power savings of 15kW. However, for a large number of homes, a simultaneous coincidence of savings might be close to a factor of 0.4, for average potential savings of 6kW/house. With respect to utility load management, for a planned development of 3000 houses, this translates into 18MMw peak power reduction, or 2% of the 900MMw San Onofre Nuclear Unit 3. This savings is only for part of a day during the heating season, but it appears that Trombe wall designs in a mild climate can offer significant load management benefits, and merits further research into strategies for linkage with TOU rates to maximize benefits to utility and customer alike, especially where utility rates are high.


## ACKNOWLEDGEMENTS

The Design Team included Energy Management Consultants Inc.(Solar), Robert G. Scott, P.E. (Mechanical) and Larry Horsman, P.E.(Structure).

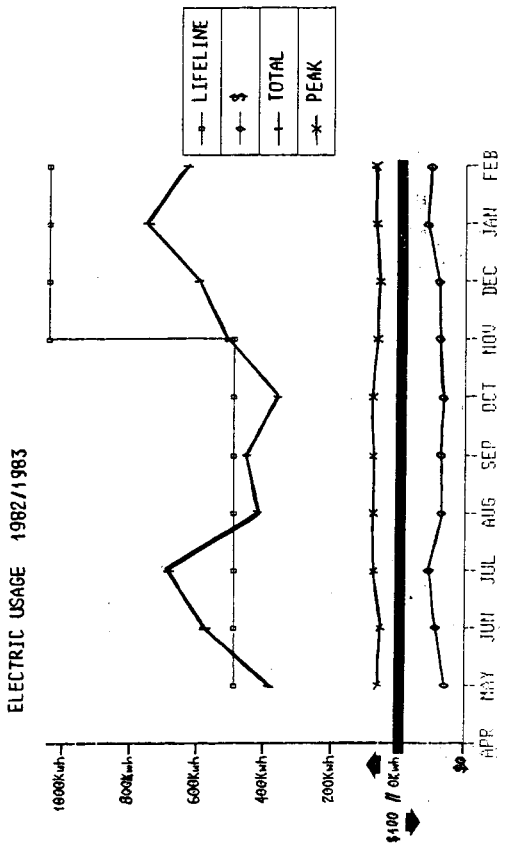




Fig. 2.

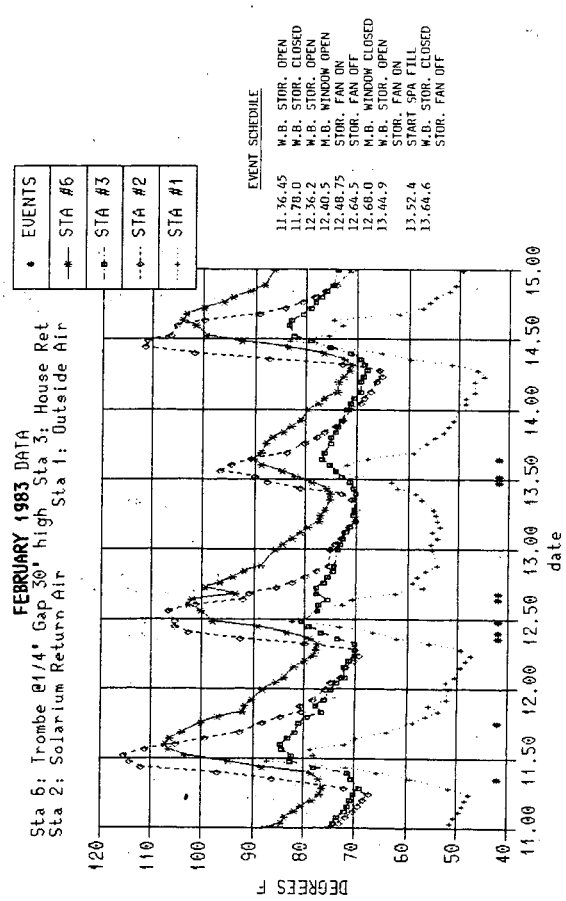



Fig. 3.

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# CLASS C SURVEY DATA VERSUS COMPUTER PREDICTIONS - A COMPARISON BETWEEN FIELD DATA AND SIMULATIONS

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## ABSTRACT

Following the Solar Energy Research Institute's (SERI) Class C survey strategy sixty-three passive solar houses located throughout California were visited and detailed information collected from the homeowners including architectural plans, management procedures, major energy uses, photographs, and at least one year of utility billing data. Using these data, inputs for DOE 2.1 and CALPAS 3.01 computer codes were prepared, and the predicted monthly energy use was obtained. The energy use predicted by the codes was compared to the energy use estimated from the billing data. As measure of performance the Building Performance Index (BPI) for each house was calculated using the billing data and the simulated performance.

Both computer codes do quite well in predicting the BPI calculated from the billing data considering the difficulty of estimating the energy delivered and often having different weather in the two methods.

## 1. INTRODUCTION

Because of the difficulty and cost of collecting and documenting performance data on residential buildings, researchers and policy makers in this area have had to rely on computer codes such as NBSLD, DOE, BLAST, CALPAS and others to provide performance predictions and design guidelines. It has been realized from the start that these computer codes needed to be carefully checked and evaluated against actual field data, however suprisingly little work has been done in this area. And so the question is continually raised, how good a predictor are the various computer codes that are now being used?

To address this question sixty-three passive solar houses were visited and several hours spent with the homeowners obtaining building and appliance specifications, management procedures, architectural plans, photographs and at least one year of utility billing data. With this information a thermal performance parameter was calculated for a heating season for each of the houses. In addition the information collected for each house was used to develop the inputs for the CALPAS 3.01 and DOE 2.1 computer codes and then run to predict the same performance parameter. The performance parameter chosen was the Building Performance Index (BPI) which is usually defined as the energy used for space heating per square foot of floor area per heating degree day ($BTU/ft^2/HDD$). The division by floor area and degree day partially normalizes the heating energy by removing the effects of house size and weather. By comparing the value of the BPI calculated from the billing and survey data to that predicted by the two computer codes, some measure of the predicting power of the codes is achieved.

## 2. DATA COLLECTION

There were four steps involved in collecting and processing the survey and billing data.

1) Site Selection

Geographic location and solar system type were two of the main criteria for inclusion in the study. To select the Class C sites a telephone survey of more than 300 solar houses located throughout California was conducted. On the basis of this preliminary survey and the homeowner willingness sites were chosen for the survey. Over 80% of the houses surveyed by telephone used some wood for backup heating. The use of wood introduces a large uncertainty in the energy used, however it was necessary to include many of these sites in the sample.

2) Site Visits

In order to collect the needed data at each site it generally took three to four hours working with the homeowner. The survey forms used were developed by SERI(1) and consisted of two parts, one dealing only with thermal performance and the second with marketing information. In order to improve

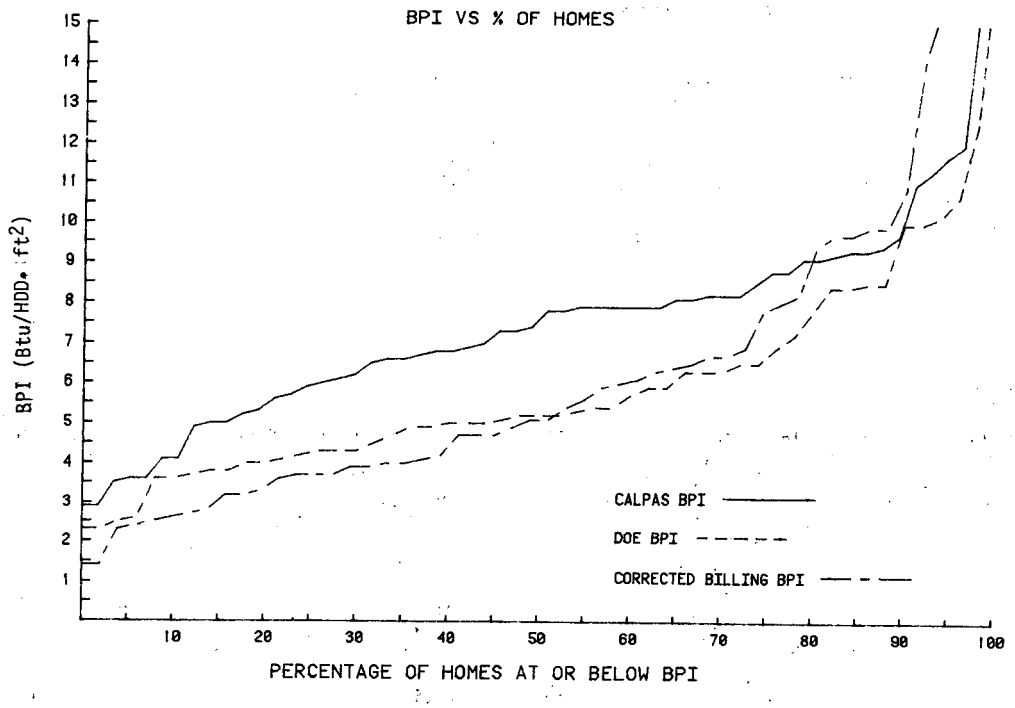



Fig. 1. BPI vs percentage of houses at or below the corresponding BPI for both computer simulations and the billing data.

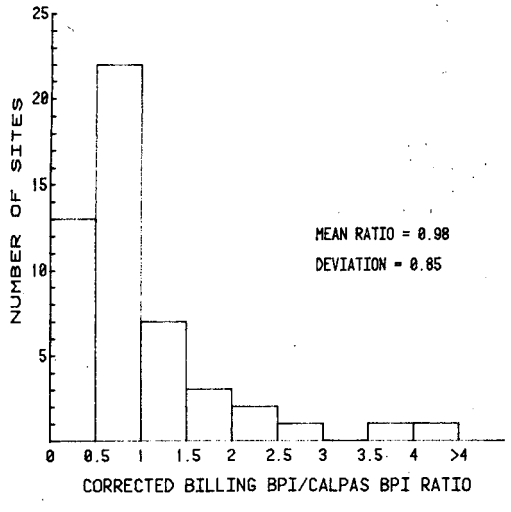



Fig. 2. Histogram of number of sites for a given billing to CALPAS 3.01 ratio.

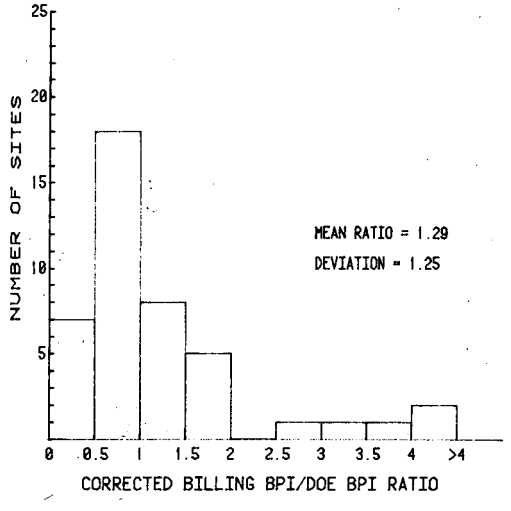



Fig. 3. Histogram of number of sites for a given billing to DOE 2.1 BPI ratio.

gain and required no special consideration, but others such as Trombe walls took extra effort to develop inputs. CALPAS 3.01 has specific commands for Trombe walls, greenhouses, and rockbeds, while DOE 2.1 does not. In general, modeling a house with CALPAS 3.01 was a good deal easier than with DOE 2.1.

## 5. RESULTS

Of the 63 sites originally surveyed the data for 57 were judged to be complete enough to develop the inputs to the two codes and to calculate the energy delivered ($Q_{aux}$ + $Q_{int}$). Only 51 sites had complete enough data from utility billing, delivered energy and weather to calculate BPI values for the corrected billing data. Listed in Table 1 are the BPI values estimated from the billing data and taken from the CALPAS 3.01 and DOE 2.1 computer simulations. This same data is plotted in Fig. 1 as the percentage of houses with BPI values at or below a given BPI. Given the quality of the data the agreement of the three plots is quite good with DOE 2.1 and billing data agreeing very well and the CALPAS 3.01 values of BPI tending to be higher. Both computer codes predict few houses to have a corrected BPI greater than 13 (3% for DOE 2.1, 4% for CALPAS 3.01), while the billing data results indicate 12% of the houses have a BPI greater than 13. A possible cause of this discrepancy is that some houses may be poorly managed and did not perform up to their theoretical potential. Since all houses were simulated as if they were managed well, the houses that weren't would have larger BPI values than predicted. Ignoring those houses with BPI values greater than 18.0, larger than the largest BPI of either computer code, the mean corrected BPI for billing data of the remaining 50 houses is 6.16, quite close to the mean corrected BPI of 6.04 for DOE 2.1 and reasonably close to the CALPAS 3.01

TABLE 1. Available BPI Values for Corrected Billing Data, CALPAS 3.01, and DOE 2.1

| House | BPI | | | House | BPI | | |
|---|---|---|---|---|---|---|---|
| | Corrected Billing | CALPAS 3.01 | DOE 2.1 | | Corrected Billing | CALPAS 3.01 | DOE 2.1 |
| 1 | 9.73 | 9.10 | - | 33 | 9.85 | 8.16 | 6.55 |
| 2 | 6.65 | 9.30 | - | 34 | 2.58 | 2.87 | 2.53 |
| 3 | 4.23 | 7.78 | 4.51 | 35 | 7.95 | 7.39 | 6.31 |
| 4 | 3.91 | 5.02 | 4.28 | 36 | 6.39 | - | - |
| 5 | 9.36 | 11.0 | 8.36 | 37 | 4.08 | 3.55 | 2.59 |
| 6 | 1.42 | 6.10 | 4.95 | 38 | 5.14 | 11.3 | 8.46 |
| 7 | 4.69 | 9.67 | - | 39 | 3.20 | 6.57 | 4.74 |
| 8 | - | 7.87 | 5.00 | 40 | 15.6 | 3.52 | 3.58 |
| 9 | 6.28 | 6.76 | - | 41 | 5.60 | 7.93 | - |
| 10 | 6.49 | 5.19 | 3.96 | 42 | 3.30 | 8.75 | 4.16 |
| 11 | 2.50 | 6.73 | 4.34 | 43 | 5.90 | 5.95 | 4.29 |
| 12 | 10.9 | 7.06 | - | 44 | 4.68 | 11.7 | 10.0 |
| 13 | 5.06 | 8.14 | 8.52 | 45 | 9.94 | 8.04 | 7.17 |
| 14 | 3.71 | 6.64 | 5.22 | 46 | - | - | - |
| 15 | 3.59 | 6.79 | 5.23 | 47 | - | - | - |
| 16 | - | 6.91 | 4.96 | 48 | 3.86 | 7.33 | 6.35 |
| 17 | - | 5.64 | 4.88 | 49 | 3.74 | 8.24 | 7.75 |
| 18 | 15.8 | 7.86 | 6.28 | 50 | 4.69 | 8.16 | 5.86 |
| 19 | 2.72 | 7.89 | 5.46 | 51 | 9.71 | 9.22 | 10.0 |
| 20 | 4.02 | 5.97 | 5.14 | 52 | - | 7.27 | 5.87 |
| 21 | 2.75 | 7.89 | 8.37 | 53 | - | - | - |
| 22 | 6.68 | 8.54 | 5.38 | 54 | 22.5 | 8.84 | 6.50 |
| 23 | 4.01 | 4.07 | 3.57 | 55 | 5.44 | 9.34 | 6.78 |
| 24 | 14.2 | 5.75 | 3.97 | 56 | 6.12 | 16.0 | 12.5 |
| 25 | - | - | - | 57 | 6.01 | 6.54 | 5.04 |
| 26 | 4.87 | 7.87 | 5.66 | 58 | 8.18 | 12.0 | 10.2 |
| 27 | - | 5.34 | 3.84 | 59 | 3.59 | 6.22 | - |
| 28 | - | 16.1 | 17.7 | 60 | 7.81 | 4.90 | 4.15 |
| 29 | 3.20 | 4.98 | 3.71 | 61 | 16.1 | 4.08 | 2.28 |
| 30 | - | 9.36 | 10.7 | 62 | - | - | - |
| 31 | 2.30 | 7.84 | 5.32 | 63 | 2.41 | 9.06 | 5.19 |
| 32 | 6.88 | 3.59 | 3.77 | | | | |

accuracy, architectural plans were obtained and photographs taken.

3) Billing Data

Using a release form signed by the homeowner, monthly billing data for one year were obtained from the utility companies. Using the billing data along with information about the location of major appliances and the water heating system, estimation of the energy delivered to the house was made. At many of the sites some wood was burned, and so a special effort was made to determine the amount of wood used and to classify the wood stove and the way it was used.

4) Weather

Data from over 450 weather stations throughout California are available from the National Oceanic and Atmospheric Administration (NOAA). Using the data from a nearby weather station the number of heating degree days (HDD) was determined for the same period as the billing data for each site.

The weather data used with the two computer codes, DOE 2.1 and CALPAS 3.01, are the standard weather tapes which were developed for each of the sixteen California Thermal Zones (CTZ). These zones are quite large and so the local weather at a particular site might be quite different from the CTZ weather. This discrepancy in weather in seven cases for DOE 2.1 added significantly to the uncertainty of the comparison, and so these sites were not included in the results presented below. This problem of weather tapes being unrepresentative of actual climates in the other cases is partially removed by using the BPI since the number of HDD is proportional to the heating energy used.

## 3. ANALYSIS OF SURVEY DATA

In the process of calculating the BPI from the surveys and the billing data a number of difficulties were encountered. First, the energy used by the water heaters was estimated and subtracted from the total purchased energy. The fact that many of these sites had solar water heaters made this estimation even more difficult than it usually is. Second the estimates of the energy delivered by wood stoves was fraught with uncertainty in many cases. Third the number of HDD that were accumulated at a nearby weather station were often quite different than those of the appropriate CTZ used in simulation. And fourth the duration of the heating season had to be defined separately for each site since there are widely different climates. The heating season was defined as any month with at least 200 HDD for the period of the billing data. Given the above difficulties the appropriate energy to use in the numerator of the BPI was chosen carefully to reflect both the quality of the data available and the intended use to be made of the index. For billing data a BPI based on total purchased energy is clearly the easiest to calculate but is not necessarily an accurate indicator of heating performance. For computer simulations, however, a BPI based on delivered energy ($Q_{aux} + Q_{int}$) is both the easiest to obtain and is also the most direct measure of heating performance. The BPI values based on both approaches are defined as follows:

Uncorrected BPI = Purchased energy/HDD/floor area

Corrected BPI = $(Q_{aux} + Q_{int})$/HDD/floor area

Here the purchased energy is taken directly from the billing data and no corrections are made for efficiency. And $Q_{aux} + Q_{int}$ was estimated from the billing data using the following:

$Q_{aux} + Q_{int}$ = (purchased gas energy - energy used for water heating)*efficiency + (purchased electric energy - electric energy for water heating - appliance outside living area)*efficiency + (wood energy)*efficiency

The wood use efficiency was taken to be 50% for wood stoves and 5% for fireplaces. The purchased DHW energy which does not enter the living space was estimated on a case-by-case basis using the location of the water heater, the form of energy used to heat water, the ground water temperature, the thermostat setting of the water heater, thermal efficiency and estimated hot water consumption. Efficiency of electrical energy into the living space was also estimated on an individual basis. It ranged from 70% to 80% depending on several factors, such as type of cooking energy, location of dryer, and auxiliary system duct work. In this paper only the results of the corrected BPI values are presented. A more detailed discussion is available in the technical report submitted to the California Energy Commission on this work(2).

## 4. SIMULATION

Using the building plans and the Class C survey data the inputs for DOE 2.1 and CALPAS 3.01 computer codes were developed. Inputs are divided into three categories: (i) house construction details, (ii) mechanical heating and cooling systems, and (iii) operating strategies. The heating setpoint in the models was taken to be 65°F and the cooling setpoint 80°F. Venting was used for cooling whenever the exterior temperature allowed and it was sufficient to cool the house. Most houses were direct

TABLE 2. Mean, Standard Deviation and Extremes of BPI

| | $\bar{x}$ | $\sigma$ | Smallest | Largest |
|---|---|---|---|---|
| DOE 2.1 | 6.04 | 2.79 | 2.28 | 17.7 |
| CALPAS 3.01 | 7.57 | 2.61 | 2.87 | 16.1 |
| BILLING DATA | 6.48 | 4.23 | 1.42 | 22.5 |

value of 7.57. Given in Table 2 are the mean, standard deviation and extremes for all cases with calculated BPI values.

Another comparison between DOE 2.1 and CALPAS 3.01 and the billing data is to take the ratio (billing data BPI/simulation BPI) for each house. The results are given in Fig. 2 and Fig. 3. Unlike the graphs of Fig. 1 where house identities are lost this compares the simulation results to the billing data results for the same house. With these plots the systematics of the comparisons can also be seen. If the most extreme 5% of the data is disregarded the DOE 2.1 ratios seem to be relatively close to unity while those for CALPAS 3.01 are slightly higher.

The BPI calculated from the billing data is plotted in Figs. 4a and 4b versus the corresponding values determined by simulation. The houses are coded in these plots according to how well the auxiliary energy used is known. The Xs in Figs. 4a-b are data from eleven SERI Class B sites which were instrumented and the energy delivered measured relatively accurately. The *s are houses using electricity or gas for heating and the energy considered to be known next best. And finally the os are for houses using some wood or propane energy for heating and thought to be least accurate. The scatter in the plots in some ways is the opposite to what was expected. the wood and propane sites have good agreement while the Class B and electricity and gas sites have the most scatter. This indicates that the Class B data which is much more costly to collect may not provide a significant improvement in accuracy.

## 6. CONCLUSION

From the limited sample of data available in this study it appears that the Class C survey data appears reasonably well with the simulation predictions. Specifically the DOE 2.1 comes somewhat closer to predicting the mean BPI than does CALPAS 3.01, but given the uncertainty in the survey data and the weather differences in the two calculations the agreement is as good as can be expected. The mean value for the BPI for the 51 houses of 6.48 Btu/HDD • $ft^2$ is probably statistically significant and a fair measure of the performance of solar houses in California. Obviously the data base needs to be extended and improved by eliminating sites with wood stoves. With more data the validity of the two codes can be tested further.

## 7. REFERENCES

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(2) Mahajan, S., Newcomb, C., Shea, M., and Mort, D. Performance of Passive Solar and Energy Conserving Houses in California. California Energy Commission report, January, 1983.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

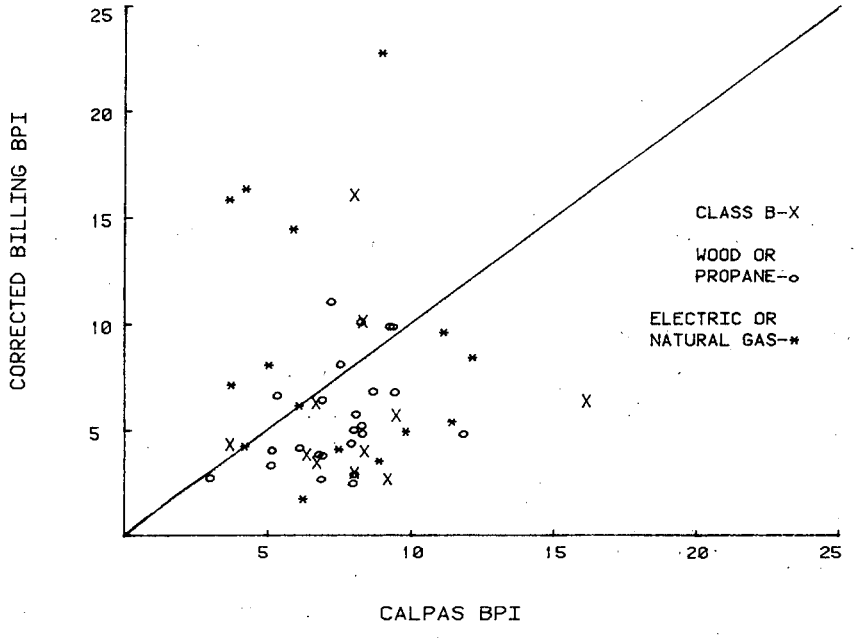



Fig. 4a. Scatter plot of corrected billing BPI vs. CALPAS 3.01 BPI presenting type of primary space heating for the site.

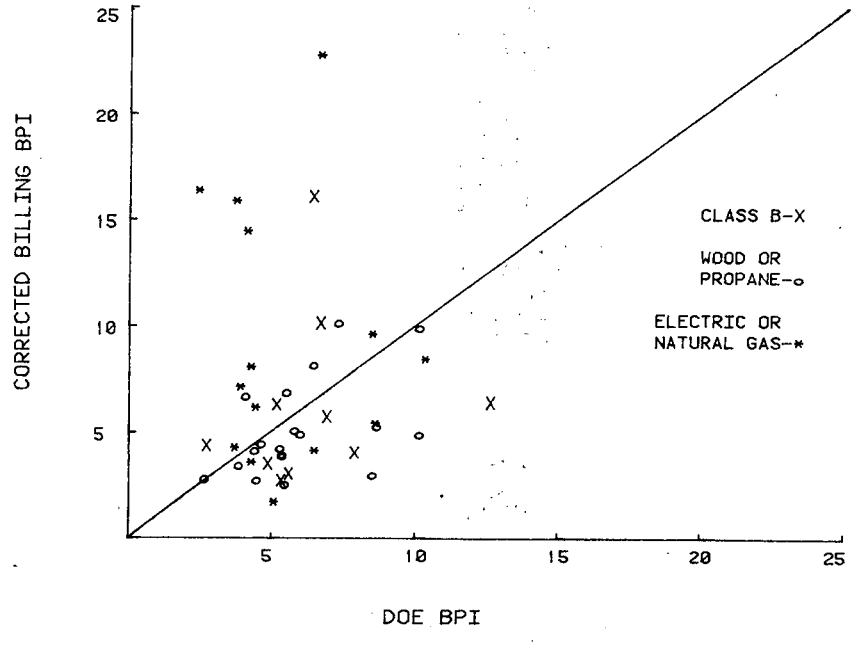



Fig. 4b. Scatter plot of corrected billing BPI vs. DOE 2.1 BPI presenting type of primary space heating for the site.

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# GROUND TEMPERATURE PROFILES FOR SELECTED NEW MEXICO LOCATIONS

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## ABSTRACT

Earth-sheltering techniques can provide considerable savings in the energy used for the heating and cooling of buildings. These savings are due to the reduction in heat losses from earth-sheltered buildings in winter and to the reduction in heat gains to buildings in summer. To evaluate the potential thermal benefits due to earth sheltering, information about the variation of earth temperatures with depth (below the surface) and with the time of year is required for the proposed building location. Information of this nature is not currently available for locations in New Mexico.

In this paper, an existing mathematical model for ground temperatures (as discussed by Labs (1, 2) and others) is used to generate predicted ground temperature profiles for selected New Mexico locations. Information on local temperatures (from existing long-term weather data) and local soil conditions is used in the model to predict ground temperatures as a function of depth and time of year. Predicted ground temperature profiles are compared with the few ground temperature measurements that are available.

## 1. INTRODUCTION

The potential benefits of using earth-sheltering techniques in the design and construction of buildings are many (3). Advantages often listed include design aesthetics, potential land-use benefits, environmental benefits, acoustical isolation and reduced maintenance. Earth-sheltered buildings often have increased resistance to the effects of natural and man-made disasters (fires, earthquakes, storms and tornadoes, and nuclear attack and fallout).

While all these benefits can be significant, the decision to use earth-sheltering techniques often stems from the considerable savings which can be achieved in the energy used to heat and cool the building. Earth-sheltering can significantly reduce the wintertime heat loss from a building and the summertime heat gain. Further reductions in the costs of heating and cooling can be achieved by integrating solar heating and cooling systems into the design and construction of earth-sheltered buildings. Estimates of the heating loads of earth-sheltered passive solar houses predict that most (and sometimes all) of their heating requirements can be provided by the solar/earth sheltering combination. Similar estimates show that equivalent above grade houses can have summertime cooling loads which are up to eight times greater than an earth sheltered house (4).

In order to estimate the thermal benefits of earth-sheltering, it is necessary to know the variation in earth temperature with depth and time of year for the location in question. This information can also be used to make decisions about the optimum placement and value of insulation for best year-round energy performance and comfort. Detailed information like this is not available for New Mexico locations. Since New Mexico has widely varying local climates (from about 2,500 to 9,700 heating degree F days, and 0 to 2,000 cooling degree F days) (5), information on the ground temperature profiles for various locations in the state would be useful to designers and builders.

## 2. PREDICTION OF EARTH TEMPERATURES

The variation of ground temperature with time of year and depth below the surface can be described by the following expression:

$$T_{(x,t)} = T_m - A_s e^{-x\left(\frac{\pi}{365\alpha}\right)^{\frac{1}{2}}} \cos(\beta) \qquad [1]$$

where:

$T_{(x,t)}$ = temperature at depth x at time t

$T_m$ = mean annual earth temperature

$A_s$ = amplitude of surface temperature wave

$x$ = depth below surface

$\alpha$ = thermal diffusivity of soil

$t$ = time of year

$t_o$ = a phase constant

$\beta = \frac{2\pi}{365}\left(t - t_o - \frac{x}{2}\left(\frac{365}{\pi\alpha}\right)^{\frac{1}{2}}\right)$

T and A are usually expressed in degrees F, x in feet, $\alpha$ in square feet per day, and t and $t_o$ in days (where t = o at the beginning of the calendar year).

In order to use equation (1) to predict earth temperatures T for various depths x, values of $T_m$, $A_s$, $\alpha$, and $t_o$ must be assumed for the location of interest. Typical values for these quantities have been discussed in detail elsewhere (1, 6) and the main salient features are briefly described here. $T_m$ can be assumed to be equal to local well-water temperatures, provided the wells are not too deep (less than about 100 feet) and are not significantly affected by geothermal activity in the area. Alternatively, $T_m$ can be set 2 or 3 degrees F above the local mean annual air temperature. Analysis by Kusuda and Achenbach (7) has shown that $A_s$ can be taken as equal to (or slightly higher than) the local annual air temperature amplitude. The thermal diffusivity $\alpha$ of the soil depends on the type of soil and on its moisture content, but typically ranges between 0.26 to 0.60 square feet per day for light dry soil to heavy damp soil (ASHRAE 1978 Applications Handbook). Labs (6) has pointed out that the analysis of Kusuda and Achenbach (7) gives values of 35± 10 days for $t_o$.

## 3. ASSUMPTIONS FOR NEW MEXICO

Information on well-water temperatures for various New Mexico locations is limited compared with air temperature data. For the purposes of this study, $T_m$ has been set 2 degrees F above the local mean annual air temperature. The only experimental data which could be located for comparison was obtained from observations of earth temperatures in Las Cruces (for depths up to 10 feet) during 1979 (8). These yield an average earth temperature of 62.0 degrees F; average air temperature in Las Cruces for 1979 was 59.6 degrees F (9). These figures are consistent with the guidelines discussed above.

Observations of soil temperatures at a depth of 4 inches are available (9) for selected New Mexico locations. Data for the past three years has been analyzed in order to obtain estimates of $A_s$ and $t_o$. Least squares analysis was performed on average monthly temperatures to obtain the average minimum surface earth temperatures $T_{min}$ and the calendar day for these minima. The latter number equals the phase constant $t_o$, since $t_o$ is measured in days from the beginning of the calendar year. This data is presented in table 1, along with the amplitude of the surface earth temperature $A_s$, which was calculated as the difference between $T_{min}$ and the annual average surface earth temperature. Table 2 compares the amplitudes of the surface earth temperatures $A_s$ with the amplitudes of the air temperatures $A_A$ for the same locations; good agreement is obtained between these two quantities. From the data presented in tables 1 and 2, $t_o$ and $A_s$ have average values of about 40 days and 24°F respectively. This agrees well with the guidelines given by Labs (1). Also, $A_s$ is higher than $A_A$ by about 2°F on average, which agrees with the analysis of Kusuda and Achenbach (7).

Attempts to obtain direct information on the thermal diffusivity of soil for different New Mexico locations have been unsuccessful to date. Fortunately, an average constant value is usually sufficiently accurate for prediction purposes (6). For the purposes of this study, values of $\alpha$ between 0.26 and 0.60 square feet per day were estimated based on available information on the soil type and local average precipitation.

## 4. PREDICTIONS FOR NEW MEXICO

Equation (1) was used to predict earth temperatures as a function of time of year and depth below the surface for various New Mexico locations including Las Cruces. The predicted temperature profiles for Las Cruces were compared with measured temperatures for depths of 6 and 10 feet that were made during 1979 (8). A best fit between predicted and measured data were obtained for values of $t_o$ = 2 days, $\alpha$ = 0.5 square feet per day, $A_s$ = 19°F, and $T_m$ = 64°F rather than the average values of 40, 0.3, 24, and 62, respectively which were used to generate the original predicted curves (see figure 1). Labs (2) has drawn attention to the necessity for curve-fitting of this nature; in particular, a decrease in the phase constant $t_o$ by 2 to 3 weeks is sometimes necessary to obtain agreement between the theoretical predictions and actual observed temperature profiles. The value of $t_o$ = 2 days which fits the experimental data seems abnormally low, and the reason for this is not understood at this stage. Further comparisons between experimental and theoretical earth temperature profiles are needed to shed more light on these results.

TABLE 1.
Values of $T_{min}$ (°F), $t_o$ (days), and $A_s$ (°F) for Selected Locations

| Location | 1980 - 1981 | | | 1981 - 1982 | | | 1982 - 1983 | | |
|---|---|---|---|---|---|---|---|---|---|
| | $T_{min}$ | $t_o$ | $A_s$ | $T_{min}$ | $T_o$ | $A_s$ | $T_{min}$ | $t_o$ | $A_s$ |
| Artesia | 45.5 | 34 | 19.2 | 50.0 | 43 | * | 43.8 | 38 | 24.6 |
| Clovis | 36.3 | 43 | 18.4 | (23.5) | (52) | (29.3) | 37.9 | 45 | 20.5 |
| Clovis 13N | 37.3 | 39 | 19.9 | 35.7 | 47 | 21.6 | 30.9 | 44 | 24.1 |
| Farmington | 42.1 | 43 | 18.9 | 32.1 | 46 | (28.9) | 35.7 | 41 | 18.1 |
| Florida | 45.0 | 40 | 20.5 | 43.2 | 42 | 22.3 | * | * | * |
| Las Cruces | 45.9 | 34 | 21.5 | 45.7 | 39 | 22.5 | 44.7 | 38 | 22.8 |
| Los Lunas | 39.4 | 40 | 20.9 | 41.1 | 38 | 19.2 | 37.4 | 39 | 23.5 |
| Tucumcari | 47.8 | 37 | 17.5 | 41.7 | 44 | 23.6 | 36.5 | 43 | 26.7 |

* insufficient data available
( ) data appears to be questionable

TABLE 2.
A Comparison of $A_s$ and $A_A$ (°F) for Selected Locations

| Location | 1980 - 1981 | | 1981 - 1982 | | 1982 - 1983 | |
|---|---|---|---|---|---|---|
| | $A_s$ | $A_A$ | $A_s$ | $A_A$ | $A_s$ | $A_A$ |
| Artesia | 19.2 | 19.1 | * | 20.0 | 24.6 | 22.2 |
| Clovis | 18.4 | 17.5 | (29.3) | 19.9 | 20.5 | 20.2 |
| Clovis 13N | 19.9 | 15.7 | 21.6 | 19.5 | 24.1 | 20.2 |
| Farmington | 18.9 | 17.7 | (28.9) | 22.7 | 18.1 | 19.6 |
| Florida | 20.5 | 18.1 | 22.3 | 18.1 | * | * |
| Las Cruces | 21.5 | 16.6 | 22.5 | 17.4 | 22.8 | 19.1 |
| Los Lunas | 20.9 | 18.3 | 19.2 | 19.3 | 23.5 | 20.3 |
| Tucumcari | 17.5 | 14.8 | 23.6 | 20.7 | 26.7 | 21.0 |

* insufficient data available
( ) data appears to be questionable

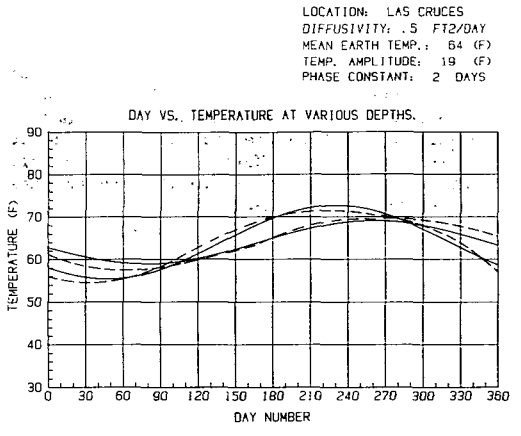



Fig. 1. Experimental and Theoretical Earth Temperature Profiles for Las Cruces. Solid Lines - theoretical; broken lines - experimental.

The predicted earth temperature profiles for various New Mexico locations have therefore been recalculated using input values which should provide more realistic predictions; in particular, a phase constant value $t_o$ = 20 days has been used. A sample set of profiles is shown in Figure 2. Similar figures are available for some 30 locations in the state (10), and predictions for other locations can be generated as required.

## 5. FUTURE WORK

Further comparisons between predicted and measured temperature profiles are planned for the future. Three thermocouple rakes (two in Las Cruces and one in the Alamogordo area) have recently been installed in order to obtain additional data for these comparisons. The predicted earth temperature profiles will be further refined as these data become available. Attempts will also be made to improve the theoretical model on which they are based.

An earth-sheltered passive solar house in the Alamogordo area is being monitored; this should provide data which can be used to relate undisturbed earth temperatures to those encountered around an earth-sheltered building. This information will be used

(together with the predicted earth temperature profiles) to draw up guidelines for the design and construction of passive solar earth-sheltered buildings in various New Mexico locations.

## 6. ACKNOWLEDGMENTS

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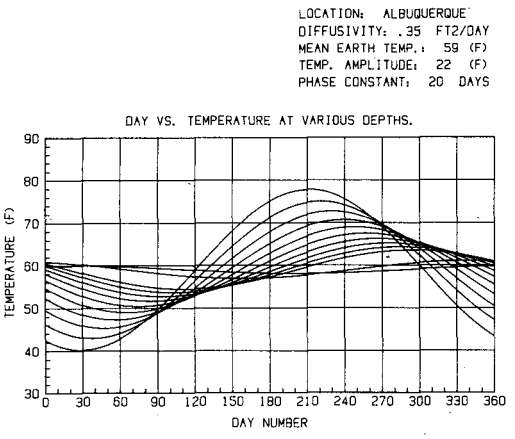



Fig. 2. Predicted Earth Temperature Profiles for Albuquerque at Depths x = Integral Values of 1 through 10, 15, and 20 feet.

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# MEASURED VERSUS SLR-PREDICTED PERFORMANCE OF A MONITORED DIRECT GAIN HOME

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## ABSTRACT

The purpose of this paper is to compare the actual energy usage of an occupied, newly constructed direct gain home with the original Volume II SLR predictions made during the building's design process and post-design Volume III predictions. The latter predictions have been made using the more appropriate correlations with both the original input data as well as data revised on the basis of observations and measurements resulting from five months of a Class B monitoring program. Both the predicted and measured results are presented. The key questions to be answered are: how good were the original predictions, how much better (or worse) are the predictions based upon the newer correlations and improved input data, and how can actual use of the predictive methodology provide better answers? Because detailed monitoring results are available, the sensitivity of the predicted results to a number of key parameters is analyzed and discussed. The parameters examined include: the setpoint temperature, the infiltration rate, the internal gains, and differences between the R-values of design-specified and as-built building components. Based on the results of this comparative study, recommendations are made for appropriate usage of the SLR design methodology, and needs for improvements in the methodology itself are also noted.

## 1. INTRODUCTION

The designer of a passive solar home needs an easy to use, reasonably valid method of analyzing and predicting its performance so that an optimum balance of solar and conservation features can be selected. A variety of methodologies are in use. The most widely known technique is the Solar Load Ratio method presented in Volumes II and III of the US DOE Passive Solar Design Handbook (1, 2). Emphasis is placed on predicting the average annual auxiliary heating energy consumption with an accuracy in the 10-15% range. This study focuses on how well the method works for one house which was designed for the Portland, Oregon, Solar Homebuilders Program sponsored by Western SUN and the Bonneville Power Administration (BPA). During the design phase, the performance of the building was optimized using the Volume II SLR method for detailed analysis (3). After the house was completed and occupied, its performance was monitored in detail as part of a Class B passive solar monitoring program sponsored by BPA (4). This study was initiated to make a detailed comparison of the predicted and the actual monitored performance of the house. In other words, after a designer has made his or her best guess using the SLR method, how closely will the actual performance correlate? It is expected that refinements in the SLR technique incorporated in Volume III would result in better predictions than using Volume II. The original as well as the as-built design parameters were used to make performance predictions in order to compare Volume II and Volume III predictions with the actual performance.

## 2. DESCRIPTION OF THE TEST HOUSE

The test house is located just outside of Portland, Oregon. In appearance it is a conventional one-story tract house with most of the glass moved to the south side. Its selling price is approximately $65,000. The house has 109.5 $m^2$ (1180 $ft^2$) of living floor space with three bedrooms, two bathrooms and an open kitchen, dining and living space. It uses typical wood frame construction with a full crawl space and 2x6 walls with insulating sheathing. It incorporates a direct gain passive solar system with 9.8 $m^2$ (105 $ft^2$) of south glass and 5.5 $m^2$ (59 $ft^2$) of non-south glass; a 0.10 m (4 in.) concrete slab provides a 1:2.8 ratio of south glass to mass area. All windows are wood frame with 0.025 m (0.5 inch) air gap double glazing without night insulation. Backup heating is provided by recessed electric wall heaters with separate controls in each room. Particular attention was given to insuring that the house would have a low infiltration rate by installing a skin of 6 mil polyethylene and sealing all electrical and plumbing penetrations, as well as

windows and doors, with foam.

## 3. MONITORING RESULTS

The Bonneville Power Administration made available data collected at the site using the SERI Class B passive solar monitoring methodology and equipment (4). The data were processed and reduced to show a breakdown of electricity use into the categories of space heating, water heating and lights & appliances. The various sources of space heating were then analyzed to give the relative contributions of the backup electric heat, lights & appliances & people, and passive solar. In addition, the average monthly indoor temperatures, monthly degree-days, and monthly vertical and horizontal insolation were obtained from the test data. Other BPA-generated data came from a one-time coheating test which determined a measured overall building heat loss coefficient and a blower door test to determine the natural infiltration rate (0.11 ach). At this writing, only the data for October through March of the 1982-83 heating season had been processed. The measured horizontal insolation for October was judged to be unreliable due to equipment problems, and so the performance for that month has not been analyzed. The monthly monitoring results are presented in Table 1. The BLC values were obtained from the coheating test with correction for the monthly average wind speed. The VS and DD values in parentheses are long-term average values taken from Volume III (2) for comparison. For November through March the measured vertical insolation was 20% higher than the long-term average, whereas the measured DD55 was 15% lower than the corresponding average.

The house was occupied by two adults who both work regular hours. The monthly average interior temperature is a UA-weighted average for the whole house that accounts for two unheated bedrooms and both daytime and nighttime setback. However, during any given month, the living space temperature was fairly stable and rarely changed more than about plus or minus 3°C (5°F) from the average. The five month average indoor temperature was 17.7°C (63.2°F). The fact that the indoor temperatures are relatively low is indicative of the occupants' work schedule and the use of setback; in addition it is partly due to the fact that good comfort can be achieved using a relatively lower air temperature in a tight, well-insulated house because of the decreased stratification and draftiness. The internal gains average for the five-month period is just slightly greater than the value assumed by Balcomb (1) of 20,000 Btu/hr/person. Note, however, the considerable month-to-month variation.

## 4. PERFORMANCE PREDICTION PROCEDURE

The performance of the house, as designed and analyzed (3) using Volume II prior to construction, was used as an initial base case. Measurements were then taken at the house and from plans to identify changes between the original design and the as-built and actually operated condition. The Volume II calculations were repeated one at a time with each of the changes to check the sensitivity of the auxiliary heating requirement to their variation. For comparison, the performance calculations were also repeated for the same base case and changes using Volume III (direct gain design type B1).

A new base case was then formulated which incorporated all of the as-built design changes together, and calculations were again made using both methods. Since the actual weather was milder and sunnier (see Table 1) than the long-term average values used in the Volume III methodology, it was necessary to do the calculations month by month using the actual monthly weather data in order to determine the influence of the non-standard weather. Thus, further computations using the new base case were made substituting the actual monitored data for each month's degree-days, solar radiation, and internal gains. The measured average indoor temperature for each month was treated as the set point. To determine what auxiliary energy use a designer might predict, the calculations were repeated using the same measured monthly weather data, but with the average measured temperature for the five month period as the set point temperature and the number of occupants (two) rather than the measured internal gains. In each of the above cases, the building load coefficient used was computed from standard UA values for the construction materials. Finally, the measured BLC value from the coheating test was included in a Volume III calculation using all measured data.

Comparisons were then made of the actual and predicted values of the auxiliary heating requirement for each type of calculation.

## 5. PREDICTION RESULTS AND DISCUSSION

Table 2 shows the auxiliary energy use results for the five month November through March period calculated using both Volume II and Volume III (monthly) SLR approaches. The initial base case result is what was predicted when the house design was originally optimized prior to construction. It assumed three occupants, a setpoint temperature of 17°C (62°F) that accounted for night setback, and a BLC of 4659 Btu/DD, based in part on an

assumed air change rate of 0.20 ach. The as-built house and occupancy turned out to be somewhat different, and Table 2 indicates the auxiliary energy use for the initial base case with each of a variety of different as-built and occupied characteristics. Also shown is the percentage change in auxiliary energy use that resulted when each change was accounted for (relative to the base case use). Finally, the base case was analyzed with all the design modifications incorporated (BLC = 4739 Btu/DD); this became the new base case for further calculations.

The initial base case result from Volume III is seen to be about 20% higher than that from Volume II; that is expected since the calculated solar input to the house is considerably lower using Volume III. Actual measurement of the glass aperture areas indicated that the south glass area should be reduced by 18% or 2.6 $m^2$ (28 $ft^2$), whereas the non-south glass area should increase by 31% or 1.6 $m^2$ (17 $ft^2$). The south glass change had a negligible influence on the auxiliary use prediction, as expected (5), whereas the non-south glass change had some effect. A hefty 45% reduction in infiltration (0.11 ach actual versus 0.20 ach assumed) resulted in a roughly 20% reduction in auxiliary heating requirements while using two occupants instead of three reduced the internal gains and caused a dramatic increase in predicted energy use. That is because a major fraction of the home's space heating needs are provided by internal gains. In addition, the performance is extremely sensitive to the assumed setback temperature. Increasing the average set temperature by only about 0.6°C (1°C) produced an 18% jump in required auxiliary energy use. This is probably one of the most sensitive parameters, and it is hard to know precisely during design. Finally, incorporating all the changes resulted in nearly a doubling in the auxiliary heating requirement. Given that an as-built house will always be somewhat different than what was designed on paper, that the actual natural infiltration rate is hard to estimate accurately, and that occupancy characteristics (internal gains and thermostat settings) are hard to pinpoint, it seems clear that the SLR methodology is best suited to examining the relative benefits of design strategies aimed at optimizing performance. It was never meant to be an exact predictor of auxiliary energy use, and it clearly should not be used for that purpose.

It is also important to note that the Volume III new base case prediction was 58% higher than the actual monitored energy usage. However, that result is not terribly meaningful because the actual weather was different from that used in the predictions. In order to compare predicted results with actual usage properly, it is necessary to make performance prediction calculations utilizing the actual weather conditions. Thus the new base case calculation was redone month-by-month, using the actual measured monthly solar and degree-day data as input data, along with the actual monthly internal gains and monthly thermostat temperatures. The result is shown in Table 3. Assuming the new base case BLC is reasonably close to correct, the SLR method (II or III) predictions agree quite closely with the monitoring result. Of course, a designer would not know the actual internal gains or interior temperatures, yet using the assumed number of occupants and average set point temperature with actual weather data also gives reasonable accuracy (16% difference).

During the monitoring program a coheating test was run to determine a measured BLC value. The value obtained was about 6200 Btu/DD, as compared with the new base case calculated value of 4739 Btu/DD. Using the wind-corrected measured BLC value for each month (see Table 1), along with the measured weather data, measured internal gains, and measured interior temperatures, resulted in an auxiliary energy use prediction that was 69% greater than the measured actual energy usage. At least the SLR prediction is conservative. That overprediction result suggests that either the BLC value determined from coheating is incorrect or the SLR methodology for direct gain houses does not properly predict the annual energy consumption. It could also be that the internal gains are not quite correct, or the measured average interior temperature used in the calculations is not appropriate, especially when some setback is utilized.

It is possible that the coheating result is incorrect since, strictly speaking, it provides a BLC value that would only exist under steady nighttime conditions. However, the stability of conditions required during a test is hard to achieve in long time constant houses. Because of the large difference between predicted and measured results, the coheating test results are being re-evaluated. It is hard to imagine why the calculated BLC value would be off by 31% in this case, especially with the infiltration rate measured.

Another possibility to explain the above noted discrepancy between results is that the present SLR methodology does not provide correct predictions. That is possible, although the excellent agreement found when using actual measured data as the input data (solar, DD, Qint, Tset) suggests otherwise. Most likely, reasonably accurate predictions cannot be achieved without modifying the methodology to incorporate more detailed information about the internal gains and the

set point temperature. Unfortunately, that information is seldom well known during the design stage.

## 6. CONCLUSIONS

For a single, occupied, direct gain house whose energy use characteristics were carefully monitored, a detailed comparison has been made between the measured auxiliary energy use and that predicted using both Volume II and Volume III versions of the Solar Load Ratio methodology. When using the actual measured month-by-month weather and solar conditions as data inputs, along with measured monthly internal gains and average interior temperatures, and a carefully calculated BLC value, the predictions agreed surprisingly closely with the monitored result. Repeating the calculations using a measured BLC value that was 31% greater than the calculated BLC value resulted in the predictions being 69% greater than the measured energy use. These results suggest that the measured BLC value may be in error; thus, it is being re-evaluated.

While this detailed look at one house has produced some interesting results, it would be of even more value if the results could be compared to those from similar studies of other passive solar homes. More similar studies would likely either confirm the results seen here or point out the anomalies of this particular case. Nonetheless, based on the results of this study, it would appear that the SLR methodology does in fact produce reasonably accurate predictions when the input conditions (solar, weather, internal gains, interior temperatures) are well known.

However, during design or even after construction has been completed, the necessary input data for the SLR methodology are not particularly well known. For example, it is hard, if not impossible, to estimate infiltration rates accurately, or internal gains, or an average set point temperature, or even to calculate a BLC value accurately. Yet the effect on the required energy use of even small variations in those parameters can be substantial. It would not be unusual to have a predicted result be 100% different from the actual auxiliary energy use. Thus the SLR method should not be used to make what would be thought of as reasonably exact predictions of auxiliary heating requirements for a given house and occupants. Rather, it should be used, as intended, as a sufficiently valid predictive tool for making design choices and optimizing the design of a building to achieve low auxiliary energy consumption. For that purpose, the SLR method's flexibility and ease and speed of use make it an extremely useful design tool. Its repeated use in microcomputer format is invaluable in helping to develop an intuitive feel for the influence of design variations on the auxiliary energy use.

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TABLE 1. MONITORING DATA AND RESULTS

| Month | Wind Speed (mph) | HS (Btu/ ft$^2$ day) | VS (Btu/ ft$^2$ day) | DD55 (°F day) | DD65 (°F day) | BLC (Btu/ DD) | Qint (Btu/ day) | $\bar{T}_i$ (°F) | Qaux (MMBtu/ month) |
|---|---|---|---|---|---|---|---|---|---|
| Oct | 4.7 | - | 1125 | 115 | 414 | 6115 | 35,400 | 64.9 | 0.12 |
| Nov | 6.1 | 638 | 996 (558) | 375 (295) | 675 (591) | 6163 | 35,600 | 61.6 | 0.91 |
| Dec | 6.5 | 425 | 773 (381) | 449 (444) | 759 (753) | 6187 | 21,700 | 59.7 | 1.5 |
| Jan | 5.9 | 307 | 361 (441) | 353 (524) | 663 (834) | 6163 | 45,900 | 62.6 | 1.9 |
| Feb | 7.2 | 560 | 642 (718) | 241 (343) | 517 (622) | 6211 | 63,571 | 64.2 | 0.74 |
| Mar | 6.5 | 954 | 813 (903) | 188 (293) | 483 (598) | 6187 | 59,354 | 66.1 | 0.39 |
| Avg/ Total (N-M) | | | 3585 (3001) | 1606 (1899) | 3097 (3398) | | 45,225 | 63.2 | 5.44 |

TABLE 2. SENSITIVITY OF PREDICTED RESULTS TO INPUT CHANGES

| | Volume II | | Volume III | |
|---|---|---|---|---|
| | Qaux [GJ](MMBtu) | Δ* [%] | Qaux [GJ](MMBtu) | Δ* [%] |
| Initial base case | 4.2 (4.0) | - | 5.3 (5.0) | - |
| *Base case with changes:* | | | | |
| South glass reduction (-18%) | 4.2 (4.0) | 0 | 5.3 (5.0) | - 0.3 |
| Non-south glass increase (+31%) | 4.5 (4.3) | + 7.5 | 5.7 (5.4) | + 8.7 |
| Infiltration reduction (-45%) | 3.3 (3.1) | -22.5 | 4.2 (4.0) | -20.5 |
| Fewer occupants (2 instead of 3) | 6.5 (6.2) | +55.0 | 7.9 (7.5) | +49.1 |
| Added doors | 4.2 (4.0) | 0 | 5.3 (5.1) | + 1.3 |
| Higher set temperature (+2%) | 5.0 (4.7) | +17.5 | 6.2 (5.9) | +18.1 |
| All design changes (new base case) | 8.1 (7.7) | +92.5 | 9.0 (8.6) | +71.5 |

*Changes relative to initial base case Qaux.

TABLE 3. PREDICTED RESULTS

| | Volume II | | Volume III | |
|---|---|---|---|---|
| | Qaux [GJ](MMBtu) | Δ* [%] | Qaux [GJ](MMBtu) | Δ* [%] |
| Calculated BLC; Balcomb DD, S; 2 people, 62°F | 8.1 (7.7) | +42 | 9.0 (8.6) | +58 |
| Calculated BLC; Balcomb DD, S; actual Qint, $T_i$ | 7.1 (6.8) | +24 | 8.0 (7.6) | +40 |
| Calculated BLC; Measured DD, S; actual Qint, $T_i$ | 5.7 (5.5) | 0 | 5.4 (5.1) | - 1 |
| Calculated BLC; Measured DD, S; 2 people, 63.2°F | 6.7 (6.4) | +17 | 6.7 (6.3) | +16 |
| Measured BLC; Measured DD, S; Qint, $T_i$ | 9.7 (9.2) | +69 | 9.7 (9.2) | +69 |

* Changes relative to measured Qaux (5.44 MMBtu).

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# HEATING SEASON PERFORMANCE AND THERMAL CHARACTERISTICS OF THE NCSU SOLAR HOUSE

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## ABSTRACT

This paper presents an analysis of heating season performance of the North Carolina State University Solar House. A microcomputer based data acquisition system was used for detailed monitoring during four periods in the winter of 1982-1983. Measurements of 52 temperatures and 4 insolation values in and around the structure were recorded for subsequent analysis. Electrical usage was metered separately for lighting and appliances, domestic hot water, and auxiliary heat (heat pump). Manual logs were kept noting building occupancy and the operation of controllable building features. Using this information, experimental estimates were made of the building loss coefficient, balance point temperature, and other thermal parameters. Monthly building energy consumption was broken down into internal gains, auxiliary heat, and solar gains for both 1981-1982 and 1982-1983 heating seasons. Performance was consistent for the two seasons and the results presented here confirm the effectiveness of the house design.

## 1. INTRODUCTION

The NCSU Solar House is a fully furnished two-story residential building of traditional design located on the campus of North Carolina State University in Raleigh, NC. The site is at latitude 35°47' north, longitude 78°42' west, and elevation 132m(433 ft). The climate is temperate, with mild winters, warm humid summers, and much pleasant weather in the spring and fall. Serving as a research, demonstration, and educational facility, the house has been open to the public on weekdays since its dedication in September 1981. A discussion of the house design (1), construction costs (2), and performance results for the first year of use (3) have been reported previously. Further details and background on the results presented here may be found in reference (5).

### 1.1 Building Description

The house contains 158$m^2$ (1700$ft^2$) of living space plus 30$m^2$ (320$ft^2$) in the sunspace. Built into a south sloping site, the lower level north and west walls are earth sheltered. Upper level walls are of conventional 2x4 wood stud construction with fiberglass batt insulation and styrofoam sheathing for 3.3 $m^2$*°C/W (R-19) resistance. The ceiling is insulated with blown mineral wool to 5.3 $m^2$*°C/W (R-30). All windows are double pane glass, weatherstripped, with wood sash for a 0.30 $m^2$*°C/W (R-1.7) rating. The four windows on the north side have weatherstripped, operable insulating shutters. Exterior doors to the living space are foam filled metal doors, 0.88 $m^2$*°C/W (R-5), with spring bronze weatherstripping. Extensive silicone caulking was used during house construction to reduce air leakage through the building skin. An active solar domestic hot water system is installed, consisting of 6$m^2$ (60$ft^2$) of collector mounted on the south slope of the roof.

### 1.2 Passive Solar Heating System

The primary passive solar heating feature in the house is a two-story sunspace. The sunspace is enclosed in the living space, which wraps around it in a U-shaped fashion. Every room of the house may be opened to the sunspace by either windows or doors, permitting free movement of warm air from the sunspace to the rest of the house. The aperture of the sunspace consists of 24$m^2$ (260$ft^2$) of vertical south-facing double pane glass. Thermal mass is provided by 20cm (8in) thick brick walls on three sides and mass floor of 1.27cm (0.5in) quarry tile on a 2.54cm (1in) grout bed over a 15cm (6in) concrete slab. The sunspace may be ventilated by opening four awning windows along the bottom of the glass wall and by a manually controlled two-speed attic fan located in the sunspace ceiling. Shading of the sunspace during warmer months is provided by a 0.97m (3.17 ft)

roof overhang spanning the width of the sunspace and by a system of drop-in wooden louvers supported with a 3.66m by 6.40m (12ft by 21ft) framework, which shades the lower portion of the glazing and the brick patio outside.

There are two Trombe walls, one-story high, in the lower level bedrooms. Each Trombe wall has 20m$^2$ (64ft$^2$) of double pane glass separated by a 10cm (4in) air space from the masonry wall, which is 30cm (12in) thick. The Trombe walls are shaded by a 0.91m (3ft) overhang with removable wooden louvers at the top of each wall.

Each Trombe wall contains a window which, together with the two south facing windows on the upper level, comprise the direct gain solar heating features. Total direct gain window aperture is 2.7m$^2$ (29ft$^2$).

### 1.3 Backup Heating and Air Conditioning

Auxiliary heating and cooling is provided by a water-to-air heat pump. This unit has a heating capacity of 7.3 kW (25000 Btuh) and a cooling capacity of 7.9 kW (27000 Btuh). The outside heat source/sink consists of 73m (240ft) of 10cm (4in) cast iron pipe buried through the septic field at a depth of about 1.5m (5ft). Water is the heat exchange fluid and is circulated through the pipe in a closed loop. The heating season coefficient of performance (COP) is 2.8 according to manufacturer's information; this value for the COP is used to estimate the auxiliary heat delivery for the analyses reported here. There is also a wood stove in the sunspace and a fireplace in the living room.

## 2. PERFORMANCE MONITORING

Detailed performance data was taken during four monitoring periods in the 1982-1983 heating season. These periods were

1. Jan 26 - Feb 2, 1983 ( 8 days)
2. Feb 7 - Feb 19, 1983 (13 days)
3. Mar 10 - Mar 14, 1983 ( 5 days)
4. Apr 16 - Apr 25, 1983 (10 days)

for a total of 36 full days of data. During these periods, 56 sensors were scanned at 5-minute intervals and hourly average temperatures and cumulative insolation were recorded. A log book was kept during the monitoring periods; in this were recorded sunspace and living room air temperatures, position (open or closed) of the doors between the sunspace and the living space, and other information related to the operation of the passive and auxiliary heating systems. Also available are watt-hour meter readings for total electrical usage, heat pump usage, and electric hot water heater usage; these were provided by the local electric utility company, Carolina Power and Light.

### 2.1 Controls During Monitoring

The house was operated normally during the January, March, and April monitoring periods. The building was open to the public on weekdays and occupied by a student during the evenings. The thermostat setting for the heat pump was 20°C (68°F). Sunspace doors (upstairs and downstairs) were opened when it was observed by the occupant that sunspace temperatures equaled or exceeded the living room temperature. The doors were closed when the sunspace temperature fell below the living room temperature. No fires were built in the wood stove or fireplace.

During the February monitoring period, the house was closed to the public so that controlled performance evaluation could be done. Auxiliary heat (the heat pump) was turned off at 8:00 PM on February 6 and remained off throughout the monitoring period. The solar domestic hot water system was shut down at 11:30 AM on February 7, and remained off for the remainder of the monitoring period. The solar hot water system is not monitored by the data acquisition hardware, so that thermal input from it into the living space cannot be evaluated. The electric hot water heater, which is separately metered, remained on, although hot water consumption by the single occupant was minimal. Sunspace doors were operated normally. Exterior insulating shutters on all north facing windows remained shut and the thermosiphon vents in the brick Trombe wall remained closed.

### 2.2 Instrumentation

Copper-constantan (type T) thermocouples are located throughout the house and are available for placement as needed for air temperature measurements. An Eppley pyranometer is installed above the roof for measurement of horizontal insolation. Three Licor pyranometers measure insolation on vertical south facing planes inside the sunspace, outside the sunspace, and outside the brick Trombe wall.

All sensors are connected to a central terminal board in the utility room from which they can be connected to a digital voltmeter. Automated monitoring of selected sensors is provided by a Hewlett Packard (HP) model 3054 data acquisition system. This consists of a microcomputer with tape drive and a digital voltmeter with 57 channels available for connection to sensors.

## 3. ESTIMATION OF BUILDING THERMAL PARAMETERS

A basic notion underlying performance analysis for the house is that energy losses can be characterized by a building loss coefficient. The rate of heat loss is equal to the product of this coefficient times the indoor-outdoor temperature difference. Building losses may be categorized into losses by conduction through the materials of the structure and losses by convection (termed infiltration) through openings and cracks in the structure. In evaluating passive solar buildings, it is useful to break the losses down into a portion due to the passive solar features of the structure and a portion due to the rest of the structure. Analytic estimation yields a net loss coefficient (excluding losses through the passive solar components) of 108 W/°C (4900 Btu/°F*day) and a total building loss coefficient of 255 W/°C (11600 Btu/°F *day). However, since the building loss coefficient is such a key parameter in subsequent analyses, an experimental estimate is desirable.

Regression analysis was done to obtain an estimate of the total building loss coefficient during the heating season based on measurements taken under conditions of actual house use. Daily measurements of temperature, insolation, and electrical consumption were fit to a single-node energy balance equation, which includes a one-day thermal storage term. The basic form of the equation is

$$L*(Ti-To) = Qa + F*Qs + C*(Ti-Tp) \qquad (1)$$

where L is the total building loss coefficient, C is the effective thermal capacitance of the building, and F is the fraction of solar energy available outside the glazing which contributes to heating the house. Ti and To are the average daily indoor and outdoor temperatures, Tp is the indoor temperature of the previous day, Qs is the daily measured insolation striking the vertical south facing glazing area, and Qa is the daily electrical consumption. The parameters L, C, and F were to be estimated by regression (least squares fit) to the measured temperature and energy data.

Several forms of eqtn 1 were used for parameter estimation with data from monitoring periods in January and February. The result for L yielding the smallest standard error, 0.43°C (0.77°F), was 255 W/°C (11600 Btu/°F*day), which matches the analytic prediction given earlier. The resulting value for effective thermal capacitance (C), 19 kWh/°C (35900 Btu/°F), was higher than the design thermal mass of 14 kWh/°C (26700 Btu/°F). The estimate for F was 26%.

Another result of the regression analysis was a value for an intercept of 1.2°C (2.1°F) with a standard error of 0.43°C (0.78°F). This value, being positive, can account for energy gains (such as those from occupants and the solar domestic hot water system) which were left out of the energy balance equation.

## 4. HEATING SEASON PERFORMANCE

A performance breakdown in terms of solar versus auxiliary heat was determined from the metered electrical consumption, daily average outdoor temperatures, and the estimated building loss coefficient. Monthly heating loads were computed by multiplying an indoor-outdoor temperature difference integral, expressed as degree days per month, times the building loss coefficient. So that the results would be independent of internal gains due to lighting, appliances, and occupants, a reference heating load was used in the analysis rather than the actual building heat loss.

### 4.1 Energy Balance Analysis

The heating season performance analysis was based on a house energy balance of the form

$$L*(Tset-To) = Qint + Qaux + Qsun \qquad (2)$$

where Tset is the desired indoor temperature (thermostat set point), Qint is internal gains, Qaux is auxiliary heat supplied, and Qsun is the balance, attributed to solar gains. The thermostat set point, 20°C (68°F), was used rather than the actual indoor temperature so that solar gains causing the house to rise above the set point were not counted as useful gains.

Internal gains were computed from the metered total electrical consumption by subtracting the heat pump usage and adding estimated gains from occupants. Occupant gains were estimated from log book and visitor's register records using a value of 132 Watts (450 Btuh) per occupant.

A reference (balance point) temperature was defined for the time periods under consideration by the relation

$$Tref = Tset - Qint/L \qquad (3)$$

in which Qint was taken as the daily average internal gains over the time period. Physically, Tref represents the outside temperature below which internal gains are not sufficient to maintain a minimum indoor temperature of Tset. The reference heating load for the time period was then defined as

$$Qref = L * DDref \quad (4)$$

where DDref are degree days computed to the base Tref. The total building loss coefficient used was the empirically estimated value of L equal to 255 W/°C (11600 Btu/°F*day). Reference temperature was not found to vary greatly from month to month around the seasonal average of 16.7°C (62°F), so this value was used for the analysis.

The solar contribution for space heating was then evaluated by subtracting the measured auxiliary heat used from the reference heating load. A solar heating fraction was calculated as

$$Fsun = 1 - Qaux/Qref \quad (5)$$

Tables 1 and 2 contain the results of these calculations for the 1981-1982 and 1982-1983 heating seasons.

4.2 Observations and Discussion

No auxiliary heat was needed in October and November even though there were significant heating requirements for these months. Their heating load was met entirely by the passive solar heating system. Note that heating load as used here refers to the space heating requirements over and above that met by internal gains. February was an exception for the 1982-1983 season because of the monitoring period from February 6 through February 22, during which time the house was closed to the public and the heat pump turned off. Consequently, the 91% solar heating fraction shown for February 1983 is certainly not representative of performance when a comfortable set point temperature is being maintained.

Performance for the first season (1981-1982) looks somewhat better than for the second season, particularly since the winter was colder on a degree day basis. However, the house was occupied by a different student that year, and operated in a more electricity-conserving manner. The heat pump was turned off during periods when the house was not occupied and the wood stove and fireplace were occasionally used. During most of the 1982-1983 heating season, the heat pump was left running with the thermostat set at 20°C (68°F) and neither the wood stove nor fireplace were used. Aside from the 17 days in February previously mentioned, the only extended time the heat pump was off was during the holiday break from December 21 through 31, 1982. One can therefore conclude that overall performance was quite consistant for the two seasons.

The values for solar gains depend on the value of the building loss coefficient, since they were inferred by subtraction from an estimated heating load rather than measured directly. Calculations were done to assess the sensitivity of the computed solar gains to uncertainties in the building loss coefficient. The above analysis was repeated for building loss coefficients higher and lower than the estimated value of 255 W/°C (11600 Btu/°F*day). For an uncertainty in the building loss coefficient of 25%, the range of solar fractions was 68% to 84%, indicating that overall performance was quite good for likely values of the building loss coefficient.

4.3 Normalized Results

A useful way of summarizing the heating season performance of a passive solar house is suggested in reference (4). The total building heat loss for the season and its breakdown into internal gains, auxiliary heat, and solar gains were normalized by dividing by the heating degree days for the season and the floor area of the house. Table 3 presents the data in this manner. In this table, total heat loss was computed as the product of the building loss coefficient times the number of heating degree days for the season. Internal gains were subtracted from the total loss, leaving the heating load to be met by the passive solar heating system and the auxiliary heating system (heat pump). Subtracting the measured auxiliary heat leaves the inferred solar gains. It should be noted that the total heat loss includes losses through the passive solar components of the building, so that the bottom lines in Table 3 are solar gains, including those needed to make up losses through the passive components.

Normalized performance was quite consistent over the two seasons, and the values shown here compare well with those reported in a survey of 38 monitored passive solar buildings (4). The ratio of glazing area for the house to floor area is 0.25, which is in line with the ratios reported there. The normalized total heat loss for the house was 1.6 $W/m^2*°C$ (6.8 $Btu/ft^2*°F*day$). This value, which is a measure of how well energy conservation is implemented in the structure, is somewhat higher than the median value (6.5 $Btu/ft^2*°F*day$) reported in the survey. The NCSU Solar House ranks among those buildings having the lowest normalized auxiliary heat requirements. It is higher than average in internal gains due to the high electric light usage when the house is open for visitors on weekdays.

A seasonal solar collection efficiency for the passive components can be computed using normal insolation values for the locale. The insolation received on a vertical south-facing surface from October through April is 675 kWh/$m^2$ (214,000 Btu/$ft^2$). For the 39$m^2$ (417$ft^2$) aperture of the NCSU Solar House, this yields 26000 kWh (89 million Btu) per season. Using this as a base resulted in seasonal collection efficiencies of 23% for 1981-1982 and 20% for 1982-1983. The difference in efficiency may not be meaningful because actual insolation was certainly not the same for both years. It is worth noting that the 20% to 23% efficiency calculated here is close to the value for F of 26% obtained with the regression analysis discussed earlier.

### 4.4 Temperature Stability

Indoor temperatures were quite stable during the periods of observation. On sunny winter days, the temperature in the living room on the upper level of the house generally fluctuated from the thermostat set point of 20°C (68°F) up to around 24°C (75°F). The highest temperature recorded was 26°C (78°F), which occurred at 2:00 PM on February 1, 1983. This day was bright and sunny with the outdoor temperature reaching a high of 14°C (58°F), and it followed two previous sunny days with highs over 16°C (60°F). Indoor temperature swings were more moderate later in the season, when outdoor temperatures were warmer on the average but the sun was higher in the sky.

Sunspace temperature was also quite stable. The daily fluctuation was typically in a range of about 3°C (5°F) below to 5°C (8°F) above the average daily temperature in the sunspace. The maximum daily fluctuation observed was from a low of 13°C (55°F) to a high of 23°C (73°F) on February 7. The maximum sunspace temperature recorded during the winter was 28°C (82°F) on both January 31 and February 1, 1983, which were unusally warm sunny days for that time of year. The minimum observed sunspace temperature was 9°C (48°F) at 7:00 AM on February 15. This was during the February monitoring period when auxiliary heat in the house had been off for a week. The outdoor temperature was 1°C (33°F) at the time and the two previous days had been cold and cloudy.

## 5. CONCLUSIONS

The results presented here affirm the excellent heating season performance of the NCSU Solar House reported earlier (3) on the basis of the low auxiliary energy requirements for its first year of operation. The good performance can be attributed to the good passive solar design, particularly the energy conservation features and the sunspace. The enclosed sunspace is aesthetically pleasing as well as thermally efficient with three sides adjoining the living space and ample window and door openings to permit exchange of heat to the living space. That sufficient thermal mass is included in the design is evidenced by the good temperature stability of both the living space and the sunspace. Energy conservation was emphasized; this is important in the southeastern region of the United States to minimize summer cooling as well as winter heating needs. The effectiveness of sufficient insulation, high quality components and construction technique, with special attention paid to caulking and weatherstripping needed to reduce infiltration losses, has been demonstrated.

The results given here apply to heating season performance. That summer performance is also good, as has been shown by the low electrical consumption for cooling (3). Evaluation is needed, however, of the cooling load liabilities (particularly in early autumn) that might be imposed by the Trombe walls and sunspace. Further research on the NCSU Solar House is needed to detail the component-by-component performance, both winter and summer, of the passive solar features.

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TABLE 1. 1981-1982 Heating Season Monthly Performance

| Month | Avg Temp °C | Avg Temp °F | Degree-days (18°C) | Degree-days (65°F) | Avg Hrs of Sun | Int. Gains | Ref. Load | Aux. Heat | Solar Gains | Solar Fract. | Heat Bill | Total Bill |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OCT | 14 | 57 | 131 | 253 | 6.9 | 459 | 591 | 0 | 591 | 100% | $ 0 | $ 24.60 |
| NOV | 11 | 51 | 226 | 425 | 5.9 | 586 | 1152 | 0 | 1152 | 100% | 0 | 31.38 |
| DEC | 4 | 40 | 421 | 776 | 4.8 | 585 | 2321 | 311 | 2011 | 87% | 6.66 | 37.98 |
| JAN | 2 | 36 | 494 | 907 | 4.4 | 602 | 2766 | 700 | 2067 | 75% | 15.00 | 47.22 |
| FEB | 8 | 46 | 290 | 538 | 4.8 | 718 | 1550 | 543 | 1007 | 65% | 11.64 | 50.10 |
| MAR | 11 | 52 | 219 | 411 | 6.1 | 643 | 1108 | 258 | 851 | 77% | 5.52 | 39.96 |
| APR | 14 | 57 | 128 | 244 | 7.2 | 513 | 598 | 36 | 562 | 94% | 0.78 | 28.26 |
| Season | 9 | 48 | 1907 | 3554 | 5.7 | 4105 | 10088 | 1848 | 8240 | 82% | $39.60 | $259.50 |

Energy values are reported in kWh and bills are based on an electricity cost of $0.06/kWh

TABLE 2. 1982-1983 Heating Season Monthly Performance

| Month | Avg Temp °C | Avg Temp °F | Degree-days (18°C) | Degree-days (65°F) | Avg Hrs of Sun | Int. Gains | Ref. Load | Aux. Heat | Solar Gains | Solar Fract. | Heat Bill | Total Bill |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OCT | 16 | 61 | 95 | 182 | 5.5 | 592 | 438 | 0 | 438 | 100% | 0 | $31.70 |
| NOV | 11 | 52 | 209 | 392 | 4.1 | 605 | 1071 | 0 | 1071 | 100% | 0 | 32.40 |
| DEC | 9 | 48 | 292 | 542 | 2.8 | 503 | 1560 | 219 | 1341 | 86% | 4.70 | 31.63 |
| JAN | 3 | 38 | 452 | 828 | 4.6 | 628 | 2498 | 946 | 1552 | 62% | 20.28 | 53.92 |
| FEB * | 5 | 41 | 366 | 675 | 5.1 | 467 | 2009 | 186 | 1823 | 91% | 3.98 | 29.02 |
| MAR | 11 | 51 | 233 | 438 | 6.2 | 633 | 1183 | 452 | 730 | 62% | 9.69 | 43.57 |
| APR | 12 | 54 | 161 | 305 | 7.1 | 632 | 788 | 249 | 540 | 68% | 5.33 | 39.20 |
| Season | 9 | 49 | 1805 | 3362 | 5.1 | 4059 | 9547 | 2052 | 7495 | 79% | $43.98 | $261.46 |

Energy values are reported in kWh and bills are based on an electricity cost of $0.06/kWh

* The heat pump was off for 17 days in February 1983, so performance for that month is atypical.

TABLE 3. Normalized Heating Season Performance of the NCSU Solar House

| | October 1981-April 1982 | | | October 1982-April 1983 | | |
|---|---|---|---|---|---|---|
| | $10^3$kWh | W / $m^2$*°C | Btu / $ft^2$*°F*day | $10^3$kWh | W / $m^2$*°C | Btu / $ft^2$*°F*day |
| Total building heat loss: | 12.1 | 1.6 | 6.8 | 11.5 | 1.6 | 6.8 |
| Internal gains: | 4.1 | 0.5 | 2.3 | 4.1 | 0.6 | 2.4 |
| Heating load: | 8.0 | 1.1 | 4.5 | 7.4 | 1.0 | 4.4 |
| Auxiliary heat used: | 1.8 | 0.3 | 1.1 | 2.1 | 0.3 | 1.2 |
| Solar gains | 6.2 | 0.8 | 3.4 | 5.3 | 0.7 | 3.2 |

Normalization is based on the living space floor area of 158 $m^2$ (1700 $ft^2$) and total building loss coefficient of 255 W/°C (11600 Btu/°F*day).

Solar Glazing area of the house is 39 $m^2$ (417 $ft^2$); ratio to floor area is 0.25.

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# MARKETING ATTACHED GREENHOUSES IN AN AFFORDABLE SUBDIVISION FAIRWAY VILLAGE SANTA FE, NEW MEXICO

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## ABSTRACT

Fairway Village is a 154-unit middle-income subdivision under construction by Chapman Builders in Santa Fe, New Mexico. Chapman is a traditional, production homebuilder delivering over 100 units a year. Participants in HUD's and NAHB's Joint Venture for Affordable Housing Demonstration, Fairway Village homes are priced from $49,950 to $69,500 and targeted toward first-time buyers with incomes of $20,000 to $30,000.

Designed primarily with affordability in mind, the project offers greenhouse kits which the builder will install as an option.

The greenhouse option makes Fairway Village unique among HUD Affordable Housing participants. This paper discusses the process by which a traditional builder attempts to enter the market with an optional solar system, given the tight cost constraints of an affordable subdivision.

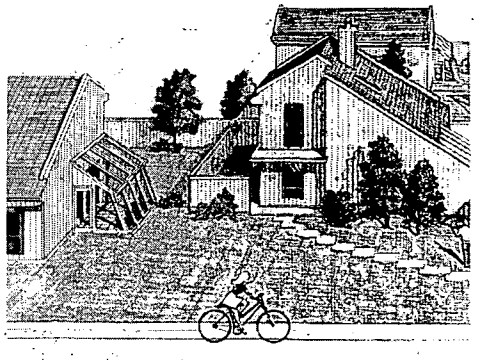


Fig. 1: Partial rendering, Fairway Village.

Optional premanufactured greenhouse kits replace the site-built versions pictured here. Contractor's higher price for the site-built version versus the installed kit price is the reason for the substitution.

## 1. THE BUILDER AND THE CONSULTANT

Chapman, the homebuilder, has a reputation in Santa Fe for high quality construction at a very competitive cost per square foot. Developer/builders of Park Plazas, a 460-unit, award-winning community, Chapman has been building homes in Santa Fe for 17 years. Fairway Village is the first project in which the builder has offered greenhouses as a standard option.

Passive Solar Services specializes in thermal performance analysis, cost estimating, and marketing of passive system applications in residential and light commercial buildings. PSS assists architects and builders throughout the country to develop cost-effective passive systems for retrofit and new construction. Committed to consumer education as well as expert consultation, PSS develops tools which builders can use to educate their buyers in passive systems performance.

## 2. PASSIVE SOLAR, A REAL ESTATE PRODUCT

Probably the most important concept for a builder-developer to understand is that passive solar is a design/construction technology -- and therefore, a real estate product, as opposed to a piece of hardware mounted on the roof. Because the walls, roof and floors of the home are the collector, storage, and distribution system, passive solar is an integral part of the real property and can, as such, enhance the value and use of that property. (Conversely, active solar systems begin to depreciate once they are installed.)

Just as a well-designed passive system can enhance the value of a building, a poorly designed or sited one can detract from the building's value and use. More to the point, poorly designed solar features can destroy an otherwise good reputation for quality construction. For this reason, Passive Solar Services approached Chapman before the Fairway Village project broke ground, to offer its experience and expertise in passive solar performance calculation.

Chapman welcomed the input but told the consultant that certain building system decisions and greenhouse kit selections were "fixed" because of cost constraints. (The 1000 to 1600 square foot units are selling in the $40-49 per square foot range.)

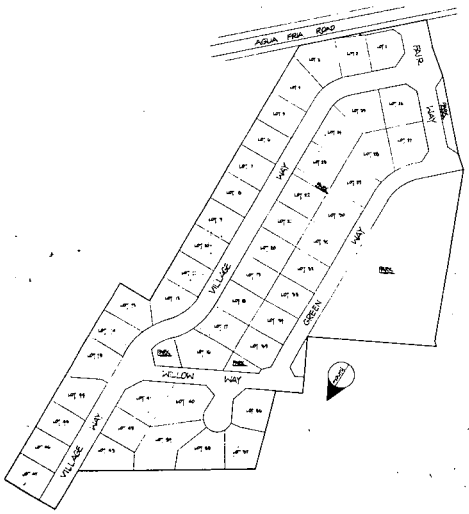



Fig. 2. Site plan, Fairway Village.

PSS committed to analyzing the heating performance of the greenhouses and developing a strategy to market them. (The greenhouse manufacturer offered no solar calculations or siting information.)

## 3. THE FAIRWAY VILLAGE MARKETING PLAN

Affordability is the keystone of the Fairway Village marketing plan. Two of the three models offer unfinished square footage within the homes' shells -- for example, an unfinished master bedroom and bath upstairs off the loft balcony. The marketing logic is very sound -- give the young buyer or family "grow" space which can be finished out later, by the owner, when income increases. This concept begins to turn the classic homebuyer "trade-up" mentality upside down because the Fairway Village homes have features that make first-time buyers feel like second-time buyers at the time they finish out their extra space.

Other features -- cathedral ceilings, loft-balconies overlooking open living-dining-kitchens, walk-in closets, and 2-car garages -- give the buyer the feel of expanded space for a reasonable cost per square foot. The first-time buyer doesn't have the feeling, "This house is temporary. I've got my foot in the housing door; I'll grin and bear it, 'til I can buy something bigger or more luxurious." Instead, Fairway Village buyers feel they've got a "special" home with features that will satisfy their future needs.

## 4. CONSERVATION FIRST

Affordability meant more to the builder than costs per square foot. It meant a commitment to energy conservation so that homeowners' fuel bills would be affordable as well.

Wall systems at Fairway Village are constructed of 2 x 6 studs -- 24" on center with a single top plate, two stud corners, and placement of windows at stud locations. Proper alignment of studs and 2 x 10 joists provide for a home more structurally sound than most, yet using 30% less wood than typical construction. More insulation in the walls, and less wood, provides a stronger, tighter house. In addition, all insulated space is wrapped with a polyethylene vapor barrier and careful attention is paid to infiltration by sealing all plates and voids with an expandable foam. Windows, of course, are double glazed. In addition to the energy conservation package, homeowners can choose an optional wood-burning stove.

## 5. GREENHOUSE OPTIONS

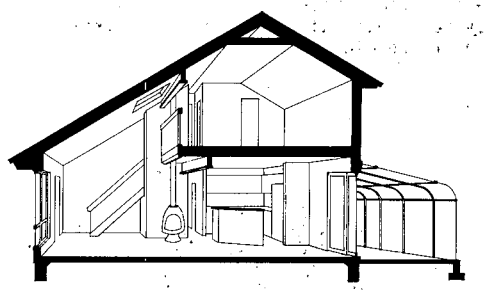


Fig. 3. Section, Model 1, with optional greenhouse.

Fairway Village is unique among affordable Housing Projects because it offers greenhouses as options. Homes are sited in a pinwheel fashion with varying setbacks, allowing each floor plan a living or dining room wall on the south. An optional greenhouse either 5'x 8' or 8' x 13' is then available as part of the package at the time of sale, or can be added by the homeowner later.

The simplicity of adding the greenhouse off the existing frame south wall appealed to the builder more than attempting to incorporate optional passive systems into the

south walls themselves. (Early attempts to design a site-built kit were discarded.) With a pre-manufactured kit it would also be possible for the homeowners to install themselves. (The type of greenhouses and sizes are predetermined by the builder to assure architectural continuity within the project.)

## 6. MARKETING VALUE--PLANT ENVIRONMENT, HEATING CONTRIBUTION, OR LIVING SPACE?

The greenhouse as a marketing feature has been well established in recent years. Greenhouses are pleasurable sunspaces that add square footage to the living area. As well, they provide indoor growth environments for plants and vegetables, and of course greenhouses can substantially lower a home's need for auxiliary fuel.

While a greenhouse offers this possibility for triple duty--heat production, plant growth and additional living space--different greenhouse geometries maximize different efficiencies. In other words, what's good for plants is not necessarily best for heating efficiency or comfortable for human habitation.

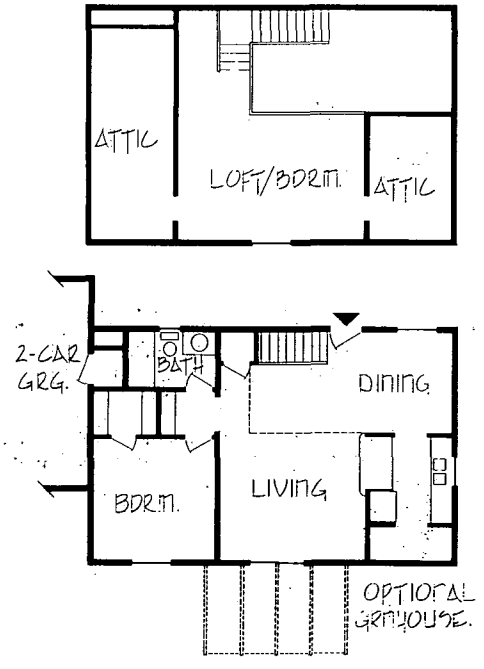



Fig. 4. Upper and lower floorplans, Model 1, Fairway Village.

In general, greenhouses with substantial amounts of overhead glazing and glazed east and west end walls, provide the most conducive plant environment; however, overheating is a critical problem and exhausting (even in winter) is required to stimulate healthy plants and prevent disease. Along with overheating, excessive buildup of moisture often leads to condensation problems. The energy used or evapotranspiration in the greenhouse is energy which otherwise would be available for heat storage.

For heat production and storage, a different geometry emerges--less overhead glazing, an insulated roof, insulated east and west end walls, and thermal mass for heat storage. In addition, a method of delivering air to adjacent spaces is required. This may be as simple as a set of doors or perhaps a small wall fan. Often, nighttime insulation is used to significantly lower heat losses and improve efficiency.

If a greenhouse is to be used as a living space, different considerations prevail--issues of comfort, convenience, headroom, for example--and these dictate a different geometry, usually a vertical south wall which is easier to shade and control. Mass is required to minimize temperature swings but furniture and rugs can prevent the sun from ever reaching the mass. (In all three cases it is critically important to isolate the living spaces thermally from the greenhouses, or they will use more energy than they gain.)

## 7. THE GREENHOUSE SELECTION--A COMPROMISE

Chapman's decision to go with a double-glazed, un-thermally broken, curved greenhouse kit was based on price and marketability. The curved overhead glazing was seen as very marketable because of its pleasing aesthetics, both as an addition to the south elevations and as a visual amenity when seen from the living spaces.

Passive Solar Services quickly pointed out that conduction through the un-thermally broken metal glazing system would result in heat losses 20% higher than the thermally broken version. However, a thermally broken version was not available in the sizes selected by the builder.

The geometry of the greenhouse selected by the builder has glazing characteristics consistent with optimum plant growth rather than heat collection, storage, and distribution or living space use. Therefore, a high solar fraction was not expected by the consultant. The builder found the trade-off acceptable because he felt comfortable with the marketing value of the curved overhead glazing on the greenhouse.

## 8. PREDICTED PERFORMANCE

Performance analyses of Models I and III at Fairway Village are summarized in Tables 1 and 2.

KEY TO TABLE HEADINGS

LCR--Load Collector Ratio
SSF--Solar Savings Fraction
SHF--Solar Heating Fraction
SS--Solar Savings
AUX--Auxiliary Full Requirement
AUX($)--$ value of Auxiliary
ISC--Incremental Solar Cost
*ROI--Return on Investment
Assumes 5-year investment, 8% property growth rate, and 14% annual increase in the price of natural gas.

TABLE 1
HEATING CONTRIBUTION
MODEL I FAIRWAY VILLAGE

1000 $ft^2$ BASE PRICE $49,950

| | LCR | SSF | SHF | SS (MMBTU) | AUX (MMBTU) | AUX ($) | ISC ($) | ROI* (%) |
|---|---|---|---|---|---|---|---|---|
| 1. | 46 | .227 | .357 | 7.3 | 24.9 | 196 | 3350 | 10.4 |
| 2. | 46 | .283 | .395 | 9.1 | 23.1 | 182 | 3854 | 13.86 |
| 3. | 38 | .304 | .409 | 9.8 | 22.4 | 176 | 4750 | 13.09 |
| 4. | 38 | .410 | .484 | 13.2 | 19.0 | 149 | 5884 | 13.94 |

1. Base house with 5x8 Greenhouse.
2. Base house with 5x8 Greenhouse with R-5 night insulation.
3. Base house with 8x13 Greenhouse.
4. Base house with 8x13 Greenhouse with R-5 night insulation.

TABLE 2
HEATING CONTRIBUTION
MODEL III FAIRWAY VILLAGE

1656 $ft^2$ BASE PRICE $61,950

| | LCR | SSF | SHF | SS (MMBTU) | AUX (MMBTU) | AUX ($) | ISC ($) | ROI* (%) |
|---|---|---|---|---|---|---|---|---|
| 1. | 48 | .235 | .345 | 10.4 | 33.9 | 266 | 4750 | 11.62 |
| 2. | 48 | .293 | .391 | 13.0 | 31.3 | 249 | 5884 | 13.94 |
| 3. | 40 | .273 | .403 | 9.4 | 25.0 | 196 | N/A | N/A |

1. Base house with 8x13 Greenhouse
2. Base house with 8x13 Greenhouse with R-5 night insulation.
3. Base house with Master Bedroom closed with 8x13 greenhouse. No night insulation.

Analysis of the heating contribution of attached greenhouses on Models I and III show heating contribution in the range of 34-48% depending upon the size of the greenhouses, the shading and night insulating accessories installed by the homeowners (in the case of Model III, Table 1, #3 the unfinished master bedroom/bath heat losses were excluded from the load, assuming that this space is closed thermally from the rest of the house at least until it is finished out.)

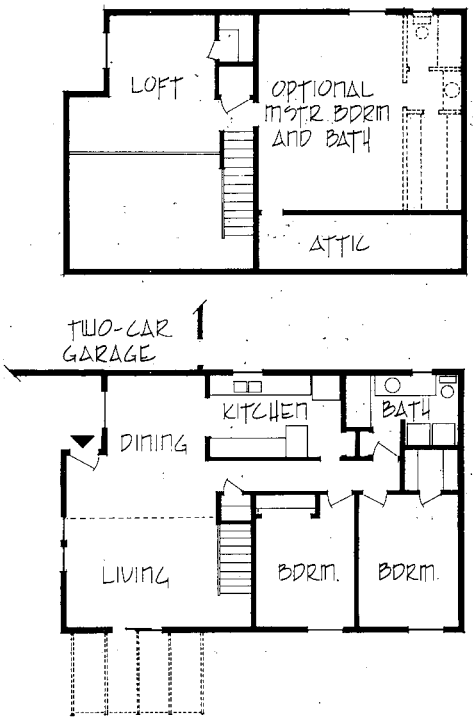



Fig. 5. Upper and lower floor plans, Model 3, Fairway Village

9. CONCLUSION

Consultant and builder agreed that the greenhouses should be marketed with emphasis in the order of plant environment, living space, heating contribution, because of the particular geometry and characteristics of the kit selected. Heating contribution would be recognized but only as an assist rather than a primary source. The builder was satisfied that he could market the product with knowledge of its expected performance and its best use.

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# THE ENERGY-EFFICIENT HOME PROJECT OF OREGON

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## ABSTRACT

The Energy-Efficient Home Project of Oregon was a joint public/private effort, involving mortgage investors, government agencies, professional associations, a lending institution, energy consultants and homebuilders in the design, construction and mortgage financing of sixteen moderately priced solar/energy conserving homes.

The broad array of participants was brought together for a pilot project to demonstrate how an approach which encompasses the entire shelter industry can:

- create a favorable atmosphere and an attractive investment vehicle for energy-efficient residential construction;
- introduce new concepts such as a uniform energy rating system for homes and Energy Mortgage Valuation (EMV) in a context of the participants' typical business practices;
- result in homes built and sold; and
- prove in the marketplace the benefits of energy-efficient housing for all participants, from secondary mortgage market to homebuyer.

Project funding came from the Oregon Department of Commerce's Housing Division, which provided $900,000 in low-interest-rate mortgage funds, and Bonneville Power Administration, which provided the administrative costs contract to the Energy-Efficient Housing Group -- the consultant which ran the project. Other co-sponsors included: Far West Federal Bank, which made the primary mortgage loans; the Oregon State Homebuilders Association, which provided publicity and logistic support; and the Oregon Department of Energy, which provided technical assistance.

## 1. INTRODUCTION

The concept which generated this project was developed in late Winter 1981 at the Western Solar Utilization Network (Western SUN). Gregg Smith, Administrator of Oregon's Housing Division, paraphrased lines from a recent movie to describe how Western SUN's Finance Program Manager approached him: "We've got a great concept here! Why, this is such a great concept, with a million bucks we could turn this into an idea!"

The idea was to demonstrate to homebuilders, mortgage lenders and buyers the market acceptability and specific advantages of solar/energy conserving construction in the starter home market.

The attention getter was the Housing Division's mortgage endowment: $900,000 of state-backed bond money, offered at a 9.75% fixed thirty-year rate. (At the time the project was being put together, conventional mortgage rates were above 15%.) Western SUN would run a design competition for builders, selecting winners on the basis of energy savings potential and overall quality of the designs. Buyers of the winning $60,000 homes would be qualified by the mortgage lender with energy savings taken into account. The Housing Division would then purchase the portfolio of loans.

The basic scope of work and cooperation of institutional co-sponsors (primarily a lender and the homebuilders associations) had all been agreed upon when, in spring 1982, the U.S. Department of Energy closed down the nation's Regional Solar Energy Centers.

The idea for the project and the enthusiasm of the participants remained alive. Rather than let a million-dollar portfolio of low-interest energy-conserving home mortgages slip away, the organizers of the project at Western SUN sought alternate means to deliver the project as proposed. In late summer 1982, the Bonneville Power Administration accepted an administrative costs proposal and contracted with the Energy-Efficient Housing Group to run the project.

## 2. PROJECT ORGANIZATION

The Energy-Efficient Home Project of Oregon (EEHPO) was implemented in a ten-month span between September 1982 and July 1983. This

compressed timeline was inherent in the use of the state's bond money; the bonds had been issued in 1980 (hence the low interest rate) and, by Internal Revenue Code regulations, the proceeds had to be spent within three years of the Housing Division's receipt of the bond sale proceeds.

As many readers can imagine, to proceed from initial program publicity through a design competition to closed mortgage loans in under ten months is much like the prospect of skateboarding Mt. Everest while eating soup: everything goes very smoothly, or it doesn't go at all.

The authors don't offer the simile to be frivolous, but rather to make a serious point. To succeed even as a one-time project, and certainly to be useful in changing standard practice in the future, any program which proposes to demonstrate new design and construction techniques (energy-related or otherwise) in the built environment must have a financing component. EEHPO succeeded despite the tight time schedule, largely because it was a mortgage financing arrangement which helped balance risks for all participants.

## 3. INDUSTRY CONTEXT: Primary Actors

The Pacific Northwest is a very important area of the country today from the standpoint of changes in energy use policy and practices. With the formation of the Northwest Electric Power Planning and Conservation Act, a process was set in motion which would affect new home construction practices in the region for the rest of the century and beyond. Charged by Congress with developing a regional conservation and renewable resources development plan, the Council has become an entity whose activities are an element of every discussion about the future of homebuilding in this four-state region.

During the course of the Energy-Efficient Home Project of Oregon, the Council released Proposed Model Standards for Energy Conservation in New Buildings, a discussion document which proposed energy-use goals for new residential units at a level approximately 65-75% lower than current building codes standards require!

Lively discussion is ongoing throughout the region as to precise thresholds of cost and thermal effectiveness of such standards. However, the general message from the Council is a present reality in the shelter industry's consideration of its future. The Pacific Northwest's new housing stock in the late 80's and 90's is going to be highly energy-efficient with greater attention to solar/renewable resource contributions to space- and water-heating loads. If the experience of the U.S. automobile industry in the past decade is not to be repeated in housing, the entire shelter industry, from secondary mortgage market lenders to sub-contractors and realtors, must make adjustments in their day-to-day business practices to accommodate this energy-conservation imperative.

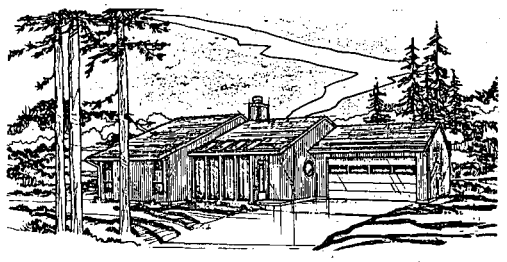


Fig. 1. Steve Pyles, builder; Gary Reddaway, architect.

Bonneville Power Administration funded the Energy-Efficient Home Project of Oregon as part of its new home construction conservation efforts. Such projects further their goals of increased builder and buyer awareness and acceptance of solar/conservation homes. The wide range of EEHPO participants provided an opportunity for BPA to work with a unique coalition of public and private entities. Since BPA is cast in the role of implementor for the Council's Plan, this groundwork with lenders, state agencies and builders groups was valuable.

The Oregon Department of Commerce's Housing Division manages an ongoing program to provide mortgage financing on affordable homes to below-median-income families in the state of Oregon. The funds are raised through state-backed bond sales, and are typically offered at below-market rates through participating lenders which make the primary mortgage loans.

The Division's Single Family Mortgage Purchase Program establishes qualification guidelines for home sales under the program, including income limits and sales price ceilings, in this case $60,000. The Housing Division regarded EEHPO as an opportunity to test an idea: for new housing stock, why not carry the concept of an "affordable" home beyond sales price and interest rate into the operating costs for the term of the loan. This approach was consistent with the Division's public-purpose orientation, as well as its specific program requirements: lower energy costs for a home could mean an expanded pool of qualifiable buyers, without raising the income limits for program eligibility. As a major secondary market lender in Oregon (providing mortgage funds and guidelines to over 25 lending institutions), the Housing Division's policies could strongly affect the availability of mortgage funds, and the accuracy of underwriting practices, for solar/energy conserving homes.

Far West Federal Bank serviced the mortgage loans. In qualifying buyers, a method of adjusting the usual loan-to-income ratio to reflect energy savings of the house was used. Energy Mortgage Valuation (EMV)[1] takes into account the savings of the subject home (as compared to a conventional "code-standard" home) in such a way as to either: 1) qualify a buyer for a solar/energy conserving home of a higher sales price than could be afforded in a conventional home; or 2) allow a buyer who is on the borderline for a loan on a conventional home to qualify more easily for a solar/energy conserving home of the same price.

The energy savings were determined in this project using a system called the "Uniform Energy Rating System," developed by the Western Resources Institute. The rating system provides mortgage lenders and appraisers with an accurate energy usage prediction for a subject home. With such a tool for comparison, the energy quality of the lender's portfolio can be assessed, risk of mortgage foreclosures on energy sieves is reduced, and the value of a solar/energy conserving home can be more accurately appraised.

Far West saw EEHPO as an opportunity to test the revised appraising and underwriting techniques described here. This practical experience, gained at several of the lender's branches throughout the state, should provide the bank a market advantage in making more accurate, higher quality loans for energy-efficient homes in the future.

The Oregon State Homebuilders Association (OSHBA) backed the project as an entrepreneurial and educational opportunity for its membership. EEHPO also followed through on the HBA's prior efforts at developing standard practices for Solar and Energy Efficiency homes (the SEE program). The publicity and logistic support for the project was offered to focus attention on how well Oregon builders responded to a voluntary program for above-code energy conservation standards. The Association's point has been that an incentive approach (in this case, the mortgage financing link-up) is much more effective for a high-risk industry such as homebuilding than a regulatory approach, enforced through prescriptive standards.

The Oregon Department of Energy (ODOE) provided valuable technical review of project materials in the development stage, and continued to be 'on line' for technical questions concerning code, tax credits, climate data, etc. ODOE also helped to refine the review process and served on the evaluation committee for the design competition.

[1] See Solar Age, June 1982, pp. 41-45, for a discussion of Energy Mortgage Valuation, "Nailing Down Home Energy Savings."

## 4. PROJECT NARRATIVE

### 4.1 Publicity

Promotion and publicity for the design competition was accomplished via press, homebuilders associations (HBA's) and direct mailings to builders. Executive officers of local HBA's received cover letters from the Oregon State HBA president, and bulk quantities of the Program Description. In the direct mail efforts, there was a deliberate focus on builders rather than architects and engineers, who were encouraged to adapt a standard starter home model to be more energy-efficient rather than to design from scratch.

A press release about the project appeared in at least thirteen newspapers around the state; five radio stations also picked up on the item.

Responses came in from 155 builders. We asked all respondents to indicate how they had heard about the project. Tallied results: 40% from direct mailings; 29% through HBA's; 17% from news media; and 14% from word-of-mouth.

### 4.2 Design Competition

All respondents were sent a competition application packet. This document contained: a complete program description; the program rules and underwriting guidelines; full instructions on how to apply; a special section of "Alternative Component Measures," describing various means of achieving non-prescriptive R-values and air-change rates for the home; a Conservation Worksheet, really a simplified UA heat loss calculation method; and, finally, a set of Energy Rating Forms (one for each of four house types in three climate zones).

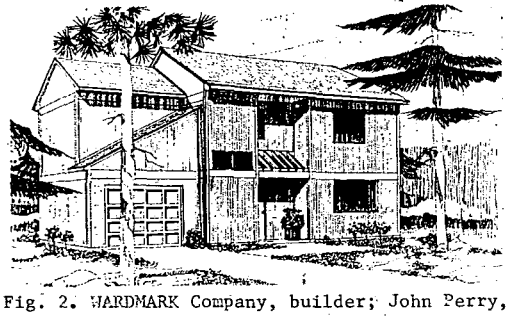


Fig. 2. HARDMARK Company, builder; John Perry, architect.

These forms were an early draft of the Uniform Energy Rating System (UERS). In typical use, a bank appraiser would use the rating form to quickly assign points to a subject house according to its insulation levels, orientation for solar gain, air infiltration reduction measures in place, etc. The 100-point scale allows for simple house-to-house comparisons, as well as for an individual energy rating for the house, describing its energy use qualities.

In the competition, a conversion chart was provided to applicants so that the effective R-values from the worksheet could be converted directly to the point system on the UERS form. The packet also included an energy rating form for each house type filled out to current Oregon code minimum standards. Thus, a builder could pre-test a design to see how well it would score against the code comparison. A very important aspect!

4.3 Proposal Evaluation

By the submittal date, a total of 68 design entries had been received from 52 builders. This response level exceeded the project managers' hopes: over 1/3 of the 155 application requests had resulted in a design proposal.

The quality of entries was likewise surprising: only one applicant failed to understand and follow through on the instructions.

The review team was assembled, representing not only the co-sponsoring organizations but a cross-section of professional specialties ranging from design, engineering and construction, to lending, appraising and sales. The eight team members agreed upon criteria and weighting factors to assess each entry, and prepared an evaluation form.

A winning design had to excel in several areas. Though technical considerations were of major importance (55% of the possible score), the team also scored on the marketability of the design (30%) and the builder's financial qualifications and experience record (15%). Here again, the selection process was set up to maintain the project's major emphasis: that the production of solar and energy conserving homes is not a radical departure from the homebuilding industry's normal practices. It was of high importance that the homes excel not only on paper, but in the marketplace as well.

Proposals came from all over Oregon, and competed within their specific climate zones. Three were designated for the project initially, but were later merged to two: ZONE 1, west of the Cascades with a 4000-6000 HDD range, and ZONE 2, with a 6000-8000 HDD.

Sixteen winners and five alternates were selected. The winning designs averaged 1160 square feet. All used at least sun-tempering in addition to a tight well-insulated envelope. There were twelve serious passive solar designs. Most of these employed simple direct gain schemes; five included sunspaces, and there were two designs which used partial trombe walls. Winners prepared working drawings over the next month and secured lots. Upon approval of final designs and materials specifications, builders lined up construction financing and began work.

A press conference was called to announce the winners, all of whom were presented an award letter from the Housing Division. The project was described by administrators and executives of the Bonneville Power Administration, State of Oregon, State Homebuilders Association and Far West Federal Bank. The attendant press coverage created a deluge of calls. Over 400 telephone inquiries were logged in the ensuing two days from prospective homebuyers wanting to purchase one of the winning homes. As a result, a majority of the EEHPO homes were pre-sold!

4.5 Energy Underwriting

With such serious levels of buyer activity, the monthly energy savings computations were the next task. From the final working drawings, the savings predictions were calculated and the data supplied to Far West Federal Bank for use in buyer qualifying. The following chart (Table 1) illustrates how the savings figure is used to qualify an otherwise marginal buyer.

First the Energy Mortgage (EMV) is figured. EMV analysis asks the question: "What is the value today, at a given mortgage rate and term, of one dollar saved per month on energy?" This value can also be expressed as the "present value of $1 per period." The EMV for a given home can be subtracted from the loan amount by the lender, to derive an 'effective loan amount' which is then used to qualify the buyer of the energy conserving home. The chart uses EMV as a check of another qualifying method, PITI minus Energy saved. The lender in the example below was using a typical 28% maximum mortgage debt-to-income ratio and a 38% limit for the total debt-to-income ratio.

It can be seen from this example that this means of energy underwriting qualifies more buyers. These underwriting tools were explained to builders and Realtors in the marketing segment of the Energy-Efficient Home Seminar, which was held in Portland in late February. The specific savings information for each home was provided to each builder for their use in future sales of their winning model, and as a practical example of how energy-efficiency can be used as a marketing tool for homes sales in general.

4.6 Construction and Sales

The project managers made site visits as the homes were in various stages of completion. A collection of slide photographs of the best-installed details from EEHPO will become part of future educational and promotional efforts for this type of construction.

Several builders took full marketing advantage of their success in the program. Of the winners, at least nine firms generated their own

TABLE 1. ENERGY UNDERWRITING PROCESS

| LOAN DATA | ENERGY UNDERWRITING WORKSHEET |
|---|---|
| SALES PRICE: $60,000<br><br>DOWN PAYMENT: 5%<br><br>ENERGY SAVINGS:<br>Code $56<br>Efficient - 20<br>SAVINGS $36(a)<br><br>LOAN AMOUNT:<br>$57,000<br><br>LOAN-TO-VALUE - 95% (private mortgage insurance req'd)<br><br>BORROWER'S INCOME:<br>$2,100/month<br><br>TIME OBLIGATIONS:<br>$190/month<br><br>The "Effective Loan Payment" should equal the "Total Payment - Energy Savings" | (1) ENERGY MORTGAGE VALUATION (EMV):<br>Present value of $1 @ 9.75% for 30 yrs. = $116.40 (b)<br>Energy saved (a) times Present value (b) = EMV<br>36 x $116.40 = $4,190 (EMV)<br><br>(2) LOAN PAYMENT: Principal & Interest $489.72<br>Taxes 100.00<br>Private Mortgage Insurance 23.75<br>TOTAL LOAN PAYMENT $623.47<br><br>(3) QUALIFYING:<br>A. Conventional home:<br>$\frac{\text{Ttl loan pmt}}{\text{Income}} = \frac{623.47}{2100} = 30\%$ $\frac{\text{Pmt+oblig.}}{\text{Income}} = \frac{813.47}{2100} = 39\%$<br>B. Energy-efficient home:<br>$\frac{\text{Pmt-savings}}{\text{Income}} = \frac{587.47}{2100} = 28\%$ $\frac{\text{Pmt+oblig-savings}}{\text{income}} = \frac{777.47}{2100} = 37\%$<br><br>(4) EMV VERIFICATION: Loan $57,000<br>Minus EMV - 4,190<br>"EFFECTIVE LOAN" $52,810<br><br>PAYMENT: Principal & Interest $453.72<br>Taxes 100.00<br>Insurance 10.00<br>Private Mortgage Insurance + 23.75<br>TOTAL "EFFECTIVE LOAN PAYMENT" $587.47<br><br>NOTE: Items (2) & (3) above = "PITI - Energy Saved" Method and "EFFECTIVE LOAN" Method |

publicity and/or the home as a model to generate further sales.

### 4.7 Monitoring

The Bonneville Power Administration provided extra meter heads for the winning homes and reimbursed the builders for associated wiring charges. It should be noted that this cost to BPA (average: $200) was the only cash payment to the builder for the incremental costs incurred by building an energy conserving home. Virtually the entire incentive for their participation was, in other words, the advantageous mortgage financing and underwriting.

## 5. CONCLUSIONS

The Energy-Efficient Home Project of Oregon was a successful cooperative effort carried out by a unique coalition of public and private sector participants. By taking a marketplace approach and involving a full range of shelter industry participants, each actor was shown how they can benefit from their role in the process of building and selling solar/energy conserving homes.

The major points demonstrated by EEHPO:

- A mortgage financing/underwriting component will stimulate energy conserving housing activity, probably at much lower direct governmental cost than isolated award or training programs.
- Homebuilders will respond favorably to a non-prescriptive approach to more stringent conservation standards. The Northwest Power Planning Council's proposed new construction model standards for residential space heating in Oregon are 2.0 kWh/ft$^2$/year in Zone 1, and 2.6 kWh/ft$^2$/year in Zone 2. In EEHPO, it can be seen from Table 2 on the following page that 14 of 16 winning designs surpassed the model standards in a voluntary program! Allowing each builder to achieve a total performance target for space heating would probably meet much less resistance than the prescription of specific component standards.
- The sixteen homes are predicted to save over 2.8 million kWh of energy over the term of the morgages. BPA's project investment leveraged over $40 of mortgage money per dollar spent on the project.
- The experience with EEHPO is a major factor in the decision of the primary sponsor,

TABLE 2

ENERGY-EFFICIENT HOME PROJECT OF OREGON -- ENERGY USE PREDICTIONS FOR WINNING DESIGNS
(based on Uniform Energy Rating System)

| Firm | Area ($Ft^2$) | Predicted Space Heating | Space Heating Use Comparison $kWh/ft^2/year$ | | Predicted Water Heating | Code Water Heating |
|---|---|---|---|---|---|---|
| | | | Actual | Code | Actual | Code |
| ZONE ONE - West of Cascades - 4000-6000 HDD | | | | | | |
| ADVANCE | 1192 | 2346 kWh | 1.97 | 4.43 | 2053 | 4399 |
| EDWARDS | 1000 | 2053 | 2.05 | 4.40 | 2933 | |
| FULLER | 1224 | 2346 | 1.92 | 4.40 | 2053 | |
| HEARTWOOD | 1106 | 2199 | 1.99 | 4.37 | 2933 | |
| KOROBKIN | 1031 | 2053 | 1.99 | 4.41 | 2053 | |
| NORWOOD | 1216 | 2346 | 1.83 | 4.60 | 2933 | |
| NOVI | 1181 | 2199 | 1.86 | 4.40 | 2053 | |
| STEVE PYLES | 1194 | 2346 | 1.96 | 4.42 | 2933 | |
| GARY REID | 1184 | 2346 | 1.98 | 4.33 | 2053 | |
| S. CONCEPTS | 1080 | 2199 | 2.04 | 4.40 | 2053 | |
| WARDMARK | 1248 | 2053 | 1.64 | 4.40 | 2054 | |
| GREENWOOD | 1239 | 2346 | 1.89 | 6.15 | 2053 | 4399 |
| ZONE TWO - Eastern Oregon - 6000-8000 HDD | | | | | | |
| ADAIR | 1254 | 3226 | 2.57 | 7.02 | 2786 | 4692 |
| JOHNSON | 1161 | 2933 | 2.53 | 7.58 | 2786 | |
| PODOREAN | 1584 | 3226 | 2.04 | 7.41 | 2785 | |
| SUNDIGNE | 1300 | 3519 | 2.71 | 7.22 | 2933 | 4692 |

the Housing Division, to mount an effort to create the Energy Conserving Home Mortgage Program. Working again with BPA, the Housing Division's proposed program would involve upwards of 25 lenders and over 60 times the mortgage funds commitment. In terms of program dollars to mortgage funds, this two-year program would leverage over $25 of mortgage money for low-cost, energy conserving homes for each dollar spent.

The Energy-Effficient Home Project of Oregon opened the door for these possibilities.



## 6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the support and ongoing assistance of the following people: Gregg Smith, Administrator of the Housing Division, Oregon Department of Commerce; Sheila Baker, manager of the Single Family Mortgage Purchase Program; Robert Newbold, Oregon Department of Energy; the Western Resources Institute, for use of the Uniform Energy Rating System; Debbi Allen, of EEHG, and Marion Hemphill, of MH Energy Associates, for their assistance with the project; and finally, thanks to Wayne Hart of BPA, for being an especially helpful project manager.

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# TURNING ENERGY SAVINGS INTO SALES

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## ABSTRACT

Wonderland Hill Development Company has been building passive solar homes since 1974. Throughout this time period we've been the recipients of numerous energy-related awards based on our innovative design concepts and our emphasis on energy efficiency as an overall company identity. We believe that there are four factors that go into developing and implementing an effective energy marketing program. These four factors consist of design-build concepts, education of sales staff, advertising and public relations, as well as financing the last and most crucial of the four factors.

Here in the Denver area we are actively pursuing the Lending Community to recognize the potential advantage that energy savings can offer the marginal home buyer. Our latest project, The Cottages, an AFFORDABLE subdivision has received initial recognition from the lenders. Through presenting an accurate and thorough analysis of the projected energy savings the lenders in question have modified their conventional underwriting standards in order to take into account the long-term value of those estimated energy savings.

This paper will explore in detail how the market place takes the passive solar design principles to the home-building community, how we market, train, and advertise these savings, and how we convince the lenders that these savings will help more consumers qualify for a better, more energy-efficient home.

## 1. INTRODUCTION

As the price of energy has risen and the public has become more aware of energy issues, builders across the country have begun to take advantage of energy conservation as a factor effecting a home's marketability.

Jim Leach, Wonderland Hill President and the reelected chairman of the National Association of Home Builder's Energy Committee, is involved with training builders in understanding the market advantages that energy-efficient design and construction can offer.

The NAHB Energy Committee was originally established in 1979 to deal with pending federal energy regulations that would have severe impacts on the housing industry. Today the committee has a major focus directed toward promoting different ways that a builder can market energy.

Members of the Energy Committee and we at Wonderland Hill Development Company recognize that energy should be an issue with builders, not just because of the potential to foster more local or federal requirements, but because it has the potential to sell new homes. We've learned what it takes to put an effective energy marketing program together. We explain these four factors in detail in our comprehensive general brochure that we've entitled "Energy Economics." The following information is abbreviated from our brochure and our program.

## 2. DESIGN/BUILD CONCEPTS

In order to market an energy efficient home successfully it is important for our clients and our sales staff to understand what makes that home energy efficient in the first place. For this reason in our brochure we have a column donated to explaining how the combination of energy conscious design and quality construction results in lower utility bills for our homeowners. We point out that those highly marketable items such as greenhouses, tile floors, and brick walls contribute to the solar performance of the home as well as the livability.

In addition to these design/build concepts, we point out that we take the City of Boulder's building code, which is one of the strictest in the country and improve on it. In the chart below you'll see the NAHB Thermal Performance Standards for the Denver area and the Wonderland Hill Development Company

standard building procedures.

| | NAHB Standards | Boulder Code | WHDC Standards |
|---|---|---|---|
| Sidewall Insulation | R12 | R19 | **R19** |
| Basement Insulation | R3 | R10 | **R10** |
| Ceiling Insulation | R19 | R30 | **R30** |
| Air Change Rates | No Standard | No Standard | **0.5 per hour** |
| Window Requirements | Double Pane | Double Pane | **Wood Casement Double Pane** |
| Mechanical Equipment Requirements | No Standard | No Standard | **Electric Ignition Flue Dampers** |
| Solar Contribution | No Standard | No Standard | **Maximum Passive Gain Active DHW** |

Fig. 1. NAHB Thermal Performance Standards.

3. EDUCATION

Ten years ago most consumers were not interested in MPG comparisons when purchasing an automobile, also at that time energy costs to the homeowner were a relatively minimal expense. Today most consumers are concerned not only with MPG ratios but also with the energy costs associated with home ownership. We believe it is important for our customers to understand just how much energy costs have escalated over the past decade and what the projected energy costs are for the future. As the graph indicates, energy costs have risen steadily throughout the past decade. Between January 1, 1970, and January 1, 1982, the Public Service Company of Colorado recorded a 900% increase in gas rates. In other words, the average residential gas bill rose from $50.00 per year to $450.00. According to testimony from the Colorado Utilities Commission, natural gas prices are expected to increase 84% by 1985. From 1986 to 1992, gas prices are expected to increase 15% per year in our Scenario A and 7% per year in our Scenario B.

At Wonderland Hill Development Company we wanted to offer our potential buyers more detailed information on estimated energy performance and how that affects the actual costs to the homeowner. We hired The Energy Institute, a local energy research and engineering firm, to compare the calculated energy performance of three homes: a home built to Boulder code requirements, a typical 10-year old home and the Wonderland Hill NAHB Energy Saver Home. The Energy Institute (E.I.) used the existing monitoring data on the NAHB home (see caption) and tested the home for air infiltration and mechanical efficiency. Then they used these results to perform a comparative analysis between our home and the two other examples.

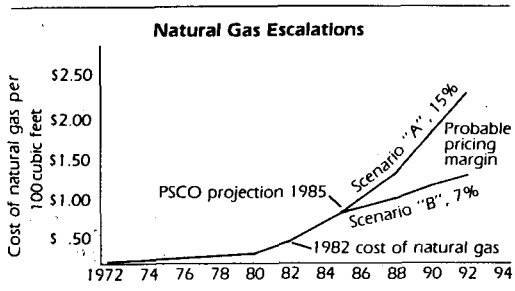



Fig. 2. Energy Costs.

**ENERGY ECONOMICS**

| Home | BTU/Year (millions) | Gas Costs 1972 | 1982 | 1985 | 15% Escalation 1992 | 15% Escalation 1982-1992 | 7% Escalation 1992 | 7% Escalation 1982-1992 |
|---|---|---|---|---|---|---|---|---|
| Average 10-year-old Boulder home* | 195 | $162 | $1040 | $1918 | $5084 | $30,042 | $3097 | $23,595 |
| New home built to Boulder city code | 130 | $180 | $ 696 | $1283 | $3401 | $20,097 | $2072 | $15,785 |
| **NAHB Home** | **27** | **$22** | **$144** | **$266** | **$704** | **$4,160** | **$429** | **$3,267** |

*According to City of Boulder 1980 Energy Study (average home adjusted to 2,300 square feet, same as NAHB home).

Fig. 3. NAHB Home Compared to Other Boulder Homes.

This information gets passed on to our sales staff. Not only do they understand basic principles of energy efficient design and construction but they have a good idea of how energy costs are expected to rise in the future and how that will impact a potential homeowner.

At this point in time we are hiring outside firms to actually come in and test our homes for air infiltration. This third party testimonial backs up in-house projections and shows potential home buyers that we are energy efficient builders. The firms compile their technical data into a computer printout which is part of a formal display in each of our models as well as an effective closing tool for our sales people.

## 4. FINANCING

With substantial energy savings as a part of the marketing package there should be a financing advantage for the prospective buyer. In certain areas of the country the more liberal lenders are reviewing current underwriting standards to take into account the advantage that energy savings can make for the potential home buyer. Basically the projected energy savings can be applied to the mortgage payments rather than to utility costs.

In our latest project, The Cottages, we have developed with the assistance of the Energy Institute a pilot energy financing program for the Denver area, entitled the Home Energy Loan Program (H.E.L.P.). The Energy Institute is now marketing their H.E.L.P. services to builders throughout the Denver area.

Their service involves a series of tests: air infiltration, furnace efficiency, and thermal performance analysis. The results of these tests are then programmed into their computer program which translates projected energy savings into today's value for the loan underwriter. This is just one type of financing program, there are several others in existence at this time. One assistance program available for builders utilizes a slide rule calculator for demonstrating and documenting estimated energy savings. According to Emmanuel Levy of Steven Winter Associates, Inc., who was involved with developing the program, "The use of the guidelines and slide rule concept provide the essential economic information necessary for builders to secure better financing terms with their lenders." In Oregon, Debbi Allen is working with the Bonneville Power Administration on evaluating current trends in energy related financing and she concludes, "Energy related financing is a viable alternative for the first time buyer who wants a more energy efficient home."

In conclusion there are some real opportunities for those builders and realtors who would like to do similar programs with the current solar tax credits still in effect. There are ample opportunities for others to convince the lending communities what innovative approaches to energy savings can mean to the marginal home buyer.

## 5. ADVERTISING AND PUBLIC RELATIONS

Implementing energy marketing into your advertising can be done subtly at first. At Wonderland Hill Development Company we like to stress the overall image of a particular project and highlight the projected energy efficiency in our copy. Our logo (see below) is a graphic illustration of our land (it's very hilly in Boulder) with a sunburst. Simple but it works. If you are building or selling energy efficient homes it is important that the general consumers in your area can identify that. Any and every channel should be used. Point out your energy involvement on your business cards, your brochures, and your signage programs!

Take advantage of the notariety that energy/solar still has. For example, schedule solar seminars for your local realtors. In Boulder we periodically hold evening get-togethers for realtors where we explain the basics of energy design as well as our latest housing projects. This same approach can be adapted to the local press community, articles on energy are still somewhat in demand and articles well placed in the local paper work a lot better than any ad campaign.

One word of caution, do not implement your advertising/public relations energy campaign before you educate your sales staff!!! Once you start drawing interest from potential home buyers in energy, make sure you have a staff prepared to answer energy-related questions, otherwise the whole concept may backfire.

## 6. CONCLUSION

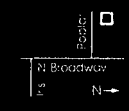
There is no question in our minds that energy is here to stay as an issue in housing. The energy quality of a home will be as important in the future as the interior finish, the appliance package, and volume spaces. Good energy conservation in a house implies a higher level of quality. This should be an important issue to the vast majority of today's home buyers. This extra quality does not come free - it adds to the general cost of the home. Therefore, like any other feature, it needs to be carefully considered in terms of its value to the potential home buyer and its need to be effectively marketed so the home buyer recognizes its value. This translates into energy marketing as a structure that home builders across the country are beginning to consider for their own in-house sales staff.

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# THE INCREASED USE OF PASSIVE SOLAR ENERGY IN SINGLE-FAMILY DWELLINGS, COLORADO SPRINGS, COLORADO U.S.A.

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## ABSTRACT

The cost of hydrocarbon energy increased drastically in the early 1970s. Because of a declining resource base, international politics,and an increasing inflation rate, the population of the United States became aware of an energy crisis.

The City of Colorado Springs and surrounding communities were more fortunate than many other areas throughout the United States. The cost of energy increased but because of a city-owned public utilities and advantageous contracts the cost of energy to residents remained in the lower 10% of energy costs through the United States. Even so, contractors. developers, local politicians and the average resident wanted to keep energy costs as low as possible. With both gas and electrical pricing increasing due to pass through rate adjustments and changing federal regulations the use of alternative energy sources started to become more common.

In Colorado Springs three energy sources became more frequently utilized: (1) electrical generation by wind; (2) active solar with hot water heating the domimant use; and (3) passive solar use for space heating.

The use of passive solar energy was used in both new building construction and as a retrofit procedure. Because of the cost of retrofitting this form of utilizing the sun's energy has not been as widespread as new construction but the use of greenhouses, Trombe walls, and increased window development on southern exposures has increased greatly since 1980 (Figure 1). The various uses of these techniques have been architecturally and technologically innovative and will be presented during the conference. The greatest increase in new passive solar developments has also occurred since 1980 but a major increase in the number of homes and business developments using this technology started in 1978 (Figure 1). A larger percentage of new homes in the $100,000+ category have occurred until recently when the new suburban developments of lower cost have been constructed on master plans which increase the southern exposure pattern. New homes of $50,000+ cost have an increasing number using passive solar energy for space heating. Several developments have all homes in the planned area using passive solar energy.

The liklehood that passive solar energy use will increase in the Colorado Springs region is also evident when three other factors are considered: (1) the increase in the sale of lots with southern exposures; (2) the subsequent increase in the purchase price for lots with a southern exposure (Figure 2); and (3) the ability to sell and rent passive solar homes.

As long as the people of Colorado Springs could rely on cheap fossil fuel sources for their energy needs; new, unknown energy sources were not considered. However, in the early 1970s the energy crisis became evident, because of the supply/demand resource base, the use of fossil fuel resources by importing nations, particularly OPEC, as a political lever and the worldwide inflation problem.

## 1. INTRODUCTION

The City of Colorado Springs owns the public utilities which has a capacity nearly double the peak demand needs. Because of this situation the city can sell the energy not needed by its local consumers to other electrical companies causing a considerable savings to the local community. However, as the prices increased due to federal regulation and pass through rate adjustments many individuals and groups, including contractors and developers in the building industry, politicians at all levels of government, and the individual home owners started investigating alternative sources of energy.

Because Colorado Springs is located in one of the two best possible climatic areas for solar energy utilization (cool/arid and hot/arid) (Figure 3), the construction industry immediately became aware that solar energy could be a useful energy source. Three specific solar energy

systems became more utilized: (1) electrical generation by wind; (2) active solar with hot water heating the dominant use; and most importantly (3) passive solar space heating.

The many groups and individuals in the construction industry became aware of the cost efficiency of passive solar energy over energy sources (Figure 4).

In addition, such site determinants as meteorlogic and climatic factors, topography, vegetation, ground surface moisture, as well as the subsurface factors became important in housing location, design, and construction. By using passive solar energy the relationships of the site determinants to such environmental conditions as solar lighting, protection and heating, wind use and protection, temperature, and the reduction of heat transfer became recognizable. This enhanced understanding increased the liklehood that we can live with and use our natural environment for a better living condition while attempting to maximize human comfort and minimize energy requirements.

In Colorado Springs topography is becoming the most important site characteristic. Not just because of the possibility of an enhanced scenic view but because of a combination of the local geology and climatic conditions. The area's urbanization is occurring primarily north and south across broad flat areas trending east from the mountain front. The flat areas have been dissected by stream erosion so approximately half of the land area is oriented to the south. Lots oriented in this direction are usually sold for 25-40 percent more than lots oriented in any other direction (Figure 2). There is a slightly higher price for southeast or south facing lots over southwest lots which is probably a result of the prevailing northwest winds during the fall, winter and spring seasons.

Also of importance is the location and kind of vegetation. The primary type of natural vegetation is coniferous trees. More and more this type of tree is left to the north of the home and often deciduous trees are planted to the south. This orientation is especially evident on passive home lots. Within the passive homes vegetation is becoming important in increasing the humidity of the home in this arid to semi-arid environment. Over 95 percent of the homes visited had an abundance of vegetation located along the southern exposure.

## 2. PROJECTS

Both new passive solar homes and retrofit construction are being developed in Colorado Springs with three new homes being built for every two retrofit modifications. This ratio is probably due to the general belief that it is more difficult and costly to modify an existing building for solar heating than it is to incorporate solar into new construction. Also, the building must be properly oriented to the sun and access to sunlight must not be blocked. However, the number of retrofitted passive solar homes shows that, at least in Colorado Springs, passive solar use is making sense as an add-on or modification to existing buildings. Many of the additions are also being designed to provide suitable roof space for active solar collectors to heat water. Unlike previous regional and national studies that indicate just over half of the existing passive solar applications are retrofits in Colorado Springs, 30 to 35 percent are retrofit (Figure 1).

Various varieties of passive solar systems have been used in the Colorado Springs region. Direct gain and thermal storage varieties dominate with reflector mechanisms being used to a much lesser degree (Table 1).

Several developments have all homes using passive solar energy. Seventy-five homes will be constructed at a passive solar single-family subdivision in Woodland Hills Village. These homes will sell between $85,000 and $100,000, contain 1,200 to 2,100 square feet and will be energy efficient with R-27 walls, R-40 and R-50 ceilings.

Sundance Estates will include 42 2½-acre lots with passive solar homes costing between $150,000 and $250,000 while Solar Ridge will include 30 such homes at a cost of between $100,000 and $115,000.

Southface/Rockrimmon will consist of zero-lot-line or patio passive solar homes while Stepping Stones West will include 160 condominium units using both passive and active systems. An additional twelve, two-bedroom, earth-sheltered homes are being constructed at Mesa Terrace. Totaling the above homes and projecting the present increase of retrofit homes there will be approximately 500 passive solar homes in Colorado Springs by the end of 1984. This is a yearly increase of 150 percent since 1980.

Passive solar energy will be utilized more and more in the Colorado Springs region. This is due to three factors: (1) the increase in southern exposure lot sales, (2) the subsequent increase in the purchase price for lots with a southern exposure and perhaps more importantly (3) the increased ability to sell and rent passive solar homes.

Just how passive solar home owners viewed the ability to sell and rent passive solar

homes is especially important considering the high rate of turnover in ownership throughout Colorado Springs due to the military personnel and high-tech industrial workers. It was discovered that after persons investigated the situation the following was believed: (1) If proper energy conservation was utilized passive solar buildings have lower overhead due to less maintenance, no or very little fuel cost, and reduced wear on the required conventional heating equipment installed to back up the solar system. (2) There is an increased sense of self-sufficiency and security against other energy supplies price increases and disruptions. (3) The belief that passive solar heated buildings will increase in value and marketability especially if fossil fuel prices continue to raise.

By observing the present data and the proposed plans passive solar energy homes will continue to increase rapidly in the future.

TABLE 1: The use of passive system varieties in percent. Totals are greater than 100 percent because more than one variety may be used in any given house.

| | | |
|---|---|---|
| A. Direct Gain | | 100 |
| 1. Greenhouse | 65 | |
| 2. Roof monitors | 45 | |
| 3. Window walls | 25 | |
| B. Thermal Storage | | 65 |
| 1. Glass-covered masonry walls | 35 | |
| 2. Drum wall | 45 | |
| 3. Roof-pond | 5 | |
| C. Reflectors | | 5 |
| 1. Reflective insulating panels | 5 | |
| 2. Pyramidal optic reflectors | 1 | |

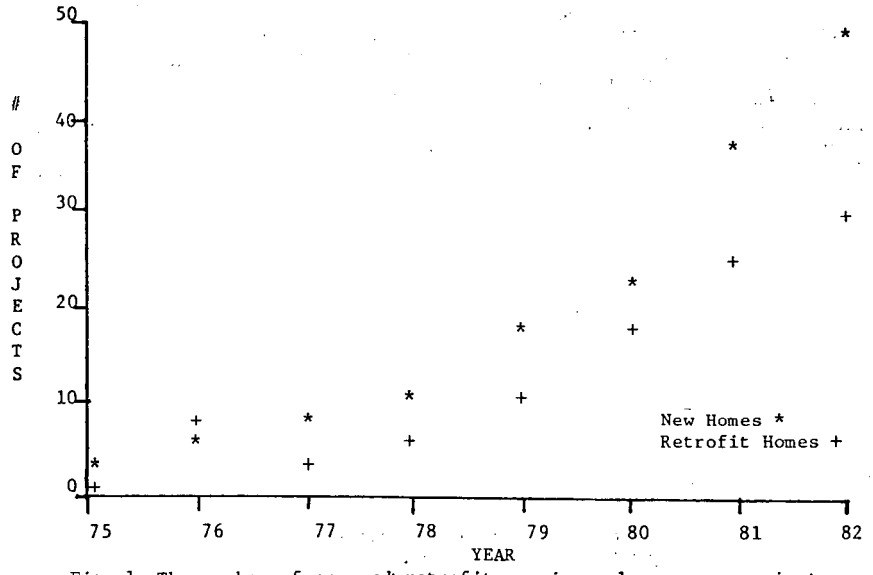



Fig. 1. The number of new and retrofit passive solar energy projects.

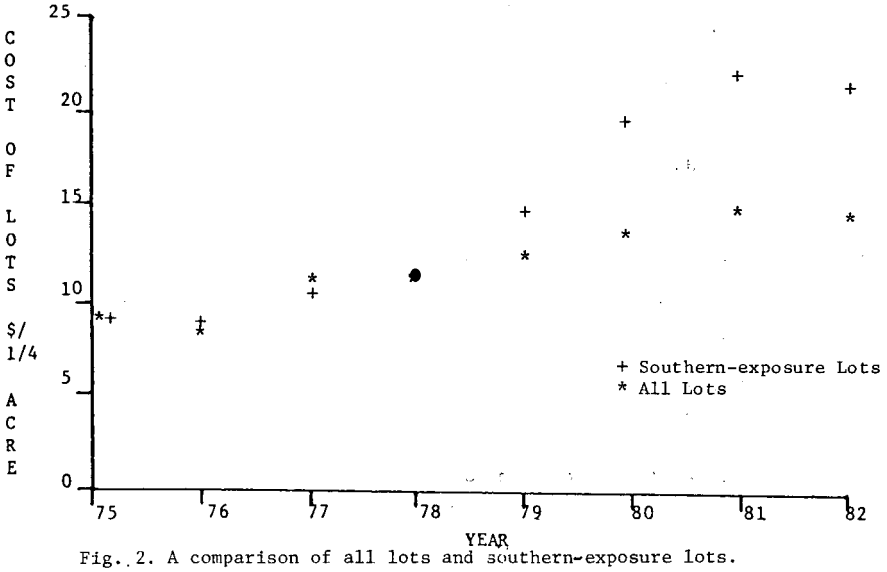



Fig. 2. A comparison of all lots and southern-exposure lots.

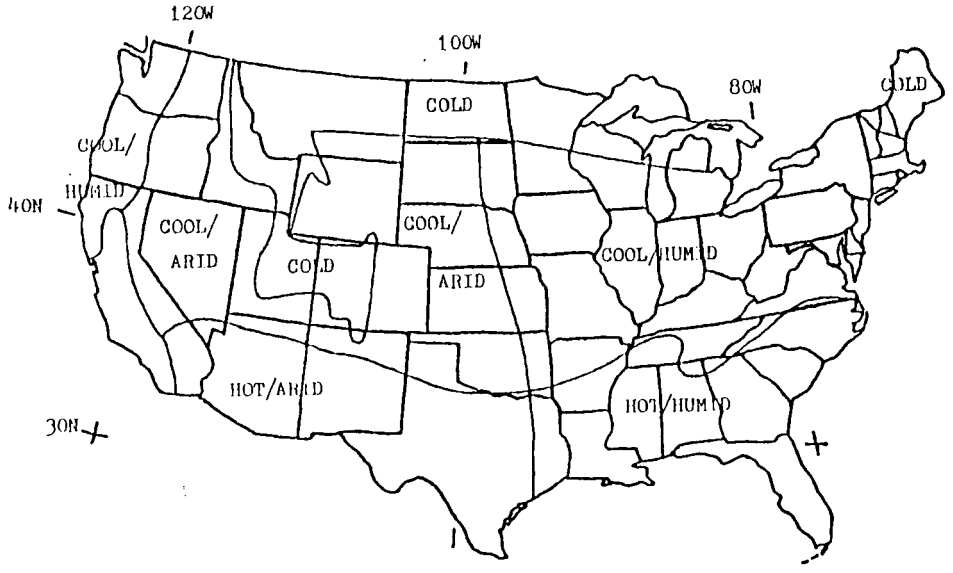



Fig. 3. Macroclimatic regional map of the United States.

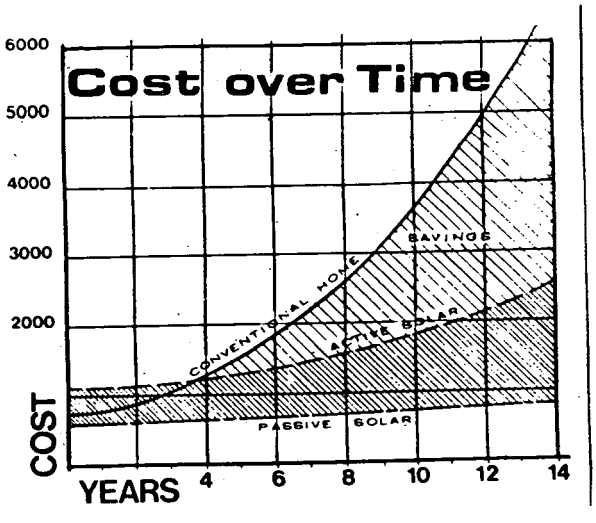



Fig. 4. The saving of money by using passive solar energy in single-family dwellings.

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0731-8626/83$3.00

# A BETTER UNDERSTANDING OF THE POTENTIAL PASSIVE SOLAR MARKET

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## ABSTRACT

The following information is presented in an attempt to clarify exactly how passive solar construction can best fit into today's housing market and identify the specific factors that make passive solar a marketable commodity. Informed builders can capitalize on an understanding of the variety of components -- including the general trend toward energy efficiency -- which affect a buyer's decision to purchase a home with solar features.

## 1. INTRODUCTION

Several major surveys will be compared in an effort to draw these conclusions. The first survey reflects a representative sampling of SOLAR SPEC plan modifications conducted by INNOVATIVE DESIGN. The others were selected because they polled both builders and buyers of both conventional and energy efficient homes.

## 2. THE 'SOLAR SPEC' PROGRAM DATA/ PROFESSIONAL BUILDER' SURVEY

The SOLAR SPEC program was originally developed through a grant from the N.C. Energy Division to implement passive solar concepts into the State's speculative home market. The program educated the speculative builders and worked with them in modifying their plans to incorporate passive design elements. Several other states in the Southeast subsequently subscribed to the program and, to date, approximately 450 different plans have been modified by INNOVATIVE DESIGN with savings in heating dollars averaging in excess of 50%. SOLAR SPEC program data was taken from 200 representative examples of the 450 designs modified. This survey represents the builders' perceptions of what the current housing market will bear. In working with each builder, the staff of INNOVATIVE DESIGN made every effort to maintain the style and major design features which the contractor thought were important for selling the home.

(For more information of the N.C. SOLAR SPEC program, see the proceedings of the SIXTH NATIONAL PASSIVE SOLAR CONFERENCE, p.547.)

The "Professional Builder", "Builder", and "Selling the Solar Home '80" surveys were chosen as a comparison because they reflect the preference of builders and buyers of "average" homes across the country, not just "solar" homes. For homes in various price ranges, the survey points out what is important to the buyer and what is being provided by the builder.

By looking at all the items important to the buyer, one can gain a better understanding of the average home buyer's concerns. By relating desirable elements to those that are also a feature of passive construction, the most logical and efficient means of implementation can be achieved.

(In reviewing the following information, remember that the SOLAR SPEC survey was conducted on homes modified for builders who were largely from North Carolina. Some differences may occur in other areas of the country.)

## 3. STYLE PREFERENCE

In the PROFESSIONAL BUILDER survey, one sees that traditional styles are still preferred

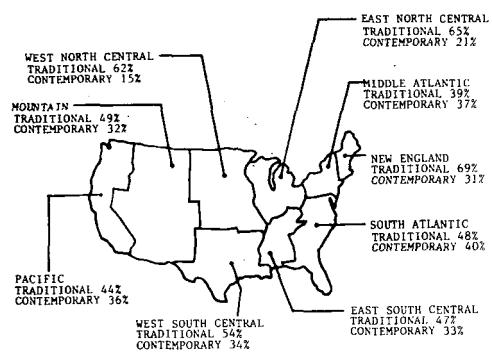



Fig.1. Buyer Style Preference.*

over contemporary designs throughout the country.

A look at the passive designs generated through SOLAR SPEC confirms this trend. Only 4% of the homes that came through the program were considered "contemporary." Most of the home designs could be classified as "modern" or "rustic," depending on the choice of exterior materials.

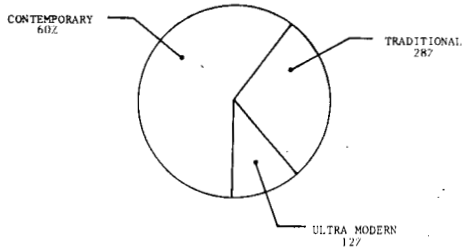



Fig.2. Style of Solar Homes **

## 4. SIZE

Both surveys indicate that the major market is in the 1000 - 2000 square foot range. This is no doubt affected most strongly by financial consideratons. In designing and building a passive solar home on a speculative basis, it would be considerable more risky to ignore the apparent financial restrictions of the majority of potential home buyers.

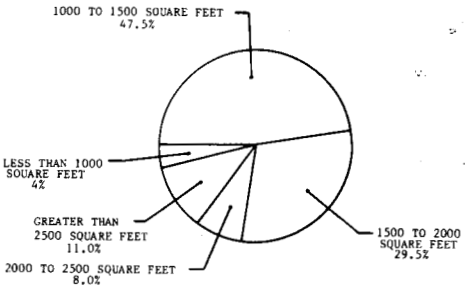



Fig.3. Size of Passive Homes

## 5. ARRANGEMENT OF SPACES

The SOLAR SPEC survey indicates that the easiest plans to work with for passive designs tend to be those that are one story (63%), probably because of the ease of introducing thermal storage in ground floor designs as opposed to strategies required by second story areas.

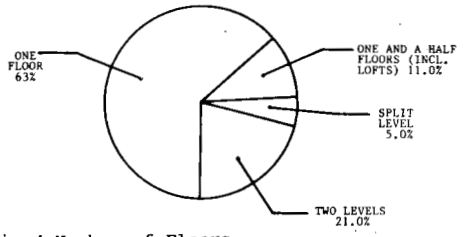



Fig.4. Number of Floors

The openness of plans affects convective air flows and the willingness of builders and buyers to utilize an open plan should be strongly considered when designing the home. In the SOLAR SPEC plans, horizontal openness did not seem to present a major problem for the builders, but vertical openess was much harder to achieve.

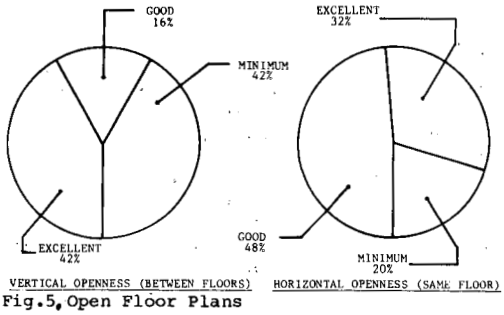



Fig.5. Open Floor Plans

Horizontal openness was more prevalent, mainly because of the trend toward smaller, more open homes. Openess is created primarily to make spaces seem bigger (e.g., great rooms); but nonetheless, it helps the air flow and thereby the solar performance.

## 6. ADVANTAGES AND DISADVANTAGES OF SMALL HOMES

In the next chart one notices energy efficiency is considered a major advantage to 40% of the buyers, second only to initial investment cost (68%).

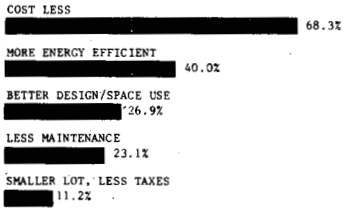



Fig.6. Advantages of Smaller, More Affordable Housing ***

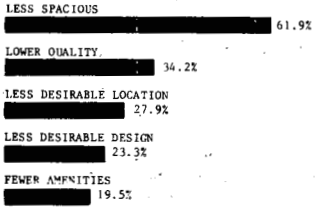



Fig.7. Disadvantages of Smaller, More Affordable Housing ***

And good passive design can often turn the major perceived disadvantage of smaller housing into a strong selling point. The large amounts of glass on the south side of passive homes, coupled with the vaulted ceilings often utilized to enhance air flow into second story spaces can easily increase the feeling of spaciousness in smaller homes. This can help overcome a major hurdle in selling a small home.

## 7. EXTERIOR APPEARANCE

The exterior appearance has for some time been a major factor in selling a home. So it is with passive homes. In comparing the two surveys, however, we find the first discrepancy. The national survey indicates that brick masonry is preferred by both builders (33%) and buyers (54%) of average homes; but 64% of the builders of passive homes are using wood siding.

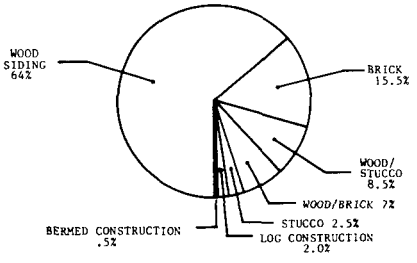



Fig.8. Exterior Finish of Passive Homes

This could be because passive home builders simply perceive wood siding as a more preferred exterior finish by the solar home buyer. Or perhaps because of the economic recession during the past few years, wood siding was selected more to reduce first cost than for aesthetics or maintenance reasons.

The exterior finish is not the only element that is important for "curb appeal." Of the features which the buyer is willing to pay more for, over and above those items which the average builder is providing, one item which stands out is landscaping. 33% of the consumers said that they would be willing to spend more for landscaping than was being provided by the builder. If this is indeed the case, this highly preferred option should not be overlooked as an energy saving measure.

## 8. INTERIOR CONSIDERATIONS

The national survey indicates that of the desired interior features, glass patio doors are items which nearly half of the average buyers are willing to pay more for, regardless of whether or not the design is solar. This item could therefore most easily be justified if they were also collection areas in a passive system. Another highly rated item was a ceramic tile entry area. If located on the south, this could also provide some thermal storage.

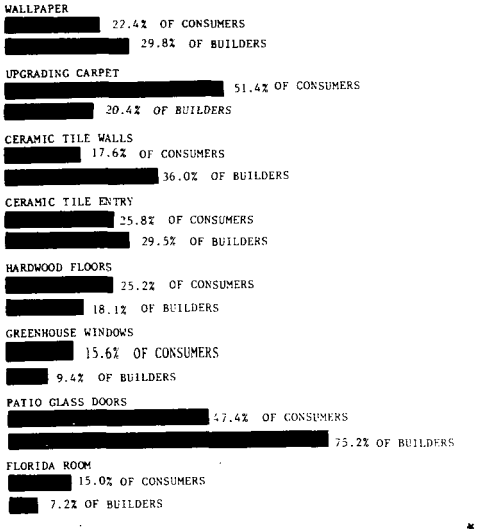



Fig.9. Interior Options Preferred vs. Provided*

Both surveys, however, indicate that carpet continues to be a very highly preferred floor finish. Throughout the SOLAR SPEC program, the most important factor determining the type or design of the passive system was whether or not carpet was to be the floor finish in a particular room. 81% of all builders insisted on carpet in the living or great room areas.

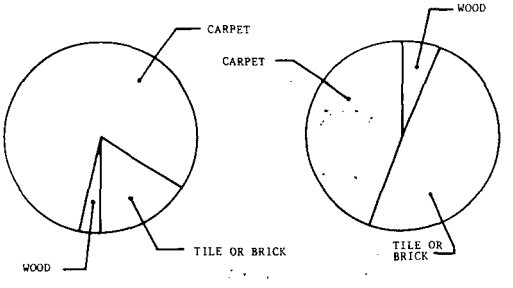



Fig.10. Floor Finishes in Passive Homes

This led to the selection of Indirect Gain, adjacent Isolated Gain, or confined thermal storage areas within Direct Gain spaces as logical options for areas that were to be carpeted. An adapted solution to this problem was the "Sunspot" which concentrated the thermal storage within several feet of the glass, was positioned to allow for light in and view out, and served to block the radiation from striking the furniture or carpeted area (often the entire living room).

Dining rooms were significaty different in terms of a preferred floor finish with close to 50% of the builders actually chosing brick or tile finishes, making "Direct Gain" a more viable solution for these areas.

"Spacious Feeling" and "Vaulted Ceiling"--both highly desirable features to the home buyer--can easily be achieved in passive designs, although they may sometimes conflict with the average home buyer's desired privacy. These seemingly conflicting criteria are often hard to achieve effectively simultaneously. The operable insulation necessary for maximum solar efficiency does, however, provide an option that, in addition to its thermal properties, gives the owner privacy and in some cases security.

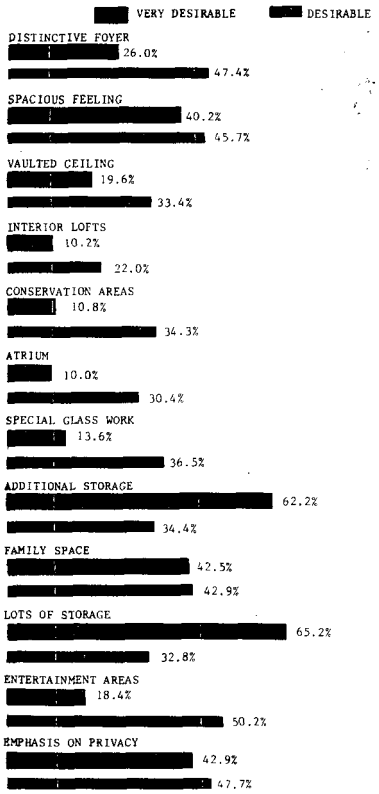



Fig.11. Desirability of Features *

A few other features deserve noting. The "Distinctive Foyer" indicates an area where the buyer is willing to spend additional money. Tile floors are a logical option in this space. Throughout the SOLAR SPEC program many builders have opted for creating a Sunspace entrance foyer or a Direct Gain solution with the appearance of a Sunroom.

The "Extras for the High End Buyer" graphic demonstrates again that the average buyer is willing to spend money for many items included in most passive designs regardless of whether or not it was solar related. $300 for tile floors in entry areas was favored by 53% of the buyers. This can serve as thermal storage as can the mass for fireplaces of which 77% of consumers will spend $2500. 36% of buyers will spend $1500 to create the open feeling associated with sloped ceilings in family rooms. Attitudes about windows and other glazed areas are also encouraging. 47% will pay up to $600 for skylights. $1700 for a bay window is an item that 48% of the buyers consider important. And 24% of the purchasers would pay $4000 for an atrium. Remember that this is regardless of solar considerations.

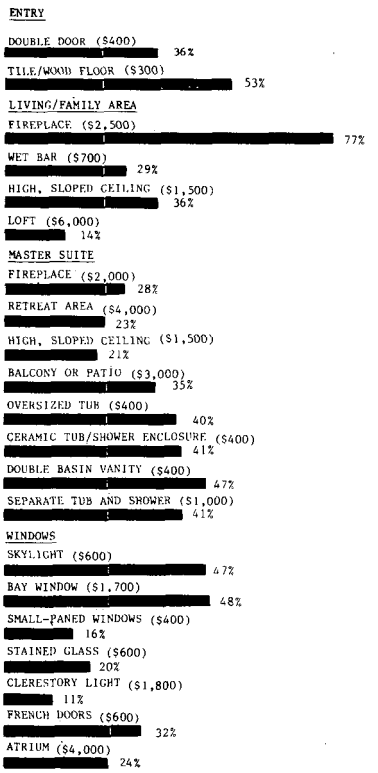



Fig.12. Extras for the High End Buyer ****

The "Lower End Buyer" will also pay extra for many of these same items; skylights - 40%, tile entry - 40%, greenhouse windows - 35%, and sloped ceilings - 54%. All of these are applicable to passive design.

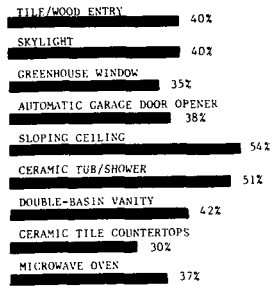



Fig.13. Extras for the Low End Buyer ****

This information indicates that there are many items which the consumer already wants and which designers of passive homes can incorporate to enhance the solar contribution. The systems selected by the SOLAR SPEC builders reveals several interesting facts. 96% of the homes modified incorporated at least some Direct Gain features. Of these, the most popular concept was the "Sunspot" which was built for its "greenhouse" appearance as well as the items already discussed. Indirect Gain system were designed into 17% of the homes, with only 1% of the residences utilizing water storage, presumably because of aesthetics. The Isolated Gain and Indirect Gain solutions were used with about the same frequency (16.5%). Although the Sunspace was aesthetically the favorite of the various systems, most of these homes were between 1200 and 1850 square feet, leaving little space to sacrifice to an area with high temperature swings. For this reason, "Sunspots" were more often built.

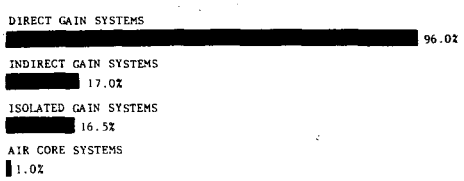



Fig.14. Types of Passive Systems

## 9. SPECIFIC ENERGY OPTIONS

To the home buyer energy consumption is a major concern with only "Interest Rate," "Monthly Payment," and "Location" being more significant.

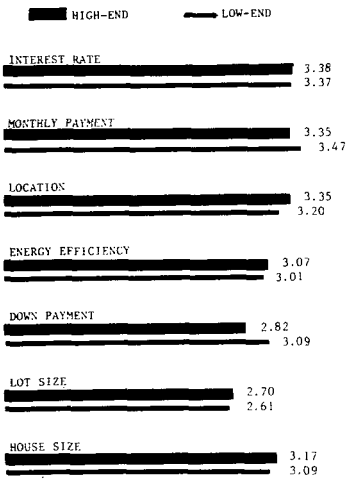



Fig.15. Factors in the Buying Decision ****

In looking at the energy options that the average buyer will pay more for, 16% - 23% indicate that they would finance an additional $4000 for a solar domestic hot water system and 17% to 20% see the value of spending $9500 for solar space heating. Consumers are increasingly aware of the advantages of energy conservation and are willing to pay additional money up-front to get it. Yet only 2.2% of the builders are supplying solar water heating, and solar space heating is virtually unheard of in the speculative market.

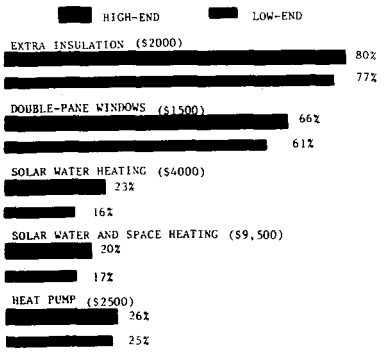



Fig.16. Energy Saving Extras ****

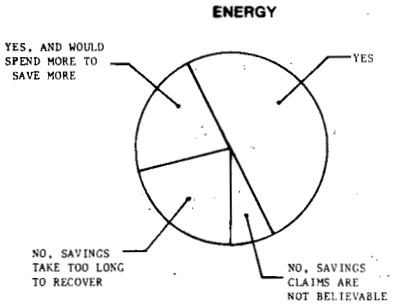



Fig.17. Up-Front vs. Long Term Costs *

## 10. CONCLUSIONS

The passive solar designers and builders can use information presently available on what potential buyers want in homes and what they are willing to pay for; by successfully integrating these features into passive solutions, the end product should be desirable regardless of its solar benefits. The additional cost of passive systems need not be an issue. Amenities cost more in any home. By creating dual functional amenities, passive solar will be much easier to sell.

* Source: PROFESSIONAL BUILDER, Dec. 82.

** Source: SELLING THE SOLAR HOME '80.

*** Source: PROFESSIONAL BUILDER Jan. 83.

**** Source: BUILDER, Jan. 83.

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# ENERGY CONSERVATION TO REDUCE SUMMER COOLING COSTS IN PALM SPRINGS

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## ABSTRACT

Various energy conservation techniques (ECTs) which can be retrofit installed on most houses to reduce summer cooling loads are evaluated from technical and economic criteria. Palm Springs represents one of the most severe summer climates in the United States and is chosen for study. The impacts of several ECTs are considered including: insulating stud walls, insulating window shutters, shading windows, installing double pane windows, and application of reflective tint film to windows.

A methodology is developed to estimate the reduction in heat gain attributable to each ECT during the summer, and also winter performance, and to estimate the dollar value in terms of reduced air conditioning bills. The annual dollar benefit attributable to each ECT for different compass orientations is estimated for 1981 residential consumer energy prices. An economic Figure of Merit (FOM) is employed to allow ranking of the candidate ECTs.

## 1. INTRODUCTION

This paper reports on a study dealing with residential energy conservation in hot desert areas. Palm Springs was chosen as a representative desert area; each summer day the average shade air temperature can reach 110°F (43°C), with 120°F (49°F) not being uncommon. Minimum summer nighttime air temperature can remain above 80°F (27°C). Weather data used in the analysis were taken from monthly degree-day compilations (Ref 1), hourly insolation data (Ref 2) and hourly temperature data (Ref 3).

The effects of retrofitting certain energy conservation techniques (ECTs) in residential buildings are estimated. The analysis also estimates how much heat can be saved throughout the winter heating months and the attendant heating bill reduction attributable to the ECT. This study places the technical and economic performance of each of these ECTs into proper perspective. The list of candidate ECTs considered here is not exhaustive, but has been selected from a list of readily available and common items.

## 2. CANDIDATE ENERGY CONSERVATION TECHNIQUES (ECTs)

It was previously shown from economic considerations that any house without attic insulation in hot desert climates should have insulation retrofit installed (Ref 4). The other obvious ECT which should be installed in every case without question is weather-stripping (Ref. 5). Therefore, it is assumed in this paper that attic insulation and weatherstripping are already applied prior to consideration of the ECTs described below.

In this section we consider the impact of windows on different sides of the house and the reduction in summer heat gain which can be achieved by different conservation techniques (ECTs). The effect of ECTs on heat gain through hollow stud walls is also considered. The hourly and daily heat gain for an average July day in Palm Springs is estimated through both a west window and a south window, and also through stud walls, along with the cost to air condition a house due to these gains. An east window (wall) performs somewhat similar to a west window (wall), and in July a north window (wall) is not dissimilar in performance from a south window (wall), particularly if the south window has a modest overhang. The calculations are made for several window conditions, including:

Case 1 -- unprotected window;
Case 2 -- window protected with reflective see-through tint;
Case 3 -- window protected by large awning to provide complete shade to the window and surrounding ground;
Case 4 -- unprotected double pane window;
Case 5 -- a window protected with an insulating shutter.

## 3. APPLICATIONS AND RESULTS

Heat gain through windows is due to two major components: direct solar gain (which includes a diffuse gain of 30 to 40 $Btu/hr\text{-}ft^2$), and thermal conductance due to elevated exterior air and effective radiation temperature. Space precludes presenting the analytical development of the equations which were used to estimate annual summer and winter energy

This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the Southern California Edison Company.

savings due to the ECTs, but the full development is available (Ref. 6). Basically, an energy balance was made on the window or wall, accounting for radiative contributions from both direct insolation, diffuse sky radiation, and diffuse radiation from the ground. Note that the ground radiative contribution can be substantial, since the ground temperature can reach 160°F in full sun. For window analysis the base case was the single pane window in full sun (unprotected). Estimates were made for total heat gain during both the summer cooling season and also winter heating season for windows facing south, east and west. Then the quantity of heat reduction through the considered component over a summer heating season is estimated for each ECT for each compass orientation, relative to the base case. For a wall the base case is an uninsulated 2x4 stud wall (R-4.8 hr-ft$^2$-°F/Btu , and the insulated wall has R-12.3. Retrofit insulation of a 2x4 stud wall was found to cost 60¢/ft$^2$ when installed by professional contractors.

The equations are valid either for a double pane light transmitting window or an opaque wall, insulated or not.

After summer cooling season heat admitted through the window or wall is estimated for all conditions, then the seasonal cost of removing the heat gain by a mechanical air conditioner is estimated. This annual undesirable heat gain is $Q_{in}$. Every Btu which enters through the skin must be removed by the air conditioner, for which the coefficient of performance (COP) depends upon both the interior air temperature ($T_{in}$) and the ambient air temperature ($T_{out}$). The cost of removing the heat gain is given by equation 1.

$$COP = \frac{\text{Useful Cooling Effect}}{\text{Power In}} = \frac{Q_{in}}{P_{in}}$$

Unit Power Cost = UPC = (¢/kWh is the electricity cost to the consumer. Power consumed is

$$P_{in} = \frac{Q_{in}}{COP(3414\ \frac{Btu/hr}{kW})} \qquad Q \equiv Btu/hr\text{-}ft^2 \qquad P \equiv kW/ft^2$$

so

$$COST = UPC * P_{in} = \frac{UPC * Q_{in}}{3414 * COP} \qquad (1)$$

The cost of electricity was assumed to 8.197¢/kWh for air conditioning. The air conditioner EER = 10.2 (COP = 3.0) when the outside temperature was less than 100°F and EER = 8.2 (COP = 2.4) when $T_{out}$ was 100°F or greater.

Similar type calculations were produced for each ECT for each compass orientation, for each hour of a "typical" day (Ref. 3). To facilitate comparisons, the salient results for summer are assembled in Table 1, where energy and money savings per unit area in July are quantified for different conditions. Let us first consider windows in Table 1. From the daily heat gain column and cost of heat removal column, it is apparent that windows allow a much greater quantity of ambient heat to enter the house interior per unit area than do walls, and the cost of heat removal per unit area is much greater for windows than for walls. But comparisons also indicate that opportunities to reduce heat gains through windows are greater for windows than for uninsulated and unshaded walls. Comparing reflective tint (Approach 2 in Table 1) with double pane windows (Approach 4) one sees that the July effect in heat gain reduction is nearly equal for each approach, with an east or west window tending to favor the tint due to the high solar exposure, and the south window favoring the double pane or storm window because of the reduced direct solar incidence and the 24 hour/day protection provided by the double pane. The double pane window provides also a winter benefit, whereas a tinted window can reflect welcome sun in the winter - a seasonal disbenefit.

Maintaining the window and surrounding ground in shade (Approach 3) is technically more effective for windows of all summer orientations than either double panes or tinted glass; it will be shown below that shading windows is also more cost effective than the other two approaches. The beneficial summer effect of shaded windows and surrounding ground, while being intuitively obvious and consistent with observations and experience of most people, is quantified in Table 1. The costs of heat removal per unit area are somewhat proportional to the heat gain reduction, and for shaded windows the savings come during the day, when peak loads occur. From technical performance criteria, the most effective conservation technique considered for summer window heat gain reduction is insulated reflecting shutters (Approach 5). 95% of the heat gain can be eliminated with a reflecting shutter having an R-8 hr-ft-°F/Btu insulating value.

Most houses in Southern California are of 2x4 stud construction without insulation. An uninsulated east or west facing stud wall in Palm Springs in July gains 144 Btu/day-ft$^2$, and retrofitting insulation reduces the gain by 61% to 56 Btu/day-ft$^2$. Placing the same wall (and surrounding ground) in the shade reduces the heat gain by 42%, to 83 Btu/day-ft$^2$, from which we can conclude that insulation is technically more effective than shading. Insulation also produces a winter thermal benefit, whereas the shading capability does not. Combining both wall energy conservation techniques (ECT s) insulation and shading, gives a total reduction of 77%, to 33 Btu/day-ft$^2$. Similar results pertain to the south wall. The result is that insulation of a cavity wall yields better summer performance than shading the wall.

Note that when combining ECT s applied to the same element (wall or window) it is not possible to add the separate contributions, since in the wall case the total saving would have been 61% for insulation and 42% for shading; 61% + 42% = 103%, an impossibility. Generally, application of ECT s reach a point of diminishing returns, since as the heating or cooling load is reduced by the first ECT then the contribution possible by succeeding ECT's is reduced.

Since the ECTs will be ranked according to economic performance criteria, it is necessary to estimate the annual money saved by application of each candidate ETC. Column 4 of Table 1 summarizes the estimates made in previous calculations for cost saving per unit area for a typical July 24-hour period. It is necessary to extend these estimates to annual savings. We expand the daily money saving accured to each ECT to an annual saving by considering that money expended to provide cooling is proportional to the cooling load as defined by cooling degree-days.

$$\text{ANNUAL SAVING} = \frac{\text{(July Saving)}}{\%\ \text{Cooling Load in July}} \qquad (2)$$

Annual money saving per unit area calculations are summarized by the last column in Table 1.

These ECTs will in most cases be installed year round and have an impact on the winter heating bill also. Therefore the winter effect and money saved (or lost!) by each ECT must be considered in order to make a valid life cycle cost comparison.

Using a typical January day (from Ref. 3) a similar winter calculation was conducted for each considered ECT as was done for the summer condition in Table 1. Window tint and shading produce winter disbenefits, whereas double pane windows, insulating shutters and insulated walls produce winter and summer benefits. The results are quantified in the study. Three modes of heating are considered and the annual winter money required to make up heat lost through (or saved by gain) is estimated for each mode. The three modes of heating evaluated are: (1) electric resistance heating (8.2¢/kWh ), (2) heat pump with COP = 2.4 and electric cost of 8.2¢/kWh and (3) natural gas heating at 50¢/Therm.

The results are presented in Table 2, where it is assumed that the cost of gas is 35¢/Therm, and with a combustion efficiency of 70%, the actual cost of delivered heat to the house is 50¢/Therm.

The results of the financial performance for each ECT summer and winter condition are taken from Tables 1 and 2 respectively, and added in Table 3, which yields the annual economic performance achieved by each installed ECT. Table 3 then provides the input necessary for a life cycle costing calculation.

## 4. RANKING THE CANDIDATE ECTs

The appropriate tool for ranking the candidate ECTs is life cycle costing, since most consumers are motivated by pecuniary considerations. Thus, each ECT will be considered only as a financial investment relative to an alternative investment which pays an after-tax interest rate i (or conversely i could be the after-tax interest rate on borrowed money over the life of the investment). The life cycle cost leads to an economic figure of merit (FOM), developed elsewhere (Refs. 5, 6, 7 or 8).

FOM =

$$(1+i)^L \left\{ \frac{R/S}{j-i} \left[ \left( \frac{1+J}{1+i} \right)^L - 1 \right] - 1 \right\} \quad (\text{for } j \neq i) \qquad (3)$$

When i = j we get

$$\text{FOM} = (1+i)^L \left[ \frac{(R/S)L}{1+i} - 1 \right] \quad (\text{for } i = j)$$

where

S = Initial cost of installed ECT ($)

R = First year annual energy saving ($/year)

i = Interest rate which the investor could realize on an alternative investment, or the interest rate on borrowing money, after taxes (a decimal)

j = Energy annual cost escalation factor (a decimal)

L = Useful Lifetime of ECT (years)

Note that R is the first year annual energy dollar saving ($/ft$^2$-year) listed in Table 3. Since S is the installed cost of the ECT, S/R is the simple payback period which ignores the time value of money. The reciprocal of S/R, namely R/S, is the first year capital recovery factor. The Figure of Merit (FOM) expressed by equation 3 is used in this study to rank the various ECTs against each other by comparing them to an alternative other than the ECT investment which the prudent investor could make. A negative value means that the ECT should not be installed for the considered condition, since an investment paying compound interest at rate i would be economically preferable. A positive FOM means the ECT is a better investment than the conventional alternatives. Also, it is stressed that 2 ECTs applied to a window (or generally in series) reduce the effect of each other. Thus, ECTs characterized by the highest FOMs are the devices which should be installed first.

To evaluate the previously considered ECTs using 1981 economic conditions, it is assumed that the after-tax interest rate which a taxpayer-homeowner can earn in a safe investment is 10% year (i = 0.10). It is also assumed that the taxpayer can achieve a 10%

return on money saved on utility bills by the installation of ECTs. The energy annual cost escalation factor used in this report is 14%/year (j - 0.14), which is consistent with economic experience over the past decade.

The initial installed cost of the ECTs considered in this chapter are estimated from telephone surveys to commercial retailers in Southern California, such as hardware stores and insulation contractors. Lifetime of each device is estimated from information gained through these surveys, commercial literature, and various reports.

Examination of Table 3 indicates that the investment in ECTs is sensitive to energy cost, and that some ECTs have the potential to save much more money than others. In fact, some ECTs produce a net annual money loss because the winter disbenefit outweighs the summer contribution; the prime example of this net annual loss is reflective tint applied to south facing windows, which for all conditions in Table 3 results in a net annual money loss due to increased energy bills! Note in Table 3 that the same reflective tint applied to west or east facing windows can produce a net annual money gain, depending upon the cost of winter energy for heating.

The technique is applied to estimating FOMs for the candidate ECTs with their compass-point deployments, and the results are listed in descending order of FOM value in Table 4. Table 4 is self explanatory.

5. REFERENCES

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(2) ASHRAE Handbook of Fundamentals, 1977

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(5) Turner, R.H., Birur, G. C., and Daksla, C., "Retrofit Energy Conservation in Residential Buildings in Southern California"; JPL Publication 82-55, June, 1982

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

TABLE 1

DAILY AVERAGE HEAT GAIN AND COST OF HEAT REMOVAL THROUGH WINDOWS AND STUD WALLS IN PALM SPRINGS

$T_{Inside}$ = 75°F = 24°C

Energy Cost = 8.197¢/kWh

| Case and Description | Daily July Heat Gain, $Q_T$ Btu/day-ft$^2$ | Heat Reduction Percent Compared to Base Case | Cost to Remove $Q_T$ ¢/ft$^2$-day | Annual Money Saved Compared to Base Case $/ft$^2$/year |
|---|---|---|---|---|
| West or East Windows | | | | |
| 1 Unprotected-Single Glazed | 1792 | 0% | 1.70 | 0 |
| 2 Reflective Tint | 1053 | 41% | 1.00 | 0.90 |
| 3 Window and Ground Shaded | 438 | 76% | 0.42 | 1.65 |
| 4 Double Pane | 1255 | 30% | 1.19 | 0.66 |
| 5 Insulating (R-8) and Reflecting Shutter | 72 | 96% | 0.09 | 2.07 |
| South Windows | | | | |
| 1 Unprotected-Single Glazed | 1210 | 0% | 1.15 | 0 |
| 2 Reflective Tint | 892 | 26% | 0.85 | 0.39 |
| 3 Window and Ground Shaded | 438 | 64% | 0.42 | 0.94 |
| 4 Double Pane | 714 | 41% | 0.68 | 0.60 |
| 5 Insulating (R-8) and Reflecting Shutter | 66 | 95% | 0.06 | 1.40 |
| West or East Stud Walls | | | | |
| 1 No Insulation (R-4) In Sun | 114 | 0% | 0.136 | 0 |
| 2 Insulated (R-12) In Sun | 56 | 61% | 0.053 | 0.107 |
| 3 No Insulation (R-4) In Shade | 83 | 42% | 0.079 | 0.073 |
| 4 Insulated (R-12) In Shade | 33 | 77% | 0.031 | 0.135 |
| South Stud Walls | | | | |
| 1 No Insulation (R-4) In Sun | 121 | 0% | 0.115 | 0 |
| 2 Insulated (R-12) In Sun | 47 | 61% | 0.045 | 0.090 |

TABLE 2

EFFECT OF ECTs THROUGH A TYPICAL PALM SPRINGS WINTER (November through March)

$T_{Inside}$ = 70°F = 21°C

Electricity Cost = 8.2 ¢/kWh

Gas Heating = 50¢/Therm

+1 Therm = 100,000 Btu price includes combustion efficiency of 70%)

| Case and Description | 1 Heat gained(+) or Lost (-) Btu/Winter-ft$^2$ | 2 Btu/Winter-ft$^2$ Heat Saved Compared to Base Case | 3 $ Heat Saved Compared to Base Case | Money saved (+) or lost (-) due to ECT each winter $/Winter-ft$^2$: 4 Electric Resistance Heating | 5 Heat Pump COP = 2.4 | 6 Gas Heating |
|---|---|---|---|---|---|---|
| West or East Windows | | | | | | |
| 1 Unprotected-Single Glazed | +41,274 | 0 | 0% | 0 | 0 | 0 |
| 2 Reflective Tint | -19,727 | -61,100 | -148% | -$1.47 | -$0.61 | -$0.31 |
| 3 Window and Ground Shaded** | -26,800 | -68,072 | -165% | -$1.63 | -$0.68 | -$0.34 |
| 4 Double Pane | +54,974 | +13,700 | +33% | +$0.33 | +$0.14 | +$0.07 |
| 5 Insulating (R-8) and Reflecting Shutter* | +92,113 | +50,839 | +181% | +$1.22 | +$0.51 | +$0.25 |
| South Windows | | | | | | |
| 1 Unprotected-Single Glazed | 150,072 | 0 | 0% | 0 | 0 | 0 |
| 2 Reflective Tint | 14,743 | -135,330 | -90% | -$3.25 | -$1.35 | -$0.68 |
| 3 Window and Ground Shaded** | -26,800 | -176,872 | -118% | -$4.25 | -$1.77 | -$0.88 |
| 4 Double Pane | 148,540 | -15,320 | -190% | 0 | 0 | 0 |
| 5 Insulating (R-8) and Reflecting Shutter* | 200,900 | +50,800 | +34% | +$1.22 | +$0.51 | +$0.25 |
| Stud Walls | | | | | | |
| 1 No Insulation (R-4) | -7,440 | 0 | 0% | 0 | 0 | 0 |
| 2 Insulated (R-12) | -2,480 | +4,960 | +67% | +$0.12 | +$0.05 | +$0.025 |

*It is assumed that the shutter is open during the day to allow sunlight to come into the room through the window, and closed at night to reduce heat loss.

**

TABLE 3

SUMMER AND WINTER ELECTRICITY COST = 8.2¢/kWh

ANNUAL ECONOMIC PERFORMANCE OF EACH ENERGY CONSERVATION TECHNIQUE (ECT)

| Case and Description | Summer Money Saved Compared to Base Case (From Table 9) $/ft²-Summer | Money Saved (+) or Lost (-) Due to ECT Each Winter (From Table 11)($/ft²-Winter) | | | Annual Money Saved (+) or Lost (-) Due to Each ECT with Mode of Winter Heating $/ft²-year | | |
|---|---|---|---|---|---|---|---|
| | | Electric Resistance Heating | Heat Pump COP = 2.4 | Gas Heating | Electric Resistance Heating | Heat Pump COP = 2.4 | Gas Heating |
| West or East Windows | | | | | | | |
| 1 Single Glazed (Base Case) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 Reflective Tint | +0.90 | +1.47 | -0.61 | -0.31 | -0.57 | +0.29 | +0.59 |
| 3 Window and Ground Shaded, Winter and Summer | +1.65 | -1.63 | -0.68 | -0.34 | +0.02 | +0.97 | +1.31 |
| 4 Window and Ground Shaded, Summer only | +1.65 | 0 | 0 | 0 | +1.65 | +1.65 | +1.65 |
| 5 Double Pane | +0.66 | +0.33 | +0.14 | +0.07 | +0.99 | +0.80 | +0.73 |
| 6 Insulating Shutter | +2.07 | +1.22 | +0.51 | +0.25 | +3.29 | +2.58 | +2.32 |
| South Windows | | | | | | | |
| 1 Single Glazed (Base Case) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 Reflective Tint | +0.39 | -3.25 | -1.35 | -0.68 | -2.86 | -0.96 | -0.73 |
| 3 Window and Ground Shaded, Winter and Summer | +0.94 | -4.25 | -1.77 | -0.88 | -3.31 | -0.86 | +0.06 |
| 4 Window and Ground Shaded, Summer only | +0.94 | 0 | 0 | 0 | +0.94 | +0.94 | +0.94 |
| 5 Double Pane | +0.60 | 0 | 0 | 0 | +0.60 | +0.60 | +0.60 |
| 6 Insulating Shutter | +1.40 | +1.22 | +0.25 | +0.25 | +2.62 | +1.91 | +1.65 |
| Stud Walls | | | | | | | |
| 1 No Insulation (R-4) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 Insulated (R-12) | +0.10 | +0.05 | +0.25 | +0.025 | +0.22 | +0.15 | +0.125 |

TABLE 4

RANKING THE CONSIDERED ECTs

Summer Cooling Electricity Cost = 8.2¢/kWh and Heating by Gas at 50¢/Therm or Heat Pump with COP = 2.4 and Winter Electricity at 4¢/kWh (1981 Rates)

| Rank | ECT and Orientation | ECT Cost Range | FOM Range | Comments or Observations |
|---|---|---|---|---|
| 1 | Insulating Shutters West Window | $1 to $3/ft² | 12 to 40 | May require daily task |
| 2 | Window and Ground Shade - West or East, Summer Only | $1 to $2/ft² | 13 to 28 | Requires seasonal task |
| 3a | Reflective Window Tint-E or W | 90¢/ft² | 10 if life time of tint is 15 years | |
| 3 | Insulating Shutters South Window | $1 to $3/ft² | 9 to 28 | May require daily task |
| 4 | Window and Ground Shade - West or East, Permanent | $2 to $4/ft² | 9 to 18 | |
| 5 | Window and Ground Shade - South, Summer Only | $1 to $2/ft² | 7 to 16 | Requires Seasonal Task |
| 6 | Insulating Shutters West | $4 to $6/ft² | 6 to 9 | May require daily task |
| 7 | Insulating Stud Walls | 60¢/ft² | 5 | House Exterior needs to be painted after retro-fit insulation installation (not included in FOM) |
| 8 | Insulating Shutters South | $4 to $6/ft² | 4 to 6 | May require daily task |
| 9 | Double Pane Windows West | $2 to $3 | 3 to 5 | Low care, may help reduce infiltration |
| 10 | Double Pane Windows South | $2 to $3 | 3 to 4 | Low care, may help reduce infiltration |
| 11 | Reflective Window Tint - West | 90¢/ft² | 3 | Lifetime = 5 years |

MONEYLOSER!: Reflective Window Tint on South Window; winter reflected solar input disbenefit outweighs summer reflected heat benefit.

VERY POOR INVESTMENT!: Permanent shade for south windows.

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# AN ANALYSIS OF THE BENEFIT-COSTS OF ALTERNATIVE FENESTRATION ASSEMBLIES FOR INTERNAL-LOAD-DOMINANT BUILDINGS NOTING SOLAR HEAT GAIN CONTROL AND DAYLIGHTING PROVISION

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## ABSTRACT

A series of alternative fenestration assemblies for a prototypical office building located in Seattle has been analyzed in terms of energy-efficiency and cost-effectiveness. Three computer programs -- UWLIGHT, SUNSXN, and HOUSE -- are exercised to estimate annual energy requirements for supplemental electrical lighting, thermal conditioning, and fan operation. Cost estimates for envelope and mechanical systems and for energy consumption are prepared and compared using a Net-Benefits model. The analysis indicates the greatest profitability for assemblies with heat-reflective or tinted glass.

## 1. INTRODUCTION

Achieving energy conservation in today's buildings has become an important goal for architects, developers, and building operators. As the unit costs required for the purchase of energy continue to increase, these groups have recognized that the control of energy consumption rates can markedly affect the profitability of any venture. Creating economically successful buildings depends initially on identifying energy-efficient components and incorporating them into the building design. Subsequently, following the careful assembly of these components, the building and its various systems must be operated with intelligence and sensitivity. Basically, to foster energy-efficiency, it is necessary to control -- frequently, to reduce to its lowest practical limits -- the rates of energy usage for thermally conditioning and ventilating a building. The challenge thus becomes selecting which devices and systems will provide appropriate levels of conditioning and ventilation while displaying efficient energy consumption. And, finally, to be successful in the marketplace, the choice of these devices and systems must be shown to provide cost-effective building form and operation.

Commercial office buildings generally display thermal performances which feature rates of heat gain that are greater than coincident heat loss mechanisms. Thereby, these buildings are described as being internal-load-dominant. The most common source of heat gain for these buildings are (1) internal sources such as occupants, electric lighting systems, and business and process equipment and (2) solar radiation transmitted through fenestration assemblies. Of these sources the energies consumed for operating the lighting systems and for offsetting the heat gained from the lights and any transmitted solar radiation represent the greatest contributions to the internal-load dominance. To reduce energy consumption rates required for operating these buildings, it is necessary, simultaneously, to foster the admission of daylight (decreasing the usage of electric lighting) and to minimize the penetration of solar radiation into the building. This two-edged requirement establishes two conflicting goals requiring trade-off analyses: (1) how to permit daylight to enter through fenestration assemblies without experiencing solar heat gain; and (2) which assemblies will afford both energy-efficiency and cost-effectiveness?

An earlier paper by the present authors [1] examined the cost-effectiveness of alternative shading devices (when the opportunities for daylighting were not considered). In that paper we presumed electric lighting systems to be operated fully and continuously during the hours of occupancy. After estimating energy consumption rates for operating offices with alternative fenestration assemblies and preparing itemized cost estimates for envelope and associated mechanical (HVAC) systems, we performed a present-value analysis for the several cases. These studies conducted for identical building spaces located in three different cities (i.e., New York, Phoenix, and Seattle) provided the same results for all three cities: namely, that fenestration assemblies using heat-reflecting or tinted glasses offer greater cost-effectiveness than assemblies using clear glass with or without internal or external shading devices. Such heat-reflecting or tinted glasses, of course, provide substantially reduced daylight trans-

mittance and would afford little effective means for decreasing usage of electric lighting. Subsequently, we developed a study technique for estimating to what extent daylighting could reduce dependence on artificial illumination for common building settings. Linking that technique with thermal simulation devices that we had previously established enabled us to determine both the thermal and illumination performances of buildings with alternative envelope management strategies [2]. The application of these techniques to study such strategies thus becomes the focus of this paper. Herein we will report on estimates of cost-effectiveness for employing alternative fenestration assemblies for Seattle.

## 2. THE STUDY METHOD

The fundamental question that is addressed in this paper is, "For a specific climate, building form and use schedule, and cost environment (i.e., for building construction and energy unit prices), which alternative fenestration assembly will provide the largest economic profitability?" To answer this question we will describe a prototypical building space and analyze it iteratively using a four-stage study process. This process is intended to be generic, applying devices that could be employed for any location. But, to demonstrate its method, we will seek to answer the question for Seattle. First, we need to determine the amounts of energy that will be consumed for furnishing (a) supplemental electric lighting, (b) thermal conditioning, and (c) ventilation fan operation. Then, noting the current unit cost of energy and its projected escalation rate, we can establish short and longer-term operating energy costs. Second, we will prepare cost estimates for constructing the envelope and mechanical systems. Third, using appropriate economic variable ranges, we will render all costs and benefits into present-value terms. And, fourth, we will conduct a "Net Benefits" comparison amongst the several fenestration assemblies to determine which ones are the most economically desirable.

### 2.1 Determination of Operating Energies

The procedure used for predicting energy needs for lighting and thermal conditioning of a building space (or zone) has been described in a previous paper by the current authors [2]. Three computer programs, all developed at the University of Washington -- UWLIGHT, SUNSXN, and HOUSE -- are employed sequentially to calculate these energy needs.

We initially use the UWLIGHT program to determine a daylight factor profile throughout a space. By noting the room geometry, the character of the surfaces (i.e., their light locations and reflectances), and the daylight transmittances at various angles of incidence, we establish the illumination level at the workplane height in terms of daylight factors. Next, we design a lighting fixture plan for placing the electrical fixtures which will be used to provide supplemental illumination. Employing UWLIGHT repeatedly, we generate isolux contour records for groups, or banks, of these fixtures. Then, these contour files and the daylight factor profile for the space are passed to the SUNSXN program for further manipulation.

The SUNSXN program applies hour-by-hour sky luminance data to determine daylight illumination levels on the workplane, this time in footcandles. Subsequently, SUNSXN compares these daylight levels with a user-defined minimally acceptable lighting level and, observing the isolux contour records for the several banks of fixtures, calculates the fixture usage rate required to supplement the daylighting. The result of this computation is an hour-by-hour record of the rate of electric lighting usage. This record of electrical energy consumption (and its concommitant heat contribution to the building space) can then be passed to the HOUSE program. However, before discussing HOUSE, we will note an additional capability of SUNSXN: when an operable sun control device such as drape or blind is included as part of a fenestration assembly, SUNSXN will test the hourly solar heat gain potential to open or close the device before establishing supplemental fixture usage.

The HOUSE program is an interactive device and functions as a one-zone, transient thermal simulation model. To use this program we describe (1) the building envelope (in terms of its materials, their thicknesses, and any special properties), (2) the occupancy and use schedules (e.g., rates of ventilation or business equipment usage), and (3) operating conditions (e.g., a thermostat dead-band). We also include the file of electrical fixture operation from SUNSXN. Then, running HOUSE against a suitably-prepared TMY weather record [4], we establish the hourly thermal conditioning loads for the space. We have recently modified HOUSE so that it will estimate the energy required for operating the fan employed for ventilating the building space, especially for times when elevated air flow rates are used in economizer cycles. Finally, we sum the energies required for electric lighting, thermal conditioning, and fan operation. This sum thus describes the annual energy consumption required for the primary environmental conditioning systems utilized for the building space.

### 2.2 Estimates of Building System Costs

Initially, we generate a preliminary schematic design for the prototypical building and the study space within it. Then we identify the components of the building and study space, which will be altered on a case-by-case basis.

TABLE 1. ALTERNATIVE FENESTRATION ASSEMBLIES AND THEIR PERFORMANCE DATA

| ASSEMBLY | COMPOSITION | DAYLIGHT TRANSMITTANCE FOR ASSEMBLY | SHADING COEFFICIENT FOR ASSEMBLY |
|---|---|---|---|
| CASE 1 | Double-pane, clear float | 0.78 | 0.80 |
| 2 | Double-pane, gray-tinted float | 0.37 | 0.53 |
| 3 | Double-pane, inside light clear float, outside light w/film on inside surface | 0.18 | 0.28 |
| 4 | Double-pane, clear float w/ light-colored venetian blind between the lights | OPEN: 0.47<br>CLOSED: 0.05 | CLOSED: 0.33 |
| 5 | Double-pane, clear float w/ light-colored venetian blind at bay side of inner light | OPEN: 0.47<br>CLOSED: 0.05 | CLOSED: 0.51 |
| 6 | Double-pane, clear float w/ light-colored semi-open weave drape inside bay | OPEN: 0.78<br>CLOSED: 0.45 | CLOSED: 0.47 |
| 7 | Double-pane, clear float w/ overhang & fins projecting 1 foot from outer glazing | For glazing, 0.78 | Variable |
| 8 | As w/ Case 7, except that overhang & fins project 1.5 feet from outer glazing | For glazing, 0.78 | Variable |
| 9 | As w/ Case 7 plus light shelf (refl = 80%) projecting 1 foot out under glazing | For glazing, 0.78 | Variable |
| 10 | As w/ Case 1 plus light shelf (refl = 80%) projecting 1 foot out under glazing | For glazing, 0.78 | Variable |

Sources: For Cases 1-3, "Glass for Construction," Libbey-Owens-Ford Co., January 1983;
For Cases 4-6, 1981 ASHRAE Handbook of Fundamentals, Chapter 26

We prepare itemized cost estimates for the components and, adding the several component costs, arrive at an incremental cost for including these specific components in the overall building. To determine the incremental costs associated with constructing the alternative fenestration assemblies and operating the study space, we will therefore need to establish construction costs only for the fenestration assemblies and the mechanical (HVAC) systems components whose capacities will be sized to satisfy attendant conditioning loads. As we will discuss in Section 3, the electric lighting systems for the several cases will be identical, all being designed to match the maximum power rating permitted by the applicable energy code.

2.2.1 Envelope Costs

Developing envelope costs is limited here to establishing fenestration assembly costs (i.e., for the glazing and any internal or external shading devices). All other envelope components will essentially be the same across the several study cases. We find these costs by performing quantity take-offs for the fenestration assembly components. We determine average materials and installation unit costs for the components using the 1983 Means Building Construction Cost Data book [5] and include suitable overhead and profit figures suggested in the Means book. Multiplying the quantities by the unit prices produce national average costs for the assemblies. Finally, these average costs are modified by the regional cost factors for Seattle (again, as supplied by the Means book.

2.2.2 Mechanical Systems Costs

We prepare these costs in a similar fashion. Noting likely design conditions we estimate thermal loads for the study space and the overall building employing systematically the various fenestration assemblies. We then suggest a schematic HVAC system design for the building and calculate the capacities for the several system components which would be sufficiently altered in response to differential capacities. The components whose costs are most sensitive to alternative capacity needs are the ductwork, the central air handler (or fans), the chiller, and the cooling tower (note that all may be present in multiples if the building is suitably large). We estimate the heating needs for boilers and/or heat exchangers and the related supplemental perimeter radiation to be small and to be closely alike across the several fenestration assemblies we consider. Control devices, sensors, and other instrumentation also will be similar for the several study situations. Lastly, following the procedure identified in Section 2.2.1 and using the 1983 Means Mechanical and Electrical Cost Data book [6], we calculate contributory HVAC systems costs for the study space with each of the various assemblies.

2.3 Incremental Cost Manipulations

The cost analysis we will use is the "Net

TABLE 2. ENERGY CONSUMPTION FOR LIGHTING, THERMAL CONDITIONING, AND FAN OPERATION (ALL EXPRESSED IN KWH/YEAR)

| FENESTRATION ASSEMBLY ALTERNATIVE | SUPPLEMENTAL ELECTRIC LIGHTING | THERMAL CONDITIONING* | FAN OPERATION | TOTAL ANNUAL CONSUMPTION |
|---|---|---|---|---|
| CASE 1 | 2020 | 12880 | 1600 | 16500 |
| 2 | 2170 | 9600 | 1130 | 12900 |
| 3 | 2300 | 7180 | 1020 | 10500 |
| 4 | 2190 | 9060 | 1350 | 12600 |
| 5 | 2200 | 9050 | 1350 | 12600 |
| 6 | 2060 | 11660 | 1580 | 15300 |
| 7 | 2080 | 11970 | 1550 | 15600 |
| 8 | 2120 | 11550 | 1530 | 15200 |
| 9 | 1930 | 12040 | 1530 | 15500 |
| 10 | 1880 | 12840 | 1580 | 16300 |

*Using an economizer cycle with a flow rate of up to 0.5 CFM/$ft^2$ of floor area.

Benefits" comparison [7]. Here, the energy cost savings (for some period of time) will be viewed against the differential costs (of construction, maintenance, replacement, and salvage) incurred to achieve these savings. To provide a basis for examining energy savings and differential costs, we establish a reference case as point of comparison and test all of the other alternatives against this reference. All benefits and costs are treated by the appropriate money-time parameters to produce present values. For an alternative to be desirable economically, the "Net Benefits" (or, benefits less the costs) for employing some alternative must render a positive number.

We determine the annual energy cost savings using the three simulation programs described in Section 2.1 and multiplying the consumption rates by the unit prices. Future savings values are established employing an energy escalation rate. The construction costs are found by summing the fenestration assembly and HVAC systems costs (using the technique explained in 2.2). Maintenance and replacement costs across the several cases studied here will be set at zero, largely because we do not have any values to use for either. Salvage values will also be ignored (as a benefit) because we are presuming the period of ownership (and the useful lifetime of the various components) will exceed our study time length.

## 3. THE PROTOTYPICAL STUDY SPACE AND THE ALTERNATIVE FENESTRATION ASSEMBLIES

The study space for this analysis is one bay along the south elevation of a high-rise commercial office building. This bay has a perimeter width of 24 feet and an interior depth of 30 feet. It is one of perhaps five such bays along this elevation, is not at either corner of this elevation, and is located on an intermediate storey (but it is high enough so that it has a clear sky view). The five bays comprise an open-plan, landscaped space. The floor-to-floor dimension is 12 feet with a ceiling "sandwich" (for structure and environmental controls) of approximately three feet height. The primary, non-glazed surfaces in the room are of the following materials: the finished ceiling is acoustical tile; the walls (where present) are gypsum wallboard; and the floor is carpeted. The reflectances of these surface materials are, respectively, 80%, 50%, and 20%. The non-glazed south wall consists of a lightweight curtain wall panel with a U-factor equal to 0.09 Btu/hr-$ft^2$-$^oF$.

We have listed the ten alternative fenestration assemblies in Table 1, along with relevant performance data. The size of the assemblies will uniformly be 23 feet in width and 3.5 feet in height with the sill located three feet above the floor. We have chosen this uniform size for all the assemblies because it is the largest area which a double-pane, clear float assembly (Case 1) can be to comply with the Overall Thermal Transfer Value (OTTV) criterion of our Washington State Energy Code [8]. The presence of mullions in these assemblies has been ignored in our analyses.

To study the performance of this test bay we are presuming the following conditions. First, seven people will occupy the space, on average, from 8 am until 6 pm, Mondays through Fridays. Outside of these periods the building will be unoccupied. Second, the lighting system will operate only during the time of occupancy. We have predicated the choice of lighting fixtures that will be used in the space again on complying with the maximum power budget permitted by the Energy Code [8]. This Code allows a power budget for offices of 2.0 watts per square foot of floor area (including lamp and ballast wattage). In this paper, as with the previous one [2], we will employ the Parabolume 1' x 4' one-lamp fluorescent tube fixture (as manufactured by Columbia Lighting, Inc., Spokane, Washington). Series of this fixture will be placed in groups of five, linked end-to-end beginning two feet in from the bay edge and running to within two feet of the other bay edge (east to west). Six such rows of end-to-end linked fixtures will be placed first at 2.5 feet from the south ele-

TABLE 3. SUMMARY OF SYSTEMS AND ENERGY COST DIFFERENTIALS

| Assembly | Fenest. Assembly Cost | HVAC Systems Cost | Assembly + System Costs | Cost Differ. vs. Case 1 | One-Year Energy Cost | One-Year Energy Cost Savings vs. Case 1 |
|---|---|---|---|---|---|---|
| Case 1 | 1015 | 2193 | 3208 | -- | 353 | -- |
| 2 | 1122 | 1745 | 2867 | + 341 | 261 | + 92 |
| 3 | 1228 | 1412 | 2640 | + 568 | 206 | + 147 |
| 4 | 2530 | 1463 | 3993 | - 785 | 264 | + 89 |
| 5 | 1343 | 1737 | 3080 | + 128 | 264 | + 89 |
| 6 | 1379 | 1612 | 2991 | + 217 | 332 | + 21 |
| 7 | 1452 | 1965 | 3417 | - 209 | 332 | + 21 |
| 8 | 1652 | 1766 | 3418 | - 210 | 320 | + 33 |
| 9 | 1791 | 1965 | 3756 | - 548 | 327 | + 26 |
| 10 | 1353 | 2420 | 3773 | - 565 | 348 | + 5 |

1. All costs and savings are expressed in 1983 US$.
2. Costs are pro-rated on a "per bay" basis.
3. Electricity unit costs for commercial buildings in Seattle are approximately $0.020/kWh (including effects of seasonally-adjusted demand and consumption costs.)

vation and then at five-foot intervals to 27.5 feet from the south wall. We are considering the fixtures to be surface-mounted (rather than recessed into the ceiling "sandwich" space.) The workplane height throughout the study space is uniformly set at 30 inches above the floor. We will seek to maintain a minimum of 70 footcandles of illumination on this workplane.

The third set of operating conditions concerns the expected performance of the mechanical (HVAC) system. During the period of occupancy we will maintain the building within a deadband temperature regime of 68 to 78 °F. However, when the building is unoccupied (i.e., at nights and on weekends), we will permit the study space to float between 60 to 85 °F. An all-air, variable volume system will insure ventilation and thermal conditioning. We will provide an economizer cycle for cooling whenever the external dry-bulb temperature is suitable. This economizer cycle will operate with a flow rate up to 0.5 CFM of fresh air per square foot of floor area served.

During the exercising of the three simulation programs described in Section 2.1 above, we will use an hourly TMY weather record of the Seattle area [4]. We also will employ sky luminance data for Seattle provided us by Robbins [3]. For our benefit-cost estimates, the electricity unit prices have been derived from the City of Seattle Lighting Department rate structure [9]. This cost structure is founded on a monthly maximum hourly demand and total consumption model. Our manipulations of this model indicate an average unit price of about $0.020/kWh of consumption.

## 4. RESULTS OF THE ANALYSIS

We present in Table 2 the results obtained from using the three computer programs. Use of the UWLIGHT and SUNSXN programs enable us to predict the annual electric lighting energy needs required to supplement daylighting. The cases with the light-shelving under the glazing (#9 and #10) afford the lowest supplemental energy consumptions. The double-pane, clear float assembly (#1) is next best, whereas the heat-reflective assembly (#3) causes the largest electric lighting energy consumption of these ten cases. But, when energy required for ventilation and thermal conditioning is considered and the three energy needs are summed, the heat-reflective assembly is the most conservative. The gray-tinted glazing and the two assemblies with the venetian blinds (#2, #4, and #5, respectively) also indicate they are relatively good conservation strategies. The results for the double-pane, clear float assembly (#1) suggest it will offer the poorest performance.

Table 3 displays a summary of the several systems and energy consumption costs associated with the ten cases. As we have noted previously in Section 2.2, we are determining costs only for those components of the envelope and mechanical systems, which are altered by differences in materials or capacities. Our cost estimates are based on a pro-rated, "per bay" price for the individual components and, therefore, for the totals. In Column 5 of Table 3, after designating Case 1 as the reference point, we list the systems cost differentials between each of the other nine alternatives and Case 1 (i.e., a positive number here indicates that case has a lower cost than Case 1; a negative value suggests a higher cost.) In Column 6 of Table 3 we note the predicted one-year costs for energy consumption for operating the office bay. These costs have been projected using the rate structure for variable demand and consumption amounts as set by our local utility [9]. In Column 7 of Table 3 the one-year energy cost savings are catalogued for each of Cases 2 through 10 in comparison with #1. Consistent with the totals shown in Table 2, the heat-reflective assembly (#3) provides the greatest annual energy savings with Cases 2, 4, and 5 all being approximately second-best.

TABLE 4. ALTERNATIVE CALCULATIONS FOR THE "NET-BENEFITS" COMPARISON

| Assembly | One-Year Energy Savings | i = 8.5%; e = 17.5% 20-Year Energy Savings | i = 8.5%; e = 17.5% Total Bldg & Energy Savings | i = 17%; e = 17.5% 20-Year Energy Savings | i = 17%; e = 17.5% Total Bldg & Energy Savings | i = 17%; e = 8.5% 20-Year Energy Savings | i = 17%; e = 8.5% Total Bldg & Energy Savings |
|---|---|---|---|---|---|---|---|
| Case 1 | -- | -- | -- | -- | -- | -- | -- |
| 2 | 92 | 4690 | 5031 | 1925 | 2266 | 932 | 1273 |
| 3 | 147 | 7494 | 8062 | 3076 | 3644 | 1489 | 2057 |
| 4 | 89 | 4537 | 3752 | 1862 | 1077 | 901 | 116 |
| 5 | 89 | 4537 | 4665 | 1862 | 1990 | 901 | 1029 |
| 6 | 21 | 1071 | 1288 | 439 | 656 | 213 | 430 |
| 7 | 21 | 1071 | 862 | 439 | 230 | 213 | 4 |
| 8 | 33 | 1682 | 1472 | 690 | 480 | 334 | 124 |
| 9 | 26 | 1325 | 777 | 544 | - 4 | 263 | - 285 |
| 10 | 5 | 255 | - 310 | 105 | - 460 | 51 | - 514 |

1. All savings, whether positive or negative, are expressed in 1983 US$.
2. i = discount rate; e = energy escalation rate.
3. All savings are pro-rated on a "per bay" basis.
4. The "Net-Benefits" criterion for profitability requires that total savings be positive.

Finally, in Table 4, we estimate a twenty-year energy savings using a Uniform Present Worth Formula modified for energy cost rate escalation [7]. Because of the patent uncertainty in projecting discount and energy cost escalation rates we have included three sets of calculations, each based on a different set of economic circumstances. In Columns 3, 5, and 7 we list the twenty-year cost savings for the nine cases, and in Columns 4, 6, and 8 we state the final "Net-Benefits" sums for the systems and energy consumption cost savings. These results indicate that Cases 3, 2, and 5 -- in that order -- offer the greatest profitability for the prototypical Seattle office building. The cases in which external shading and light shelf devices are used appear to be the least economically attractive, both because of their higher construction costs and their low energy cost savings.

## 5. SUMMARY

The results from this analysis are similar to those developed from our earlier study [1], in which the benefits of daylighting had been ignored. We have found that the amount of energy required for supplemental electric lighting was appreciably smaller that that needed for thermal conditioning and that the differences in energy consumption for lighting among the ten cases were relatively small. We presently anticipate that, if the glazing assemblies could have been larger or if the room had been less deep or if the sky luminance were greater, different patterns may have emerged. Thus, for other buildings located in cities with greater sky luminances, other glazing assemblies may be more energy-efficient or cost-effective. These questions will require further work.

Ed. Note : A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# PASSIVE SOLAR HOUSES AND ELECTRIC UTILITIES, AN IMPACTS ANALYSIS

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## ABSTRACT

In EPRI research project RP1666-1 procedures and methods were developed for determining the thermal performance of passive solar and energy conserving single family detached residential units and their potential utility impacts.

These methods were applied to determine the impact of selected penetrations of alternative residential building designs on the loads of four utilities each located in a different climatic zone. Results include a comparison among conventional, energy conserving, and passive solar housing types. The building variation of choice which minimizes the total of homeowner equipment costs and utility energy and demand costs is discussed for each location.

Intermediate results on route to the final annualized costs are discussed and compared among the four utilities. It was concluded that passive solar houses can significantly reduce homeowner and utility costs over conventional house designs and can moderately reduce these costs over energy conserving designs in some climates.

## 1. INTRODUCTION

Interest in passive solar systems has increased significantly in the United States in recent years as one response to higher energy prices and the growing popularity of virtually all solar technologies. Yet, while a number of new homes and other buildings incorporating passive solar designs have been constructed, little work of a rigorous nature has been done to determine what impact these buildings might have on electric utilities and what economic benefits, if any, they might offer homeowners and utilities.

The purpose of EPRI Research Project 1666-1 "Utility Impacts Assessment of Residential Passive Solar Systems" was to provide the electric utility industry with a tool to use in analyzing both the positive and negative impacts upon the utilities and their customers of passive solar residential construction within their service areas - specifically single-family, detached houses.

The three specific objectives of the study were:

- To produce a computer methodology for assessing energy use and costs in passive solar designed houses;
- To predict the economic impact large numbers of passive solar designed houses would have on a given utility in terms of changes in kWh use, system load factor, and generation reliability; and
- To identify "preferred" passive solar designs for given utility systems.

Passive solar design elements include proper building orientation, energy conservation measures, significant amounts of south-facing glass, and building construction using heat storing materials such as brick, adobe, concrete, and water. Passive solar systems collect, store, and distribute the sun's energy by natural, nonmechanical means (i.e., conduction, free convection, and radiant heat transfer). They are more design than technology based and may not be readily distinguishable from the remainder of the structure. In general, energy conservation measures are integral to passive design since they represent basic strategies for retaining heat and cool air within a building.

For this study the contiguous 48 states were divided into seven analysis regions based primarily on climatic considerations because climate is the primary influence on the requirements and performance of passive solar systems and conservation measures. Within each of these regions, a representa-

tive electric utility was solicited and selected to provide data and information for the analysis.

Energy conservation measures and passive solar features were reviewed as design elements and those expected to make their way into the residential housing construction in significant numbers were selected for the analyses. Subsequently, reference house designs were developed for each region by the architectural firms participating in the study. These house designs then served as a basis for developing a data base of relevant material necessary for the modeling effort in the methodology.

Parametric investigations of passive solar options and discussions with the architects led to the development of final designs for conventional, energy conserving, and passive solar houses.

Building thermal analysis was conducted for house designs in all regions, whereas the full impact of selected penetrations of these alternative residential building designs on the loads of four utilities were evaluated. It is the results of the full impact evaluations which are presented in this paper. Partial results for two of the utilities were previously presented in the Passive and Hybrid Solar Energy Update Conference sponsored by the U.S. Department of Energy in September 1982.

## 2. STUDY DESIGN

The four participating utilities and their approximate locations are shown in Fig. 1.

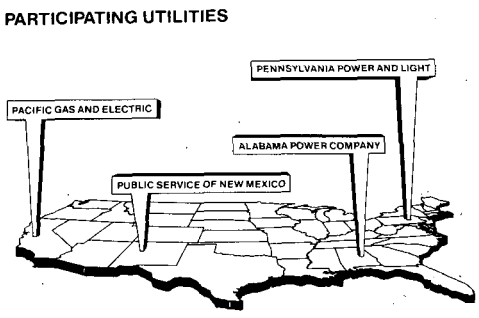



Fig. 1. Participating Utilities

The general approach for building variations was to select a conventional version, an energy conservation version, and at least one passive version of the house design developed for the region.

The conventional house is based upon what one might expect to find in speculative developments. The insulation level is representative of construction practice in the 1970 s. The house is built with standard two-by-four studding with fiberglass insulation between.

The energy conserving house incorporates some of the better energy conserving features in use today in the development house. It achieves the higher insulation levels by either using fiberglass between two-by-six studding or by adding two inches of Styrofoam to the outside of the conventional two-by-four construction. A polyethylene vapor barrier and increased attention to detail reduce the infiltration rate.

The direct gain house is based upon these same houses and includes all aspects of the energy conserving house as well as incorporating direct gain features.

With direct gain passive solar, the actual living space is directly heated by sunlight through south facing glazing.

For Alabama Power Company (APC) and Pacific Gas and Electric (PGandE) the passive variations were limited to the direct gain, whereas, for both Pennsylvania Power and Light Company (PP&L) and Public Service Company of New Mexico (PNM), a variation utilizing a mass wall was also analyzed.

Table 1 contains a summary of descriptive data for the reference structures.

Table 2 indicates the number of passive homes estimated for each location.

Building thermal analysis was conducted for each of the building variation in each of the locations. Table 3 presents the energy performance of each of the structures in terms of the energy required to be supplied from the utility. The totals have been divided into the energy requirements for heating and cooling. Significant variations in these requirements among the utility locations reflect the variations in climatic conditions.

## 3. UTILITY IMPACTS

Comparisons of system load shapes, load factors, fuel savings, and generation reliabilities were made among the different building designs with forecasts of 1995 system loads and fuel prices provided by the participating utilities. In addition, each utility projected its 1995 mix of generating equipment. The system load shapes and system load factors were compared for each modified system load, and fuel savings were calculated from changes

TABLE 1. SUMMARY OF DESCRIPTIVE DATA FOR REFERENCE STRUCTURES

| Location | Size ($ft^2$) | Stories | Const. | Foundation | Garage | # of Bed-Rooms | Space Conditioning | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Heating | Cooling |
| Fresno, CA | 1560 | 2 | Frame | Slab | 2 Car | 3 | Heat Pump[1] | Heat Pump |
| Albuquerque, NM | 1575 | 1 | Frame, Stucco | Slab | 2 Car Ext. | 3 | Electric Resistance | Evaporative Cooler |
| Harrisburg, PA | 2000 | 2 | Frame | Slab | 1 Car | 3 | Electric Resistance | Vapor Compression Air Conditioner |
| Montgomery, AL | 1230 | 1 | Frame | Slab | Optional-Detached | 3 | Heat Pump[1] | Heat Pump |

1. All heat pumps are backed up with resistance heating.

TABLE 2.

| | APC | PGandE | PP&L | PNM |
|---|---|---|---|---|
| Total Home Additions | 173,000 | 810,000 | 150,000 | 157,200 |
| Passive | 30% 51,900 | 20% 162,000 | 10% 15,000 | 25% 39,300 |

in production costs as compared to the cases for either conventional or energy conserving homes.

A generation reliability index which is similar to a loss of load probability (LOLP) was computed, and those associated with the passive designs were compared to a target reliability.

The production cost runs were used to generate the utility fuel costs for each of the alternative variation of house design. These costs were then levelized over the life of the system. Table 4 presents these annual levelized utility fuel costs for supplying each house design.

Based upon the generation reliability index measurements, capacity credits were developed for appropriate cases. A reduction in load increases the reliability of the generating system. The capacity credits were developed under the assumption that the reduction in capacity that returns the

TABLE 3. ENERGY PERFORMANCE OF BUILDING VARIATIONS

(Annual kWh required from the utility)

| | APC | PGandE | PP&L | PNM |
|---|---|---|---|---|
| CONVENTIONAL | | | | |
| Heating | 4000 | 6700 | 18600* | 15500 |
| Cooling | 4600 | 5000 | 500 | 3800 |
| Total | 8600 | 11700 | 19100 | 19500 |
| ENERGY CONSERVING | | | | |
| Heating | 1500 | 2300 | - | 6700 |
| Cooling | 3300 | 4100 | - | 300 |
| Total | 4800 | 6400 | - | 7000 |
| DIRECT GAIN PASSIVE | | | | |
| Heating | 1300 | 2000 | 11100 | 4400 |
| Cooling | 3500 | 5200 | 1000 | 300 |
| Total | 4800 | 7200 | 12100 | 4700 |
| PASSIVE WITH MASS WALL | | | | |
| Heating | - | - | 11200 | 2900 |
| Cooling | - | - | 600 | 300 |
| Total | - | - | 11800 | 3200 |

*For PP&L a "baseline design" typical of recently constructed homes in the utility's region was modeled instead of the reference "conventional" or "energy conserving" versions.

TABLE 4. ANNUAL LEVELIZED UTILITY FUEL COST PER HOUSE

| | APC | PGandE | PP&L | PNM |
|---|---|---|---|---|
| Conventional | 690 | 3650 | 3520* | 1890 |
| Energy Conserving | 400 | 2080 | | 850 |
| Direct Gain Passive | 430 | 2160 | 1600 | 660 |
| Passive with Mass Wall | - | - | 1600 | 500 |

*"Baseline design".

reliability index to that of the system with conventional houses, can be attributed to the particular house variation. Capacity savings were then produced by obtaining the annual levelized cost of the particular capacity removed. Table 5 shows the kilowatts of utility capacity savings per house as compared to the conventional house.

TABLE 5. UTILITY CAPACITY SAVINGS PER HOUSE

| | APC | PGandE | PP&L | PNM |
|---|---|---|---|---|
| Energy Conserving | 1.7 kW | 2.1 kW | - | 2.7 kW |
| Direct Gain Passive | 1.2 kW | 1.5 KW | - | 3.1 kW |
| Passive with Mass Wall | - | - | - | 3.7 kW |

These benefits to the utility do not come without some cost. The increased cost to the homeowner of including conservation measures and passive features in the building variations must be considered in the overall analysis. The additional costs were developed and converted to annual levelized costs considering mortgage rates and other homeowner financial parameters. Table 6 shows these costs for each of the house variations at each utility location.

For the study, the building variation of choice was defined as that for which the sum of utility fuel, utility capacity, and homeowner incremental costs was the least.

TABLE 6. HOMEOWNER ANNUALIZED INCREMENTAL SPACE CONDITIONING COSTS

| | APC | PGandE | PP&L | PNM |
|---|---|---|---|---|
| Conventional | 406 | 360 | 432* | 336 |
| Energy Conserving | 588 | 714 | - | 947 |
| Direct Gain Passive | 677 | 906 | 744 | 1108 |
| Passive with Mass Wall | - | - | 1171 | 1625 |

*"Baseline design".

These costs are presented in Figs. 2A through 2D. The sums are also presented in Table 7 and the variation of choice for each utility are boxed in.

For the PP&L and PNM territories, the direct gain passive design showed the lowest cost, while for PGandE and APC, the energy conserving design proved best.

## 4. CONCLUSIONS

The passive solar and energy conserving houses significantly outperformed the conventional house (and baseline house, where substituted) in terms of both improved energy efficiency and lower operating costs. In addition, the direct gain passive house outperformed the mass wall passive house for those locations where both of these designs were modeled.

In comparing the direct gain and energy conserving house, the direct gain house performed better on systems with high heating loads (PP&L and PNM). On systems with high cooling loads (PGandE and APC) the energy conserving house performed better. The poorer performance of the direct gain house on high cooling-load systems is accounted for by its larger glass area. In winter months this greater area allows more sunlight inside the house and helps reduce the heating load. In summer months, however, it can contribute to increased cooling loads. At the PGandE and APC sites it increased the cooling load more than it decreased the heating load.

The comparison between the energy conserving and conventional houses in the study indicates that conservation measures always produce significant energy cost savings. A separate conclusion is that while passive

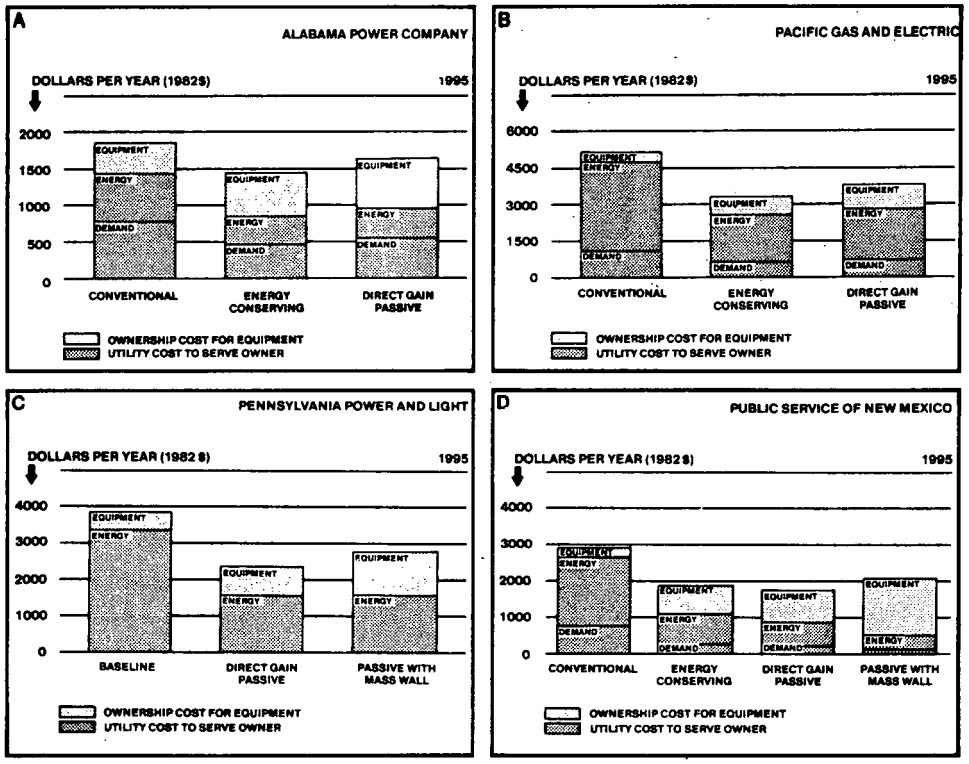



Fig. 2. Annualized ownership and utility costs

TABLE 7. COMBINED HOMEOWNER AND UTILITY COSTS IN 1995

| | APC | PGandE | PP&L | PNM |
|---|---|---|---|---|
| Conventional | $1860 | $5080 | $3860* | $2980 |
| Energy Conserving | $1480 | $3340 | - | $1920 |
| Direct Gain Passive | $1650 | $3370 | $2380 | $1820 |
| Passive with Mass Wall | - | - | $2780 | $2020 |

*"Baseline design".

homes can impact electric utilities, the extent of the impact - and whether it is positive or negative - is strongly influenced by local climate, the specific characteristics of the utility, and the loads served.

The addition of energy conserving measures to a conventional house design always results in significant reductions in electricity consumption for heating and cooling. The addition of passive solar features to an energy conserving design may produce significant additional savings in heating and cooling energy; however, this will depend upon the combination of climate and particular house design. The influence of additional south glazing area varies and is highly dependent on climate. In warmer regions it will reduce backup heating needs, but may also increase the required backup cooling energy. Whether or not one offsets or exceeds the other is highly dependent in the combination of house design and climate.

A thermal storage wall can be an effective passive solar feature from the standpoint of building thermal performance. However, the cost of adding one may offset the added savings that result. If improved materials and construction practices could reduce this cost, improved performance of passive solar units might be economically achieved.

For the limited number of cases studied, the presence of passive solar or energy conserving units in a utility's service appeared to improve operating reliability and resulted in significant savings in fuel consumption (per house) to provide backup heating and cooling needs.

The peak demand of an individual residence was also reduced significantly (37 to 70 percent). Thus, there is a potential for significant reductions in demand if a large number of passive solar units were built in a utility's service territory.

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# ASSESSMENT OF PASSIVE FEATURES IN RESIDENTIAL BUILDINGS

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## ABSTRACT

The following passive solar options were assessed: selective surface mass walls, highly reflective exterior surfaces, infra-red reflecting window film, and triple pane windows. The options were assessed for thermal and economic performance for Casper, Wyoming, and Fresno, California. Each of the options is described in detail. Of the three passive solar options, the infra-red reflecting window film appears to be the most economically attractive for both locations. This is followed by the triple pane windows, the selective surface for mass walls, and then by the highly reflective exterior surfaces.

## 1. INTRODUCTION

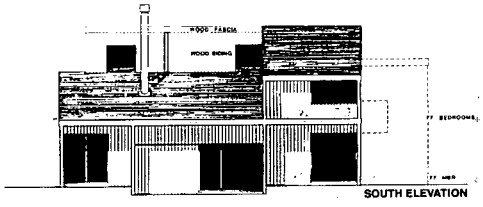
In EPRI Research project RP1666-1 procedures and methods were developed for determining the thermal performance of passive solar and energy conserving residential units, their potential effects on an aggregated residential load, and their potential utility impacts.

The passive options mentioned in the abstract were applied to a residential, single family, 1560 $ft^2$, passive solar house. This house is shown and described in Figs. 1 and 2.

A hot climate represented by Fresno, CA, and a cold climate represented by Casper, WY, were used in the study. The infra-red reflecting window film and the triple pane windows were analyzed in both climates. The highly reflective exterior surface option was analyzed in Fresno. The selective surface mass wall option was analyzed in Casper.

EMPS 2.0 was used for the thermal analysis. EMPS-2 is a comprehensive residential and small commercial building loads program. The program performs a detailed, hourly heating and cooling simulation of single and multi-zone buildings. There are three categories of inputs to the program: building specifications, life-style data, and weather data. The output includes hourly HVAC electrical demand.

Breakeven costs, the maximum economically viable equipment cost, for each of the passive options were computed by both a life-cycle cost method and a simple payback method. The life-cycle cost method of computing the breakeven costs is based on summing the present values of the following: downpayment on equipment costs; mortgage payments, net of tax deduction; replacements; maintenance and insurance; sales




DIRECT GAIN PASSIVE HOME

| BUILDING CHARACTERISTICS | | |
|---|---|---|
| INTERIOR SPACE | | |
| FLOOR AREA | 1560[1] | $FT^2$ |
| VOLUME | 18900 | $FT^3$ |
| INFILTRATION RATE | .5 | ACHR |
| INTERNAL MASS WEIGHT | 35000 | LBS |
| INTERNAL MASS SURFACE AREA | 5460 | $FT^2$ |
| BUILDING INSULATION | R-VALUE | |
| ROOF | 30 | |
| WALLS | 19 | |
| SLAB | 0 | |

| PASSIVE SOLAR CHARACTERISTICS | | | | |
|---|---|---|---|---|
| GLAZING | N | S | E | W |
| NET AREA $FT^2$ | 36 | 135 | 48 | 34 |
| # GLASS PANES | 2 | 2 | 2 | 2 |
| NIGHT INSULATION | -- | -- | -- | -- |
| MASONRY WALL | | | | |
| AREA | | | | 0 $FT^2$ |
| THICKNESS | | | | 0 FT |
| ABSORPTANCE | | | | -- |
| SHADING | | | | |
| SOUTH WALL OVERHANG | | | | 2 FT |
| DRAPES ON SOUTH WINDOWS | | | | NO |

| BACK UP EQUIPMENT CHARACTERISTICS | | | |
|---|---|---|---|
| HEATING: | | COOLING: | |
| SYSTEM | ELECTRIC RESISTANCE | SYSTEM | VAPOR COMPRESSION AC |
| THERMOSTAT SETPOINT | 68 F | THERMOSTAT SETPOINT | 78 F |
| NATURAL VENTILATION (TO PREVENT OVERHEATING) | YES | MECHANICAL VENTILATION | NO |
| | | NATURAL VENTILATION | YES |

JBF 3032

1 CONDITIONED SPACE

Fig. 1. Direct gain passive home

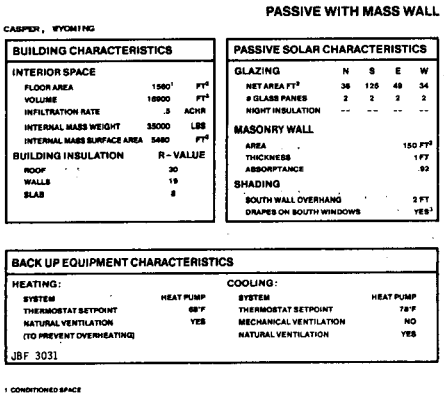



Fig. 2. Passive with mass wall

tax, net of tax deduction; property tax, net of tax deduction; and fuel costs. The period of analysis, mortgage interest rate, term of mortgage, discount rate, personal income tax rate, and real escalation in electricity prices are separately specified. The equipment cost is the incremental building cost associated with the passive option as compared to the house without the passive option.

The simple payback method of computing breakeven costs is based on a 5-year payback. The breakeven cost by this method is the annual energy savings summed over 5 years.

## 2. THERMAL PERFORMANCE

### 2.1 Infra-Red Reflecting Window Film and Triple Pane Windows

The infra-red reflecting window film is a coated plastic film mounted between two panes of sealed insulated glass. The plastic film insulates by reflecting radiant heat back to the source - inside the room in winter and back outside in summer. In addition, the film insulates by creating air spaces on both sides of the film. It is available in three different light transmittances: IR-88, IR-77, and IR-55. IR-88 is for colder climates or for buildings with large heating loads. IR-77 is for warmer climates or application where cooling loads and natural daylighting are important. IR-55 is designed for buildings with large cooling loads.

The infra-red reflecting window film and triple pane windows were investigated for two sites: Casper, WY, and Fresno, CA. Casper, WY, is a cold climate with about 7600 heating degree-days and 460 cooling degree days while Fresno, CA, is hot with only about 2600 heating degree-days and 2650 cooling degree-days. The IR-88 film was used at the Casper, WY, site. The IR-77 film was used at the Fresno, CA, site.

Fig. 3 compares the IR-88 window with conventional double and triple pane windows for the Casper home. This comparison is made for the months of January and July. As shown in Fig. 3, the IR-88 window results in significantly reduced kWh consumption for January over both the double and triple pane conventional windows. Changes in kWh consumption are less significant for the cooling month of July.

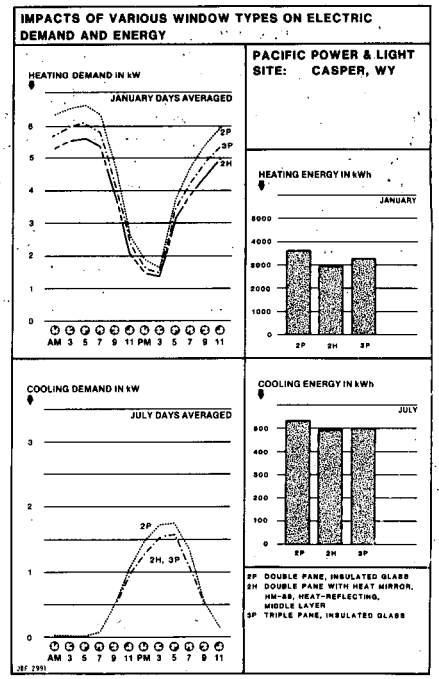



Fig. 3. Impacts of various window types on electric demand and energy - Casper, WY

Casper, WY has cold Januarys, resulting in high heat demand, and cool Julys, resulting in low cooling demand. Significant reductions in electricity consumption by the IR-88 window are thus found in January but not July. Casper has a cool and dry enough cooling season to forego air conditioning entirely. For homes without air conditioning, the IR-88 window will make living conditions slightly more comfortable by reducing the indoor temperature.

Fig. 4 compares the IR-77 window with conventional double and triple for the Fresno, CA, site. The IR-77 window results in a 15% reduction in heating load and about a 10% reduction in cooling load over the double pane window. The IR-77 window outperforms the triple pane window by a smaller margin. Peak cooling demand is reduced by about 15% by the IR-77 window over the double pane window. This is a definite plus for the electric utility.

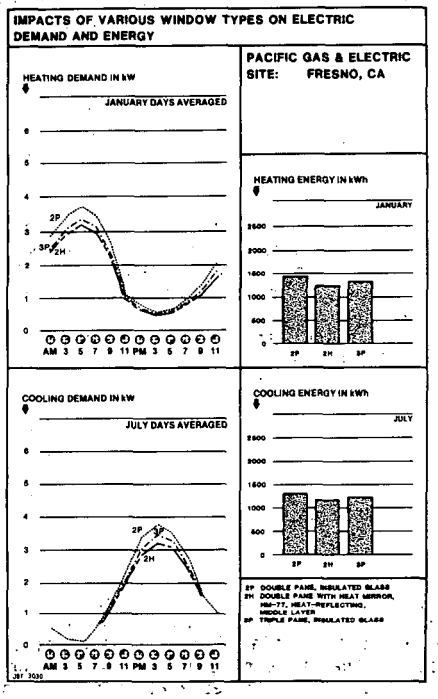



Fig. 4. Impacts of various window types on electric demand and energy - Fresno, CA

In all cases, Casper and Fresno and for both January and July, the triple pane window results in electricity consumption that is between the double pane and infrared reflecting window film.

## 2.2 Selective Surface Mass Walls

A selective surface has a combination of a high solar radiation absorptance and a low long wave radiation emittance. Most of the short wave solar radiation is absorbed by the surface but very little long wave thermal radiation is emitted. This makes the selective surface an excellent collector of heat. Typical values of solar absorptance and thermal emittance for a flat black surface are .92 and .90, respectively. A selective surface is likely to have the same value of solar absorptance, .92, but might have a thermal emittance as low as .10.

The above values of solar absorptance and thermal emittance were used in a comparison of selective and flat black surfaces on mass walls. This comparison was made in Casper, Wyoming, for the heating season.

Fig. 5 shows results from three EMPS-2 runs. The figure shows a minor reduction in heating load, for January, by the flat black mass wall over the house without a mass wall. Another minor reduction in heating load - about 5% - is shown in going from a flat black surface to a selective surface on the mass wall. The largest reduction in hourly heating demand occurs at night during the peak heating demand.

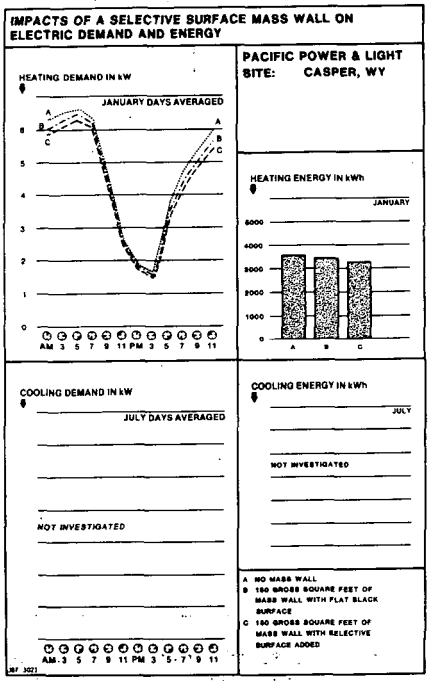



Fig. 5. Impacts of a selective surface mass wall on electric demand and energy - Casper, WY

## 2.3 Highly Reflective Exterior Surfaces

The objective of these highly reflective exterior surfaces is to reduce summer time cooling loads by reflecting solar radiation

away from the building. Thus, Fresno, California - a cooling dominated climate - was chosen for the analysis.

Fig. 6 compares a home with normally reflective walls and roof to a home with highly reflective walls and roof. In July, the cooling energy was reduced by about 13%. Peak cooling demand on the averaged July day was reduced by about 10%. In January, the reflective exterior surfaces increased the heating energy by about 10%. In absolute numbers, the reflective surfaces decreased cooling energy by 170 kWh for July and increased heating energy by 147 kWh in January. If, however, the electric resistance heating were replaced with a heat pump, then the heating energy for January would be increased by only about 49 kWh (this assumes a heat pump COP of 3.0).

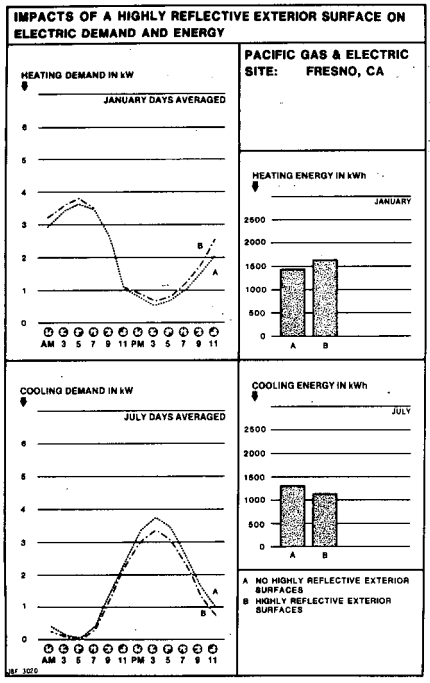



Fig. 6. Impacts of a highly reflective exterior surface on electric demand and energy - Fresno, CA

## 3. ECONOMIC ANALYSIS

A breakeven cost is computed for each of the passive options and then compared to the actual cost of the passive option. The breakeven cost is the maximum economically viable equipment cost that would allow the present value of savings in electricity to equal the present value of all added costs associated with the passive option over the period of analysis.

Table 1 shows electricity consumption in kWh/year for the house without the passive option and for the house with the passive option. The last two columns of Table 1 show the total breakeven life-cycle costs and the breakeven costs per square foot of window area (exterior surface area in the case of highly reflective exterior surfaces) respectively. These are actually breakeven cost differentials between the house with the passive option and the house without the passive option. In other words, the homeowner with the passive option would have been willing to pay up to the breakeven amount above the house without the passive option. The economic assumptions for these values are listed in Table 2.

The economic performance of both infra-red reflecting film and triple pane windows is better in Casper, WY, than Fresno, CA. This is because of the severe climate in Casper compared to Fresno. There is a significant difference between the highly reflective surface case with electric resistance heat and this case with heat pump heat. The reason is that the highly reflective exterior surfaces reduce the cooling load but increase the heating load. Thus, a heating load that is satisfied with a heat pump instead of resistance heat will yield greater savings over the year.

Table 3 shows breakeven costs in $/ft$^2$ for various economic assumptions. Column 3 shows breakeven costs for the economic assumptions listed in Table 2. Column 4 lists the breakeven costs if a 0% real escalation rate for the price of electricity is assumed instead of a 2% real escalation rate. Column 5 has the same assumptions as Column 4 except that the price of electricity is $0.06/kWh instead of $0.08/kWh. Finally, Column 6 shows breakeven costs based on a simple 5-year payback with electricity priced at $0.08/kWh.

Table 4 lists the breakeven payback ratios as a function of the economic assumptions. The breakeven payback ratio is the ratio of the dollars invested in order to breakeven to the dollars saved in the first year. In other words, an investor would be willing to invest X dollars if X divided by the first year savings is less than the breakeven payback ratio. The breakeven payback ratio for a 5-year simple payback is 5 by definition. The breakeven payback ratio for the economic assumptions of Table 2 is 28.05. Changing the real fuel escalation rate from 2% to 0% per year reduces the breakeven payback ratio to 20.89. Changing

TABLE 1. ELECTRICITY CONSUMPTION AND BREAKEVEN COST

| Case | Location | Electricity Consumption w/o Option (kWh/year) | Electricity Consumption w/Option (kWh/year) | Breakeven Life-Cycle Cost ($) | Breakeven Life-Cycle Cost ($/ft$^2$) |
|---|---|---|---|---|---|
| Infra-Red Reflecting Window Film* | Fresno, CA | 8,310 | 7,230 | 2,424 | 9.93 |
| Infra-Red Reflecting Window Film* | Casper, WY | 14,176 | 11,832 | 5,259 | 21.55 |
| Triple Pane Window* | Fresno, CA | 8,310 | 7,626 | 1,535 | 6.29 |
| Triple Pane Window* | Casper, WY | 14,176 | 12,864 | 2,944 | 12.06 |
| Selective Surface on a Mass Wall** | Casper, WY | 13,612 | 13,008 | 1,355 | 9.03 |
| Highly Reflective Surfaces with $I^2R$*** | Fresno, CA | 8,310 | 8,241 | 155 | 0.06 |
| Highly Reflective Surfaces with Heat Pump*** | Fresno, CA | 5,386 | 5,023 | 815 | 0.32 |

*244 ft$^2$ of window area.

**150 ft$^2$ of window area.

***2573 ft$^2$ of exterior surface area.

TABLE 2. ECONOMIC PARAMETERS AND VALUES

| Economic Parameter | Value |
|---|---|
| Down Payment | 20% of Breakeven Cost |
| Mortgage Rate | 12.5% per Year |
| Mortgage Term | 30 Years |
| Discount Rate | 10.5% per Year |
| General Inflation Rate | 8.5% per Year |
| Insurance Costs that Inflate with General Inflation | Initially 1.0% of Breakeven Cost |
| Equipment Life | 30 Years |
| Sales Tax Rate | 5% of Breakeven Cost |
| Property Tax Rate | 0% |
| Electricity Cost | $.08/kWh |
| Electricity Cost Real Escalation Rate | 2% per Year |
| Income Tax Bracket | 37% |

the price of electricity only in the first year does not affect the breakeven payback ratio.

Actual costs for the various passive options are shown in Table 5. The infra-red reflecting window film and triple pane glass costs are the total cost minus the cost of double pane glass. All of the costs are retail, uninstalled costs. Installation costs should, however, be the same between the window film and triple pane windows, and the double pane windows. The total installed costs for the selective surface will be slightly higher than is shown in Table 5.

## 4. CONCLUSION

By comparing the actual costs of Table 5 with the life-cycle breakeven costs of Table 3, it is concluded that infra-red window film, triple pane windows, and selective surfaces applied to mass walls are economic for both Casper, WY, and Fresno, CA. On the basis of a 5-year simple payback, however, it appears that only the infra-red window film and the triple pane window in Casper, WY, make economic sense. For the highly reflective exterior surfaces to be economic, the actual cost of the surface must be very low; at least lower than 32¢/ft$^2$ and perhaps as low as 1¢/ft$^2$ depending on economic assumptions and backup heating equipment.

TABLE 3. VARIATION OF BREAKEVEN COSTS WITH ECONOMIC ASSUMPTIONS

| (1) Case | (2) Location | (3) Assumptions of Table 2 ($/ft$^2$) | (4) 0% Real Escalation Rate for Electricity ($/ft$^2$) | (5) Electricity Costs of $.06/kWh and Real Escalation Rate of 0% ($/ft$^2$) | (6) 5-Year Simple Payback ($/ft$^2$) |
|---|---|---|---|---|---|
| Infra-Red Reflecting Window Film | Fresno, CA | 9.93 | 7.40 | 5.55 | 1.76 |
| Infra-Red Reflecting Window Film | Casper, WY | 21.55 | 16.17 | 12.04 | 3.85 |
| Triple Pane Window | Fresno, CA | 6.29 | 4.68 | 3.51 | 1.13 |
| Triple Pane Window | Casper, WY | 12.06 | 8.99 | 6.74 | 2.15 |
| Selective Surface on a Mass Wall | Casper, WY | 9.03 | 6.73 | 5.05 | 1.60 |
| Highly Reflective Surfaces with $I^2R$ | Fresno, CA | 0.06 | 0.04 | 0.03 | 0.01 |
| Highly Reflective Surfaces with Heat Pump | Fresno, CA | 0.32 | 0.24 | 0.18 | 0.06 |

TABLE 4. BREAKEVEN PAYBACK RATIOS

| Economic Assumptions | Breakeven Payback Ratio $ Invested / $ Saved/First Year |
|---|---|
| Listed in Table 2 | 28.05 |
| Table 2 Except 0% Real Escalation Rate for Electricity | 20.89 |
| Table 2 Except 0% Real Escalation Rate for Electricity and Electricity Price of $0.06/kWh | 20.89 |
| 5 Year Simple Payback | 5.00 |

TABLE 5. ACTUAL COSTS FOR VARIOUS PASSIVE OPTIONS

| Passive Option | Actual Cost Differential (1983 $/ft$^2$) |
|---|---|
| Infra-Red Window Film (Sliding Glass Doors) | 3.19 |
| Infra-Red Window Film (Small Windows) | 4.08 |
| Triple Pane Glass (Small and Large) | 2.06 |
| Selective Surface with Adhesive Backing | 2.20 |

# COMMERCIAL BUILDINGS


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# MONITORED PERFORMANCE OF PATOKA NATURE CENTER: A Direct Gain Building with BEADWALL$^{tm}$ Night Insulation in Southern Indiana

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## ABSTRACT

The monitoring and analysis of the passive solar heating performance of Patoka Nature Center is described. The Center is located in southern Indiana and was designed by the author (who is also Principal Investigator for the monitoring project). The building has a floor area of 3200 square feet, is heavily bermed and well insulated.

The building features 1390 net square feet of direct gain solar collector. This collector is equipped with BEADWALL$^{tm}$ night insulation. Thermal storage is provided by a masonry floor and 40 water-filled fiberglass tubes.

During the 1981-82 heating season, the building used 257 million Btu for space heating. This was supplied from: auxiliary heating equipment (28%), electric lighting (22%), other equipment (2%), and solar (48%). The annual solar heating efficiency (solar utilized/solar incident on collector glass) was 21.3%.

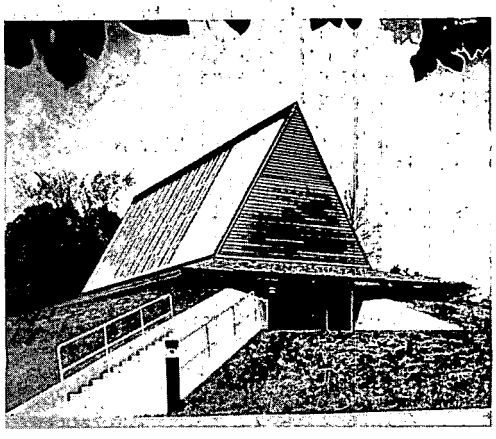


Fig. 1. East entry and south solar aperture

## 1. BUILDING DESCRIPTION

Patoka Nature Center is a public building that houses nature exhibits at this State Park, is the point of departure for hiking trails, and is used for lectures and slide shows. It has a floor area of 3200 ft$^2$ and a direct gain passive solar heating system (1390 ft$^2$ collection area). It utilizes a thermostatically controlled BEADWALL$^{tm}$ R-15 night insulation system. Construction is single story slab on grade, bermed to four feet around an 8inconcrete knee-wall (insulated to R-11). Above ground construction is frame with A-frame roof on laminated wood arches.

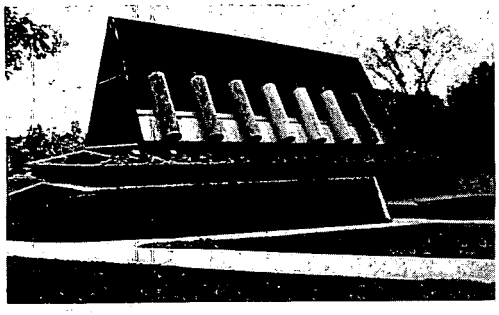


Fig. 2. North facade, showing BEADWALL$^{tm}$ storage tanks, and clerestory.

## 2. PERFORMANCE MONITORING

The performance monitoring strategy used for this project was essentially that used in the SERI Class B Monitoring program.

The ANNUAL PASSIVE SOLAR HEATING CONTRIBUTION is determined indirectly as the TOTAL ANNUAL BUILDING HEAT LOSS less HEAT GAIN FROM ALL INTERNAL SOURCES (including auxiliary heating, heat from equipment, and lighting, but excluding occupants).

The TOTAL ANNUAL HEAT LOSS is the sum of CONDUCTIVE LOSSES and INFILTRATIVE LOSSES. CON-

DUCTIVE LOSSES are the product of the calculated TOTAL UA (U-value x area) times the INDOOR/OUTDOOR TEMPERATURE DIFFERENCE measured by the DAS. (In the present building, U-value of glazing varies with the position of night insulation which is monitored with status sensors). INFILTRATION LOSSES are the product of INFILTRATION RATE (air changes per hour) times VOLUME/AIR CHANGE times the SPECIFIC HEAT OF AIR at the local elevation times the monitored INDOOR/OUTDOOR TEMPERATURE DIFFERENCE.

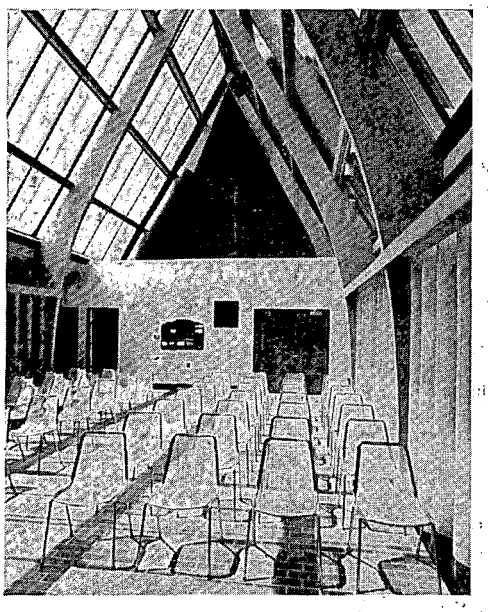


Fig. 3. Interior. Notice reflective ceiling (upper left), top gable vent with shutter, and water tubes and quarry tile floor for thermal storage.

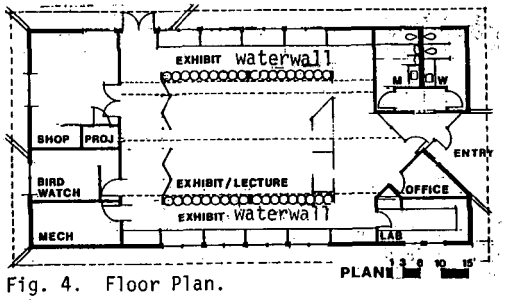



Fig. 4. Floor Plan.

INFILTRATION RATE is computed by a formula which uses a one-time measurement of infiltration, monitored windspeed (which affects the rate due to aerodynamic factors), monitored indoor/outdoor temperature difference (which affects rate due to the "stack effect" of the buoyant inside air), and monitored door and window openings.

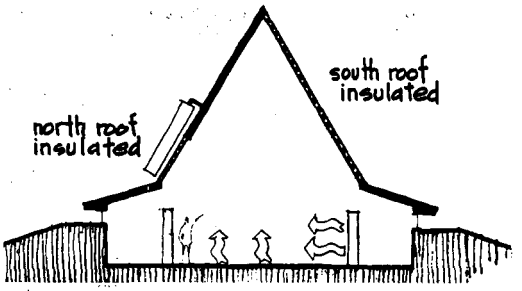



Fig. 5. Winter Night Mode.

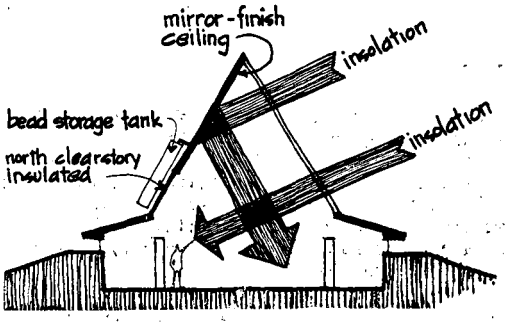



Fig. 6. Winter Day Mode.

The HEAT GAIN FROM INTERNAL SOURCES is the sum of HEAT GAIN FROM AUXILIARY HEATING, EQUIPMENT And LIGHTING. Heat gain from AUXILIARY HEATING is the product of the AIR TEMPERATURE DIFFERENCE (temperature of heated air supplied minus temperature of return air in the HVAC system) times the AIR VOLUME (determined by one-time manometer measurements) times the SPECIFIC HEAT OF THE AIR. Heat gain from EQUIPMENT (such as domestic water heaters) and LIGHTING is determined by power consumption which is measured either directly using Hall-effect current transducers (if load is variable) or one-time current measurements with an on/off status sensor (if load is constant). A utilization factor is used for certain equipment (i.e., DHW) where some of the energy would not contribute to heating the building.

The Data Acquisition System (DAS) for this project included:

- Aeolean Kinetics (AK) PDL 24 processor with two expansion terminals;
- Lamda Instruments pyranometer;
- AK integrated circuit temperature sensors;
- AK radiation shields;
- AK anemometer;
- custom BEADWALL$^{tm}$position photo-electric sensors;

- Hall-effect current transducers for measuring electric current;

- voltage sensor;

- status sensors (shutters open or closed, etc.);

- counting event sensors (number of door openings).

## 4. SOLAR HEATING PERFORMANCE

Data acquisition was begun at the Patoka site on July 15, 1981 and was discontinued on July 17, 1982. The DAS system was installed by the author, and maintained by Nature Center personnel. Data output was in two forms: printed paper tapes recorded daily and monthly summaries. Cassette tapes recorded hourly summaries data as well as daily and monthly summaries.

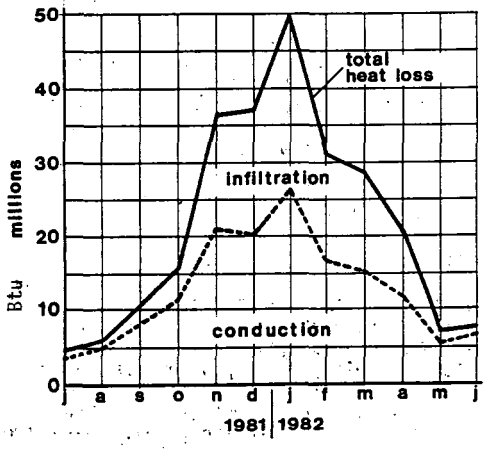



Fig. 7. Heat Losses by Month, 1981-82 Heating Season.

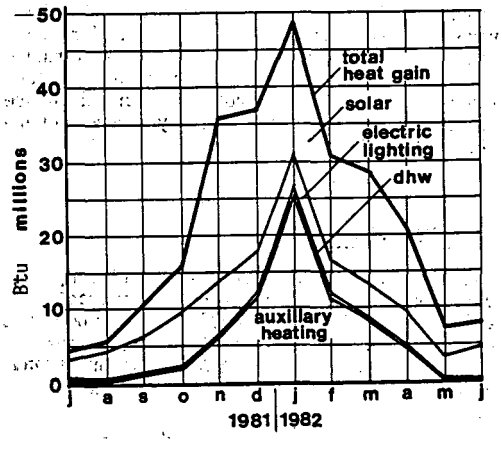



Fig. 8. Heat Sources by Month, 1981-82 Heating Season.

These were analyzed by the author using an Apple II+ microcomputer. When data acquisition was interrupted, the DAS was typically restarted from scratch by Nature Center personnel in accord with instructions from the author. This incorrect procedure resulted in the loss of the accumulated monthly summary data. As a result, monthly summaries had to be reconstructed using daily summaries. Missing data periods were reconstructed by interpolation using the available data for that month. While there was a considerable amount of missing data (119 days missing), most of this was during summer months; only 4 days of missing data occur from December thru April.

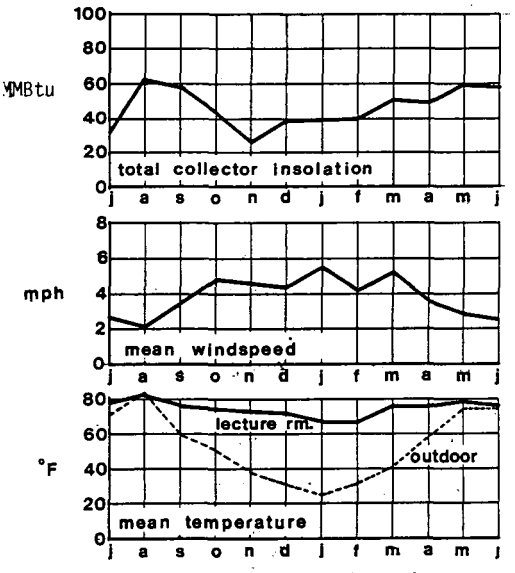



Fig. 9. Total Insolation, Mean Wind Speed, and Mean Indoor/Outdoor Dry Bulb Temperatures, by Month, 1981-82 Heating Season.

## 5. EFFECT OF NIGHT INSULATION

A series of experiments were conducted to assess the effect of night insulation on the buildings heating and lighting performance during both the heating and cooling seasons.

If BEADWALL$^{tm}$ night insulation had been left out of the north and south glazing during the entire 1981-82 heating season, the total annual heat loss would have been increased by 86.7 MMBtu (based on a calculated increased loss of 307.2 BTuh/F and the assumption that 75% of the heating degree days occurred during the hours that the night insulation would have been in place). The annual solar heat contributed would have remained approximately the same at 124.5 MMBtu (although a small increase might have been experienced in the spring and fall transition months). However, the annual solar heating fraction would have been reduced from 48% to 35%. It is likely that all

of this additional heat required would have been supplied by the central heat pump. Based on the present electric power cost of $.06 per kilowatt and a system C.O.P. of 2.0, the additional heating would have cost approximately $772.

If the night insulation had been left in place during the entire heating season, the annual heat loss would have been reduced by 24.2 MMBtu However, the entire solar heating contribution of 124.5 MMBtu would have been excluded, resulting in a net deficit of 100.3 MMBtu Assuming that half of this deficit would have been replaced with the heat from the additional electric lighting required, the additional heating/lighting costs would have been $1,342 during the heating season.

## 6. POST-OCCUPANCY OBSERVATIONS

Based on the author's involvement with this project as architect, solar consultant, and energy analyst, the following observations are presented.

### 6.1 Design

The strategy of zoning the winter activities into perimeter rooms, while allowing the large lecture exhibit space to fluctuate in temperature appears to have worked well.

The lack of convenient controls for the summer BEADWALL$^{tm}$ operation has resulted in an unexpectedly large usage of electric lighting. (See previous discussion).

The building was designed to use "night flushing" as a summer cooling strategy. Large louvered exhaust eave vents and small awning windows over the exhibit booths proved very effective in inducing stack effect ventilation at night during the summer of construction. During that summer, interior temperatures typically remained 10-15°F below outside. Although the windows are too small to allow intruder entry, building personnel close these windows at night for security reasons. Even with the eave vents open, the lack of any inlet prevents night ventilation cooling. A better design choice for such a non-residential building would have been shuttered louvered vents and fixed glazing instead of the operable windows used.

### 6.2 BEADWALL$^{tm}$ Night Insulation

Given the owner's design requirement that the passive system be "visually exciting" and completely automatic in operation, the decision to use BEADWALL$^{tm}$ night insulation appears to be justified, based on alternatives available in 1976. A full height test panel was constructed and operationally tested prior to the final decision to use this system. The test model worked perfectly.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

Initially, the system was designed to utilize prefabricated fiberglass glazing panels manufactured by Kalwall Corporation. Kalwall withdrew from the project during the bidding phase and a field-fabricated greenhouse glazing system was substituted. While this was an initial disappointment, the internal access afforded by the latter system proved invaluable in the subsequent modifications and maintenance required of the BEADWALL$^{tm}$.

When construction of the building was completed in November 1979, primary electrical service was not available to the site. The BEADWALL $^{tm}$ equipment was operational and checked out using portable generators for the required electric power. In the absence of permanent power to supply the mechanical and electrical system, the building could not be occupied, and an unvented propane heater was installed to provide maintenance heating. The following April, with permanent power finally available, the BEADWALL $^{tm}$ was operated. At that time it was discovered that the polystyrene beads had deteriorated during the winter and left a whitish deposit on inner glazing surfaces. The inner glazing was removed and both surfaces cleaned. The defective beads were removed, the storage tanks cleaned, and the new beads installed.

In operation, the newly installed beads repeatedly exhibited static build-up. This resulted in frequent clogging despite repeated applications of recommended anti-static solutions injected in to the beads. At one time the problem was so severe that sparks approximately 18 inches long were discharging from the beads. (These discharges were estimated at 150,000 volts). The problem was the frequent movement of one insulating material (the beads) in contact with another insulating material (glass and plastic pipe). The author made numerous visits to the site attempting various remedies, most of which involved attempts to discharge the components using grounding devices. The problem was finally resolved with the application of 100% glycerine in lieu of the manufacturer's recommended anti-static solution. After two applications the static problem has not re-occurred in over 18 months of operation. The system now operates satisfactorily.

## 7. ACKNOWLEDGEMENTS

Funding for this project was provided by the U.S. Department of Energy under Contract #DE-FG02-79 CS 34030. Additional support was provided by Miami University. The author wishes to particularly thank Carol Grove and other Nature Center staff members, as well as Doug Halprin and the Aeolean Kinetics group, for their considerable and enthusiastic assistance.

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# MONITORED HEATING SEASON PERFORMANCE OF THE MOUNT AIRY PUBLIC LIBRARY BUILDING

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## ABSTRACT

Actual energy consumption by end use during the winter months for the passive solar library building in Mount Airy, North Carolina is compared to the predicted values and major differences between these two are explored and explained based on data and interpretation of performance. Key elements are occupant reaction to the building and changes in the operational strategies for the building based on feedback from the data acquisition system.

## 1. INTRODUCTION

The new passive solar public library building in Mount Airy, North Carolina was designed, built and is now being monitored with partial funding from the Passive Solar Commercial Buildings Program (PSCBP) sponsored by the U.S. Department of Energy (DOE). The PSCBP is a three phase program. The first phase was the design of the building in which the Architects, J. N. Pease Associates, and the Solar-Architectural Consultants, Mazria/Schiff and Associates, worked closely with the owner, the City of Mount Airy, and representatives of DOE to explore and evaluate numerous building design, solar design and mechanical system options. The second phase was the construction of the building. The general contractors, John S. Clark Company, worked closely with the designers in constructing the passive solar building. The third phase is the monitoring of the buildings performance. Methodology for the performance monitoring was established by Burt, Hill, Kosar, Rittelmann Associates under contract to DOE. This methodology requires that the energy consumed for the major end uses of space heating, domestic water heating, air conditioning, lighting, blowers, passive hybrid systems, appliances and total energy be measured and reported as weekly and monthly totals for each fuel serving the building. Architectural Energy Corporation was hired to install an Aeolian Kinetics PDL-24 microcomputer controlled data acquisition system in the building and to program it to take and process data and printout results on-site each day in a format which directly satisfies the reporting requirements to DOE.

This paper contains descriptions of the building, its passive systems, its mechanical systems and the data acquisition system. Design assumptions, occupancy patterns and the design tools used to predict performance are explained along with predicted monthly energy consumption values for the major end use categories. Deviations of actual consumption from predicted values are discussed, but detailed performance calculations or additional performance simulations are beyond the scope of this paper.

## 2. BUILDING DESCRIPTION

### 2.1 Design Process

Prior to developing schematic designs for the library, actual buildings with similar occupancy and climate were studied to determine their energy consumption for the major end uses. The two buildings which were most useful were the Mount Airy Municipal Building and the Elkin Public Library. The Mount Airy Municipal Building has an area of 17,367 square feet, is located adjacent to the library and was constructed in 1978. The Elkin Public Library has an area of 15,000 square feet, is located 25 miles from Mount Airy and was constructed in 1969. It was determined that heating and lighting requirements comprised 70 to 80% of the annual fuel usage in these buildings. Since the Mount Airy Library was going to have air-to-air heat pumps, providing greater heating efficiency than the systems in the other two buildings, then the largest use of energy would be for artificial lighting. A decision was made to use natural lighting to the largest extent possible, thereby reducing the total lighting load. Passive solar heating and natural ventilation strategies are used extensively throughout the building. Due to the complexity of the design problem, energy

goals and architectural concepts had to be integrated very early in the design process.

## 2.2 Architecture

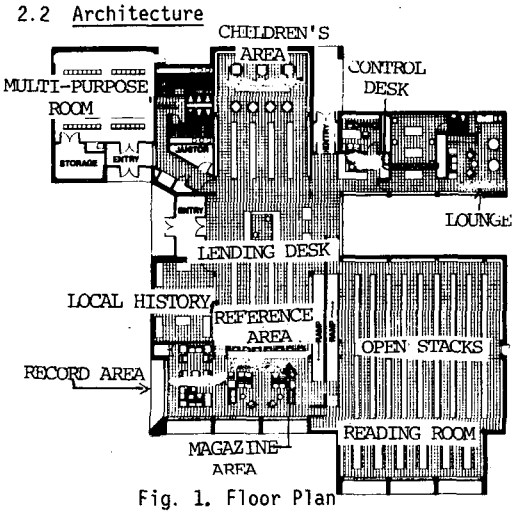



Fig. 1. Floor Plan

The building has 13,570 square feet of floor area and uses extensive amounts of daylighting throughout the three floor levels. The floor plan is an "open space" design to compliment the lighting and to promote an open feeling and the general spacial relationships. A multipurpose room has been incorporated into the design and is used for library functions or by the public when the remainder of the library is closed. Shelves of books are used to separate the children's area from the rest of the library. These shelves also provide good acoustic separation from the adult areas of the library. Staff work areas are located in a "wing" separated from the remainder of the library.

Areas for reading and other tasks requiring higher levels of illumination are strategically located under clerestory windows or near light shelves along the southern edge of the building for best use of daylighting. This eliminates the need for artificial lighting for these tasks except at night or on very cloudy days. Approximately 2,000 square feet (66%) of the building glass area faces south. Glazing comprises approximately 11% of the total skin area. All glazing is insulated glass (double pane) except for entrances where code requires tempered glass.

Reinforced concrete is used for the structural frame. All exterior walls are twelve-inch thick concrete masonry, grouted solid. The building skin is native white granite quarried in Mount Airy. Urethane insulation (R-20) is placed between the granite and the concrete block walls. The roof system is also insulated with urethane (R-20). Interior finishes consist of exposed concrete, wood and quarry tile. The architectural context of the library is compatible with the adjacent Mount Airy Municipal Building. Landscaping and site design are an integral part of the project and their effect on building performance was an important consideration during design.

## 2.3 Passive Features

The passive features of the building were designed to provide daylighting, space heating and ventilation for cooling. These include extensive use of south facing, saw tooth clerestory windows over the central section of the building for daylighting and solar gain, light shelves along south walls to shade glass in summer and to reflect light for daylighting all year and overhangs designed to provide summer shading yet allow for direct solar gain in winter. The open space plan and operable windows at various levels are used for natural ventilation during spring and fall. Solid grouted masonry walls provide extensive amounts of building mass. Tile floors with limited amounts of carpet for noise control provide additional building mass. Also, the more than 80,000 books stored in the library contribute to the thermal mass. Conservation features include the large amounts of roof and wall insulation and unheated air locks on two of the buildings three entrances. Preservation of existing, mature trees provides substantial shading to the east and west.

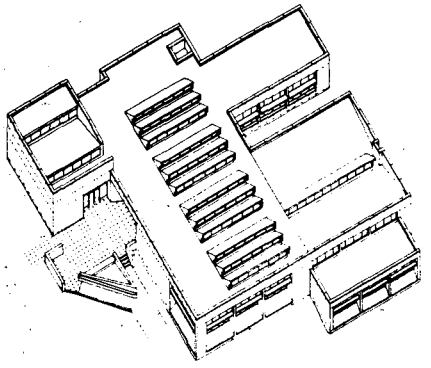


Fig. 2. Perspective View

## 2.4 Mechanical Systems

The mechanical systems for this building are not elaborate. Electricity is the only utility supplied energy source serving the building. Five air-to-air heat pumps, located on the roof, provide mechanical heating, cooling and ventilation

to zones within the library. These are equipped with electric resistance elements for extra heat when the heat pumps alone are not sufficient to meet the heating load. An economizer cycle, using outside air for cooling, is used whenever possible. Each heat pump is controlled by a "smartstat" programmable thermostat for heating, cooling, fans, night set-back and daily temperature functions. Unit heaters are located in restroom areas for additional heat in these spaces. Strip diffusers for air delivery are incorporated into the ceiling system and are concealed above the wooden ceiling grid. Relief vents and exhaust fans are installed above the attic spaces. Domestic water is heated by an active solar system.

The stacks are illuminated with special fixtures which are attached to the top shelf of each rack and serve as task lighting to the aisle below. Task lighting also provides higher lighting levels at reading surfaces in the magazine section, lending desk and children and adult reading areas. Area illumination in general is accomplished by reflecting light from the sloped ceilings, indirectly illuminating the spaces and simulating the daylighting technique.

## 3. DATA ACQUISITION SYSTEM

During construction, conduit and instrumentation wire were installed for the data acquisition system. The data logger being used is the microcomputer controlled PDL-24 manufactured by Aeolian Kinetics. The system, as configured, will accept 22 channels of input data and is expandable to accept up to 88 data channels. Meeting the reporting requirements of the PSCBP was the criteria used for determining the parameters to measure and sensors to use. An additional constraint was to have no more than 22 data channels, since any more than this would not have been within the budget for the project. The following are parameters being measured:

a. Solar Radiation on Horizontal Surface
b. Outside Air Temperature (Dry Bulb)
c. Indoor Air Temperature Near Thermostat-Stat #1
d. Indoor Air Temperature Near Thermostat-Stat #2
e. Indoor Air Temperature Near Thermostat-Stat #3
f. Indoor Air Temperature Near Thermostat-Stat #4
g. Indoor Air Temperature Near Thermostat-Stat #5
h. Heat Pump #1 Energy Consumption
i. Heat Pump #2 Energy Consumption
j. Heat Pump #3 Energy Consumption
k. Heat Pump #4 Energy Consumption
l. Heat Pump #5 Energy Consumption
m. Demand of Electrical Panel "L"
n. Demand of Electrical Panel "P"
o. Status of Unit Heater #1
p. Status of Unit Heater #2
q. Status of Unit Heater #3
r. Status of Water Heater
s. Status of Solar DHW Pump
t. Status of Vent Fan #1
u. Status of Vent Fan #2
v. Status of Outdoor Lighting

The programmable features of the data logger are used to set the channel scan rate, input sensor calibration coefficients, select data storage and print intervals and to process data. All input channels are scanned once every 15 seconds. This is also the frequency with which the data reduction program is executed. Hourly averages or totals of the raw channel values are calculated and stored on cassette tape. A set of 51 daily functions of processed data is calculated and printed at midnight each night. Another set of monthly functions is printed at the end of each month. The data logger's ability to process raw data decreased the total number of sensors required to separate the energy consumed by heat pumps into the heating, cooling and fan energy categories based on measurements of both the instantaneous rate of energy consumption and the air temperature in each zone.

The data acquisition system was installed in August, 1982 and has taken data without interruption since then. The paper tape printouts are used to prepare reports to DOE on the energy consumption of the building and the hourly data on cassettes has been transferred by AEC to a mainframe computer system and will be archived at the AIA Foundation in Washington, D.C. All types of data are being used to learn more about the operation of the building.

## 4. ENERGY PERFORMANCE PREDICTIONS

The predictions of monthly auxiliary energy required by the building were made using a three step process. The first was to calculate the peak heat gains and losses through the building skin (roof, walls, windows) at the annual temperature extremes. The second was to input the heating and cooling loads, coefficients of performance for the heat pumps, temperature settings, occupancy schedules and the base loads for lighting, appliances, etc., into the ECAL program for purposes of calculating the auxiliary energy required each month for the major end uses. The ECAL program was developed by J. N. Pease Associates and accounts for internal gains from lights, appliances and people as providing useful heating or contribut-

ing to the cooling load. It uses a temperature bin method to calculate the heating and cooling loads for 2.78°C (5°F) temperature increments between -17.78°C (0°F) and 35°C (95°F). Binned temperature data are available from military manuals or from the weather bureau. Models were built to simulate the lighting levels within the clerestory spaces for purposes of determining the energy required for auxiliary lighting. The program uses steady-state ASHRAE methodoloy, and is not a dynamic simulator. An independent calculation was made of the passive solar gains using a passive solar absorbed radiation technique.

Credit for the passive solar gains was then taken by subtracting the predicted gains during the heating months from the auxiliary heating energy required predicted by the ECAL program. An adjustment was made for months in which the outside temperature rises above 21.1°C (70°F).

The predicted auxiliary energy for each of the major end uses for the heating months of November through April is shown in Table 1.

## 5. ACTUAL ENERGY PERFORMANCE

The measured auxiliary energy consumed for the heating months is shown in Table 2. A comparison of the values in Tables 1 and 2 shows that the predicted values in almost all categories are substantially different than the actual values. The significant differences are for space heating and blowers/fans, which are greater in the actual building than in the predictions, and lighting, which is less in the actual building than in the predictions.

Differences in space heating energy are sometimes explainable by differences between the actual weather and the long term average weather used to make the predictions. A comparison between these two is contained in Table 3. Though January and February were slightly colder than the long term average, the winter was actually sunnier and warmer than normal. The space heating energy cannot be explained by weather (i.e., temperature and sunshine). The blower/fan energy usage is tied to the space heating energy since fan energy is required to distribute mechanically heated air. An explanation of the space heating energy will provide an explanation of the blower/fan energy.

TABLE 1

PREDICTED AUXILIARY ENERGY (Million Btu)

| | November | December | January | February | March | April |
|---|---|---|---|---|---|---|
| Space Heating | 1.12 | 11.31 | 11.22 | 5.27 | 2.40 | 0.32 |
| Hot Water | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |
| Cooling | 0.37 | 0.04 | 0.02 | 0.02 | 0.30 | 2.44 |
| Lighting | 7.22 | 7.22 | 7.22 | 7.22 | 7.22 | 7.22 |
| Blowers/Fans | 4.51 | 4.01 | 3.90 | 3.86 | 4.51 | 4.75 |
| Active Pump | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Miscellaneous | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 |
| TOTAL | 14.07 | 23.43 | 23.21 | 17.22 | 15.28 | 15.58 |

TABLE 2

ACTUAL AUXILIARY ENERGY (Million Btu)

| | November | December | January | February | March | April |
|---|---|---|---|---|---|---|
| Space Heating | 7.21 | 17.60 | 42.80 | 31.66 | 20.03 | 14.10 |
| Hot Water | 0.22 | 0.39 | 0.28 | 0.18 | 0.13 | 0.12 |
| Cooling | 0.29 | 0.46 | 1.02 | 0.12 | 2.99 | 0.00 |
| Lighting | 4.97 | 4.73 | 3.84 | 3.60 | 4.87 | 3.94 |
| Blowers/Fans | 4.91 | 6.96 | 11.39 | 9.09 | 7.41 | 5.92 |
| Active Pump | 0.03 | 0.02 | 0.02 | 0.05 | 0.06 | 0.05 |
| Miscellaneous | 0.41 | 0.45 | 0.43 | 0.35 | 0.41 | 0.39 |
| TOTAL | 18.04 | 30.62 | 59.85 | 45.04 | 35.89 | 24.52 |

TABLE 3

COMPARISON BETWEEN ACTUAL AND LONG TERM AVERAGE WEATHER

| | November | December | January | February | March | April |
|---|---|---|---|---|---|---|
| LONG TERM AVERAGE | | | | | | |
| Solar Radiation | 839.2 | 658.7 | 715.3 | 970.0 | 1313.2 | 4496.4 |
| Temperature | 48.3 | 39.6 | 38.7 | 40.6 | 47.8 | |
| Maximum Temperature | 60.1 | 49.9 | 48.8 | 51.4 | 59.4 | |
| Minimum Temperature | 36.5 | 29.2 | 28.5 | 29.7 | 36.1 | |
| Heating Degree Days | 500.0 | 787.0 | 814.0 | 682.0 | 544.0 | 332.7 |
| ACTUAL | | | | | | |
| Solar Radiation | 925.2 | 653.5 | 897.6 | 1104.8 | 1397.4 | 4978.3 |
| Temperature | 48.2 | 43.0 | 35.9 | 38.3 | 47.9 | |
| Maximum Temperature | 61.1 | 52.6 | 46.9 | 50.2 | 59.7 | |
| Minimum Temperature | 37.0 | 34.3 | 26.6 | 28.1 | 37.8 | |
| Heating Degree Days | 478.5 | 668.0 | 875.7 | 749.6 | 503.7 | 3275.5 |

The lighting energy was assumed to be constant in each month, as indicated in Table 1. The measured values show that this is very nearly true, though the magnitude is different, and with a decrease in lighting energy usage during December, January and February. It would appear that either the estimated lighting levels derived from studies of models over estimate the actual lighting energy by approximately 165% or the occupants are satisfied with lower lighting levels than assumed.

Additional sources of disagreement that need to be considered are that the predictions of energy usage could be in error, the usage and occupancy of the building could be different than assumed, the building could be constructed differently than modeled, or a combination of all three. The last two of these are most easily examined.

The building is constructed as modeled with the exception of a light shelf that was deleted from the staff area because of building code requirements and the wiring for an emergency lighting circuit that had to be changed. These are not significant changes and do not impact the energy consumption. Occupancy and usage are different than assumed. An average of 127 people are using the library each day compared to the assumed number of 50. The building is open longer hours and more days per week. This has decreased the number of hours that the building has been on night setback and has increased infiltration. The thermostat settings for both night setback and daytime use have been changed because of complaints about comfort. The 20°C (68°F) daytime temperature was too cold and has been increased to 21.1°C (70°F). Similarly, the 10°C (50°F) night setback temperature was too low and has been increased to 16.7°C (62°F). All of these will increase energy consumption for space heating. Even with these explanations, the differences between actual and predicted consumption are not fully explained and it would appear that the technique used to make the predictions does not produce the accuracy desired. A thorough review of this process has not been done.

## 6. MONITORING FEEDBACK

Having the data acquisition system in the building has provided a convenient opportunity to learn about the operation of the building and its mechanical systems, that normally is not possible. For instance, the thermostats were found to need frequent adjustment to maintain proper calibration. The set point for daytime and night setback have been changed to increase comfort without sacrificing economical operation. The data have helped to identify mechanical system malfunctions that would otherwise go unnoticed and uncorrected. The data have also indicated when unit heaters have been left on or when lighting has been on when sufficient natural lighting was available. The data acquisition system will continue to be used in the future to fine tune the

operational practices for the building. As an example, the data indicate that the cooling system should be manually locked off during the heating season and vice versa. During certain transition months both heating and cooling can be locked off. This was done during May, 1983 with no sacrifice in comfort.

Though the predicted values for energy consumption do not agree with the actual consumption, a more meaningful comparison to determine the effectiveness of the passive design is the energy consumption of this building relative to other buildings. During the winter of 1982/1983 the library used 9,881 Btu per square foot for heating. The municipal building adjacent to the library used 70,252 Btu per square foot, seven times more energy for heating alone. For all other purposes during this same time period, the library used 6,672 Btu per square foot while the municipal building used 36,694 Btu per square foot. The municipal building required 5.5 times more energy for these purposes. The energy consumption of the Mount Airy Library is extremely small compared to the adjacent conventionally constructed building.

The number of visits to the libary are 254% greater than was projected. Visitors generally enjoy the daylighting and rarely request that additional lighting be turned on. Some people have complained of being too cool, but most of these problems have been corrected.

## 7. CONCLUSIONS

Calculations of performance for the Mount Airy Public Library underpredict the auxiliary energy requirement for space heating and fans, and overpredict the energy required for lighting. The actual energy consumed for space heating is seven times less than the energy consumed by an adjacent conventional building. The actual energy consumed during the heating season for all other uses is five and one-half times less than the conventional building.

The conclusion to be made on the basis of available measured performance data is that the library is performing well. The passive heating and daylighting systems have made major contributions to reducing non-renewable energy consumption.

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# THE DOE PASSIVE SOLAR COMMERCIAL BUILDINGS PROGRAM: PRELIMINARY RESULTS OF PERFORMANCE EVALUATION

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## ABSTRACT

The U.S. Department of Energy is conducting performance evaluation of the buildings in the Passive Commercial Buildings Program. The objectives of the effort are: 1) to determine how much auxiliary energy is being saved by these passive solar buildings over non-solar buildings, and 2) to determine whether the buildings function, or are perceived to function, as well as non-solar buildings. Some preliminary results of the evaluation are that the buildings are, in fact, saving significant amounts of energy in comparison to non-solar buildings; that a majority of the occupants are satisfied overall with the buildings; that occupancy of the buildings can be substantially different than what was assumed during design; and that passive buildings require a great deal of communication between designers, vendors, and contractors for successful construction.

## 1. INTRODUCTION

The U.S. Department of Energy is sponsoring the Passive Commercial Buildings Program to experiment with the use of passive solar techniques in non-residential buildings. The projects in the Program have been funded for the cost of designing and constructing passive solar elements and are required to conduct performance evaluation of the completed buildings. The objectives of the performance evaluation are:

1) to determine how much auxiliary energy is being saved by these passive solar buildings over non-solar buildings, and

2) to determine whether the buildings function, or are perceived to function, as well as non-solar buildings.

To meet these objectives, each project will be measuring energy use with submetering and/or automated data collection equipment. Each project will also be regularly surveying the occupants of the passive building to determine how well they think the building is working. All thermal and occupancy data are being submitted on standard forms and analyzed according to a consistent procedure so that there will be a basic "core" of data and analysis for all projects.

## 2. THERMAL PERFORMANCE

As of June, 1983, data have been been processed for three projects with at least a year of data collection. Six other projects were collecting data at that time but, with less than a year's worth of data, it is difficult to compare their energy consumption to a well-accepted standard. Therefore, the analysis of thermal results presented here only deals with the three projects mentioned above.

The energy consumption of the three passive commercial buildings is shown in Table 1. As a comparison, BEPS base building consumption figures are also shown. Figures are drawn from the BEPS project's survey of base buildings designed during 1973-76.

Some preliminary conclusions can be drawn from the figures in Table 1. It is clear that the buildings use substantially less energy than their BEPS counterparts designed in the middle 1970's. The percentage reductions are 33%, 12%, and 77%. It should be said in the case of the Gunnison Terminal (12% reduction) that the match of building types (airport terminal vs. store) and locations (Gunnison vs. Denver) is not particularly close. In particular, Gunnison has 9941 heating degree days as compared to 6016 in Denver. A more appropriate comparison would perhaps be a store in Bismarck, North Dakota with 9043 heating degree days. The BEPS energy consumption of this building is 95,000 Btu $ft^{-2}$ $yr^{-1}$, making Gunnison Airport's 70,600 Btu $ft^{-2}$ $yr^{-1}$ a respectable 25% reduction in energy use.

TABLE 1. ENERGY CONSUMPTION OF DOE PASSIVE COMMERCIAL BUILDINGS VERSUS BEPS BASE BUIDINGS

(Units are MBtu $ft^{-2}$ $yr^{-1}$)

| PROJECT | BUILDING TYPE | HEATING | COOLING | LIGHTING | OTHER | TOTAL | BEPS BASE* |
|---|---|---|---|---|---|---|---|
| Rensselaer Polytechnic Institute, Troy, NY | Visitors' Center/ Security Center | 19,000 | 1,400 | 12,100 | 14,300 | 46,800 | 70,000 (Small office - Albany, New York) |
| Gunnison City Airport Terminal, Gunnison, CO | Airport Terminal | 29,800 | 0 | 40,200 | 600 | 70,600 | 80,000 (Store, Denver, CO) |
| Community United Methodist Church, Columbia, MD | Church Addition | 13,400 | 0 | 1,500 | 1,300 | 16,200 | 71,000 (Community Center - Columbia, MO) |

*Represents the mean energy use of BEPS base buildings for a given building type and location. Values were determined from a large sample of buildings designed in 1973-76. Source: Energy Budget Levels Selection: Technical Support Document for Notice of Proposed Rulemaking on Energy Performance Standards for New Buildings, U.S. Department of Energy, November 1979.

How much of the energy savings of the DOE Program buildings can be attributed to passive solar design will not be proven conclusively by the program's performance monitoring efforts. It was decided early in the program that the basic monitoring effort would not involve an energy balance but, rather, only a measurement of auxiliary energy consumed (1). Hence, energy savings can be attributed not only to passive design, but also to intensive energy conservation measures and careful operation by the occupants.

## 3. OCCUPANT SATISFACTION

The whole subject of occupant interactions with the buildings in the program is being explored in another paper at this conference by M. Kantrowitz. To avoid repeating the content of that paper, only the question of the occupants' overall satisfaction with the building will be covered here.

Information about building occupants' attitudes is being gathered by means of monthly questionnaires. The answers to a question on overall satisfaction with the building have been tabulated to determine an average percent of occupants responding each month who are satisfied with the building. Seven projects have submitted occupancy forms thus far. An average of well over two-thirds of each month's responses for each project show the respondents to be satisfied or highly satisfied with their building. Nearly all respondents indicated that they were at least neutral about the building. Hence, it seems that these occupants are probably as satisfied with their buildings as occupants of all commercial buildings.

## 4. QUALITATIVE OBSERVATIONS

Some results of the program cannot be quantified, at least as yet, but can be stated with some certainty nonetheless. One observation concerns the adequacy of design procedures in dealing with building occupancy. It is clear from the results so far that occupancy of the building can have significant effect on energy consumption. The paper by M. Kantrowitz in these proceedings deals with the point at length. It is interesting to note further that occupancy of the building is difficult and uncertain for the designer to predict. This has important implications for the whole approach to passive design.

Two of the projects in the program illustrate the unpredictability of occupancy. The RPI Visitors' Center was designed with two zones of occupancy. Zone 1 is located just north of the building's sunspace and was supposed to contain all the offices in the building. Zone 2 along the north side of the building was to consist of areas which would not be constantly occupied--storage rooms, restrooms and the like. Therefore, Zone 1 was to be fully conditioned for human comfort and Zone 2 was to be heated and cooled only for occasional use. As it turned out, the owner of the building transformed part of Zone 2 into office space. Since full comfort conditioning is necessary, it seems certain that the building's energy use has been increased as a result.

The Blake Avenue College Center in Glenwood Springs, Colorado has not yet begun data collection, but the energy use of that building is almost sure to be affected by its changed occupancy. During design, the College Center was scheduled to be occupied only during weekdays. In addition, the atrium on the south side of the building was thought to be little more than a large foyer, through which students and faculty would rather quickly pass to classrooms and laboratories in other parts of the building. For these reasons, the atrium was not to be conditioned at all.

In contrast to designers' expectations, the building is receiving a good deal of evening use. In addition, the expanse and the ambience of the atrium have made it a central gathering place as well as a foyer. For these reasons, the decision has been made to condition the space the same as the rest of the building. This will undoubtedly have an important effect on energy use.

In general, designers have to base their decisions on the most probable occupancy of the building. However, these examples suggest that passive designers--and designers of building energy systems in general--should consider other possible occupancies than the most probable one in their calculations. It may be that, because of a passive element, energy use will be much more sensitive to the occupancy change than a conventional building would. For example, the presence of large glass areas may make commercial building energy use very sensitive to extended nighttime use. The designer may at least want to be aware of this energy use risk factor and may want to include measures to decrease the sensitivity of energy use to occupancy. For example, nighttime insulation may be considered in the case of large glass areas even though, based on probable occupancy, the insulation would not be cost-effective.

Another qualitative observation about buildings in the Passive Commercial Program is that it is more difficult to achieve proper construction of these buildings than with conventional buildings. Difficulties include installation of newly developed components and misunderstandings by contractors about the proper construction and operation of the passive buildings.

In one instance, construction was delayed by the fabrication of a newly-developed thermal shutter system. Once the system was installed, further adjustments were necessary to make the shutters more tight-fitting. In another case, a thermal shutter system simply did not perform as required, requiring extensive modifications by the building owner who still has not been able to make the system fully operational.

Another project has encountered a long delay in the installation of the building control system. Apparently, because of the complexity of the control scheme, the controls contractor misinterpreted what was required and installed his version of the system before the errors were discovered. Now the owner and contractor are negotiating for the completion of the system as originally specified. In another case, conventional dampers were installed by the contractor instead of tight-fitting models. At this time it is unclear how the matter will be resolved.

A preliminary conclusion to be drawn from these instances is that it is especially important for the passive designer to communicate extensively with suppliers and contractors and to clarify specifications as much as absolutely possible. Many passive products are not proven in the marketplace and many contractors are unaware of the importance of mechanical and architectural details to successful passive building performance.

A final observation is that a performance evaluation system may be useful not only to measure the energy use of the building, but also to determine if the building's energy systems are working properly. In particular, an automated data logger system can be set up to provide a time varying record of energy use and environmental conditions. This provides the building operator or designer with a detailed record of energy system response to weather conditions, inside temperature, the presence of occupants, and other factors.

One project in the Program using an automated data logger has encountered much higher heating energy use than was predicted by the designer. The data recorded by the logger was crucial in determining that the heating units were operating illogically in relation to interior temperature. For instance, the units were often turned on when the temperature of the space was above the heating setpoint and at other times were turned off before the setpoint had been reached. A faulty control system was thus indicated by the data from the logger. Diagnosis of the problem otherwise would probably have been more difficult and costly--and perhaps erroneous.

A final preliminary conclusion is that a performance evaluation system can be extremely useful for reviewing building systems operation, as well as for collecting energy use data. Short-term instrumentation of any new building with complex energy systems may be useful to assure proper operation of those systems.

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# DAYLIGHTING PERFORMANCE DOCUMENTATION OF TWO INNOVATIVE LOW RISE COMMERCIAL BUILDINGS

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## ABSTRACT

Two low-rise commercial office schemes with design emphasis on daylighting have been documented in their ability to provide natural lighting. Illumination levels, surface luminance and auxiliary requirements of the spaces are presented. Parametric studies of design components are also presented.

## 1. INTRODUCTION

The Butler Manufacturing Company Prototype Building in Grandview, MO and the Princeton Professional Park Office Complex have been designed and built with the aid of US DOE grants awarded in the 1979 Passive and Hybrid Solar Manufactured Buildings and Passive Solar Commercial Buildings Programs. Butler Manufacturing Company markets pre-engineered metal buildings around the world; Princeton Professional Park (PPP) is a speculative office project in Princeton, NJ. Sections and reflective ceiling plans are shown in Figures 1 and 2. Each of the buildings is designed to minimize heating, cooling and lighting costs. In both cases the design team felt that a major determinant in the evolution of the design was the need to bring daylight into the building from overhead. In general, perimeter lighting from vertical perimeter windows is adequate to roughly 15 ft which is also the depth of a closed office. To allow additional light penetration given these constraints, the Butler building uses a set of three roof apertures to selectively bring in north or south light as the season requires. PPP uses a glazed atrium with interior clerestories which allow a view of

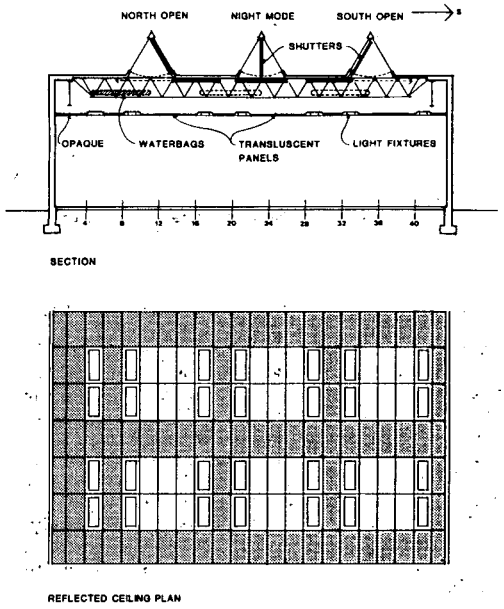



Fig. 1. Butler Mfg. Co. Maintenance Shop. Diagram shows 3 modes of shutter operation, waterbag option, translucent panels.

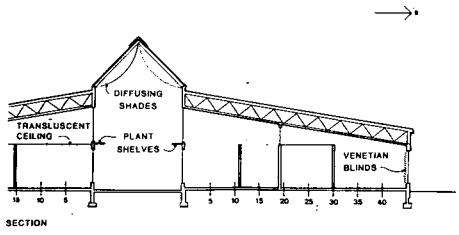



Fig. 2. Princeton Professional Park. Section showing north office with translucent ceiling, atrium with sun diffusing shade and south office with Venetian blinds.

the sky dome from deep within the office space. This paper documents the degree to which the designs are successful in respect to both the ability to provide natural light, and to answer the more essential question: Under what conditions can auxiliary lights be turned off?

The common yardstick of daylighting design is illuminance levels (footcandles) or the daylight factor on the workplane. We present these indices, as well as luminance ratios within the space, in order to understand more clearly issues of lighting quality.

## 2. BUTLER MANUFACTURING COMPANY, GRANDVIEW, MO PROTOTYPE BUILDING

### 2.1 General Information

The Butler prototype building houses three types of spaces: office, maintenance shop and warehouse. Each receives daylight from three overhead double sided roof apertures equipped with opaque insulating shutters. The shutters have three modes of operation to allow 1) only the south aperture to be open, 2) only the north aperture to be open, 3) both apertures to be insulated from the interior at night (see Fig. 1). All three shutters operate in tandem. Thermal storage was designed into the building in the form of waterbags located between trusses in the roof plenum. Direct solar gain in the winter is absorbed by the waterbags; diffuse north light enters the space below through the translucent panels.

Dropped ceiling heights are 8ft in the office, 10ft in the maintenance shop. The warehouse is similar to the shop except the dropped ceiling and HVAC ducting have been omitted and the apertures can be viewed directly from below (Fig. 1). The dropped ceiling contains translucent prismatic diffusers which allow light penetration from the double sided roof apertures. Opaque acoustical tiles and 2 x4 ft lighting troffers complete the ceiling configuration. This paper will focus on the shop with additional reference to the office and warehouse areas as needed.

The shop ceiling reflectances are estimated at 60 to 80% for all but translucent panels which are 20%; walls, due to heavy shelving and hardware, range from 20 to 70% reflectance; the floor is concrete. Black work tables are organized throughout the space. The auxiliary lighting system is occupant controlled, with three tiered on-off switching. It has characteristics shown in Table 1. Typically, laborers at work stations in the shop do detailed work (without task lights), and report that they require two levels of auxiliary lighting if no daylight is provided. The lighting system provides 87 fc at 2 $W/ft^2$ using standard bulbs and ballasts.

TABLE 1. BUTLER PROTOTYPE BUILDING: AUXILIARY LIGHTING SYSTEM PERFORMANCE

| | Tiers of Lighting | $W/ft^2$ | fc (avg.) |
|---|---|---|---|
| Maint. Area | 1 | 0.9 | 45 |
| | 2 | 2.0 | 87 |
| | 3 | 3.0 | 131 |
| Office Area | 1 | 1.1 | 27 |
| | 2 | 2.2 | 58 |
| | 3 | 3.3 | 87 |
| Warehouse | 1 | .6 | NA |

### 2.2 Test Results

On-site data have been taken on three different occasions in late April and mid-September 1982, and again in late April 1983 (waterbags removed). Data were recorded using single north/south rake of sensors spaced at five foot intervals. Initial testing indicated that this rake sufficiently describes lighting levels in the room. The following general issues were studied in a series of parametric tests:

1. effect of shutter mode (south open vs. north open),
2. effect of waterbags (waterbags in vs. waterbags out),
3. effect of dropped ceiling (maintenance vs. warehouse), and
4. effect of translucent panels (panels in vs. panels out).

Table 2 summarizes the data, which were taken at all hours of the day under as many weather conditions as possible. We have chosen average Daylight Factors (average interior footcandles on workplane divided by diffuse exterior horizontal illumination times 100%) to represent lighting levels. Variations in Daylight Factors are produced by changes in sky luminance distributions, and by the introduction of beam sunlight to the workplane on some clear days. Typically, solar profile angles during testing on clear days ranged from 50° to 90° for south facing surfaces.

TABLE 2. AVERAGE MEASURED DAYLIGHT FACTORS (%) FOR THE BUTLER PROTOTYPE BUILDING

| | Overcast Sky | | Clear Sky | |
|---|---|---|---|---|
| Aperture Open | North | South | North | South |
| Maintenance Shop | | | | |
| Waterbags In | 1.7 - 1.8 | 1.6 - 2.1 | 2.2 - 2.6 | 2.2 - 3.8 |
| Waterbags Out | 2.0 - 2.3 | 1.8 - 2.1 | 2.0 - 2.5 | 2.2 - 10.7 |
| Warehouse | 8.2 | 8.1 - 9.8 | 8.9 - 10.0 | 11.3 - 33.0 |

Daylight Factors = $\frac{\text{Average interior footcandles on workplane}}{\text{Diffuse exterior horizontal illumination}} \times 100\%$

Shutter Mode Comparison: Under overcast skies with waterbags in, the data indicate the apertures to be nearly equivalent in performance. Removing the waterbags, the north aperture is slightly better, by a nominal 10%. Under clear sky conditions with waterbags in, the south aperture, which allows beam sunlight to penetrate into the plenum, results in 0 to 50% more light on the workplane. The south exposure showed no benefit at extreme angles of incidence. As one might expect, a little beam penetration into the plenum provides very significant increases in lighting below. With waterbags out (south aperture open), up to 400% increases in light levels occurred.

Patterns were similar in both shop and warehouse spaces: marginal differences between the two apertures on overcast days, substantial increases on clear days. It should be noted that whereas a significant glare problem occurs in the warehouse on clear days, the shop experiences no problem due to the mediating effects of the suspended ceiling. See Figs. 3 and 4 for a typical distribution curves.

Effect of Dropped Ceiling: Table 2 allows one to assess the dropped ceiling (maintenance shop) compared with a relatively unobstructed space (warehouse). Under overcast skies, 380% more light was distributed to the warehouse workspace than the shop, with an open north aperture and no waterbags; 450% more through an open south aperture. On clear days the same comparison shows a 420% increase as indicated for the north aperture, and a spread of 300 - 500% more light through a south aperture. A side-by-side comparison on an overcast days is shown in Figure 4.

Effect of Translucent Panels: An evaluation of the role of translucent prismatic diffuser panels in transmitting light was conducted on a clear day in September, by taking readings with and without panels within minutes of each other. Test results (Table 3) indicated that removing the panels augments lighting by about 20 to 30%. See Figure 5 for the effect of translucent panels with north aperture open.

Also, referring to the reflected ceiling plan it can be noted that additional opaque panels can be replaced with diffusers to increase lighting levels, particularly along east and west walls and in the center aisles. Removing 12 acoustical tile panels along the west wall nearly doubled illumination levels on the workplane below. This retrofit is particularly beneficial in increasing surface brightness of walls.

TABLE 3. DAYLIGHT FACTORS WITH PANELS OUT AND IN

| | North Aperture Open (DF) | South Aperture Open (DF) |
|---|---|---|
| Panels out | 3.1 | 5.4 |
| In | 2.6 | 3.8 |
| Out/In | 1.19 | 1.31 |

Waterbag Comparison: Table 2 indicates that under overcast skies, removal of waterbags increased lighting levels by an average of 25% for the north aperture, and 5% for the south aperture. Fig. 1 shows that removal of the waterbags increases the sky factor as viewed through the north apertures from the translucent panels. However, the test results indicate that the increase in lighting is moderate through the south aperture on overcast days. A conclusive comparison for clear days is difficult to render since beam radiation, sky luminance, and profile angles of the sun hinder an accurate comparison of the two options (waterbags were removed one year after initial tests). One set of comparable conditions is shown in Fig. 6 with the aperture open. For the north aperture, it can be reasonably concluded that on clear days the removal of waterbags has only a minimal effect.

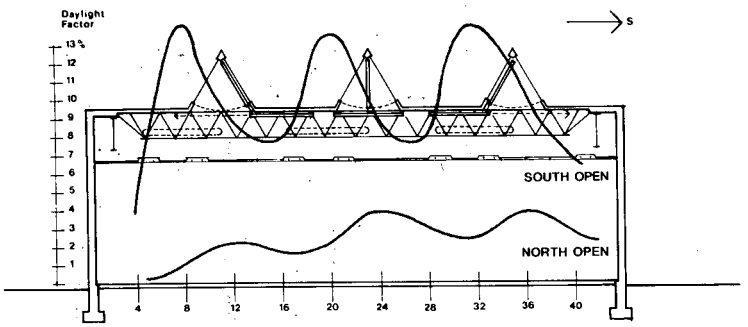



Fig. 3. Butler Mfg. Co. Maintenance Shop: Shutter mode comparison (clear, 62° profile angle).

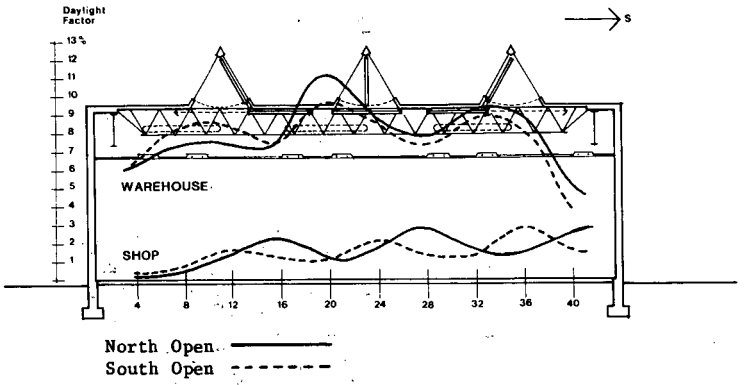



Fig. 4. Butler Mfg. Co. Maintenance Shop: Shutter mode comparison (overcast).

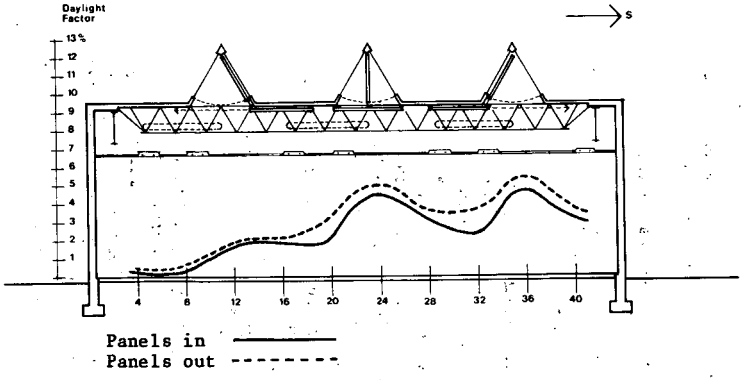



Fig. 5. Butler Mfg. Co. Maintenance Shop: Effect of Translucent Panels (clear, north open, 50° profile angle).

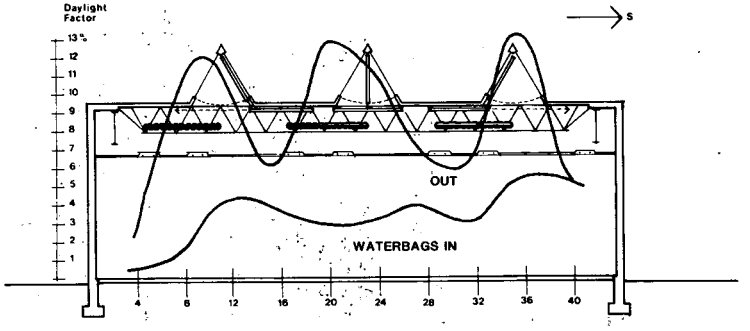



Fig. 6. Butler Mfg, Co. Maintenance Shop: Waterbag Comparison (clear, south open, 56° profile angle).

## 2.3 Auxiliary Lighting Requirements

Although three tiers of on/off lighting are available in both the maintenance shop and office, experience has shown that only two are required (87 fc maintenance, 58 fc office) even in situations with no daylighting. This will be the reference for auxiliary lighting savings attributed to daylighting. During a sixteen month period from May '81 to September '82 auxiliary requirements were recorded mid-morning, noon, and mid-afternoon for 73 days. For the maintenance area, with no daylighting the occupants used 79% auxiliary; with the south aperture open, 59%; with the north aperture open 61%. The adjacent office, which has about half the floor space, generally lighter wall colors , and two small windows in the west wall, used 40% of its full load (two tier) auxiliary lighting capacity.

Conversations with the maintenance shop personnel indicate that substantial lighting savings might accrue to the space if it had an interior design with lighter colored (white) walls, and a more typical open plan commercial decor. The overriding need for ambient lighting stemmed from the fact that space "felt rather gloomy" even when daylight provided 50 footcandles. We suspect rather strongly that the decor of the room, which included gray shelving, black bench tops, walls of 20 to 70% reflectance, and to some extent the cool cast of the translucent panels, tended to produce this feeling and a concommittant desire for a brighter environment. (See Luminance Testing.)

## 3. PRINCETON PROFESSIONAL PARK

### 3.1 General Information

The Princeton Professional Park (PPP) buildings are less elaborate in their control of daylight. The atrium, which acts as a thermal buffer to the professional offices flanking it, has overhead glazing sloped at 45° facing south and north. The glazing allows both diffuse and beam sunlight to reach the interior offices through a clerestory located high on the atrium wall. The arrangement of interior spaces varies greatly depending on the occupant's desire for natural light which is best with "open plan" office layouts or the privacy afforded by more traditional partitioned offices. Most occupants have struck a compromise between light and privacy by using a section similar to that presented in Figure 3 with a mixture of open and partitioned spaces. Typically, a reception area is next to the atrium with direct exposure to the skydome. Private space and utilities are in the center; additonal sidelighting is supplied at the outside walls. Some tenants employ dropped ceilings with translucent panels to filter the sunlight. Others have selected sloped ("cathedral") ceiling treatment to maximize daylight contribution.

### 3.2 Daylighting Performance

A large automated translucent curtain is used for glare control, solar control and night insulation in the atrium. PEG has documented illumination levels in the building both with and without the curtain. (See Figs. 7 and 8). Also, Venetian blinds on the south show daylight factors for a typical day under clear conditions. The upper curve represents lighting levels with the atrium curtain open and with white Venetian blinds. Reception areas on both sides of the atrium have daylight factors in the vicinity of 3 - 5%.

Although this level of lighting is adequate for the reception areas, a glare problem exists in the atrium on clear days. Table 4 indicates that brightness ratios on the order of 4000 occur. Pulling the diffusing shade eliminates the glare problem. In the south atrium offices, lighting levels remain quite high since the curtains tend to scatter previously undirected light and are by themselves a bright source of light. North atrium offices incur a 1/2 to 1/3 reduction in lighting when the shade is

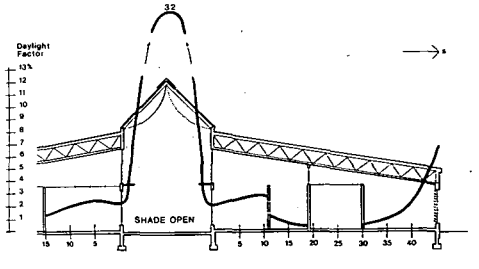



Fig. 7. Princeton Professional Park: Daylight Factor curves (clear, 70° profile angle).

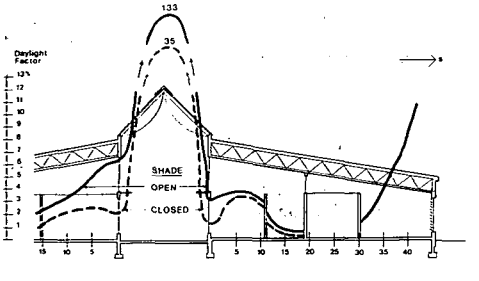



Fig. 8. Princeton Professional Park: Daylight Factor curves (overcast day).

pulled on clear days. This is to be expected since the north office views the south sky dome which without the shade is extremely bright.

On overcast days, no shading is required. Figure 8 shows lighting characteristics on an overcast day, with the atrium curtain open and Venetian blinds up.

3.3 Luminance Testing

In an attempt to better understand a complex lighting environment PEG documented surface luminances at Butler, PPP, and a Princeton Energy Group north facing office. A comparison of contrast ratios was undertaken to establish whether this parameter could be useful in determining whether a space has a "gloomy" or "dull" appearance. Results are shown in Table 4. We concluded that: 1) surface contrast ratios of 30 - 200 are quite common in typical working environments but; 2) there is no apparent correlation between contrast ratios and acceptability of the lighting in this range; and 3) given spatia characteristics and surface reflectances some threshhold illumination level will make the room ambiance palatable enough to the eye so that additional light is not required. For example, two levels of auxiliary lighting in the Butler shop made the lighting acceptable. However, brightness ratios did not change appreciably compared to one level of auxiliary lighting.

A comparison between the Butler maintenance shop and a PEG north office shows that in the former case 30 - 50 fc with a contrast ratio of 67 is "dull", whereas in the latter case roughly the same values require no auxiliary light. The difference in perception lies in the fact that the PEG north office is predominantly white in its surface treatments; the maintenance shop has somewhat grayer tones. The implication here is that even though lighting may be adequate, the choice of color and room decor is also very significant in subjectively determining when one desires more light.

TABLE 4. LUMINANCE RATIOS AND ILLUMINATION VALUES FOR SELECTED SPACES

| | Brightness Ratio in Field of View | Illumination (footcandles) | Quality |
|---|---|---|---|
| Butler Maintenance Shop | | | |
| Overcast, North open | 35 | 20 - 40 | grayish, dull |
| Clear, North open | 60 | 20 - 80 | grayish, dull |
| Auxil. lights, 1 tier | 67 | 30 - 50 | grayish, dull |
| Clear, South open | 30 | 180 - 440 | no auxiliary needed, not gloomy |
| Auxil. lights, 2 tiers | 86 | 60 - 100 | not gloomy; acceptable |
| Auxil. lights, 3 tiers | 67 | 85 - 150 | very well lit, almost too bright |
| Butler Warehouse | | | |
| Overcast, North open | 50 | 150 - 250 | very comfortable |
| Clear, North open | 30 | 100 - 200 | very comfortable |
| PPP Leasing Office (clear day) | | | |
| Atrium shades closed | | | |
| Lights off | 90 | 20 - 30 | functional for working but slightly dull |
| Lights on (2 tiers) | 90 | 80 - 100 | OK; almost too bright |
| Atrium N. shade open, | | | |
| Lights off | 110 | 40 - 55 | OK |
| Atrium S. shade open, | | | |
| Lights off | 160 | 50 - 75 | very pleasant, no auxiliary required |
| PPP Atrium (clear day) | | | |
| shades closed | 200 | 500 - 600 | very pleasant, cheery |
| N. shade open only | 120 | 700 - 800 | very pleasant, cheery |
| S. shade open only | 4000 | 700 -2300 | discomfort glare from overhead glazing |
| PEG North office | | | |
| Viewing North | 80 | 30 - 40 | OK, pleasant |
| Viewing West | 180 | 30 - 48 | OK, pleasant |
| Viewing South | 2.5 | 30 - 48 | OK, pleasant |

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# A BASELINE FOR ENERGY DESIGN

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## ABSTRACT

This report documents a project which aims to summarize the energy conscious redesign data of 168 commercial buildings conducted in 1978 under the Department of Energy (D.O.E.) sponsorship. Average end use bar charts for all building types are provided along with descriptions of specific strategies employed. Conclusions concerning these results are presented along with descriptions of the original research including its strengths and weaknesses.

Over the past six years $30 million has been spent on research initiated to produce "baseline" data on the energy performance of new buildings and to determine maximum practical levels of potential annual energy conservation for the design of new buildings. The effort was primarily to develop a data base that did not exist at the time to support the proposed Building Energy Performance Standards (BEPS). Literally hundreds of reports have been produced. The purpose of this project is to take those hundreds of reports and summarize them into one concise readable document which contains the important results of the original work.

## 1. RESEARCH EFFORT

The original effort was divided into two main phases (plus follow-on research). The objective of the first phase was to develop "baseline" data about the energy performance of new buildings. The purpose of the second phase was to determine potential levels of energy reductions that could be achieved from the baseline. This project is basically limited to the phase two effort conducted during 1978 in which 168 commercial and multifamily buildings were redesigned by their original design teams in an effort to reduce the buildings energy consumption.

Separate performance estimates were made for 16 different major building types, recognizing the strong impacts on energy requirements caused by a building's function and the diversity of such functions in commercial buildings. Designs were selected from 37 cities to examine a range of climatic impacts. Factors that could significantly affect the energy use of a building, but which are not under the control of the building designer, were either normalized (e.g., hours of operation) or eliminated from consideration.

To launch the redesign experiment, the design teams participated in a three-day workshop in energy-conscious design concepts and strategies, and received an energy information workbook. At two subsequent points over a period of months, they presented their work and received a detailed peer review and feedback from energy consultants.

Although the design teams had few constraints on their redesign efforts, they were required to adhere to the building owner's original program requirements, the site, and the general range of the construction budget. They were encouraged to use "passive" techniques, including natural ventilation and daylighting. Active solar systems were not permitted unless included in the original designs (there were four).

Summary estimates of first-cost differences between original and redesign were submitted by the designers as part of the exercise. At the end of this phase, on the average, the redesigners reduced energy use by 38% and increased first cost by less than 5% from the original buildings. The cost effectiveness of the redesigns could not be adequately assessed from the redesign data, and a follow-up initial life-cycle cost analysis was conducted in 1979-1980 for three typical office buildings from the sample.

Not all of the redesign attempts succeeded. According to reviewers of the completed redesigns, many designers did not take advantage of obvious conservation opportunities. Nine redesigned buildings (6% of the total) "failed" in the sense that the redesigns used more energy than the original

buildings. In a number of cases, designers either used strategies that were inappropriate or used potentially effective strategies but misapplied them.

An important factor was the amount of variation in the results. The average decrease varied considerably by building type. It was greatest for warehouses (55%), and for small offices (50%), and smallest (26%) for hotels and high-rise residential. The range of annual energy usage for most redesigned building types was smaller than the usage range estimated for the original buildings. This is illustrated in Figure 1, and suggests that carefully selected design strategies can temper overall regional influences on both energy use and percentages of end use.

## 1.1 Targets of Opportunity

A key factor in energy-conserving design is an understanding of how energy flows in buildings. One aid in identifying broad targets of opportunity for energy conservation is to examine the amount of energy used for building energy functions or "end uses." A familiarity with energy end uses and their relationships within a building type can provide useful guidelines for focusing the design effort where it might have most significant impact.

Energy "end use" refers to those major building functions or services for which energy may be used. Typical major energy end uses in commercial buildings as presented here are: space heating and cooling; HVAC fans and pumps; lighting; service water heating; vertical transportation; and exhaust fans.

The end use charts in Figure 2 indicate the national averages for energy use in the buildings of each type. These summary charts indicate general patterns by building type, but do not necessarily show variations that can occur within a building type depending on regional influences such as climate, and fuel availability and cost. Such factors define important constraints under which designers operate.

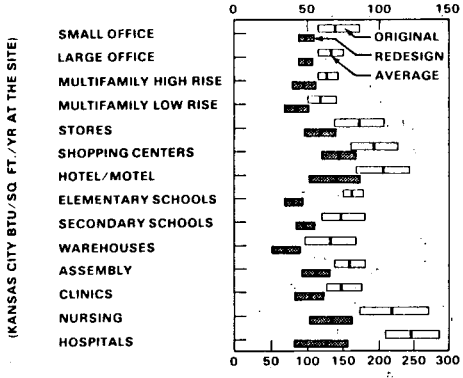



Fig. 1. Energy Performance Ranges.

Within a given building type, the heating and cooling energy end use uses were found to be particularly sensitive to regional variations, whereas other end uses such as service water heating and lighting are much more sensitive to patterns of building occupancy, functions, and mix of building functions and are influenced very little by climate factors.

In the redesigns, major reductions in lighting levels occurred. Yet in the redesigns of virtually every building type, lighting increased as a percent of total energy use. This suggests that lighting tends to become a more important energy consideration as commercial buildings become more energy efficient.

In the redesign exercise, certain building energy end uses were reduced by significantly larger absolute amounts than others. This was directly related to their predominance as end uses in the original buildings. Heating energy was reduced more than the other end uses. Especially for "skin," or external-load-dominated building types, reductions in heating energy were significant, while reductions in cooling energy were small. Likewise, building types that tend to be predominantly internal-load dominated, such as shopping centers, offices, and stores, achieved the greatest reductions in cooling energy.

## 1.2 Limits of the Energy Analysis Method

A reasonably comprehensive energy analysis computer program was used to estimate the energy use of the building designs. Like most such energy analysis programs, then and now, the program was capable of analyzing many of the design strategies, but not all.

Application of the component requirements of QSHRAE 90-75R to the original buildings also produced significant energy reductions. Exact conformance to the ASHRAE 90-75R minimum component requirements using the formal "Upgrade/Downgrade" approach resulted in a 22% reduction from the original buildings. Results of this approach are shown for 12 building types in Figure 2. The middle bars

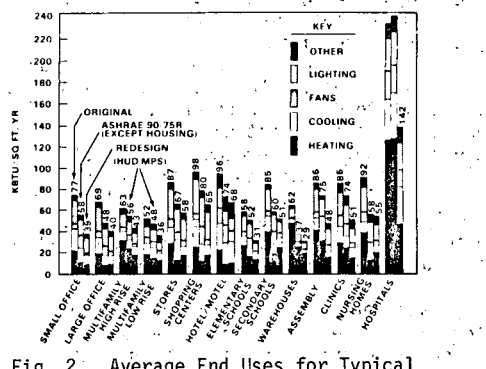



Fig. 2. Average End Uses for Typical Building Types.

for multifamily high-rise and low-rise residences show the impacts of HUD MPS.

## 2. OFFICE BUILDINGS

Of the 16 building types chosen for the overall study, the office building redesigns benefitted from some of the largest energy reductions compared to their original designs. Designers of small office buildings accomplished a 50% average annual energy reduction, while large office buildings achieved 42% reduction. These substantial cuts were achieved with an estimated 3.5% average increase in first cost of construction.

Unlike hospitals or restaurants, offices tend to be occupied during regular daytime hours. At nights and on weekends, they sit vacant or are only sparsely occupied. During office hours, they are subject to high internal thermal loads from lights, equipment, people and external solar gain. With a reasonably "tight" envelope, such heat gains can lower the "balance point" (the outside temperature below which a building needs to be mechanically heated) to 40°F or below.

Conversely, the building may need to be cooled while outside temperatures are as low as 40°F to 50°F. Control of heat gains can, therefore, be a predominant energy conservation consideration for occupied periods. At night, however, the daytime heat gain sources are largely absent and during the heating season, the temperature is lower. Thus, control of conduction and infiltration losses can be a predominant consideration. In warm climates, control of gains can be the dominant energy factor.

### 2.1 Strategy Pattern in the Redesigns

Key redesign strategies which had the most impact were grouped into two broad categories. The first froup of strategies was targeted towards optimizing thermal loads in the building by controlling solar loads, skin-related heat transfer and internal gains (primarily from lighting). Once these loads were optimized and controlled, another set of design strategies was used to meet space conditioning requirements with various types of HVAC systems and controls. Together, these sets of strategies addressed the occupied/unoccupied energy design problem characteristics of office building operation.

### 2.2 Observations and Conclusions

Some overall lessons of the office redesign process include:

- The importance of viewing energy conscious design strategies as interrelated to achieve effective control and reduction of energy usage.
- Energy conscious design strategies need not be exotic. Careful and thoughtful combinations of "conventional" design strategies were effective for a number of buildings.
- Control of heat gains, especially from lighting and solar, is an important design consideration for occupied periods as is control of heating and lighting energy use during unoccupied periods.
- As a building design becomes more energy efficient, the major targets of opportunity can shift. Typically, lighting energy strategies become more important.

## 3. RETAIL BUILDINGS

The 26% energy reduction achieved by the retail teams over their original designs is significant, but not as substantial as in other building types.

### 3.1 Retail Design Considerations

The merchandising mission of these buildings places design emphasis on the buildings interior systems more than on its exterior components. The design of lighting systems to promote merchandising has different criteria than that for increasing worker productivity as in office buildings.

Retail buildings operate longer hours than most other types. A six or seven day a week operation for 10 to 12 hours a day is not uncommon. Internal gains from equipment are minimal in most retail operations except for food-related operations such as bakeries and carry-outs. Nevertheless, they are generally considered to be "load dominated" due primarily to high uniform lighting loads and to high occupant density. As a result, retail energy use is almost "steady state" at given weather conditions and is not subject to time-related load swings such as those found in office buildings.

### 3.2 Energy Design Options Are Constrained

The form and envelope configuration of retail buildings is frequently dictated by functional space requirements and site constraints. Often there is little flexibility to adjust building orientation for energy concerns. Facade treatment may be of secondary importance in malls and department stores. Attracting customers to merchandise is done inside, virtually eliminating requirements for exterior display windows and solar control treatments.

### 3.3 Conclusions

Most of the significant opportunities for energy efficient designs in retail buildings are associated with interior systems, particularly lighting and HVAC.

Lighting and space conditioning strategies were used extensively by the redesign teams, but perhaps not to their fullest potential because of design and economic constraints. Unlike many other building types, design strategies using the retail buildings site, form and orientation may have little impact. Even conservation strategies geared toward the building envelope, such as insulation and solar control beyond minimum levels, appear to have limited potential except in strip shopping centers. In most cases a simple reduction of consumption rates and improved controls produced energy results close to the average 26% energy savings of the retail sample.

It is possible that of all the building types, innovative energy design approaches other than mechanical systems are hard to justify to a sales conscious client. Energy itself needs a hard sell.

## 4. MULTIFAMILY DWELLINGS

While considerable investigation has gone into the energy-efficient design of many building types, multifamily buildings seem to have remained outside the mainstream of research. This is surprising because multifamily residences are among the most predominant building types. This lack of attention is partly due to their hybrid status. As income properties they can be classified as commercial buildings, yet they share many characteristics with single-family residences.

### 4.1 Design Strategies

The multifamily redesigns contain many examples where major reworkings of the original design concepts were accomplished in every aspect of the project, from the site plan to the unit plan. This was found in all high-rise and low-rise subtypes regardless of rental or ownership arrangement.

### 4.2 Site and Orientation

Multifamily projects can require extensive site planning to overcome a variety of constraints. Project economics often determine the number and type of units required for successful marketing, operation, and return on investment. Site topography and access to views are also influential. In these matters, a ground rule of the redesign experiment was to adhere to the clients' original requirements. In nearly half of the redesigns, both high- and low-rise buildings were reoriented for solar access and control. In many instances, substantial site design changes followed.

### 4.3 Windows and Solar Control

The original multifamily designs had, on the average, glazing area equal to about 10 to 15 percent of their floor area. Glass areas were reduced in 8 of the 9 high-rise redesigns, while the low-rise redesigns increased glazing areas, often substantially. The selective reorientation and redistribution of glass was found in half of the cases for both high-rise and low-rise. In nearly all of the redesigns, there was a distinct trend to add more glass to the southern exposure and to decrease glass area on the north, east, and west. In many instances, north, east, and west glazing was eliminated entirely in conjunction with building reorientation and new south-facing unit plans. Depending on climate, the design teams chose double or triple glazing.

### 4.4 Passive Solar Applications

The use of passive solar strategies was mostly limited to low-rise applications in public spaces. Only a few substantial passive solar applications using thermal mass storage at the unit level were observed. Storage walls were used in two instances in conjunction with atriums. Sunspaces were also used in three instances, but were added onto the original buildings as additional public space.

### 4.5 Observations and Conclusions

The problem in treating lighting systems, appliance usage, and domestic hot water in the redesign experiment highlight the difficulty of treating multifamily buildings as a "commercial" type. Although they often resemble commercial buildings in key characteristics, multifamily buildings also have strong similarities to single-family residences: they are "skin-load" dominated. Lighting and other internal loads are relatively unimportant to their thermal balance in comparison to commercial buildings. They are effectively occupied 24 hours a day, 7 days a week and especially at night. The economic structure is difficult to predict. Tenants and building owners may share some, none, or all of the costs for common and unit energy usage.

## 5. HOUSEKEEPING RESIDENTIAL

Residential housekeeping buildings share certain important functional space type relationships. Both a guest room and a patient room need a direct relationship to some type of service area such as a kitchen, dining, laundry, or assembly area. The resulting mix of functions yields an energy mix of both internally load-dominated service area and externally load-dominated sleeping rooms.

The emphasis of the energy design, therefore, depends on the blend of these functional spaces within the individual building whose energy requirements (and conservation potential) can vary considerably.

### 5.1 Redesign Strategies

Energy reductions achieved by the hotel, motel, and nursing home redesign teams ranged between 30 and 40 percent. Architectural

strategies were prominent,, with an emphasis on reorganization of building form, relocation of functional spaces, and reduction of conduction Losses (in colder climates) by increasing insulation levels or reducing exposed wall and glazing areas. Lighting strategies were effective in reducing energy usage as were (to a much lesser extent) those aimed at mechanical systems.

### 5.2 Form and Space Organization

In reviewing the redesign strategies, two general approaches to space reorganization and changes to building form can be distinguished: opening up the building for solar exposure (if advantageous) and tightening the building against the elements. Of course the emphasis on one or the other of these strategies varied according to the individual space mix and function of the building as well as its climate and location.

### 5.3 Solar Strategies

The vast majority of the sample buildings, especially the nursing homes, profited from solar access by reorienting to the south. In the design process, buildings were elongated on the east/west axis, fanned out, or saw-toothed in an effort to relocate the bulk of the fenestration to the south. There was also near universal use of both fins and overhangings to provide external shading.

Passive solar applications included many direct gain systems as well as forced-air rock-bin storage systems and thermosyphon solar air collectors, which heated living areas directly. The energy analysis program used in the research, however, could not simulate many of these cases, and the energy savings from such strategies were not estimated.

## 6. HOSPITALS

Apart from restaurants, hospitals are by far the most energy intensive of all the building types studied in this research effort, approaching a mean annual energy consumption of 240 kBtu per $ft^2$ in the original designs. While areas as diverse as surgical suites and patient rooms have different operating hours, internal loads, and use profiles, the predominant 24-hour-a-day operation of hospitals is inherently energy intensive. Strict environmental, life safety, and regulatory requirements heavily affect design requirements for hospital HVAC systems because precise temperature and humidity levels and high ventilation rates are mantained. While this is costly from an energy standpoint, it is necessary; the environmental requirements for a burn victim or a cardiac patient can be nearly as critical to their recovery as drugs and medical treatment.

The widespread perception that hospitals are internal-load-dominated is questioned by certain aspects of the energy results. The design energy data show that the predominant energy consumption is for heating, taking seasonal heating and cooling equipment efficiencies into account. Heating energy consumption would generally not be that high in buildings that are internally loaded. However, major portions of hospitals have substantial heating needs. Patient areas, corridors, and certain support areas that do not experience high internal loads are often ventilated continuously. Another cause of high heating energy is humidity control of ventilation air in areas that require narrow temperature and humidity ranges.

The problem of analyzing energy use in these hospitals is further complicated, as "process" energy loads were not modeled in the computer energy analyses. The lack of this process energy in conditioned spaces could have caused heating energy to be erroneously exaggerated. Unfortunately, there are not adequate redesign data to answer these process load questions for this complex building type. Extensive statistical analysis that tried to relate weather data to the hospital sample's energy use uncovered no significant cause and effect relationship. Indeed the BEPS energy targets for hospitals are a uniform 140 KBtu per $ft^2$ per year nationwide.

## 7. SCHOOL REDESIGN STRATEGIES

The school redesigns range in size from 11,000 to 276,000 square feet and include neighborhood schools, regional high schools, vocational shcools, a business college, and a law school. With the exception of the five-story law school, all buildings are one and two stories in height.

The redesign strategies concentrated on the control of conduction during unoccupied periods, the reduction of artificial lighting energy, and minimizing the coditioning of ventilation air. With these strategies, the elementary and secondary school redesign teams reduced mean design energy consumption by 47 percent and 40 percent respectively.

In the majority of instances, the combination of site, form, envelope, and daylighting strategies led to a markedly different concept for the buildings' form and space organization.

### 7.1 Control of Heating and Cooling Loads

Since much of a school's annual heating energy requirements in cold climates are for its considerable unoccupied periods, conduction losses were minimized wherever possible. This particular energy design problem appears to have been considered in many of the original buildings. Original designs located in these climates were already well insulated and major improvements in wall U-values were observed only in the warmer locations. Glass U-values were improved in nearly every instance by upgrading from single to double glazing. In

almost all the schools, however, glass area in both the original design and the redesign was generally minimal. In half the buildings, galss area was less than five percent of gross floor area, and in the remainder, all but four were ten percent or less. Protection from vandalism, rather than energy efficiency may have been the major motivation for this.

### 7.2 Observations and Conclusions

The homogeneity and geographic representation in the school sample adds confidence to the energy effectiveness evident in the redesign solutions. Indeed, the energy savings would have been even greater were it not for the limitations of the energy analysis method for evaluating the widespread use of daylighting strategies. Modifications to building plan, form, and envelope to control conduction not only addressed the dominate unoccupied status of school spaces, but also accommodated a variety of complementary natural lighting and solar control schemes for occupied use. Fundamental architectural concepts were coordinated with well-controlled mechanical systems to meet both full- and part-load conditions efficiently.

## 8. RESEARCH SHORTCOMINGS AND CONCLUSIONS

The redesign experiment was complex and fast-tracked, and subject to a number of geographic, energy, and economic analysis shortcomings. Building samples were limited to 37 different cities throughout the nation. In many instances, buildings from the Rocky Mountain states and the Sunbelt were under-represented or not represented at all.

There also were flaws in the data. The energy analysis computer program, while sophisticated for its time, was unable to estimate the energy savings due to daylignting strategies or those attributable to the use of the temperature "deadband." There were also certain data handling errors, which resulted in unrealistic end use estimates for service water heating and appliance usage in certain building types. More important, energy usage and Internal loads from process equipment were not included.

A significant shortcoming to the redesign experiment was the lack of economic analysis to test the cost effectiveness of the redesign strategies. Economic data for the redesigns are limited to the change in first cost of construction in the redesign compared with that of the original building, a crude measure at best. The only detailed economic analysis performed was that of a life-cycle cost study conducted on three office buildings one year after the major research was completed.

These limitations do not invalidate the basic findings of the research and the conclusions on energy characteristics and strategy patterns. A different set of design strategies could have emerged if the major objective of the original BEPS research had been to reduce energy costs instead of energy consumption. Had the pricing structure of energy types been explicitly taken into account, it is certain that more emphasis would have been placed on the reduction of electric demand, for example, and perhaps less emphasis on reducing fossil fuel consumption for space and service water heating. Current building research, with its emphasis on cost effectiveness, has taken this cue.

Another major obstacle, was that the data were not intended to evaluate the energy effectiveness of particular design strategies. While the particular strategies used were known, and their combined impact of each design element was often unavailable. "Whole building" energy results came from a combined package of redesign strategies. Analysis of incremental effects often involved using the redesigners' estimates. The broad patterns for design options were evident, however, even if individual contributions could not be segregated.

## 9. THE RESULTS

The principal product of the original BEPS research, from a design standpoint, was the development of design energy targets in a consistent and methodical manner. Ranges of energy use for 13 commercial building types in 78 geographic locations are now available for use by design professionals. Other DOE studies on contemporary energy-efficient building designs have shown that these targets are both reasonable and achievable.

The research for this series has looked beyond these abstract energy numbers to identify an additional set of products: the actual architectural and mechanical design strategies responsible for the substantial energy savings achieved by the redesign teams. The patterns of using these strategies in the redesign are useful generic design data that can be effectively used by designers, especially in the early stages of design.

## 10. ACKNOWLEDGMENTS

This research effort was sponsored by the Buildings Division of the U. S. Department of Energy.

The preliminary results of this project appeared as a series of articles in Progressive Architecture magazine, much of this presentation is a direct summarization of those initial articles.

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# ENERGY STRATEGY SELECTOR FOR SMALL OFFICE DESIGN

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## ABSTRACT

A project has been undertaken to develop energy conservation handbooks for the first of several building types. The work is in support of the Battelle Pacific Northwest Laboratories and the U.S. Department of Energy research project on energy conservation in commercial buildings.

The Handbook of Energy Strategies for Small Office Design is viewed as a catalyst that will provide sound guidance by a simple method for the design of energy efficient buildings. It is based on the best current knowledge and state-of-the- art research and demonstration work in energy conservation/passive solar. Extensive investigation on base case building character charstiis, utility rate structures and energy strategies underlie the project. Building performance modeling has been carried out with the ESE program (an ASHRAE TC 4.7 based program) with comparison runs on DOE 2.1b.

## 1. CONCEPT

The Energy Strategy Selector for Small Office Buildings is based on the thesis that decisions made on energy conservation options with this class of buildings are determined on cost considerations rather than energy use reduction. A corollary is that electricity demand may, in decision making, be a factor as important as other energy cost components. It is further believed that this class of building has generally a very limited input from architects or engineers during the design/construction process. For speculative buildings, cost conditions are very competitive and design fees are severely constrained. Much of the design process may be supported by the services of contracting organizations such as mechanical or electrical contractors. For this reason it is believed that any conservation handbook for this class of buildings must be: a) simple, b) cost based, and c) directly applicable to the actual building situation. The Energy Strategy Selector for Small Office Buildings has been developed to be just this.

## 2. PROCESS

The project has approached the development of the manuals in a process which includes the following steps:

a. Definition of several representative base case buildings. This has been accomplished from analysis of existing data on building characteristics such as size, number of buildings in a size group, building code constraints and mechanical system types. The base was further refined through review by a panel from the Building Owners and Managers Association and Technical Advisors.

b. Computer modeling of the base case buildings in five climates: Madison, WI (cold); Seattle, WA (temperate); Washington, DC (hot/cold); Lake Charles, LA (hot humid) and El Paso, TX (hot arid) to generate energy consumption data.

c. Consolidation of these individual building energy problem types (EPT's) into a limited number of representative EPT's for further strategy set analysis.

d. Development of a set of utility cost profiles representative of the range of utility costs that may be experienced for this class of buildings across the country. This has been done by analysis of two national utility cost data bases: 1) Typical Electric Bills. 1981, DOE/EIA; and 2) Commercial Utility Rate Guide for Solcost Data Bank Cities, Nov. 1982, U of A, Johnson Environmental Research Center.

e. Developing and analyzing energy cost problems (ECP's) based on the base case EPT's and 10 representative utility cost profiles.

f. Developing strategy sets applicable to the energy cost problems for the representative energy problem types.

g. Developing for each strategy set the associated construction cost and energy saving.

## 3. BASE CASE MODELING

### 3.1 Base Case Buildings

The major characteristics of the base case buildings, selected by the handbook user are outlined in Fig. 1. This figure is for Madison, WI. The other four climates are similar, with minor differences.

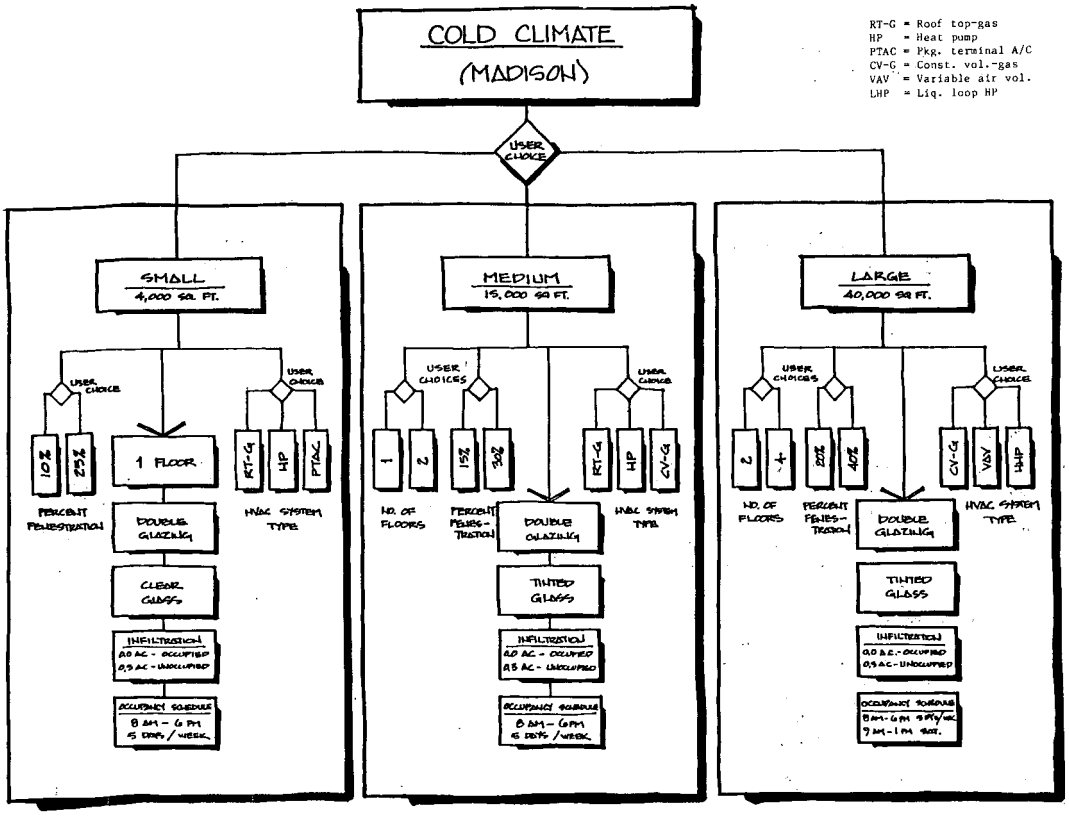



Fig. 1.

### 3.2 Base Case Modeling Results

Figures 2 and 3 present the results of modeling the base case buildings in the Madison climate. Figure 2 graphs the run results by building and system type the sorting that is used in the Design Selector portion of the handbook. Figure 3 illustrates a consolidation of these into a limited number of representative EPT groups that are similar in HVAC system characteristics and illustrate comparable energy consumption behavior. For Madison, as for all climates, lighting energy is a major component, but here alone heating is an important energy component. Cooling is of generally minor significance from an energy consumption standpoint. The heat pump systems in the large building are the most efficient of all systems from an energy consumption standpoint and show a balance of heating and cooling.

All of this changes when the energy cost problems are developed for the 10 representative utility profiles. The utility profiles are as follows:

1. low gas, high electricity, no demand
2. med. gas, med. electricity, no demand
3. high gas, low electricity, no demand
4. low gas, low electricity, high demand
5. low gas, high electricity, low demand
6. low gas, high electricity, high demand
7. med. gas, med. electricity, med. demand
8. high gas, low electricity, low demand
9. high gas, low electricity, high demand
10. high gas, high electricity, low demand

Figure 4 graphs the 10 representative utility profiles as applied to the large four-story building, with 40% glass area. This building was chosen to illustrate maximum climate dependent variances for the Madison case. Figure 4 demonstrates the very strong influence of a particular utility rate structure on the energy cost problem. The apparent efficiency of the heat pumps has been lost. Heating done with gas is a modest- to low-cost component in all cases (the same pattern would be true for oil).

### 3.3 Sensitivities/Strategies

Having developed both energy problem types (energy consumption by system) and energy cost problems (energy cost by fuel-type) for the base case buildings, it was possible to begin to analyze these for various types of changes. Figures 5 and 6 present the results of testing a number of sensitivities on the base case:

a. Variation of lighting levels (low, medium, high) gives some indication of the power of daylighting strategies. They produce a strong and predictable impact.

b. Natural ventilation is simulated on the small building, where its employment is most likely. As expected, its benefit is a significant reduction in cooling energy.

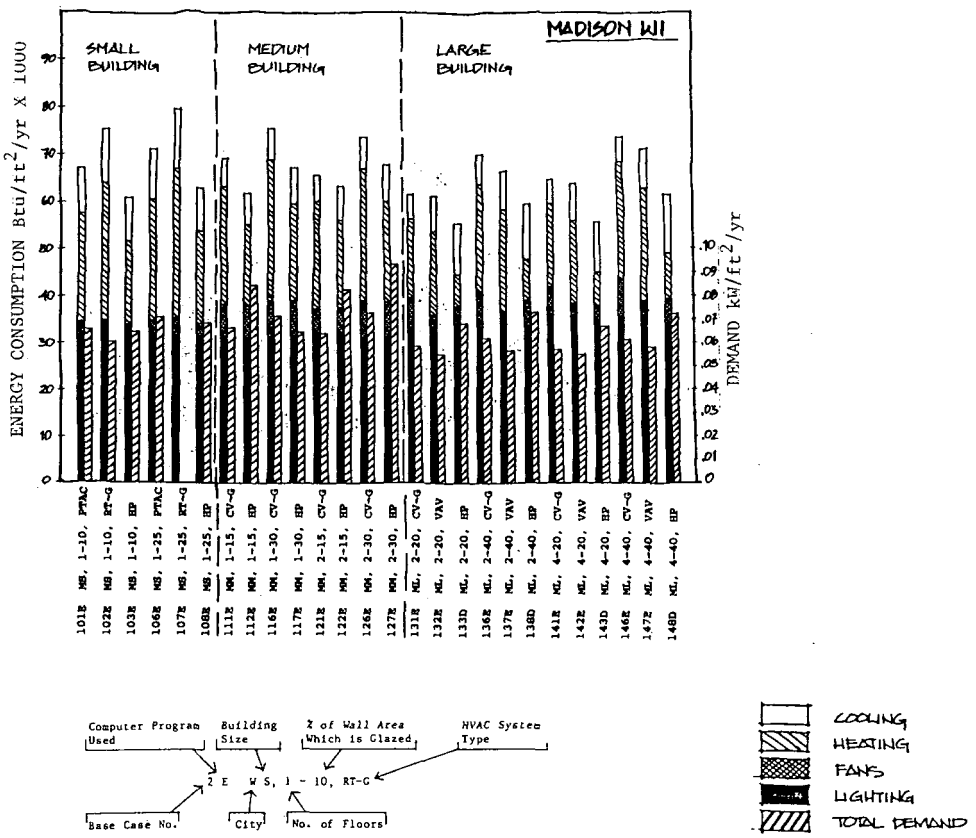



Fig. 2. Original Energy Consumption Runs

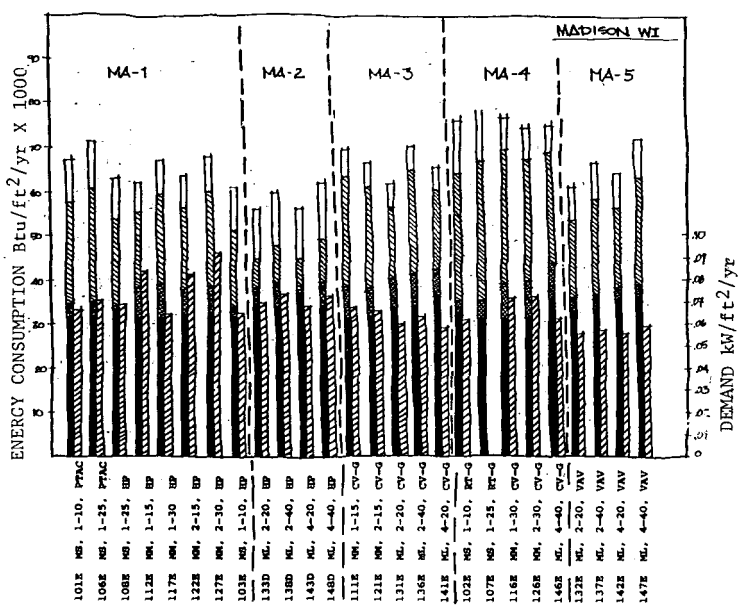



Fig. 3. Representative EPT Groups

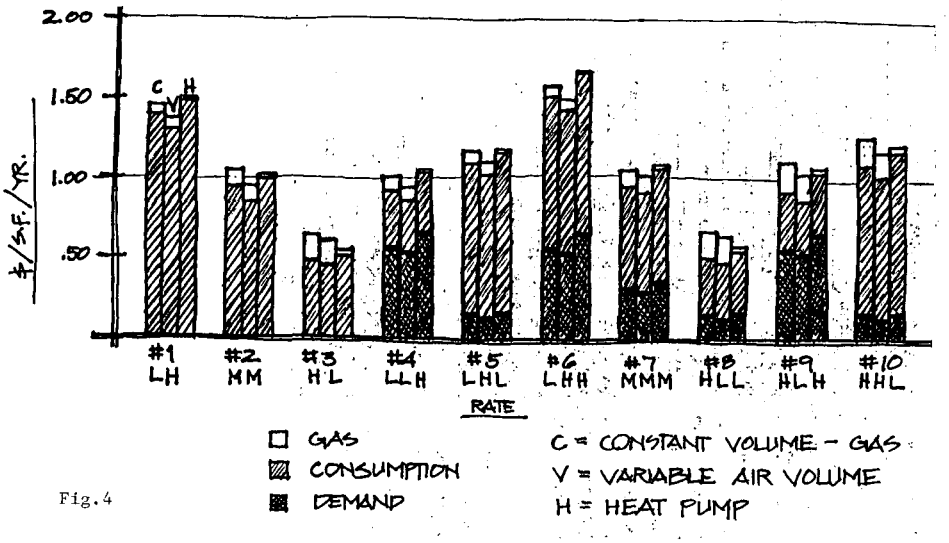



Fig.4

c. Variation of control strategies illustrates the great importance in commercial buildings of selecting appropriate control strategies. Normal OA reset (old) and zone control perform well while unsuitable ranges (NBS ramp) and fixed set points extract a severe penalty in energy consumption.

d. Percent glazing graphs the two levels included in the base case (20%, 40%) against the practical maximum glass area (60%). As can be seen, without ameliorating actions, this increase results in a signficiant growth in energy consumption.

e. Strategy-Reflective Glass (S C = .18). The practical maximum reduction in window transmission has significant effect in cooling climates and little effect in heating climates, as expected.

f. Non-uniform glazing configures the building with 40% glass on the south elevation and 20% glass on the N, E and W elevations. This base case building appears to be relatively insensitive to this change from a uniform 20% glazing on all elevations.

The strategy development work will be continued to develop strategy sets that address the defined energy cost problems through representative buildings and systems and their energy problem types.

## 4. THE SELECTOR PROCESS

This work all leads to the Energy Strategy Selector for Small Office Buildings. The selector Process is currently envisioned as outlined in the flow diagram of Figure 7. The process should guide the design-responsible individual to choices of actions that make the most sense for the particular design/economic criteria that apply to the project. These choices will include a balance of building envelope, mechanical/electrical system and operational strategies tailored for greatest benefit for the given situation The final choice must be made on the design/cost combination that is best for the project.

## 5. CONCLUSION

A research project has been conducted to develop a simple handbook to encourage the incorporation of cost saving energy conservation strategies into the design of small office buildings. Modeling of base case buildings has been accomplished and a limited set of Energy Problem Types have been defined as typical of the full spread of runs. Representative utility rate profiles have been developed which (along with the EPT's) have guided the selection of energy conservation strategy sets. These strategy sets address the important aspects of the energy cost problem in any particular utility for any base case building. Means to determine representative construction costs and energy cost savings provide the "bottom line" for strategy selection.

The "Energy Strategy Selector for Small Office Design" is intended to be a handbook that is simple, cost based and directly applicable to actual building situations.

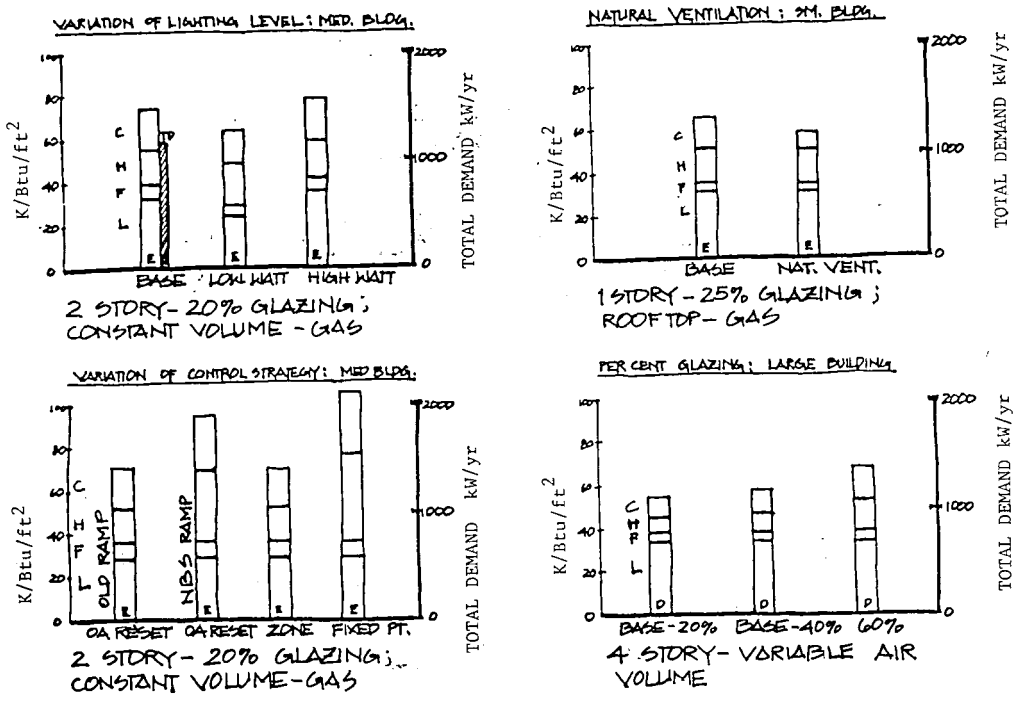



Fig.5. WASHINGTON, D.C - SENSITIVITY CALCULATIONS

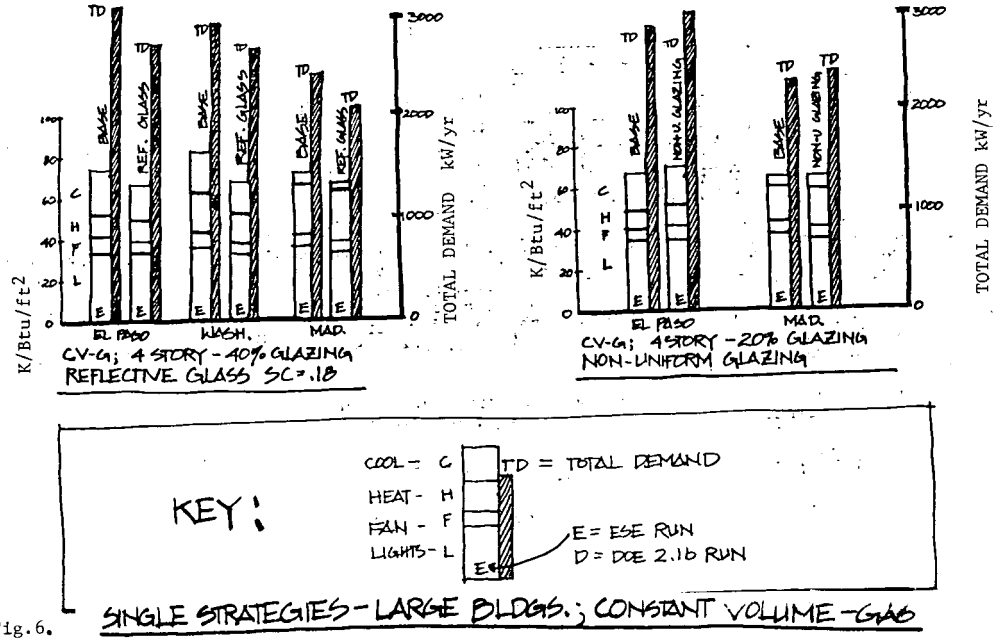
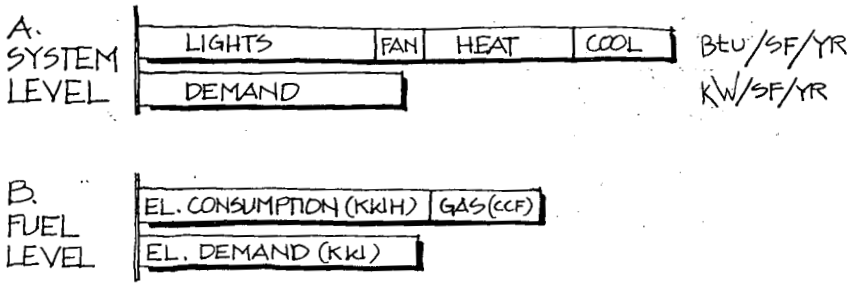



Fig.6. SINGLE STRATEGIES - LARGE BLDGS.; CONSTANT VOLUME - GAS

1. Climate Selector.
   - o Select your climate
     Cold - Temperate - Hot/Cold - Hot Humid - Hot Arid

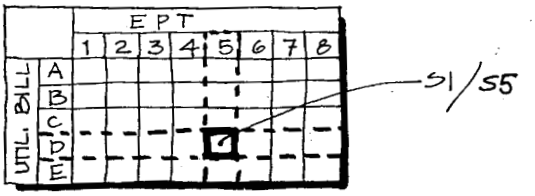
2. Design Selector.
   - o Identify your building's preliminary characteristics
     Size - glass characteristics - HVAC system
   - o This determines your Energy Problem Type (EPT) expressed as: A-System Level, and B-Fuel Level




3. Utility Selector.
   - o Price B-Fuel Level from your utilities and determine the nature of your total bill on a cost basis




4. Strategy Selector.
   A. Enter the Strategy Selector tables with descriptions from your utility bill and energy problem type.




   B. Strategy Set Description tables will tell you for your combination of utility profile and energy problem type the Fuel Level energy savings to be realized and the incremental cost associated with the strategy set.
   C. Calibrate these cost elements to your location.
      1. Price your fuel cost saving with the information from your utilities.
      2. Correct the representative construction cost (based on Means data) to your city and year.
   D. Cost based selection.
      1. By whatever method is appropriate for your project, determine attractiveness of the strategy set selected. For example, simple payback:

$$\frac{\text{S1 cost}}{\text{S1 savings}} = \frac{\text{your construction cost}}{\text{your utility cost saving}} = \text{years payback}$$

      2. Repeat steps for another strategy set, if desired, and compare for greatest benefit in your circumstance.

Fig. 7. Energy Strategy Selector For Small Office Design

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# PASSIVE SOLAR COOLING SYSTEM CONCEPTS

# FOR SMALL OFFICE BUILDINGS

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## ABSTRACT

This paper summarizes the efforts of a small group of building design professionals and energy analysis experts to develop passive solar cooling concepts including first cost estimates for small office buildings. Although estimated annual energy savings from passive cooling technologies range from modest (5-10% savings) to substantial (up to 40% savings), the first costs of these systems appears to be low (from 0 to 8% over comparable buildings). If these preliminary estimates are borne out in real world applications, simple paybacks from 0 to 5 or 10 years could make passive cooling an attractive energy saving design alternative.

## 1. INTRODUCTION

In June, 1982, the Systems Analysis Working Group (including researchers from Lawrence Berkeley Laboratory and Los Alamos National Laboratory) completed an assessment of passive cooling technologies. The assessment used simulation tools (BLAST and DOE-2) to make preliminary estimates of the energy savings that could be achieved with individual passive cooling technologies. These analyses were, by definition, theoretical and not limited by any existing materials or design solutions. As a result of the assessment, research priorities for the passive cooling technologies were rank ordered according to their estimated energy saving potential:

- Priority 1: Natural lighting and cooling load control
- Priority 2: Evaporative cooling and ventilative cooling
- Priority 3: Dehumidification

Because of the limited scope of the cooling assessment, no estimates of first cost were made for any of the technologies (and could not have been, based only on theoretical concepts).

Readers should realize that this exercise was organized as part of an overall research and development activity and was limited to a single building type, a single building size, and a single climate. Although the work presented here suggests valuable new lines of inquiry, it should be applied to other buildings with healthy amounts of professional judgement.

## 2. BASE CASE BUILDING

The goal in defining a base case building is to provide a benchmark for comparison of improvements in both energy performance (Btu/ft$^2$-yr) and energy costs ($/ft$^2$) that result from the application of a passive cooling technology. Improvements in energy

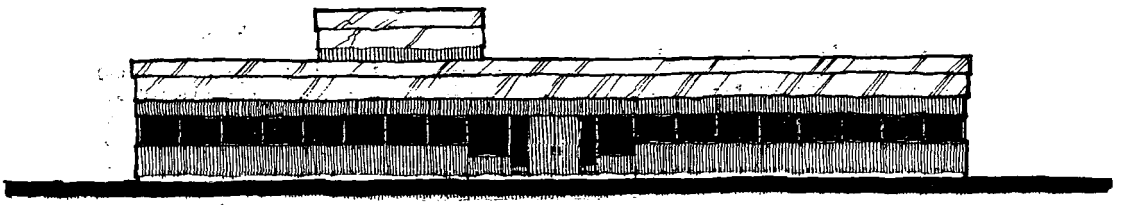


FIG. 1. ELEVATION OF THE BASE CASE BUILDING

TABLE 1. BASE CASE BUILDING/SUMMARY SPECIFICATIONS

| | |
|---|---|
| ASPECT RATIO: | 1:1 |
| GROSS FLOOR AREA: | 10,000 $ft^2$ |
| HEIGHT: | 12 ft (FLOOR TO ROOF DECK) |
| EXTERIOR WALLS: | R-14 CURTAIN WALL |
| WINDOWS: | 1/4" CLEAR DOUBLE GLAZE<br>50% GLASS ON ALL WALLS |
| FLOOR: | SLAB-ON-GRADE, PER. INSUL. |
| OCCUPANTS: | 175 $ft^2$ (GROSS) PER PERSON<br>TYPICAL OFFICE SCHEDULE (8-5) |
| LIGHTS: | 2.5 $W/ft^2$ (GROSS)<br>RECESSED 2-LAMP TROFFERS |
| EQUIPMENT: | 0.35 $W/ft^2$ |
| VENTILATION: | 10 CFM/PERSON @ OCCUPANCY |
| HVAC SYSTEMS: | HEATING - TSTAT BASEBOARD<br>COOLING - ROOFTOP DX WITH VAV<br>TEMPERATURE ECONOMIZER |
| HVAC ZONING: | 5 ZONES<br>4-115' PERIMETER ZONES (N,S,E,W)<br>1-70' x 70' CORE ZONE |
| SET POINTS: | $68^{\circ}$ F NORMAL<br>$55^{\circ}$ F NIGHT SETBACK |

performance are based on analysis of the whole building, with the technology under study included. Improvements in energy costs are measured by comparing the typical annual energy bill for the base case building to the bill for the building as modified by the technology.

The base case building for this study (see Figure 1) is configured to represent currently "typical" new construction. It is presumed to have been designed by a competent and conscientious designer, but one who has no special incentive or mandate to achieve significant energy cost savings. The building is also configured to be flexible in its design and specifications, to make it suitable for various clients and generally acceptable to a speculative builder. It is intended that the building be neutral to both climate and regional building characteristics -- that is, not violate regional design practice significantly, although it clearly cannot be "most typical" of construction or all regions simultaneously.

## 2.1 Thermal Specifications and Energy Use

The base case building was originally specified to meet the requirements of the simulation programs used in the analysis (BLAST and DOE-2). A summary set of specifications is shown in Table 1.

Although the cooling assessment investigated representations of all U. S. climates, the design workshops were limited to consideration of only one climate (Northeast -- including New York and Washington, D.C.).

BLAST and DOE-2 simulations for the base case thermal specifications resulted in the following annual energy requirements:

- Fuel: 0.04 MCF/$ft^2$-year
- Electrical consumption total:
  - lights and equipment: 9.8 kWh/$ft^2$ year
  - cooling: 1.9 kWh/$ft^2$-year
  - fans: .975 kWh/$ft^2$-year
- Demand: (summation of monthly peaks): 0.054 kW/$ft^2$-year

## 2.2 Base Building Cost Estimate

Detailed costs estimates for the base case building were developed only for the greater Washington, D.C. area -- in keeping with the limited focus of the workshop. Based on a cost estimate by Scharf-Godfrey Associates, the base case building will cost $50.89/$ft^2$, not including site work. The cost estimators feel that this cost is somewhat high but within 5-10% of average costs for a speculative office building in the Washington, D.C. area.

## 3. BEAM DAYLIGHTING CONCEPTS

The first design workshop was devoted to investigation of beam daylighting for a small office building. For a number of reasons, work to date by the researchers investigating passive technologies at the laboratories has focused on the use of direct beam daylight for illumination. At least in single story buildings, this application is possible over the whole roof and is independent of building orientation. It is also desirable because capturing an intense beam of light can result in maximum illumination with minimum amounts of glazing and minimum negative effects due to thermal conduction. However, the difficulty of dealing with beam daylight architecturally can be substantial -- "like trying to drink from a firehose," commented Si Daryanani.

Based on analyses and modeling performed at the labs to date, the following constraints applied to two problems:

- South facing roof aperture
- Glazing tilted up $60^{\circ}$ from horizontal (representing the best trade-off between an ideal angle for overcast conditions -- horizontal -- and a good angle for clear conditions -- vertical)
- Total aperture (tilted) to be 2-3% of floor area.

The specification of so small an amount of aperture was based on lab analysis (1) which indicated that maximum savings in annual operating costs due to natural lighting can be achieved with very small aperture area to floor area ratios (see Figure 2.)

### 3.1 Beam Daylighting with Roof Systems Only

In the first problem, design teams were to focus only on the roof. While ignoring the effects of perimeter lighting, the design teams were to get 50 foot candles of uniform light at the height of work surfaces throughout the building.

The suspended ceiling plenum was to be retained and the roof system was to be "punctured" as required to achieve proper lighting. It was assumed that 1 foot-candle of sunlight could replace 1 foot-candle of artificial light.

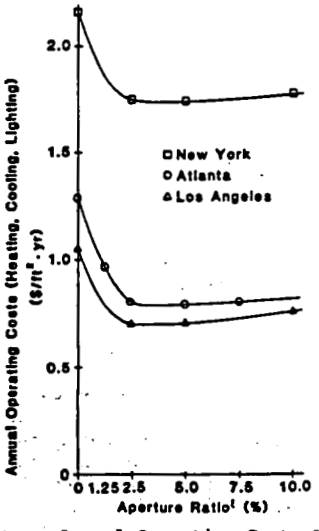



FIG. 2. Annual Operating Costs As A Function of Aperture Ratio (Roof Aperture ÷ Floor Area).

Modifications were to be made for the lowest net increase in total building cost over the base case.

Interestingly, both teams settled on angular skylight-like "fixtures" as a solution. One team's solution is shown in Figure 3. The "fixture" 3ft X 4ft opening at the base. The frame of the fixture uses readily available metal rigging. It is designed so it could be built as a unit in the shop and simply bolted or shot into place. The strength of the frame also provides solid support for drywall used on the interior of the coffer and a rigid joint for butting ceiling tile to the fixture. The steel framing also provides enough space for insulation.

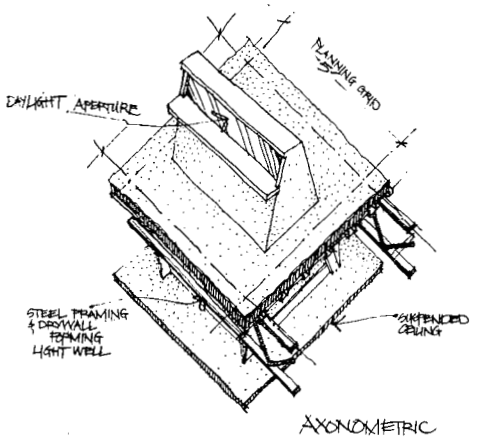



FIG. 3. A Daylight "Fixture" Designed For 2-1% Aperture Ratio

Cost for both solutions was approximately $3 per $ft^2$, more than the base case. In both cases the increased cost was largely for increased labor and materials to make and install the "fixtures."

### 3.2 Beam Daylighting by Building Redesign

In the second daylighting problem, the design teams had to accomplish the same levels of uniform illumination using beam daylight but they were free to investigate trade-offs in the roof and wall systems or to do a complete redesign of the building from the foundation up.

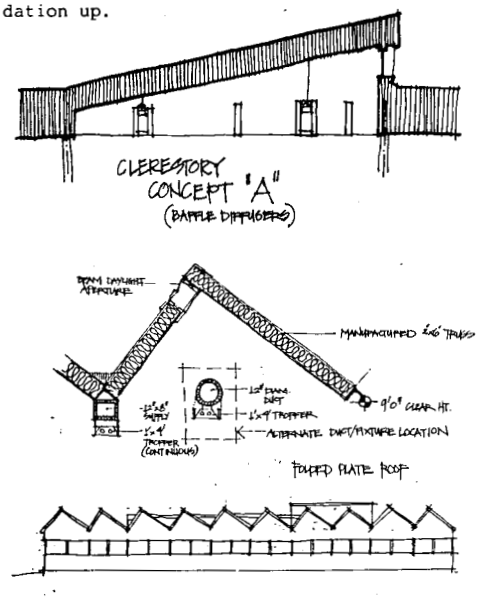



Fig. 4. Two Concepts for Roof Design with 2-1/2% Aperture. A Clerestory (above) and a Wood-Truss Folded Plate Roof.

One team summarized their strategy as follows:

- Do not daylight the mechanical core
- Daylight perimeter offices with vertical wall glazing (diffuse daylight)
- Daylight "intermediate" spaces (between perimeter and core) with "borrowed light" from the perimeter and two beam daylight clerestories.

All building elevations were redrawn to take advantage of less costly pre-manufactured wood windows. The south elevation was changed so that daylight aperture (above) could be separated from view glazing (below).

Two clerestory designs were developed. One (A) used ceiling baffles to diffuse incoming light (see Figure 4). The other (not shown) used an adjustable blind just behind the clerestory glass to control and diffuse beam daylight. Both concepts located fluorescent lamps to shine upward onto the sloped roof of the clerestory to diffuse artificial light when it was required.

In this solution, modest increases in cost for added accoustical panel, glazing, and labor in the clerestory were more than offset by using cheaper side windows, 4-lamp instead of 2-lamp fixtures, and an improved structural system with smaller bays. The net result was that this daylight solution was $\$2.50/ft^2$ cheaper than the base case.

The other team took a more radical approach, replacing the steel deck roof in the base case with a "folded plate" roof made of manufactured wooden trusses. (Shown in Figure 4). liminary cost analysis suggested that the folded plate wooden roof could be very cost competitive. The trusses would be manufactured out of 2in x 6in material with internal structure as required. They would be plywood top and bottom and be filled with fiberglass batt insulation with a plastic vapor barrier. Trusses would be bolted to an angle iron at the base which, in turn, would rest on structural beams. The trusses would be fastened at the top with mullions leaving space for glazing.

It was decided to drop the roof in all areas, using the folded plate, leaving a higher ceiling in the central core as discussed above. Besides fitting well with the HVAC distribution strategy, the lower ceiling height would mean 15-20% savings on the interior and exterior facade and modest reductions in steel costs because of shorter columns. Partitions would end at 9ft with the space above open into the sawtooth. The cost of wood glazing and other materials in the new roof system was more than offset by savings from eliminating roof deck and joists and reduced wall height. The net result was a \$1.00 savings per $ft^2$ below the base case.

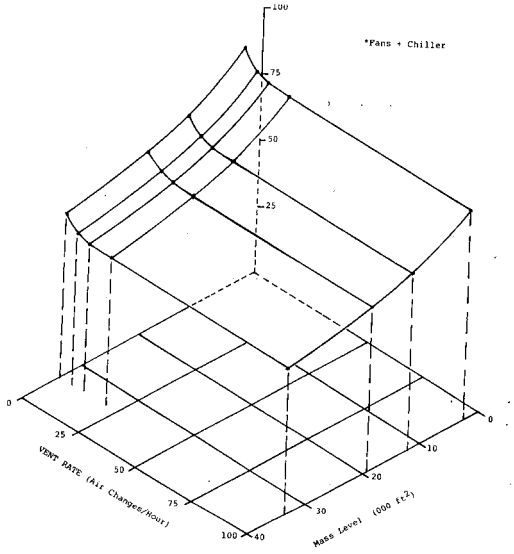



FIG. 5. Annual Operating Performance For Various Combinations Of Ventilation Rate And Mass Area (2 in. Thick)

## 4. MASS WITH NIGHT VENTILATION SYSTEMS

The second major passive cooling strategy investigated in the design workshops was the combination of building mass with night ventilation. In this case, two variables have to be considered simultaneously, the area of exposed mass and the rate of ventilation. (Mass thickness was held constant at 2in. that being approximately the optimum thickness as judged by previous lab analysis.) Figure 5 illustrates the reduction of energy use based on the combination of the two variables-- computed by simulation. As shown, the greatest reductions in energy use occur below 25 air changes per hour. There is no clear "breakpoint" in terms of mass area. which means there

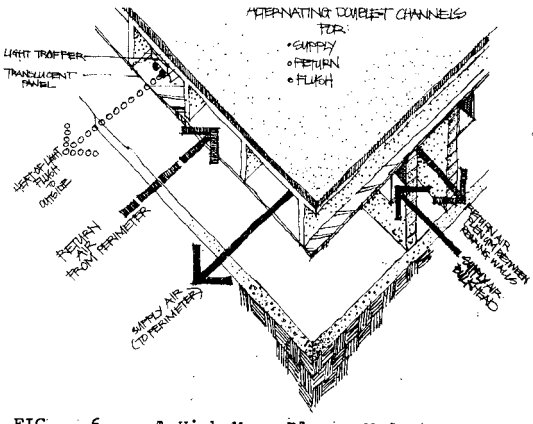



FIG. 6. A High Mass Plenum Made From Pre-Cast Concrete Double-T's

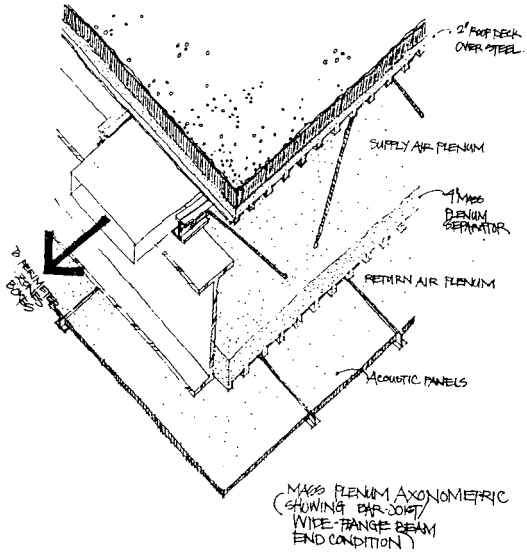



Fig. 7. A High Mass Plenum made from Site-Fabricated Concrete Slabs

is no "ideal" amount of mass to be used. At the extremes, electrical consumption for cooling could be reduced 23% (over the base case), annual electrical demand 14%, and heating energy 7%.

The solution arrived at by the first team is affectionately called the "half-massed" solution. The goal of this solution is to put approximately 15,000 $ft^2$ of exposed mass into the building -- rather than the 32,000 $ft^2$ which the labs presumed to be about the maximum possible in a building of this size (10,000 $ft^2$ ).

First, the team replaced the open-web joists and metal deck in the base case solution with pre-cast concrete "double tees" (Figure 6).

The second focused on the mechanical system aspects of the design. Rather than use massive double-T's, the team developed a new concept -- two concrete slabs separated by open web joists (all site fabricated) to form a supply air plenum (see Figure 7). A suspended ceiling below the bottom slab would create a return air plenum. Connections from the supply air plenum to lay-in diffusers in the ceiling were made of flexible duct. The cost of all the mass (well over $2.00 per square foot) was offset by elimination of nearly all ductwork and some savings in steel. The net result was a cost of roughly $.60 per square foot over the base case.

## 5. EVAPORATIVE COOLING SYSTEMS

Los Alamos National Laboratory researchers developed two "realistic" evaporative cooling systems for simulation as part of the Cooling Assessment work: a direct evaporative system and a direct/indirect system. The direct/indirect system is shown in Figure 8. Each system was comprised of readily available (off-the-shelf) mechanical system components.

The cost-estimating team was asked to develop an estimate of the approximate first-cost of the proposed system if added to the reference building design. No benefit was estimated for the potential elimination of the primary mechanical cooling equipment.

Major cost differences include:

- Air washers: $5,160.00
- Z Duct System: $9,320.00
- Return Air Fan: $2,750.00
- Additional ductwork: $1,650.00
- Additional controls: $2,150.00

Depending on performance of the system in a particular climate, the incremental cost for both evaporative systems might be reduced through elimination of conventional mechanical chillers. A recent unpublished investigation by Los Alamos National Laboratory indicates that the mechanical cooling can be entirely displaced by evaporative cooling in the Pacific Northwest, Fresno/El Paso, and Central Mountain climate regions of the U.S. In addition, variations in the design of other building systems, in the same manner as solutions to design problems involving application of beam daylighting and mass with night ventilation technologies, could reduce system total incremental costs even further. A reasonable estimate of the net incremental cost over the base case for the evaporative cooling system is $.80-$1.20/ $ft^2$.

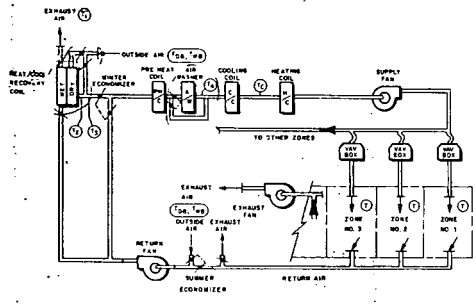



FIG. 8. Schematic Diagram Of A Direct/ Indirect Evaporative Cooling System

## 6. INTEGRATED SOLUTIONS

To date, there has been no systems analysis of combined passive cooling technologies. Therefore, it was impossible for the design teams to work on a design solution integrating technologies with the same guidance from the national labs as in all the previous problems. Nevertheless, the teams did attempt one integrated solution for a 2-story 10,000 square foot office building in Denver.

Space limitations of this paper do not allow presentation of final results. They are available in the final report on this project.

## 7. ECONOMICS OF PASSIVE COOLING SYSTEMS

System economics are important to both building designers and government energy research managers. System first cost must be weighed against potential savings by every designer who proposes an energy efficient solution to a client. The lower the first cost and/or the greater the annual energy savings, the easier it will be to gain acceptance of each new passive cooling technology. The design solutions presented above give an indication of potential first-cost of each passive solar cooling technology considered.

When increases in first cost are divided by annual savings, the result is simple payback. Although a crude financial measure, simple payback is commonly used and is adequate for our simple comparison across technologies. The minimum and maximum payback for each technology studied is summarized in Table 2.

## 8. ACKNOWLEDGEMENTS

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TABLE 2. COMPARISON OF SIMPLE PAYBACK AMONG PASSIVE SOLAR COOLING TECHNOLOGIES

| | CONCEPT NUMBER | FIRST COST INCREASE | UTILITY COST SAVINGS | | YEARS TO SIMPLE PAYBACK | |
|---|---|---|---|---|---|---|
| | | | MIN | MAX | MIN | MAX |
| • NATURAL LIGHTING: - Roof Only | 1 | +2.93 | .10 | .53 | 6 | 30 |
| | 2 | +3.32 | .10 | .53 | 6 | 33 |
| - Building Redesign | 1 | -2.50 | .10 | .53 | 0 | 0 |
| | 2 | -1.00 | .10 | .53 | 0 | 0 |
| • MASS WITH NIGHT VENTILATION | 1 | + .44 | .01 | .12 | 4 | 40 |
| | 2 | + .58 | .02 | .23 | 3 | 30 |
| • EVAPORATIVE COOLING | 1 | • .90 | .01 | .09 | 10 | 90 |

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# A PROPOSED NEW ENERGY STANDARD FOR COMMERCIAL BUILDINGS

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## ABSTRACT

A project was established to develop a new energy standard for commercial buildings, using the widely accepted ASHRAE/IES Standard 90A-1980, "Energy Conservation in New Building Design"; as a starting point and general pattern. Under this project, 90A-1980 was analyzed to determine its effectiveness and to define shortcomings; research was conducted to develop a technical/economic basis for setting improved cost-effective requirements for energy conservation; recommendations were developed for an improved standard; and the recommendations were tested across a suite of 10 building types in 8 climates. Preliminary results from these tests indicate that design compliance with the recommendations provides 15-30% annual energy savings in office buildings and smaller but significant savings in other building categories (as compared to buildings designed in compliance with 90A-1980.) The recommendations also provide for expanded design freedom in demonstrating compliance, especially compliance with envelope requirements. The recommendations and technical support information were presented to ASHRAE to assist in its periodic upgrading of Standard 90, and to the U.S. Department of Energy as major input to its Congressionally-mandated process of developing minimum design standards for federal buildings and voluntary guidelines for the private sector.

## 1. INTRODUCTION

During 1982 and 1983, Pacific Northwest Laboratory managed a research project sponsored by the U.S. Department of Energy, and conducted cooperatively with the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) through its Special Project #41. The purpose of the project was to analyze the primary existing design standard for commercial buildings (ASHRAE/IES Standard 90A-1980, "Energy Conservation in New Building Design"), and to develop recommendations for an improved standard.

The project was initiated to provide a basis for the upgrading of commercial building design standards and codes. Standards and codes need to be periodically upgraded to ensure that they reflect the ever-changing capital cost/energy savings tradeoffs, to capture the benefits of improving technologies, and to accommodate the increasing use of renewable resources. The best way to encourage the upgrading of energy codes is, of course, through revision of the underlying standard. Standard 90 was selected as the starting point and pattern for the project because it is widely recognized and is the basis for energy codes in about 40 states.

It must be clearly understood that the purpose of the project was not to develop a standard for immediate adoption and/or codification by any entity. Rather, the project's recommendations are intended to serve as input to the conventional standard-setting processes of ASHRAE, the U.S. Department of Energy, and any other jurisdictions or organizations that may wish to use the information.

## 2. PROJECT STRUCTURE

The project was comprised of four major elements performed sequentially, but with considerable overlap. These elements were: 1) evaluation of the existing standard and identification of problem areas; 2) basic research to develop improvements/fixes; 3) formulation of recommendations; and 4) testing for conservation and economic effectiveness. The initial work was performed on a section-by-section (building component-by-component) basis, and then sections were brought together for integration and evaluation as a whole-building standard.

### 2.1 Evaluation of the Existing Standard

The provisions of the existing standard were evaluated through a careful line-by-line review of the language, through investigation of reported problems encountered in use and

enforcement of the standard, and through a rigorous test of its energy and economic impacts on buildings.

This test involved the application of the existing standard to 10 real building designs. Plans for the buildings were reconfigured for compliance with both 90-1975 and 90A-1980 in each of 8 cities. DOE-2.1B energy analyses were then conducted and detailed construction, operation and maintenance, and energy cost estimates were made. Finally, life-cycle-cost (for three economic perspectives) and payback period were calculated as indicators of economic performance. These DOE-2.1B runs and economic results were then closely evaluated to identify energy problems and potential cost-effective improvements to 90A-1980.

Evaluation of the existing standard and its impact on buildings revealed numerous areas where the standard needed to be improved in order to improve clarity and tighten (or moderate) requirements. In addition, major modifications to form and/or substance were recommended for the sections controlling each of the major building systems: envelope, heating ventilating and air conditioning (HVAC), and lighting.

In general, envelope requirements were, prescriptive, not allowing the designer adequate flexibility to demonstrate compliance. Many of the most important consumption determinants were ignored entirely (such as external shading, glass placement, orientation, configuration, and the need to match envelope design to internal loads). Other considerations (such as thermal mass and the advantages and disadvantages of insolation) were treated inadequately. The investigations also raised some questions about the regional equity of the existing standard.

For HVAC systems, the major energy problem seemed to be system selection. In the tests energy consumption varied more between different systems (identical buildings in the same location) than between different locations (identical buildings with the same systems). Something needed to be done to encourage selection of the most cost/energy-effective systems during the building design process. The strengthening of system control requirements and improved equipment COP's and piping insulation levels also seemed to be major keys to system performance improvement. And finally, revision of the way the Air Transport Factor (ATF) is applied to various systems was identified as desirable.

For lighting two major modifications seemed appropriate: reduced compliance complexity and significantly lower power densities. In addition, the need for requiring a minimum level of control was identified, and some way to encourage the use of automatic room-occupancy and daylighting controls was deemed necessary. Finally, the need for some lighting performance (quality) requirement was identified.

## 2.2 Background Research

A major proportion of the project was dedicated to background research in each of three main technical areas: envelope design, HVAC systems and equipment, and lighting.

### 2.2.1 Envelope Research

The major objective of this research was to understand the way in which envelope design moderates the relationships between climate, internal loads, and thermal comfort, thereby leading to the development of design strategies that minimize energy consumption in peripheral zones. Because daylighting technologies significantly reduce energy consumption, this enormously complicating factor also needed to be understood and quantified.

An ambitious sub-project was conducted at Lawrence Berkeley Laboratory to quantify the impact of wall, fenestration, and lighting impacts upon energy consumption in the peripheral zone of commercial buildings. An intermediate-floor building module was defined - a 100ft x 100ft core surrounded by four 15ft x 100ft peripheral zones - as the basic unit for the research. Numerous DOE-2.1B analyses were run on various permutations of building design and operation across 14 climates. Factors investigated include: $U_o$, orientation, configuration, percent glass, number of glazings, shading coefficient, external shading, internal loads and lighting power, perimeter zone depth, daylighting controls, and building schedule. BLAST runs were also made to quantify the impact of thermal mass.

When a large data base had been developed, multiple regression analyses were conducted to develop simplified correlation expressions for predicting annual heating, annual cooling, and peak cooling energy consumption from readily available climate and building parameters. These parameters were then employed as the basis for developing the new envelope requirements.

### 2.2.2 HVAC Systems Research

Research behind development of new systems requirements fell into two areas. First, specialized analyses were conducted to determine the effects of control strategies. Second, in-depth surveys of equipment shipments and catalog availabilities were made to determine reasonable levels for minimum equipment coefficients of performance (COP's). Case studies of air transport energy were investigated to help

determine a better way to apply the Air Transport Factor to system design.

### 2.2.3 Lighting Research

Lighting research concentrated upon determining a suitable power density level for various tasks in commercial buildings. Several levels of power reduction from the 90A-1980 maximums were investigated. A 25% reduction from the existing level was easily met for all test buildings, while maintaining the following criteria: 1) meet target illumination requirements for task activities, 2) no significant decrease in fixture count, 3) no color degradation, and 4) no increase in fixture coefficients of utilization.

Economic analyses were also conducted to determine cost-effective levels of lighting control. New power density determination procedures were investigated to establish a simplified means of determining power levels in buildings. Finally, a performance requirement for minimum horizontal illuminance was tested and discarded because of its complexity, and because it overemphasizes the quantity aspects of lighting quality.

## 3. RECOMMENDATIONS

When the basic research had been conducted, the next step was development of recommendations for the upgraded standard. A summary of these recommendations follow.

### 3.1 General Recommendations

The recommendations generated by the project apply only to the design of commercial buildings, rather than to all buildings, as is presently the case under Standard 90. Specifically, mobile homes, single-family dwellings, and low-rise multi-family buildings (3 or less stories) are excluded. (Both ASHRAE and DOE will issue separate standards for energy consumption in new commercial and residential buildings.)

The organization of 90A-1980 is also changed in the recommendations. For the first time this component-based standard will allow interaction between the requirements for different building systems, i.e., envelope compliance will now depend upon decisions made in the lighting compliance procedure. Hence, the sections of the recommendations have been reordered to reflect this sequencing.

Further, these recommendations reunite Sections 10 (Systems Analysis) and 11 (Requirements for Buildings Utilizing Solar, Geothermal, Wind, or Other Non-Depleting Energy Sources) with the component-based sections of the standard. These sections were part of the original 90-75, but they were later broken out separately from the main body of the standard for further study and refinement when the 90A-1980 revisions were made. Section 12 of 90-75 (Annual Fuel and Energy Resource Determination) has been eliminated.

The recommended numbering system is presented below, with the old section numbers following each section name in parentheses.

| | |
|---|---|
| 1.0 | Purpose (1.0) |
| 2.0 | Scope (2.0) |
| 3.0 | Definitions (3.0) |
| 4.0 | Illumination Systems (9.0) |
| 5.0 | Exterior Envelope Requirements (4.0) |
| 6.0 | HVAC Systems (5.0) |
| 7.0 | HVAC Equipment (6.0) |
| 8.0 | Service Water Heating (7.0) |
| 9.0 | Auxiliary Systems and Equipment (8.0) |
| 10.0 | Systems Analysis (90B-75R) |
| 11.0 | Requirements for Buildings Utilizing Solar, Geothermal, Wind or other Non-Depleting Energy Sources (90B-75R) |

### 3.2 Changes in Envelope Requirements

The recommendations for upgrading the exterior envelope requirements are the most radical of all the recommendations.

90A-1980's separate treatment of roof, floor, and walls is maintained. Roof and floor treatment is similar to 90A-1980, but is tightened, with the allowable thermal transmittance decreasing as a function of increasing heating degree days. Relaxed transmittances are allowed for roofs with skylights where daylighting benefit can be assured through the use of automatic daylighting controls.

Treatment of wall design is completely different from 90A-1980. Walls must now meet three separate criteria: peak cooling, annual cooling, and annual heating. Compliance with each criterion is demonstrated through an equation as a function of 1) conductive load, 2) solar load through windows, and 3) internal lighting load modified for daylighting, with each of these factors summed across building exposures. Climate, orientation, shading, building mass, operating schedule, and other important building-specific factors are included as coefficients in the equations. All relevant coefficients are provided in the standard as a function of building/climate-specific factors that are selected by the building designer. This approach is ideal for either worksheet or microcomputer compliance procedures.

The results from the lighting compliance section now enter into the wall compliance

procedure as a power density, and thus internal loads are considered in envelope design, allowing the designer to integrate design of the lighting and envelope systems. If the designer opts for a high lighting power budget under Section 4, then envelope compliance will be more difficult for the peak cooling and annual cooling criteria, but easier for the heating criterion. However, the designer may also opt for a daylighting approach to compliance (automatic controls required) and then he is allowed significant credits for compliance with the peak and annual cooling criteria (and penalties for the heating criterion), and his envelope design will need to shift accordingly.

### 3.3 Changes in HVAC Requirements

HVAC systems and equipment and service hot water requirements are not radically changed, but rather reflect the continuing incremental technical improvements that have occurred over the past decade. The equipment efficiency requirements mandated for January 1984 (by 90A-1980) remain unchanged. New minimum efficiency levels are mandated for January 1988; these exhibit about 2-8% improvement over 1984 levels. Insulation requirements for pipes and boilers are also strengthened.

The recommendations require the designer to evaluate various system and control options during his design process, including the use of Variable Air Volume systems (VAV), heat recovery, night setback, and reset control by exposure. In addition, it is recommended that the designer conduct an annual energy consumption analysis during his system selection process.

Finally, application of the Air Transport Factor (ATF) has been clarified, and separate ATF's have been recommended for ducted returns, non-ducted returns, constant volume systems, and variable air volume systems.

### 3.4 Changes in Illumination Requirements

The recommended procedure for illumination system compliance (Section 4) is based upon the 90A-1980 lighting requirements, but it provides both significant energy savings and compliance simplication. The major changes are listed below:

- Separate power budgets are required for the building interior, exterior activity areas, and facade lighting.
- In developing the power budget for the building interior, the designer no longer must calculate a budget on a room-by-room basis, but rather on an activity-by-activity basis. Hence, for a large office building, only one calculation need be made for all of the office-type space, as opposed to the existing standard, where a separate calculation must be made for each individual office. The room configuration factor is still applied, but on an average basis rather than on a room-by-room basis. For the project test buildings, this simplified approach to budget determination reduced calculations by 70%.
- Small rooms (50 square feet or less) are exempted from the compliance requirements.
- Power densities are reduced by approximately 25% across all interior task activities.
- 20% additional power is allowed for all luminaires that are controlled by automatic daylighting sensors, and 10% is allowed for luminaires controlled by room occupancy sensors.
- Control requirements are more stringent to allow more economical use of illumination systems.

## 4. TEST RESULTS

After the standard was developed, the energy and economic impacts of the recommendations were rigorously tested across 10 building types: each configured with 3 HVAC systems across 8 climate zones from 4 economic perspectives. Daylighting was also fully tested, where appropriate. In general, for office buildings, the average energy savings were between 15 and 20% without daylighting control, and about 25% with automatic daylighting controls. Other building categories displayed less but still significant energy savings. Economic analysis demonstrated a reduced life-cycle cost in almost all situations investigated. Only in Seattle, which has a very low cost of electricity, were cases of increased life-cycle cost discovered.

The energy and economic results for the medium office building test are presented in Figures 1 and 2. A continuous downward trend is displayed across levels of standard (A: 90-75, B: 90A-1980, C: new recommendations, and D: new recommendations with automatic daylighting controls) both for annual energy consumption and for life cycle cost. The only exception is the life-cycle cost in Seattle, which rises slightly because the capital cost increases caused by the new recommendations are not fully compensated for by decreases in energy cost. (Economic results from the daylighting analyses were not yet available at the time this paper was written.)

## 5. SUMMARY

The overall effect of the standard (if adopted) should be to reduce energy consumption in commercial buildings, while allowing the building designer considerably more flexibility in demonstrating compliance than is possible under 90A-1980. This is especially true for envelope design, where the designer can optimize building configuration, orientation, glass placement and shading factor to harmonize with the operation and internal loads of the building. Daylighting is heavily emphasized, with energy credits given both in the lighting and envelope compliance procedures. The design community has been given an opportunity (in the compliance process) to benefit from the energy savings that daylighting can provide.

One of the real benefits of the standard is its instructive potential. The exterior envelope compliance procedure is very informative, identifying the building's energy problems, and providing feedback on what factors to adjust to improve envelope energy performance for cooling and heating problems.

Finally, the compliance process will be significantly altered. Lighting compliance has been grossly simplified, and much less work will be required for development of a building power budget. The exterior envelope compliance procedure is longer, reflecting the increased complexity necessitated by consideration of additional energy-related variables. It is, however, well-suited to automation on a microcomputer or programmable calculator. Some increase in HVAC compliance calculations may be required, as well, as an indication of proper system selection.

## 6. ACKNOWLEDGEMENTS

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The work was conducted by a team of researchers and practicing architects and engineers, and included personnel from the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), Pacific Northwest Laboratory (PNL), Lawrence Berkeley Laboratory (LBL), the National Bureau of Standards (NBS), Alden E. Stilson and Associates, The Deringer Group, W.S. Fleming and Associates, the National Conference on Building Codes and Standards (NCSBCS), the American Institute of Architects Foundation (AIA), and the U.S. Department of Energy.

## 7. APPENDIX: SUMMARY OF TEST CONDITIONS

The test conditions for which the recommendations were tested are described below in tabular form. All of the test results are carefully documented, and are available through NTIS.

### 7.1 Test Climates

Washington, DC
El Paso Texas
Houston, Texas
Milwaukee, Wisconsin
Seattle, Washington
Los Angeles, California
Omaha, Nebraska
Boston, Massachusetts

### 7.2 Test Buildings

Small office building
Medium office building
Large office building
Strip stores (2) in shopping center
Anchor store in mall (department store)
Convention hotel
High-rise apartment building
Warehouse
School
Assembly building (multi-use church)

### 7.3 Economic Perspectives

Federal government
State/municipal/local government
Private: owner occupied
Private: speculative owner

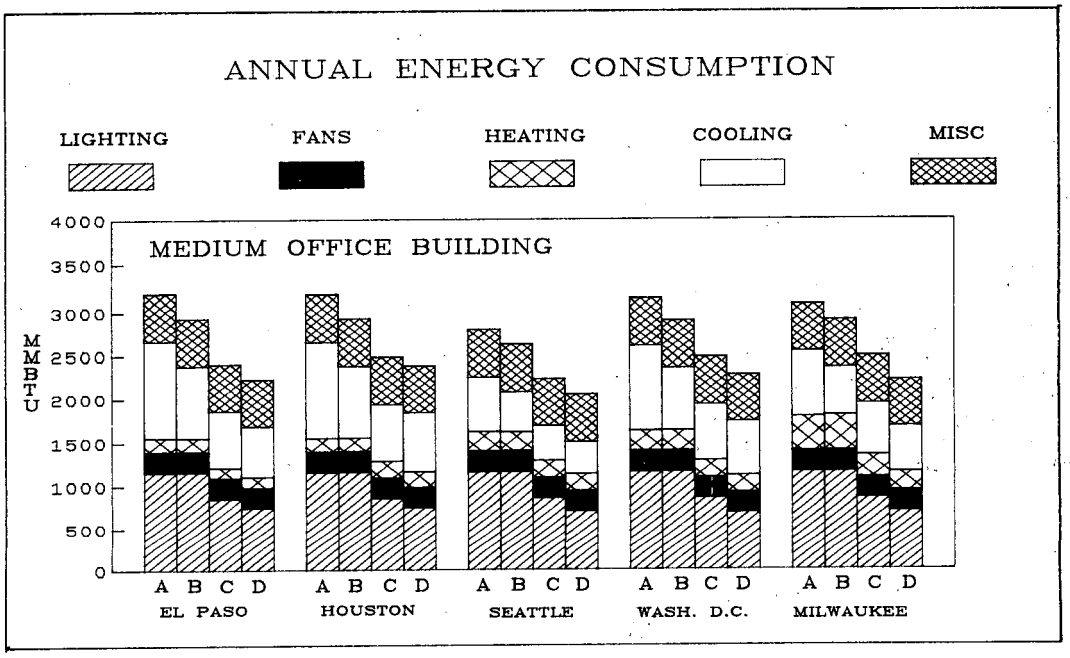



Fig. 1. Estimates of annual energy consumption for a medium office building (48,000 $ft^2$) configured to 90-75 (A), 90A-1980 (B), recommendations without daylighting control (C), and recommendations with daylighting controls (D).

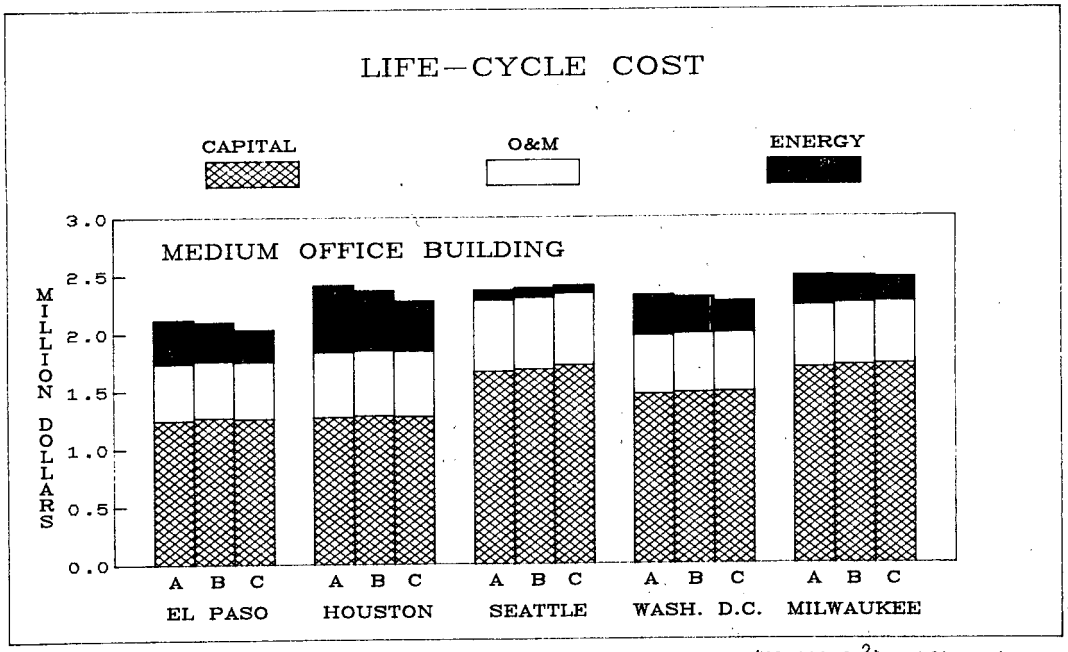



Fig. 2. Estimates of life-cycle cost for a medium office building (48,000 $ft^2$) configured to 90-75 (A), 90A-1980 (B), and recommendations without daylight control (C). An owner-occupied economic perspective is assumed.

# COMFORT, INTERIORS AND SAFETY


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# OCCUPANT EFFECTS AND INTERACTIONS IN PASSIVE SOLAR COMMERCIAL BUILDINGS: PRELIMINARY FINDINGS FROM THE US DOE PASSIVE SOLAR COMMERCIAL BUILDINGS PROGRAM

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## ABSTRACT

While some data on the substantial impact of occupancy factors on energy use in residential buildings exist , these effects in commercial buildings have not been systematically investigated. This paper presents the approach to examining the relationship between occupants and energy use currently being implemented through the U.S. Department of Energy Passive Solar Commercial Buildings Program. The buildings in this program include airports, schools, commercial retail and office space and a variety of community facilities located across the U.S., from Alaska to Alabama. Preliminary findings related to how occupant behavior influences energy use and how users respond to these passive solar commercial buildings are presented.

Although data from the buildings in the program are incomplete, they do point out several important conclusions and relevant issues. Most building users seem to be satisfied with conditions in the buildings--the patterns of the relatively few complaints about comfort reveal cool, sometimes drafty mornings and warm afternoons. Some concern about acoustics has also been expressed.

The issue of user operations in the buildings is a more pervasive one--there are many instances of improper operations of the buildings, due to a variety of factors. There is a need for clear, well managed user orientation programs and an explicit transfer of responsbility for certain building operations to the users.

Changed occupancy patterns and changed building operations are consistent factors which help explain discrepancies between energy use predictions and actual disaggregated measures of energy use in these buildings.

## 1. INTRODUCTION

The U.S. Department of Energy is sponsoring the Passive Solar Commercial Buildings Program to experiment with the use of passive solar techniques in non-residential buildings. The 23 projects in the Program are undergoing a comprehensive performance evaluation, based on a standardized data collection system. These data relate to the three hypotheses that underlie the Program. These hypotheses are:

- Passive design affects building energy performance
- Building performance influences occupant reactions
- Occupant behavior affects building energy performance.

The Occupancy Evaluation component of the Performance Evaluation addresses the second and third hypotheses.

In "standard" residential buildings, such as those studied in the frequently cited Twin Rivers studies, users can strongly influence energy use. The Twin Rivers studies found that occupant behavior accounted for the majority of the explained variance between actual and expected energy use.

> "In a sample of twenty eight identical townhouses, variation in energy consumption was found to be as great as two to one. Since these houses are identical in floor plan, position in the interior of a townhouse row, builder, construction materials, and climate, it is likely that most of the consumption variance is due to the different behavior of the people in the houses." (1).

In more recent work by Alan Edgar, a detailed study of a 4% random sample of single family dwellings in a small Kansas town revealed

that occupant related factors such as household income, age of occupants, and attitudes toward conservation accounted for much more variation in energy use than did structural characteristics of the houses.

> "..the environment in which a dwelling is located, the physical characteristics of a dwelling and the occupant-related parameters for the use of the dwelling interact to determine the energy use of the dwelling. In the Marysville Project, the first four 'best' predictors of energy use were occupant-related measures." (2)

Recent work by Duncan Case (3) supports the importance of occupant perceptions and behavior in a series of case studies of 14 passive solar residences.

These findings in the residential sector point to the potential importance of occupancy factors in more complex commercial buildings. While energy use monitoring studies which include consideration of occupancy factors in "standard" commercial buildings are currently just in the planning stages (e.g. Battelle Pacific Northwest Laboratory Building Energy Use Monitoring Project), this project is currently studying occupant/energy use interactions in a variety of passive solar buildings.

## 2. METHODS

Each building in the Department of Energy Passive Solar Commercial Buildings Program is required to complete one year of monitoring and data collection designed to evaluate the performance of the building. The project team at each building received a set of data collection and reporting forms, accompanied by explanatory manuals which describe the collection procedures in detail. Basically, each project team reports the projected energy use for the building and the design, occupancy and operational assumptions which underlie those predictions. Then, monthly reports of energy use, building operations and a variety of occupancy-related factors are submitted. Both full time and part time building users complete short questionnaires which relate to comfort conditions in the building as well as to their operational interactions with it. Thus, it is possible to evaluate the relationship between predicted and actual energy use each month within the context in which that building actually operated during that month.

The Performance Evaluation System can be viewed conceptually according to Figure 1. It is structured along 2 dimensions:

> Do the buildings save auxiliary energy?
>
> - Do they function as well as nonsolar buildings?

Imbedded within these questions are a variety of occupant-related hypotheses, including:

- Users will manipulate the building to acheive comfort, either by the means intended by the designer, or by any other means they can devise.
- Changes in occupancy patterns (number, timing, activity and location) will have profound influence on energy use and operational characteristics of buildings.
- "Educated" users and building operations staff are more likely to acheive expected levels of energy performance in a building, since passive solar buildings are especially sensitive to interactive effects which can be influenced by a wide variety of improper or unexpected patterns of building operations.

  Clarity in roles and responsibilities for building operation is crucial in passive solar commercial buildings, since they are not usually "automatic" as are most 'standard' commercial buildings.

As can be seen in Figure 1, the Performance Evaluation System is designed to answer these questions within the larger contexts of determining likely reasons for discrepancies between predicted and actual energy use, and of examining a variety of factors comparing users comfort and response to the buildings.

## 3. DATA AVAILABILITY

Although 23 projects are in the Program as a whole, many of them are still under construction or are in the midst of having their energy use monitoring equipment installed and calibrated. Seven of the buildings have partial or complete data for the 12 month post occupancy evalution period.

Since building users completed the questionnaires on a voluntary basis, some data are unavailable. Available data are subject to the same potential sources of bias as are all self-reported data.

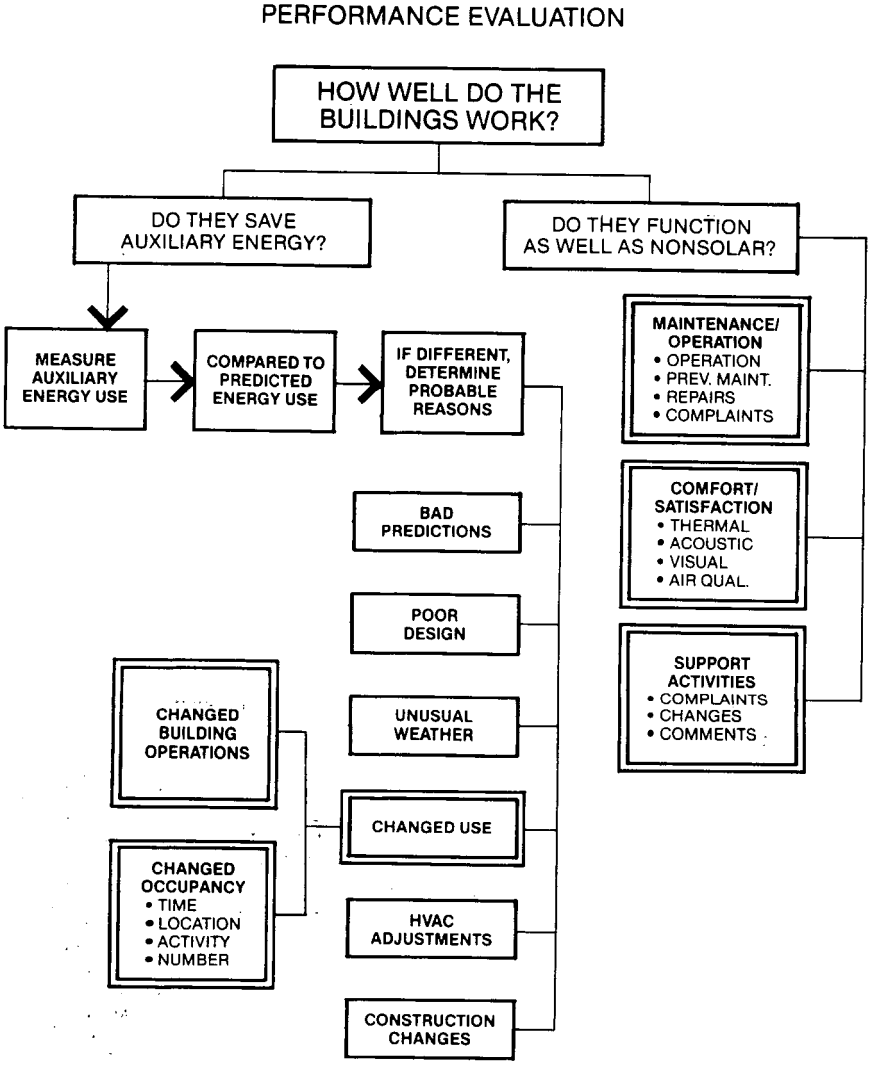

PERFORMANCE EVALUATION
HOW WELL DO THE BUILDINGS WORK?
DO THEY SAVE AUXILIARY ENERGY?
DO THEY FUNCTION AS WELL AS NONSOLAR?
MEASURE AUXILIARY ENERGY USE
COMPARED TO PREDICTED ENERGY USE
IF DIFFERENT, DETERMINE PROBABLE REASONS
MAINTENANCE/ OPERATION
• OPERATION
• PREV. MAINT.
• REPAIRS
• COMPLAINTS
COMFORT/ SATISFACTION
• THERMAL
• ACOUSTIC
• VISUAL
• AIR QUAL.
SUPPORT ACTIVITIES
• COMPLAINTS
• CHANGES
• COMMENTS
BAD PREDICTIONS
POOR DESIGN
UNUSUAL WEATHER
CHANGED USE
HVAC ADJUSTMENTS
CONSTRUCTION CHANGES
CHANGED BUILDING OPERATIONS
CHANGED OCCUPANCY
• TIME
• LOCATION
• ACTIVITY
• NUMBER

Fig. 1.

## 4. DESCRIPTION OF BUILDINGS

This section briefly describes some important characteristics of those seven buildings for which some data are available.

1. Airport--Gunnison, CO
   9,700 $ft^2$
   Heating: Direct Gain
   Mass Wall
   Cooling: Natural Ventilation
   Shading
   Daylighting: Clerestories

2. Store--Wausau, WI
   3,212 $ft^2$
   Retrofit
   Heating: Sunspace/Atrium
   Cooling: Shading
   Daylighting: Monitors

3. Educational Facility--Columbia, MO
   5,493 $ft^2$
   Heating: Direct Gain
   Storage Floor
   Mass Wall
   Cooling: Natural Ventilation
   Shading
   Night Flushing
   Daylighting: Clerestories
   Lightshelves

4. Mental Retardation Training Center--New Braunfels, TX
   4,805 $ft^2$
   Retrofit
   Heating: Direct Gain
   Cooling: Shading
   Night Flushing
   Daylighting: Windows

5. Visitor Center--Troy, NY
   4,316 $ft^2$
   Heating: Sunspace/Atrium
   Storage Floor
   Earth Contact
   Mass Wall
   Cooling: Earth Contact
   Natural Ventilation
   Shading

6. Library--Mt. Airy, NC
   13,450 $ft^2$
   Heating: Direct Gain
   Storage Floor
   Mass Wall
   Cooling: Natural Ventilation
   Reflective Material
   Shading
   Daylighting: Clerestories
   Light Shelves

7. Office Building--Salt Lake City, UT
   15,000 $ft^2$
   Heating: Direct Gain
   Storage Floor
   Cooling: Night Flushing
   Daylighting: Clerestories
   Light Shelves

Projected occupancy schedules in each of these buildings followed expected patterns.

## 5. OCCUPANT IMPACT ON ENERGY USE

A variety of occupancy-related factors has influenced energy use in these buildings. Each factor will be described briefly, along with a relevant example.

### 5.1. Changed Occupancy Levels

Number of Occupants: In several of these buildings, occupancy levels increased dramatically after the buildings were opened. In at least two of the cases, building operators reported that the building itself was so attractive that people wanted to spend more time in it. As a result, however, more energy was used in these buildings than was projected. In addition, there was some difficulty maintaining comfort conditions since the passive systems and their mechanical backups were sized for original occupancy levels.

Time of Occupancy: In a similar way, a number of buildings experienced user pressure to expand building operating hours. In one building, for example, the design had been based on primary occupancy during late afternoon and early evening hours. After the building opened, it was so popular that people would be waiting for the door to open at 8 a.m. However, since the passive systems were not designed to provide heat at that hour, auxiliary heat sources were used.

Location of Occupants: Significant changes in location of building activities influenced energy use in these buildings. In one building, a loft area which had not been designed for occupant use was converted into extra office space shortly after the building was completed. Since the energy system had not been designed with that area as an occupied zone, users in that area experienced some discomfort, and more energy was used to try to acheive comfort conditions in that zone.

Activity of Occupants: Since internal heat gains are such a significant factor in passive solar commercial buildings, changes in occupant activity can strongly influence energy use. In one building, an area designed for active physical exercise was used for showing slides. By darkening the skylights to accomodate the changed activity and by decreasing the internal heat gain due to user activity, the energy demands on the space were changed.

5.2 Changed Building Operations

During the design process, architects make assumptions about how a building will be operated. As part of the Performance Evaluation, the designer of each building specified which actions were supposed to be taken to optimize the building energy use and under what set of "triggering conditions" these actions were supposed to occur. For some buildings, these "operational protocols" took the form of written instructions; for others, designers had informal discussions with building users and operators. There are several important issues relating to changed building operations and building energy use--communication, responsibility and heirarchy of actions.

It is essential that the operational protocols associated with optimal energy functioning of buildings be communicated in a clear, direct manner to those people who will be most directly involved with operating the buildings. In one building, for example, although users were told which actions were available to them if they felt too warm, the correct order was never clearly communicated. As a result, the heirarchy of operations which the designer assumed in designing for predicted energy use was not followed. On a late fall afternoons, for example, when users in one building became too warm, they opened the windows to the outside rather than lower the shading curtain.

In several of the buildings a variety of actions are possible for users to take to achieve comfort conditions. Preliminary analysis has shown that in the absence of clear directions, users depend on familiarity, proximity and ease of use as the three deciding factors for using operable building components.

Responsibility for building operation is another complicating factor. For some buildings, the person owning the building, operating the building, paying the utility bills and the people using the building on a daily basis are different. In these cases, it is extremely difficult to maintain the operational protocol as the designer intended. One-time instructions about building operation seem insufficient.

## 6. BUILDING OCCUPANT RESPONSES

Users were asked a variety of questions about their response to these buildings. The questions dealt with thermal comfort, lighting, acoustics and air quality. If discomfort was reported, respondents were asked about the time of day and location, as well as being asked what actions, if any, they took to try to acheive comfort. This process allows the comparison of energy use and perceived comfort under defined sets of conditions on a monthly basis.

In general, users were highly satisfied with the buildings. Users felt the buildings were more attractive than non-solar buildings and had relatively few complaints about comfort conditions.

6.1. User Intervention: A number of specific instances of user intervention in the buildings point out the types of actions users will take to try to be comfortable. In a few buildings, some users brought in auxiliary portable electric heaters because slow warm up in the mornings resulted in uncomfortably cool temperatures. In other buildings, the combination of daylighting and articificial light was insufficient in some areas of the building, usually deep inside the space; in those areas some users added table or clamp-on lamps. In one building, a user added a "white noise machine" near his desk because the noise from other areas of the building was distracting.

6.2. Thermal Comfort: Although most buildings had few thermal comfort problems, the pattern of too cool mornings and warm afternoons was repeated in several buildings. The role of the amount, exposure and distribution of thermal mass in this pattern is currently being examined.

6.3. Acoustic Comfort: Occasional problems with distracting noise making it difficult to concentrate were reported in several buildings. On site visits, acoustic problems were noted in

most buildings. Although this project cannot specifically address this issue, the role of exposed thermal mass, open space planning necessary for convection, and fans used in many hybrid systems may exascerbate this problem.

6.4. Visual Comfort: Daylighting techniques were used extensively throughout all buildings. Users reported few problems in most buildings, but glare was a persistent issue in some of the others. Comparisons between beam and diffuse daylighting techniques may shed some light on this issue.

6.5. Air Quality: Few complaints about air quality were noted, but stuffy or drafty conditions were mentioned by some users. No building user complained about conditions being too smoky.

## 7. ISSUES

Occupancy-related issues clearly have a significant impact on energy use. Individual users can manipulate the buildings in unexpected ways, occupancy patterns can be altered by a variety of circumstances, and user comfort can be obtained or sacrificed. As more data become available from the buildings in the Program, more information about these issues will be available.

Several issues arise:

### 7.1. User Control

While the assumption that buildings should have totally controlled environments is not usual for passive solar design the way it is for design of more standard commercial buildings, the degree and locus of user control and the number and location of operable building components is a significant issue for design and operation of passive solar commercial buildings.

A range of control strategies is available--from automatic dimmer systems that balance the daylight and artificial light contribution to maintain constant light levels, to operable windows that users open when they want ventilation. Two different points of view result.

"One point of view waives the concept of user involvement, alleging that the more automatic the building is the better, since people will never learn how to operate the building correctly, are not really interested, and have a documented history of just ruining the designers intent. The other point of view maintains that there are opportunities for people to become more involved with their buildings. Perhaps if continued involvement with buildings were possible, increased satisfaction, similar to that found with involvement in design, would result." (4)

### 7.2. User Education; Building Operation

In order for buildings with operable components to work optimally, information about the assumptions which underlie the design must be made explicit and be transferred to the appropriate users in a consistent manner. The responsibility for this documentation and information transfer is the issue. Should the architect develop an operations manual for the building? Should the owner develop operations policies for the building and then somehow enforce them? Should consultants train building users in proper building operations?

### 7.3. Energy Programming

The relatively large number of occupancy factors which influence building energy use point out the need for changes in architectural programming. The programming process for a passive solar commercial building must address issues of occupancy schedule, lighting and acoustical requirements, and user functional requirements in a different way.

## 8. ACKNOWLEDGEMENTS

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# SOME REFLECTIONS ON PSYCHOLOGICAL COMFORT AND ITS APPLICATION TO ENERGY CONSCIOUS DESIGN

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## ABSTRACT

A biological basis for human psychological comfort is proposed, and its evolutionary origin is hypothesized in relation to the satisfaction of basic human needs. Environments which support these needs are experienced as pleasurable, attractive, psychologically and physically comfortable and are sought out. Environments which do not meet these needs, or which demand too great a psychological or physical adjustment, are experienced as unpleasant, unattractive, uncomfortable, and often anxiety-producing or stressful. Implications for energy conscious fenestration design are discussed in terms of the impact on view, access to sunlight and daylight, and responses to major lighting sources.

## 1. HUMAN COMFORT IN THE BUILT ENVIRONMENT

The effects of the thermal and visual environments on physical comfort have been the topic of intensive research for several decades. The concept of psychological comfort, on the other hand, is a much more recent interest to the design profession. Engendered in this concept are issues of health and well-being, emotional satisfaction, feelings of pleasure and security, and notions of adaptation between organism and environment.

Researchers who have dealt with the person-environment milieu in architecture have tended to focus their efforts on behavioral observations and unobtrusive measures. Much less attention has been paid to the ways in which people think about their environments, how they assess them emotionally, and how the physical environment makes people feel. Furthermore, much of the work in person-environment relations has not had a theoretical basis and thus has been lacking the predictive power of a theoretically derived analysis of psychological comfort as it relates to the design of the physical environemnt. To date, there is a great deal of speculation, much of which is intuitively appealing (see 1), but little actual data exist to support speculations about what is and is not psychologically satisfying. In order to begin the task of measuring psychological comfort, we need first to ask what it is.

### 1.1 Evolution and Human Psychological Comfort

We propose that human psychological comfort is a biologically evolved, emotionally satisfying state that is founded upon the fulfillment of basic human needs. Physical environments which support these needs are experienced as pleasurable, attractive, psychologically and physically comfortable, and are sought out. Environments which do not meet these needs, or which demand too great a psychological or physical adjustment, are experienced as unpleasant, unattractive, uncomfortable, and often anxiety-producing or stressful.

In order to determine what these "basic needs" are and how the physical environment supports or inhibits their fulfillment, it is necessary to consider the evolutionary history of the human species. A number of investigators, working independently in geography (2), psychology (3,4,5), and ecology (6) have recently analyzed human emotional responses to the environment from a biological perspective. While their work has focused on the landscape, it has important implications for the indoor built environment.

Appleton (2) regards human safety and security as the fundamental needs influencing environmental preferences. Survival, according to Appleton, is contingent upon an organism's ability to anticipate and thus avoid dangers from both animate sources (e.g., predators) and inanimate sources (e.g., bad weather). Environments are judged in terms of their capacity to provide visual access (what Appleton refers to as "prospect") while simultaneously offering places to hide ("refuge"). Appleton predicts that environments that offer the best opportunities for both prospect and refuge will be experienced

as pleasurable and will be sought out.

Kaplan (3,4) analyzes the biological basis of environmental satisfaction from an information-processing perspective. According to Kaplan, early humans were likely to have lived in a hostile and uncertain habitat where mental skills were at a premium for hunting, foraging, avoiding predators, and finding the way home. As a result of our long evolutionary history in such environments, humans have come to like those settings which make information acquisition not only easy, but also enjoyable. Environments which foster the processing of information are characterized by their clarity and by their capacity to draw the observer into the landscape by the promise of more information.

While Appleton and Kaplan have dealt with a generalized early human environment, Orians (6) ties environmental satisfaction more directly to the actual habitat in which the human species is presumed to have evolved -- the African savannah. Deriving his arguments from theories of habitat selection, Orians proposes that emotional responses co-evolve with the intrinsic capacity of an environment to support biological survival. For early humans, the savannah afforded a higher resource base and better protection from predators than did dense forest or wide-open desert habitats. Orians' theory suggests that the millions of years in which humans lived in savannah type habitats have produced psychological and physiological systems that, while flexible, are best satisfied when people live and work in environments that contain the fundamental features of a savannah.

Such features include semi-tropical temperatures, open spaces, sunshine, green plants and trees, fresh air, places in the environment for refuge, changes in elevation that afford expansive views of the landscape, and locations that support social contact as well as privacy.

Although Orians develops his theoretical model in relation to landscape preferences, it is an interesting fact that architects and designers have unconsciously recreated in the built environment many of the basic elements of the African savannah:

- Buildings are designed to operate within a narrow range of temperature and humidity.
- Windows are provided to admit daylight and sunlight and are frequently positioned and sized to offer the best and most expansive view of the external environment.
- Plants are extensively used with the assumption that they are in some way psychologically comforting.
- Changes in elevation within a building as well as in external spaces often serve as focal points for viewing the environment.
- The most successful plazas offer a balance between prospect and refuge.
- Interior spaces are carefully designed to protect privacy and yet offer needed contact with other people.

The idea that the indoor built environment could maximize psychological and physical comfort if it were designed to mimic the important features of the African savannah was first suggested by Logan (7) more than 30 years ago. He derived a lighting design from an analysis of the maximum and minimum daily light flux at the African site presumed to have been the original human habitat. He hypothesized that humans are adapted to these lighting conditions and that they should be integrated into office design.

More recently, Lam (1) has suggested that lighting design ought to take into consideration human biological needs. While he doesn't use the African savannah as a starting point, Lam does propose that lighting design should highlight those aspects of the interior environment that have biological relevance (i.e., places of escape; location of water and social activites; presence of other living things; places of refuge) and that it downplay less relevant aspects of the setting.

### 1.2 Human Needs and Environmental Satisfaction

The suggestion that humans feel best when they live and work in environments that support their needs is hardly a novel idea. Behavioral scientists have been proposing models of person-environment congruence for decades, beginning with Lewin (8). Furthermore, Lam (1) provides an extensive list of human needs as they relate specifically to the lighting environment. We have merely expanded existing ideas and have attempted to place them in a larger theory of human psychological comfort. Underlying this perspective are several important suppositions:

(1) Psychological comfort is primarily a biological phenomenon.

(2) Emotions form the infrastructure of psychological comfort.

(3) Emotional responses to the environment have evolved to assure that humans seek out those environments in which they are most likely to survive and flourish and avoid environments that are detrimental.

(4) Emotional responses operate largely at an automatic, unconscious level; as a result, people may often have an immediate response to a place

without knowing exactly why.

(5) Basic human needs are not equivalent in their impact on psychological comfort.

(6) The more important the need, the less conscious and more emotionally intense will be the response to the environment and the more it will be influenced by biology rather than culture or individual experience.

We suggest that there are four primary levels of human needs as they relate to the physical environment:

(1) Physical safety and security. This involves the availability of places where one can hide from dangers and places from which dangers can be seen.

(2) Physical and social resources. This level has to do with the provision of comfortable temperatures and adequate light as well as access to sunlight, fresh air, water, food, green spaces, and contact with other people.

(3) Satisfaction of information needs. This level deals with the capacity of environments to effectively satisfy needs for information related to planning, decision-making and locomotion in the environment.

(4) Aesthetic features. The final level is the satisfaction of needs for aesthetically pleasing features.

We envision built environments as lying along a continuum of psychological comfort. At one end are environments which are very uncomfortable and unsupportive of psychological well-being. The other end represents environments which are highly pleasurable, comfortable and supportive of well-being. The environments at this positive end would meet all four levels of human need, while those at the extreme negative end would provide very minimal support. The vast majority of built environments would fall somewhere in the middle of the continuum, by satisfying some, but not all, of the levels.

### 1.3 Measurement of Psychological Comfort

It is one matter to define comfort in these terms and quite another problem actually to measure it. Most studies that have ventured into this arena have been content to deal with the analysis of environmental preferences. These preferences, while informative, do not tell us much about the underlying psychological processes that lead one environment to be preferred over others. Recent work on lighting design, however, has begun to look at the underlying psychological qualities of different environments (9,10,11). These projects have had subjects rate different lighting designs on a number of bi-polar scales such as relaxing-tense, satisfying-frustrating.

The measurement of psychological comfort should ideally include not just environmental evaluations of this sort, but also an assessment of the impact of different settings on feelings and mood states, health, and performance. These latter components of comfort are difficult to measure in field settings. They require -- at least in the initial stages of investigation -- a controlled laboratory setting where all variables except those of interest are held constant.

Field testing, however, can provide a useful foundation for the development of structured laboratory analysis. The usual model is first to investigate ideas in laboratory settings, and then test them in the "real world." However, by conducting field studies first rather than last, the investigator can enhance the validity of the questions being pursued. This is an approach that has been used successfully in ethological studies of animal behavior: the behavior of interest is first observed in a natural state and then detailed investigations of the factors that influence the behavior are carried out in field or laboratory experiments. This is the procedure we are following in analyses of occupant responses to energy conserving design.

## 2. PSYCHOLOGICAL COMFORT AND ENERGY CONSCIOUS DESIGN

Although research is currently underway at a number of institutions, for the most part energy conservation strategies have been undertaken without knowledge of their impacts on human psychological comfort and environmental satisfaction. Issues of how (or even whether) to maximize psychological comfort have lagged far behind concerns for energy efficiency and cost effectiveness.

Fenestration design has a major impact on energy consumption, and it is this issue to which we will devote the rest of the paper. A number of previous studies (12, 13, 14, 15) have analyzed people's responses to windows of different sizes and placement. Our concern here is with the use of reflective glazing which has gained increasing popularity in highrise office buildings.

### 2.1 The Psychological Impact of Heat Reflecting Glazing

While heat reflective glazing appears to achieve thermal goals (16), it may do so at the expense of occupant psychological comfort. At issue are several important aspects of window and lighting design: view, the availability of daylight, the availability of sunlight, and color rendering of the view and room surfaces. Much research

suggests that these aspects of windows are important characteristics of a comfortable work environment (12,17,18,19,20,21). Contact with sun, daylight, and the external world are regarded as fundamental human needs (17,18,19, 23,24). This suggests that the presence or absence of windows in an environment will greatly affect measures of psychological comfort. Environments which interfere with these needs are expected to be less psychologically comfortable and satisfying than environments with good access to views, daylight, and sunlight. This does not necessarily mean, however, that all three of these needs are equivalent in their importance or that they have similar psychological impacts. Studies by Ne'eman (24) and Longmore and Ne'eman (25) suggest that view is a more important contributor to environmental satisfaction than is the provision of daylight or sunshine. If this is so, then it suggests that there may be a hierarchy of psychological needs in relation to window design. The most important would be view (because it provides extensive and relevant environmental information). Of lesser importance would be daylight and sunlight followed by color rendering of the view and room surfaces. This predicts that the most negatively regarded energy conservation strategy would be one which deletes windows or drastically reduces window size. The most satisfying strategy would be one which utilized clear glazing while also controlling the negative effects of the sun in ways that do not obstruct views [a design strategy proposed by Lam (26) and referred to as "SUNLIGHTING."] The use of heat reflective glazing, the topic of our current research, is expected to fall somewhere in between these two extremes: it still affords opportunities for views, but may have a negative impact on feelings about daylight, sunlight, and color rendering.

## 2.1 The View from the Window

Heat reflective glazing, by its very nature, decreases the brightness of the light entering the room and alters the colors of the view in comparison to clear glazing. Heat reflective glazing will pose psychological discomfort if: (a) occupants perceive the view color and brightness as different, and (b) if view brightness and color are important to visual and psychological satisfaction.

There is some indication that ratings of view brightness are correlated with visual satisfaction. Markus and Gray (27), in a study of residences, found that brightness of the visible scene was among the most important factors in ratings of visual preferences. However, an extensive investigation of building occupants' responses to heat absorbing and reflective glasses (28) found no correlation between glass type and ratings of brightness or colors in the view. Nor did these investigators find any correlation between glass type and ratings of view pleasantness. Lower transmission glasses did not appear to have a negative influence on ratings of view brightness or pleasantness.

Before one takes these data to mean that solar glazing does not have an impact on occupant responses, it should be noted that the buildings in the Cooper et al. study had a wide range of glazing types. Daylight transmission values ranged from 15% to 85%, with only two buildings out of eleven having transmission values of less than 24%. Six of the buildings had glazing with values of 50% or higher. Glazing with daylight transmission values of 10-20% are in common use at this time, and it is these types which are most likely to affect perception of view brightness and color.

Furthermore, people seem to respond differently to heat reflecting and heat absorbing glass--a fact which Cooper and his colleagues had learned from the pilot studies upon which their office study was based. As reported in Collins (12), Cooper and his research group found a negative response to heat reflective glass with transmission values of between 12% and 15%. People objected to the darkness of the external view; the high levels of artificial lighting that were constantly required; and the window reflections produced when the external light levels were less than those in the building interior. These findings are particularly relevant, since the use of low transmission glazing is among the more energy efficient fenestration devices and because the heat reflective glazing has achieved considerable popularity.

## 2.2 Daylight Satisfaction

It is widely assumed that daylight is a more psychologically satisfying and desirable form of illumination than electric lighting (17,18,26). If this is so, then solar reflective glazing which admits only a small percentage of available daylight may lead to some psychological discomfort and dissatisfaction with the environment.

Little empirical data actually exist, however, on people's responses to and perceptions of daylight or on the effects of daylight on people's psychological state. In one of the few available studies, Wells (20) found that 69% of 2500 employees said it was better to work by daylight than by artificial light, and only 3% said artificial light was definitely as good. However, Wells also found that people were not able to estimate accurately how much of the lighting in their workspace actually came from daylight. The further from the windows they were, the more they overrated the amount of daylight available. This suggests that people may not be able to distinguish between daylight and electric light, although this hypothesis has not been

tested under controlled laboratory conditions where the actual light source is masked.

### 2.3 The Perception of Daylight vs Electric Light

Whether or not people can distinguish between these two major lighting sources is an important issue for lighting and window design. If people cannot distinguish the two, then it is likely that the loss of daylight in offices with reflective glazing will not produce psychological discomfort, because occupants will not realize they are being deprived of natural light. (Whether or not it produces negative health effects is another issue. The available data on this topic are controversial, particularly with respect to their impact on humans. However, for speculations on the role of daylight on human well-being see 29,30,31,32.)

Furthermore, if it is not possible for people to distinguish daylight from electric light, it may be feasible to simulate daylight in windowless spaces and thereby improve psychological comfort. Research on windowless buildings present some conflicting results (see 12). Nontheless, it appears that many people do suffer from the loss of windows, particularly if they work in routine jobs which keep them more or less in one space for most of the day.

The studies on windowless buildings do not adequately address the issue of what it is that people miss -- is it a view of the external world or daylight? Both of these responses appear frequently in the research literature. Our model of hierarchical needs predicts that the loss of windows as sources of information will be the most severe deprivation and will cause the most psychological discomfort. However, it may be possible to lessen the discomfort by providing simulated "daylight." It may even be feasible and desirable to develop surrogate views that, while not as satisfying as the real item, may nonetheless be a psychological boost in comparison to having no view at all.

### 2.4 Sunlight Satisfaction

With the exception of recent design strategies developed by Lam (26), window design has emphasized the reduction of the negative effects of sunshine (heat gain and glare) rather than maximizing its positive features (such as the addition of light, cheerfulness, physical and psychological warmth). Heat reflective glazing may reduce the benefits of sunshine by changing its character (i.e., reducing psychological warmth and cheerfulness) while not necessarily reducing the negative effects of glare (see Cooper et al, 28).

### 2.5 The Effects of Heat Reflective Glazing on Lighting Design

One of the problems posed by the use of reflective glazing is that interior illumination must be provided almost entirely by electric sources. Not only does this increase energy costs, there is also reason to believe that it is less satisfying to occupants. A number of studies have suggested that people prefer daylight to electric light, particularly when the primary source of illumination is overhead fluorescent fixtures -- the most common form of office lighting. Our preliminary pilot data support these findings.

If office design were more variable and incorporated the features suggested by Lam (1) and others (9,10,11), there is reason to believe that psychological comfort and environmental satisfaction would improve.

## 3. A FIELD STUDY OF THE PSYCHOLOGICAL IMPACT OF HEAT REFLECTIVE GLAZING

The study on which we are currently working is measuring psychological comfort and environmental satisfaction in relation to:

(1) responses to view brightness and color

(2) assessments of window brightness and glare

(3) daylight and sunlight satisfaction

(4) ratings of illumination design

(5) perception of color rendering of room surfaces

(6) comparisons of daylight and electric light relative to a number of physical and psychological outcomes

Psychological comfort will be measured in a number of ways. First, we are asking subjects to rate the lighting environment on a number of psychological dimensions such as like-dislike, comfortable-uncomfortable, secure-apprehensive, relaxed-stressed, want to stay-want to leave. Second, we are assessing the relative importance of different aspects of the lighting environment and different lighting designs using a subjective expected utility model. Third, we are measuring the extent to which people would like to change the lighting environment.

Subjects in the study are primarily clerical staff in a new highrise building in Seattle. They have been chosen from offices in both lower elevations and upper floors and are divided into two groups: those with desks near the windows and those with desks at a distance from the windows.

The study utilizes a repeated measures design that will allow us to assess how people's judgment of the lighting environment are affected by climate and weather conditions. Occupants will be surveyed over the course of a year under three conditions: (1) bright, sunny skies; (2) bright, overcast skies; and (3) dark, overcast skies. Measures will be taken of internal and external illumination levels at each administration of the survey, and behavioral observations will be made of occupants' use of blinds, personal task lighting, and orientation with respect to the windows.

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# THE IMPACT OF OCCUPANTS ON THE PERFORMANCE OF PASSIVE SOLAR COMMERCIAL BUILDINGS

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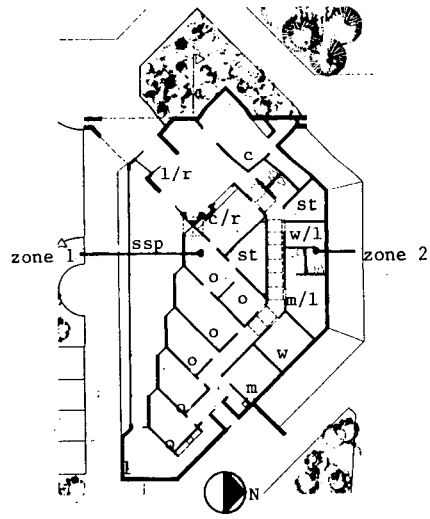
## ABSTRACT

The Visitors Information Center at Rensselaer Polytechnic Institute, Troy, New York, is a passive solar commercial demonstration project funded in part by the U.S. Department of Energy. The building's energy conscious design features integrate energy conservation, passive heating, cooling, and daylighting techniques with innovative comfort technologies, multiple-path-comfort options, multifunction energy flow controls, and HVAC systems. The building has been designed to be user-friendly and provides the means for individual occupants to meet their personal comfort requirements.

The building has been occupied since February 1981, and detailed measurements on the building's performance have been collected for two years. Although the occupants are very satisfied with the comfort provided by the building, the hour-by-hour simulation results on energy consumption, used during the design phase, are significantly lower than real-time measurements. The hour-by-hour simulation uses standard thermostat set-points, infiltration rates, and lighting levels in conjunction with the Albany, NY, weather-tapes, yet actual energy consumption is 39% higher than predicted. Despite this increased energy consumption the building only consumes 31% of the energy a non-solar building, constructed according to the applicable energy code, would use. The results presented in this paper suggest that people, and not buildings, determine energy consumption, regardless of standards and accurate performance simulations.

## 1. INTRODUCTION

Rensselaer Polytechnic Institute in Troy, New York, designed and constructed a passive solar Visitors Information Center (VIC), occupied since February 1981. This project was partially supported by the U.S. Department of Energy through a Design Assistance and Demonstration grant. A schematic of the VIC's floor plan is shown in Fig. 1. The building's large south elevation accommodated a sunspace to collect and store solar energy. The central hallway, with skylights and adjustable curved reflectors on the exterior, functions as a daylighting and direct gain system for the hallway and spaces located on the northern perimeter, zone 2. Thermally sensitive spaces are cocooned between the infrequently occupied spaces in zone 2 and the sunspace. The thermally controlled floor area is 401 $m^2$ (4,300 $ft^2$) and the total floor area, including the uncontrolled sunspace is 484 $m^2$ (5,200 $ft^2$). The sunspace glazing area is 63 $m^2$ (690 $ft^2$). More detailed description of the building is contained in the Final Design Report (1).




LEGEND

| | | | |
|---|---|---|---|
| l/r | lobb/reception | w/l | women's & |
| c/r | control/reception | m/l | men's lockers |
| c | conference room | l | lounge |
| ssp | sunspace | w | workroom |
| o | offices | | |
| st | storage room | | |

Fig. 1. Floor Plan

The passive solar systems of heating, daylighting, and cooling are all integrated with the HVAC and energy flow control systems. Occupants within offices have multiple comfort options to achieve thermal, visual, and acoustical comfort. Individual thermostats, operable windows in the sunspace, radiant heating ceiling panels, movable insulation and shading devices, a fireplace, a thermal chimney (light/vent tower) and skylight reflectors are just a few of the energy flow controls through which the occupant can achieve visual and thermal comfort.

All auxiliary energy consumption is electric. A variable air volume system, integrated with an electrical resistance heating element and a cooling coil provides for back-up heating and cooling. Detailed descriptions of the energy flow controls, comfort systems, monitoring systems, and performance are documented (2, 3).

## 2. OCCUPANT-ORIENTED DESIGN FEATURES

Throughout the design phases numerous design decisions were made based on the belief that building energy consumption is determined by the occupants. Recognizing that occupants vary in their comfort requirements, a majority of energy flow controls were designed for manual operation. In addition, the design provides multiple means by which thermal and visual comfort needs can be satisfied. Given these objectives, the design team had to depend on the occupant contributing towards energy conservation.

### 2.1 Thermal Energy Flow Controls - Heating

The following summarizes the various means by which an occupant can achieve heating comfort:

- Thermally sensitive offices in zone 1 can achieve heating by opening windows to the sunspace (if heat is available); heat can be trapped in the sunspace by manual override of the thermal insulating curtains; a radiating ceiling panel movable to coincide with furniture arrangements) can be actuated through a timer-switch; the thermostat can be manually adjusted; and, the door can be opened to the hallway containing heat from the direct gain system.

- The infrequently occupied spaces in zone 2 can provide thermal heating comfort by baseboard heating units with an integral thermostat; fixed radiant ceiling panels, actuated by a timer-switch; and doors can be opened to the hallway to gain heat from the direct gain system.

- The lobby area is equipped with a fireplace, and the occupant can activate the "Heatolator" fireplace which has a separate outside combustion air duct and glass doors.

- An office thermostat calling for heat activates a set of sensing devices searching for free heat in the sunspace or the hallway, provided the temperature is 10°F above the required heat supply. When such heat is available it is delivered to the office through the HVAC/variable air volume system. This same system allows fireplace generated heat to be transported to offices.

- Movable insulation panels at the skylights can be closed whenever desired, or when a signal light at the control desk indicates recommended positions.

- Skylight reflectors are manually adjusted three times a year to maximize the solar gain to the hallway and the zone 2 spaces and to shade the skylights in the summer.

### 2.2 Thermal Energy Flow Controls - Cooling

- Operable windows in the sunspace and an operable door to the light/vent tower create a thermosiphoning effect thus naturally venting the sunspace during the summer.

- The thermal curtain in the sunspace also acts as a shading/reflector device and contributes to minimizing solar gain in the sunspace. The thermal curtain has a manual override. Under automated conditions the thermal curtain is lowered when the temperature exceeds 85°F, and the light/vent tower exhaust fan is activated.

- By opening office doors and the windows to the sunspace, natural ventilation is provided.

- Skylight reflectors are manually lowered over the skylights to provide shading while allowing sufficient daylight to penetrate to the hallway and zone 2.

- Doors to the zone 2 space can be opened since these spaces have a thermal mass insulated on the exterior. Thus the natural convective flow is created.

### 2.3 Daylighting Energy Flow Controls

- The thermal insulating curtain in the sunspace can be lowered to various heights, and although they are automatically operated, a manual override allows for personal preference.

- Skylight reflectors with their dual function as shades keep the hallway and

zone 2 relatively cool.

- Task lighting installed in December 1982 allows reduction of lighting energy consumption. Footcandle levels at desk height average 40 fc on an overcast day.

## 3. OCCUPANT RESPONSE

Each of the occupants received a detailed operations manual illustrating the various energy conscious design features and alternative ways by which the occupant can achieve thermal and visual comfort. In addition, four seminars were held over a six month period to help the occupant understand the features of the building. During the first year of operation (January 1981 to December 1981) several discomfort problems occurred due to an unusually long de-bugging phase. Neither the design team nor the occupant realized that it would take an entire year before the building could be operated the way it was designed. The HVAC system, sensors, thermal curtains, and the conversion of a zone 2 space to an office space were just a few of the main problems encountered in the first year. The manual operation of the movable insulation panels in the hallway also presented a problem through malfunctioning hardware. In addition, the panels are too heavy for some of the occupants to operate.

Since January 1982 the occupant response to the overall thermal and visual comfort within the building is very favorable. Only in January, February, July and August do a few of the occupants indicate infrequent discomfort. The following conditions have been identified through a continuous user evaluation process:

- The domestic hot water system (instant flow heat) is unsatisfactory in terms of water temperature. The instant flow heaters are improperly installed.
- The Lobby area tends to be too cold during the winter evenings. This is due to the large amount of pedestrian traffic in and out of the lobby. This problem is restricted to the person at the control desk.
- The Conference Room feels too cold near the window. Three different thermal curtain repairs failed to place it in operating condition. It has been eliminated until a satisfactory product can be found.

## 4. OCCUPANT-DETERMINED ENERGY CONSUMPTION

Although the occupants are satisfied with thermal, functional, and daylighting performance of the building, the simulated energy consumption of the building disagreed with the actual energy consumption monitored since January 1982. The hour-by-hour simulation, used during the design phase -- an "in-house" computer simulation tool coupled to the Albany, NY, design year tape -- predicted that the building would have a total energy consumption of 22.63 kBtu/ft$^2$-year, or 118 MMBtu/yr.

To everyone's surprise this performance was not achieved in actuality. Close observation of the occupant behavior and use of the building, as it relates to the energy consumption, revealed the following:

- Thermostats were consistently set at 72°F in zone 1 both during winter and summer days and nights.
- The Ventilation/Infiltration rate of one-half air change per hour originally assumed in the simulation was much too low. The traffic in and out of the building was at least three times the original estimate, and all of the occupants tend to use the main entrance instead of the staff entrance.
- Ceiling lights are continuously left on despite the fact that the user evaluation and on-site measurements clearly indictate that daylighting and task lighting are sufficient to do the work.
- Ceiling exhaust fans in the bathroom are linked to the lights according to the building code. Occupants consistently leave the bathroom lights on thus venting warm indoor air to the exterior.
- Doors to zone 2 spaces are left open in the winter thus creating increased heat loss.
- Whenever the fireplace is used the glass doors are left open thus increasing the wood consumption, as well as losing indoor heated air.
- Skylight movable insulation is not closed when signals indicate. Sunspace thermal curtains are often left on the manual setting. These two conditions cause an increased heat loss since the control desk person cannot always leave the area when thermal conditions call for it.

The actual total energy consumption for heating, cooling, lighting and HVAC equipment of the VIC is 33.28 kBtu/ft$^2$-yr or 173.1 MMBtu/yr. as compared to the simulated 22.63 kBtu/ft$^2$-yr. This 41.5% error needed to be explained. After adjusting the load parameters, as shown in Table 1, to represent the actual conditions of the building, a 2% error existed between the actual energy use of the building and

the adjusted simulation.

Figure 2 shows the total energy consumption for the original simulation, the adjusted simulation and the actual performance of the building. Thus conservative assumptions about door openings (infiltration) and thermostat settings explain the discrepancy between simulated and actual results. Figure 3 shows the overall building performance compared to the adjusted simulation.

Table 2 presents the differences in simulated, adjusted simulation, and actual energy consumption for heating, cooling, lighting and HVAC equipment. While actual cooling loads are lower than anticipated, the increased lighting and heating load, as effected by the occupant, is clearly demonstrated. Figure 4 shows the actual and adjusted simulation energy consumption for heating, cooling, and lighting on a monthly basis.

TABLE 1. COMPARISON OF DESIGN PHASE SIMULATION TO PRESENT SIMULATION

Important Load Parameters - Overall Conductance (UA)

Design Simulation

| | | |
|---|---|---|
| Zone 1: Transmission | UA = 124 | W/°C = 234 Btu/°F-h |
| Ventilation/Infiltration (One-half air change/h) | UA = 29.0 | W/°C = 44 Btu/°F-h |
| Zone 2: Transmission | UA = 133 | W/°C = 252 Btu/°F-h |
| Ventilation/Infiltration (One-half air change/h) | UA = 20.1 | W/°C = 38 Btu/°F-h |

Present Simulation

| | | |
|---|---|---|
| Zone 1: Transmission | UA = 124 | W/°C = 234 Btu/°F-h |
| Ventilation/Infiltration (One air change/h) | UA = 58 | W/°C = 110 Btu/°F-h |
| Zone 2: Transmission | UA = 136 | W/°C = 257 Btu/°F-h |
| Ventilation/Infiltration | UA = 40.2 | W/°C = 78 Btu/°F-h |

Thermostat Heating Set Points

Design Simulation

| | | |
|---|---|---|
| Zone 1 | 18.3°C (65°F) day | 12.8°C (55°F) night |
| Zone 2 | 15.5°C (60°F) day | 12.8°C (55°F) night |

Present Simulation

| | | |
|---|---|---|
| Zone 1 | 22.2°C (72°F) day | 22.2°C (72°F) night |
| Zone 2 | 22.2 C (72 F) day | 12.8°C (55°F) night |

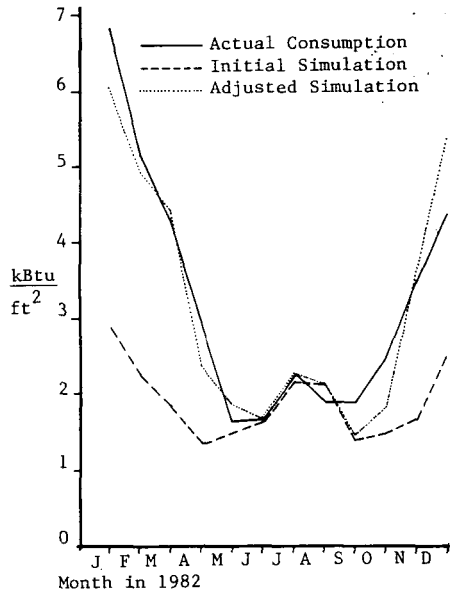



Fig. 2. Comparison of Simulated to Measured Performance: Month-by-Month Total Energy Use.

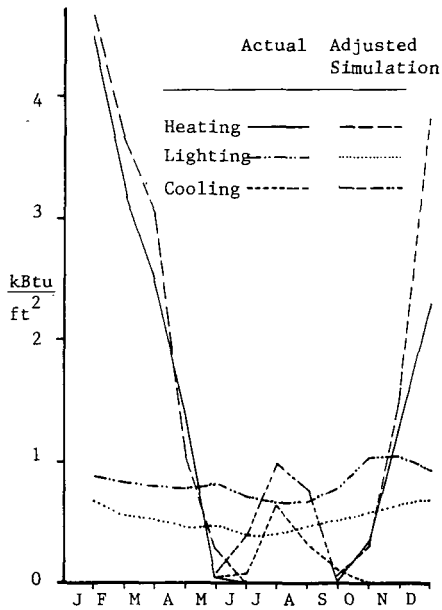



Fig. 4. Comparison of Simulated to Measured Performance: Month-by Month Heating, Cooling, and Lighting Energy Use.

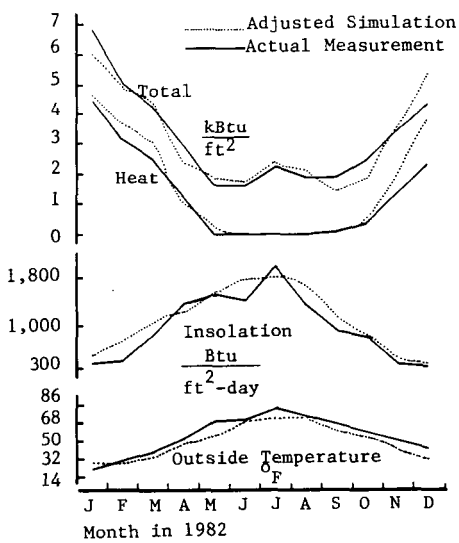



Fig. 3. Overall Building Performance: Month-by-Month Energy Use

## 5. CONCLUSIONS

Even though the VIC consumes 69% less energy than the maximum allowable by the applicable Energy Code, our present experience suggests that this saving could be increased to 79% if the building were operated according to the initial load parameters and the attitudes towards energy conservation by the occupant could be improved. On the other hand, the VIC experience once again proves that it is people who consume energy, not buildings, and regardless of what standards are set or enforced, people will strive to be comfortable according to their own needs and differences.

Nevertheless, RPI's Visitors Information Center, as a passive solar building, is without a doubt a success. The occupants are comfortable. They have the means to determine their own comfort, and the building uses only 31% of the energy a non-passive solar building would consume, given the same function and climate.

TABLE 2. SIMULATED AND ACTUAL YEARLY ENERGY

| Purpose | Design Simulation | Adjusted Simulation | Actual Energy Use |
|---|---|---|---|
| | Energy Use Total (MMBtu/yr) | | |
| Heating | 20.1 | 96.7 | 80.6 |
| Cooling | 11.2 | 11.7 | 6.1 |
| Lighting | 33.0 | 33.1 | 51.8 |
| HVAC | 35.5 | 35.5 | 34.6 |
| Other | 18.0 | 20.0 | 28.0 |
| Total | 117.8 | 197.0 | 201.1 |
| Maximum Allowable according to State Energy Code = 561.0 | | | |
| | Energy Use Per Unit Gross Floor Area (kBtu/ft$^2$-yr) | | |
| Heating | 3.86 | 18.6 | 15.5 |
| Cooling | 2.16 | 2.25 | 1.16 |
| Lighting | 6.35 | 6.35 | 9.96 |
| HVAC | 6.82 | 6.82 | 6.66 |
| Other | 3.44 | 3.84 | 5.39 |
| Total | 22.63 | 37.86 | 38.67 |
| Maximum Allowable according to State Energy Code = 108 | | | |

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# PASSIVE SOLAR HOMES: INCENTIVES FOR OWNERSHIP AND SATISFACTION ASSOCIATED WITH FUNCTIONAL CHARACTERISTICS

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## ABSTRACT

Twenty-eight owners of passive solar homes (PSH) in various areas in Virginia responded to a self-administered questionnaire. The data for this project were gathered during the spring of the 1981-82 academic year.

Generally, owners were highly educated, fairly affluent individuals with small families. These persons were characterized as ecology minded, do-it-yourselfers.

Incentives for residing in a PSH included saving expenditures on fuel, positive feelings about the design characteristics, conservation of natural resources, and the aspects of natural sunlight and warmth. Most respondents reported having little or no trouble locating well-documented information about solar adaptation to meet specific needs.

An overwhelming majority of the participants were satisfied with the general interior, exterior, and overall features of their PSH. These levels of satisfaction may be due in part to the degree of involvement in home functioning that the owners reported.

Subjects responded to open-end questions and shared many and varied experiences about their PSH. These are described to a greater extent in the text.

## 1. INTRODUCTION

Since the emergence of the first modern fuel crisis in the early 1970s research in the field of solar energy has exploded. Innumerable projects utilizing specialists from many academic disciplines have emerged. However, until recently, many scientists perceived the use of solar energy within a very narrow context focusing on the thermal properties and responses to the system. During the past few years, there has been a vigorous renewal of interest among social scientists in the relationship among human behavior, attitudes and the physical environment. As behavioral scientists and designers we conducted this research in order to determine (1) some of the characteristics of owners of PSH, (2) sources of information on solar energy utilization owners used when building or retrofitting their homes, (3) general satisfaction with the home, and (4) experiences of owners with their homes.

## 2. METHODOLOGY

### 2.1 Sample Selection

Various chapters of the Virginia Solar Energy Society were contacted in order to determine the availability of owners of PSH especially in the Richmond, Roanoke, Tidewater, and Lexington areas. A total of 63 individuals expressed interest in participating in the study. However, in the final analysis, 28 of that group or 44% responded with usable data.

### 2.2 Instrument Development

Working with associates having special expertise in environmental design, psychology and interior design an opinionnaire appropriate for self-administration was devised and tested. This effort was an attempt to combine interests from several areas and meld them into a single instrument. Therefore the subjects would not consider themselves over-researched. The opinionnaire was designed with several subsections to assess feelings about or rationale for living in a PSH. Another section dealt with satisfaction with various aspects of the home. A third section focused on solar system functioning. A brief background data sheet was also included. On the final questionnaire a cover letter was added which denoted the purpose of the research, solicited the cooperation of the respondent, and advised subjects that all data gathered would be used only for statistical purposes.

## 2.3 Data Collection Procedures

At a regularly scheduled meeting of several local chapters of the Virginia Solar Energy Society the researcher was present to provide some general information to potential respondents. Each was given a small booklet explaining participation in the Virginia Passive Solar Study. This literature contained graphics that were designed to motivate the homeowner to want to contribute to this research effort. Questionnaires were distributed at these meetings along with a self-addressed, postage paid envelope in which to return the opinionnaire. Owners of PSH near the researcher's base were contacted through local sources. Instruments and corresponding return envelopes were hand delivered to these potential subjects. Since it appeared that the sample would be fairly limited every effort was made to guarantee a high return rate. After a two-week waiting period the subjects were contacted again by telephone to remind them of their prior commitment. Follow-up correspondence was sent to non respondents urging their participation. By the end of June 1982 all usable questionnaires that had been returned were included in the analyses.

## 2.4 Data Analyses

Since there were responses from only 28 individuals, advice on how to analyze the data was sought from a statistical consultant. He suggested that it was inappropriate to compute statistical tests to determine relationships among variables. The most realistic alternative was to use frequency and percentage distributions to describe all of the data.

# 3. FINDINGS AND DISCUSSION

## 3.1 Characteristics of Respondents

Both males and females completed the opinionnaires although the relative proportions are unknown. Most households consisted of a couple and one child (Table 1); however, two single males were also owners. These families in general were fairly young and (67%) usually less than 40 years of age. Overall they were quite affluent with 25% having incomes in excess of $50,000 per year. It is not known whether these figures represent one or two earner units. These descriptors characterize the sample as innovators as defined by Rogers (1).

TABLE 1. Respondents

| Characteristics | No. | % |
|---|---|---|
| Sex of Adults in Household | | |
| Male | 27 | 52 |
| Female | 25 | 48 |
| Total | 52 | 100 |
| Ages of Adults | | |
| 20-29 | 14 | 27 |
| 30-39 | 21 | 40 |
| 40-49 | 12 | 23 |
| 50-59 | 2 | 4 |
| 60 and above | 3 | 6 |
| Total | 52 | 100 |
| Family Income | | |
| $20,000-34,999 | 9 | 32 |
| $35,000-49,999 | 9 | 32 |
| $50,000-74,999 | 5 | 18 |
| $75,000 and above | 2 | 7 |
| No response | 3 | 11 |
| Total | 28 | 100 |

## 3.2 Incentives for ownership of PSH

Respondents were asked to check reasons for the selection of their PSH and to note the sources of information that were used to aid in the decision. The majority (96%) indicated that saving money on fuel was a major factor (Table 2). The feelings of sunlight and warmth, liking the design

TABLE 2. Reasons for Choosing Passive Solar Homes

| Reasons | No. | % |
|---|---|---|
| Save money on fuel | 27 | 96 |
| Feeling of sun/warmth | 23 | 82 |
| Like the design | 22 | 79 |
| Save resources | 21 | 75 |
| Alternative energy usage | 12 | 43 |
| Best house available | 4 | 14 |
| Other | 7 | 25 |

and saving other precious natural resources were second, third, and fourth respectively. These findings suggest that owners of PSH

were interested in environmental and conservation issues, such as easing the energy shortage and preserving the natural environment.

Means of acquiring PSH were of interest. Slightly less than half (46%) had their homes custom built to specification, while 21% hired an architect to design their homes. Still others (33%) bought existing solar homes or adapted traditional residences to maximize the use of solar energy.

### 3.3 Information on Solar Energy Utilization

Twenty-four (86%) families became informed about solar energy utilization through personal research and articles in magazines and newspapers. Others (64%) consulted periodicals, extension specialists and practicing architects (64%), and books obtained from local libraries (29%) concerning solar adaptations. Other studies have shown that information on solar equipment was most often found through solar equipment dealers, magazine articles, friends, and neighbors.

One-half (50%) reported having no trouble locating information about solar adaptations to meet specific needs. Some trouble was encountered by 43% and a few noted difficulty in procuring literature. Perhaps since some time has elapsed, information relevant to solar adaptations has become more readily available to the public.

### 3.4 Satisfaction with Solar Features

An assessment of the performance of specific solar features incorporated into these homes was deemed important. Subjects rated five solar features on a three-point scale designated as "high", "ok", and "low". The "high" and "ok" evaluations were combined and equated with the term satisfactory. The following is the listing of solar features and the percentage of owners who were relatively satisfied: direct gain system, 82%; indirect gain, 43%; isolate gain, 32%; hybrid systems, 32%, and a combination system, 22%.

### 3.5 Satisfaction with Home

General exterior, interior, and overall features of the PSH were rated on a six point continuum utilizing categories from very dissatisfied through very satisfied. The vast majority (92%) were satisfied or very satisfied with both the exterior and the interior (97%). A similar trend was noted for overall satisfaction with 97% being satisfied or very satisfied. Using the rating scale no real dissatisfaction was indicated by the owners.

Following the rating scale on the questionnaire, blank space was provided to give respondents an opportunity to make specific comments relative to satisfaction with their homes. Although some of these notes were positive, more negative ones than positive ones were found when all responses were examined.

Both positive and negative comments were often given by the same owner. One individual noted that with a 600 square foot solar aperture that his home had good direct gain on the middle and upper levels. Another was very satisfied with the "solar look" but commented that the neighbors said it was "too solar" for the subdivision; the sheetrock job was average, and plumbers ran two hot water lines under the slab without insulation. He also mentioned that the passive design works very well. Another commented that he liked the architect and the design but disliked the builder -- especially his attitude. The respondent said that some features were not constructed properly and that the builder refused to do anything until he received payment. This particular builder also was accused of "cutting corners."

Another individual mentioned that he had not used the solar heat in winter yet but the cool mode was working well to date, and no problems were encountered. The solarium maintained its preset temperature of 76 degrees on 90 plus degree days. Little or no condensation problems were evident, and the humidity in the solar portion had been reduced in relation to outside air.

One of the direct gain systems was less than satisfactory for another subject. He suggested that the insulated shades were not moving optimally in winter with the best sun exposure. A considerable temperature difference between first and second floors existed as well as from front (North) to back (South) of the townhouse. Commenting on the greenhouse, one owner noted that it was too hot in the summer and too cold in the winter. Another was genuinely upset with his indirect gain system since an exterior thermal pane glass had cracked either from the heat fluctuation or from a flaw in the manufacturing process.

Frustration was also expressed by another owner who characterized her PSH as not being as efficient as expected. Some parts of the house were extremely cold in the winter and too hot in the summer. Lack of specific answers to problems associated with the solar system was also anxiety producing. Yet another suggested that cooling in summer continued to be a problem even with earth tubes and a solar chimney.

A variety of other complaints emerged. One

noted that the glass in the roof had been very difficult to deal with because of water leaks. Sometimes the homes were stuffy. One individual suggested that high outside vents were needed to evacuate air in the sunspace.

### 3.6 Owners Share Their Experiences

At the end of the questionnaire respondents had an opportunity to share their experiences as owners of PSH. In this section the reactions tended to be very positive. Reflected were feelings of energy independence, satisfaction with natural lighting, appreciation of aesthetic qualities, and delight. Specific information is detailed below.

On the plus side, one individual said that "he felt like a pioneer opening the way." Another expressed his exhilaration in designing and building the house. He said "the heat from the direct gain felt great... we have a good feeling about ourselves since we are conserving energy and not polluting the atmosphere." Also enjoyed was the openness and brightness; spirits were lifted. Another suggested that "the economy was great; the life style keeps us young, and our friends are envious."

Reflections on past experiences were also enlightening. One couple stated "they were more convinced than ever of the wisdom of their choices and the need for the country to follow suit." They indicated they would like to try again to improve the present design and said that they would always try to build or retrofit in the future. Another person noted that "if he had to do it over again he would retrofit rather than build from scratch."

Delight was expressed that a passive system is cheaper and more efficient than an active system. Further stated was the opinion "that passive design is within the reach of every builder, that solar beats the power company rates, and that solar is delightful." The owners further commented "that they promoted the use of solar energy to the greatest extent possible."

## 4. SUMMARY

Twenty-eight family members completed the opinionnaire with useful data. They expressed no difficulty in responding to both closed and open-ended questions. In general it was apparent that they were very enthusiastic about their choice of dwelling.

The individuals participating in this study were well-educated, quite affluent, young, had small families, and could be characterized as early adopters of alternative housing. From the reasons given for having chosen a PSH it might be concluded that these owners were highly concerned about environmental and energy conservation issues, as well as preserving the natural environment.

Responses to all rating scales indicated that the subjects felt very positively about the interior, exterior, and general overall features of their PSH. Only in the open-ended portions of the instrument were their dissatisfactions expressed. These tended to center on some construction or design detail, rather than the overall features. Like many individuals they offered comments so that others in similar situations could benefit from their learning experience.

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# BEHAVIORAL IMPLICATIONS OF LIVING WITH PASSIVE SOLAR HOMES

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## ABSTRACT

Case studies of fourteen households in Michigan and Tennessee are examined for behavioral adjustments to operation and maintenance of passive solar and wood burning homes, as well as space/time displacement of household activities. Possible loss of privacy and increased conflict through use of an "open plan" design are investigated.

## 1. INTRODUCTION

Households which choose to live in passive solar homes take more risks and make more sacrifices than households which choose more conventional housing. It is not only the fact that there are risks and sacrifices, but the uncertainty as to their exact nature which deters more households from trying this relatively new technology (1) (2) (3). Until passive solar becomes more widely adopted these uncertainties will persist. In the interest of clarifying some of these uncertainties, this paper describes the findings from 14 case studies of passive solar and woodburning households from Michigan and Tennessee during 1981(4).

Originally undertaken to develop user-oriented design guidelines, this research also examined the behavioral implications of living with passive solar. These behaviors included 1) the effect of adding new tasks to the daily household routine, 2) space/time displacement of activities to achieve thermal comfort, and 3) the potential for activity conflict in an "open plan" design.

## 2. CHANGES TO HOUSEHOLD MANAGEMENT ROUTINE AND NEW FAMILY DECISION-MAKING PATTERNS

### 2.1 Passive Solar Household Routine

Most households examined in this study were found to follow the routine summarized in Figure 1. Upon rising in the morning, the first task is to assess the weather: will the sun shine or cloud over. In addition to consulting weather reports, personal assessments are made by checking the thermometer,

PASSIVE SOLAR TASKS AND ROUTINES

Initial Assessment and Decisions
1. Assess weather conditions
2. Decide mode of operations
   - A. Solar
   - B. Auxiliary

Solar Mode
1. Raise shades/insulation on collectors
2. Open vents for interior heat loop (may be automatic as there is a delay to heating after opening the blinds).
3. If too much heat, dump hot air or cover shades.
4. Evening solar shut down (if solar was chosen).
   - A. From 4 p.m. on, close shades, etc.
   - B. Turn up aux. heating as needed.
5. Retire for night, shut down.

Auxiliary Mode
1. Leave insulation on collectors in place.
2. Decide which auxiliary system to use.
   - A. Auto auxiliary -- set thermostat.
   - B. Wood stove - stoke fire
     - adjust damper, etc.
3. Reassess weather conditions and decide whether to continue as is or readjust.

Figure 1. Task and Routines for Operating a Passive Solar Home

studying cloud patterns, and watching for signs in nature and animal behavior. Early morning outdoor chores facilitate this assessment for many.

While this assessment process is going on, the next task is "to take the chill off the house." Two methods are generally avail-

able, a wood stove and a conventional auxiliary heating system. Conventional auxiliary heating is used if the sun is already out and only a quick warm-up is needed. The wood stove is used if it is clouded over and long term heating is required. If someone forgets to bring in wood the night before (a frequent occurence), however, the auxiliary heating is used.

As the time approaches for household adults to depart for the day, a final judgment has to be made about projected weather conditions. If a solar choice is made, window shades or blankets are opened, as are interior doors and windows necessary for circulation of heated air. (Automated venting systems eliminate the need for this latter task.) If a non-solar choice is made, window shades are left closed and the thermostat adjusted for the conventional heating system, or the wood stove is stoked, or both (that is, the stove is stoked to last only 4-6 hours with the auxiliary heating thermostat set to turn on when the temperature drops).

For most families the morning decision of which heating system to use becomes a fixed choice which can not be altered until their return in the afternoon or evening. This was a significant problem in our sample because most households were dual career leaving no one at home to make any further adjustments. These families reported feelings of intense frustration when the weather unexpectedly changed and they were helpless to correct the situation till nightfall.

When family members return in the late afternoon, their first task is to close window shades/quilts as most of the sun's insolation value has dissipated by this time of the day. The auxiliary heating system is brought into use as the home begins to cool or to take the chill off if it has been a cold non-solar day. Households which have a choice of auxiliary systems are more likely to choose woodburning in the evening than in the morning. When the adults finally retire for the night, the thermostat is usually set back on the auxiliary system, and the stove if used is given its final stoking for the night and dampered down.

Climate appears to be a mediating factor in the complexity of tasks and decisions required in operating a passive solar home. In Tennessee, where the winters are much milder, there appears to be a consensus that movable window insulation is not necessary. Without window tretments to adjust, the urgency of critically assessing the weather in the morning and reaching a correct solar decision becomes unnecessary. While nonetheless concerned about the weather the Tennessee passive solar household does not have to fret later in the day about an incorrect earlier judgment.

It should be apparent from this discussion of tasks and routines in a passive solar home that more decisions are required than in a conventionally heated home. A conventionally heated household makes one or two decisions while at home about the thermostat setting, with occasional attention to opening or closing window blinds. Temperature setting decisions are divorced from exterior weather conditions, and the heating system is forgotten upon leaving the house. In contrast, a household that combines passive solar with one or two auxiliary heating systems (i.e., wood and/or gas) lives in constant awareness of their heating systems and its relationship to external climatic conditions. Decisions based on weather assessments made in the morning are closely followed throughout the day while away from home.

The greater complexity of a passive solar routine sometimes leads to ambiguity in decision-making. This is especially apparent in solar homes with two back-up heating systems, wood-burning and conventional (electric, gas, oil). For households which use wood-burning as the only source of auxiliary heat, a dedicated pattern of use is found. However, when a second back-up system exists, households become ambivalent towards their use of wood. A chicken and egg problem evolves whereby the convenience of an automated central heating system undermines the need to keep up with chopping wood and bringing it in the night before. Lack of chopped wood next to the stove is an easy excuse for not burning wood and falling back on the alternate system in the morning. Also, wood is more often burned for aesthetic reasons in solar homes (doors left open on stove for fire viewing). These wood users are less conscientious than full-time wood users and therefore realize less efficient use of their stoves. Also, since most all the households studied are living in newly constructed structures, they have no measure of previous heating bills to provide an incentive for being more efficient in woodburning, whereas woodburning retrofits from conventional heating systems tend to have a single-minded fixation on cutting their prior fuel bills, proudly measuring present progress against past behavior. Presently, passive solar home owners are more likely to be operating out of a faith that they are saving costs than out of factual knowledge.

Another difference between conventional and solar routines is the constantly on-going routine. Although most daily tasks involved in operating a combination heating system are of short duration, they are not easily consolidated. Optimal solar and wood system operation requires monitoring at invervals. Consolidating all tasks in convenient blocks

of time is not appropriate or possible.

## 2.2 Controlling Heat Level in a Passive

Perhaps one of the more challenging routines to master in a passive solar home is adjusting for heat swings. They can arise from two sources: 1) normal wood stove operation and 2) night time cool down of the thermal heat mass.

Getting the stove to burn at just the right temperature without overheating the house is an art each household must master when first adjusting to its wood-burning system. Factors affecting this objective are properly judging the weather conditions outside, using the right type of wood, and staying ahead of the stove. The amount and type of wood to put in the stove is determined from weather assessments. For very cold days hard woods such as maple or hickory are used; on warmer days, softer woods.

Keeping ahead of the stove means judging in advance how hot to burn the stove (wood type and how far to open the damper). As there is a substantial heat lag between burn adjustment and current heat output, a person can not determine when to make adjustments merely by sensing changes in room air temperature. Even if the stove is throttled back at this point it will continue to get hotter for 10-15 minutes before finally cooling down. Therefore, one must stay ahead of the stove. This task is made much easier if one has a flue temperature gauge and a bi-metallic thermostat damper control. The flue temperature tells you when the fire is beginning to cool down before the stove does. The damper control slows down the fire as the firebox gets hotter. Most households state that they developed a "feel" for properly burning their stove based on experience.

The most difficult time for controlling heat swings is the between-seasons of spring and fall. Greater solar gain and broader external temperature swings can lead to easy overheating during the day. If softer woods are being used, greater caution must be taken to prevent creosote build-up; daily hot burns become a necessity. Hot burns result in space overheating. Controlling heat swings under these conditions is difficult.

Heat swings from the thermal mass take the form of an "early morning chill." This results from the inevitable drop in temperature of the mass as it gives up its heat during the night. Ideally a passive solar home, if designed properly, will keep this temperature range within 5 to 10 degrees of some acceptable norm, say 68 degrees Fahrenheit. But this is under average conditions. In the depths of winter in northern climates during extended periods of overcast weather the range would be more severe if it weren't for the auxiliary or back-up heating system. Termperatures are still chilly in the morning (55 to 60 degrees) as thermostat set back is used by most families to conserve energy. If wood stoves are used as a back up they can augment "morning chill" as the overnight burn has usually been reduced to coals by morning.

## 2.3 User Experience: Likes and Dislikes

Given the significant differences between operating a conventional home and a passive home, it is of interest to know whether the households studied feel that a burden is being placed on them. Their perspectives are no doubt biased because of the large investments in time and money they have put into their homes as well as their dedication to make passive solar work. Nonetheless these households admit to both dislikes as well as likes.

The most frequently reported dislikes concern the auxiliary heating system, particularly wood. The mess caused by carrying and burning wood, removing ashes, cleaning the stove, and cleaning the chimney flue is a common complaint. Another includes the hard labor associated with cutting and hauling wood. In several instances, the houses are not designed for convenient access between stove and wood storage. Wood has to be carried through several intervening activity areas requiring expenditure of extra human energy leaving behind a trail of debris which requires periodic cleaning.

Dislikes about the solar system itself are infrequent and those reported have no consistent pattern. One problem, already cited, concerns the frustration created by seeing a sunny day turn overcast with no one left at home to adjust the blinds. Some complaints are expressed about the inconvenience of waking to a cold house in the morning and having to wait for the auxiliary system, especially a wood stove, to heat up the house. For households with a conventional auxiliary heating system, this inconvenience would be no more difficult than a conventional home working with a thermostat night set back system.

In general, the passive solar households in this study do not perceive any of these problems to be very bothersome, certainly not enough to make them want to forsake their commitment to passive solar. Likes are far more frequently volunteered than dislikes, many reporting unexpected benefits and pleasures of their passive solar systems. The most commonly mentioned like is the physical and psychological comfort of both solar and wood heat. The radiant heat produced by both is found to be especially soothing. Almost every household has a chair or two near the stove or in a sunny

window for individuals to sit in and soak up the heat. An additional advantage mentioned is the quiet operation as compared to a forced-air heating system. Another is lowering the thermostat and still being able to maintain ample thermal comfort. These houses tend to be more comfortable than conventional homes even at lower temperatures because of the extra wall and ceiling insulation as well as greater weather-tightness.

Those houses incorporating a greenhouse into their systems are pleased by the addition of a new intermediate living zone between inside and outside. Nature is brought into the home through gardening activities which can be practiced nearly year round. (The large amounts of external glass in both greenhouses and direct gain homes also provides residents with an increased awareness of nature as does having constantly to be aware of the weather.) The greenhouse is looked upon as a season extender in northern climates, allowing not only gardening but sunning in fall and spring when most other households have to retreat from the cold to give up both. For those households seeking wholistic life styles, food production represents one more accomplishment towards independence and responsible ecological management. For some, entering the greenhouse on a sunny day and "experiencing" the sun is like a ritual found among some wood--burners of gazing into the fire of a newly kindled stove and gradually experiencing its surge of warmth.

## 3. SPACE/TIME ACTIVITY DISPLACEMENTS

Beyond having an impact on daily and weekly chores it was also anticipated that other behaviors, not directly associated with maintaining the heating system, would be affected. Two principles were hypothesized to be at work. First, uneven space heating between the central living areas (where the stove, collector, and heat mass are located) and the peripheral buffer areas (bedrooms where temperatures were expected to be cool) was expected to result in a centripedal effect of drawing family members and their activities into the central living area. Second, as a consequence of this concentration of activity, conflicts would result. Use of the open plan concept to facilitate even heat convection was expected to compound this problem as few if any walls would exist to separate previously divided spaces (living room from dining room, dining room from kitchen) and the activities which occur in them.

### 3.1 Thermal Comfort and Activity Patterns

The first behavioral assumption was found to be true; family members are attracted to the central living spaces to take advantage of its warmth, whether to sit in the sun, or more commonly, to soak up heat from the wood stove. Warmth alone is not the sole reason as sunning and watching the fire are pleasurable activities in and of themselves.

On the other hand, it is not necessarily the case that family members are leaving uncomfortably cool buffer zone areas to be in the family living area. If the home has an upstairs or loft, these spaces are found to be almost as comfortably heated by the downstairs stove as the downstairs itself, providing there is an adequate convection path (a central stair well will do). Respondents also reported that first floor bedrooms and studies are also acceptably comfortable. It is suspected that the higher level of insulation and weather tightness in these homes accounts for this latter finding.

### 3.2 Activity Conflict and Displacement in Open Plans

The assumption that conflict would result among activities attracted to the central living areas of the home is not borne out. While household members can identify activities which would result in conflict if done simultaneously, few report problems in finding a time or place to do them. The list of activities which can be pursued simultaneously without conflict in the same space is surprisingly long. Individual family members are found reading the newspaper or a magazine, sewing, playing board games, sitting by the stove, or watching TV all at the same time in the same space. The primary activities which can not be accommodated in this setting are intense reading or intense bookwork (homework, budget, briefcase material). If it is necessary to have quiet in the central living area to pursue such an activity, other family members relocate their activities. TV watching is a frequently displaced activity, most homes having a second TV in someone bedroom. Or it is just as likely that the intent worker will retreat to another place in the home. Several homes have studies or family rooms which further reduce the possibility of conflict.

This dispersion is not a hardship, as originally thought. Buffer areas, such as bedrooms (a primary zone of retreat), are not as cool as expected; in fact, they seem to be quite comfortable. A more significant finding is the apparent misconception that communal activities will only occur in central living areas. Retreat to bedrooms is not a second best solution, but rather a preferred location for many communal activities, especially for teenager visiting and TV watching. The places where so-called communal activities occur is far more diverse than conventional wisdom would suggest; conversely, so-called private areas

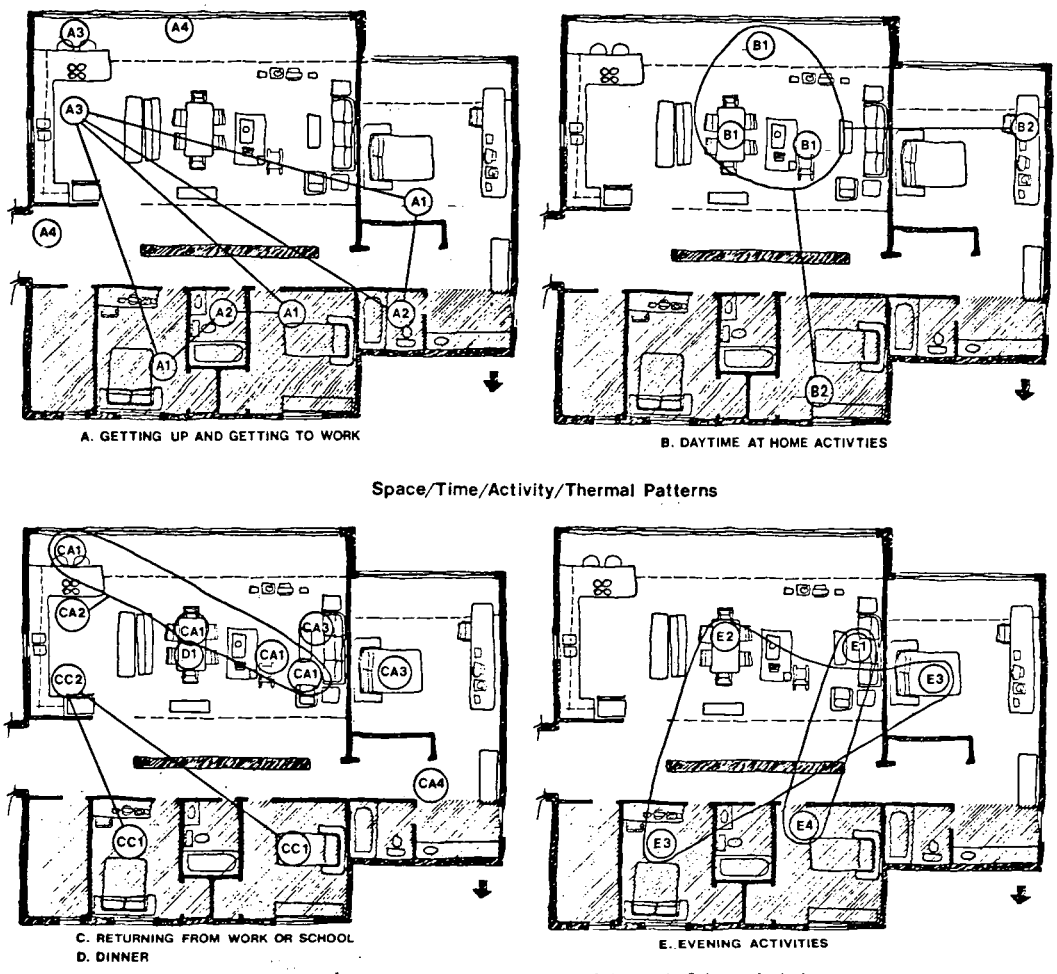



Fig. 2. Space/time distribution of household activities

such as the bedroom are far less private than originally presumed. The discovery of this same behavior among non-solar households in our sample suggests this pattern is not unique to passive solar homes.

When time is introduced as a factor in the analysis of activity patterns the potential for conflict is reduced even further. Not all activities are pursued at once and not all family members are home at the same time. Thus individuals can self-schedule activities to minimize conflict. For example, adults left at home during the day can do reading or letter writing in the living room with no fear of intrusion on their privacy. Or children home from school in mid-day can spread their homework out on the dining room table without concern that the TV might interfere. It is the finding of this research that people can and do distribute their activities in time and space in a manner which minimizes the potential for conflict despite the open plan design.

This space/time distribution of household activities is represented graphically in Figure 2. In the morning, activities tend to concentrate in the bedroom/bath area (A1, A2 - dressing and personal hygiene) and in the kitchen/dining area (A3 - meal preparation and eating). The principal thermal comfort issue at this time is keeping warm while the "chill" is being taken off the house by the auxiliary heating system. Although the bathroom and kitchen eventually warm up from self-generation of heat, the first users of these spaces find them rather brisk. By mid-morning most adults and children have left the home. In those cases in which an adult remains, time spent in communal area (B1) vs. time spent in outlier

sections of the home (B2) seems evenly divided. Activities tend to be desk work or shop projects (the person left at home was frequently self-employed). Lunch usually brings individuals to the kitchen/dining area, with return to the previous pattern for the afternoon. If it is a solar day, occasional and sometimes permanent visits are made to the solar space to soak up sunshine (B1). Of those household members who leave for the day, the first to return home are children; this occurs mid-afternoon. Most of the time they gravitate to their bedrooms (CC1 - to study). Pre-dinner adult activities consist of taking naps (CA3), doing chores outside, reading newspapers (CA1), and preparing meals (CA2). Adults tend to occupy the communal area (dining/kitchen) catching up on the events of the day. Children might still be in their bedrooms or some other part of the home. At dinner, all congregate in the dining area (D1). After dinner, the communal areas see almost constant use till bedtime.

Activities are not strictly communal, however, as previously indicated. Non-conflicting activities such as reading or working on a project around the dining table (2, E1) allow several family members to be in the room at a time, usually adults. TV watching can even be occuring. Individuals desiring privacy or just a different setting for their activity work in their bedrooms (E3, E4 - or study or study/guest room). Children seem to gravitate to their rooms regardless of whether it is to watch TV, do homework, or visit with friends.

## 4. CONCLUSIONS

The most difficult problem faced by households adjusting to living with passive solar is their inability to make system adjustments once leaving home for work. This problem is confined to dual-career households in northern climates. However, substitution of automatic devices in place of the now predominatly manual systems would probably be appreciated by all. Wood stove maintenance and operation is another source of concern. Cleaning up is a constant chore, and learning how to prevent heat swings is an art only acquired with experience. Learning to live with temperature variations is a basic condition of passive solar homes, not only because of wood heat but also because of the inherent heat swing of the thermal mass. Operating a passive solar system involves many choices over a conventional heating system and can result in ambiguity and inefficiency in overall system operation. Space/time displacement of household activities is found to occur in most passive solar homes with household activities concentrating in the central living areas. Outlier areas of the home however are not necessarily cold so that individuals seeking privacy can do so without sacrificing comfort. Most households are able to adjust to the open plan of their homes without creating conflict in household routine.

## 5. ACKNOWLEDGEMENTS

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# SIZE PREFERENCES AND USER REACTIONS TO DIRECT GAIN AND INDIRECT GAIN CONFIGURATIONS

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## ABSTRACT

A 1/12 scale model was constructed to simulate a residential group living space in order to study user preferences of window size or direct gain/indirect gain configurations. Twenty human subjects were asked their reactions to four configurations of the south wall: direct gain, indirect gain, combination, and partial height. The most preferred configuration was the combination or 44% of wall covered by window. The indirect gain received a negative response. Preferences were strongly related to a user's desire for sunlight and the need for privacy.

## 1. INTRODUCTION

Passive solar design involves a manipulation of windows towards the south side of the house. In direct gain types especially, this results in a large amount of sunlight entering the living space. Although much research has been done on optimizing the thermal comfort and energy savings of this design strategy, little work has been done on the psychological impact of all these south-facing windows on the people who live in the house. Most of the research on people's reactions to living in a solar home has concentrated on the homeowner's satisfaction with the home (1)(2)(3) or the user's maintenance of the passive solar system (4). Little research has been done on people's responses to window configurations or people's preferences of passive solar design types. Thus, this study focuses on user preferences and psychological reactions to direct gain and indirect gain systems and the resultant window size and placement these systems effect in residential group living spaces. This study should be helpful to designers who wish to design passive solar housing which is compatible with user needs.

## 2. REVIEW OF RELATED RESEARCH

The majority of the studies regarding the psychological effects of windows are limited to commercial environments, and many of these were done in Europe. In a study of preferred window size in offices, Ne'eman and Hopkinson found that the mean acceptable size was 25% of the wall (8 feet wide by 7 feet high) and that size was dependent upon the type of view (5). Keighley's scale model studies on the window size in offices reveals that users prefer a wide window, 25% of the wall and positioned in the center of the wall (6). In my own research, I found that preferred window size is dependent upon the importance of the function of the window to a user as well as the type of room in residential group living spaces. Also, a correlation exists between a subject's ranking of view as the primary window function and preferences for large window size (7)(8).

The desire for sunlight in the home is documented in a study by Bitter and van Ierland who found that 85-90% of housewives in Holland strongly preferred sunlight, particularly in the living room (9). Collins suggests that the desire for sunlight is dependent upon the latitude where users are located and thus is "strongest where the duration of sunshine is the most limited" (10). Brierly disagrees with the importance of sunlight claiming that provision for a view is a more important function of the window for residents (11).

People's preferences in passive solar design types is limited to one study. Davis conducted a questionnaire survey by mail and found that isolated gain or greenhouse was the preferred type while indirect gain was the least preferred. Later, when she did a scale model study and received user reactions, she found that the indirect gain (waterwall) was better accepted (12).

## 3. METHOD

After considering several types of methodology, I chose to utilize the 1/12 scale model to study user reactions. According to DeLong who uses scale models to conduct user evaluations before buildings are constructed, people can most easily relate to the 1/12 or 1"=1' scale model (13). They are able, through scaled figures, to project themselves into the space and give their reactions to the environment. Lau also discusses the validity of scale models in behavioral research: ". . . it may be hypothesized that miniaturization does have an enhancement effect but it is not manifested when relatively simple assessments are called for. In such instances, observers appear to be able to 'funnel' their critical ability to the task at hand" (14).

A 1/12 scale model, then, was constructed to simulate a residential group living space (375 feet, 15 feet by 25 feet) with provisions for dining, conversational grouping, entertainment center, and a woodburning unit. The south wall was composed of eight 32" by 78" openings simulating windows constructed of standard size thermal replacement glass. Modular mass walls were then constructed and placed in front of the glazing to simulate the various direct gain and indirect gain configurations. Reflectances were 85% for the walls and ceilings and 15% for the floor. A flat ceiling was used with a two-foot roof overhang which is commonly specified in the Knoxville, Tennessee, area (3590 heating degree days) where this experiment was located.

### 3.1 Procedure

The scale model was set up in a darkened room and placed it in a south-facing window with orientation due south. This was done during the winter months from 12:00 to 1:30 p.m. in order to allow an ample amount of sunlight on the interior of the model. I set up the direct gain and indirect gain configurations in the following order (See Figures 1 through 4):

Direct Gain: All windows uncovered (or 88% of the wall covered by window openings).



Fig. 1. Direct Gain

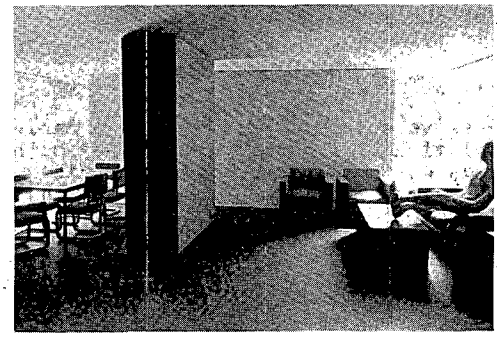


Fig. 2. Indirect Gain

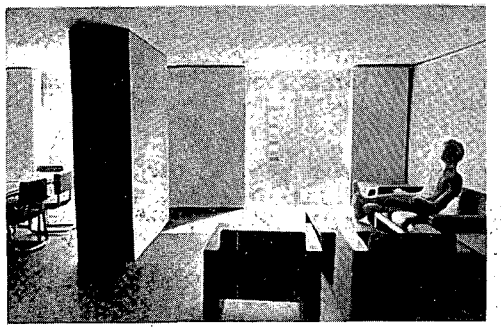


Fig. 3. Combination

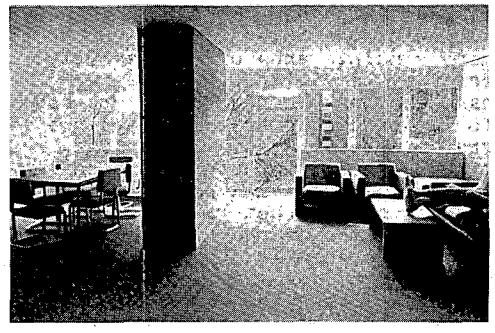


Fig. 4. Partial Height

Indirect Gain: 2 windows uncovered; 6 windows occluded by full height mass walls (22% of wall covered by window).

Combination: 2 windows uncovered in dining and 2 windows uncovered in living area; 4 windows occluded by full height mass walls (44% of wall covered by window).

Partial Height: Upper part of windows uncovered; lower part occluded by two 36" height mass walls (65% of wall covered by window).

The subjects were asked to arrange the furniture in the living area in response to each configuration. I then asked the subjects several questions regarding their reactions: "What is your impression of the space? Which wall do you prefer?" I probed for reasons for their most preferred configuration as well as how usage of the room might affect their preference. The subjects were asked also to arrive at their most preferred combination of direct gain and indirect gain or window area by manipulating the modular mass walls themselves.

### 3.2 Characteristics of the Sample

The subjects had no prior background in design or passive solar. Other characteristics include age (range 20 to 65); sex (12 female and 8 male); and occupation (5 clerical, 6 professional/managerial, 6 graduate student, 3 housewife).

## 4. RESULTS

The results are graphically depicted in Figure 5. As the bar chart indicates, the combination of direct gain and indirect gain or 44% of wall covered by window area was the most preferred configuration. Although the ranking of the configurations produced interesting results, further probing of the subjects revealed some consistent patterns of why each subject chose his or her preferred configuration:

Direct Gain (88% of wall covered by window): The person who prefers this configuration has a very strong preference for sunlight: "I like this because of all the sunlight." "It is nice to sit in all that sun." Several subjects, however, qualified this as their favorite only if the house were located in the country where neighbors could not see into the living space. One still preferred the direct gain in the suburbs or city even though she wanted privacy. Her simple solution to this apparent dilemma was to place large indoor trees and houseplants in front of the glazing for privacy. Preference for this configuration, thus, may also be correlated with a strong desire for houseplants as several who preferred this configuration indicated it was because they could raise more plants. Only one subject who preferred the direct gain was completely unconcerned about privacy, not caring whether the neighbors or passersby could see on the inside of the house.

Not too surprising, there were some strong negative reponses by those who did not rank this as their number one: "Too much sun!" "I could not read in all that sunlight." One subject said she might like this configuration if there was a spectacular view. But when the sunlight poured into the room at midday, she would pull the draperies even though she realized this would interfere with the solar collection. In arranging furniture, almost all of the subjects hesitated in placing furniture in front of the glazing so some objected to the direct gain because of this restriction of furniture placement.

Indirect Gain (22% of wall covered by window): This was the least preferred of the four; no one preferred it as number one while only three stated it was their second choice. Perhaps the window area placed in the two corners contributed to the negative response. One subject who presently lived in a residence with windows in the corners of the room vehemently objected to this placement: "It only allows you to view out in one direction." Restriction of view, then, may be one reason for the negative response. Case and DeJonge have suggested this as a reason that solar homeowners do not strongly prefer the indirect gain configuration(15). But the majority of the subjects in this experiment were negative about the indirect gain because of the lack of sunlight that it provides. Those who were more positive about the indirect gain combination were obviously not fans of the sun. In fact, the three subjects who preferred this as second choice seemed to be reacting to the profuse amount of sunlight in the direct gain configuration: "This is better; not so much sunlight." All three, though, preferred the combination of direct gain/indirect gain (44% of window area) over the indirect gain.

Combination (44% of wall covered by window): Ten people preferred this as their number one choice while nine people preferred it as their second

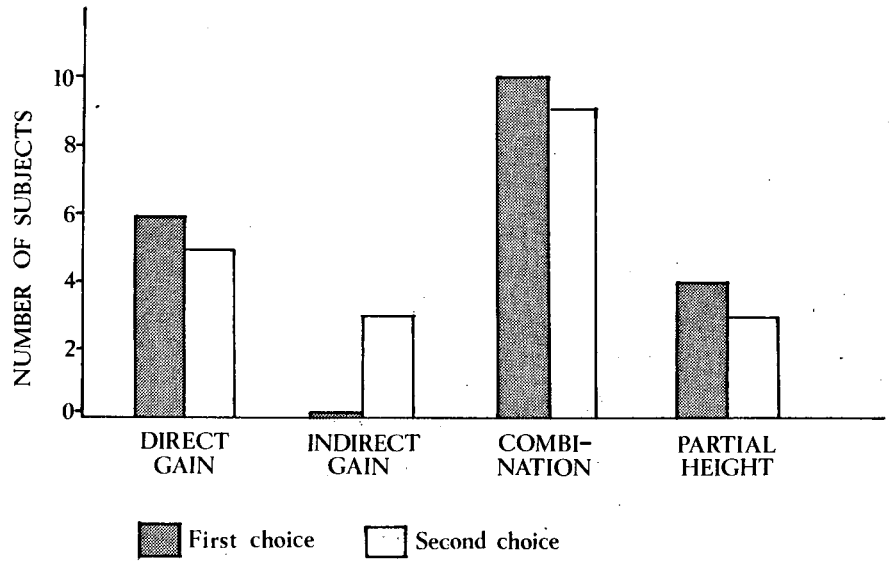



Fig. 5: Bar chart of the subjects' first and second choice of south wall configuration.

choice. Equally important, everyone responded very favorably to this configuration: "It has the right amount of sunlight coming in." "This is a nice balance." One subject commented that she liked this configuration because it gave her a choice of sitting in the sun or not.

Many of the subjects seemed to prefer this one because it was familiar to them: "This is normal." "I am used to this." Since the configuration is equivalent to two sliding glass doors, these comments are not inconsistent with other research which shows that preference is correlated with familiarity.

Several subjects commented on the ease with which furniture could be arranged with this configuration. There is more wall area for hanging pictures as well as placement of furniture. One subject also thought that window treatments would be easier to purchase.

Partial Height (65% of wall covered by window): The person who most prefers this combination has a strong desire for sunlight as well as a need for privacy. All four who preferred this one as their number one choice commented that they could read or watch television without anyone being able to see. Two volunteered that they liked the fact that the light comes over the shoulder: "It won't hurt my eyes and I like the sun."

Interestingly, reactions were either intensely positive or negative. Two subjects who groaned at the sight of the partial height combination indicated they preferred full height windows in the living area. Several subjects seemed bothered by the lack of integration of the partial height wall with the window area: "It looks stuck there." "Perhaps if it was connected to the windows better." Two commented that it was not appropriate for a living room: "It looks like a store (or a kitchen.)"

Most Preferred Configuration: After the subjects were shown the four configurations, they were given the modular mass walls and asked to arrive at a configuration of the south wall they might like better than the ones that I showed them. Most subjects stayed with their preferred choice however. Those who did devise a new configuration made just a slight variation on their most preferred one. For instance, one subject who preferred the combination (44% of window area) simply put a partial height wall in the dining area to achieve more privacy. Another added one more window opening to the combination for more sunlight in the living area. One subject kept the windows uncovered in the living area while keeping only two windows uncovered in the dining room thus desiring more light in the living area.

## 5. DISCUSSION

This experiment was designed to study people's reactions to direct gain and indirect gain systems and the window size and placement that these designs dictate. Although the study was exploratory in nature, several important observations can be made from an analysis of the results.

Truly, people's preferences in window area or direct gain/indirect gain configurations are closely linked with other psychological needs. In this experiment, preference for sunlight was clearly a predominating factor influencing people's choice of a configuration. Those who have a strong desire to sit in the sun while reading or a desire to sunbathe in the wintertime were favorable towards the large direct gain aperture which covered 88% of the wall. Those who dislike the sun, in contrast, reacted very negatively to the same configuration. Most people though probably have a moderate desire for sunlight, and thus it is not surprising that the combination of direct gain and indirect gain where 44% of the wall is covered by the window was the most strongly preferred by subjects. These results indicate also that preference for sunlight as well as large window size may be stronger for people in the home than for people in commercial environments such as in an office.

Preference for a configuration is also closely linked with the need for individual or family privacy. Privacy needs, too, vary considerably from individual to individual. While preference for sunlight may be correlated with large window sizes, a strong need for privacy seems correlated with less window area. The partial height mass wall or a sill height of 30" to 36" seems to satisfy a need for privacy for some while still providing a view and sunlight. In this experiment, the partial height mass wall placed in activity areas and full height window area in the non-activity area provides a sense of privacy and fulfills a strong need for sunlight for the subjects who preferred that configuration.

Other functions of the window also can interrelate with sunlight and privacy to influence preferences. For instance, a window provides sunlight for plants. Plants, in turn, fulfill other needs for the user, i.e. satisfaction, reduction of glare, privacy, etc. The need for a view outside, too, is an important function of the window which may not be compatible with preference for sunlight. For example, when sunlight pours into a direct gain living area, the user cannot look out without suffering from discomfort glare (16).

By now the reader is getting the picture that providing for user psychological preferences in passive solar configurations or window design is a complex affair. Indeed it is. And couple this with energy and other physical considerations and designer/builders may want to throw up their hands in despair. But there is no cause for dismay. As this research indicates, a balanced approach to the design of passive solar configurations is best. Any design which results in an extreme departure from what is already being done in window design may only appeal to a small group of home buyers. This may be, in fact, what has happened with passive solar housing. The early adopters appear to be a special group of people who are willing to make lifestyle adjustments for the sake of energy conservation and even pride themselves on being innovative (2)(15). But if passive solar is to move beyond this early adoption stage, careful consideration must be given to make designs compatible with a new group of people who may not be so innovative nor willing to compromise their own needs for the sake of collecting sunlight in their homes. Consequently, passive solar designs must fulfill as many psychological and social needs of users as possible while still maintaining energy savings if the designs are to be truly successful.

## 6. ACKNOWLEDGEMENT

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# PASSIVE SOLAR ENERGY IN ARIZONA: HOMEOWNERS' ATTITUDES AND PERCEPTIONS

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## ABSTRACT

As passive solar energy continues its rapid growth, increasingly diversified information is needed to assess what has been accomplished and in which direction to proceed. Included in this information must be feedback from the homeowner detailing how he is getting along with passive solar. Is he satisfied with his energy savings? Is his carpet fading because of that nice direct gain we've brought in? How did he learn about passive solar design and what post-occupancy information would be helpful?

This paper will discuss a mail response survey filled out by the owners and residents of 27 passive/hybrid solar homes throughout Arizona. Questions were qualitative in nature and focused on the attitudes and perceptions of the respondent regarding such issues as economics, performance, and satisfaction with their solar homes. While no "hard core" statistical methods were applied or assumed, the conclusions drawn from the compiled results should help solar professionals to gain a better understanding of user's concerns and design with these needs in mind.

## 1. INTRODUCTION

The intent of this study was to identify and highlight some of the important issues dealing with the relationship of the occupant to his solar home. In particular, the survey focused on passive/hybrid homes in the state of Arizona. Approximately 45 sites were identified by a wide range of techniques: other professionals in the building or solar field, personal visits, newspapers, previous lists of solar homes and word of mouth. An unexpected benefit of this work was the compilation of a data base of passive/hybrid homes which can potentially be used by other researchers. It was found that no such data base of homes was existent, prior to this study, for Arizona.

## 2. METHODOLOGY

An eight page mail response questionnaire was designed, for the most part eliciting a response from multiple choices and occasionally requesting a brief comment. The survey form was modeled after the forms used in the SERI Class C study [1] and the New Mexico Greenhouse survey done by Scott Morris and others [2]. It is critical to design a questionnaire which can be easily completed while supplying the desired information. Long and detailed forms or ones which appear to pry too deeply are likely to be discarded by potential respondents. The survey form consisted of eight main section headings which are listed below:

Section 1: Household Profile
(occupation, age, educational level, etc.)

Section 2: General Building Information
(square feet, estimated value, designer and builder, etc.)

Section 3: Financing/Tax Credits
(sources of financing/were tax credits applicable?)

Section 4: Passive Features--General
(types of passive systems, general questions on system performance)

Section 5: Sources of Information
(what were the homeowner's initial and follow up sources?, how this information is spread to others)

Section 6: Importance of Passive System's Attributes
(what factors are important to the homeowner as associated with the use of a passive design)

Section 7: Problems with System Performance (what were the problems and the degree of seriousness?)

Section 8: Satisfaction with Passive Solar Features (degree of satisfaction in certain key areas and overall level of satisfaction)

At the head of the form were two questions dealing with the confidentiality of the homeowners' responses. It is a strong positive note that a large majority of the survey participants were willing to either be included in a possible follow up study or to have their home placed in a listing. Complete anonymity of responses was assured in all cases. A cover letter explaining the purpose and importance of the survey was enclosed along with a stamped return envelope, with a two week maximum period suggested for returning the form.

It was very gratifying to note that of the 27 households who returned the form all of the questions were completely answered and many additional or unrequested comments were offered. A brief telephone follow up to those who had not responded revealed that privacy concerns and problems associated with their participation in other studies were most often the reasons cited for non-participation.

## 3. SUMMARY OF RESULTS

An abbreviated summary of the results will follow. A completed report may be obtained from the author at the above address.

Because of the wide variety of climatic zones in Arizona, ranging from the arid, hot, low-lying deserts to the severe winters experienced by residents at the 7000 foot level and above, it was desired to obtain a cross section of respondents. The state was divided into three broad climatic zones and mailings concentrated on the main population centers of each region. It was felt that residents of these areas, having to respond to a variety of climatic conditions, would employ a wide range of passive solar designs.

The findings revealed that the occupants were well distributed over the full range of age groups. This seems to indicate that passive solar, while being a fairly new technology, is not confined to the young homeowner, but enjoys a wide base of interest. The education level of the adult occupants fell toward the high end of the scale with the majority completing a four year college program or beyond. This is in keeping with prior expectations, as those who have had the opportunity to pursue higher learning are usually more open to the more speculative technologies. This group generally also has more access to capital to invest in these ideas.

Professions of the respondents were highly varied, with only 37% working either in the building trades or in the solar energy field. One respondent reported that his 82 year old mother was active in these professions and still going strong! It was felt that since a majority of the households were not professionally involved with passive solar design a more objective response sample would be achieved.

The majority of the homes, 75%, were built in 1978 or later, with 81% having passive solar features when occupied. The great majority of these houses had between 1500 and 3000 $ft^2$ of floor space, indicating a fairly spacious living situation. While most of the homes were built by outside contractors, a good percentage of the owners participated actively in the building/design process with assistance from family, friends and professionals. Not every homeowner should undertake to design his own passive home, but those who are able to be involved in the process, even in a small way, will certainly benefit from being more informed about the systems which allow their houses to collect and store solar energy.

A somewhat unexpected and significant response was that 63% of the respondents did not associate a payback period with their home's passive solar features. Payback is widely used in determining the economic sense of an emerging technology and can in fact decide the viability of a certain approach. It seems, at least in this survey, that passive solar design may not be so easily categorized, as other factors such as increased self-sufficiency or environmental considerations appear to be at work and are difficult to predict and quantify.

Direct gain was by far the most prevalent passive system reported, although many of the homes employed combinations of systems. Another positive note was that an overwhelming 93% of the homeowners felt that their passive systems performances either met or exceeded the heating contributions which had been expected.

One survey section concentrated on information dissemination to determine how the awareness of passive solar design was spread and what factors were having either

benefical or negative impacts on its growth. About 60% of those responding reported knowing of another passive home built or retrofitted because of their own home. Again as the great majority of respondents were not involved with solar energy professionally, it appears that these are people that have had good experiences with their passive solar homes and are interested in telling others about something that works for them.

The most important motivating factors for the use of a passive solar design were found to be economic considerations. Conservation of energy and self-sufficiency also were ranked highly. A partial listing of identical problems with the passive solar systems and their perceived seriousness are shown in Table 1.

It should be noted that none of the respondents perceived any of these problems as "not tolerable." The only problem reported to exist by more than 30% of the homeowners were: leaking, fading of furniture or walls, cool or overheated rooms, and condensation. These have all proved bothersome to designers in the short history of passive solar design, and it is not surprising that they have again turned up in the survey.

In the final section concerning overall homeowner satisfaction, 67% reported "very satisfied," while no one reported "not at all satisfied." The only individual factor which received a slightly lower satisfaction rating was heat distribution, which nevertheless received a mean rating of better than satisfactory. The high level of satis-

TABLE 1

DEGREE OF SERIOUSNESS OF PROBLEMS WITH PASSIVE SOLAR SYSTEM

| Possible Problem | Mean* |
|---|---|
| Leaking | 1.89 |
| Cool rooms | 1.74 |
| Overheated rooms | 1.59 |
| Condensation on windows | 1.44 |
| Fading of furniture walls | 1.41 |
| Covering sloped windows | 1.36 |
| Glare | 1.26 |

*Scale value: 5 = Not tolerable
4 = Very serious
3 = Serious
2 = Somewhat serious
1 = No problem

Larger mean values indicate greater perceived seriousness.

faction reported here was matched by that reported in conclusions drawn in the SERI "Class C" study. It appears that despite some persistent problems, Arizona homeowners are overall quite pleased with their passive solar homes.

## 4. CONCLUSIONS

Based on the results of the survey, we find that the passive solar homeowner in Arizona represents a wide cross section of the population. The homeowner seems to take a strong interest in the early design and building stages of his home. He maintains this interest through the post-occupancy period and is not hesitant to recommend the use of passive solar design in other homes. His primary motivation for using a passive solar design is to save on fuel costs, but increased self-sufficiency, energy conservation, and using renewable fuels are all important to him. A strong need for information from building professionals and other solar homeowners has been expressed in order to better understand his home's solar workings. Some problems with performance do exist, but in these cases none were reported to be overwhelming. The great majority of homeowners polled were extremely satisfied and supportive of passive solar design and seemingly willing to share their experiences.

This study seems particularly relevant in light of the current tight economy and the prevailing attitude that solar must prove itself in the marketplace. Follow-ups to this study concentrating on specific areas such as on-site audits comparing actual energy records to perceived performance or the status of reported design problems would prove useful to solar professionals.

What has been found during this research should provide a good starting point for these more focused studies, leading to a greater comprehension of some of the subtler consumer issues relating to passive solar design.

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# MARKETING AND TECHNICAL RESEARCH: SOLAR USERS IN ARKANSAS

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## ABSTRACT

The introduction of any new product requires market research sometimes as extensive as the technical research involved in design of the product. This paper describes a study conducted in Arkansas which addresses the two major areas of marketing and technical research.

## 1. INTRODUCTION

There are major factors that affect the sales of nontraditional products. One of the factors which is often ignored in the promotion of alternative energy technologies but is commonly used in the development of other products/services is research into the composition of the marketplace.

When investigating the marketing of non-traditional products such as energy related systems and in particular solar or renewable energy systems, the research must be conducted simultaneously on two distinct levels--the technical/energy related composition of the structure and the psychographic (the study of activities, interests, and opinions) characteristics of the owners. Demographic data (sex, race, family income, number and age range of children, etc.) are also important parameters.

The Arkansas Power and Light Company (AP&L) is very interested in the development of solar energy systems and views it as a potential product for diversification. The preliminary work prepared for management included technical, marketing and economic assessments.

Not having the marketing expertise on staff, the University of Arkansas at Little Rock was consulted because of their experience in marketing research and consumer behavior.

The preliminary results examined solar vs. nonsolar residential customers. This paper will briefly describe the methodology used in the original work and the expanded results of the Arkansas Solar Study.

## 2. OBJECTIVES

In an attempt to determine the characteristics of the solar marketplace in our state, the University of Arkansas and the Arkansas Power and Light Company developed and implemented a research project with the major goals of:

1. Identifying the solar energy users in Arkansas;

2. Determining the type of solar system;

3. Comparing the energy characteristics of the structure as well as the psychographic and demographic characteristics of active solar users, passive solar users and a randomly selected control group.

## 3. METHODOLOGY

To achieve these goals, the following methodology was developed.

### 3.1 Identifying the Participants

Since the Arkansas Power and Light Company (AP&L) provides electrical service to only a portion of the state (AP&L serves 444,000 residential households in 63 of the 75 counties in the state), the help of the remaining utilities, municipals and electric cooperatives was requested. The utilities listed in Table 1,

identified the solar users (both active and passive), in their respective service territories. Other utilities, not listed, were not aware of any of their residential customers being solar users.

Table 1. Arkansas Electric Power Suppliers Providing The Solar Sample

Arkansas Power and Light Company
Arkansas Valley Electric Cooperative Corporation
Carroll Electric Cooperative Corporation
Clay County Electric Cooperative Corporation
Craighead Electric Cooperative Corporation
First Electric Cooperative Corporation
Mississippi County Electric Cooperative, Inc.
North Arkansas Electric Cooperative, Inc.
Oklahoma Gas and Electric Company
Ozarks Electric Cooperative Corporation
Petit Jean Electric Cooperative Corporation
Quachita Electric Cooperative
Rich Mountain Electric Cooperative, Inc.
South Central Arkansas Electric Cooperative, Inc.
Southwestern Electric Power Company
The Conway Corporation

The tally of residential solar users identified by the 16 electric power suppliers amounted to 125 homes. A random sample of 150 nonsolar residential customers of AP&L was used as a control or comparison group.

Questionnaires were mailed to both the solar and nonsolar samples with a letter from the University of Arkansas explaining the project. To encourage response, after two weeks follow-up letters were mailed followed by a phone call in the third week. Ultimately, 46 per cent of the nonsolar users and 60 per cent of the solar users responded.

3.2 The Questionnaire

The questionnaire consisted of 12 type written pages and a cover letter from the University of Arkansas at Little Rock which explained the purpose of the study.

Five types of information were requested from all the respondents both solar and nonsolar:

Home Construction Characteristics. These included type, levels of the dwelling, and whether the home was custom-built or speculative.

Energy Use Characteristics. These included type of fuel and system used to deliver primary heating and cooling, water heating, and the types of systems used to provide them.

Energy Conservation Characteristics. Characteristics measured included type, direction, and protection of windows; existence, type and R-value of attic, floor, duct, wall, and crawl space insulation; and attic ventilation.

Demographic Characteristics of Respondents. Sex, race, age, number, and ages of children; education, occupation of the head of household; and total household income were the characteristics measured.

Psychographic and Personality Characteristics of respondents. "Psychographics" is a loosely defined term which has come to mean about the same thing as life-style analysis -- the study of the interrelationships among the activities, interests, opinions of consumers, and the relationship of these to individual acts of consumption. As a body of study and a research tool, psychographics are of increasing importance to marketing researchers. Consumers of a certain product or service -- such as solar energy -- are often indistinguishable by demographics such as age and income, yet they may be identified by activities (such as hiking and camping), interests (such as health or energy conservation), or opinions (such as support for environmental protection regulation.)

"Personality" is comprised of complex characteristics including behavioral and emotional tendencies, personal and social traits, attitudes or habits. The technique used to measure these characteristics is the "Summated (Likert) Scale." This device allows respondents to indicate how strongly he agrees or disagrees

with each statement. Each degree of favor or unfavor is assigned a numerical range from one to six.

For this study, 72 questions were asked to measure 16 different personality and psychographic traits. The scores were summed for all questions measuring a particular psychographic characteristic to determine the respondent's total score for that trait. The trait and life-style characteristics measured are listed in Table 2.

Table 2. Sixteen Psychographic Characteristics Measured

Inner directed - outer directed
Liberal - conservative
Control - subjection
Optimism - pessimism
Social - private
Thrifty - extravagant
Intellectual - superficial
Innovative - traditional
Handy - inept
Outdoors - indoors
Home centered - not home centered
Swingers - homebodies
Movable feast[1] - private enjoyment
Culturati[2] - uncultured
Adventurers - sticks-in-the-mud
Environmentalist - nonenvironmentalist

[1]Enjoys any activity as long as accompanied by appropriate other persons.
[2]Consumers of culture - plays, books, art, etc.

Nearly all the statements for measuring traits were taken from standard personality inventories or from adaptations previously used and validated in previous marketing research projects.

Nineteen questions were asked regarding the energy characteristics of the home. These questions included size and type of home, type of water heating system, type of energy and equipment used for heating; type of energy and equipment used for cooling; type and orientation of windows and window treatment; R-values and type of ceiling, attic and floor insulation; type of attic ventilation and location of air conditioning ducts.

## 4. SUMMARY OF FINDINGS

Datawere analyzed using frequency distribution techniques. A table was prepared showing interval limits, frequency of occurrence, and per cent for each interval of the demographic and psychographic questions. The exact datawere analyzed and tested for the home characteristics questions.

### 4.1 Home Characteristics

Table 3 describes the "typical" passive solar home, active solar home and nonsolar home. As the data indicate, passive solar homes tend to be somewhat larger that active solar homes and much larger than that of the control sample. Solar dwellings both active and passive are better insulated and, as expected, more commonly use window protection. A large number of the passive solar homes do not use mechanical air conditioning.

### 4.2 Demographic Characteristics

One of the most striking findings of the study was the socioeconomic status of the passive solar users. Their image is slightly above the active solar users and substantially higher than the nonsolar users. Table 4 illustrates the demographic parameters of the solar users, which points out that they would seem to be the elite of the state.

### 4.3 Psychographic Characteristics

The psychographic findings were somewhat less revealing than the other portions of the study. The results illustrated that the characteristics of the active and passive solar users were similar, with attitudes of the passive group somewhat more intense.

## 5. CONCLUSIONS

This project was a unique study to characterize the solar energy users in our state. The results of this work provided the marketing and technical data that identified the Prime

Solar Adapter. This information is an invaluable tool for those in the business of selling solar, either active or passive. Now the businessman knows his potential clients and can aim his advertising and other marketing strategies at the type person who is likely to be interested.

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Table 3. "Typical" Passive Solar, Active Solar and Nonsolar Homes

| Characteristic | Passive Homes | Active Homes | Nonsolar Homes |
|---|---|---|---|
| Square Feet | 2359 | 2164 | 1655 |
| Building Type | Custom Built | Custom Built | Custom Built |
| Water Heating | Electric | Solar | Gas |
| Heating Fuel | Solar | Wood | Gas |
| Heating System | Solar | Heat Pump | Furnace |
| Cooling Fuel | Electric | Electric | Electric |
| Cooling System | Passive Solar | Central | Central |
| Windows | Double Pane | Double Pane | Single Pane |
| Overhangs | Yes | Yes | No |
| Movable Insulation | Yes | Yes | No |
| Ceiling Insulation | R-Value 33 | R-Value 36 | R-Value 24 |
| No Answer/Don't Know | 29% | 33% | 81% |
| Wall Insulation | R-Value 23 | R-Value 17 | R-Value 18 |
| No Answer/Don't Know | 24% | 53% | 89% |
| Attic Ventilation | Louvers/Soffits | Louvers/Soffits | Louvers/Soffits |
| Duct Location | Conditioned Space/ Under Floor | Under Floor/Attic Conditioned Space | Attic/No Ducts Under Floor |

Table 4. Demographic Characteristics of Passive and Active Solar Users

- Executive, professional, managerial, white-collar.
- Fifty-nine per cent (passive solar), forty-four per cent (active solar) are college educated as opposed to 15 per cent nonsolar.
- Sixty-five per cent (passive solar), forty-eight per cent (active solar) have $25,000 and above annual income as opposed to 15% nonsolar users.

Table 5. Psychographic Characteristics of Passive and Active Solar Users

| Passive Solar Users | Active Solar Users |
|---|---|
| Inner directed | Inner directed |
| Conservative | As conservative as control group |
| In control | In control |
| Optimists | Optimists |
| Private | Private |
| Extravagant | Extravagant |
| Intellectual | Intellectual |
| Innovative | Innovative |
| Handy | Handy |
| Indoorsey | Outdoorsey |
| Home centered | Home centered |
| Swingers | Homebodies |
| Mobile | Mobile |
| Cultured | Cultured |
| Adventurous | Adventurous |
| Environmental and nonenvironmental | As environmental as control group |

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# AN EXPLORATORY STUDY OF THE RELATIONSHIP BETWEEN OWNER ATTITUDES AND CHARACTERISTICS OF EARTH-SHELTERED HOUSING

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## ABSTRACT

On-site interviews were conducted with 24 respondents living in earth-sheltered homes in Texas during the summer of 1982. The majority of the respondents were married, between the ages of 31 and 50 years, had children living at home, had at least some college, were employed in a professional occupation, lived in rural or open country area and had owned single family housing before buying earth-sheltered housing. Additional information is presented regarding the structure, near environment and energy use of the earth-sheltered home. Generally, owners tended to be upscale in innovations and attitudes toward alternative housing. Statistically significant relationships were found between the attitude scales, demographic variables and earth-sheltered housing variables.

## 1. INTRODUCTION

Very few studies have been published that have tested the relationships between the types of earth-sheltered housing, energy use, neighborhood characteristics, owner demographics and selected attitudinal constructs that may be related to innovative housing behavior. While the movement toward earth-sheltered housing has shown rapid growth and acceptance in states such as Minnesota and Oklahoma, other parts of the United States have experienced slower growth patterns. Arguments in favor of earth-sheltered housing range from safety to economy, yet many lenders and builders are hesitant to make major ventures into the marketplace. There is a need for additional knowledge regarding the characteristics of earth-sheltered housing "consumers."

It is the purpose of this research to provide additional knowledge regarding a statewide sample of the owners of earth-sheltered housing. It is hypothesized that the unique nature of an earth-sheltered home required some level of innovative behavior on the part of the owner.

## 2. METHODOLOGY

Information on earth-sheltered homes and their owners was collected during on-site interviews throughout the state of Texas. An eleven page questionnaire containing questions regarding demographic information, near environment characteristics, use of professional assistance, energy use, interior characteristics, and house design was used. Two attitudinal scales, consisting of 30 items designed to measure innovation-proneness and the other a 10 item scale designed to measure attitudes toward alternative housing were included. The on-site visit was conducted by the interviewer. The attitude portion of the questionnaire was left with the respondents to be completed and mailed to the researchers.

Since the number of respondents (n=24) was relatively small and the variance on some variables was slight, only descriptive statistics and Pearson's Correlation Coefficient were calculated. The reader should use caution in generalizing from the data to the United States as a whole.

## 3. FINDINGS

Due to the limited number of earth-sheltered homes visited throughout Texas, the findings should be regarded as preliminary in nature. In the instances where the total number of respondents does not total to 24, the respondents refused to answer or did not know the answer to the questions. The presentation of these results is an effort to stimulate more comprehensive studies of the relationships between the characteristics of earth-sheltered homes and owner attitudes and demographics.

### 3.1 Sample Characteristics

The number of people in the household ranged from single persons to five people. The mean number per household was approximately three. Well over one-half of those responding were between the ages of 31 and 50 years. Almost two-thirds were college graduates, and well over one-half of those respondents held

advanced degrees. Incomes tended to be upscale when compared to the median family income in Texas. Occupations were skewed in the direction of professional and self-employed categories.

TABLE 1.

NUMBER IN HOUSEHOLD

| Number | Frequency |
|---|---|
| One | 2 |
| Two | 7 |
| Three | 7 |
| Four | 4 |
| Five | 4 |
| | 24 |

TABLE 2.

AGE OF RESPONDENT

| Age in years | Frequency |
|---|---|
| 30 or less | 3 |
| 31 - 40 | 8 |
| 41 - 50 | 7 |
| 51 - 60 | 3 |
| 61 - 65 | 2 |
| | 23 |

TABLE 3.

EDUCATION OF RESPONDENT

| Level | Frequency |
|---|---|
| Less than high school | 1 |
| High School | 1 |
| Some College | 6 |
| College degree | 6 |
| Advanced degree | 9 |
| | 23 |

TABLE 4.

ANNUAL FAMILY INCOME

| Range | Frequency |
|---|---|
| $10,000-14,999 | 1 |
| $15,000-19,999 | 0 |
| $20,000-24,999 | 1 |
| $25,000-29,999 | 1 |
| $30,000-34,999 | 3 |
| $35,000 and above | 16 |
| | 24 |

TABLE 5.

OCCUPATION OF RESPONDENT

| Category | Frequency |
|---|---|
| Professional and self employed | 16 |
| Building trades | 4 |
| Retired | 4 |
| | 24 |

Twenty of the respondents owned their earth-sheltered home and four rented. Sixteen of the respondents lived in single family housing before moving to the earth-sheltered house, three lived in apartments and five lived in mobile homes.

### 3.2 Earth-sheltered housing characteristics

The time necessary to complete the earth-sheltered homes in the study ranged from four months to 49 months with the average completion time being one year and two months. One-half of the twenty-four respondents did not visit any earth-sheltered houses prior to beginning construction while ten of the respondents visited only one or two houses. The remaining respondents visited from three to six earth-sheltered houses prior to construction.

The use of experts or other information sources provides some interesting insights into the decision process. While mail order sources were used by only one respondent, the category of expertise noted most often by respondents was self. Contractors and engineers received the next highest number of mentions.

TABLE 6.

UTILIZATION OF EARTH SHELTERED HOUSING INFORMATION AND EXPERTISE SOURCES

| Type | Yes | No |
|---|---|---|
| Contractor | 11 | 12 |
| Designer | 8 | 15 |
| Engineer | 11 | 12 |
| Mail Order | 1 | 22 |
| Architect | 8 | 15 |
| Self | 16 | 7 |
| Other | 10 | 12 |

The location and population of the area surrounding the earth-sheltered home were described as rural by a majority of the respondents on both categories. While eleven of those responding were living 300 feet or closer to their neighbors, the remainder of the respondents were from 300 feet to one mile from their neighbors. However, nine of the respondents noted that neighbors had complained about the construction of an earth-sheltered home in the area.

TABLE 7.

NEAR ENVIRONMENT OF EARTH-SHELTERED HOUSE

| Population | |
|---|---|
| Open/country/rural | 15 |
| Less than 1,000 | 1 |
| 1,000 -9,999 | 4 |
| 10,000-49,000 | 2 |
| More than 50,000 | 2 |
| | 24 |

| Location | |
|---|---|
| Rural | 12 |
| Rural Subdivision | 6 |
| Urban Subdivision | 5 |
| | 23 |

| Nearest Neighbor | |
|---|---|
| Within 50 feet | 2 |
| Within 300 feet | 9 |
| Within 1 mile | 12 |
| | 23 |

The floor system used in one home was wood while twelve utilized slab-on-grade and the remaining eleven had slab-below-grade. Frame construction was used on the interiors of twelve homes while nine had poured concrete and two used concrete blocks. One house used other materials. Several methods of ceiling treatments were used. Suspended ceilings were favored by seven respondents while applied plaster or other ceilings were mentioned by two respondents, respectively.

TABLE 8.

CEILING TREATMENT

| Treatment | Frequency |
|---|---|
| Exposed or painted | 6 |
| Applied plaster | 2 |
| Tile or drywall | 4 |
| Suspended | 7 |
| Furred tile or drywalls | 3 |
| Other | 2 |
| | 24 |

Several paradoxes exist with respect to temperature control and air distribution in the earth-sheltered houses. While logic suggests that there are many benefits from the standpoint of lessened resource usage, many of the respondents chose conventional methods of heating and cooling their homes. Central electric heat and central air conditioning delivered by central ducts in the ceiling are traditional methods of temperature control in a non-traditional type of housing.

TABLE 9.

EARTH-SHELTERED HOUSE TEMPERATURE CONTROL

| Heating | |
|---|---|
| Passive solar | 3 |
| Stove or Fireplace | 4 |
| Electric baseboards | 1 |
| Central electric | 9 |
| Central gas | 2 |
| Heat pump | 5 |
| | 24 |

| Cooling | |
|---|---|
| None | 2 |
| Natural ventilation | 1 |
| Mechanical ventilation | 2 |
| Central Air | 12 |
| Heat Pump | 5 |
| Window air conditioning | 1 |
| Evaporative | 1 |
| | 24 |

| Distribution | |
|---|---|
| None | 2 |
| Natural circulation | 3 |
| Space fans | 2 |
| Central ducts-ceiling | 10 |
| Central ducts-floor | 4 |
| Other | 3 |
| | 24 |

### 3.3 Statistical Relationships

A ten item scale designed to measure attitudes toward alternative housing was used. The answers were on a four point continuum ranging from agree strongly to disagree strongly. A thirty item scale designed to measure innovativeness along a five point scale was used. Both scales were coded so that a higher score would indicate a positive attitude toward the concept.

The minimum possible score on the alternative housing scale was 10 and the maximum was 40. The mean score was 33. The minimum possible score on the innovativeness scale was 30 and the maximum was 150. The mean score was 99.

Pearson's r was calculated between the alternative housing scale and the innovativeness scale, and no significant relationship was found. Only level of education among the demographic items had a significant relationship (.01 level) to the alternative housing scale (r= -.63). Of the variables describing the earth-sheltered house and it's construction, only seeking of the advice of an architect was related to the innovativeness scale (r= -.62) at the .01 level.

The negative relationship between level of education and alternative housing attitudes was somewhat surprising. However, it should be noted that the sample tended to be upscale in education, and the categories really represented a quite highly educated group of people. The finding of a negative relationship between the use of an architect and innovativeness may be due to the use of "self" as a source and being innovative in one's own ability to design a structure. Finally, the lack of a statistically significant relationship between the housing scale and innovativeness may be a lack of consideration toward a special type of innovativeness that is present during the purchase of "big-ticket" items such as a house. There is a definite need for further study in this area.

## 4. CONCLUSIONS

There needs to be a further examination of the number of conventional temperature control methods used in a non-conventional type of housing. The relatively few who used passive solar for heating may point to a deeper rooted behavior regarding some mainstream housing practices.

The number of people who shunned professional help when making a relatively large investment is very interesting. Future studies need to focus on the relationship between housing satisfaction and the use of professional assistance.

Researchers need to focus on the development of attitude dimensions and scales to measure them which will help to identify the pro-earth-sheltered housing person. Identification would allow professionals and educators to focus educational and research efforts on them as well as allow the developing industry to reach them with their advertising.

Finally, researchers in states with large numbers of earth-sheltered houses need to begin developing data bases on large samples so that more powerful statistical techniques may be used. The possibility of selecting a control group of conventional home purchasers matched on selected demographic characteristics would allow for the analysis of differences between earth-shelter purchasers and other home buyers.

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# CONSUMER RETROFIT RESPONSES

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## ABSTRACT

Energy costs continue to climb. Most consumers cannot afford to purchase a new energy efficient home; therefore, retrofit becomes an important part of energy conservation. A survey of the Unit neighborhood in Lubbock, Texas revealed that consumers are concerned about energy, were not knowledgeable of passive solar alternatives and that all would consider some form of retrofit. Most consumers indicated that a fifty percent or less reduction in energy costs would be acceptable for them to consider a retrofit. The majority of those surveyed had not visited a passive solar dwelling. This points to the need for models, open houses and ongoing educational activities.

## 1. INTRODUCTION

In the past several decades, America's residential energy has been supplied either directly or indirectly by fossil fuels. By the middle 1970s Americans were consuming 36 percent of the world's yearly supply of fossil fuel energy while comprising only six percent of the world population.

Of the energy alternatives being investigated, passive solar is considered by many to be most immediately feasible. With the rising costs of fuels, passive solar is becoming cost competitive. Still, use of passive solar is somewhat slow. Widespread use of any alternative relies on consumer acceptance. The number of dwellings in existence points to the need for widened acceptance of passive solar retrofit.

Passive solar energy is the historical manner in which solar heat was used. Passive solar systems operate on the natural energy already available in the environment. The building acts as the heat collector and the storage and distribution are inherent in the building structure (7). These systems use no mechanical equipment to transfer, collect, or store heat. Therefore, no energy produced outside the system is used except for the energy sometimes required for operation of valves, dampers, and insulating features.

Hybrid systems are a combination of active and passive. They use a minimum amount of mechanical equipment. The equipment is used either to move the heat from collection to storage, or from storage to distribution, but not both (7). Many hybrid systems are also considered passive because the amount of mechanical equipment is so small. An example would be the use of fans to move collected heat from one area to another in the house.

Of the three forms of solar applications, passive uses less energy and therefore would be the most logical for saving valuable energy resources. These systems also are "relatively inexpensive, have no maintenance requirements, and last indefinitely because there are no moving parts to wear out" (3).

## 2. OBJECTIVES

Consumer reaction is important in understanding the constraints to passive solar retrofit. Three objectives were therefore established: 1) to determine consumer preference for four styles of passive solar retrofit -- direct gain, greenhouse, Trombe wall, and water wall; 2) to survey what percentage of utility savings would be necessary to stimulate adaptation of passive solar retrofit; and 3) to examine consumer characteristics consistent with positive responses toward passive solar retrofitting.

## 3. METHODOLOGY

One thousand surveys were mailed to a unit development in a neighborhood approximately

30 years old in Lubbock, Texas. The neighborhood borders Texas Tech University on its north boundary. Age of houses in the area vary from 10-75 years. The survey was for the entire housing unit -- renters and owners.

One of the reasons for selecting the area was the variety of socioeconomic and demographic characteristics expected among the residents. 297 responses to the survey were received, representing 32 percent of the sample. The four passive solar designs used in the survey were direct-gain, Trombe wall, water wall and greenhouse. Questionnaires were color coded to identify frontal orientation of the house, either north or south.

Frequency distributions and percentages were computed for each question. Further statistical analysis was conducted using chi-square test of independence, discriminant analysis, and multiple regression techniques. Pearson Product-Moment correlations were also computed.

## 4. FINDINGS

### 4.1 Demographic Characteristics of the Sample

The 297 respondents' ages ranged from twenty years to eighty-eight years, with the mean age being forty-nine years. Thirty percent of the sample were over sixty-five years of age. Nationally, the percentage of household heads sixty-five or older is 20 percent, and the median age of the population is thirty years (6). In comparison to government statistics, the sample population was primarily grouped at the extremes of the age range and the median age was forty-four years.

One hundred sixty-one males and 134 females answered the survey, accounting for 55 and 45 percent, respectively. The majority (176) of the respondents were married. The non-married household heads were divided primarily among single or widowed persons, with divorced or separated persons accounting for only 5 percent of the respondents.

In 1976, the national median was 12.5 years of schooling (8). While exact comparisons could not be made, due to different statistical grouping, national statistics showed that 67 percent of the population had at least a high school education (6). Thirty-seven percent of the household heads sampled had completed some graduate work or held Masters' or Doctoral degrees.

Forty-five percent had some college education, and an additional 9 percent had attended junior colleges or technical schools. This high education level might be partially explained by the proximity of the neighborhood to the Texas Tech University campus.

Occupations were divided into twenty-two categories and later collapsed into six for use in chi-square analysis. The six categories were students, laborers, retired, professional, sales/service workers, and artisans/teachers.

Income levels varied greatly within the sample group. The yearly pre-tax income ranged from zero, usually students supported by someone outside their immediate household, to over $100,000. Twenty-four percent of the respondents made less than $15,000 annually, and an additional 31 percent were in the $15,001 to $25,000 income bracket. The median income group for all the respondents was $20,000 to $25,000 in comparison to a 1978 national median of $17,640 (6).

### 4.2 Housing Characteristics of the Sample

The large majority of the respondents owned their own homes. Two hundred forty-nine homeowners, compared to forty-eight renters, is a majority of 84 percent to 16 percent. Sixty-five percent of the homeowners were previous homeowners, and first-time homebuyers accounted for 35 percent.

The respondents' length of residence ranged from less than one year to 51 years, with the mean being 13.33 years. Forty-two percent of the respondents had lived in their homes less than five years, and 9 percent less than one year. Thirty-three percent had lived in their homes from six to twenty years, and 17 percent thirty years or more. This lack of mobility may result from the high number of older, retired respondents in the sample.

The home ages were also widely varied, from five years to 75 years, with the mean being 36 years and eight months. The largest group of homes were forty years old, which represented 23 percent of the sample group.

The responses regarding the predominant source of heat for their homes were heavily weighted toward gas heat. Ninety-four percent of the homes were heated by gas, 3 percent were electric heat, and 3 percent used both gas and electric heat. This response may be related to the areas of the homes and their geographic locations.

The survey also requested information on the amount of insulation utilized in the homes. Six percent of the respondents did not know whether their homes were insulated or not; 15 percent stated that their homes were not

insulated at all; 50 percent reported partial insulation; and 34 percent responded their homes were fully insulated.

### 4.3 Consumer Attitudes Toward Passive Solar Energy

Consumers answering the survey believed that there was definitely an energy shortage. Sixty-four percent answered "yes, definitely" to the question, "Do you believe there really is an energy shortage?", while another 21 percent answered "maybe". This high degree of belief in an energy shortage might be explained in part by the higher educational levels of the respondents. In comparing the answers for both males and females, the mean was the same at 3.43, indicating that sex was not a factor in opinions on this question. In the correlations, as educational level increases, so does the belief in the energy shortage, which would seem to substantiate the notion that belief in the energy shortage is related to educational level.

### 4.4 Consumer Acceptance of the Four Designs

The respondents were asked to rank any of the four designs they would use in the order of their preference. For the purpose of coding, the number "5" was made the highest preference and "1" the lowest. A few respondents marked the designs but did not rank them, and these were all given the same ranking of a 5. One hundred fifty-five of the 188 respondents answering the question would consider retrofitting their homes to use passive solar designs. This number represents 82 percent of the positive responses. Direct-gain received the most responses when computing responses only. The next highest in number of positive responses was the greenhouse design, having 149 of the rankings, representing 79 percent of the positive responses. The lowest, with only 104 rankings. Only 55 percent of the persons that would consider using passive solar designs would consider the water wall as one of their choices. Choices are detailed in Table 1.

Respondents were also questioned whether they had previously visited a passive solar home. Two hundred sixteen had not visited a home using passive solar heat or cooling. This was 74 percent of the 291 persons answering the question.

The level of acceptance of the designs was also examined by a question concerning whether respondents would live in a home heated by passive solar means if the house was equipped with a back-up conventional heating system. A majority of people were favorable to the idea of living in a passive solar home.

The final question examining consumer acceptance was a problem question. It was stated that in order to adapt (retrofit) an existing house to passive solar heat, many variables had to be considered which would vary the cost of the adaptation. It was then hypothesized that for the consumers' homes, it would cost $1,500. It was then asked what savings on their utility bills would be necessary for the respondents to adapt one of the designs.

The answers ranged from 0 percent to 500 percent, with the mean being 38.57 percent. Less than 5 percent of the respondents desired over 75 percent savings; 85 percent of the consumers required 50 percent or less; and 55 percent of respondents would want 40 percent or less savings.

## 5. CONCLUSIONS

Based on the results of this study and its limitations, the conclusions which might be drawn from the major findings include:

1. The demographic characteristics affecting passive solar retrofitting are age, with

TABLE 1. PREFERENTIAL RANKING OF FOUR DESIGNS.

| | 5 (Most Preferred) | 4 | 3 | 2 | 1 (Least Preferred) | TOTAL |
|---|---|---|---|---|---|---|
| Direct Gain | 68 | 52 | 21 | 14 | | 155 |
| Greenhouse | 97 | 30 | 11 | 9 | 2 | 149 |
| Trombe Wall | 20 | 33 | 47 | 16 | | 116 |
| Water Wall | 4 | 15 | 27 | 57 | 1 | 104 |
| TOTAL | 184 | 120 | 106 | 96 | 3 | |

sex, educational level, and occupation exhibiting significant influence.

2. It appears that prior knowledge of passive solar energy does not affect consumers' choice of passive solar design.

3. No relationship or difference could be found between consumers' frontal housing orientations and their design preferences.

4. Consumers were accepting of passive solar retrofitting after being given diagrams and explanations of passive solar principles.

5. This set of respondents would live in passive solar homes if they were supplemented with conventional heating systems.

6. The amount of utility savings required for consumers to adapt passive solar retrofitting is within the realm of possibility in many cases. This helps make passive solar retrofitting more marketable as an energy alternative.

7. Income, sex, prior passive solar knowledge, marital status, size of family, amount of home insulation, and perceived energy shortage do not appear to be reliable predictors of passive solar retrofitting acceptance.

Consumer preferences and expectations are very much a part of the total energy issue. This information should be a part of government incentive programs and marketing by private industry. Models and consumer education continue to be needed.

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# "WATER TUBES ?....NOT IN MY LIVING ROOM!" HOMEOWNER ATTITUDES TOWARDS PASSIVE SOLAR AESTHETICS

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## ABSTRACT

Passive solar homes often contain new and different looking products and design features. Many are viewed with skepticism and are often installed on the insistence of the designer; explaining that they are essential to the performance of the passive system. In addition to their appearance, many are expensive. We felt it was important to get feedback from the owners as to how they felt about these features, whether or not they were being used to their fullest, how the owners felt about their homes now that they had lived with them a while, and what they might do differently if they were to build again. In order to investigate these attitudes and to get feedback on completed designs a questionnaire wasdistributed to clients who had lived in their homes for at least one year. Additional information was gathered on post-occupancy interviews and site visits.

## 1. INTRODUCTION

When first introduced to passive solar heating techniques and components during a slide presentation at our office, a client took one look at a transluscent fiberglass tube, eight feet tall, filled with water and said, "I don't want those things in my house." "But, one cubic foot of water can hold twice as many Btu as a cubic foot of concrete or brick," we pointed out, "and you can't beat the price."

After they had lived in their new passive solar home for a year, we asked her how she felt now about living with "those tubes" filled with water sitting in the master bedroom and weighing 450 pounds. Replying that she now "almost liked them", she was pleased that "light comes through them during the day to brighten the room, and at night we can even see the moon through them from our bed."

Many owners of passive solar homes have had similar initial responses to some aspects of solar design: south glass, thermal mass, and movable insulation. Some after living in their homes have likewise changed their opinions. In order to investigate these attitudes and to get feedback on completed designs a questionnaire was sent to those clients who had lived in their homes for at least one year. Part of the questionnaire was specifically focused on their use of and satisfaction with a particular automatic thermal curtain and was part of a larger study on people's use of, and reaction to, windows in architecture completed at the University of Michigan School of Architecture and Urban Planning (1). The rest of the questionnaire dealt

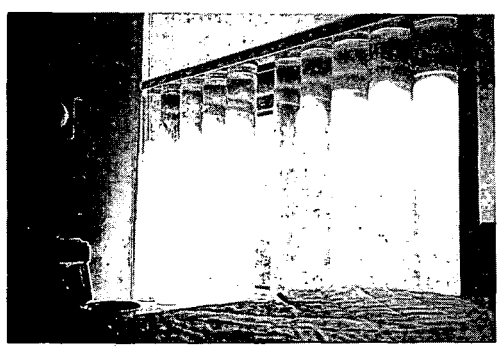


Fig. 1. Water Tubes in Master Bedroom.

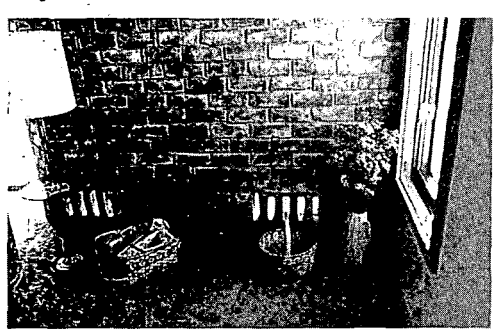


Fig. 2. Mass Wall in Living Room.

with the owners' attitudes towards the passive solar components and the home as a whole. I consisted of a series of multiple choice and short essay questions.

## 2. FINDINGS

A series of questions were asked regarding concerns often voiced by potential clients. Privacy in homes with large amounts of direct gain glass turned out not to be a porblem; almost all the respondents stated that they almost never felt a lack of privacy. Owners were cleaning their glass about once per year the same as non-solar homes. When asked about glare, 80 percent responded that they seldom of never considered that their homes were too bright and only one stated that they had any problems with fabrics fading(this may be due to the fact that many of the homes were only two years old).

Although passive solar residences inherently have temperature fluctuations larger than conventional homes, all of the respondents described the fluctuations as small, 5.5°C (10°F) and the level of comfort as good to excellent.

It is often difficult for the solar designer to convince the client to get enough thermal mass in the home. Most like carpeted floors ruling out the use of floorslabs for mass, like the bright, airy feeling of direct gain spaces and almost all have expressed an aversion to water tubes. In one case the structure was designed into the floor to support water tubes but the owner did not purchase them. The first summer we received a call from the client asking for the phone number of the water tube manufacturer. Sometimes direct experience can be more convincing than a well informed designer. In several cases clients have begrudgingly okayed the installation of water tubes in the bedrooms and have chosen brick and concrete floors and mass walls for the public areas. When clients were asked to comment on their feelings about the various mass elements used in their homes, mass floors were considered "very comfortable" and good looking although one couple admitted that their quarry tile floor was hard to keep clean with a "dirty dog". It has also been found that tiled floors are too cool in bedrooms where people walk around in their bare feet unless the floor is heated(radiant slab). Water tubes are one of the most notably different looking components used in passive homes. Most owners still did not express a fondness for them although many like the diffuse light that comes through them. Several individuals admitted that the water tubes definitely more effectively reduced temperature fluctuations than either mass walls or floorslabs.

Many have had concerns about overheating in the summer. Most respondents stated that with proper use of the insulating curtains and opening the house up at night and closing it during the day that the house remained cool and comfortable. One person remarked that several of his friends had remarked upon entering his home on a hot summer day,"Oh, I didn't know you had air conditioning." He doesn't! His only complaint was that sometimes he dresses too warmly, not realizing until he gets outside how hot it is.

Most people in this "neck of the woods" want some means of supplementing their heat with wood. Many just like to sit by an open fire. Although we always recommend an efficient woodstove, more than one client has insisted on having a fireplace. In every case where a fireplace was built, the clients have later admitted that they use too much wood and should have taken our advice and put in a woodstove.

Probably the most expensive passive solar device used in these homes is an automatic insulating curtain with a gold mylar finish. These high R-value shades are very important in cold climate design, basically doubling the net solar gain. This increase in performance will only be realized if they are actually used as intended. If the shades were operated manually, or not at all, they would not be as effective. A number of concerns existed about the acceptance of these curtains. We wondered whether or not they were being left to operate as intended, how the owners felt about them, and if they functioned well. Since the curtain is controlled by an outside temperature/solar sensor, it raises and lowers at different times each day. We wondered how well people accepted this irregular behavior. Several of these curtains have been installed in people's bedrooms where the unexpected raising of the shade might be undesirable, but surprisingly only one respondent said they would override the shade if they planned to sleep late. One even said that the opening or closing of the curtain gives them a sense of the weather. If it is going to be a hot summer day the shade closes earlier. They use the shade as a cue to close the windows for the day during the summer. All felt that the shades positively affected the comfort of the space. Most responded that the fabric was "too flashy" and that it was chosen principally for its thermal characteristics. It was surprising to find that most people only override the control two or three times per month usually for view or greater illumination. This indicates that the shades are, for the most part, being used effectively.

One of the interesting results of this study has to do with the automatic control of the curtain. It appears that it is not ideally suited for the cold, cloudy Michigan climate

(it was tested and manufactured in sunny Colorado). Although most owners only change the temperature setting three or four times per year, there was a rather large range of temperature settings(35° to 65°) and two respondents indicated that they changed it quite often. One tried to keep the temperature at 5.5°C to 8°C above the expected ambient daytime temperature while the other said he had adjusted it once or twice a week for a long time and finally went completely to manual operation. It appears that the single glazed tube that the sensor is in may lose too much heat to the out side and is therefore too dependent on the outside temperature; not an accurate simulation of the solar wall. Operation might be improved by adding a second layer of glazing.

Almost all of the respondents said that they were satisfied and would only make minor (non-solar) changes if they had a chance to build again.

When asked "How have your friends and guests reacted to your new home?",most responses were "most love it","very positively", "many are curious as to how the passive solar works" and one stated,"well received,.. ... but we have polite friends,too."

## 3. CONCLUSIONS

Generally, it has been found that owners are quite satisfied with their passive solar homes and have accepted the different solar features as things that help make their homes unique. It is important for solar designers to keep in mind that there are other parameters besides solar performance and that user preference and aesthetics should be foremost in the design process. Views and site conditions often override solar considerations. It is very important to conduct post-occupancy project reviews; to keep "looking back". Questionnaires are easy and inexpensive ways of getting feedback and post-occupancy site visits can be informative and fun especially if you bring a bottle of champagne. After all, we can't afford to make the same mistakes twice, there are always too many new ones to be made.

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# THE HUMAN ELEMENT-INFLUENCES ON SOLAR DESIGN AND PERFORMANCE

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## ABSTRACT

This paper discusses the critical human element in the design and performance of passive solar homes. The effect of occupant lifestyle on the performance of the home is explored via the likelihood that the occupant will perform certain design dependent operations. It is found that occupants by and large perform the operations, although not always in a manner that maximizes solar performance. Adequate instructions on how to operate the systems and whether or not someone is available to perform them appear to be two critical factors in determining how well the occupant performs the operation. Homeowners in this sample had very positive reactions to their homes and their expectations closely matched reality. Both of these are felt to have positive impacts on performance of operations.

## 1. INTRODUCTION

The thermal performance of a passive solar home depends upon two factors: 1) design of the home including construction quality, and 2) occupant behavior. While much has been done to monitor and calculate the effects of the design component of thermal performance little has been done towards analyzing the effect of occupant behavior. There is little doubt that occupant behavior is important in the energy performance of a home. It may in fact be the major cause for variation in consumed energy in similar homes. While the findings of the Twin Rivers study, which first analyzed this phenomena, can not be generalized to a set of solar homes they do lead to speculation that a similar effect may exist for passive solar homes. This speculation is, in fact, shared by a number of architects and builders.

The occupants of passive solar homes can affect the home's energy performance in two ways: 1) through the same type of energy saving activities available to all homeowners (eg., taking shorter showers), and 2) by performing or not performing certain design dependent operations (eg., using night insulation). This paper addresses the latter option. Studies have been done which indicate that persons considering living in a solar home would be willing to perform certain operations. This study is an attempt to determine if occupants of solar homes actually do perform these operations and what influences whether or not they perform them. In the beginning of the study a determination was made to examine four areas: lifestyle, knowledge of passive solar heating systems, reaction of the homeowner to the home and the design of the system used in performing the operation. A subsequent literature review suggested eight specific factors that could be influential. Occupants were also asked what they thought influenced whether or not they performed the operation.

The information provided by homeowners in this sample is particularly meaningful as 60% of these families did not buy the homes because they were solar homes.

## 2. METHOD

Ten passive solar homeowners were interviewed. The names of 15 homeowners were provided by builders and architects in Spokane. Each homeowner was contacted to determine if he/she would be willing to participate in a one to two hour interview. Two homeowners refused. Three were used as a pretest of the interview instrument. The remaining 10 constitute the sample for the study. The sample is small and not randomly selected. The results are, therefore, suggestive and can not be generalized.

The interview instrument was a 60 question form covering four areas: design and operation of the home, performance of the home, reactions and expectations to the home and demographics. To the extent practical questions were open ended to allow maximum freedom of responses.

The interviews lasted from one to two hours. Both husband and wife were interviewed together whenever possible. The interviews were conducted in the homes to give occupants an opportunity to demonstrate the operations when necessary. If it seemed that occupants were unsure about the answers to design questions, builders were contacted to confirm or provide the information. In cases where the husband and wife gave different answers both responses were recorded.

## 3. THE SAMPLE

### 3.1 Demographics

Fifty-six percent* of the owners were 31-45 years of age while 22% were younger than this and 22% older. Eight of the homes were occupied by married couples and two by single persons. One of the single persons had a roommate. In all but two of the married households the wife was employed full time. Four families had children under 18. The maximum household size was four, but 40% of the homes were occupied by only couples. 56% of the occupants had a college degree or more. Fifty percent of the households had incomes of $30,000 but less than $40,000 and 40% had incomes of $40,000 or more. The average length of occupancy was 9.9 months but all except one single occupant had lived in the homes for the past winter. This short occupancy period, a reflection of the solar market in Spokane, helps to ensure that information regarding initial reaction to the home and difficulties with the system would be more reliable as the experiences were more recent. It also suggests a need for follow-up to verify the findings after a longer occupancy period.

### 3.2 Design of the Homes

Twenty percent of the homes were custom built while 40% were semi-custom and 40% were spec homes. Nine of the homes were built as solar homes and one was a retrofit. Table 1 indicates the passive solar heating types.

The most common storage type was masonry floors in sunspaces although two homes had trombe walls and two had water storage combined with masonry floors. Ceiling insulation varied from R-19 to R-53, wall insulation from R-13 to R-40. All houses used vapor barriers, double or triple glazing and insulated doors. Eight homes had air lock entries and five had some degree of berming.

* The percentages in this paper are not always equal to the number of responses divided by 10 because sometimes the response referred to number of operations or occupants not households.

TABLE 1. PASSIVE SOLAR HEATING TYPES

| Type | # Of Sites |
|---|---|
| Indirect gain plus solar tempered | 1 |
| Indirect gain plus isolated sunspace | 1 |
| Isolated sunspace | 1 |
| Isolated sunspace plus direct gain | 4 |
| Isolated sunspace plus solar tempered | 2 |
| Envelope | 1 |

## 4. OCCUPANT PERFORMANCE OF OPERATIONS

### 4.1 Types of Operations

The types of operations that had to be performed are listed in Table 2. As indicated some of these operations were performed automatically. Some of the operations that were manual had to be performed only once or twice a year. Table 3 shows the number of operations that had to be performed on a daily basis.

TABLE 2. OPERATIONS BY TYPE

| Operation | Auto | Man |
|---|---|---|
| insulated window covering | 3 | 5 |
| shading devices | 0 | 10 |
| exhaust fans | 5 | 2 |
| transfer fans | 8 | 0 |
| ceiling fans | 0 | 5 |
| vents | 5 | 6 |
| windows for heat transfer | 0 | 6 |
| doors for heat transfer | 0 | 9 |

TABLE 3. NUMBER OF MANUAL DAILY OPERATIONS

| # Oper. | # of Houses | # Oper. | # of Houses |
|---|---|---|---|
| 1 | 1 | 4 | 2 |
| 2 | 2 | 5 | 1 |
| 3 | 3 | 7 | 1 |

### 4.2 Performance of Operations

While the following discussion pertains to those operations that had to be performed manually, it should not be assumed that because an operation was designed to be performed automatically that it was. Homeowners could override the automatic controls and in some cases the automatic systems experienced mechanical problems and did not work at all.

Occupants were asked to describe how and when they performed the operation in question. Responses to these questions were

analyzed to determine if the occupant was operating the system correctly and seemed to understand why it was important. In general the occupants of this sample appear to be operating the systems fairly well in the sense that they operate them correctly with a fair degree of consistency. The performance of the house is probably affected more by the following factors than by whether the operation is not performed at all:

1) Occupants must guess when to perform the operation (eg., will it stay sunny all day);

2) Occupants are sometimes hampered from performing the operation at the proper time (eg., they work late).

In reviewing the responses two exceptions stand out. Two homes had exterior shading systems for collectors which were designed to be manually operated. They were not because it was difficult to do so. Once they were put in place (generally the first hot spell in spring) they stayed in that position until they were removed. This obviously limited the potential for solar gain during any cool periods that followed. Secondly, respondents do not have a clear idea of what type of window treatment is effective in preventing heat loss during the winter. Products designed primarily for shading were often quoted as preventing night time winter heat loss. Partly because of this occupants were not interested in insulated window coverings, if they did not already have them.

4.3 Factors Affecting Performance

In addition to the homeowners' reaction to the home, eight factors were examined to determine if they had any affect on the likelihood that the operations would be performed. These factors included: 1) the ability to tell the difference when the system was used, 2) the extent to which the system was problem free, 3) whether or not someone was at home to perform the operation, 4) knowledge of passive solar systems, 5) whether or not adequate instructions were given on how to operate the home, 6) whether or not occupants expected to perform the operation, 7) feedback that performance made a difference and 8) the belief that the operation was important.

All of the occupants reported being able to tell the difference when they opened or closed insulated window coverings and vents. In four cases they were unable to tell the difference if a fan, shade or door was operated, but they performed the operation anyway.

There were few problems reported in performing the operations. The only problems preventing the occupant from performing the operation were the problems with the exterior shades for collectors mentioned previously.

In 12 percent of the incidences where an operation had to be performed manually the respondents said it was a major problem that no one was at home when they felt it would have been appropriate to perform the operation. As expected this group consisted of persons who worked all day and single occupants. Not being at home was sometimes a problem for 15% of the occupants. While no one reported that they did not perform the operation at all because of this factor, they certainly felt that they were not optimizing the system.

Twenty-one percent of the occupants reported having little or no knowledge of how a passive solar home operated before moving into this home. This group seemed to exhibit just as good a sense of how to operate the systems as the 79% who reported some to a great deal of knowledge. Everyone except the owners of the custom home and the retrofit said they had not been at all involved in the design of the solar features of the home. This lack of involvement does not appear to affect the likelihood that the occupants will perform the operations.

Seventy percent of the homeowners got instructions from either a builder, an architect or realtor on how to operate their home. Of the three homeowners who did not get instructions two would have liked them. In fact the only person who did not think instructions would have helped was a member of the local solar association and very well versed in how solar homes operate. Of those who received instructions 28% thought they were inadequate.

Only one family was given an instruction booklet. The other six families were divided as to whether or not they thought written instructions would have been helpful. The three who had good rapport with their builder did not feel the need for written instructions. They could and did contact the builder if something was not working properly. The other three thought written instructions would have been useful. Learning about the home took some time. It also took practice on the part of the occupants to fine tune the homes so that they were comfortable. Lack of instructions that were adequate made this difficult, but at this point all but one homeowner seems to understand how both the manual and automatic operations are performed. The necessity for this learning period and the fact that builders may not be available for ongoing instruction does seem to indicate that an instruction booklet would be very useful for future owners.

Occupants generally expected to perform the operations required of them.

Ninety percent of the occupants strongly agreed or somewhat agreed with statements that "It is important that I do whatever I can to save energy." and "I am very conscientious in saving energy in my own home and at work." This would seem to indicate an underlying belief in the importance of helping the home to perform well. Research has shown, however, that people can hold "appropriate attitudes" and still not act in a manner consistent with these attitudes. Caution must be used in assuming that a homeowner who exhibits similar attitudes would actually perform the operations required.

As for feedback all of the occupants examine their utility bills and 60% compare them with neighbors. Research on feedback procedures and studies examining how consumers analyze their utility bills seem to indicate that, as they are now distributed, utility bills are not very effective feedback mechanisms. They are, however, the only type of feedback that most consumers get and this would seem to indicate a need for further research as to how they could be utilized.

Occupants were asked what they thought influenced whether or not they performed the operations. Table 4 presents a summary of these responses.

TABLE 4. MOTIVATORS

| Motivator | # of Responses |
|---|---|
| privacy | 5 |
| needs of plants | 4 |
| heat transfer | 10 |
| comfort | 17 |
| light control | 2 |
| other | 6 |

Not unexpectedly thermal comfort and the desire to transfer heat plays the largest role. Responses to the question tended not to be very introspective so that the question of what specific lifestyles influence the likelihood that the operations will be performed is still unanswered.

## 5. REACTIONS AND EXPECTATIONS

Reasons for buying the home and reactions versus expectations were also analyzed for a possible influence on whether or not the occupants performed the required behaviors.

### 5.1 Reasons for Buying the Home

Sixty percent of this sample did not buy the homes because they were solar homes. The reasons they gave for buying the homes were similar to any new homeowner: they liked the design, "it was a good deal financially." Four of these owners did report, however, that the concept of solar was also a factor in their decision to buy this particular home. The fact that people buy a home for reasons other than it is a solar home does not seem to mean that they will not perform the operations required.

### 5.2 Expectations Versus Reality

Eight percent of the occupants had a very positive initial reaction to the home. The other 20% were also positive but this was tempered by the feeling of difference between this home and their former home. Other than "I loved it or liked it," openness and light were the most frequently mentioned initial reactions to the home.

Only one couple expected to make changes in their lifestyle as a result of living in a solar home. This was the couple who remodeled the home to include a 350 $ft^2$ greenhouse. They made the change anticipated (involvement with the greenhouse) and consider it a life enhancer. Three other homeowners reported lifestyle changes that they did not expect. The changes by household were: 1) spend less time worrying about keeping the house warm, 2) now has a house sitter when she is gone to take care of plants in the greenhouse, and 3) more considerate of space and privacy of others because of the openness of the design.

When asked how living in the home compared with their expectations, 50% said better than anticipated, 33% said about the same and 17% had a negative reaction. In both cases the negative reaction was due to mechanical systems. One said the fans were too noisy and the other had a mechanical system which did not work at all.

Three of the families are using some of the solar heated spaces differently than they thought they would. In two cases the sunspace did not get warm enough to use in the manner they would like to. In the third case the couple found that they preferred eating in the direct gain area and not in the dining room which was located behind the greenhouse.

Ninety percent of the families said they were very pleased with the performance of their home. The remaining homeowner was somewhat pleased. Eight of the homeowners reported the level of satisfaction was related to both the solar and other aspects of the home.

This sample had a very positive reaction to the homes and were also very pleased with their performance. Their expectations were generally met with the realities of living in the home. The only major problems men-

tioned consistently was dislike for the two stage fan that circulated room temperature air and the fact that the greenhouse was too hot or cold to really use as an additional space. As none of the occupants expressed negative reactions to the home or had expectations vastly different from reality, it is difficult to say whether or not these factors influence the likelihood of occupant performing the operations.

## 6. PERFORMANCE

Actual monitoring of the homes to determine thermal performance was beyond the scope of this study. In an attempt to examine performance three measures were used: calculations showing the effect of night insulation solar saving fraction, occupant perception, and total purchased energy. Table 5 shows the percent of solar fraction supplied to a direct gain system in the Spokane area with and without night insulation of R-5. Table 6 shows the amount of energy that homeowners thought was supplied by the solar.

TABLE 5. SOLAR SAVINGS FRACTION WITH AND WITHOUT NIGHT INSULATION (Direct Gain 250 $ft^2$ Glazing)

| Month | With | Without |
|---|---|---|
| Oct | .80 | .58 |
| Nov | .22 | 0 |
| Dec | .06 | 0 |
| Jan | .07 | 0 |
| Feb | .25 | 0 |
| Mar | .44 | .18 |

TABLE 6. OCCUPANT PERCEPTION OF ENERGY PROVIDED BY SOLAR

| Percent | # of Responses |
|---|---|
| less than 25 | 1 |
| 25-30 | 2 |
| 50 | 2 |
| 90 | 1 |
| not much | 1 |
| didn't know | 3 |

Eighty percent of the owners were very pleased with the energy performance of their homes and 20% were somewhat pleased. This is not surprising in view of the fact that all of the homeowners thought the solar home was much more efficient in an energy sense than the home they lived in just before they moved into this home.

The total purchased energy, normalized for weather, is presented in Table 7. This figure can be used to compare houses to each other and to other non-solar homes. These figures are somewhat high because they were extrapolated from the occupancy period which, except for number 11, was less than a year.

TABLE 7. TOTAL PURCHASED ENERGY

| Site # | KWH/$m^2$ | Site # | KWH/$m^2$ |
|---|---|---|---|
| 4 | 342.75 | 9 | 166.20 |
| 5 | 183.70 | 10 | 352.30 |
| 6 | 253.10 | 11 | 85.60 |
| 7 | 169.90 | 12 | 291.70 |
| 8 | 200.40 | 13 | 282.10 |

## 7. CONCLUSIONS

The occupants of the passive solar homes in this sample had from one to eight operations that they had to perform daily to ensure maximum performance of their home. It was found that while most of the occupants performed these operations they were not always able to do so in a manner that would maximize performance because: 1) they were not always able to anticipate the weather conditions, 2) they were not always there to perform the operation when it needed to be performed, 3) the prime motivator for performing the operation was sometimes contrary to what was best for thermal performance (eg. one owner would close the insulated window covers during the daytime in winter if she thought her plants were getting too much light). With the exception of large exterior shading devices none of the occupants expressed an unwillingness to perform the operation. Adequate instructions on how to operate the home appear to be a critical factor in determining whether or not the occupant really performs the behavior appropriately. Some of this sample would have preferred them in writing but this does not appear to be necessary if the builder can be contacted. It is suggested that a booklet would be more important to future homeowners.

One of the common solutions suggested to the problem of occupant maintenance is to automate the systems. While this is certainly an option to consider in some cases it does not appear that this solution needs to be or should be adopted universally. First of all it assumes that an automated system will always work. This was not the case in this sample and the frustrations of the homeowners who had mechanical problems were much greater than those who wished they could have raised their insulated window coverings when a cloudy day turned sunny. Besides as one homeowner who had an insulated curtain

wall pointed out: "What would I do if the power went out and the curtain wall was down?" Rather than totally automate the systems, adding additional cost, another approach may be to build the systems so that they could be automated if the owner wished to.

Finally, it appears that, as the market for solar homes expands to homeowners who buy the homes for other reasons, these new generation homeowners will also willingly perform the operations required to make the home work. The most notable exception to this might be the choice of window treatments other than insulated window coverings.

## 8. ACKNOWLEDGEMENTS

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# PASSIVE SOLAR HOMES: OWNERS REACT TO THEIR INTERIOR ENVIRONMENTS

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## ABSTRACT

Perceptions of owners of the interior environment of 28 passive solar homes (PSH) in Virginia were investigated during spring 1982. Almost half reported changes in room use in their current residence as compared to a previous non-solar home. Some noted they entertained to a greater extent therefore staying at home more frequently than in the past.

Thermal comfort during different weather conditions was ascertained. Most subjects found their homes to be fairly comfortable year round. Some were cooler than they preferred in winter and warmer than they desired in summer. None of the respondents described their homes as uncomfortably hot or uncomfortably cold during the four seasons.

Almost all subjects were satisfied with the interiors of their dwellings and general enthusiasm was apparent. For the most part furnishings had not been purchased especially for these homes. However, those who did so selected pieces that would be less prone to sunlight degradation. Some owners had not lived in their residences long enough to give conclusive evidence regarding appearance or other changes in their artifacts.

## 1. INTRODUCTION

Interior spaces in homes and other man-made environments affect people perhaps more directly than outdoor spaces or buildings as structural configurations. However, interior space and how individuals deal with it as their micro-environment has received less attention from researchers than it deserves. It is reasonable to expect that there is a great deal to be learned about the real meaning of personal housing space, feelings of comfort, and satisfactions associated with the use of that space.

Of course, most persons exhibit rather protective and defensive attitudes toward the interior of their dwelling place. Yet it is obvious that one's most intimate life space, the residence, affects the well-being and extent of life satisfaction at least as strongly as any other aspect of the environment.

This research investigated attitudes of owners of PSH, toward various considerations associated with the interior environment including articulation of design features, use and performance of rooms, thermal comfort, and general satisfaction.

## 2. METHODOLOGY

### 2.1 Instrument Development and Data Collection

During the winter of 1982 an interdisciplinary team of researchers from the Colleges of Human Resources, Architecture and Urban Studies, and Arts and Sciences cooperated in determining the types of information that were of specific interest to them that they believed that owners might readily share. A decision was made to collect data through the use of a self-administered questionnaire. Therefore the most experienced survey researchers designed the instrument incorporating questions that reflected the interests of the entire team.

Several drafts of the instrument were developed and revised as deemed appropriate in consultation with the other scientists. Pilot testing was conducted during early spring with several owners of PSH who were not included in the study. As a result some minor refinements of several questions were made for clarity of intent and ease of administration.

Attached to the questionnaire was a cover sheet outlining the general purpose of the study. In addition, potential respondents

were assured that the information provided by them would be of benefit to the research community, would be held in strictest confidence, and used only for statistical purposes.

### 2.2 Sample

At various area chapter meetings of the Virginia Solar Energy Association, the researcher contacted approximately 60 owners of PSH in late winter 1982. Attendees were asked to cooperate in an interdisciplinary research project regarding their feelings and perceptions about their dwellings. The major proportion of individuals indicated a positive response and were given attractive booklets detailing participation in the Virginia Passive Solar Study. Along with the questionnaire all potential respondents were given a self-addressed postage-paid envelope in which to return the completed instrument.

Some owners in one section of the commonwealth were contacted on a one-to-one basis and asked individually to respond. The data collection procedure was essentially the same as for the other subjects.

When subjects did not return their questionnaires within a couple of weeks after distribution, follow-up telephone calls were made encouraging the participants to return the completed forms. In addition, post card reminders were also utilized. Although initially many of the owners appeared enthusiastic, 28 or 44% elected to return usable data.

### 2.3 Assumptions

Three assumptions emerged during the formulation of the research: (1) the sample was convenient in nature and was not necessarily representative of all PSH owners in Virginia, (2) owners were well-educated and were in the middle income bracket, and (3) respondents would have a strong interest in PSH design.

### 2.4 Treatment of Data

Advice of a statistician was sought regarding appropriate methods to characterize the data. It was determined that statistical analyses to determine relationships among variables were inappropriate due to the limited sample size. Therefore frequency and percentage distributions were calculated to describe the sample and characterize the other general findings.

## 3. FINDINGS AND DISCUSSION

### 3.1 Subjects

Families who chose PSH tended to be small and were fairly young. Two-thirds of the respondents were less than 40 years of age. An approximately equal number of adult males (27) and adult females (25) were present as well as 23 children. Youngsters were generally school aged with a fairly equal distribution between six and fourteen years. Incomes were fairly high. About two-thirds were in the $20,000 - $50,000 per year range; an additional 25% earned in excess of $50,000.

### 3.2 Design Input

Articulation of design features was important to this group of home owners. Three-quarters (76%) worked directly with their architects and builders to make sure that generally desirable features were incorporated into their plans. The selection of specific solar features was also of major concern. Design of the floor plan or space for living involved 68% of the subjects. Almost the same proportion (68%) were involved in decisions relative to the building site. Owners were also highly involved during the building phases. Almost half (43%) contributed physical labor in conjunction with construction or renovation process.

### 3.3 Specific Room Use

One page of the questionnaire consisted of a grid with a list of activities in the left-hand margin and the designation of various rooms across the top as columns. Subjects were instructed that for each of the activities listed to check the room or rooms in which that event occurred in their homes. Tasks such as reading and book work, television viewing, telephoning and visiting were among the activities given.

Intense as well as light reading was most prevalent in the living room (50%) and in the bedroom (54%). Communal television watching behavior was highly similar to that for reading/book work tasks. Private and family music listening most often occurred in the bedroom (43%), followed by the living room (29%), and in the den or family room (21%).

Food related functions were also of interest. Informal table dining was most

predominant in the kitchen area (54%); 39% had meals in the dining room or space, and 11% ate in the living room. Formal dining predominated in designated dining areas (64%). Snacking was an acceptable activity in various rooms. Kitchens were first (61%), dining areas were next (29%), and the living room was a close third (25%).

Bedroom areas were selected for a number of tasks including table games, napping and sleeping. Childrens' games were most often played in the bedroom (36%), dining area (32%) and kitchen (14%). Eighty-two percent chose a bedroom for napping; however, the living room was second with 39%. Night sleeping for the most part was confined to the bedroom. One or two persons slept in their living room. Perhaps this was for lack of furniture or that the home had not been completed in its entirety.

Telephones were available in many rooms. The bedroom (79%) was the location most often chosen. This area tends to provide for more privacy than other types of rooms. The kitchen was also a popular telephoning center (61%). Dining (21%) and living room areas (18%) were also convenient.

Patterns associated with visiting by adults and children differed to some extent although not surprisingly. Socializing with other adults was most likely to occur in the living room (75%) followed by the dining room (14%) and bedroom (14%). Visits by children were most common in the living room (43%), family room (25%) and in the dining area (11%).

Handiwork tasks such as machine sewing were most often confined to the bedroom (43%) followed by the dining room (11%). Hand sewing was done in areas of general social activity: living room (36%), bedroom (25%), and in the dining room (8%).

### 3.4 General Home Use

Respondents were asked to identify the ways in which their current PSH were used differently from previous non-solar residences. Some changes were noted as reported in Table 1. Ten (36%) made greater use of common rooms, six (21%) stayed at home more and entertained to a greater extent. Although not reflected on the previous table, four subjects (14%) described the use of rooms in different seasons. Greenhouses were used as places for entertaining in the summer and as a location for work and enjoyment of sun in the winter. Two individuals noted that bedrooms were used for fewer activities in winter because of the lower ambient room temperatures.

TABLE 1. Changes in Home Use

| Changes | No. | % |
|---|---|---|
| Use common rooms more | 10 | 36 |
| Stay at home more | 6 | 21 |
| Entertain more | 6 | 21 |
| Use "great" room | 3 | 11 |
| Use bedrooms less | 2 | 7 |
| Use bedrooms more | 1 | 4 |

There appears to be a trend toward more functional design features incorporated into PSH. Common rooms were used for various family activities as well as more formal entertaining. The greenhouse served as a functional solar collector and was used throughout the seasons for various family activities.

### 3.5 Perceptions of Interior Comfort

Subjects were presented with another grid and asked to rate on a nine point scale the thermal comfort in their homes during various weather conditions (cloudy, sunny) and in the different seasons (winter, spring, summer, fall). Because of the small sample these nine categories were collapsed into three representing warmer than comfortable, comfortable, and cooler than comfortable. About 20% noted that they were a bit cool in the winter and slightly too warm in the summer. During the winter season they were more comfortable on sunny days than on cloudy ones. The reverse occurred in summer where more owners (68%) reported being uncomfortably warm on sunny days. Overall, most respondents were happy with the thermal conditions during the spring and fall seasons. It is interesting to note that none of the subjects checked a one (uncomfortably cold) or a nine (uncomfortably hot) on the grid which was an indication of severe discomfort.

When the ambient room temperatures were unsatisfactory the subjects devised various coping strategies to insure greater comfort. During extremely warm periods windows were opened to increase air flow; subjects wore less clothing and sometimes activated air conditioning units and fan systems. When homes were not quite warm enough wood stoves and fireplaces were utilized; auxiliary heating systems were made operational and subjects wore heavier and more layers of clothing. Regardless of condition, clothing appeared to be the first system regulated followed by those which consumed other energy resources.

### 3.6 Satisfaction with Interior Environment

A decided majority of the respondents (54%) were very satisfied with the interior of

their home. An additional 43% were satisfied bringing the total to 97%. Several (14%) suggested that as a result of the earth-sheltering and the excellent insulation that their homes provided an interior atmosphere of privacy and quiet not heretofore experienced. Several others (14%) said that they found the natural warmth and light from the sun most enjoyable and very satisfying. Two respondents noted that the interior atmosphere was "healthier" because they did not have induced heat and cooling systems. The natural lighting was cited as a distinct advantage.

Complaints were few regarding the interiors. Three (11%) reported problems with high humidity. Elimination of odors without significant heat loss was mentioned by only two subjects (7%). Most other negative comments that were recorded were related to various aspects of the exterior features.

### 3.7 Interior Construction and Furnishings

Seventy-five percent of the home owners had thermal masses in the floors of their solar homes. Of these, 18 (64%) were satisfied with the hard floor surface. Those who were dissatisfied suggested that the thermal mass used was not an appropriate material for solar heat gain and storage. Eight subjects (29%) covered part of the thermal mass with an area rug. With the exception of one individual these were placed beyond the point of sun penetration and covered only a small amount of floor space.

The majority (82%) of the participants had not purchased specific furnishings that they felt would perform well in their solar homes. Those who did purchase specific furnishings chose light airy pieces and light to earth tones so that fading would not be readily apparent. Eleven percent had trouble with fading window treatments, wall hangings, upholstered pieces, carpeting, and accessories. Important to note is that many respondents had not lived in their homes long enough to give conclusive evidence about fading of these artifacts. Seven (25%) home owners experienced problems with glare due to the solar features of the home, however the majority corrected these types of problems with shades, blinds or draperies.

Three-fourths of the home owners reported the use of some type of energy efficient window treatment. Several (25%) had double or triple pane windows, two (7%) had insulated draperies, and 25% used shutters or shades. An additional five (18%) respondents indicated that they had made or purchased window quilts. This window treatment is most often a roller-like shade device of one or more sheets of aluminized Mylar, sometimes in combination with fiber-filled cloth. Many times these treatments were used in combination with interior shutters to add an extra layer of insulation.

## 4. SUMMARY

As a total group this sample of 28 owners seemed to react very favorably to the interior environment in their PSH. These persons were highly involved in the design and construction processes and were therefore committed to the concept of solar energy utilization.

Living room, dining spaces, and kitchens served as the areas for the focus of many individual and family activities. Some tasks which required privacy or specialized concentration or equipment were often associated with the bedroom.

Some families said that they used their homes differently from previous non-solar dwellings. A small number stayed at home more and were pleased with the privacy and new appreciation of nature that they experienced.

A majority of the subjects expressed real satisfaction with the interiors of their homes. Most had not purchased special furnishings. However, a few persons noted that fading of their furnishings and other artifacts tended to be a slight problem.

For the most part, subjects found their homes thermally suitable for their needs. If the dwellings were either too warm or too cool, coping strategies were devised to bring the temperature into balance.

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# THE OTHER DEBATE OF OVERHEAD GLAZING: SAFETY

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## ABSTRACT

This paper examines the recent concern about the actual risk of safety glazings, specifically tempered, laminated and wired glass in overhead applications. This debate has been prompted by several spontaneous failures of skylights in populated areas. The primary questions are: how does overhead glazing fail, what are the failure rates and what are the risks associated with those failures?

A brief report of ICBO, CABO and Southern Codes shows wide divergence on this issue. Proposed changes in these codes will reflect the conclusion of this national debate.

This paper will report the information which has been compiled by City, State and Regional governments; Manufacturers of Glass and Glazing Systems, Independent Test Laboratories and Professional Designers. The paper's purpose is to inform design professionals better about the potential risks involved with overhead glazing.

## 1. GLASS AND ITS INCREASING ARCHITECTURAL USE

The debate historically at ASES Conferences on sloped glass centered on economics, thermal performance and aesthetics. One assumed safety glass was just what it was labeled.

Glass in general has some attractive properties; clarity, durability, versatility, cost, transmissivity, and strength. As a supercooled liquid, attention needs to be paid to its limitation of configuration. Greater glass strength is derived where primary loads are placing the piece in compression. Relatively little strength is available when placed in tension — high strength when used as a column (vertical-compression), much less when used as a beam (sloped-tension).

A comparison of features of safety glass:

Wired - The industry standard for many years for skylights. Most building codes still are based on wired glass as the only fire-rated glass available. Some disadvantages are: strength; about one-half as strong as plate glass of equal size; it is easily broken in shipping and installation. Wired glass is not recommended for insulated units nor for use with tints. The presence of wire is an aesthetic drawback for some.

Laminated - Entering the market in the 1950's. Laminated annealed glass offered an alternative to wired glass which could be tinted. Annealed laminated has approximately the same strength as wired glass. It has one of the highest breakage rates for shipping, handling and installation. In earlier years edge separation and fading caused concern over longevity. Proper installation and appropriate selection of laminate should insure failed lites to stay within the frame.

Tempered - The strongest of all safety glass is approximately 10 times as strong as wire glass of equal thickness. One unique drawback is upon failure of the lite it will fall from the opening. When tempered glass breaks it crystalizes; however, these crystals interlock and some very large pieces of interlocked crystals can fall.

Spontaneous breakage is an unknown variable caused by inclusion of nickel sulfide stones. All glass may contain nickel sulfide stones. They are formed from nickel, a foreign material in the glass batch and from sulfur from the glass furnace. These chemicals combine to form spherical stones in the molten glass. These stones are tiny and cannot be readily observed or eliminated from the glass sheet.

As the glass cools the stones expand producing microscopic vents in the glass. This condition does not create a problem within annealed glass. With tempered glass, on the other hand, the sudden cooling prevents changes in the size of the nickel sulfide stones and causes internal stresses around the stones.

Spontaneous breakage occurs when tempered glass containing nickel sulfide stones is exposed to solar radiation. When exposed to solar heat a change in the nickel sulfide stones takes place and tension stress occurs. The amount of stress depends upon the amount of solar heat and the length of time the glass is exposed to the heat. Excessive heat and time will cause spontaneous breakage in fully tempered glass.

## 2. THE OPINIONS

The recommendations Tishman makes to its clients - and which we believe have general acceptance by a large number of skylight manufacturers, curtainwall consultants, and glazing manufacturers - to specify the use of laminated glass on the inboard lite if insulating glass is used, or to use a single laminated sheet if the skylight is a single lite.

Laminated glass, if broken, will typically stay in the frame if it has been properly installed and not fall, endangering occupants below.

The laminated glass should be made up of heat-strengthened glass, with its thickness dependent upon the size and structural requirements. The outer lite in an insulating unit should then be monolithic heat-strengthened glass. There are those who prefer the use of laminated tempered or annealed on the inboard and monolithic tempered on the exterior lite.

Tishman does not recommend the use of screens, even though the new versions of the codes will allow their use. While screens restrain the large fragments from falling, a large number of smaller fragments, some dagger-like, still fall through. These can cause substantial damage below. They will injure people and, in at least one instance to my knowledge, this fall-through has caused substantial damage to architectural components below.[1]

From our viewpoint the use of tempered glass or, in some cases, heat-strengthened glass, for the exterior light is pretty well accepted. For the interior lite, we feel strongly that laminated glass, which can be heat-strengthened and will be retained in the opening even if it does become shattered, is more satisfactory than tempered glass. The latter, upon breakage either spontaneously or from impact, can fall to the area below sometimes in clusters.

There is no question that fully tempered glass will withstand far more impact than annealed or heat-strengthened laminated glass. But, balancing that against the "final safety" of the laminated glass is what determined our choice, and it appears that major glass companies and skylight systems manufacturers are also leaning in this direction.[2]

Fully tempered glass has been traditionally used in place of other glass products in applications requiring increased strength and fail-safe characteristics. It withstands greater wind loads and snow loads than other glasses of equal size and thickness. When tempered glass fails the particles are small and relatively harmless. For this reason, it is used in storm doors and patio door assemblies. Tempered glass has a high resistance to thermal stresses and most types of impact. This makes it an ideal product for uses such as spandrel areas and escalator and stairway balustrades. The combination of its properties has resulted in its preferred use in skylights and sloped glazing. Laminated glass, wired glass, and some rigid plastics are also appropriate within certain limits. These limits are related to impact resistance and the greater deflection of these materials under loads compared with tempered glass of the same size and thickness. A secondary consideration is the lower cost of tempered glass.

On the rare occasion when tempered glass fails, it may fall completely from the opening. This is less likely to occur with laminated glass providing the glass size is small and the breakage is not caused by a large impacint object. For large panes of laminated glass, the glass may deflect, crack, and "fold" and come out in a single piece.

The fragments from tempered glass are typically cubical in shape. Some fragments may be elongated. The shape of the fragments is related to their proximity to the point of the break origin. A number of fragments may be loosely "knitted" together and fall in this manner. The fragments do not have the sharp edges normally associated with broken glass.

The history of tempered glass in skylights is excellent. Injury to people and serious property damage have been negligible.

The use of retaining nets or screens may be reasonable added protection under certain skylights regardless of the type of glazing used. This would be dictated by the risk of

breakage and the resulting consequences. There is no valid reason, however, based on the experience of skylight manufacturers to require nets or screens for tempered glass and not for the other products. To do so would unfairly penalize the skylight manufacturers who use tempered glass without any compensating benefit related to public safety and welfare.[3]

2.1 Minimizing Glass Breakage from Inclusions

Breakage of fully tempered glass from inclusions is rarely more than a fraction of a percent in any building. However, there are certain applications where even a lower potential incidence may be necessary. This can be achieved by a special factory heat-soaking process. In this process the combination of time and temperature used are more likely to cause transformation of an inclusion than exposure of the glass to natural weather conditions for the normal life of a building. Thus, glass that may have later failed in a building can be expected to break in the heat-soak process.

All fully tempered glass furnished by LOF for the following applications is heat-soaked.

1. skylights
2. glass sloped more than 15 degrees from vertical.
3. spandrels.

In cases where the strength and breakage characteristics of fully tempered glass are not required, the specifier might choose heat-strengthened glass.[4]

The breakage pattern for ordinary annealed glass is well known. Heat-strengthened glass breaks in a similar way when it fails. Tempered glass is designed to fracture into small, roughly cubic bits when it fails, but effective "dicing" requires a residual compressive stress of at least 15,000 psi, substantially above the 10,000 psi required by ASTM standards. In addition, particles may remain attached, falling in large plates or shards until separated by impact. If the plates fall vertically, the force behind the cutting edge may be substantial.

Finally, it should be noted that while people expect their windows to break, they do not necessarily expect pieces of their roofs to fall in, either by impact or overloading. Given the chance of serious injury should failure occur, it would seem prudent to design skylights both to carry the design load, and to provide a "safety net" or "basket" to protect people below from the effects of a skylight failure.[5]

Because of its very low retention capability, tempered glass is presently the subject of considerable controversy in the skylight and glazing industry. Some skylight manufacturers consider tempered glass as potentially harmful and suggest that a wire mesh screen be situated below the glass to disrupt dice clustering (loosely knitted mass of cubical particles) and therefore minimizing chance for serious injury. Other skylight manufacturers contend that there is no significant injury record to justify the new restriction. It is not the intent of this guideline to take a position, but only to present the basic argument. The design professional should consult applicable model or local building codes for possible restrictions. Depending upon the building code, tempered glass may be used in a single glazed or as either the exterior or interior lite of an insulating glass unit.[6]

Our firm has been employed to gather the data and report the results on a historical data collection of sloped glazing applications. All data collected are confidential and only totals have been released on this report.

The following data encompass a composite total of 37 years. The years range from 1975 thru 1980 with the average per response being four years.

Of the 13 firms resonding to the survey, only nine had data as four firms did not use tempered glass.

Number of individual contract jobs involving the use of single or multiple layer monolithic tempered glass, 4,001.

Approximate total number of lites involved, 63,471.

Specific number of in-place or post installation breakages, 62.

Specific number of breakages involving property damage, 1.

Specific number of breakages involving human injury, 2.

2.2 Breakage Comments

1. Approximately 10 lites on one project — glass was improperly tempered (per lab. response) and all replaced.

2. One unit: Single lite — ⅛ BRZ temp.

3. Three units: (Two reflective, one clr.) top lite breakages.

4. One unit: (Bottom clr.) caused property damage (broke light fixtures) and minor cuts to pedestrian; approximately 10' below skylight.

5. One unit: (Bottom clr.) hit person — two floors below; no injury.

6. One unit: No property damage; no injury.

7. Total breakages only 2 involved people — one with injury; property damage negligible.[7]

3. CODES

The wheels of progress turn slowly. Two model codes (Southern and Building Officials & Code Administrators - BOCA) currently have sections on skylights which require the use of either laminated glass or annealed or tempered glass protected by screens. The Board for Coordination of Model Codes (BCMC) recommended to the Council of American Building Officials (CABO) the use of standardized code language adopted by BOCA. The International Conference of Building Officials (ICBO) on the West Coast is currently considering the issue and will address the issue again in this round of code changes.

The ICBO code is as follows:

"All glass in skylights shall be wired glass, laminated glass with an approved interlayer having a minimum thickness of 0.030 inch or tempered glass, minimum thickness 7/32 inch, except that skylights over vertical shafts extending through two or more stories shall be glazed with plain glass as specified in this section, provided that wired glass may be used if ventiliation equal to not less than one-eighth the cross-sectional area of the shaft but never less than 4 square feet is provided at the top of such shaft.

"Any glass not laminated glass with an approved interlayer having a minimum thickness of 0.030 inch, wired glass or fully tempered glass shall be protected above and below with a screen constructed of wire not smaller than No. 12 U.S. gauge with mesh not larger than 1 inch. The screen shall be substantially supported below the glass.

"Ordinary glass may be used in the roofs and skylights for greenhouses, provided the height of the greenhouse at the ridge does not exceed 20 feet above the grade. The use of wood in the frames of skylights will be permitted in greenhouses if the height of the skylight does not exceed 20 feet above the grade, but in other cases metal frames and metal sash bars shall be used."

4. SUMMARY

As stated earlier there is no uniform consensus of standards for skylights and sloped glass, nor test procedures to establish performance. Agreement has been reached that it is possible for tempered glass to spontaneously break and possible for clusters of glass to fall together. The debate remains what is the probability of such occurrences? Is the increased impact strength a necessary ingredient for some applications?

Individual application decisions will ultimately default to the architect, designer or contractor of the project. Careful weighing of desired structural characterics will best guide the choice.

For a list of references on this topic including 78 articles and papers request, in wiring, from the author at the above address.

Special thanks in compiling information is given to Justin Dune, City of Portland, OR., and Rob Lerner, Northern Sun, Seattle, WA.

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# RADON LEVELS IN METROPOLITAN DENVER HOMES

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## ABSTRACT

Radon measurements were made in 30 relatively-new electrically heated houses in the metropolitan Denver area. The sample was selected from a group of 59 in which air leakage measurements had been determined previously. The sample was not intended to be representative of the Denver area.

The study had two prime objectives: to evaluate radon/radon-daughter levels in the sample tested; to determine if a correlation exists between radon-derived radioactivity and air leakage.

Radon detectors (Track Etch® Type B, bare) were placed in basements or crawl spaces, living and bedroom areas of the house sample and radon was monitored during February and March 1982, a time of normally minimum ventilation.

Radon daughter standards do not exist for the Denver area. In comparison with those established elsewhere, high levels were found in a small, but not insignificant, percentage of the sample tested. An approximate inverse linear relationship was observed between radon daughter concentrations and air leakage, suggesting that the tighter the home, the greater the opportunity for increased indoor radioactivity.

Options for remedial actions were described. These should be given serious consideration in construction of tight energy-efficient houses.

## 1. INTRODUCTION

Public concern with unnecessary exposure to ionizing radiations is realistic, however contributions from radioactivity in the home are often ignored. This source of exposure may be exacerbated by using certain energy-conserving measures. For example, it is recognized that restriction of exchange between indoor and outdoor air will increase the concentration of indoor air pollutants. Of the latter, radon gas is perhaps one of the most hazardous, particularly when trapped in a closed environment for periods sufficiently long for it to build up significant concentrations of its short-lived progeny. These highly radioactive daughters of radon have long been associated with the formation of lung cancer in miners working in poorly ventilated underground uranium mines.

The exposure potentials in the home are far less severe than in mines; nonetheless, a larger segment of the population is affected and occupants may be exposed for longer periods of time.

This article reviews early measurements of radon levels in a sample of metropolitan Denver houses. [1] It examines also the generic sources of the problem in the home, considerations of health effects attributable to exposure to radon daughters, and mitigating actions which can be taken to reduce their radioactivity levels.

## 2. RADON CHARACTERISTICS AND SOURCES

Radon (Rn-222) is the immediate daughter of radium (Ra-226), itself a decay product in the uranium (U-238) series. Uranium is ubiquitous in the earth crust, and it is found in all soil and rock at average concentrations of about three parts per million. Along Colorado's Front Range, uranium is known to exceed the crustal average by approximately a factor of 2. [2] Radium, by virtue of its greater mobility, is frequently distributed differently than uranium. Any material containing uranium will also contain radium and must be seen as a potential source of radon. Construction materials, such as aggregate, are generally obtained locally. Thus, houses constructed in regions of higher radioactivity may be expected to utilize building materials of relatively high radioactivity values, often contributing materially to the radon source term. Other potential indoor sources of radon are well

water, if drawn from a radium-bearing aquifer, and natural gas used for heating and cooking. These latter sources were not considered viable in this study (see next section).

Although radon is formed continuously, release of the gas from soil or rock is dependent on the physical integrity of the matrix material containing radium. Its ability to migrate from the radium source is governed by physical laws of diffusion and permeability of the medium, meteorological parameters, such as pressure, temperature and moisture, and radon's 3.8 day half-life. Thus exhalation may not scale proportionally with radium concentration.

Radon entry into the house is primarily via the basement through diffusion and transport from the soil, floor and walls. Inadequately sealed plumbing penetrations in the floor and cracks in the floor and walls expedite its entry.

## 3. DENVER HOME SURVEY

Measurements were made during a two month span (February and March) in 1982, a period of normally minimum ventilation, in 30 relatively new electrically heated Denver suburban houses. The sample was selected from a group of 59 in which air leakage had been determined previously.[3] The sample was too small to serve as a basis for inferring radon progeny levels in Denver area houses. However, it may be used as a "barometer" for those which enjoy tight construction.

*Track Etch*® *Type B bare radon detectors* (Terradex Corporation) were used in the testing program. One detector was placed in the basement or crawlspace, one in the living area and one in the bedroom. Each was located generally on walls near the ceiling, and positioned for access to normal free air movement. Radon levels in picouries per liter (pCi/ℓ) were converted to working levels* using WL ratios (WLR) of 0.33, 0.50, and 0.67. WLRs were assumed from a grouping of air leakage results, i.e. 0.33 - highest and 0.67 - lowest air leakages. Grab sampling, by collecting air samples, filtering and alpha counting was performed using calibrated equipment in four houses with high WLs. Reasonably good agreement was found with Track Etch results.

Air leakage tests were performed on these houses by Manville Corporation in 1981, under an Electric Power Research Institute contract. The fan pressurization/depressurization method (ASTM E 779-81) was used in each house, with basements isolated. Insufficient data exist to relate fan air leakage data with normal air changes per hour (ach), however ratios of 4-20 have been suggested, i.e., ach = 1/4 to 1/20 of the fan data.

### 3.1 ANALYSIS OF RESULTS:

To determine if a correspondence exists between air leakage and WLs, living and bedroom area WLs were averaged and plotted against induced air changes per hour (IACPH). Considerable scatter was noted at WLs approximately 0.02 and lower - the values whose measurement uncertainty is greatest. (Terradex reports Track Etch B detector errors as follows: ± 15 percent at 0.015 WL; ± 25 percent at 0.007 WL; ± 50 percent at 0.004 WL.) At levels exceeding 0.02, however, there appears to be an approximate inverse linear relationship between IACPH and WL. Although these high values have greater certainty, insufficient data caution against drawing firmer conclusions from this test.

Track Etch data were ranked by WLs for each house location, shown in Table 1. A lower cutoff of 0.02 WLs was used to establish compatibility with health risk assessments, described in the next section. As expected, the highest values appeared in the basement/crawl space areas - usually concrete construction materials in direct contact with soil. (Note that 77 percent of the sample had full basements.) However, the data show that 20 percent of the living areas exceeded arbitrary cutoff potential of 0.02 WLs, as did 30 percent of the bedrooms.

## 4. HEALTH RISKS AND STANDARDS

Since radium is a common radionuclide in the earth's crust, radon is generated continuously in the soil. Some of this gas is exhaled into the atmosphere, but its concentration in ambient air usually remains low (0.1-1 pCi/ℓ) due to its dispersal through normal outdoor air circulation.[4] When contained in a closed, or relatively closed environment, however, such as a tight house, radon may be given more than sufficient opportunity to decay into elevated levels of its short-lived daughter products (Po-218, $t_{\frac{1}{2}}$ = 3m; Pb-214, $t_{\frac{1}{2}}$ = 27m; Pb-214, $t_{\frac{1}{2}}$ = 20 m; Po-214, $t_{\frac{1}{2}}$ = 1.6 x $10^{-4}$s). Extensive epidemiological data, based on lung cancers found in underground uranium miners, has mandated an annual limit of four working level months (WLM),** and a lifetime maximum cumulative exposure of 120 WLMs.[5]

* A working level (WL) is any combination of short-lived radon decay products in one liter of air that will result in the ultimate emission of alpha particles with a total energy of 130 billion electron volts. Working level is a measure of the concentration of radioactivity in the air, not of how much radiation a person actually receives.

**A working level month (WLM) is defined as exposure to 1 WL for 170 hours. It is a convenient unit for expressing cumulative exposure to radon progeny.

There are no generally applicable WL standards for indoor-nonoccupational exposure to radon daughters. The EPA has issued such standards recently for buildings located in close proximity to inactive (abandoned) uranium processing sites, and they are: "In any occupied or habitable building - the objective of remedial action shall be, and reasonable effort shall be made to achieve, an annual average (or equivalent) radon decay product concentration (including background) not to exceed 0.02WL. In any case, the radon decay product (including background) shall not exceed 0.03 WL."[6]

Although the above indoor WL exposure standards do not apply to Denver, they are used here for guidance only.

To convert WLs into WLMs, the extent of occupancy (hr./mo) is required. Using 75 percent occupancy, a number suggested by the EPA, radiation exposure over a 70 year life span can be estimated as seen in Table 2.

As noted earlier, 120 WLMs represents the lifetime occupational limit for underground uranium miners. It is also seen that lifetime exposure of home occupants can approach a significant percentage of the maximum allowed for uranium workers, if we assume the residency time of 75 percent is realistic.

At these levels, actions leading to reductions of WLs are necessary.

## 5. CONSTRUCTION FACTORS

Reduction in radon progeny levels can be obtained by using the factors listed in Table 3 for new construction. Flexibility in the choice of building sites may be limited, but building materials can be tested for radium content and/or radon exhalation if obtained in a region of high natural radioactivity. If limitations on their radium values and/or radon release can not be achieved, consideration should be given to reducing progeny levels by using items 3-5 in the table. Heat exchangers are viable, but they may be expensive. Air cleaning is useful, although a less effective option. Barriers have the greatest potential for development and they may prove to be equally effective in comparison with heat exchangers at lower costs. Their long-term performance has not yet been evaluated.

Tightened older houses require measurements of indoor WLs and, if high, recourse to the remedial actions noted above is suggested.

## 6. CONCLUSIONS

Given this area of higher than average terrestial radioactivity, it was not unexpected to find elevated levels of radon progeny in tight Denver houses. High radon daughter levels were observed during the two-month test period in a small, but not insignificant, percent of the sample. The small sample size precludes any extrapolation of results across the Denver area, but the data do suggest potentials for increased radiation exposure in houses with a low air exchange rate (ach<1).

Expectations are that new construction, especially solar-heated and earth-sheltered houses will be tighter than those built prior to the 1970s. These and older houses retrofitted to reduce air infiltration may require effective remedial actions to reduce both radon progeny concentrations and opportunities for indoor radiation exposures. Radon barriers may become the best and lowest cost option for dealing with this problem in new construction. However, long-term performance test data remain to be developed.

A slowly increasing number of studies, such as this one, are reporting elevated WLs in houses in non-uranium producing areas. At the moment, radiation standards are confined by the EPA to former uranium processing sites. At some later time, recognition may be given to the potentials for indoor radiation exposure on a far broader basis.

There is an apparent need to disseminate information on the causes of the problem, its potentials for increased indoor exposure, and most importantly, the options for its mitigation.

Finally, there is an urgent need for the involved professions and trades to become aware of the indoor-radiation issue. Radon entry can be minimized by modified house design, building materials selection, etc. Removal of radon progeny may be effected by using existing remedial options. Continued research is required to improve those currently available, as well as to develop new alternatives.

## 7. ACKNOWLEDGEMENT

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Table 1.

Working Level Ranking in 30 Metro Denver Homes*

| | Basement/Crawl Space** | | Living Area | | Bedroom | |
|---|---|---|---|---|---|---|
| | No. | % | No. | % | No. | % |
| 0.02 WL or greater | 14/3 | 57 | 6 | 20 | 9 | 30 |
| 0.03 WL or greater | 12/2 | 47 | 4 | 13 | 3 | 10 |
| 0.04 WL or greater | 11/1 | 40 | 4 | 13 | 1 | 3 |
| 0.05 WL or greater | 9/1 | 33 | 3 | 10 | 0 | -- |
| 0.06 WL or greater | 6/1 | 23 | 2 | 7 | 0 | -- |
| 0.07 WL or greater | 6/0 | 20 | 2 | 7 | 0 | -- |
| 0.08 WL or greater | 6/0 | 20 | 1 | 3 | 0 | -- |
| 0.09 WL or greater | 3/0 | 10 | 0 | -- | 0 | -- |
| 0.10 WL or greater | 1/0 | 3 | 0 | -- | 0 | -- |

* WLs measured during February - March, 1982. They are not annual values.
** Full basement: 77 percent of sample.

Table 2.

Population Exposure to Radon Progeny

| WL* | WLM | WLM/ Lifetime | Percent of Occupational Limit |
|---|---|---|---|
| 0.01 | 0.38 | 26 | 22 |
| 0.02 | 0.75 | 53 | 44 |
| 0.03 | 1.13 | 79 | 66 |
| 0.04 | 1.50 | 105 | 88 |

Table 3.

Radon Progeny Reduction - New Construction

| Factors | Remarks/Possible Actions |
|---|---|
| 1. High radium levels in soils. | 1. Ventilate crawl spaces.<br>2. Improve slab construction - increase thickness or use other barriers. |
| 2. Selection of building materials. | Use of masonry with high radium values can provide a continuous source of radon for the entire life of a house. |
| 3. Increase ventilation. | Air-to-air heat exchangers can provide effective interior ventilation without excessive heat loss. |
| 4. Filtration and air cleaning. | Any system which removes dust from the air also may be effective in reducing the concentration of radon daughters. |
| 5. Barriers (sealants) | Although extensive data are not presently available, it is likely that a variety of sealants, paints and coatings of various kinds will prove effective IF properly applied and maintained on surfaces such as concrete basement walls and floors. |

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# THE EFFECTS OF COLOR ON HUMAN COMFORT LEVELS, HEATING AND COOLING LOADS, AND TASK PERFORMANCE

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## ABSTRACT

Human beings have evolved from the light of the sun and will predictably respond to the constituent colors of the sun's light. Recent studies have shown that color frequencies will cause a fluctuation in the heart beat, respiration, and blood pressure. Recent studies have shown that color frequencies will affect a person's physical, emotional and psychological comfort levels. The correct color of an interior decoration has been shown to lower the heating or cooling load of a building, and to increase the speed and accuracy at which work tasks are performed. This experiment will analyze what effects the color of a room will have on the comfort levels of human beings, and the corresponding heating and cooling loads of a building's interior environment.

## 1. INTRODUCTION

On the second weekend of May, a color test module was set up at a county fair to register the effects of various colors on human comfort levels. The color test module had a 16 $ft^2$. floor area. The front wall was 4 ft x 6 ft-5 in. with a 44 in. x 5 ft.-6 in. entrance door, which had two 3 ft x 3 ft window openings. The back wall of the test module was 5 ft-6 in. x 1 ft-6 in. in size. The ceiling was, therefore, raised on the front wall, sloping downward to the back wall, 4 ft away from the front wall.

The door was designed to facilitate easy changing of three pairs of different colored 3 ft x 3 ft plexiglass panels. The chosen colors were red, orange, and blue.

The interior and exterior walls of the color module were painted white with a medium range reflectance. The interior walls, therefore, reflected the color of the various colored plexiglass panels mounted within the windows of the door. The test module was set 1.5 in. off the ground for ventilation and even temperatures. A wooden chair was placed within the color test module.

The subjects were randomly chosen from the people who attended the county fair. The subjects' blood pressure was taken. They were then asked to sit within the color test module for five minutes. After said time, the subjects' blood pressure readings were registered. The subjects were then informed of their results.

## 2. RESULTS

When the sunlight was filtered through the blue colored plexiglass (after a five minute stay within the color test module), the subjects' blood pressure dropped from its original level to a lower level.

When the sunlight was filtered through the orange colored plexiglass, the subjects' systolic blood pressure generally remained the same, while the diastolic pressure dropped.

When the red colored plexiglass was placed within the windows of the test module's door, the subjects, upon entering the test module, began to show signs of being over-heated. They began to fan themselves with their hands, shirts, or whatever was available. The subjects were therefore left within the test module for less than the prescribed five minute period. The subjects complained of an accelerated heart rate.

## 3. DISCUSSION

When the human body has an accelerated heart rate, respiration, or an increased blood pressure reading, then the human body is generating a higher personal heat level. The amount of the subjects' personal body heat level will therefore demand either a higher or lower building heating level for continued human comfort. When the human body is producing a high personal body heat, then the heating load of the building will be less and the cooling load will be higher. When the human body is producing less personal body heat, then the heating load will be higher and the cooling load will be lower.

Although the data in this experiment has been collected from one experiment, the experimentor has been conducting it for three years. The data from the blue colored test module resemble exactly the results which have been found over that three year period. That is, it generally takes about three minutes for there to be a visually noticeable change in subject character after a short stay within a blue colored environment. If the child or adult is over-reactive, hyperactive, or suffering from tension, after 3-5 minutes within the blue color test module the child or adult will be noticeably calmer, and much more subdued.

Many subjects, when leaving the blue colored environment, will explain how calm and relaxed they feel. In this experiment the blood pressure was shown to take an immediate nose dive. If a person (either at work or at home) desires a calming, relaxing atmosphere, this can be achieved within a generally blue environment. This calmness will be noticeable in the physical, emotional and psychological human responses. The body is truly relaxed, with a lower blood pressure and respiration. The research suggests that a cooling, calming, relaxing blue atmosphere will need a higher heating load to sustain a normal human comfort level. However, within a rather hot external environment, a cooling, calming, blue colored internal environment will assist in reducing the building's cooling load.

During the three year period of the experiment, the orange colored module has had a rather strong effect on the subjects' physical, emotional, and psychological responses. The orange environment has an amazing ability to energize and vitalize a person's analytical capacities. In a number of cases when a person was mentally depleted, either from analogical testing, or working with meticulous tasks, a 3-5 minute stay within the orange test module totally invigorates and revitalizes the person. The effect is similar to having a cup of coffee in the morning to get going. This experiment did not find a direct correlation between the change in blood pressure, heart beat or respiration, and the subjects' responses of feeling refreshed, and revitalized. The orange colored environment correlated with past responses to the orange color module. The blood pressure readings received in this experiment, however, do not show a clear correlation between an orange colored environment and the heating and cooling loads of a building. However, the subjects found the environment to be warm and cheerful.

Upon entering the red color module, one generally receives immediate heightened stimulation. There is an immediate sense that something is changing within the body. In some cases, it will cause the heart to suddenly begin to race. In others, it will send undefinable bursts of stimulus from their feet to their heads. But for everyone there was a strong sensation of warmth and dynamic movement. From the tests which have been performed over the last three years, all the subjects who entered the red color module felt warmed by the red colored environment. As such, the red colored environment will lower the heating load of a building, while raising the cooling load of a building.

When designing the interior environment we need to strongly consider the type of people who will be using the building, along with the task to be performed. There are various establishments which purposefully have an orange to red interior color scheme. From this experiment it was shown that an orange colored interior environment will generally cause the diastolic blood pressure to drop. This physical response is also linked to a psychological response to an orange environment, which causes people to feel an urgency to continue with the task which they are performing. As such, the particular project, or job task best performed

within a generally orange colored environment would be one where there is a strong need for continued clarity of the mental facilities (such as a library), so that a systematic prescribed set of instructions, or tasks, can be effectively completed (such as a fast food business), where patrons are encouraged to quickly buy their items and leave.

The refreshing and awakening human response to the orange color is very effective in areas where the work task is consistently the same, and where the precision of that work task is of high importance (e.i., production line work). I'm sure that you will find the employees within a generally orange environment to be cheerful and efficient on repetitive job tasks, and less likely to ask for a rise in the interior room temperature. This is because the orange environment demands an active response of the human body. It boosts the human activity level, while refreshing and energizing overstressed mental facilities.

The orange color may be easily added into all interior environments by installing an orange/golden color rug, or using woods with an orange/yellow tone to them, or having various orange colored items within the visual range of the work task area.

Interior decorators who generally wish to soothe and relax a human being, would be very effective in using the blue colored environment to lower the body's blood pressure, heart rate, and respiration. If the purpose is to facilitate a relaxed mental and physical human response, or a generally cooling atmosphere, the blue color range of the color spectrum is most effective. The cooling, calming effect of the blue colored environment prevents it from being used within many work task areas. If the environment is to be mainly used by people who are over forty years old, then the blue environment would be extremely helpful in reducing the general high blood pressure which seems to accompany older age. Many areas of the interior environment may effectively use the relaxing blue tones on either rugs, walls or ceilings.

In our passive solar buildings located within rather hot climates, the blue colored environment is a sure way to lower the cooling load of the building. If your passive solar building is located within an area where the seasonal temperatures are rather cold during the winter and hot during the summer, then the heating load of that building will be generally higher during the winter months and generally lower during the summer months, due to the blue color itself.

There have been questions as to why a passive solar building will appear to be warmer at times and cooler at other times, although the interior temperature is the same. A blue color will appear to be cooler on a winter day, causing you to feel cooler, and because your blood pressure is lower, the human body feels chilly. Whereas, on a summer afternoon, the blue color will appear to be warmer (due to the summer temperatures), when, in fact, the body is responding with a drop in blood pressure, heart rate and respiration, thereby producing a specific human response, which actually cools you both in the winter and summer seasons.

One would suggest that during the winter months, the occupant should add warm vibrant colors to his/her environment, whereas, during the summer months one would remove the warming colors and supplement items within the cooling blue range of the color spectrum.

In all cases, the amount of the red color within an environment needs to be carefully placed. It should comprise a rather small area of the interior environment. As earlier stated, the red color will lower the heating load of a building. However, because of its ability to rapidly raise the blood pressure, respiration and/or heart rate, much care needs to be taken when using a large amount of red within an internal environment.

## 4. CONCLUSIONS

The subjects who were immersed within the blue light of the color test module gave responses such as, "I really felt the difference", and "It has such a calming and sedating effect, I want to go back in". These statements reflected the drop in blood pressure which the subjects had experienced.

The subjects who were placed within

the orange colored test module said that, "It felt so refreshing, I would have liked to have stayed in longer". However, the blood pressure readings for the orange colored test module were different in each case. The various blood pressure levels rose and fell from subject to subject. However, the subjects found the orange environment to be awakening, refreshing and revitalizing.

The red color test module was by far the most dynamic and was used with a great deal of caution. Any subject with even a slightly high pre-blood pressure reading was not asked to enter the red color test module. Of those who did enter, they all left the color test module in less than the specified five minute test period. Their responses were, "It was so hot" or "my heart started racing". The experimentor decided to limit the red color test module experiments.

We therefore conclude that an environment which is generally blue will reduce the cooling load of a building and add a calming, relaxing effect, while raising the heating load of the building.

An orange colored internal environment will elicit a physical change in the human body. However, its correlation with heating and cooling building loads has not been demonstrated in this experiment.

A red colored internal environment will reduce the heating load of a building and increase the cooling load of a building.

With the correct usage of lighting and color we can lower the heating and cooling loads of a building. We need more research to be performed in the usage of lighting and color on human beings within their present day internal environments. With a greater understanding of these human responses to the effects of lighting and color, we can design a more healthy human environment, while lowering the heating and cooling loads of our living and working community.

## 5. ACKNOWLEDGMENT

The information presented in this paper resulted from contributions made by the many researchers who have explored the study of light and color throughout history.

I would also like to thank the solar consultants of Sunstone Solar Associates for their much needed help in completing this paper, and a personal thanks to all of my friends.

Mr. Keith Bogue-Solar Consultant, Designer/Builder

Ms. Trudy Turner-Solar Consultant, Designer

Ms. Lory Osterhauber-Personal Friend

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# EFFECTS OF DAYLIGHT ON INTERIOR WOODS AND WOOD FINISHES

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## ABSTRACT

A review of literature was completed in order to determine the extent of research data available on the effects of daylight on interior woods. It was found that color change and loss of moisture content were the most important contributors to visual or physical wood deterioration. Recommendations are made that will help decrease wood deterioration when exposed to daylight in passive solar interiors.

## 1. INTRODUCTION

The result of direct gain systems used in energy conscious buildings causes some problems in the interior environment. Those problems noted and documented by users are particularly related to the fading and deterioration of interior materials. To date, little information has been made available on specifications of woods and wood finishes used in furniture, flooring or trim. Compounding the lack of information is the fact that most research done on woods has been done for exterior applications and raw woods. Obviously, the ultraviolet effect is more relevent for exterior applications than interior. Research on raw woods concentrates on the reaction of the fibers not on an end-product. In order to determine what research data are available, a comprehensive literature review has been completed. The review focused on the effects of daylight and humidity on interior woods and wood finishes. Performance characteristics and properties of wood that were reviewed included fading, discoloration, drying, dimensional change, and mildew. Color change and decreased moisture were found to be the most common effects.

## 2. COLOR CHANGE OF WOODS

Interior daylight contains a fraction of exterior daylight's ultraviolet rays due to the absorption of ultraviolet by the glass. Most research conducted on the effect of ultraviolet light on woods have used exterior wood products as the sample specimen. Manufacturers of exterior wood products then specify additive finishes that inhibit ultraviolet light. However, visible light will cause a color change in most materials, including woods. Users of passive solar residences have been astonished when wood flooring or wood furniture has faded after a relatively short period of time. Perhaps they do not realize that woods will fade or change color, just as textiles will, when exposed to daylight.

The question, then, is how to stabilize the color change. Unfortunately research studying the effect of daylight on interior wood surfaces and therefore, stabilizing color change has not been done. The following recommendations are based on data pertaining to wood properties and characteristics.

A. If time permits, test various stains and woods to determine the extent or direction of color change. Expose wood samples behind glass for a period of six months to one year. Generally, woods will lighten after exposure to daylight, however, some very light woods will darken after exposure.

B. Some stains actually speed up the color change. That is, a natural wood will change color at one rate but after being stained, a different chemical process occurs and the stain pigment changes, not the wood pigment. Therefore, test stained woods as well as natural woods.

C. Move furniture to various positions in the space, trying to expose all parts equally as well as expose various floor or wall areas equally.

D. On a smaller scale, if a wood surface has accessories on it (a lamp on a table) try to move the accessories to different positions on the surface so they will not leave an unfaded spot.

E. Wood color change will continue to occur, but the majority of change occurs in the first year. If care is given to positioning of

woods, the effect will tend to stabilize after one year.

## 3. DECREASED MOISTURE CONTENT OF WOODS

The second factor involving loss of wood performance and appearance concerns the effect of humidity, or lack of it. Passive solar residences tend to have fluctuating humidity levels due to reduced use of mechanical systems that control the environmental conditions.

Wood products shrink as they dry and swell as they absorb moisture, either liquid or vapor, from the atmosphere. Unless these changes in dimension are kept to a minimum, they may result in unsatisfactory service of wood products. Fortunately, most of the difficulties caused by moisture can be practically eliminated by drying the wood, to the moisture content best suited for the intended use, before the wood is put into service. The optimum moisture content will be midway between the extreme values that the wood is likely to reach. If the wood is too wet when it is put into place, it will eventually dry to a moisture content approximating that of the conditions under which it is used. This drying in place will be accompanied by shrinkage. In furniture, woodwork, flooring, sash, doors, cabinets, and other products, swelling and shrinking may split, crack, or warp the part; open joints and loosen nails and other fastenings; cause gluelines to fail; and mar the finish of the product. Table 1 gives the recommended moisture content values for interior woods at the time of installation.

Once the correct moisture content is determined, woods can be further protected from moisture absorption by various coatings.

### 3.1 Control of Moisture Content by Finishes

Furniture is finished primarily for decoration and improvement in appearance but most finishes likewise have a protective function in that they help to keep the wood from fluctuating too much to either side of an average moisture content. Protection occurs by slowing down the passage of moisture in or out of wood through the surface. (Browne, 1953)

No wood finish prevents all movement of moisture. For that reason wood kept indefinately under constant conditions of dampness or dryness will come to the moisture content at which it is naturally in equilibrium with those conditions. Furniture used in the dry parts of Arizona, for example, will average lower in moisture content regardless of any protective finish than will furniture in the more moist climate of New Orleans or Seattle; while furniture in the humid tropics will attain still higher average moisture content. Nearly everywhere, however, humidity and temperature fluctuate considerably from day to night, day to day, and season to season. Unprotected wood strives to keep in step with such changes and consequently fluctuates above and below its average moisture content, Wood protected with coatings lags behind each swing and stays closer to its average moisture content (Browne, 1953).

TABLE 1. RECOMMENDED MOISTURE CONTENT VALUES FOR INTERIOR WOODS

| Use of wood | Moisture content for: | | | | | |
|---|---|---|---|---|---|---|
| | Most areas of United States | | Dry southwest area | | Damp, warm coastal areas | |
| | Avg. | Individ. pieces | Avg. | Individ. pieces | Avg. | Individ. pieces |
| | % | % | % | % | % | % |
| Interior: Woodwork, flooring, furniture, wood trim, laminated timbers | 8 | 6-10 | 6 | 4-9 | 11 | 8-13 |

"Moisture Content of Wood in Use", U.S.D.A., Forest Service Research Note, FPL-0226, 1973

Protection is greatest, of course, against fluctuating conditions in which the periods of extreme dampness or dryness are short and are followed by conditions permitting return to the average moisture content. Against day to day changes, finishes of low effectiveness furnish adequate protection, but for seasonal changes in which there is a six month swing in one direction followed by six months in the other, even the most effective coatings permit considerable change in moisture content.

The protection afforded by coatings in excluding moisture from wood depends on a great number of variables. Among them are film thickness, absence of defects and voids in the film, type of pigment, chemical composition of the vehicle, volume ratio of pigment to vehicle, vapor-pressure gradient across the film, and length of exposure period.

The relative effectiveness of several typical treating and finishing systems for wood in retarding adsorption of water vapor at 97 percent relative humidity is compared in Table 2. Perfect protection, or no adsorption of water, would be represented by 100 percent effectiveness; complete lack of protection (as with unfinished wood) by 0 percent. Wood was initially conditioned to 80°F. and 65 percent relative humidity and then exposed for two weeks to 80°F. and 97 percent relative humidity. ( Wood Handbook, 1974)

TABLE 2. TYPICAL VALUES OF MOISTURE-EXCLUDING EFFECTIVENESS OF FINISHES

| Coatings | Effectiveness |
|---|---|
| Interior Finishes | % |
| Uncoated wood | 0 |
| 3 coats of phenolic varnish | 73 |
| 2 coats of phenolic varnish | 49 |
| 1 coat of phenolic varnish (sealer) | 5 |
| 3 coats of shellac | 87 |
| 3 coats of cellulose lacquer | 73 |
| 3 coats of lacquer enamel | 76 |
| 3 coats of furniture wax | 8 |
| 3 coats of linseed oil | 21 |
| 2 coats of linseed oil | 5 |
| 1 coat of linseed oil (sealer) | 1 |
| 2 coats of latex paint | 0 |
| 2 coats of semigloss enamel | 52 |
| 2 coats of floor seal | 0 |
| 2 coats of floor seal plus wax | 10 |

U.S.D.A. Agriculture Handbook No. 72, 1974, Wood Handbook

As a rule a balance in protective power of the finish on opposite sides of wood pieces in furniture, particularly large flat pieces, such as table tops, is highly desirable. When moisture content changes more rapidly through one face than through the other there is a tendency to warp with the drier side becoming concave. Equality of moisture movement normally tends to keep the piece flat or at least more nearly so than when one side changes faster than the other. For such reasons a highly protective finish on the side exposed to view calls for a similarly highly protective finish on the concealed side.

Protective finishes can play a significant part in stabilizing the moisture content, dimensions, and shape of furniture in service although finishing cannot be relied upon to overcome defects caused by poor design, poor construction, and poor moisture control in making furniture. Greater technical consideration should be given to the protective power of furniture finishes and its use to improve the perfomance of furniture in service (Browne, 1953).

## 4. IMPLICATIONS FOR FURTHER RESEARCH

At the time of this writing, a proposal to test the effects of daylight on interior woods and wood finishes has been submitted by the Department of Home Economics and Consumer Sciences at Miami University. A 1982 market survey by the Fine Hardwoods/American Walnut Association shows the favorite species of woods used in furniture construction by furniture manufacturers. These survey data, presented in Table 3, was the basis for selecting which woods need to be tested.

TABLE 3. MANUFACTURERS' USE OF WOODS FOR CASE GOODS, OCTOBER 1982, MARKET

| Species | Percent of Total |
|---|---|
| Oak | 25.4 |
| Pine | 14.4 |
| Cherry | 10.7 |
| Pecan | 7.4 |
| Maple | 6.1 |
| Mahogany | 4.6 |
| Ash | 2.6 |
| Walnut | 2.4 |
| European Ash Burl | 1.5 |
| Elm | 1.2 |
| Primavera | .9 |
| Beech | .8 |
| Birch | .5 |
| Other Woods (2) | 3.0 |
| Other Materials | 18.5 |
| Total | 100.0 |

Since data are available regarding the effect

of humidity on various interior woods, this research will focus on color change.

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# INTERIOR DESIGN FOR OFFICE DAYLIGHTING

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## ABSTRACT

The performance of a daylit building can be jeopardized by inappropriate interior design. The interior designer must be supplied with surface light reflectance requirements, acoustic control information, and illumination distribution requirements in order to competently specify interior components and workstation layout. The following is a guideline for the interior designer of office spaces illuminated by daylighting.

## 1. INTRODUCTION

The objective of daylighting application is to integrate natural light through penetration of space while maintaining required levels of illumination for specific users. The performance of an architect's calculations for the building design can be jeopardized by inappropriate interior design. The architect loses control of building performance when an interior designer, who is not familiar with daylighting methods, is hired to specify interior components. This leads to inappropriate selection of panel heights, surface finishes, color, artificial lighting, furniture types, and methods of acoustic control.

A solution to the problem of inappropriate interior specifications for daylit buildings is to encourage the architect to supply the designer with the following information:

1) light reflectance requirements of all surfaces so texture and color can be specified;
2) acoustic requirements so textures and finishes for horizontal and vertical surfaces can be specified; and
3) a three-dimensional "footprint" of illumination distribution so proper panel and workstation height can be determined.

## 2. LIGHT REFLECTANCE REQUIREMENTS

The Illuminating Engineering Society (1981) makes the following recommendations for light reflectance of horizontal and vertical surfaces in office spaces:

| | |
|---|---|
| Ceilings | 80% or more |
| Furniture | 25-45% |
| Floors | 20-40% |
| Partitions | 40-70% |
| (Including high vertical surfaces) | |
| Walls | 50-70% |

As can be noted from the recommendations, there is a broad range of acceptability in all categories. When specifying colors and textures for a daylit building this broad range may be detrimental to the function of the design. By dividing the space into lighting zones, more specific light reflectance recommendations can be made. Table 1 identifies the zones and surface reflectance percentages. (Table 1 on following page.)

Once reflectance recommendations are established, the interior designer selects colors and textures for all surfaces that meet these requirements. While that appears obvious and fairly simple, problems occur at this stage because reflectances are not always made available by the manufacturer of surface finishes and textiles. Generally, paint, wall covering and carpet manufacturers include light reflectances in their product specifications or are available upon request. This is not generally true of textile or furniture manufacturers. Since window and furniture textiles can be a fair proportion of surfaces in a building, they cannot be ignored.

The percentage of light reflectance can be easily calculated with the use of an inexpensive footcandle meter. By measuring footcandles (Fc=quantitative measure of illumination striking the surface) and footlamberts (Fl = quantitative measure of

TABLE 1

RECOMMENDED SURFACE REFLECTANCES FOR DAYLIGHTING ZONES

| Surface | Ceiling | | Furniture | | | Floor | | | Partitions | | | Walls | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % Reflectance | 80 | 90+ | 25 | 35 | 45 | 20 | 30 | 40 | 40 | 55 | 70 | 50 | 60 | 70 |
| ZONE 1<br>South Exposure | X | | X | | | X | | | X | | | X | | |
| ZONE 2<br>East or West Exposure | | X | | X | | | X | | | X | | | X | |
| ZONE 3<br>North Exposure | | X | | | X | | | X | | | X | | | X |
| ZONE 4<br>Core without top lighting | | X | | | X | | | X | | | X | | | X |
| ZONE 5<br>Core with top lighting | X | | | X | | | X | | | X | | | X | |

illumination reflected from the surface) then dividing Fl by Fc, the percentage of light reflection for diffuse or matte surfaces can be determined. Example, Fl ÷ Fc = % reflectance or if Fl = 50 and Fc = 100, then 50 ÷ 100 = .50 or 50% reflectance.

A third method of determining reflectance of a surface is to compare one sample to a standard Reflectance Value Chart such as the one produced by General Electric (TP-129). The problem being the human's inability to judge value and intensity levels accurately as well as account for textural variation. It should be emphasized that texture or finish of a surface is very important in determining reflectance.

This paper's emphasis on light reflectance does not mean to ignore other factors such as contrast between task and surround, veiling reflectance, and angle of light, which are mandatory design criteria for effective lighting design. However, the surface light reflectance recommendations are interior design considerations necessary to fine-tuning a daylit building, allowing it to operate at its optimum.

## 3. ACOUSTIC CONTROL

The second area of concern to the interior designer of daylit buildings will be the control of sound. Office spaces are furnished with many hard surfaces. Those hard surfaces aid light reflectance but also reflect and transmit sound. The solution lies in balancing appropriate light reflectance surfaces with materials that will reduce sound reflectance and transmittal. It is also important to understand that the goal of good acoustic design is to create an environment free of distraction. When an office is made too quiet, other sounds cause distraction from the work task, leading to a perceived loss of privacy, a common user complaint about open offices.

As sound spreads it will be absorbed, transmitted or reflected from surfaces. To determine how effective various materials are in controlling sound, two rating systems are commonly in use. NRC, or Noise Reduction Coefficient, is a number between 0 and 1 which represents the percent of energy (sound) striking a material which is absorbed. An NRC of 0 means no sound is absorbed while an NRC of 1 means all sound is absorbed by the material. Manufacturers of ceiling tiles, furniture panels, and floor coverings will specify the NRC of their products. Ceilings and open office panels should have an NRC of .80 or higher, floorings .20-.40.

The STC (Sound Transmission Class) is a one-number rating that describes the ability of a material to block the transmission of sound through it. STC of 0 means there is no drop in level through the material while STC of 50 means very little sound goes through. Open office panels should provide STC 23 or higher. STC of floor and ceiling materials is not always available since transmission through the porous surface covering is reduced by a solid inner material.

When sound is generated it travels in all directions, not just the direction in which the source is facing. It will bend or defract over the top or around the sides of panel dividers, as well as traveling outward from the source. In office design

there are three vertical zones needing acoustic control, the floor, the ceiling and the work plane. The floor should be carpeted to reduce sound reflectance and the ceiling should be covered with a sound absorbing material. The zone containing the work plane (approximately 24"-48" above the floor) should receive priority attention as most sound producing sources are contained within this zone such as voices and office equipment. In addition to NRC and STC ratings as previously specified, the following recommendations are made to control sound in this zone:

1) freestanding work surfaces for sound producing equipment so sound will not be transmitted through the surface to another area,
2) acoustical pads should be placed under sound producing office equipment,
3) do not leave space between wall and a panel which would allow sound to pass around the end of the panel, and
4) use 55"-60" panels with an NRC of .80 and a STP of 23 (higher panels would be better for sound control but not for illumination distribution).

## 4. THREE DIMENSIONAL ILLUMINATION DISTRIBUTION FOOTPRINT

"Footprints" or a three dimensional graphic description of illumination distribution within a space relying primarily on daylight are essential for design and placement of workstations in an open office system. In a space where the work surface is uniform and no interior partitions or obstructions exist, a single composite footprint is sufficient. When panels are used, however, footprints of planes at panel heights (55"-75") must be considered. This is essential when using sidelighting or toplighting which is adjacent to the planes to be studied such as a skylight in a 9ft ceiling. When footprints are united in a series of overlays or done in an isometric they provide a tool for design and specification of workstation components. Conclusions can be drawn from this tool and the space can be zoned into areas so panels of various heights can be used, overhead storage can be located, etc.

Figures 1-3 demonstrate the use of footprints depicting illumination distribution at various planes, 30 inches, 55 inches, and 75 inches above the floor. The next step would include an orthographic projection of the workstation overlayed with the footprints to determine the heights at which distribution is blocked. (Figs. 1-3 on following page).

When positioning panel systems in areas primarily illuminated by sidelights within the user's work height of 3 feet to 6 feet, illumination levels and distribution at the plane of the highest obstructions (panel) height) should be used as the distribution pattern upon the primary work plane. Therefore, the lower the panel height the greater the levels of illumination that will strike the work plane. The recommendation is to use the space adjacent to sidelights for employees requiring minimal privacy and therefore lower panels. In the event overhead storage bins are required, they should be placed perpendicular to fenestration. The top of bins could be materials of high reflectance to increase penetration into the space, such as birch veneer or a light laminate.

In areas primarily affected by toplighting, illumination levels at the work plane are sufficient. Distribution patterns of secondary planes (panel heights) are irrelevant. The recommendation is to use this space for stations requiring greater privacy with any storage bins in this area having task lighting underneath. Workstations outside these areas should be used for tasks requiring lower levels of illumination, including CRT functions.

## 5. SUMMARY

For open office daylit interiors, it would appear the most appropriate choice of panel height is a 55" or 60" panel. This should have a light reflectance of 40%-70% depending on zone of use, NRC of .80 or higher, STC of 23 or higher. This panel height allows for adequate daylight distribution while maintaining visual and audio privacy. Floors should be carpeted with an NRC of .20-.40 and light reflectance of 20%-40%. Ceilings should have an NRC of .80 or higher and light reflectance of 80%. The key to a good space plan for workstations is the use of the three dimensional footprint integrating workstation and panel heights with daylight distribution from top or side lighting.

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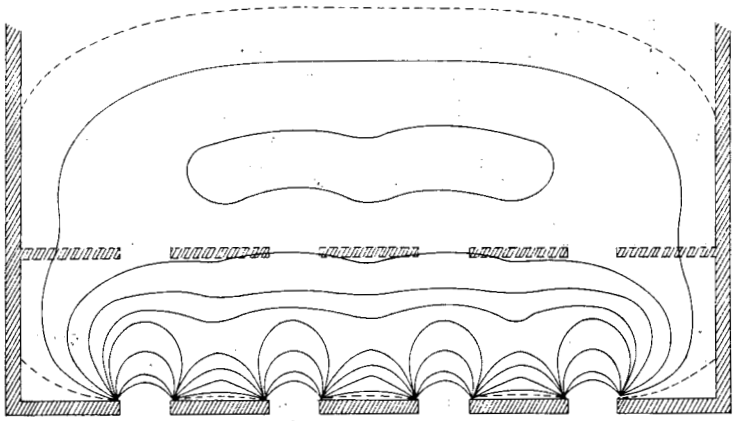


FIG. 1. ILLUMINATION DISTRIBUTION AT 30"
H/W=1 S/H=2 H/W=2 S/H=0 (Millet, 1980)

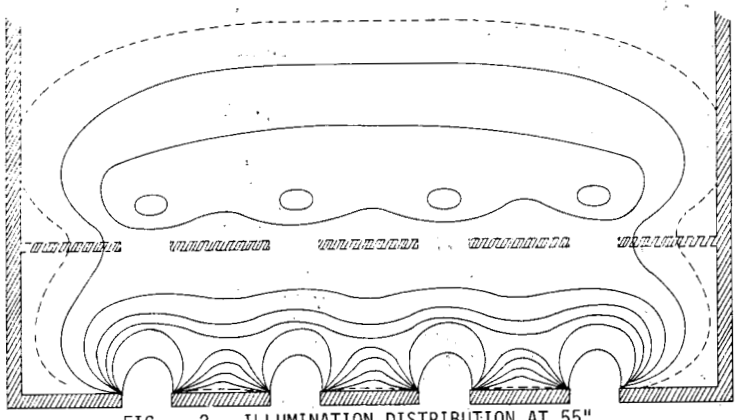


FIG. 2. ILLUMINATION DISTRIBUTION AT 55"
H/W=1 S/H=1.5 H/W=1.3 S/H=0 (Millet, 1980)

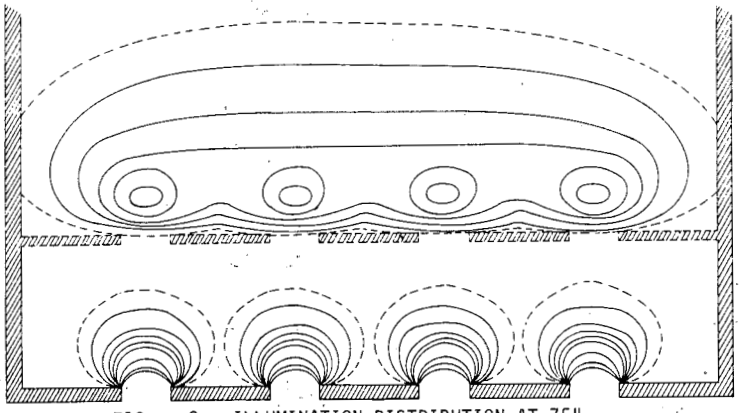


FIG. 3. ILLUMINATION DISTRIBUTION AT 75"
H/W=1 S/H=1 H/W=.75 S/H=0 (Millet, 1980)

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# CREATIVE INTERIOR DESIGN FOR THERMAL STORAGE WALLS

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Lakewood, CO 80228

## ABSTRACT

The creative interior design for thermal storage walls can dramatically improve a passive building's thermal performance, aesthetic characteristics, and human comfort (thermal and luminous). Recent examples of unique designs are documented and presented in this paper. Color, texture, natural lighting, form, performance, cost, and comfort factors of the thermal storage walls are described for the various designs.

## 1. INTRODUCTION

Often, designers have been concerned about the aesthetic character, view limitations, and light penetration of "Trombe walls" or thermal storage walls using indirect solar gain. Several examples of creative design addressing these issues have been constructed in recent years. Three of these designs--a louvered-mass wall, a floating-mass wall, and a stained glass in a mass wall--are presented in this paper.

## 2. LOUVERED-MASS WALL

The Franta residence in Lakewood, Colorado, uses a "louvered-mass wall" to provide a passive solar heating system combining direct and indirect solar gains. This design selectively provides winter morning direct gain heating, natural lighting, view, afternoon thermal storage mass, and prevents overheating.

The louvered-mass wall (Fig. 1) is located on the south wall of the living room (upper level) and the master bedroom (lower level). This mass wall has four rectangular columns (Fig. 2) reaching two stories in height. These columns have their long horizontal axes pointing southeast, allowing the early morning winter sun to penetrate into the livingroom and the master bedroom for quick heat-up. The afternoon sun is absorbed by the mass wall and becomes a source for radiant heating during the night.

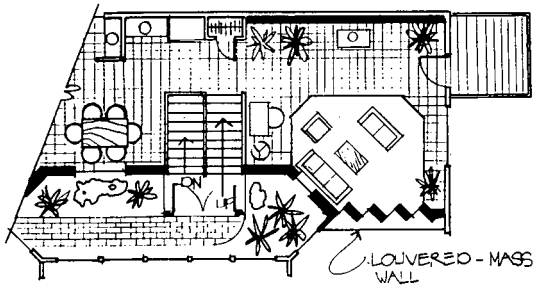



Fig. 1. Partial plan of the Franta Residence upper floor.

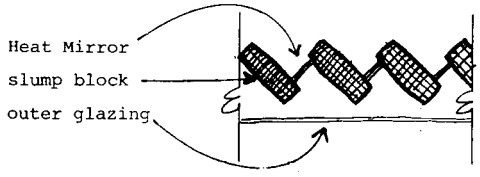



Fig. 2. Plan detail of the louvered-mass wall.

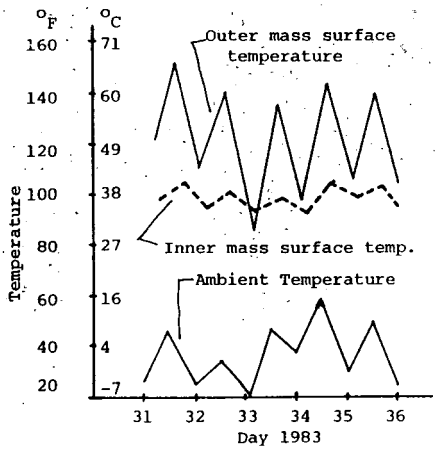



Fig. 3. Performance monitoring (temperature data) of the louvered-mass wall in 1983.

The original design of the louvered-mass wall was conceived by Gregory Franta, AIA, while conducting research at the Roaring Fork Energy Center in Aspen, Colorado. The design was developed and incorporated into the Franta Residence plans in 1978. The home was constructed in 1980, and the thermal performance has been monitored from 1980 through 1983. Figure 3 illustrates temperature data of the mass wall for days 31 through 36 of 1983.* Reference 1 presents further thermal performance data of the Franta Residence.

Construction materials for the louvered-mass wall included brown concrete slump block with concrete-filled cores, insulating glass with Heat Mirror$^{tm}$,** and wood trim finishing. The slump block was installed on metal plates that were fastened to the top of the foundation wall and contained reinforcing bars penetrating into the concrete block (Fig. 4). These rectangular columns reach over five meters to the ceiling of the upper level (Fig. 5). The Heat Mirror$^{tm}$ glazing system was added to the block and secured with finished wood stops (Fig. 6).

The 1980 incremental cost of the louvered-mass wall was $9.39 (U.S. Dollars) per square foot of south glazing area ($1446.00 total). The incremental cost was calculated to include the filled-core slump block, insulating glazing with Heat Mirror$^{tm}$, wood trim, and construction labor. The cost does not include the exterior glazing, for it is self-supporting and is assumed to be needed if the mass wall was not constructed.

For additional reference, a similar concept using a louvered-mass wall without the high performance glazing was designed by Jim Bier in Ferrum, Virginia (2).

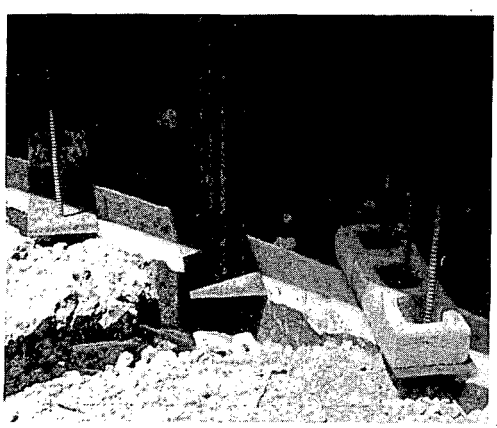


Fig. 4. Construction photograph of louvered mass wall showing metal plates on top of foundation wall.

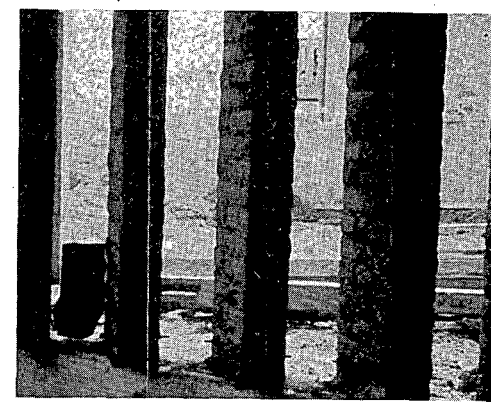


Fig. 5. Construction photograph of louvered mass wall showing the slump block column prior to glazing installation.



Fig. 6. Interior view of completed louvered mass wall.

3. FLOATING-MASS WALL

A floating-mass wall is a design that includes the use of glass block within a concrete slump block, mass wall to allow natural light penetration into the great room of the Lucas Residence in Franktown, Colorado. Again, this design combines the use of direct and indirect solar gains.

It is a stagnating mass wall of 12 in. thickness, built with concrete slump block with all cores grouted full of concrete. It is stained dark brown on the exterior surface and glazed with standard insulating patio door replacement units (34 in. X 76 in.).

---

* The residence is located at 1828 meters (6000 ft.) in elevation and has approximately 3000 heating degree days C (5500 dd F).

** Heat Mirror$^{tm}$ is a high transmission, low emissivity glazing material manufactured by Southwall Corporation, Palo Alto, California.

The term "floating-mass" is derived from the appearance that the slump block wall is floating in the glass block. The glass block surrounds the massive slump block on the top, bottom, and sides (Fig. 7).

Designed in 1982 by ENSAR Group of Lakewood, Colorado, the Lucas residence is being constructed in 1983 at an elevation of 1877 meters (6153 ft.) and has approximately 3660 heating degree days C DD @ °F). The actual incremental cost of the floating-mass wall is still unknown, but is estimated at $12 to $15 (U.S. dollars) per square foot of south glazing area. Thermal performance is not available.

Construction detailing is somewhat unusual but not difficult. Vertical reinforcing from the foundation up through the mass wall is usually required. In this case, it was a little harder because of the band of glass block at the bottom of the wall. The solution was to use a steel box with open ends and reinforcing bars extending down into the foundation and up into the slump block. This provided a secure connection to the foundation. For support and stability at the top of the wall, 36" long bolts were extended from the roof framing down through the joints between the glass blocks and into the cores of the slump block (Fig. 8).

The loading on the glass block is of no concern, since it has a compressive strength of 400 psi, and the actual load is approximately 13 psi. The mass wall is not load bearing. The roof structure was designed to span the width of the mass wall and transfer the loads down on each side.

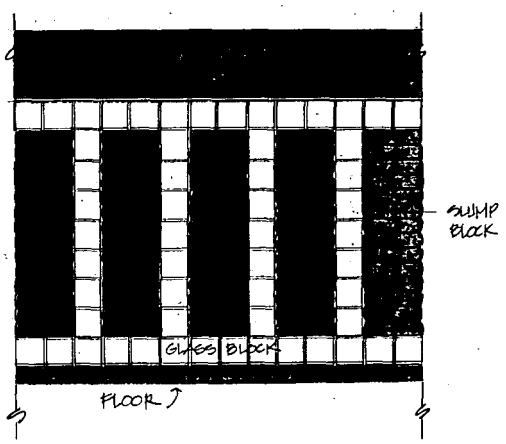



Fig. 7. Floating-mass wall elevation.

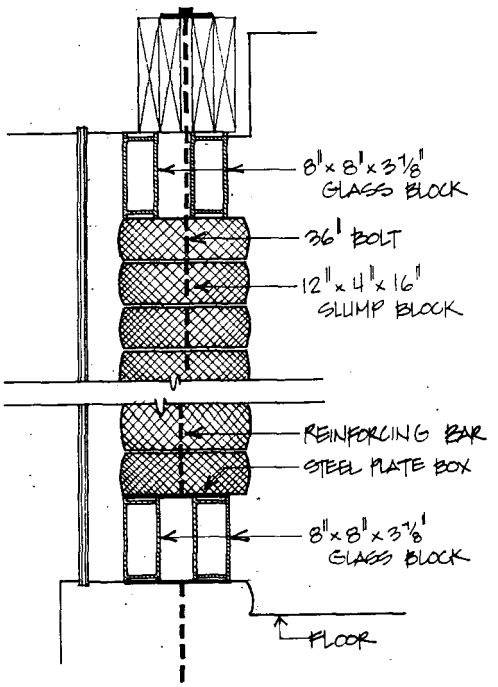



Fig. 8. Vertical section of floating-mass wall.

4. STAINED GLASS IN A MASS WALL

Stained glass in a mass wall has been used successfully by various designers to enhance the aesthetic character of mass walls and provide daylight penetration.

In 1978, Peter Dobrovolny, AIA, of Snowmass, Colorado, incorporated a combination of clear and stained glass in a thermal storage wall for the Kairath Residence, near Glenwood Springs, Colorado (Fig. 9). The interior brick of the mass wall is earth-toned (brown and tan) colors, and the exterior has a deep blue surface on the brick towards the exterior glazing.

A thermal curtain is used between the mass wall and the exterior glazing to minimize heat loss at night.

The magnificent views of Mt. Sopris are captured through the clear glass in the mass wall (Fig. 10). This same glazing allows for some direct solar gain and daylighting. Of course the incremental cost of this concept varies tremendously with the complexity and value of the stained glass. It is assumed that most stained glass units installed in a mass wall will add $100 to $1000 (U.S. dollars) to the cost of the mass wall.

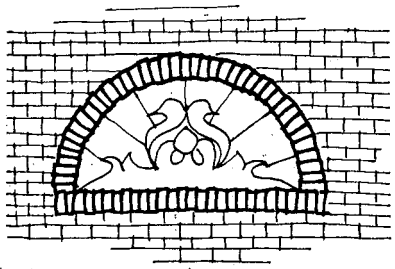


Fig. 9. Stained glass in a mass wall (elevation).

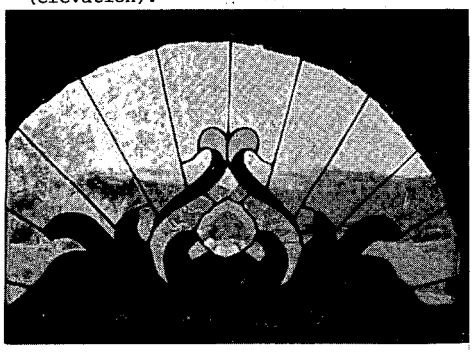


Fig. 10. Interior photograph of stained glass in a mass wall with mountain view beyond.

## 5. SUMMARY

The creative design of thermal storage walls can result in attractive and functional passive solar systems. The louvered-mass wall, floating-mass wall and the stained glass in a mass wall illustrate designs that improve the thermal performance, aesthetic characteristics and human comfort (thermal and luminous) of selected passively solar heated residences.

New opportunities to improve the interior design characteristics of thermal storage walls are being pursued by ENSAR Group and other designers in order to have the best match of function, aesthetics, performance and cost for specific projects.

## 6. REFERENCES

(1) Franta, G., Connoly, M., Winn B., "Utility Impact and Thermal Performance of the Franta Residence," Proceedings of the Sixth National Passive Solar Conference, American Solar Energy Society, Newark, DE, (1978), p. 643.

(2) Bier, J., "Performance of a Low-Cost, Owner-Built Home Using Vertical Solar Louvers," Proceedings of the 3rd National Passive Solar Conference, American Solar Energy Society, Newark, DE, (1979), p. 643.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# ENERGY EFFICIENT COMMUNITY AND SUB-DIVISION DESIGN FOR TUMBLER RIDGE, BRITISH COLUMBIA: PASSIVE SOLAR AND OTHER DIMENSIONS.

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## ABSTRACT

This paper discusses procedures which offer increased energy efficiency for the new resource community of Tumbler Ridge, B.C. This town will house the personnel associated with the mammoth Northeast B.C. Coal Project, upon which the provincial government has staked a significant portion of its economic future. Cost comparisons for road and service layout, site orientation, passive solar gain and other forms of climatic response are presented along with their implications. These lead to changes in both community layout and configuration. The study offers precedents for similar settlements across Canada as well as the United States, (Project commissioned by Canada Mortgage and Housing Corporation, with cooperation of the B.C. Ministry of Energy, Mines and Petroleum Resources and The District of Tumbler Ridge).

## 1. INTRODUCTION

The Province of British Columbia is approximately as large as the entire nation of France. It harbours vast natural wealth in the forms of minerals, timber and petroleum resources. The recently re-elected provincial government has staked part of the province's economic future on the Northeast Coal Block located in the Rocky Mountain Foothills west of Dawson Creek, B.C. Metalurgical grade coal will be mined here for shipment via Prince Rupert to Japan and other major industrial manufacturing nations. An essential component of this vast project is a new community, Tumbler Ridge, where the workers and their families will live. At this writing (June, 1983), the first occupants have already taken up residence and the construction of the town centre with its services and commercial facilities nearing completion. This town will have an ultimate population of 10,500.

Situated at 55 degrees north latitude, Tumbler Ridge is located in boreal forest. The townsite occupies a series of south facing terraces overlooking the Murray River and Flatbed Creek. It receives southwest winds which funnel up the river valley averaging 18 km $hr^{-1}$ throughout the year. Gusts in excess of 40 km $hr^{-1}$ have been recorded during winter months.

Much of the site was cleared of timber to expedite the construction of roads and buildings. The potential effect of wind on human comfort and heating loads could be critical for both the town centre and residential neighborhoods. Snow drift and wind chill can be severe.

Although low sun angles and short hours of daylight limit solar benefit during the December/January period, passive solar access is possible throughout the longer "shoulder" heating season. Orientation and lot layout become important considerations.

The town's remote location requires the transportation of people and goods over considerable distances. Therefore, measures which reduce the need for individual travel and which encourage efficient community layout to minimize the cost of service installation, road construction and maintenance are important in formulating an approach toward energy conservation at Tumbler Ridge. Although the town has a commanding setting, the site is constrained on all sides and the buildable land area is limited, necessitating a compact community form so as not to waste this resource and to allow some flexibility for future expansion.

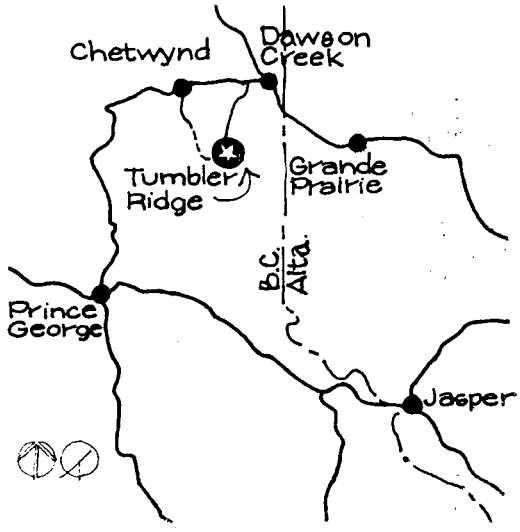



Fig. 1. Location of Tumbler Ridge, B.C.

## 2. THE POTENTIALS

Significant cost savings in remote resource community development can be achieved through a comprehensive examination of energy efficiency and the application of inexpensive and easily implemented principles at the community, neighbourhood and site planning levels. A recent project funded and directed by Canada Mortgage and Housing Corporation (B.C. Regional Office) with cooperation from the B.C. Ministry of Energy, Mines and Petroleum Resources focuses upon examination of these potentials. Some important questions which this study seeks to answer are:

1. What types of savings can be realized through community plan modification? Can such savings be quantified?

2. What role can wind amelioration and solar access play? Can dollar values be identified for these energy conservation measures?

3. Can a series of logical directives be evolved which are applicable to Tumbler Ridge as well as to other remote resource communities?

This study, conducted over an eight month period, conclusively shows that possible savings exist in the form of:

1. Capital Costs: lot and site preparation, roads and piped services as well as the choice of heating fuel and the method of its distribution.

2. Operating Costs: included are space heating and transportation costs for households, businesses and municipal services.

Some major principles for reducing these expenses which the study reveals are:

1. Retention of major shelter belts and the introduction of intermediate wind breaks where feasible.

2. Providing radial collector roads from neighbourhoods to the town centre, and modifying arterial road patterns to reduce lengths.

3. Individual lot frontage reduction and orientation of units on their lots for optional solar access.

4. Avoidance of hazard lands and steep slopes for development.

## 3. COMMUNITY LAYOUT

A more compact community operates with greater efficiency. Shortened road and service routes are less costly to build and operate over time.

An analysis of transportation based energy savings is straightforward, as most types are either internal (i.e., town centre or school as a destination) or involve commutation to the mines, which are from 8 to 32 km from the townsite. Urban transportation studies indicate the following travel breakdown:

- home based work: 30%
- home based shopping: 15%
- home based other: 35%
- non home based other: 20%

In estimating travel, the assumption is made that apartment units will generate 6 vehicle trips per day while other housing units will generate 10 vehicle trips per day (per unit). It is anticipated that apartments will total 738 units and other housing forms will total 1,656. Therefore, trip totals (estimated) are:

| Journey | Number of Trips |
|---|---|
| 1. Home to mine | 1,537,704/year |
| Carpool reduction | 1,281,420/year |
| 2. Home to town centre | 3,532,896/year |
| 3. Home to school | 1,027,080/year |
| 4. School to town centre | 675,864/year |
| 5. Mine to town centre | 782,135/year |
| Carpool reduction | 651,780/year |

From this table it becomes apparent that an important key to cost savings in transportation is to accumulate small savings over many trips per year. Overall totals can be large. Two compact community options are developed for comparative cost purposes. These are portrayed in Figure 3.

Detailed preparation of a compact community plan might result in further improvements to these estimates. For example, the journey to work for half the community could be reduced by 1400 meters through a more efficient road alignment. The benefits of reducing collector and arterial road lengths are significant (approximately $1 million Cdn. per km in capital cost, 1982 dollars) in addition to annual operting expenses.

Further transportation savings can be realized by locating apartments in closer proximity to the town centre. Most transportation studies indicate a reluctance to travel greater distances than 300 meters from home before using a vehicle. A shift from car to walking would result in a reduction of 1 car trip per day. If an average trip length of 1500 meters is assumed, this would result in a $32,800.00 per year savings for the 738 apartment units ultimately planned for the town.

Compact Community Form A: Reduction in average trip distances for each trip purpose, as measured along arterial and collector roads, from neighbourhood boundaries to the destination (for home-based trips) in comparison with the existing Community Plan.

| | | |
|---|---|---|
| Home to mine | 1.0 km | 104,115.37 |
| Home to Town Centre | 0.5 km | 145,523.90 |
| Home to School | 0.25 km | 20,862.56 |
| School to Town Centre | 0.5 km | 20,592.73 |
| Mine to Town Centre | 0.5 km | 26,478.56 |
| | | 317,573.14 |
| Add 10% truck trips @ 12.2¢/km: | | 47,635.97 |
| | | $365,209.11 + |

Household savings: $152.50 / year

Compact Community Form B: a more conservative reduction in average trip distances:

| | | |
|---|---|---|
| Home to mine | 0.5 km | 52,057.69 |
| Home to Town Centre | 0.25 km | 71,761.95 |
| Home to School | 0.1 km | 8,345.03 |
| School to Town Centre | 0.25 km | 10,296.37 |
| Mine to Town Centre | 0.25 km | 13,239.28 |
| | | 155,700.32 |
| Add 10% truck trips @ 12.2¢/km: | | 23,355.05 |
| | | $179,055.37 + |

Household savings: $74.80 / year

Fig. 2. Cost Analysis: Compact Community Form vs. Existing Plan.

## 4. SUBDIVISION DESIGN

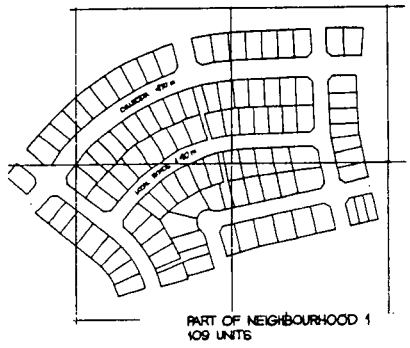
The potential contributions of site planning measures at the residential subdivision level occur in two areas:

1. House/lot relationship: compact lots with reduced width frontages.

2. Housing clusters: small groupings of units with solar access and use of cul-de-sacs and loop roads to reduce overall road lengths.

Portions of Neighbourhood One (the first phase of housing) are compared to a plan with one collector road and six cul-de-sacs which afford north-south orientation with unshaded solar access and reduced (15 m) frontage lots. The cost analysis for these alternatives appears below:

A direct result of compactness is shortened trip lengths to the neighbourhood boundaries. Approximations suggest that 4,800,000 such trips would be made each year. If the average trip length is reduced by 100 m, resultant savings for the first neighbourhood would be $45,000.00. Across the entire community the resultant savings would amount to $4,700,000.00 in capital costs. Compact form also has implications for heating and other utilities. For example, if district heating was selected for Tumbler Ridge (at the present time not being considered) the difference between a cul-de-sac and standard street layout would be $2,861.00 per unit.



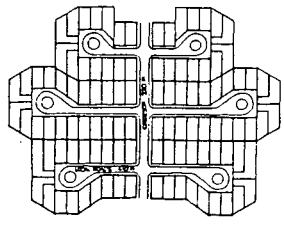




Fig. 3. Standard vs. Compact neighbourhood.

## 5. SOLAR ACCESS

Exploration of this component and wind protection are the crux of the study, and of primary concern in this paper. In establishing the value of solar access the critical factor is the difference in gain between average and best orientation. In the best situation, 50% of a unit's windows face south while in an average condition only 15 % to 20% do so. In the case of a small detached house (typical of most housing at Tumbler Ridge) the difference in solar gain between these two orientations is 5.5 GJ/year.

The Saskatchewan Research Council Report results are used for modeling. In this study (Eyres, 1982) a 50% southern orientation is assumed for all types of housing on the Tumbler Ridge site. The average condition is modeled by C.M.H.C.'s Technical Research Division in Ottawa. Results of this comparison are summarized in Figure 4.

Effects of Orientation for Passive Solar Design

Annual Savings in GJ Between Best and Average Orientations Applied Across the Entire Community

| Unit Type | Number | Standard | Measures | Retrofit | E - E |
|---|---|---|---|---|---|
| Large Single* | 511 | (5.5)<br>2,810.5 | (4.1)<br>2,095.1 | (5.5)<br>2,810.5 | (1.9)<br>970.9 |
| Small Single* | 510 | (5.5)<br>2,805 | (4.1)<br>2,091 | (3.8)<br>1,938 | (3.0)<br>1,530 |
| Large Duplex* | 68 | (4.0)<br>272 | (3.9)<br>265 | (3.5)<br>238 | (2.0)<br>136 |
| Small Duplex | 67 | (3.1)<br>210 | (3.0)<br>205 | (2.8)<br>184 | (1.6)<br>105 |
| Row Townhouses | 112 | (3.1)<br>347 | (3.0)<br>236 | (2.8)<br>308 | (1.5)<br>168 |
| Apartments | 738 | (1.0)<br>738 | (1.0)<br>738 | (1.0)<br>738 | (0.5)<br>369 |
| Manufactured | 388 | (4.0)<br>1,552 | (4.0)<br>1,552 | (4.0)<br>1,552 | (4.0)<br>1,552 |
| | 2,394 | | | | |
| Total GJ "Conservative" | | 8,734.5 | 7,282 | 7,768 | 4,851 |
| "Optimistic" (+80%) | | 15,722 | 13,107.6 | 13,982 | 8,696 |
| Conservative 1981 Value | | | | | |
| NG, 65% furnace $5.71/GJ | | 49,874<br>20.84/du | 41,580.22<br>17.37/du | 44,355.28<br>18.53/du | 27,584.45<br>11.52/du |
| Electrical $9.61/GJ | | 83,938<br>35.06/du | 69,980.02<br>29.23/du | 74,660.48<br>31.18/du | 46,424.95<br>19.39/du |
| Optimistic 1981 Value | | | | | |
| NG, 65% furnace $5.71/GJ | | 89,772.62<br>37.50/du | 74,844<br>31.26/du | 79,837<br>33.35/du | 49,65[illegible]<br>20.74/du |
| Electrical $9.61/GJ | | 151,088<br>63.11/du | 125,964<br>52.62/du | 134,367<br>56.13/du | 83,569<br>34.91/du |

* CMHC2 Model results, other values estimated

Fig. 4. Effects of Orientation for Solar Design in Different Housing Types.

The C.M.H.C. model is run on an assumption that housing units are partially blocked by adjacent homes. From the model, it appears that the benefits of solar gain can only be realized if the unit is correctly situatedon the lot without blockage and windows placed to maximize south-facing glass.

The actual plan for the first phase of Tumbler Ridge (neighbourhoods 1 and 2, Stanley Associates, 1981) is analyzed for the possibilites of unblocked solar access. In this scheme, approximately 40% of single family detached, 25% of duplex units and 2% of the mobile home sites presently have this characteristic.

In this analysis, all windows except those facing north receive some solar gain by day and all lose equivalent amounts of heat by night during the heating season. The full benefits of solar gain can only be realized if insulating shutters are used to reduce nighttime loss. This has not been modeled.

Figure 5 (above) reveals that more energy efficient forms of construction make less use of passive solar in comparison with standard construction. Reasons for this are:

- these kinds of homes (i.e., superinsulated, triple glazed) have smaller heating requirements to be offset by solar gain;
- energy efficient units are more isolated or protected from the external environment (i.e., wind chill).

However, because these energy efficient units have a lower heat need generally, the overall percentage contribution made by correct solar orientation increases markedly from 4.2% in a standard house to 7.8% in a super energy efficient model. Under the most optimistic solar gain conditions this percentage contribution ranges from 7.6% for standard construction (C.M.H.C. minimal standard) to 14.0% for super-energy efficient construction. Figure 6 portrays the benefits of good solar orientation and design, comparing conservative and optimistic estimates.

## 6. WIND PROTECTION

Although difficult to quantify in dollar terms, the effects of wind amelioration upon space heating needs can be approximated. Some important variables are:

1. House characteristics: air tightness, sheltering effect of adjacent units or vegetation and the location of openings.
2. Wind characterics: speed (duration) and interior-exterior temperature differentials.

3. Wind modification measures: effective distances for reduction, potentials for reduction and resultant changes in velocity.

Heat loss in buildings occur through crack infiltration and transmission via structural and other components. Research by Shaw and Tamura (1980) purports that effects of wind on infiltration are difficult to predict, particularly when differences between inside and outside temperatures are large. Work by Shaw (1981)[5] indicates that wind pressure on upgraded houses is often offset by temperature differences where it exceeds 20°C for 10 to 25 km wind speeds.

A study by Socolo (1978) suggests that vegetation close to the unit can significantly reduce heat loss. This study did not incorporate temperature differences in its estimates. At Tumbler Ridge, retention of major tree belts of 100 m in width particularly on terrace edges where forest species are most windfirm (height of trees: approximately 25 m) would create shelter effects up to 400 meters. Although some costs of vegetation management would be incurred, it would be less expensive than installing new landscaping which could take many years to reach effective height. Retention of these belts need not interfere with solar access to the houses.

The value of wind reduction exists primarily on the perimeter (edges) of neighbourhood or housing cluster. Houses on the windward edge tend to provide shelter for those on the inside of the group of street. In suburban or urban areas each building becomes a form which the wind passes over.

Solar access and wind reduction savings are combined in the following table. The potential contribution of both measures ranges from 9% to 18% of the heat loads to be purchased for different forms of construction.

Combined Effects of Wind Shelter and Solar Access

Annual Savings in GJ

| | Standard | Measures | Retrofit | E - E |
|---|---|---|---|---|
| Solar Orientation ("Conservative") | 8,734.5 | 7,282 | 7,768 | 4,633.9 |
| 50% of Wind Shelter | 9,687.5 | 9,425. | 3,382.5 | 2,700.9 |
| Total GJ | 18,422.2 | 16,707 | 11,150.5 | 7,531.8 |
| 1981 Monetary Value | | | | |
| NG, 65% furnace $5.71/GJ | 105,190.47<br>43.94/du | 95,397.00<br>39.85/du | 63,669.00<br>26.60/du | 43,007.00<br>17.96/du |
| Electrical $9.61/GJ | 177,037.34<br>73.95/du | 160,554.00<br>67.07/du | 107,156.00<br>44.76/du | 72,381.00<br>30.23/du |
| Percentage of Total Heat Load | 8.9% | 12.2% | 10.0% | 12.1% |
| Solar Orientation ("Optimistic") | 15,722 | 13,107.6 | 13,962 | 8,696 |
| 50% of Wind Shelter | 9,687.7 | 9,425 | 3,382.5 | 2,700.9 |
| Total GJ | 25,409.70 | 22,532.6 | 17,364.5 | 11,396.9 |
| 1981 Monetary Value | | | | |
| NG, 65% furnace $5.71/GJ | 145,089.38<br>60.60/du | 128,661.00<br>53.74/du | 99,151.00<br>41.42/du | 65,076.00<br>27.18/du |
| Electrical $9.61 | 244,180.00<br>102.10/du | 216,539.00<br>90.45/du | 168,373.00<br>69.70/du | 109,524.00<br>45.75/du |
| Percentage of Total Heat Load | 12.3% | 16.5% | 15.5% | 16.3% |

Fig. 6. Combined Effets of Wind Shelter and Solar Access (Annual Savings in GJ).

## 7. CONCLUSION

Solar access, wind reduction, compact community layout and subdivision design all have potential economic benefits.

Energy savings achieved through site planning to reduce space heating requirements vary with the conservation quality of the housing. Economic values of such energy savings varies further with assumptions about the kind of heating system and fuel costs. Taking a house standard built to C.M.H.C. measures for a nothern climate as a benchmark of construction quality, site planning principles would have the following values (1982 dollars) annually:

1. Solar Access $11.65 - 21.00/unit (natural gas)
   19.60 - 35.30/unit (electrical)
2. Wind Shelter 22.50 - 38.00/unit (natural gas - electrical)
3. Combined Effects 40.00 - 53.75/unit (natural gas)
   67.00 - 90.50/unit (electrical)

Contribution: 12.1 - 16.5% of heat load

While the above per-unit values may not appear large it should be emphasized that site planning measures are essentially free and able to be implemented without significant cost penalties. Site planning measures which affect roads and transportation do not vary with housing quality, but annual costs are highly sensitive to interest rate assumptions.

Taking the first two neighborhoods (completed, Spring 1983) as the base case, potential savings from a compact sub-division layout (1982 dollars) are:

| 1. Capital costs | | Annual |
|---|---|---|
| Roads and services | $8,266/unit | |
| | (15%): | 1,246.70/unit |
| | (20%): | 1,654.85/unit |
| 2. Operating costs | | |
| Municipal | | $94.20/unit |
| Individual and business (example only) | | 18.80/unit |
| | | $1,359.70 - $1,767.85/unit |

At the community layout scale, several refinements can be made to significantly reduce road capital and transportation costs. The following values are representative only of potential savings from compact community form and not based upon direct comparisons between two community plans:

1. Household transportation costs: savings of $75 to $150/year per household.
2. Every km of road (arterial or collector) will save $151,600 to $189,000/year to the community with a standard heating scheme and up to $318,000/year if district heating is employed (heating lines would run adjacent to roads in such a scheme).

3. Specific changes to parts of the community plan can save between $40 and $300/year per household. Part of this savings is in the form of household transportation costs and partly in community capital costs. When multipled across the entire town, these figures become very significant (several million dollars).

Review of the relative magnitudes of these benefits indicates that the highest priorityin site planning should be given to procedures which create compact community and sub-division layouts and which reduce the lengths of road and service runs. The values of these measure is further amplifiedif district heating is introduced.

Site planning steps which reduce space heating requirements have somewhat less value, but are still desireable if they can be introduced without major costs (which is apparent). The further adaptation of housing units to take full advantage of solar access has not been addressed in the study (i.e. collectors, thermal mass, curtains, etc.) but could add significantly to identified savings.

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# CITY FORM: THE CREATION OF COMFORTABLE URBAN MICROCLIMATES

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## ABSTRACT

This paper describes a method for analyzing the climate of exterior spaces in terms of human thermal comfort. Hypothetical city configurations are compared in two U.S. climate zones.

## 1. INTRODUCTION

Exterior spaces in urban settings -- plazas, sidewalks, streets, and parks -- constitute a majority of a city's land use. They form important meeting places, and their character largely determines the "image" of the city. Using natural energy to produce thermally comfortable conditions extends still more the usefulness of these spaces. Designing for sun and wind access results in the need for less built area per inhabitant annd therefore less non-renewable energy consumption. An energy-conscious city provides the most livable area for the least energy cost.

Although the importance of building form and spacing in the determination of microclimates has been discussed by several authors (Robinette[11], Chandler[5], and Miess[9]), their work does not include specific design recommendations based on human comfort. However, specific relationships between climate elements, architecture, and human comfort have been studied by Olgyay[10], Fanger[6], Arens[1], and Brown and Novitski[3]. Separately, the effect of building form on sun penetration (Knowles[8]) and wind speed (Beranek and van Koten[2], Gandemer[7], and Cermak[4]) has been determined for some building configurations. However, the impact of specific city configurations on human comfort has, to our knowledge, never been systematically quantified.

## 2. METHODOLOGY

Our work is predicated on the "Modified Comfort Zone", or MCZ, a range of temperature and humidity in which comfort is achievable with the appropriate moderation of the sun and wind. An outdoor space can be comfortable in chilly weather if the wind is blocked and the sun is available for warming (MLO), or in hot weather if the sun is blocked and the wind is available for cooling (MHI).

We define the Standard Comfort Zone, or SCZ, as that temperature range (varying with humidity) in which comfort results from the balanced interaction of the sun and wind. The cold code C is broken into three levels of insolation to indicate which solar gain heating systems may be appropriate. The hot code H is broken into three levels of relative humidity to indicate which passsive cooling systems may be appropriate.

In this paper, we concentrate on outdoor spaces at the urban scale. The generalized model we use is shown in Fig. 1. The streets are analyzed by how often they perform well thermally. For each hour in the year which falls within the MCZ, each street is evaluated according to whether it a) admits the sun and blocks the wind, when it is chilly (MLO), or b) blocks the sun and admits the wind when it is warm (MHI). All blocking and admitting are a function of the actual patterns of the wind and sun around the blocks, as determined by wind tunnel studies and conventional sun angle calculations. Selected points throughout the grid are given a score between 0 and 100%: the percent of time they perform well thermally relative to the maximum number of potential MCZ hours.

The result of the analysis is a "contour map" of the city's thermal performance. A designer can use this information in determining the appropriate location for various outdoor functions. Similar monthly evaluations are also available, so that seasonally variable functions can also be located appropriately.

TABLE 1

| City | MLO(%) | SCZ (%) | MHI(%) | Total MCZ |
|---|---|---|---|---|
| Charleston | 24 | 16 | 10 | 50 |
| Dodge City | 20 | 6 | 8 | 34 |
| Madison | 13 | 7 | 5 | 25 |
| Phoenix | 17 | 16 | 14 | 47 |

Table 1 shows the distribution of the various climate codes for several locations and helps to describe the character of each climate. The percentage given for each code is relative to the total number of hours in a year.

## 3. GENERIC PATTERNS

Using a model of a generic city grid with the block width twice the street width and the block height equal to the street width, (see Fig. 1) we evaluated the amount of time that specific street locations were comfortable. The streets were divided into a grid system, with 8 cells per block (see Fig. 2) so that climatic conditions could be observed for specific street locations.

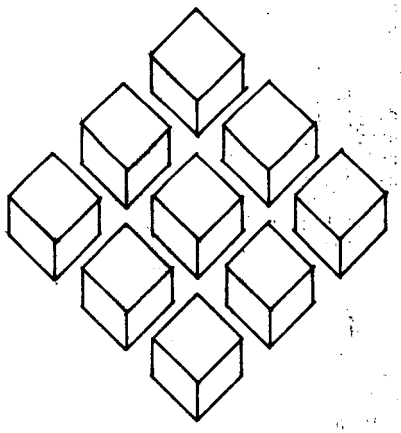


Fig. 1. Model of generic city.

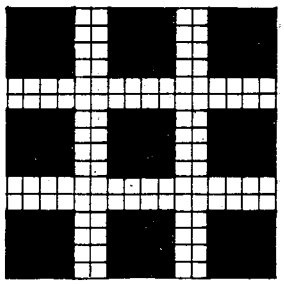


Fig. 2. Cell division of city grid.

Using climate data from Madison and Phoenix, the interaction of the sun and the wind was studied for each hour of one day for every month to determine how often each cell was comfortable, compared to the total time of potential comfort. Each hour was analyzed with a solar heliodon to determine which cells were sunny and using hourly wind directions and windflow patterns to determine which cells were windy. During MLO hours, the wind must be blocked and the sun admitted in order for a cell to be comfortable; while during MHI hours, the wind must be admitted and the sun blocked in order to achieve comfort. During SCZ hours, comfort is achievable if both sun and wind are blocked or both are admitted. For hours before sunrise and after sunset, comfort can be achieved by blocking the wind for MLO hours, admitting the wind for MHI hours or doing nothing for SCZ hours.

After all the cells in the city grid were analyzed for each month, the results were combined into seasonal and yearly percentages for Madison and Phoenix climates.

By studying the percentage of comfort actually achieved for each cell in the city grid, we discovered eight generic patterns comparing the relative percentage of comfort between different positions within the city grid (See Figs. 3-10). Each of these patterns, although derived from specific wind and sun data, occurs more frequently in specific comfort conditions (MLO, MHI, or MCZ), with some consistency between each climate location. In addition, some patterns are highly dependent on wind direction, resulting from a consistent wind direction or many nighttime MCZ hours (such as in Phoenix summers); and some patterns are highly dependent on sun conditions, resulting from a variable wind direction or many daytime MCZ hours (such as in Madison spring and fall).

### 3.1 City Grid Patterns

In pattern #1, the north-south streets are more comfortable than the east-west streets (see Fig. 3). This pattern occurs during MHI hours, caused by winds from the north or south to cool the streets and shade during the afternoon hours when MHI usually occurs.

In pattern #2, the north-south running (N/S) streets, except intersections, are more comfortable than the east-west running (E/W) streets (see Fig.4). Comfort, occurring during MLO or MCZ hours, is caused by winds from the east or west, which are blocked in these streets. Many MLO hours occur at night when comfort can be achieved just by blocking the wind; therefore this pattern is highly dependent on the wind direction. Both orthogonal and diagonal wind directions produce windy intersections, so an MLO pattern will never have comfortable intersections. During MHI hours, the intersections will be comfortable as long as the sun is blocked.

In pattern #3, the E/W streets are more comfortable than the N/S streets (see Fig. 5). Comfort, occuring during MHI hours, is caused by winds that came most often from the east or west to cool these streets, combined with shade around noon.

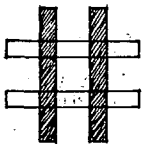


Fig. 3

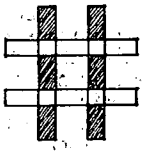


Fig. 4

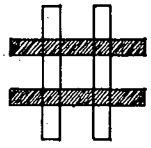


Fig. 5

In pattern #4, the E/W streets, except intersections, are more comfortable than the N/S streets (see Fig. 6). Comfort, occurring during MLO hours, is caused by winds that came most often from the north or south, which are blocked in these streets. Many MLO hours occur at night, so this pattern is highly dependent on the wind direction during MLO hours. Comfort, during MHI hours, results from a diagonal wind direction and shade around noon. The intersections are less comfortable than the E/W streets because they are sunnier than the middle of the block. The diagonal wind does not produce a strong orthogonal comfort pattern, so this pattern is more dependent on the sun during MHI hours.

In pattern #5, comfort is fairly uniform throughout the city grid (see Fig. 7). This MCZ pattern occurs when comfortable spots during MHI and MLO hours are in opposite locations, thus cancelling each other out and producing a uniform pattern.

In pattern #6, comfort is fairly uniform throughout, except the intersections are less comfortable (see Fig. 8). This pattern, during MLO hours, is caused by a mixed wind direction with many night hours. This pattern occurs as an MCZ pattern, when MHI and MLO patterns are opposite, but the intersections are less comfortable due to many MLO hours.

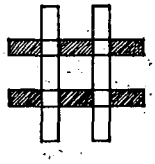


Fig. 6

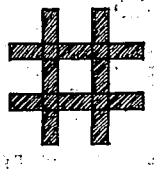


Fig. 7

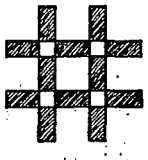


Fig. 8

In pattern #7, comfort is not achieved anywhere on the city grid (see Fig. 9). This occurs either during MLO hours, when the streets are not sunny enough to be comfortable, or during months when it is either too hot or too cold for comfort to be achieved under any sun or wind conditions.

In pattern #8, comfort is only achieved at the intersections (see Fig. 10). This could occur during MHI hours when a constantly changing wind direction would keep the intersections the coolest, as long as they were shaded.

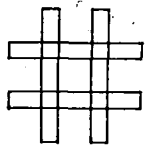


Fig. 9

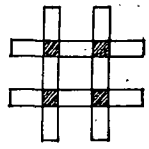
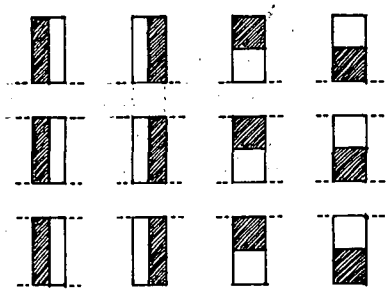
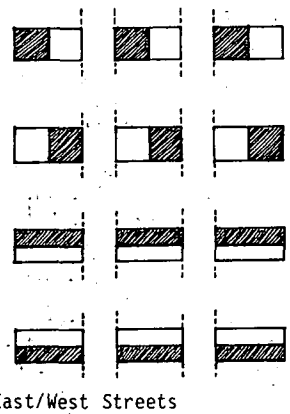


Fig. 10

In addition to these eight city grid patterns, eight patterns for variations of comfort within the street were also observed (see Fig. 11). These patterns are also specific to climatic conditions (MHI, MLO), and are usually more dependent on sun than on wind (because the wind patterns are usually more constant within a given street). These patterns, when combined with the generic city grid patterns, create more specific level of detail to describe the city microclimates.



North/South Streets



East/West Streets

Fig. 11. Street Patterns

It should be remembered that the city grid patterns indicate comfort relative to other positions in the city grid, but do not show actual percentages of comfort.

## 4. RESULTS

These observations are based on city blocks 98 $m^2$ (320 $ft^2$) of a uniform 18 m (60 ft) height. The street width is constant at 24 m (80 ft). Data points in the center of cells along the edge of each block are evaluated. The cells are arranged similarly to those in Fig. 2 with four in each intersection but with sixteen rather than eight in each street. A hot arid climate based on Phoenix weather and a cold climate based on Madison weather data have been analyzed for two grid orientations, one orthogonal and one diagonal to cardinal compass points.

The orthogonal grid achieves about a 10% larger portion of the total possible MCZ hours in the Phoenix climate than in the Madison climate. The total annual MCZ ranges from 25 to 38% of the possible MCZ for the Phoenix climate and 17 to 24% for the Madison climate. In terms of total MCZ, the E/W streets perform somewhat better than the N/S streets in the Madison climate; while in the Phoenix climate, the N/S streets perform better than the E/W streets.

Just looking at the MLO condition, the orthogonal grid performs poorly in both climates achieving comfort just 5 to 20% of the hours possible. The E/W streets, especially on the north side, perform best in the Madison climate, as would be expected because of their superior access to sun. In the Phoenix climate, however, the N/S streets perform the best because many MLO's occur at night when the wind must be blocked, but sun access is not necessary.

The orthogonal grid performs best in the Phoenix climate during the SCZ condition, when sun and wind are in balance, achieving 61 to 78% of its potential as compared to 31 to 74% of its potential in the Madison climate. In both cases the intersections performs better than the streets.

The N/S streets perform best in both climates during the MHI conditions because they offer the most shade when the sun is high during the warm months of the year. The west side of the N/S street performs best in the Madison climate because the MHI is usually an afternoon condition, and the sun is most completely blocked on the west side. In the Phoenix climate on the other hand, both sides of the N/S streets perform equally well because the MHI is both an afternoon and morning condition.

Comparing a diagonally and an orthogonally oriented grid in the same climate, Madison, the total performance score achieved is in the 17 to 24% range regardless of orientation. With the diagonal orientation both streets perform about the same; however with the orthogonal orientation, the E/W streets perform about 4% better than the N/S streets. Just considering the MLO condition, the north side of the E/W streets is the most comfortable although the northwest side of the northeast/southwest running (NE/SW) streets is almost as comfortable. The total MLO performance, the predominant condition in the Madison climate, is poor, ranging from 5 to 16% for both orientations.

During SCZ conditions, where any building influence disrupts the balance of sun and wind, the intersections are the most comfortable, and the N/S and northwest/southeast running (NW/SE) streets are the least comfortable.

Under MHI conditions the SW/NE streets of the diagonal grid perform about 10% better than the E/W streets of the orthogonal grid. However, the N/S and NW/SE streets, particularly their west sides, perform the best.

Comparing diagonal and orthogonal grid orientations in the Phoenix climate, for annual MCZ conditions, the N/S streets of the orthogonal grid perform 2 to 4% better than the more uniform NW/SE and SW/NE streets of the diagonal grid.

## 5. CONCLUSIONS

In both climates studied the streets within the diagonal grid orientation were more nearly equal in performance to each other than the streets within the orthogonally oriented grid. In the orthogonal grid either the N/S streets or the E/W streets performed best depending on climate.

Studies which are currently underway include varying building heights, city squares and two additional climate types.

## 6. ACKNOWLEDGMENTS

Wind tunnel studies were conducted at the School of Architecture, University of California at Berkeley, under the direction of Edward Arens.

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# DESIGNING AND EVALUATING A SOLAR SUBDIVISION

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## ABSTRACT

Production homes in new residential subdivisions can be naturally heated and cooled. Subdivision design guidelines show how to lay out streets, lots, buildings and vegetation to use the sun and the wind. The guidelines, along with simple shadow analysis tools, can be used either as design criteria to lay out a site or as review criteria to assess a development plan.

## 1. INTRODUCTION

Each year tens of thousands of housing units are built in subdivisions around the country. The vast majority of these units fail to take advantage of solar heating and natural cooling opportunities. This failure to use the natural advantages of a site wastes energy and, in California, it's against the law. It is now time to design production home developments that are naturally heated and cooled. This paper, based on training workshops developed by the Association of Bay Area Governments, presents "solar subdivision" design and evaluation principles and tools for use by developers and local planning officials.

If residential solar systems, both passive and active, are to make significant contributions to our nation's energy supply, they must become an accepted part of the mainstream housing construction industry. Solar technology is now proven and widely available. Yet up until now most solar homes have been custom-designed for individual home buyers. However, the majority of new homes constructed today are "production homes." Land development companies annually produce thousands of these homes in conventional subdivisions and typically use about five basic models repeatedly.

Our purpose is to introduce into the subdivision design and review process objectives to promote the use of natural heating and cooling. In this paper the term "solar subdivision" refers to a housing development that uses natural heating and cooling. It may include a mix of dwelling unit types, such as single family detached and townhouse units; and most units are at least partially solar heated.

Of course, homes in a solar subdivision must have access to the sun to use natural heating. If a subdivision is laid out without thought to solar access - a common occurrence - it may be impossible for even the best solar designer to design functional solar homes there.

In California recent legislative actions call upon cities and counties to play a crucial role in promoting solar energy in new residential development. The Solar Rights Act of 1978 requires that tentative subdivision maps provide, to the extent feasible, for future passive or natural heating and cooling in the subdivision. The Act also gives local governments the authority to deny a permit to a subdivision that fails to meet these new requirements. A recent opinion from the State Attorney General affirmed this new local government power.

While this law provides a statewide mandate, it does not provide standards for designing solar subdivisions. The guidelines presented in this paper were developed to show local governments and developers how to design solar subdivisions. They may be used either as design criteria as the site is being laid out or as review criteria when a tentative site plan is submitted to a city or county for approval.

## 2. GUIDELINES FOR SOLAR SUBDIVISIONS

Design of a solar subdivision requires the application of five basic principles. The first of these, related to solar access, is the most important and is discussed at length. The other four principles, dealing with natural cooling and protection from winter winds, are then briefly discussed.

These design principles are not new ideas; they are proven, common sense concepts that have been used for thousands of years. What is new is the application of these principles to conventional subdivisions. (Many of these ideas are discussed in Planning Solar Neighborhoods, published by the California Energy Commission.)

Principle No. 1: **LOCATE BUILDINGS ON LOTS SO THAT THE SUN CAN STRIKE THE SOUTH WALL AND ROOF OF EACH UNIT WITHOUT OBSTRUCTION.**

Solar access to south-facing walls will allow passive solar home design. Solar access to roofs will allow for solar hot water systems.

## 2.1 Existing Site Features

The first step in designing a solar subdivision should be to analyze the shadow patterns created by the existing site features. (Shadow analysis is a crucial part of solar subdivision design. It is a determination of the shadows cast by objects and an assessment of the portions of proposed buildings that may be shaded by these objects. A variety of simple tools have been developed for determining shadow patterns on plans. These tools are described briefly later in this paper.) Large hills, groves of trees, buildings and fences cast shadows that will restrict solar access in some areas. The site planner should identify these features and their shadows before beginning to lay out a subdivision. As a rule of thumb, solar access is desired between 9 a.m. and 3 p.m. on December 21 (Figure 1). At 38° north latitude, 83% of the total possible solar radiation occurs during these six hours. December 21 is the day with the lowest sun angles and, therefore, the longest shadows. It may be impractical, however, to provide solar access to all units in a subdivision during this time period. On some lots, for example, solar access from 10 a.m. to 4 p.m. or 9 a.m. to 1 p.m. may be acceptable. During the hours 10 a.m. to 2 p.m. at 38° north latitude on December 21, 60% of the total possible solar radiation comes in.

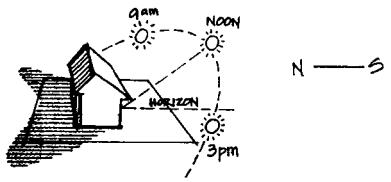



Fig. 1. 9 a.m. to 3 p.m. solar access and shadow pattern.

Examples of typical areas with poor solar access are steep north-facing slopes (Figure 2) and land on the north side of tall trees or tall buildings. If there is ample space on a site, it is best to avoid building in a 9 a.m. to 3 p.m. shadow zone. If buildings are to be placed there, special design features such as clerestory windows may achieve solar access.

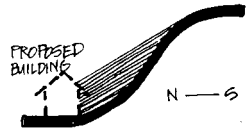



Fig. 2. North slope blocks solar access.

Topography may also enhance solar access. South-facing slopes have optimum solar access. Because shadows on these slopes are relatively short (Figure 3), higher density development can be constructed while still allowing solar access. It is often a good strategy to plan multi-family and multi-story buildings in the portions of the site with the best solar access and to plan parks, open space and low density, single-family detached housing in the areas with limited solar access.

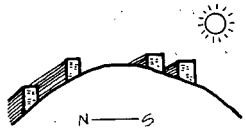



Fig. 3. South-facing slopes permit higher densities.

## 2.2 Proposed Structures and Vegetation

After completing the shadow analysis of the existing site features, determine the shadow patterns of proposed buildings on each discrete slope and slope orientation on the site--flat ground, north, west, east and south-facing slopes, etc. This shading analysis will show how far apart different sized buildings at different site locations must be placed to provide solar access. The site planner should then know roughly how to lay out streets, lots and building types to provide sunlight to the south wall of units throughout the development.

If buildings are not specified on the tentative subdivision map (i.e., only a lot layout is provided and building dimensions will not be known until the lots are purchased), assume a typical "building envelope" and do a shadow analysis based on these assumptions. The "building envelope" is the height and bulk of a building and its placement on a lot. The assumed building envelope should be consistent with the local zoning ordinance and with the type of unit built on similar property in the neighborhood. The city or county officials who review and approve subdivision plans should make these building envelope assumptions part of the conditions of

approval. If the developer later decides to make changes in the subdivision plans, the approving agency should require a revised shadow analysis.

Once a tentative subdivision map has been prepared, some lots may still have solar access problems. The site planner can then make design adjustments on individual lots or structures. The following discussion highlights some common solar access problems and design options for solving them. It should be noted that there is no single best design for a solar subdivision, such as a series of east-west streets with north-south oriented lots. Each design presents characteristic opportunities and constraints. The design for a given site should be based on a combination of physical site conditions, community standards and market factors.

## 2.3 Typical Solar Access Problems and Solutions

The most basic access problem occurs when a building shades the building on the adjacent lot to the north (Figure 4). (The shadow shown in Figure 4 and in all subsequent plan views is an approximation of the 9 a.m. to 3 p.m. shadow.) Narrow east-west oriented lots, particularly with two or more story dwellings, are particularly susceptible to this shading problem. Fortunately, there are several site and building design options that will offer sun to the south wall. Figures 5 to 11 illustrate these solutions.

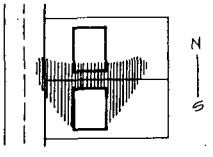



Fig. 4. Building shades building to north.

Widening the lot in the north-south direction will provide more space and sunlight between buildings. This option may also create two undesirable side effects - lower density and increased street length per lot - that increase the cost of housing.

Staggering buildings on lots (Figure 5) will allow multi-story buildings to be placed on adjacent narrow lots. Since some units will have large front yards and small back yards, front yard privacy on these lots can be gained using fences or hedges. Garages can be located close to the street to keep driveway lengths to a minimum.

Locating buildings on the north edge of lots (Figure 6) is another way to avoid shading problems. In this configuration, called "zero lot line," each property owner has control over more area to the south of his or her house. The neighbor's fence, trees and upper story addition will thus be farther away from the south wall and less likely to cast a shadow on it. Many communities, unfortunately, have zoning ordinances that require setbacks on all sides of a dwelling. A zero lot line plan may require a variance or a change in the zoning. Communities should re-examine their zoning ordinances and consider permitting the zero lot line approach for providing solar access.

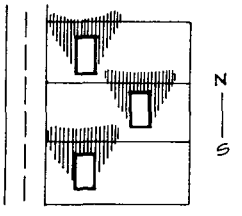



Fig. 5. Staggering buildings prevents shading.

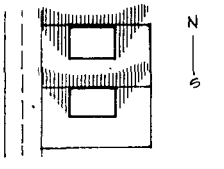



Fig. 6. Buildings placed on north lot lines.

Where a building has a single-story and a multi-story portion (Figure 7), the building can be flipped to its mirror image. On the top diagram in Figure 7, the single-story half of the center house is shaded by the house to the south and the two-story portion shades the house to the north. By flipping the center house, solar access is provided to the upper half of the two-story portion and shading of the house to the north is avoided.

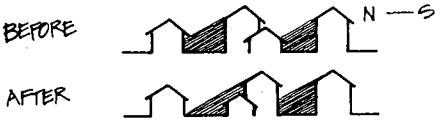



Fig. 7. Flipping center house improves solar access.

While so far only the placement of the building on the site has been altered, another type of solution affects the building design itself. A three-story unit can be changed to a two-story unit and a two-story to a one-story, thus shortening building heights and shadows (Figure 8). As a general strategy, it is best to locate the multi-story and highest density units on the sites with the best solar access, such as south-facing slopes and lots adjacent to




Fig. 8. Lowered building height reduces shading.

permanent open space. Single story dwellings are best on small lots, particularly narrow east-west oriented lots. To prevent lowering of overall subdivision density (and, thus, project profitability) density may be increased in other, more suitable portions of the site without inhibiting the solar access.

Flattening a house's roof pitch will also lower its height and shorten its shadow. A 4 and 12 roof has a slope of 18.4°. A 5 and 12 roof has a slope of 22.6°. From Table 1 and Figure 9 note that the peak of a 4 and 12 roof will cast a shadow until about 9:30 a.m. After 9:30 the shadow is cast by the north wall. With a 5 and 12 roof, the peak will cast a shadow until after 10 a.m.

TABLE 1. SUN ANGLES BY TIME OF DAY
(on December 21 at 38° north latitude)

| Time | Solar Altitude | Time | Solar Altitude |
|---|---|---|---|
| 9 a.m. | 15° | 1 p.m. | 27° |
| 10 a.m. | 22° | 2 p.m. | 22° |
| 11 a.m. | 27° | 3 p.m. | 15° |
| 12 noon | 29° | | |

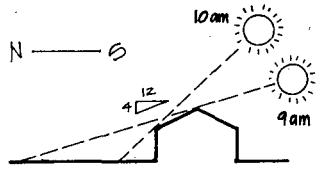



Fig. 9. Flattened roof pitch reduces shading from peak.

By lowering the roof pitch to 4 and 12 or flatter, shading from the peak is essentially eliminated. The shadow cast by the building is reduced to the shadow cast by the north wall. However, since the optimum tilt angle for rooftop solar collectors is greater than a 4 and 12 pitch, flattening the roof may make it necessary to raise solar panels off the roofline to achieve peak collector efficiency.

If solar access is restricted and none of the above alternatives are suitable, two additional home design options can be used-clerestory windows or rooftop solar collectors (Figures 10 and 11). These options can be counted on to provide solar heating even in very tight situations, although the latter alternative will usually

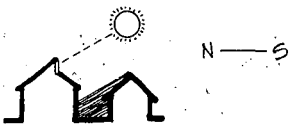



Fig. 10. Clerestory receives sun where buildings tightly spaced.




Fig. 11. Rooftop solar collectors work in very tight situations.

provide only hot water heating. Neither option will reduce subdivision density or the size of the units.

## 2.4 Common Problems with Placement of Garages and Trees

North-south oriented lots and east-west streets are often recommended as the ideal layout for a solar subdivision. This configuration has two common problems: garages and street trees on lots on the north side of the street may shade the south walls of these units (Figure 12).

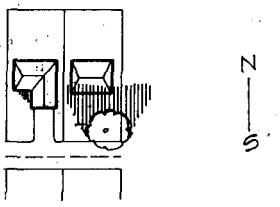



Fig. 12. Garage and street tree shade south wall.

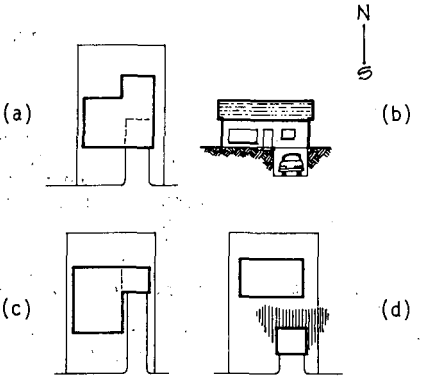



Fig. 13. Garage locations that allow solar access.

Possible solutions to the garage problem include: (a) make garage flush with the

south wall of the house, (b) put garage below house level, (c) put garage behind the house, or (d) put garage near the street and move the house farther north on the lot (Figure 13).

Street trees or home landscaping may shade south walls. Recommended solutions are (a) plant smaller trees on the north side of the street (Figure 14), (b) place houses farther north on lots, or (c) eliminate street trees from the north side of the street.




Fig. 14. Smaller tree on north side of street.

## 2.5 Cul-de-sac Lots and Lots on Intercardinal Streets

Streets and lots, of course, may not be oriented strictly on north-south or east-west axes. Where streets are intercardinal or lots have odd shapes and orientations, the key design principle remains the same; orient builds so that they have a south-facing wall with glazing. Buildings may be skewed on lots with the main facade not parallel to the street. Where solar access is restricted, many of the same alternatives discussed above, such as staggering units, can be applied.

## 2.6 Other Solar Subdivision Design Principles

The other four principles of solar subdivision design pertain to natural cooling in summer and protection from winter winds.

Principle No. 2: **USE VEGETATION AND EARTH FORMS TO SCREEN BUILDINGS AND OUTDOOR LIVING AREAS FROM WINTER WINDS**

Windbreaks should be dense and long enough to block the prevailing wind and should be close enough to the building so that the wind is forced over or around the structure. Proper windbreak design requires data on prevailing winter winds at the site and vegetation characteristics (e.g., tree height, width of crown and height to bole at maturity; winter and summer foliage density). Earth berms can also be used for similar effects, although they may be less aesthetically acceptable. Care should be taken not to let windbreaks block needed winter sun.

Principle No. 3: **USE VEGETATION AND EARTH FORMS TO CHANNEL SUMMER BREEZES TO ENHANCE NATURAL VENTILATION OF BUILDINGS AND OUTDOOR LIVING AREAS.**

Vegetation should be placed parallel to the direction of prevailing winds during the hot season. Building openings should be located on the upwind and downwind sides of the building to allow air to flow through the structure (Figure 15). If the prevailing winter and summer winds blow from the same direction or if the wind channel vegetation would block solar access in winter, a wind channel may be undesirable.

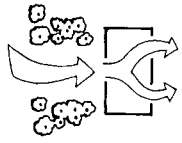


Fig. 15. Vegetation channels summer breezes.

Principle No. 4: **USE TREES AND OTHER VEGETATION TO SHADE THE EAST AND WEST WALLS OF BUILDINGS IN SUMMER.**

Low angle morning and afternoon summer sun can contribute to overheating a home. Trees, shrubs and trellises can be placed near east and west walls to block sun during these hours, but still allow south wall solar access in winter and rooftop solar access all year long. Deciduous trees are ideal for summer shading because they leaf out when shading is needed and lose their leaves in winter to allow sunlight to penetrate.

Principle No. 5: **USE TREES TO SHADE STREETS, PARKING AREAS AND DRIVEWAYS FROM SUMMER SUN.**

Paved streets, driveways, parking areas and patios absorb sunlight and transmit it back to the air above them. Shading paved areas will reduce outdoor summer temperatures and create a more comfortable environment. The local planning department, landscape architects, nurseries and reference books may help in selecting trees suitable for the site. Again, avoid placing trees where they will block solar access to buildings in winter.

## 3. SHADOW ANALYSIS TOOLS

Analysis of shadow patterns is a vital element of solar subdivision design. A variety of simple tools can aid the site planner. In contrast to the various commercially produced devices that are used by solar professionals to evaluate solar access on actual job sites, these tools are designed to be used on topographic maps and subdivision plans.

The most basic tool is a table of solar altitudes and azimuths for each hour of the day on December 21, September 21 and June 21. Using this table, a protractor and a

calculator, a planner can quickly sketch the shadows cast by objects on flat ground.

Since many sites are not flat, shadow analysis on sloping land is made easier using a simple table of shadow length multipliers for land with various slope angles and orientations. For any latitude, a table can be prepared showing shadow length multipliers for 0%, 5%, 10% slopes, etc., facing north, northeast, east, etc., at 10 a.m., 12 noon and 2 p.m. For example, the multiplier is 2.6 for a 10% northeast facing slope at 2 p.m. at 38° latitude. Thus, a 10-foot pole there would cast a 26-foot shadow (2.6 x 10 feet) along the 2 p.m. azimuth line.

Perhaps the handiest shadow analysis tool is the "solar access overlay." The overlay graphically shows the shadows cast by objects of various heights at each hour of the day (Figure 16). It can be designed for any scale, latitude, object height or day of year. It is easiest to use when drawn or photocopied onto clear acetate or mylar. When pointed due north on a plan, the overlay shows the area to the south of a window or solar collector that must be free from obstructions of various heights.

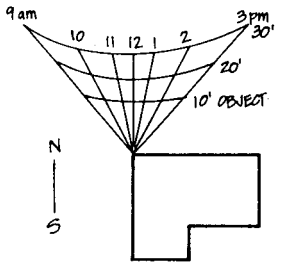



Fig. 16. Solar access overlay.

## 4. IMPLEMENTING SOLAR SUBDIVISIONS

These solar subdivision design guidelines, the shadow analysis tools and a step-by-step evaluation process offer a complete method for design or evaluation of subdivisions using natural heating and cooling. These materials are contained in a training manual used in workshops conducted by ABAG. Achieving widespread use of natural heating and cooling in production home construction, however, will require the combined support of land developers, site designers, planners, local elected officials and solar and energy conservation specialists.

There are new nationwide trends emerging in the home building industry that could conflict with solar objectives. Smaller, more compact homes are being built; townhouses and duplexes are gaining in popularity; smaller lots and higher density development are appearing in conventional subdivisions. These trends, while offering energy conservation benefits, create new development patterns with less space between structures and more likelihood of south wall and rooftop shading.

A few innovative developers around the country have built solar subdivisions for the mass market. But most developers will not readily adopt new design principles, particularly if they think it is too difficult or costly and may conflict with consumer preferences. Regulation may be the most effective way to spur the building industry to construct housing that is naturally heated and cooled.

Local government planning officials, responsible for development review, should consider adopting a new evaluation process for subdivisions. Initially, advisory design guidelines could be given to every applicant for residential projects early in the permit process. Local planning staff could work closely with developers during the early stages of subdivision design to help developers understand these new concepts and incorporate them into their designs. Then, as developers become more familiar with city or county energy objectives and the specific design alternatives that satisfy the jurisdiction's concerns, the planning officials could legally require that subdivision designs comply with the principles of natural heating and cooling.

Developers, subdivision designers and architects must work together to apply these principles to future production housing. Architects can include specifications for solar access with their home designs; these specifications would show spacing requirements when structures are placed on lots. Subdivision designers will need to add solar and energy conservation design criteria to the traditional subdivision design criteria of health, safety, aesthetic appeal and, of course, economics. Developers can provide the impetus for change by establishing natural heating and cooling as priority design and marketing objectives.

Ultimately, the public will determine the success of solar subdivisions by purchasing this innovative housing instead of the conventional type. The trend towards "fuel-efficient" homes is likely to be similar to the slow but inevitable movement of the auto industry from large gas guzzlers to smaller, fuel-efficient models. The trend is in its infancy, but both the technology and the know-how are available now to make solar subdivisions a vital element in an energy conserving future.

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# DESCHUTES COUNTY, OREGON: A UNIQUE SOLAR ACCESS PROGRAM

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## ABSTRACT

In May and June, 1983, Deschutes County, Bend and Redmond (Oregon) adopted a comprehensive set of solar access amendments to their zoning and subdivision ordinances. The Deschutes County solar access project is unique in several respects, including: the broad-based cooperative project approach used which led to the concurrent adoption of identical ordinance packages by all three major jurisdictions in the County; the comprehensive commitment to solar access protection from all major shading sources, for new and existing structures, and for all classes of property reflected in the ordinances; and the completion of all of the major administrative and technical documents needed to implement the ordinances. Deschutes County sponsored the project; Conservation Management Services, Inc. (CMS) served as project manager; and the Oregon Department of Energy (ODOE) provided technical assistance. The Bonneville Power Administration (BPA), under the terms of the Northwest Electric Power Planning and Conservation Act (Northwest Power Act), funded the project as a model for other local governments in its four-state service territory.

## 1. BROAD-BASED COOPERATIVE PROCESS

The adoption of comprehensive solar access ordinances in Deschutes County and the cities of Bend and Redmond is attributable in large part to the broad-based process used to develop the ordinances. Citizens, professionals, utilities, public interest groups, government staff, and appointed and elected officials participated. The three major jurisdictions made a common commitment to solar access protection, and worked together to develop uniform ordinances which all jurisdictions could support.

### 1.1 Committee Structure

A Solar Access Technical Advisory Committee (TAC) was formed to review existing solar access ordinances and write ordinances suitable for Deschutes County. The TAC was comprised of government planners and attorneys, solar homeowners, builders, architects, and dealers, members of the local non-profit educational organization promoting renewable resources, and a representative from the builder's association. The TAC's job was to ensure that the proposed ordinances were technically sound, that they would provide adequate protection, that they could be administered efficiently, and that they could be enforced.

A Policy Committee comprised of elected officials and individuals with some source of political power in each jurisdiction was formed to ensure that any ordinances which were recommended had a sufficiently strong core of political support to be adopted. The Policy Committee researched local and regional energy needs and the relevance of solar access protection to those needs, and resolved policy issues which the TAC brought to it. The Policy Committee included members from each of the three Planning Commissions and governing Commissions. These individuals played the primary role in marshalling the needed votes for the ordinances when the public hearings process began.

### 1.2 Community Acceptance of Solar Access

Increased government regulation is no more popular in Deschutes County than it is anywhere else in the country today. And yet the solar access ordinances were very well received by the community. Of the combined eighteen votes cast on the three Planning Commissions seventeen were in favor of the ordinances. Similarly, of the fifteen votes cast on the three elected Commissions fourteen were affirmative. During the six public hearings only two citizens spoke in opposition to the ordinances, while numerous people turned out to voice their support.

The following reasons for adopting the ordinances were among the most persuasive to local officials:

- Solar energy has an economic value to the individual seeking to reduce rising energy costs, and to the community seeking to reduce payments for imported products such as electricity and natural gas. Solar access ordinances protect that economic value.

- Providing and protecting solar access preserves future options for citizens. The ordinances do not require solar uses, they merely preserve individual options for such uses.

- Solar access is an issue which is not going to go away. The governments would be wise to establish clear standards and procedures for determining the extent of solar rights now, rather than waiting and having to resolve future disputes without such guidelines.

The only formal opposition to the ordinances came from the leadership of the Central Oregon Builders Association (COBA). COBA argued that: there was already too much government regulation; the marketplace would protect solar access; the ordinances would add to the cost of already expensive housing; and experience in other communities with solar access ordinances proved there was no need for the ordinances. Supportive testimony from other builders (most effectively from builders who were COBA members) and marketing studies showing that solar and energy-efficient housing is increasingly in demand by the public effectively neutralized the opposition from COBA.

## 2. A COMPREHENSIVE PACKAGE OF ORDINANCES

There were three major components to the solar access package. Two substantial solar access amendments were added to the zoning ordinance, a Solar Setback and Height Review and a Solar Access Permit. A Solar Access Performance Standard was added to the subdivision ordinance.

### 2.1 Solar Setback and Height Review

The Solar Setback and Height Review ensures that new structures on existing lots (platted at the time the solar ordinances were passed) are located on the lot to provide solar access to adjacent lots whenever feasible. The amendment applies to commercial structures as well as to both multi-family and single family residential structures. Structures must not cast a shadow farther than 20 feet onto adjacent properties to the north at 10:00 a.m. on December 21. (This standard is approximately equal to an eight foot solar fence at the northern property line at Deschutes County's latitude.) Exceptions to the standard are made only for physical constraints such as rock outcroppings, septic system requirements, existing legal restrictions and unusual lot dimensions.

If the first standard, which is designed to protect current and future options for south wall solar applications, cannot be met, then a second standard is applied. The second standard is designed to protect south roof solar applications. The only exceptions to the second standard are if meeting it would make it impossible to build a 16 foot (single story), single family house on a lot zoned for that purpose, or to construct a multi-family or a commercial structure on a lot zoned for that purpose. Geographical exemptions may be granted for steep north-facing slopes and heavily vegetated areas.

### 2.2 Solar Access Permit

A solar access permit is awarded by the government under certain conditions to the owner of a productive solar collector to provide protection from shade from certain vegetation. In order to qualify for a solar access permit the solar owner must show that the collector meets a minimum performance standard, that the collector has been located on the lot to minimize the burdens placed on adjacent properties, and that the collector is not shaded by any vegetation on the solar owner's property. In order to make the process as accurate as possible a sunchart photograph (a photograph taken from the lower edge of the collector surface looking due south through a Solar Site Selector™) is the only approved technique to document existing shade.

Vegetation existing at the time of application which is already tall enough to cast shade on the collector during the hours requested for protection is exempt from any restrictions on its growth. All existing vegetation not shading the collector during protected hours at the time of application, but which grows to shade the collector during those hours at some future time, must be trimmed. All future plantings must not shade the collector. Vegetation restrictions are limited to properties within 150 feet of the solar collector.

The solar owner must pay trimming costs of any non-exempt vegetation which exists at the time of the application and creates a future shading problem. The neighbor pays for trimming costs of all vegetation planted after the solar access permit was granted.

The rights and restrictions created by the solar access permit are recorded in the chain of title of all affected properties and may only be removed at the solar owners request or if it can be shown that the solar collector has not met the minimum solar collector performance standard for at least twelve consecutive months.

### 2.3 Solar Access Performance Standard

The solar access performance standard requires that all major new developments provide solar access at ground level at the southern building line of properties between 10:00 a.m. and 2:00 p.m. during the six winter months. If this is not feasible the developer must provide solar access ten feet above the southern building line during the same hours in winter months and between 9:00 a.m. and 3:00 p.m. during the six summer months. Exceptions to the standards are made for topography, vegetation and development patterns only if the developer can provide adequate documentation that these characteristics of the land make it not feasible to meet either or both of the standards.

This performance-based approach has the advantage of providing shade protection from both vegetation and structures and giving the developer the maximum flexibility to choose the best techniques to meet the solar access standard.

The developer is required to provide legal protection for the solar access over time and to file a description of the solar height restrictions on each lot with the final plat map. The solar height restrictions are described and illustrated through use of the solar envelope technique. A solar envelope is a three-dimensional rendering of the "roof" over a lot which protects neighboring properties from shade.

### 2.4 Advantages of Comprehensive Approach

Many jurisdictions have addressed the solar access issue one piece at a time -- adopting either subdivision standards, a setback review, or some form of recordation process. This approach offered benefits while the first solar access ordinances were being written and tried. The incremental approach may still be advisable in situations where, for political reasons, it is all that is possible. However, there are substantial advantages to addressing the issue comprehensively from the start: the separate ordinance amendments needed to protect solar access are intricately interrelated, and developing them concurrently helps to ensure that they are internally consistent with each other. The comprehensive approach also provides more solar access protection for more people.

## 3. SUPPORTING DOCUMENTATION

A complete set of supporting documents was prepared to help government staff administer the ordinances, citizens understand what rights and responsibilities the ordinances confer on them, and the development community comply with the ordinances. A design manual for developers was prepared to provide techniques for complying with the Solar Access Performance Standard. One of the largest gaps in the solar access field has been the lack of such documentation of the technical details of implementing solar ordinances. In addition to these technical documents, CMS currently is writing a detailed case study focusing primarily on the political aspects of getting the ordinances passed.

### 3.1 Administrative Documents

The Solar Access Permit process, in particular, requires a large number of administrative documents. Some of the documents which have been produced to help administer this ordinance amendment are: a model application form; guidelines for determining when a solar collector has been located to reduce the burden on neighboring properties to the maximum extent feasible; procedures to document whether or not the collector meets the minimum performance standard; instructions for documenting existing shade; and notices to send to affected property owners describing their rights and responsibilities when a solar access permit application has been received, when it has been granted, and when trimming of vegetation is required.

The documents produced to help administer the Solar Setback and Height Review ordinance include instructions for calculating the required setback in unusual situations such as diagonal and oddly shaped lots, and techniques for home buyers to use the ordinance to provide solar access to their own house as well as to avoid shading neighboring properties.

### 3.2 Design Manual

The Design Manual provides guidelines to help developers and government staff meet the Solar Access Performance Standard amendment to the subdivision ordinance. Because the standard is performance-based the Manual's guidelines are voluntary rather than mandatory. The Manual addresses a wide range of topics, including the following: techniques for site, street and lot design

to achieve the maximum feasible solar access; methods to document existing shade; methods to identify the buildable area on a lot which is best suited for solar uses; recommendations on Deschutes County specific vegetation cutting and planting for solar access; and instructions for constructing the solar envelopes needed to define the solar height restrictions on properties.

### 3.3 Case Study

The Deschutes County solar access project lasted eighteen months. At no point until the final votes were taken was adoption of the ordinances assured. One lesson which was learned is that high quality technical work is only one component of a successful solar access project. Because building political support for such regulations can sometimes be at least as difficult a problem as resolving the technical issues, a case study is being written by CMS which recreates in detail the political barriers which were confronted, and the strategies and tactics which were successful in overcoming them. It is hoped that the case study will be useful to others working on solar access projects by providing a complete record of the work done in Deschutes County. CMS has been unsuccessful in its attempts to locate any document similar to this in the existing literature. The case study will be completed this fall.

## 4. FOUNDATIONS FOR THE PROJECT

Deschutes County's solar access project originated in large part because of two unique pieces of legislation -- the State of Oregon land use planning law and the Northwest Power Act -- and the national leadership which has been provided by the Oregon Department of Energy in promoting solar access.

### 4.1 Solar and the Comprehensive Land Use Plans

The State of Oregon has received national attention for its land use planning processes. In the late 1970s Deschutes County's local governments adopted Comprehensive Land Use Plans to govern development in their jurisdictions for the remainder of the century. Each Comprehensive Plan contained a section on energy policies which made direct reference to encouraging the use of solar energy because it is a locally available, abundant, and environmentally benign energy resource. Two of the plans specifically addressed the need to protect solar access. Therefore, the adoption of solar access ordinances was seen by local governments as implementing an existing policy commitment.

### 4.2 The Bonneville Power Administration and the Northwest Power Act

In December, 1980 Congress passed the Northwest Power Act. This ground-breaking legislation directed BPA (a federal power authority which wholesales electricity to utilities) to promote energy conservation, including direct application solar energy, as its first priority energy resource. BPA's service territory includes the four states of Washington, Oregon, Idaho and Montana. As a result of the Northwest Power Act BPA has funded several local government demonstration projects which promote energy conservation, including the solar access work in Deschutes County. These projects will serve as models for other local governments throughout the region.

The Northwest Power Act also created an independent energy planning body, the Northwest Power Planning Council, and required it to write a 20 year energy plan for the region. That plan, adopted on April 27, 1983, directs BPA to continue providing technical and financial support to local governments throughout the region to adopt solar access ordinances.

### 4.3 The Oregon Department of Energy

In 1980 the Governor's Alternate Energy Development Commission (AEDC) adopted a comprehensive set of recommendations to move the state toward an energy future based on conservation and renewable resources. One of the AEDC recommendations was the promotion of land use standards to provide and protect solar access. Since that time ODOE has worked with local governments throughout the state to encourage the adoption of solar access ordinances. ODOE staff assistance and the solar access work done by the city of Ashland, Oregon was of great value to the Deschutes County project.

## 5. SUMMARY

Solar access work in Oregon is rapidly maturing. The primary issue two years ago was how to write a solar access ordinance that would work. Today the most important issue is how to export the solar access concept to local governments throughout the country. The primary components of the Deschutes County solar access project -- the use of a broad-based cooperative project approach involving several jurisdictions, the adoption of a comprehensive set of ordinances, and the production of a complete set of technical documentation to support administration of the ordinances -- should offer a useful model for others to use.

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# ASHLAND'S ENERGY PROGRAM FROM INCEPTION TO IMPLEMENTATION

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## ABSTRACT

The City of Ashland is a community of 15,000 people, located along Interstate 5 in southwestern Oregon about 20 miles north of the California border. This paper describes the city's solar access and energy program.

## 1. INTRODUCTION

Ashland's climate is transitional between marine west coast and mediteranean, with 5,089 annual heating degree days and precipitation which averages about 20 inches per year. This precipitation occurs mainly from October to May, with the summers generally warm and dry. Ashland is about 1,900 feet above sea level and is located on the western edge of the Siskiyou mountains.

The City is governed by an elected Mayor and City Council, with a professional City Administrator to oversee and manage the City staff. Ashland owns its own hospital, cemetary, airport, golf course, sewer, water and electric utilities. The electric utility purchases wholesale power from the Bonneville Power Administration (BPA) and resells it to about 6,500 retail customers. There are approximately 3,160 electrically heated homes within the City limits. The City has been a preference customer of BPA since February, 1982. Prior to that time, our wholesale power was purchased from Pacific Power and Light Company.

Ashland's population of 15,000 allows for a congenial small town atmosphere which is the envy of many visitors. The cultural amenities offered by the City, however, are more indicative of a much larger city. The fact that Southern Oregon State College and the Oregon Shakespearean Festival are located in Ashland provides for a much more cosmopolitan population than a typical small city in Oregon. The College, with its approximately 4,000 students, provides activities and amenities which would be nonexistent without the college. The Shakespearean Festival, which attracted over 300,000 visitors last season, also modifies Ashland's makeup. The festival has existed in some form or other since 1935 and is located on the same site as the old Chatauqua building, which during its heyday attracted many visitors and famous speakers such as William Jennings Bryan. This influx of tourists to see the festival and the cultural ambiance of the festival employees and actors adds a unique flair to the City, which generally only exists in much larger cities. The city has a long history of being concerned about energy and has undertaken a number of programs which demonstrate the city's determination to reduce energy consumption. In 1977, a group of concerned citizens, City Council members and city staff investigated the feasibility of using water retrofit program for residences and businesses currently using electricity for water heating. Preliminary research indicated that the program would be very cost effective. However, because there was no source of funding for the project, it never got beyond the preliminary stage.

In 1978-79, the Mayor of Ashland formed an energy savings task force to look at the city's internal operations and ways to reduce energy consumption by at least 10% in these operations. This task force developed and implemented a number of low-cost/no-cost measures aimed at reducing the city's energy consumption. Some of the measures included changing to more efficient interior light bulbs, weatherstripping and caulking city buildings, installing ceiling insulation and a clock thermostat in City Hall, repairing and replacing windows at the Fire Station, and installing water heater insulation wraps on city water heaters. This task force also looked at methane recovery at the city's sewage treatment plant and converting the city's vehicle fleet to run on methane. this idea proved to be uneconomical and was not implemented based on the circumstances of the city at that time.

## 2. SOLAR ACCESS

The City activities to this time had been frustrating, with a lot of discussion and very little in concrete conservation actions. Beginning is January 1980, however, the Citizens Planning Advisory Committee revitalized the City's efforts by using the City's land use powers to encourage energy conservation. There was a two-pronged attack at the problem, the first stab at it being guaranteeing solar access to every lot in town where it was practical, the second being using a more flexible type of subdivision ordinance.

The players involved in the discussion in the months that followed were many. The Citizens Planning Advisory Committee formed the main group, and was responsible for the support generated. This is a body of 16 citizens appointed by the Mayor to serve two year terms. Their main function is to assure that the City is being responsive to citizen's needs, especially in the field of land use planning. The Planning Commission, the more formal body which has most of the hearings responsibilities for planning issues, had a couple of skeptical members but generally gave its full support to the idea. Luckily, the City Council also gave unanimous support to the idea because they were convinced that it was feasible.

The home builders in the City provided both support and criticism of the project. As has been the case in many other communities which have adopted solar access legislation, home builders who were knowledgeable about solar construction techniques and were generally supportive of the concept proved invaluable in convincing their more skeptical brethren of the value of this kind of regulation.

An additional aid in developing the Solar Access Ordinance was the development by staff of nomographs which would assist in computing the solar setback. As solar setbacks are based on a shadow, which can be fairly complex to determine, a simplified version using graphic nomographs aided greatly in selling the program. After several public workshops on the issue, the Solar Setback Ordinance was adopted in August of 1980.

In December of 1982, after a general review of the performance of the Setback Ordinance, several minor changes were made and Solar Recordation was added. This is a process whereby an owner of a solar collector may record the presence of that collector and maintain protection from shading by vegetation in the future.

## 3. PERFORMANCE TO DATE

The Solar Access Ordinance has been in effect in Ashland for over three years. During that time, we have issued building permits for 130 new housing units and many additions, remodels and commercial structures. During this time, there has only been one major problem arise where a applicant submitted incorrect information on the solar setback, and was not corrected by the staff in their review. When the building was under construction, a stop work order had to be issued and major redesign of the structure was required. Other than that, there have been two other variances granted, both of them minor. The ordinance is very popular in the City of Ashland and is viewed by the populous as a solar right, not a regulation.

## 4. PERFORMANCE STANDARDS ORDINANCE

During the same time that we were developing the Solar Access Ordinance, the City developed a document that implemented a Performance Standards Development Ordinance. The intent of the ordinance was to use density bonuses to encourage desirable development characteristics. The idea was to inform the developer as to what the City felt was desirable in a development, and allow them to earn the increases in density in exchange for desirable development techniques. The largest amount of density points can be earned by building energy efficient housing. Up to 40% bonus increase can be granted for increasing levels of energy efficiency.

This incentive to encourage energy efficient housing appears to be working well despite a rather slow building period. Since the Performance Standards Ordinance has been adopted, there have been applications for 253 new building lots in the City of Ashland. Of these, 57% of the new lots will have the requirement that the homes be more energy efficient than the standard home built to Oregon codes. These savings amount to approximately a 50% increase in the energy efficiency of the standard home.

## 5. ELECTRICAL CONSERVATION PROGRAMS

When the City became a preference customer of BPA in February, 1982, a number of other avenues to save energy were opened to the City. The City immediately signed short term Energy Conservation Agreements with BPA to ensure that we could take advantage of all of the conservation programs that BPA offered. Under these programs so far, the City has installed over 860 water heater insulation wraps on commercial and residential electric water heaters in the City, and we are continuing this program

and hope to wrap an additional 400 heaters next year. The City also furnished free shower flow restrictors to all residential and commercial customers within the City.

Under the BPA Street and Area Lighting Program, the City's electric crews have converted or retrofitted our entire inventory of some 1,217 street lights from Mercury Vapor to High Pressure Sodium. The City also is facilitating conversion of Southern Oregon State College and Ashland School District's area lighting to High Pressure Sodium lighting. These conversions are paid for by BPA, with the utility doing the necessary reporting and paperwork and passing the BPA funds through to these local governments. The College has converted over 120 lights and the School District has some 100 lights that they plan to convert during the next Federal fiscal year.

The City began offering the BPA funded Weatherization Buy-Back Program in April, 1982. This program offers weatherization grants to electric space heating customers for the weatherization of their homes. The amount of the grant is determined by a BPA developed heat loss methodology which predicts electric energy savings in kilowatts and purchases one year's worth of savings at $.292 per kWh. This buy-back grant, or the cost of the weatherization measures, whichever is lower, is paid to the customer upon completion of a successful inspection by the City's Weatherization inspector.

This program started out modestly in April, 1982, with two employees completing 20 to 30 audits per month. Three additional Energy Analysts were added later in the year and audit production now equals about 75 to 85 audits per month and weatherization jobs equal about 45 completed jobs per month. As of June 15, 1983, the Weatherization program had funded the weatherization of some 370 homes. This was accomplished within 13 1/2 months. Since the utility is reimbursed $160.00 for each home in which a major weatherization is installed, it has been the Conservation Division's intent for the beginning to get high percentages of customers to complete the recommended measures. During the first 6 months of the program (April - September, 1982); the Conservation Division completed Home Energy Analyses on 196 homes and as of this date 164 or 83.7% have completed the recommended measures. This high participation rate, to the best of our knowledge, exceeds the rate of any other utility in the region which is operating the BPA Weatherization program.

These high rates can be attributed to a number of characteristics which were built into the program from the very beginning. Our analysts have experience and in-house training in both sales and customer relations. We have contended from the beginning of the program, that we must sell the idea of energy conservation and its benefits to our customers. The analyst makes a special return trip to customers to explain the program and the recommended measures, with strong emphasis on the various advantages of weatherizing their homes under this program. This personalized return of the energy analysis, is one of the inportant keys to the success and high participation rates that the Ashland-BPA program is achieving.

Another important key to the success of the Ashland Program is the computer software that is used with our micro-computer to perform the calculations and printouts of the Home Energy Analysis. In the first months of the program, all calculations were done by hand and audit results were typed indivdually by a secretary. This method was time consuming, wrought with errors and generally inefficient. Searching the marketplace and not finding any available software which we felt was adequate, the City's Community Development and Conservation staffs set out to develop our own in-house micro-computer energy analysis software. This software has been operational since September, 1982, and has, in our opinion, been one of the keys to the success of the program. One of the problems of the software which was commercially available, was the fact that the output was generally not very understandable to the person most important in the process, the actual customers. If these people don't understand the recommendations or are confused in any way, chances are slim that they will followup and weatherize their home. The output of our software is easily understandable by the customers, especially since it is hand-delivered and explained in detail by the analyst. This procedure ensures that the customer will have enough information to feel confident in calling contractors for bids to do the job. Another advantage of our computer system is that it was especially tailored for the Ashland system and therefore fits our particular circumstances very well. It has increased our in-house productivity at least three-fold and has eliminated the staff from performing the mundane time consuming work that is a necessary part of the Home Energy Audits.

The BPA Energy Conservation programs, which have all been instituted since February 1982, have saved a significant amount of electric energy. Table 1 shows the estimated savings of these programs so far.

TABLE 1

Yearly Electric Energy
Savings, by Program, June 1983

| Program | Total Savings (kWh) |
|---|---|
| Shower Flow Res. | 65,000 kWh/Year |
| Water Heater Wrap | 199,520 kWh/Year |
| Street & Area Lighting | 199,225 kWh/Year |
| Weatherization | 2,220,098 kWh/Year |
| TOTAL | 2,983,842 kWh/Year |

Also, a low-income weatherization program is operated by the City. This program, which is administered by the City with weatherization work performed by our local community action group, ACCESS, Inc., will ensure that eligible low-income customers will have their homes weatherized at no cost to them. This program has a goal of weatherizing 80 low-income residences in Ashland.

The Conservation Division has a number of other projects which we intend to pursue in the future. The City has just submitted a work plan to the Oregon Department of Energy for a commercial energy audit program as required by State laws. Upon approval of this plan, the City will have sixty days to implement the plan and offer commercial audit services to our commercial customers.

We plan on again developing our own individually tailored program to fit the Ashland situation. This will include our own reporting forms and computer and word processing software to complete and print up the audit and all of the other tasks necessary to make this program operational.

Also, we are working on our own residential weatherization data base and report writer. This work is now, about 50% complete and should be finished by October, 1983. This data base will allow us to better monitor our weatherization program and generate the various reports necessary for better oversight and management of the program. This program will again be developed totally in-house, and will be specifically custom designed for our own particular circumstances.

In addition, the Conservation Division will be aiding eligible institutional buildings in attempting to obtain funding for Technical Assistance Studies and Energy Conservation Measures under the BPA/Oregon Department of Energy Institutional Building Programs. The City has already submitted applications for funding for some City facilities and will aid other eligible entities within our jurisdiction in obtaining these funds.

## 6. CONCLUSIONS

The total effect of the City's Energy Conservation Programs over the last three and one half years have been dramatic. The awareness of energy as an issue in Ashland is higher than it ever has been before. People have incorporated the awareness of energy conservation into their buying decisions - and this is having an effect on what the developers are providing on the marketplace. People in the City are proud of their position of leadership in this field and the energy programs enjoy a broad level of support in the City.

We feel that this success can be successfully duplicated in many, many cities throughout the United States. The key thing that we have found to the successful implementation are as follows:

1) The largest ingredient for our success has been the political support at the Council level for the projects. While a unanimous support from the Council is not essential, certainly a solid majority is necessary for accomplishing anything. However, while several people on the Council are symphatetic, only one or two actually were actively involved in the development of the Ordinances and actively worked with staff on these projects. We think that it probably the best situation as local governing bodies have too many issues for everyone to be an expert on energy.

2) Grassroots acceptance by persons in the community is of course another ingredient for successful programs. We made use of persons who we knew were sympathetic to the issues involved. Most people will find that, at least in the Northwest, energy issues have broad acceptance if presented properly and if the programs are not ill-conceived.

3) There was an open process for development of all of the programs. We used the press, the educational institutions in the community and local citizen volunteer groups as much as possible so that everyone who was interested knew what was going on. This removed the traditional suspicion of local governments by their citizens and assisted in identifying issues that were of concern to our citizens.

4) Involvement of the community in regulations that affected them. This is especially important in a Solar Access Ordinance development as devel-

opment interests had very many valid arguments to make. While many of the developers in the City were opposed to any type of regulation, we attempted to use developers who were sympathetic to solar building. They were quite successful in assisting their colleagues in understanding the finer points of passive solar design and why it was a good idea to protect solar development. While we have, by no means, convinced every developer in the City, we certainly neutralized a great deal of opposition by providing a group of persons from their same general lobbying group that could speak directly to their concerns in their own language.

5) Make the program comprehensive and long range. Too many times, in the energy field, we have picked on a single flashy issue without looking at the much less "sexy", but more productive measures which could be adopted. In starting our the project we developed a strategy which we would be able to accomplish over a period of years. This has been a great help in mapping out our course over the several years that we have been working at this.

6) Have a committed staff. It is important that the staff not consider this just a job, but an opportunity to make substantial changes in the City. The staff must be competent technically, sensitive politically and enthusiastic to carry the project through successfully.

7) Keep all the programs as simple as possible. Overly complex programs have a tendency to turn people off immediately. A complex regulation that is inflexible smacks of bureaucracy and will meet with a great deal more opposition than simple regulations, presented in a straightforward.

8) Avoid using regulations and mandatory requirements where possible. The City of Ashland's programs, with the exception of solar access, are voluntary. By using a combination of incentives, marketing pursuasion, logic and economic arguments, we have accomplished a great deal without regulation.

Energy conservation can sell itself if given the chance and marketed pursuasively. Since energy costs money, saving energy saves money. This is the most important aspect of our field and one which we have too often lost sight of in our zeal.

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# APPLICATION OF MODIFIED DEGREE DAY PROCEDURES TO A RESIDENTIAL RATING SYSTEM

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## ABSTRACT

The authors have developed a residential energy efficiency labeling program for the Commonwealth of Pennsylvania. Users of the program determine energy efficiency using a printed brochure (known as the Home Energy Scorecard). This paper discusses the procedure used in the calculation of the major point values used to establish home scores (1).

A projected 1,000 Btu of annual savings in energy demand was assigned a scorecard value of one "point." Points are achieved by substituting a given energy conserving technique (ECT) for uninsulated wall, ceiling, and floor construction or for the single glazing assumed for the reference case. Points determined for each ECT differ among seven house types and four climate zones. Points were also determined for ECTs involving infiltration control, passive solar heating, domestic hot water use and heating system equipment.

Calculational methods used to determine point values ranged from hand analysis (for domestic hot water points) to hour-by-hour computer simulation (for passive solar points). Shell and infiltration points were established using the modified degree-day procedures described herein.

For estimating the space heating loads in the "skin-dominated" construction being examined, a microcomputer version of the modified degree-day method met the project team's requirements for simplicity and reduction in computer costs. The accuracy of the method is demonstrated by comparison with the results of hour-by-hour computer simulations.

Modified monthly degree-days were calculated over eight thousand times in the final run of the program, which examined all cases involving thirty-one construction possibilities, seven house types and four climates. The program predicted heating load with a standard error of only 3.9 percent, plus or minus 2.3 percent, when compared to the results of a full hour-by-hour thermal network simulation.

## 1. CALCULATIONAL PROCEDURE

Heating loads could have been computed in numerous ways, ranging from hour-by-hour computer simulations to the simplest degree-day approach. The procedure adopted was based on the established engineering methods for determining design heating loads and energy consumption in residential construction (2). We supplemented these methods with additional algorithms to account better for internal heat gains, solar gains, thermostat settings and heat losses to the ground. Heating load calculations were done on a monthly basis. Standard data on monthly average outdoor air temperature, ground temperature and solar gain were used. The monthly values of heat loss were summed to yield the seasonal values.

The general method used to determine points for shell and infiltration measures was as follows:

### 1.1 Shell Heat Load (Step 1)

To determine shell heating load, the conductance-area product "UA" of each shell component was calculated and summed. The units are Btu/hr°F. Shell components include walls, doors, windows and ceilings.

The conductance-area product for each component is given by

$$UAc = A/R$$

where A is net component area for the house type in question, and R is the R-factor of the component construction in question.

The window heat losses were calculated using the conductance-area product

$$UAg = GA/RG$$

where GA is the glass area of the house type and RG is the R-factor of the window construction. (There are both heat losses through windows and heat gains due to solar inputs. These two mechanisms are treated separately.)

### 1.2 Infiltration Load (Step 2)

Heat losses from air infiltration were calculated at an average rate that is a function of house type, tightness of construction, and climate. The effective conduction-area product (UA) due to infiltration is then

$$UAih = (ACH)\ (.018\ Btu/^{\circ}F ft^3)\ (HV)$$

where HV is the above-grade heated volume of house (cubic feet) and ACH is the average air change rate per hour. (Determination of ACH is discussed below.) Air infiltration of heated basements was fixed at 0.4 air changes per hour, so that

$$UAib = (.4)\ (.018)(BV) = .0072\ (BV)$$

where BV is heated basement volume.

### 1.3 Losses to Unheated Spaces (Step 3)

For the floor area over an unheated basement or crawl space the equivalent conductance-area product (UA) was multiplied by a correction factor which reflected the lower rate of heat loss into this thermally buffered space (7). This correction factor is

$$C = (TS - TC) / (TS - TA)$$

where

TS = Thermostat setpoint (°F)

TC = Average monthly intermediate space temperature (°F)

TA = Average monthly outdoor temperature (°F)

The intermediate space temperature calculation is discussed below. The resulting UA is

$$UA = (FA/RF)\ (C)$$

where FA is house floor area over unheated space, RF is the R-factor of the floor construction, and C is defined above.

Summing the results from Steps 1 through 3 gives the total heat loss to ambient air temperatures in Btu/hr-°F The heat gains from south-facing windows, people, and appliances are used to offset heat losses. The combination of gains and losses produces a house balance temperature that is below the house thermostat setting. The balance point temperature is the base used for determining the modified degree-days.

The monthly heating load (Q) is calculated by multiplying the heat loss rate, the modified degree-days (MDD) and the appropriate unit conversion and adding any ground heat losses.

$$Q = (\text{Sum of } UAs)\ (24\ hr/day)\ (MDD) + (\text{Ground Heat Loss})$$

## 2. SELECTED ASSUMPTIONS AND DATA

Data on average monthly ambient temperatures and solar radiation representing four climatic zones in Pennsylvania were taken from the TMY weather tapes (3). The average ground temperatures and the degree-days used in the calculations are derived from these data.

The calculations used a variety of basic parameters describing each house type. In addition to the variable areas and volumes which describe the various house types, the R-values and heat gain factors for different types of construction were used. The R-values were derived using the standard ASHRAE calculation for composite construction and included such factors as framing losses.

### 2.1 Infiltration

The method of handling heat loss due to air infiltration was based on an empirical model determined from review of the literature on the subject (6). Three levels of infiltration control were defined in accord with the LBL Walk-Through Audit Method. Effective average air change rates for each of these three levels of infiltration control were established for seven house types in four climates using the empirical model and the CALPAS3 hourly simulation program.

The basic equation for hourly air

infiltration is of the form

$$ACH = A + (B)(V) + (C)(TS-TA)$$

where TS is thermostat setting, TA is ambient temperature, V is wind velocity and A, B, and C are functions of the designated construction level (tight, medium or loose). Values for A, B and C have been experimentally derived by a number of investigators (6).

## 2.2 Internal Heat Gain Levels

Internal gains are a combination of occupancy, lighting, and equipment loads. Values for internal heat gain levels were taken from the CALPAS3 computer program defaults (4). To determine occupancy loads, CALPAS developers made assumptions about daily activities for a typical family of three. The Berkeley lighting and equipment load estimates total 7,227 kWh per year, which can be compared to similar data from the 1982 GPU System Residential Customer Survey (5). This survey, which included several Pennsylvania service territories, indicated an average consumption of 6,068 kWh/yr and 8,301 kWh/yr for houses less than 1,500 square feet and greater than 1,501 square feet, respectively. (Data are for non-electrically heated homes only.)

Figures selected for use in the modified degree-day program (including occupant gains) were 72,665 Btu/day for the row house type and 86,991 Btu/day for all other house types.

## 2.3 Foundations

Heat loss through three types of foundations, either individually or in combination, were calculated in the program. The three types are slabs, crawl spaces, and basements (with portions of wall both above and below grade).

The calculations for slab heat loss are of the form

$$UAs = (PERM)(PL)$$

where PERM is lineal foot of exposed perimeter for the house type and PL is the slab edge loss per linear foot. Values for PL at different insulation levels are taken from the NAHB Load Manual (7). This resulting effective conductance area product is multiplied by previously calculated modified degree-days to obtain the total heat loss from slabs.

## 2.4 Intermediate Space Temperatures

A crawl space or unheated basement is at some monthly average intermediate temperature between the ambient and the house setpoint. As previously stated, the effective floor heat loss rate to the ambient is modified by a factor based on this intermediate temperature. Actual intermediate temperatures depend on many factors, such as the degree of space venting, the presence of heating ducts or heating plant, and most importantly on the insulating value of the floor above. When the space is well ventilated, its temperature will be close to that of the ambient air temperature. When the crawl space or basement is tightly closed and insulated at the perimeter or it is used as a plenum (i.e., part of the forced air heating plant), the intermediate space temperature will approach that of the thermostat setpoint. For the purposes of the Labeling Program an uninsulated but relatively tight (unvented) crawl space was assumed.

For the calculation of average monthly temperatures in unheated crawl spaces and basements, the following steady state equation was used (ASHRAE, 1982).

$$Qf = Qp + Qg + Qa$$

where

- Qf = Heat gain into space from floor above (Btu/hr)
- Qp = Heat loss through perimeter walls and sill (Btu/hr)
- Qg = Heat loss to ground contact (Btu/hr)
- Qa = Heat loss due to space infiltration (Btu/hr)

In more detail, this equation can be restated as

$$(TS - TC)(FA)(RF) = (TC - TA)(Ap)(Up) + (TC - TG)(Ag)(Ug) + (TC - TA)(Vc)(.018)(ACH)$$

where

- TS = Indoor temperature (°F)
- TA = Outdoor temperature (°F)
- TG = Ground temperature (°F)
- TC = Intermediate space temperature (°F)
- FA = Area of the floor directly above ($ft^2$)
- Ap = Area of the exposed peri-

meter ($ft^2$)
Ag = Area of the ground below ($ft^2$)

RF = Average heat transfer resistance factor through the floor (Btu/hr-$ft^2$°F)
Ug = Average heat transfer coefficient into deep ground
Up = Combined heat transfer coefficient of the perimeter area
Vc = Volume of the intermediate space (Crawl space fixed at 4 ft , basement fixed at 8 ft )
ACH= Assumed air exchange rate, volume/hour (fixed at .4 ACH for basements, .67 ACH for crawl spaces.)

Using this equation the average intermediate space temperature for both crawl spaces and unheated basements was calculated for each of heating season months. The resulting average temperature was used to modify the effective conductance-area product from the floor above, as recommended by NAHB.

## 2.5 Heated Basements

We assumed that the walls of heated basements, if insulated, are insulated over their full height. Heat loss from the above-ground portion was treated in the same manner as from other above-ground walls. Heat losses from the portions below grade were calculated using the method of Poulos (8). The wall conductance is of the form

$$Ubw = DECR/RB$$

where RB is the R-factor of the basement wall and DECR is the corresponding decrement factor for below-grade construction. The basement conductance-area product was calculated from

$$UA = (Ubw)\ (BBGA)$$

where BBGA is basement below-ground area. The monthly basement loss is calculated as the product of the heat loss rate and the number of basement degree-days in the month.

The heated basement degree-days are calculated monthly from the difference between the basement temperature (which is assumed equal to the average room temperature) and the average ground temperature.

$$BDD = (ND)\ (TA - TG)$$

The average ground temperature is input from the results of calculations using the equations of Labs (9).

## 2.6 Useful Solar Gain from Windows

Solar energy entering through windows during the heating season is a useful heat gain. Such passive solar heating offsets some of the heating load in every house. What fraction of these gains is useful varies primarily with the overall rate of heat loss from the house. If the loss rate is too low relative to the gains, the result is overheating and a smaller percentage contribution to heating load. The glass area used in the reference house types was small enough so that overheating was not a concern. The monthly average solar energy incident on the south-facing window was considered a useful heat gain and was modified by a factor that correlates net productivity to overall heat loss rate (UA). (The resulting useful heat gain was converted to a daily average and added to the internal gains prior to calculating modified monthly degree-days.) Data from which the correction factor was derived came from SUNPAS (10) calculations for selected house types of differing UA. The data were best represented by an equation of the form

$$UT = (1.314)\ (\exp\ (-303.7/UA))$$

where UT is the functional utilization of incident radiation. This equation is valid for heat loss rates less than 1,100 Btu/hr °F. For larger heat loss rates, all of the incident radiation was considered useful.

## 2.7 Modified Degree-Days

The method for calculating the heating degree-days was based on equations developed by Thom (11), used by Beckman et al. (12), and is similar to that of Lunde (13). Monthly degree-days are based on the monthly average temperature, the estimated standard deviation of the daily average temperature for the month, the monthly average house temperature, average daily internal gains and overall house heat loss rate. The procedure is as follows

The balance point (BP) is first calculated as

$$BP = TS - IG/UA$$

where TS is thermostat setpoint, IG is

useful heat gain and UA is overall house heat loss rate (the sum of the effective conductance-area products calculated previously).

The difference between the balance point temperature and monthly average ambient temperature (TA) normalized by the standard deviation of the daily average ambient temperatures is then calculated

$$Z = BP - TA/s$$

where s is standard deviation, given as

$$s = 26.7 - 0.188\ TA$$

The normalized difference, Z, is used to determine a parameter, F, as follows

for $Z > 0$

$$F = (0.34)(\exp(-4.7Z)) - (0.15)(\exp(-7.8Z))$$

for $Z < 0$

$$F = (0.34)(\exp(4.7Z)) - (0.15)(\exp(7.8Z) - Z)$$

The parameter F represents the effective shift of average temperatures for degree-day calculations when ambient temperatures are above the base (balance point) temperatures. The number of monthly degree-days are then calculated from

$$DD = ND((TB - TA) + sF)$$

where ND = number of days in the month.

## 3. VALIDATION OF THE MODIFIED DEGREE-DAY PROGRAM

As a check on the accuracy of the modified degree-day program, we compared our results with results from CALPAS3, an hour-by-hour thermal network simulation program. The CALPAS3 program has been itself validated with fully instrumented residences (14). Two series of computer runs were used to establish the correlation between the modified degree-day program and the CALPAS3 program. The first series of runs compared seasonal heating loads for uninsulated versions of all seven house types in all four climate zones. These reference house heating loads form the basis for individual points associated with particular ECTS in the modified degree-day program. The second series of runs compared the fully insulated versions of the seven house types in the warmest climate zone. This series compared the lowest space heating loads as calculated by the two programs.

The results are summarized in Figures 1 and 2, "Reference Space Heating Load" and "Reference & Minimum Heating Load." In these figures, the modified degree-day program results are plotted on the horizontal axis against the CALPAS3 program results on the vertical axis. Units in each case are MMBtu/yr. A perfect agreement would be indicated by a straight line of the form Y = X. The correlation coefficient indicates the degree of correlation; the closer to unity the better the curve fit. Each of the above two

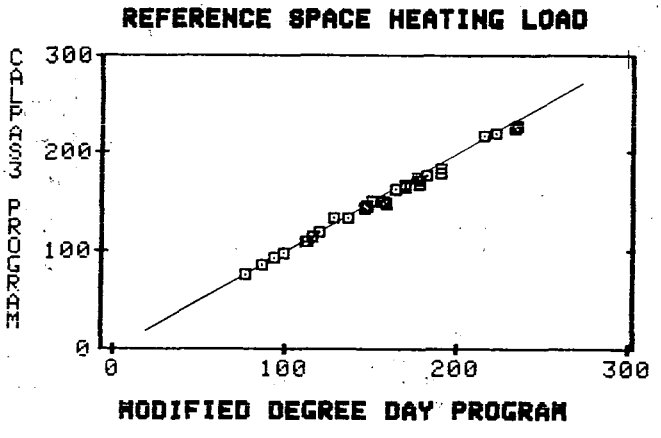



Fig. 1. Reference Space Heating Load

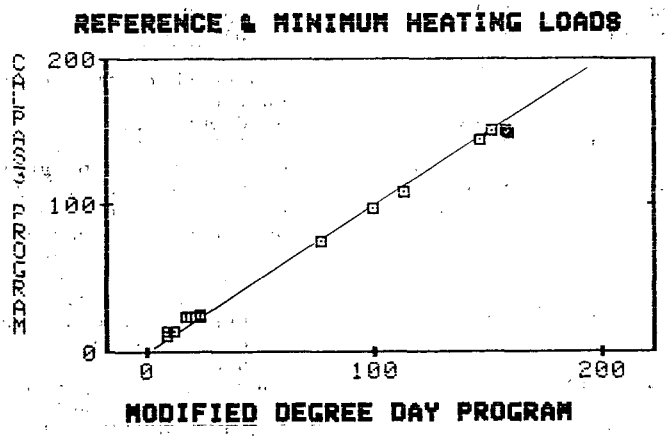



Fig. 2. Reference & Minimum Heating Loads

plots have a coefficient above .99 indicating an excellent correlation.

As the figures show, the agreement is good. Based on the data in Figure 1, the modified degree-day program calculates heating loads within 3.9% plus or minus 2.3% of CALPAS3 predictions. For the data in Figure 2, the difference is 2.6% plus or minus 11.0%. Although the standard deviation for the data in Figure 2 is 11.0%, the absolute error is small, on the order of 2 to 4 MMBtu. Year-to-year variations in weather can account for differences of twice this magnitude.

## 4. ACKNOWLEDGEMENT

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# SHOULD THE SUN SET ON STATE SOLAR TAX CREDITS: AN ARIZONA PERSPECTIVE

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## ABSTRACT

In recent years, tax credit programs have been widely evaluated due to fiscal problems encountered by state and local governments. In Arizona the state solar tax credits could be headed for extinction. Since 1978 Arizonans have received over $40 million in solar tax credits. The number of solar units in that same period exceeds 55,000, the vast majority being residential, domestic hot water applications. This paper presents a brief overview of some of the critical and legitimate issues involved in a solar tax credit analysis. Furthermore, some recommendations from the preliminary results of the cost-benefit analysis of Arizona solar tax credits are described.

## 1. INTRODUCTION

Although there has been an unlimited supply of solar energy available in our environment, the interest and development of solar resources as an alternative source of energy have been kept at the minimum in our society. To increase our understanding and the use of sun power, Maidique (Stobaugh and Yergin, 1980) argues that we should pay closer attention to psychological and institutional barriers, expanded information systems, and reasonable incentives.

In an effort to encourage the use of solar energy, Arizona enacted a solar tax credit for homeowners in 1977, and since that time the tax credit has been expanded to cover homebuilders and commercial or industrial installations. Over the years the tax credit seems to have contributed to the development of solar industries as well as to the increase in residential solar units in Arizona. However, the recent fiscal crisis in the Arizona state government, unfortunately, is forcing legislators to explore the possibility of terminating the present solar tax credit program.

The main purpose of this paper is to describe briefly the Arizona solar tax credit program and to present the preliminary findings from our current research on the costs and benefits of the tax credit program.

## 2. ARIZONA SOLAR ENERGY TAX CREDITS

The Arizona solar tax credits, enacted in 1977, allow homeowners a tax credit of 35% (up to a maximum credit of $1,000) of the installed cost of a solar energy device in a taxpayer's residence. There is a comparable 35% credit, with no ceiling on dollar total, for commercial and industrial applications. Both incentives, however, allow any excess credit to be carried forward to subsequent tax years, the residential for five years and the commercial for three. Following 1983, however, both of these credits are scheduled to decrease by 5% per year until the final phase out in 1987.

Since the introduction of the program the number of solar units installed has continuously increased, ranging from 2,834 in 1978 to 22,254 in 1981. There are now 55,000 estimated solar units in Arizona, the vast majority being residential domestic hot water applications. The following examples show items which may or may not be applied toward the solar tax credits program (Arizona's Solar Energy Tax Credits, 1982):

### 2.1 Solar Energy Devices that Qualify for Tax Credits

- Solar domestic hot water systems
- Heat transportation systems
- Thermal storage devices
  - Drum walls
  - Rock beds, water tanks for thermal storage
  - Trombe walls

-Solar daylighting devices

-Solar pool heating systems, including pool cover incorporated into active system

-Thermal installation

-Thermal transportation systems for domestic hot water systems

-Nocturnal radiation devices, photovoltaic devices that provide electrical power to the residence

-Solar ovens

-Batteries used for storage produced electricity

-Metal hydride system equipment

2.2 Items That Do Not Qualify for the Tax Credits

-Reflective screens for air conditioners

-Masonry walls

-Subterranean retaining walls

-Auxiliary heating systems

-Electrolysis of water

-Organic waste piles

-Swimming pool covers

-Cooling towers

-Vegetation

Based on available categories, the Arizona solar tax credit program, especially when used with available federal credits, is one of the most extensive packages offered in the country.

## 3. SHOULD THE ARIZONA SOLAR TAX CREDITS BE ELIMINATED?

Since 1978 many Arizonans have received over $40 million in solar tax credits. Some state legislators argue that this amount would have been in the state treasury over the years if not for the current tax credit program. What is then the real net cost of the credits to the state treasury? Why should taxpayers have to subsidize the solar industry? Why can't the solar industry make it without the tax credits at the present time? These are some of the critical and legitimate issues involved in evaluating the effectiveness of the solar tax credit program.

In an effort to carry out a cost-benefit analysis of the tax credit program we have developed for further investigation the following broad categories:

1. Total dollar amount of tax credits per year
2. Business and economic stimulus and job creation resulting from the tax credit
3. Technological development spurred by the credit
4. Conventional energy saved by the use of renewable energy resources
5. Environmental impact and cost of conventional versus renewable fuels
6. Subsidization of renewable versus non-renewable energy
7. Psychological satisfaction of consumers (self-reliance, self-esteem due to environmental protection)
8. Physical comfort (more humid environment from greenhouses)
9. Increased awareness of consumers of energy end-use patterns
10. Equity issues involved in the accessibility of tax credits to all people.

It is clear that not all of these would be easily quantifiable. Nevertheless, based on the installation of 18,000 solar units and 2,665 estimated jobs created through the solar business in 1981, we have identified such benefits: income tax on wages, tax on corporate profits, tax on rent paid for business space, licensing fees, income tax on federal solar tax credit, tax generated by exported photovoltaics, severance tax on copper (only solar-related use), sales tax (purchase by solar workers and secondary induced consumption) and 20-year energy savings. When we equate the assigned dollar value of these benefits to the cost of $14.5 million, which was returned to state taxpayers as a result of the tax credit program, a ratio of benefits to costs appears to be about 2 to 1.

However, although our initial analysis shows the total benefits outweigh the cost of the tax credits, it is important to recognize that many consumers are still concerned about a system payback on their initial investment. In order to better understand this important aspect of the tax credits we have decided to carry out an economic analysis based on a f-chart computer simulation program. The f-chart program computes the life-cycle cost of a system and compares it with a reference system containing specific economic and other technical parameters. Table 1 illustrates some of the basic assumptions made in our analysis. The collector is a single-glazed collector of 42 $ft^2$ facing due south and tilted at latitude plus 10 degrees for year-round collection. The unit cost is assumed to be $2970 with a life span of 20 years. Furthermore, since solar units in Arizona replace about 75% electric and 25% gas hot water systems, our preliminary results are based on only the electric water heaters in 1982.

Tables 2-3 summarize our findings from the f-chart analysis. When we look at the net fuel savings, which is the difference between overall fuel savings and maintenance and insurance costs, over the 20-year period, it appears that the total benefits are worth about $13.7 million more than the total cost. Furthermore, based on the present value of net fuel savings, an individual solar DHW purchaser is able to realize a payback period of 5 years on his/her initial investment.

Of course, without a detailed analysis of individual consumers it is not clear at this time whether or not this payback period will be a psychological barrier to their initial investment decision-making process. It is particularly true since any payback period will not be uniformly perceived by consumers in general. In any event, given the current tax credit structure, solar replacement of electric water heating appears to be cost-effective.

## 4. CONCLUSIONS

Based on our preliminary analysis of Arizona solar tax credits it appears that the tax credit program should continue. Along with about 55,000 solar units in 1981, Arizona ranked 3rd and 5th among 27 states in the number of solar collector manufacturers and in collector production, respectively. Although fuel savings far outweigh the cost of the state tax credit program, it is not clear whether the state legislature would perceive the fuel savings as a benefit to Arizona as a whole since savings accrue to individual residents. However, it is our belief that the tax credits generate more than enough benefits to Arizona in the aggregate and, therefore, additional efforts should be made on the economic equity of the tax credits. Are low income people excluded from buying solar equipment and services because they do not pay as much personal income tax? With the existence of the current tax credits, our next research agenda should address the availability of the tax credit program to low and moderate income families.

## 5. ACKNOWLEDGEMENTS

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TABLE 1

LIST OF f-CHART SPECIFICATIONS: ELECTRIC WATER HEATERS, 1982

```
COLLECTOR PARAMETERS
 C1. COLLECTOR AREA ..................................    42.00 FT2
 C2. FR-UL PRODUCT ...................................     0.70 BTU/HR-FT2-DEG F
 C3. FR-TAU-ALPHA (NORMAL INCIDENCE) .................     0.72
 C6. NUMBER OF COVERS ................................     1.00
 C7. INDEX OF REFRACTION .............................     1.53
 C8. EXTINCTION COEFFICIENT X LENGTH (KL).............     0.04
 C9. INCIDENCE ANGLE MODIFIER CONSTANT ...............     0.12
 C10. COLLECTOR FLOW RATE * SPECIFIC HEAT/AREA .......    14.40 BTU/HR-FT2 DEG F
 C12. COLLECTOR SLOPE ................................    43.00 DEGREES
 C13. COLLECTOR AZIMUTH ..............................     0.0  DEGREES
 C14. GROUND REFLECTANCE .............................     0.20

COLLECTOR-STORE TRANSFER PARAMETERS
 T2. UA OF COLLECTOR INLET PIPE OR DUCT ..............     1.55 BTU/HR-DEG F
 T3. UA OF COLLECTOR OUTLET PIPE OR DUCT .............     1.55 BTU/HR-DEG F

STORAGE UNIT PARAMETERS
 S1. TANK CAPACITY/COLLECTOR AREA ....................    16.26 BTU/DEG F-FT2
 S2. STORAGE UNIT HEIGHT/DIAMETER RATIO ..............     2.40
 S3. HEAT LOSS COEFFICIENT ...........................     0.05 BTU/HR-FT2-DEG F
 S4. ENVIRONMENT TEMPERATURE (-1000 FOR TENV=TAMB) ...    60.00 DEG F
 S5. HOT WATER AUXILIARY TANK UA .....................     1.10 BTU/HR DEG F
 S6. HOT WATER AUX TANK ENVIRONMENT TEMPERATURE ......    60.00 DEG F

LOAD PARAMETERS
 L3. HOT WATER USE ...................................
       81.00   93.80   95.80   72.30   73.30   75.00
       47.30   46.60   46.80   63.80   82.00  103.00          GALLONS/DAY
 L4. HOT WATER SET TEMPERATURE .......................   140.00 DEG F
 L5. WATER MAINS TEMPERATURE .........................
       67.00   67.00   70.00   75.00   77.00   85.00
       87.00   89.00   88.00   83.00   75.00   69.00          DEG F

AUXILIARY PARAMETERS
 A3. HOT WATER AUXILIARY FUEL (1=GAS,2=ELEC,3=OIL) ...     2.
 A4. AUXILIARY WATER HEATER EFFICIENCY ...............     1.00

ECONOMIC PARAMETERS
 E1. ECONOMIC OUTPUT DETAIL (1,2 OR 3) ...............     3.00
 E2. REFERENCE OR COMPARISON SYSTEM (1 OR 2) ..........     1.00
 E3. CALCULATE RATE OF RETURN (YES=1,NO=2) ............     2.00
 E4. INCOME PRODUCING BUILDING (YES=1,2=NO) ...........     2.00
 E5. DEPRC: STR,LN.=1,DC.BAL.=2,SM-YR-DGT=3,NONE=4 ...     4.00
 E6. CONSIDER FEDERAL TAX CREDITS (YES=1,2=NO) .......     1.00
 E7. LENGTH OF ANALYSIS ..............................    20.00 YEARS
 E8. TAX CREDITABLE SYSTEM BASE COST .................$ 2970.00
 E9. NON-TAX CREDITABLE SYSTEM BASE COST .............$    0.0
 E10. ANNUAL INCREASE IN PURCHASED ENERGY DEMAND .....     0.0  %/YR
 E11. TERM OF MORTGAGE ...............................     1.00 YEARS
 E12. DOWN PAYMENT (% OF ORIGINAL INVESTMENT) ........     0.0  %
 E13. MORTGAGE ANNUAL INTEREST RATE ..................     0.0  %
 E14. RESALE VALUE (% OF ORIGINAL INVESTMENT) ........     0.0  %
 E15. ANNUAL NOMINAL (MARKET) DISCOUNT RATE ..........     0.05 %
 E16. EXTRA INSUR.,MAINT. IN YEAR 1 (% OF ORIG.INV.)      2.00 %
 E17. ANNUAL % INCREASE IN ABOVE EXPENSES ............     7.17 %
 E18. EFFECTIVE FEDERAL-STATE INCOME TAX RATE ........     0.0  %
 E19. TRUE PROP. TAX RATE PER $ OF ORIGINAL INVEST ...     0.0  %
 E20. ANNUAL % INCREASE IN PROPERTY TAX RATE .........     0.0  %/YR
 E21. STATE CREDIT IN TIER ONE........................    35.00 %
 E22. STATE CREDIT TIER ONE BREAK.....................$ 2057.00
 E23. STATE CREDIT IN TIER TWO........................     0.0  %
 E24. STATE CREDIT TIER TWO BREAK.....................$    0.0
 E25. USEFUL LIFE FOR DEPREC. PURPOSES ...............     0.0  YEARS
 E26. % OF ST. LINE DEP. RATE (DC. BAL. DEPRC.) ......     0.0  %

 TYPE LIST FLDATA FOR FUEL COSTS
 ?
LIST FLDATA

        FUEL COST

ELEC (SEQUENCE OF AVERAGE ANNUAL RATES IN $/MMBTU)
    21.2   22.7   26.2   28.2   30.1   33.7   35.8   35.8   37.0   39.0
    37.2   38.9   39.6   41.0   41.7   42.9   44.5   46.7   47.8   48.4
```

TABLE 2

FUEL SAVINGS OF ELECTRIC WATER HEATERS FROM SOLAR UNITS

********** FCHART ANALYSIS (VERSION 4.0) **********

PHOENIX AZ LATITUDE 33.3

THERMAL PERFORMANCE

| | IIT (MMBTU) | TA (DEG-F) | IWLOAD (MMBTU) | QU (MMBTU) | QLOSS (MMBTU) | FOIW |
|---|---|---|---|---|---|---|
| JAN | 2.10 | 51.8 | 1.59 | 0.04 | 0.04 | 0.47 |
| FEB | 2.20 | 55.4 | 1.65 | 0.90 | 0.04 | 0.55 |
| MAR | 2.71 | 59.0 | 1.79 | 1.12 | 0.05 | 0.57 |
| APR | 2.86 | 68.0 | 1.24 | 1.07 | 0.07 | 0.83 |
| MAY | 3.00 | 77.0 | 1.26 | 1.15 | 0.07 | 0.84 |
| JUN | 2.81 | 84.2 | 1.09 | 1.05 | 0.07 | 0.91 |
| JUL | 2.71 | 91.4 | 0.71 | 0.84 | 0.10 | 1.00 |
| AUG | 2.76 | 87.6 | 0.67 | 0.76 | 0.11 | 1.00 |
| SEP | 2.72 | 84.2 | 0.67 | 0.79 | 0.11 | 1.00 |
| OCT | 2.66 | 71.6 | 1.00 | 0.95 | 0.08 | 0.73 |
| NOV | 2.22 | 59.0 | 1.39 | 0.80 | 0.05 | 0.58 |
| DEC | 2.01 | 51.8 | 1.75 | 0.02 | 0.04 | 0.42 |
| YR | 30.76 | 70.2 | 15.00 | 11.10 | 0.01 | 0.67 |

PURCHASED ENERGY SUMMARY

| | GAS | ELECTRIC | OIL | TOTAL |
|---|---|---|---|---|
| USE (MMBTU) | 0.0 | 4.64 | 0.0 | 4.64 |
| COST ($) | 0.0 | 98.38 | 0.0 | 98.38 |

LIFE CYCLE COST ANALYSIS OF CURRENT SYSTEM

INITIAL COST OF SYSTEM $ 2970.
DOWN PAYMENT $ 0.
TOTAL TAX CREDITS $ 2188.
ANNUAL MORTGAGE PAYMENT $ 2970. FOR 1 YEARS

| | ****INFORMATION**** END OF YR | | IN- TEREST PAID | COMM DEPREC DEDUCT | ******SYSTEM COSTS******* LOAN PAYMT | MAINT & INC | PROP TAX | TAX CREDIT RECALC | *ENERGY* NET FUEL COST | NET CASH FLOW | ***INDICATORS**** PW OF SUMU CASH FLOW | CUMULATIVE PW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YR | PRINC | | | | | | | | | | | |
| 0 | 2970 | | 0 | 0 | 0 | 0 | 0 | 2188 | 0 | 2187 | 2187 | 2187 |

IHO209I IBCOM - PROGRAM INTERRUPT (P) - DIVIDE CHECK OLD PSW IC 070D000F420DD002

| TRACEBACK | ROUTINE | CALLED FROM ISN | REG. 14 | REG. 15 | REG. 0 | REG. 1 |
|---|---|---|---|---|---|---|
| | ECON | 0086 | 520F1000 | 000DBE60 | 000DF354 | 000F1350 |
| | RUNSUB | 0014 | 420F1066 | 000F11A0 | 00000000 | 000F0F54 |
| | RUN | 0088 | 420DD070 | 000F0E98 | 00000001 | 00000000 |
| | MAIN | | 0000B3D8 | 000DA998 | 00000000 | 000C7EC0 |

ENTRY POINT= 000DA998
STANDARD FIXUP TAKEN , EXECUTION CONTINUING

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 2970 | 59 | 0 | 0 | 93 | 3128 | 2879 | 691 |
| 2 | 0 | 0 | 0 | 0 | 64 | 0 | 0 | 105 | 169 | 143 | 834 |
| 3 | 0 | 0 | 0 | 0 | 68 | 0 | 0 | 122 | 190 | 140 | 982 |
| 4 | 0 | 0 | 0 | 0 | 73 | 0 | 0 | 131 | 204 | 146 | 1128 |
| 5 | 0 | 0 | 0 | 0 | 78 | 0 | 0 | 140 | 218 | 144 | 1272 |
| 6 | 0 | 0 | 0 | 0 | 84 | 0 | 0 | 156 | 240 | 146 | 1418 |
| 7 | 0 | 0 | 0 | 0 | 90 | 0 | 0 | 166 | 256 | 143 | 1562 |
| 8 | 0 | 0 | 0 | 0 | 96 | 0 | 0 | 166 | 263 | 135 | 1697 |
| 9 | 0 | 0 | 0 | 0 | 103 | 0 | 0 | 175 | 279 | 132 | 1829 |
| 10 | 0 | 0 | 0 | 0 | 111 | 0 | 0 | 181 | 292 | 127 | 1956 |
| 11 | 0 | 0 | 0 | 0 | 119 | 0 | 0 | 173 | 291 | 117 | 2073 |
| 12 | 0 | 0 | 0 | 0 | 127 | 0 | 0 | 181 | 308 | 114 | 2187 |
| 13 | 0 | 0 | 0 | 0 | 136 | 0 | 0 | 184 | 320 | 109 | 2296 |
| 14 | 0 | 0 | 0 | 0 | 146 | 0 | 0 | 190 | 336 | 105 | 2401 |
| 15 | 0 | 0 | 0 | 0 | 157 | 0 | 0 | 194 | 350 | 101 | 2502 |
| 16 | 0 | 0 | 0 | 0 | 168 | 0 | 0 | 199 | 367 | 97 | 2599 |
| 17 | 0 | 0 | 0 | 0 | 180 | 0 | 0 | 207 | 386 | 94 | 2694 |
| 18 | 0 | 0 | 0 | 0 | 193 | 0 | 0 | 217 | 409 | 92 | 2786 |
| 19 | 0 | 0 | 0 | 0 | 207 | 0 | 0 | 222 | 429 | 88 | 2874 |
| 20 | 0 | 0 | 0 | 0 | 221 | 0 | 0 | 225 | 446 | 85 | 2959 |
| TOTAL | | 0 | 0 | 2970 | 2480 | 0 | 2188 | 3432 | 6693 | 2959 | |
| PW OF TOT | | 0 | 0 | 2734 | 962 | 0 | 2188 | 1451 | 2959 | | |

| | UNDISCOUNTED | ANNUALIZED | PRESENT WORTH |
|---|---|---|---|
| ENERGY COST | 3432 | 155 | 1451 |
| TOTAL COST | 6693 | 316 | 2959 |

TABLE 3

SUMMARY OF ECONOMIC ANALYSIS: ELECTRIC WATER HEATERS, 1982

| | | | |
|---|---|---|---|
| TOTAL NUMBER OF INSTALLATIONS: | 12,188 | FUEL COST WITHOUT SOLAR $/UNIT | 4691 |
| BASE UNIT SYSTEM COST: | $2970 | | |
| $ CREDIT PAID (COST TO STATE): | $14,000,000 | FUEL COST WITH SOLAR $/UNIT | 1451 |
| DISCOUNT RATE: | 8.65% | FUEL SAVINGS $/UNIT | 3240 |
| INFLATION RATE: | 7.17% | MAINTENANCE INSTALLATION COST $/UNIT | 962 |
| COST UNIT SYSTEM W/ALL CR.: | $782 | TOTAL NET SAVINGS $/UNIT | 2278 |

PAYBACK

| YEAR | FUEL SAVINGS | PRESENT WORTH FUEL SAVINGS | PRESENT WORTH MAINTENANCE COST | TOTAL PRESENT WORTH NET FUEL SAVINGS |
|---|---|---|---|---|
| 1 | $220 | $202 | $54 | $148 |
| 2 | 236 | 200 | 54 | 146 |
| 3 | 271 | 211 | 53 | 158 |
| 4 | 292 | 210 | 52 | 158 |
| 5 | 312 | 206 | 52 | 154 |
| 6 | 350 | 213 | 51 | 162 |

20 YEAR TOTAL SAVINGS: $27,764,834 ($2,278 x 12,188)

SYSTEM PAYBACK PERIOD: 5.1 YEARS (Approximately)

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# THE CALIFORNIA POINT SYSTEM -ENERGY CODE AND RATING SYSTEM- A MODEL FOR STATES

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## ABSTRACT

Many state organizations are considering the implementation of a home energy rating system or energy code. The California Residential Point System is an excellent model for both. As a rating system, the California Point System can be used to rate both new and existing structures on the same scale. Ratings can be converted to annual energy costs, and lending institutions will respond by qualifing buyers more easily for homes with lower energy costs. The rating system can be used to calculate energy savings for individual conservation features for tax credits or for other financial incentives. As an energy code, the California Point System is both simple and accurate. It allows tradeoffs between all rated energy-saving features, so builders have maximum flexibility to keep construction costs to the minimum. The California Point System is described and the methodology is given to develop and implement a Point System in other states.

## 1. INTRODUCTION

The first California Point System (1982) was developed under the technical guidance of Eugene Mallette of the Energy Commission. The second California Point System (1983) is under the technical guidance of Bill Huston of the Commission.

The California Point System is a model energy rating system and a model energy code for other states. Now that the system has been developed and refined in California, it can be adopted by other states with a minimum amount of effort. For each climate zone, it requires less than 300 annual computer calculations on variations of the base house to construct all of the tradeoff tables required by the Point System. The California Point System is described below. Basic information is also given on developing and implementing a similar Point System in other states.

## 2. HOME ENERGY RATING SYSTEMS

Hendrickson (1) classifies home energy rating systems into three categories: performance, calculational and prescriptive. In his terminology, a "performance" system is one that uses past utility bills to assign a rating. As defined, a "performance" system can not be used to rate new homes. Also it gives a rating that is not a simple function of house construction because it includes the effect of the current occupant's lifestyle.

According to Hendrickson's definitions, a "calculational" system predicts the home's energy consumption, and a "prescriptive" system assigns points to the various conservation features of a home and then rates the home on the basis of total points scored.

## 3. THE CALIFORNIA POINT SYSTEM - AS A MODEL HOME ENERGY RATING SYSTEM

According to Hendrickson's classification, the California Point System is both a "calculational" system and a "prescriptive" system. The California Point System is now being used to rate new dwellings and existing dwellings with new room additions. It may soon be used to rate existing buildings in the state's weatherization program. All dwellings are rated on the same scale.

An important potential application of the California Point System is in the development of future financial incentive programs. Tax credits based on initial costs of solar and conservation features are now outdated. Instead tax credits can be based on direct energy savings or "points." A major objective of conservation and solar tax credits is to speed up implementation of cost-effective energy-saving technology. Tax credits and other financial incentives based on direct energy-savings or "points" will automatically give less incentive to less cost-effective measures and more incentive to more cost-effective measures.

## 4. ENERGY CODES

Energy code compliance methods may be classified as prescriptive, component performance or system performance. In energy code terminology, the "prescriptive" approach requiries that a package of prescribed energy-saving measures be installed to show compliance with the energy code. This method is the simplest to use but is less flexible than the other two approaches.

The "component performance" approach allows tradeoffs to be made in the average U-Value of walls, ceilings and floors. This method does not generally give credit for increased duct insulation, interior thermal mass, space heating and cooling equipment efficiency or water heating efficiency. Also window orientation, movable insulation, exterior mass walls, window shading, and infiltration control techniques are usually poorly treated by this method.

The "system performance" approach allows a building to show compliance when it is demonstrated that the calculated annual energy consumption is less than that for the reference design.

## 5. THE CALIFORNIA POINT SYSTEM - AS A MODEL ENERGY CODE

The California Point System is a simplified version of the "system performance" approach. A builder/designer is required to get a specified point total (or higher) in the Point System in order to qualify for a building permit. The specified point total is the point score of the reference design.

Generally, compliance can be shown using the California Point System in less time than it takes to show compliance using the more common "component performance" approach. Yet this simple Point System gives credit for more energy-saving measures and therefore allows the builder more flexibility in meeting the code.

This extra flexibility is useful when the required energy efficiency is relatively low, but this flexibility becomes absolutely necessary when the required energy efficiency level is relatively high. In this case, improved equipment efficiency, interior thermal mass, and other features that can be rated in the Point System are necessary to get additional cost-effective energy-savings.

## 6. THE FIRST CALIFORNIA POINT SYSTEM

### 6.1 Basic Format

To demonstrate compliance with the first California Point System, the builder-designer fills out a one page compliance checklist. A typical entry reads, "Raised Floor R-Value . . . R-____ . . . Points____." The R-Value is entered from the design, and points are entered from the appropriate Point Table. The Point Table for Zone 16 for "Raised Floor Insulation" is shown below. One minus point corresponds to an extra energy consumption (natural gas equivalent) of 500 Btu $ft^{-2}$.

TABLE 6.1 RAISED FLOOR POINTS - ZONE 16

| R-Value of Insulation | Points |
|---|---|
| 0 - 1 | -16 |
| 2 - 3 | -12 |
| 4 - 5 | -8 |
| 6 - 8 | -6 |
| 9 - 13 | -4 |
| 14 - 18 | -2 |
| 19 up | 0 |

When the compliance check list is completed, the points are summed for all the point system categories and the point total is entered on the checklist. This point score is used to show energy code compliance or may be used as an energy rating.

### 6.2 Conservation Features Rated

Categories in the first California Point System are: slab perimeter insulation; raised floor insulation; ceiling insulation; wall insulation; glazing area and U-Value for all orientations including skylights; glazing area and summer shading coefficients for all glass orientations except north-facing; roof overhangs over south-facing windows; movable window insulation; infiltration barriers with an air-to-air heat exchanger; heating and cooling equipment efficiency including optional solar space and water heating, and interior and exterior thermal mass. The thermal mass sections of the Point System were developed by Steel (2), with help by the Berkeley Solar Group in formatting final tables.

### 6.3 Accuracy of Point System Predictions

The California Point system is accurate. Steel (2) reports data from 99 homes in Ontario, California, where the average energy for space heating and cooling was measured using utility bills and found to be equal to the average calculated using the Point System.

The California Point System is based on average occupant behavior. Comparisons of the performance of single homes or small groups of homes with results from the Point System are only valid if the test homes are operated using the same occupant behavior assumptions as used in the Point System. Steel (2) found that individual identical

homes in his sample had a difference in annual energy consumption up to a factor of two. He attributed this variation to occupant behavior. 100 homes is considered a good sample size for averaging out the effects of occupant behavior.

## 7. THE SECOND CALIFORNIA POINT SYSTEM

### 7.1 Format Improvements

The following are some of the improvements that are now planned for the second California Point System:

Point ranges are to be decreased to 1 point intervals when possible.

The 16 separate manuals for the 16 California Climate Zones are to be combined into a single manual for the whole state.

The glazing and summer shading tables have been recalculated with a refined version of CALPAS to improve accuracy.

### 7.2 More Conservation Features Rated

Several new energy-saving measures have been proposed for the second California Point System. These measures include: ceiling fans, whole house fans, ventilated attics, duct insulation, evaporative coolers, heat pump thermostats, winter shading coefficients (so permanent shading can be rated), perimeter insulation when the slab-edge is uncarpeted (current tables are for carpeted slabs), wood heat (only when no auxiliary heat is present), solar water heating with electric resistance backup (current detailed tables are only for gas backup), cooling devices and heat pumps rated in all zones (currently these are not rated in some zones), glazing U-Values down to 0.25 in all window tables, and direct-fired and instantaneous gas water heaters for apartments.

### 7.3 Phasing In the Second California Point System

It is anticipated that the first California Point System will remain a certified and usable compliance tool for at least 18 months after the second version of the Point System is certified. It is important to have this overlap period because subdivisions designed using the first Point System should not normally have to be redesigned just because an updated version of the Point System is released.

## 8. DEVELOPING A CALIFORNIA-STYLE POINT SYSTEM FOR YOUR STATE

### 8.1 Heating, Cooling and Domestic Hot Water

The California Point System has combined point tables for space heating and cooling, and separate point tables for hot water systems.

If no air conditioning is specified for a home, it is assumed that a central air conditioner having the minimum efficiency allowed in the state (SEER = 8.0) will be installed at a future date, and so cooling energy is calculated based on the performance of this future cooling system.

For Point Systems for other states it must be decided whether cooling energy will be combined with heating energy in the same tables or kept in separate tables or simply eliminated from consideration. Since heating and cooling energy are both given in a CALPAS printout (the CALPAS computer program is used for space heating and cooling computer calculations), no additional annual energy calculations are required to include cooling in any format.

It must also be decided if hot water tables are to be included in the Point System.

The advantage of combined heating and cooling tables is the potential time savings in developing the Point System and the calculational time-saving for users. The disadvantage of combined tables is that heating-only or cooling-only energy-savings cannot be evaluated.

### 8.2 Annual or Peak Energy or Both?

The California Point System is based on annual (natural gas equivalent) energy consumption per square foot of the dwelling.

The CALPAS printouts give peak hour loads as well as annual totals. Therefore no additional annual calculations are required to construct peak hour point system tables based on peak hour energy per square foot.

Therefore it is easily possible to rate either annual or peak hour energy in a Point System or to have both rated in complimentary Point Systems.

### 8.3 Gas/Electricity Equivalence Ratios

The California Point System is based on natural gas. One positive Point is equal to a savings of 500 Btu $ft^{-2}$ of natural gas metered at the homesite.

Electricity is converted to natural gas Btu by the formula: 1 kWh = 10,239 Btu. This conversion is used because occupants can save either 10,239 Btu of natural gas or save 1 kWh of electricity both at the homesite, and in both cases they will reduce the state's consumption of natural gas by the same amount.

The California conversion factor will be valid in most states.

In the northwest, where electricity is largely supplied by hydropower the same equivalence ratio may be valid. If one kWh saved in the northwest means one more kWh will be transfered to California where 10,239 Btu of natural gas will be saved, then that 1 kWh is still equivalent to 10,239 Btu of natural gas.

The other potential equivalence ratio for natural gas and electricity in the northwest is to make natural gas water heating at the minimum efficiency allowed equivalent to electric resistance water heating.

An equivalency ratio between fuels is necessary for a point system in order to rate equipment efficiencies for competitive space conditioning and water heating systems.

8.4 Climate Zone(s)

It is necessary to define a climate zone or zones in order to develop a Point System. The California Point System has 16 climate zones. This is excessive. Most states can be characterized by one or two climate zones. An annual computerized hourly weather tape must be selected that characterizes each climate zone.

8.5 Base House(s)

It is necessary to have a base house in order to develop a Point System. The base house should be typical of residential construction in the region. It may be more accurate to have full Point Systems developed for different types of base houses in a region (for example, one for attached housing and one for apartment housing as well as one for single family detached housing). This potential improvement in accuracy has not yet been evaluated in California.

The base house for most of the tables in the California Point System is a 1384 square foot single-story single-family-detached home without a garage and with a slab floor. The house is rectangular with dimensions 45 feet by 30.76 feet on the outside. The roof is flat and all walls are 8'-0" in height. For modeling with CALPAS 1A, there are two doors, one 3'-0" x 6'-8" and one 2'-8" x 6'-8", and there are no roof overhangs.

There are two other base houses that were used to develop the California Residential Energy Code: one a typical 4 unit townhouse building and the other a typical 10 unit two story apartment building. Except for some domestic hot water tables for apartments in the California Point System, these other base houses have not been used in the Point System development.

8.6 Other Energy-Cost-Independent Features of the Base House

The following base house features are determined by aesthetic or practical considerations.

Window area - The California Base House has window area equal to 16% of the floor area. 16% was selected because it is the average window area for new homes in California. However a significant number of new homes, perhaps 15% of the total, are constructed with 20% or more window area. When 15% of the homes in a region are constructed with 20% or more window area, then the base house window area for that region should be at least 20%.

Window orientation - The California Base House has 40% of the total windows facing south and 20% each facing east, west and north. A more reasonable base house for a first Point System should have 25% of the windows facing in each cardinal direction.

Exposed slab thermal mass - The California Base House has 50% of the slab assumed to be uncarpeted and assumed to be only 2" thick. In California less than 5% of new homes would have this much uncarpeted slab. An upper limit on uncarpeted 3-1/2" slab in the base house should be 20% to 25% in California. This percent would vary for other states.

Other basic thermal mass - The California Base House is assumed to contain unspecified thermal mass with Mass Capacity (Btu $^{o}F^{-1}$) = 1000 + 1.5 times the conditioned floor area in $ft^2$. This is a reasonable simplified model.

Ground reflectivity - The California Point System assumes a ground reflectivity of 0.2.

Building solar absorptivity - The California Point System assumes a uniform solar absorptivity of 0.5. A value of 0.65 would be more appropriate.

8.7 Energy-Cost-Dependent Features of the Base House

The method used by the Energy Commission to choose the energy-cost-dependent features of the base house began with the calculation of the energy consumption and 30 year life-cycle-cost of energy for the base house built to satisfy the 1978 California Energy Code.

As the next step in the process, about 10 additional energy-saving measures were identified. The identified measures were added to the 1978 base house independently, one at a time, and again using life-cycle-

cost analysis, the ratio of energy-cost-savings to conservation-feature-costs was calculated for each measure. Then the measures were put in order with the item with the greatest savings to cost ratio at the top of the list.

Next, starting at the top of the list, the new conservation features were added sequentially to the 1978 base house. As each additional item was added to the base house the total life-cycle-cost of both the energy and the new energy conservation features was calculated.

As the first several items were added the total life-cycle-cost decreased. As more items were added a minimum cost was reached, and then when more items were added the total cost began to increase rapidly. This rapid increase occured because the house was already very energy-efficient, and these last items were only able to save a little more energy, yet added significantly to the construction costs of the new home.

In the California Energy Commission life-cycle-cost analysis, marginal instead of average energy costs were used. From the consumer's point of view, the use of marginal costs can not be justified. Future analysis should only use average costs.

The following items should be considered as energy-cost-dependent features of the base house:

Insulation levels - Additional insulation for walls, ceilings, ducts, doors, windows (movable), and either slab-perimeter or raised floor depending on the base house. Movable window insulation can be roller shades with magnetic edge strips.

Summer shade screens - A minimum practical device-shading-coefficient for the base house is 0.32.

Multi-pane windows - low emissivity windows should be considered when they become commercially available.

Infiltration control measures - Until the effects of indoor pollution are better understood, credit should not be given to measures or systems that lower the average annual air changes per hour to less than 0.5.

Equipment type and efficiency - Efficient space conditioning and hot water equipment considered should include special equipment such as ceiling fans, whole house fans and batch-type solar water heaters.

Additional thermal mass - Interior sand-aggregate plaster and other interior mass walls. Additional uncarpeted slab floor areas should not be considered for the base house.

## 8.8 Occupant Behavior Assumptions

The following are the occupant behavior assumptions used for the base house.

Internal gain - The internal gain was 86,991 Btu $day^{-1}$ and was introduced according to a 24 hour schedule. This assumption is high for summertime operation.

Temperature setpoints - The heating setpoint was 65 $^{o}F$ which was a simple model to estimate the performance of a setback thermostat operating at 68 $^{o}F$ during the day and 60 $^{o}F$ at night. The cooling setpoint was 80 $^{o}F$ which corresponds to the upper comfort limit at 0.4 clo.

Window shading schedule - Cost-effective shade screens or drapes with shading coefficient equal 0.8 shaded the windows all summer and no window shading was assumed during the winter. The effective length of summer was set separately for each climate zone on a subjective basis.

Ventilation schedule - In the winter 20% of the windows were opened when the inside temperature reached 80 $^{o}F$ if ventilation would keep the house from going above that temperature. In the summer 20% of the windows were opened when the house was between 65 $^{o}F$ and 80 $^{o}F$ if cooling would occur. This ventilation schedule is too optimum to be realistic.

## 8.9 Computer Calculations to Construct the Point System Tables

The CALPAS program was used for annual computer calculations. It is recommended for development of Point Systems for other states because it will save time since it is used in the California Point System development. CALPAS 1A is the latest version of the public domain computer program and it is available from the California Energy Commission and also, for time-share use, from the Berkeley Solar Group.

After the base house features are established (through minimum life-cycle-cost analysis) point system tables are constructed by doing annual calculations varing the base house features. For example, for the ceiling insulation category, runs were made for four different values of ceiling insulation. In the second California Point System results from the annual energy calculations are interpolated for the point system tables using a cubic spline computer method.

Next a reference design is used to set the zero-point energy consumption in each category in the Point System. The reference

design is discussed in Section 9.

For example, if the ceiling insulation of the reference design is R-30, then R-30 will get 0 points. If annual energy calculations show that R-38 ceiling insulation in the base house will save 500 Btu $ft^{-2}$ then R-38 is given +1 point in the point tables.

The California Point System is constructed so that all houses that get the same point score will have, very nearly, the same annual energy consumption when occupant behavior effects are averaged-out. A house that got zero points would, very nearly, have the same annual energy consumption as the reference design in natural gas equivalent units of Btu $ft^{-2}$.

This fact can be used to convert a point score for a house into an annual energy consumption. Suppose the reference design has annual energy consumption of 20 MBtu $ft^{-2}$ and suppose a particular house has a point rating of -10 points. Then the annual energy consumption of the selected house will be 20 + (10 points)(0.5 MBtu $ft^{-2}$) or 25 MBtu $ft^{-2}$. If the cost of energy for the reference design is \$0.20 $ft^{-2}$ $yr^{-1}$ then the cost of energy for the selected design will be approximately \$0.25 $ft^{-2}$ $yr^{-1}$.

### 8.10 Documentation and public review

Documentation is absolutely essential for proper public review and improvement of the Point System over time in an orderly manner. All work should be done in a professional manner and submitted to the Program Manager for review, checking, and docketing. Each report submitted to the Program Manager should be complete and self-sufficient when it is read with the docketed reference materials. All significant assumptions and calculations must be docketed.

## 9. IMPLEMENTING A POINT SYSTEM ENERGY CODE

In the California Point System, the reference design that sets the zero-point levels is not the base house with the lowest life-cycle-cost features. I recommend for future Point System development that the reference design be the base house with the lowest life-cycle-cost features. Then the zero-point levels of the point system tell the builder and consumer what features have been found to be most cost-effective.

When the Point System serves as an energy code the builder/design must meet the required point score in order to get a building permit. To facilitate implementation of a Point System Energy Code, I recommend introducing the code with a required point score that is less than zero. Make the initial required point score something that builders feel is reasonable. This will allow the Point System Energy Code to be implemented without the difficulties faced in California. Then, perhaps every three years, as builders become more familiar with the Point System, the mimumum point requirement for a building permit can be increased.

After six or nine years the lowest life-cycle-cost features of the base house should be recalculated, and if the new features are significantly more energy-efficient, all of the point system tables should be recalculated with the new base house features. If the new base house features are only a little more energy efficient, the new lowest life-cycle-cost analysis may be used to justify a modest raise to the minimum point requirement for a building permit.

Until builders get familiar with the new Point System, it will be useful also to offer alternate prescriptive packages to smooth implementation. This was found to be useful in California.

## 10. CONCLUSION

The California Point System is an excellent model for all states for a new energy code or a new home energy rating system. It is simple, accurate, flexible, and it facilitates cost analysis by the builder which will reduce initial construction costs for an energy-efficient home to a minimum.

## 11. ACKNOWLEDGEMENT

The staff and the Commissioner's at the California Energy Commission and the many participants from industry who took part in the development of the California Point System are to be commended for their success.

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# CALIFORNIA'S POINT SYSTEM - EXPANSION AND IMPROVEMENT

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## ABSTRACT

The California Energy Commission's Point System is a simplified method to analyze the energy performance of residential buildings. Although the system is an accurate predictor of energy use, several modifications would increase its accuracy and application. This paper presents three such changes and provides examples of resulting point tables for each change.

## 1. INTRODUCTION

In January 1982, the California Energy Commission approved a simplified calculation method, called the "Point System," to be used to show compliance with the state's new residential energy building regulations. Energy budget levels for 16 climate zones were set by regulation for California. The point system considers such building features as wall, floor, and ceiling insulation, thermal mass, HVAC efficiency, shading, solar water heating, orientation, infiltration, and glazing to predict the energy consumption of the building. The method assigns positive points to devices which save energy beyond a "standard" energy budget level, and negative points to those devices which are below that level. After points have been determined for all of the building's features, a designer/builder simply adds the points together. If the total is zero or positive, the building complies with the standard; if the total is negative, additional conservation measures must be added or improved.

Although the system has been shown to be extremely accurate for new building compliance, additional improvements can allow its use in wider applications. This paper presents three such improvements:

(1) Dividing the energy budgets into separate heating and cooling budgets;

(2) Redefining the point tables from total source energy consumption to individual heating and cooling loads; and

(3) Defining new tables which display "percent of standard" rather than net changes from a standard energy budget level.

The paper presents examples, methodology, and a comparison of resulting point tables for California's Climate Zone 13 (characterized by moderate winters and hot summers).

## 2. DIVIDING THE ENERGY BUDGETS INTO SEPARATE HEATING AND COOLING BUDGETS

The approved California point system combines total heating and cooling energy into a single table for each measure. Table 1 is an example of the point-table for ceiling insulation. Values in the table were calculated by varying the R-value from a carefully defined base case house having both heating and cooling equipment. Changing the ceiling insulation, then, has an impact on both heating and cooling energy whether or not the house being analyzed contains both equipment types.

TABLE 1

CLIMATE ZONE 13
TOTAL BUDGET POINTS*

| Ceiling Insulation | Total Budget Points |
|---|---|
| R-30 | 0 |
| R-38 | +4 |
| R-44 | +5 |

*Includes source energy and equipment efficiency.

The present point system becomes more accurate, especially if cooling equipment is not included in a building's design, if heating and cooling energies are calculated separately. Table 2 separates point values for heating and cooling, revising Table 1.

TABLE 2

CEILING INSULATION--
COOLING AND HEATING BUDGET POINTS*

| Ceiling Insulation | Cooling Budget Points | Heating Budget Points |
|---|---|---|
| R-30 | 0 | 0 |
| R-38 | +2 | +1 |
| R-44 | +3 | +2 |

*Includes source energy and equipment efficiency.

Similar separated tables can be developed for each conservation and solar measure; users of the point system would keep the heating and cooling point values separate until the final measure, heating and cooling equipment, has been evaluated. If the home contains both heating and cooling equipment, then the separate values would be combined to determine whether the home complies. Buildings having only a heating system or only a cooling system need only have a zero or positive heating value or cooling value, respectively, for meeting suggested energy budget levels; however, both heating and cooling point values would need to meet the energy budget values set by regulation, the assumption being that a homeowner could put in space conditioning equipment later and consequently use more energy than the standard level, if the building does not comply with both the heating and cooling energy budgets totaled or separated.

With this improvement, when the effect of each measure on heating and cooling is displayed, designers can (1) select those features which most appropriately reduce the space conditioning needs of the home, and (2) evaluate the effectiveness of each measure on the home buyer utility bills where significant differences exist between the costs of heating and cooling energy.

3. REDEFINING THE POINT TABLES FROM SOURCE ENERGY CONSUMPTION TO LOADS

A further refinement to the point system is to develop each heating and cooling table based upon building loads rather than source use energy. The existing tables assume a 71 percent seasonal efficiency gas heater and a 8.0 SEER for the air conditioner.

More efficient equipment is considered in a separate table, based on unchanging heating and cooling loads, but this does not accurately reflect the impact of efficiency based on the proposed heating and cooling demands of the building.

Table 3 is an example of a revised Table 2 which is based upon loads rather than source energy. The new tables remove equipment efficiency altogether and simply display the effects of ceiling insulation on the building's heating and cooling needs.

TABLE 3

CEILING INSULATION--
COOLING AND HEATING LOAD POINTS*

| Ceiling Insulation | Cooling Load Points | Heating Load Points |
|---|---|---|
| R-30 | 0 | 0 |
| R-38 | +6 | +1 |
| R-44 | +8 | +1 |

*Does not include source energy or equipment efficiency.

Once similar changes are made to all the measures in the point system, point values for heating and cooling loads can be added separately to determine a total proposed heating and cooling energy consumption. Compliance with energy regulations or energy standards could be determined as follows:

$$PC = \frac{[BL - (PL \times PV)] \times SM,}{EFF}$$

PC = Proposed Consumption, kWh/$m^2$/yr;

BL = Base Load, kWh/$m^2$/yr;

PL = Proposed Load, point value;

PV = Energy value per point, examples; 1 pt = 1577 Wh/$m^2$/yr (500 Btu/$ft^2$/yr);

SM = Source energy multiplier, scaler (1 for gas and 3 for electricity in California); and

EFF = Seasonal energy efficiency of the space conditioning equipment.

If the proposed heating energy use plus the cooling energy use is less than or equal to the total energy budget, the building complies with either suggested or maximum energy use levels.

4. DEFINING NEW TABLES WHICH DISPLAY "PERCENT OF STANDARD" RATHER THAN NET CHANGES FROM STANDARD

The current tables display the energy effects of each measure in terms of net changes to the energy standard for a base case building. Some error is therefore incorporated when houses significantly larger or smaller than the base house are evaluated. Another source of error in the point system is due to the low energy budget levels in some zones, as in San Diego which has a moderate coastal climate (California Climate Zone 7); one point in California Climate Zone 15, El Centro which has a hot desert climate, is only 1.3 percent of the

energy budget, whereas in Climate Zone 7, 1 point is 8.1 percent of the energy budget. Since point values are constant throughout all climate zones, rounding values may incorporate error in those areas with small total energy budgets. For example, 4/10 of a point excluded in a calculation could be 3 percent in a mild zone but only 0.3 percent in a more severe climate.

A further improvement, after space heating and cooling energies are separated and converted to loads, is to express the table in percentages rather than an absolute energy level. Positive points convert to percentages less than 100 percent; and negative points convert to percentages greater than 100 percent. Compliance with suggested or required energy efficiency levels is shown by multiplying the values from each measure together (rather than adding them as is currently done); if the result is 100 percent or less, the design complies. Table 4 is an example of revised Tables 1 and 2, based on percentages.

TABLE 4

CEILING INSULATION--
COOLING AND HEATING BUDGET PERCENTAGES*

| Ceiling Insulation | Cooling Budget Percentages | Heating Budget Percentages | Total Budget Percentages |
|---|---|---|---|
| R-30 | 100% | 100% | 100% |
| R-38 | 94% | 94% | 94% |
| R-44 | 93% | 92% | 93% |

*Includes source energy and equipment efficiency.

## 5. POINT/PERCENTAGE EXAMPLES FOR CALIFORNIA CLIMATE ZONE 13.

The base case house for California Climate Zone 13 energy performance modeling is a passive solar building. The measures of the base case design and four example designs are shown in Table 5. These examples were run on CALPAS 1A, a public domain computer simulation program which uses a full year of hourly weather data from the representative city for the Climate Zone.

The buildings were then compared by using one of four different simplified methods to test the accuracy of the methods. However, for Climate Zone 13, one point is approximately 1.5 percent, so it is very clear that the difference in accuracy depends mainly on two things: (1) the size of the point relative to the total budget, and (2) the ease of using addition over multiplication.

Table 6 shows the comparison of the point and percentage methods for each example design. Because the size of the point is approximately the same size as a percent of budget, 1 point approximately equals 1.5 percent of the energy budget, both methods predict very closely. However, for other climates with different budgets and different point values the accuracy of each method will vary.

In Table 6, Columns A and C are based on the method presented in Part 4 analyzing separate heating and cooling energy budgets for each measure. Columns B and D are based on the method presented in Part 2 analyzing separate heating and cooling energy budgets for each measure. Column E is based on the method presented in Part 4 analyzing the total energy budget for each measure. Column F is based on the method presented in Part 2 analyzing the total energy budget for each measure. Column F is the current certified simplified calculation method in California.

The results displayed in Table 6 clearly show that a simplified method based on a total budget does not offer a builder/designer an appropriate measure of the building's energy performance. For example, the building measures for example 1 raise the energy use of the building equally for both heating and cooling in relative terms. However, the building measures for example 2 increase the building's cooling budget more than the heating budget; the result suggests a cooling-only conservation strategy such as summer shading devices with a greater shading coefficient than currently in the package of measures. A total budget method does not show which load has become a problem.

## 6. CONCLUSION

The existing California Point System is an accurate, simple, and extremely useful approach to calculate the energy performance of new residential buildings. It is, though, only a first step. Developing simplified methods which include separate heating and cooling budgets will help improve energy conscious building design. Modifications suggested in this paper will improve accuracy without sacrificing simplicity.

## 7. ACKNOWLEDGEMENTS

The authors wish to express their thanks to Stephen Frietsche and Dee Anne Ross for their valuable contributions to this paper.

TABLE 5

ALTERNATIVE COMPONENT PACKAGE MEASURES*

| Measure | Base Case | Example 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Glazing: | | | | | |
| North | 3.2% Floor Area, Double Pane (DP) | 3%, Triple Pane (TP) | 3%, DP | 6%, TP | 3%, TP |
| East | 3.2%, DP | 6%, DP | 9%, DP | 3%, DP | 6%, DP |
| South | 6.4%, DP | 3%, DP | 3%, DP | 6%, DP | 6%, DP |
| West | 3.2%, DP | 9%, Single Pane (SP) | 3%, DP | 0% | 3%, DP |
| Shading Coefficient: South Glazing | SC .36 | SC .80 | SC .36 | SC .36 | SC .15 |
| Skylight | none | none | 4%, DP, SC .36 | 2%, DP, SC .36 | none |
| Ceiling Insulation | R-30 | R-30 | R-30 | R-38 | R-44 |
| Thermal Mass (slab % of floor area) | 50% | 50% | 50% | 50% | 25% |

*Other features include R-11 wall insulation, no slab insulation, a south overhang, 0.36 SC on west glazing, a .71 Seasonal Efficiency gas heater and an 8.0 SEER air conditioner.

TABLE 6

POINT/PERCENTAGE COMPARISON FOR EXAMPLES 1 THROUGH 4[1]

| Example | A Cooling % | B Cooling Points | C Heating % | D Heating Points | E Total % | F[2] Total Points |
|---|---|---|---|---|---|---|
| 1 | | | | | | |
| Prediction | 137% | -15 | 126% | -6 | 135% | -22 |
| Actual | 132% | -14 | 126% | -6 | 130% | -20 |
| Difference | 4% | 2% | 0% | 0% | 4% | 2% |
| 2 | | | | | | |
| Prediction | 147% | -19 | 124% | -6 | 137% | -24 |
| Actual | 143% | -18 | 121% | -5 | 135% | -23 |
| Difference | 3% | 2% | 2% | 3% | 1% | 1% |
| 3 | | | | | | |
| Prediction | 105% | -2 | 111% | -5 | 109% | -7 |
| Actual | 112% | -5 | 102% | 0 | 108% | -6 |
| Difference | 6% | 6% | 9% | 21% | 1% | 1% |
| 4 | | | | | | |
| Prediction | 116% | -7 | 109% | -2 | 114% | -9 |
| Actual | 117% | -7 | 108% | -2 | 114% | -9 |
| Difference | 1% | 0% | 1% | 0% | 0% | 0% |

1. Includes source energy and equipment efficiency.

2. The total points in Column F do not equal the total obtained by adding the corresponding point values from Columns B and D because of rounding.

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# OVERVIEW OF THE RESULTS OF THE RESIDENTIAL CONSERVATION DEMONSTRATION PROGRAM

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ABSTRACT

The results of the Residential Conservation Demonstration Program are presented on the following pages. Over portions of the last two years, 170 homes in Florida have been monitored for electrical energy consumption of various energy conservation devices including passive solar design strategies, radiant heat barriers, and ventilation strategies; solar water heaters, dedicated heat pumps, heat recovery units, and high efficiency electric water heaters; high efficiency air conditioners, heat pumps, ceiling fans, and insulation; and high efficiency refrigerators. The measurements of the performance of these devices were conducted under a range of climate conditions in Florida characterized as hot and humid with sample sizes ranging from 1 to 25. Energy savings, peak demand savings, and cost effectiveness data are presented where available.

## 1. OVERVIEW OF PROGRAM DEVELOPMENT

### 1.1 Legislative Directives

In 1980 the Florida legislature passed the Florida Energy Efficiency and Conservation Act of 1980 (FEECA) which required the adoption of energy conservation goals by the Florida Public Service Commission (PSC) which is responsible for regulating utility companies. In conjunction with other state agencies, the PSC established goals of reducing the growth rate of electrical consumption to 75 percent of the level projected for 1989, reflecting growth in population. A goal of reducing the electrical peak demand to 72.25 percent of 1989 projections was also adopted. Energy conservation plans were submitted, reviewed, modified, and approved by the PSC following public hearings. These programs are monitored by the PSC for cost effectiveness. FEECA authorized a $5 million trust fund for the purpose of guaranteeing loans for energy conservation expenditures offered to the consumers by the utilities. This legislation also established the $4 million Florida Energy Trust Fund for the following purposes.

### 1.2 The Florida Energy Trust Fund

The Florida Energy Trust Fund (ETF) was established for the purposes of (1) developing and demonstrating appropriate technologies for the conservation of electricity and natural gas in the residential sector, (2) to study the relationship between solar and other conservation techniques with existing utility systems, and (3) to increase public awareness.

The $4 million trust fund financed four types of projects. These activities included (1) a public awareness campaign which included television, radio, newspaper, magazine, movie theater, and telephone media advertisements for energy conservation; (2) a study of the demographic characteristics of Florida's population and their energy consumption behaviors; (3) a computer simulation study to study the effects of combinations of energy conservation technologies on the residential load demand of the utilities, and the impact on system reliability and generation expansion plans; and (4) the Residential Conservation Demonstration Program.

## 2. THE RESIDENTIAL CONSERVATION DEMONSTRATION PROGRAM (RCDP)

In response to a Request-for-Proposals, more than 40 demonstration project proposals were reviewed and evaluated. Eight contracts were initiated which involved the retrofit of a variety of energy conservation devices on subsets of 170 homes located in the three climate zones in Florida. These homes were monitored during a portion of a 15 month time period for kilowatt-hour consumption, peak load demand, and lifestyle variables. Two projects have continued data collection for another year. In addition, the staff of the RCD Program conducted an extensive review of the literature through the use of computerized bibliographic retrieval services:

a survey of energy professionals in Florida; and personal contact with researchers, government agencies, and private industry personnel. The highlights of the results of the demonstration projects and the technical papers generated by the RCDP staff are reported below.

## 2.1 Demonstration Projects

The demonstration projects listed below were conducted in a hot humid climate in the homes of volunteers who allowed contract personnel to measure energy and water consumption through either telephone-transmitted data or direct reading of Watt-hour meters, water flow meters, demand meters, and Btu meters. In addition, the demographic characteristics, lifestyle information, and other interesting comments were collected on subsets of these volunteers. An overview of the projects is provided below listed by title and the name of the principal investigator.

2.1.1 Belser, Ted. The Effects of Solar Water Heating Systems on the Electric Utility ; by CH2M Hill, Engineering Service Group, and Gainesville Regional Utilities; Gainesville, FL.

This project compared three groups of consumers, those with standard electric resistance water heaters, old solar, and new solar water heaters. They examined the total electrical consumption of the back-up electric units, gallons of hot water consumed, and the demand profiles of electrical consumption compared to the utility peak demand periods. They found the older solar units to save an average of 35 percent compared to standard electric units. However, the new units saved approximately 66 percent of the hot water electrical consumption. The peak demands for the solar systems were found to be largely non-coincident with the peak demand of the utility and saved .85 kW in summer and 1.48 kW in the winter.

2.1.2 Cromer, Charles. Instrumentation for Side-by-Side Testing of the Energy Attributes of Mobile Homes ; Florida Solar Energy Center, Cape Canaveral; testing in Tallahassee, FL.

Two mobile homes were monitored for the energy consumption of the space conditioning units and other appliances. The two homes were identical in floor plan and orientation and had computer-simulated loads for usage of appliances. One home had additional insulation, storm windows, and an air infiltration barrier. The additional insulation reduced the air conditioning costs by 15 percent and had a payback period of 3.5 years. Measurements of air infiltration using a sulfur hexafluoride tracer gas indicated no reduction in the air infiltration rate.

2.1.3 Doering, Robert. Passive Solar and Low Energy Building Design Residential Conservation Demonstration Project ; University of Central Florida and the Florida Solar Energy Center (FSEC); Orlando and Cape Canaveral, FL.

Six homes were retrofitted with exterior insulation over concrete block, radiant heat barriers, vented wall skins, and vented roof skins. Similar configurations were tested at the Passive Cooling Laboratory at FSEC. Reductions in the radiant heat gain through the roof of 40 percent were observed for a peak demand day with the use of builder's foil applied on the underside of roof rafters in conjunction with continuous soffit and ridge vents. These data were annualized with computer simulation to save 6 to 8 percent of the air conditioning (A/C) costs. The vented wall skin configuration did not pull much air through the wall cavity, but the radiant barrier performed to reduce the A/C costs by an estimated 6 to 8 percent on an annual basis. Window shading which reduced the shading coefficient from .80 to .45 was noted to save 11 percent of A/C costs per year. Exterior insulation of R-6 over concrete block walls saved an estimated 2.5 percent. Further testing of passive solar strategies continues at the Passive Cooling Laboratory.

2.1.4 Eno, Burton. In Field Test Results of Heat Recovery Units and Heat Pumps for Domestic Water Heating ; University of Central Florida; Orlando, FL.

This project investigated the relative performance of dedicated heat pumps and heat recovery units for water heating, including an analysis of the optimum water tank storage size. Heat recovery units saved from 30 to 40 percent of the electrical consumption for water heating with a payback of 6-8 years. The preferable volume for tank storage was found to be 80 gallons. Heat pump water heaters were found to save an average of 43 percent of water heating electrical consumption and had a payback of 8.5 years.

2.1.5 Ingley, Herbert. Passive Solar Design Studies, Energy Research and Education Park ; University of Florida; Gainesville, FL.

Two instrumented homes in the Park were retrofitted with two packages of energy saving retrofits and were simulated for occupancy. The concrete block house was retrofitted with earth berms and drapery treatments. The wood frame house was retrofitted with a whole house exhaust fan, exterior shutters, and simulated landscaping. A number of other passive features such as window treatments to reduce heat gain, roof color, and shading

strategies were simulated by computer for 4 locations in Florida, covering 3 climate zones. Low energy landscaping was found to save from 8 to 19 percent of A/C costs. Whole house exhaust fans were found to have a simple payback period of less than 2 years. Due to the high earth temperature in Florida, retrofitted earth berms were simulated to have payback periods exceeding 30 years. Reflective window film and managed window quilts were found to have the shortest payback periods of 3 to 5 years in all climate zones. Other window treatments had considerable variation in cost effectiveness among the climate zones. Properly managed wind turbines and attic fans were simulated to have payback periods of 6 to 8 years in Florida, while unmanaged fans had very long payback periods.

2.1.6 Lawrence, W. Thompson. Field Test Measurements of Energy Savings from High Efficiency, Residential Electric Appliances ; Arthur D. Little, Inc., Cambridge, MA.; testing in Orlando and Miami, FL.

High efficiency and standard appliances were monitored in the same households in alternating sequence. High efficiency air conditioners saved an average of 31 percent of the A/C costs. Ceiling fans were found to save as much as 12 percent on the average in homes that had high usage of the A/C. Homes that had already reduced their A/C consumption to low levels before the study actually increased electric consumption by 17 percent of space cooling costs by using the ceiling fans. Heat recovery units saved 20 percent of the water heating consumption with recovery from standard A/C units, but only 14 percent with high efficiency A/C units. Dedicated heat pumps saved an average of 46 to 48 percent of water heating costs. Payback periods were noted to be 10.4 years for heat recovery units in Miami and 7.7 years for dedicated heat pumps in Orlando compared to 9.6 years in Miami. High efficiency refrigerators saved an average of 43 percent in Miami and 60 percent in Orlando. Paybacks of 13.9 years in Miami and 8.6 years in Orlando were reported.

2.1.7 Merrigan, Tim. Residential Conservation Demonstration: Domestic Hot Water ; Florida Solar Energy Center; Cape Canaveral; testing in three climate zones.

Four types of hot water systems were monitored in four locations in Florida to determine system performance, operating coefficient of performance, and time-of-day electrical demand. Preliminary data based on warm season performance indicate solar water heater savings of 86 percent over standard electrical resistance types. Heat recovery units saved an average of 59 percent compared to 45 percent for dedicated heat pumps. Energy conserving insulated tank electric resistance units saved 32 percent over standard versions. Solar and heat recovery units exhibited peaks off the utility system peak. Payback periods were noted to be 6.0 years for solar, 2.9 years for heat recovery units, 7.8 years for dedicated heat pump water heaters, and 2.7 years for high efficiency electric resistance units. Additional data collection is still underway for performance during weather variation.

2.1.8 Messenger, Roger. Maximally Cost Effective Residential Retrofit Demonstration Program ; Center for Energy Conservation, Florida Atlantic University; Boca Raton, FL.

Sixty participants were identified through a survey and were divided into two groups, comparison and experimental. All homes were given an energy audit to determine the maximum cost effective retrofit strategy. Insulation and other heat gain reduction devices were added before high efficiency air conditioners were installed. Solar water heaters were requested by 19 of the 25 experimental group volunteers. An average of 34 percent savings was noted for cooling, with heat pumps saving 28 percent on the average, and high efficiency A/C saving 36 percent. Zoned A/C systems saved 10 percent of the cooling energy. The solar water heaters saved 85 percent of the electrical need for water heating and 0.37 kW of demand, while heat recovery units saved 33 percent and 0.49 kW of demand. High efficiency refrigerators saved from 42 to 45 percent of the cost of food preservation with demand savings of 0.18 kW. Improvements to swimming pool pumps saved 30 percent. Electrical demand of the homes were reduced by 31 percent overall by the installation of cost effective measures recommended by an energy audit. Payback periods for solar water heaters were noted to be 4.5 years when the use of the solar system was maximized and backup use minimized. Heat recovery units had a payback of 3.6 years. High efficiency refrigerators were noted to have a payback of 5.0 years. Additional data are forthcoming on these systems under different weather conditions.

2.2 RCDP Technical Reports

In order to evaluate the universe of options available to conserve energy in the residential sector, an extensive information collection effort was conducted by the staff. Computerized bibliographic retrieval services were used to identify publications of value which were read for useful information and organized into an energy conservation information system. Additional information from other state and federal agencies, private businesses, professional organizations, and

utilities were evaluated. After extensive analysis, a series of technical reports were compiled as highlighted below.

2.2.1 Residential Sector Energy Use

Historical trends in energy use are shown in this report which indicates fuel type use, end-use consumption, population characteristics, and housing stock growth. The implications of the ways we use our energy resources are discussed.

2.2.2 Framework Analysis

This report outlines the development of the energy conservation information system. A large multidimensional matrix structure was used as a framework in which to classify information, find sectors in need of additional information, and as a structure to organize the wealth of data and information obtained through the program.

2.2.3 Management of Demonstration Projects

This report gives an overview of the selection, implementation, and management of the demonstration projects.

2.2.4 Issues Analysis

In order to evaluate all costs and benefits of different conservation strategies where possible, the literature was surveyed for a number of issues to be considered before the recommendation to use a device or procedure could be made. The issues considered included behavioral characteristics needed for optimum use, environmental or medical hazards, thermodynamic considerations, climatological constraints on efficiency, technical feasibility and performance, and the economics of purchase and operation.

2.2.5 Methods Analysis

The staff also examined the activities of other regulatory bodies, utilities, state and federal agencies, and other groups to evaluate the effectiveness of methods of implementation of energy conserving actions. These methods included regulations, laws, taxes, building codes, subsidies, rebates, loan programs, service delivery, research and demonstration projects, and educational programs.

2.2.6 Final Report

The highlights of the primary and secondary findings from the demonstration projects, each of the technical reports, and the conclusions of the entire program effort are included in this report. While none of the data collected were of statistically significant sample sizes, this report presents a collection of the findings of hundreds of authors who have written on the subject of residential energy conservation. The use of this information by professionals in the field should facilitate progress toward the goal of conserving our valuable non-renewable energy sources.

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# ENERGY CONSERVATION THROUGH LAND USE PLANNING IN EASTERN ONTARIO

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## ABSTRACT

The draft Planning Act released by the Ontario Government in December 1979 explicitly recognizes energy as a matter of Provincial concern. The Act provides the Province with a mechanism to require the consideration of energy in the planning practice of all municipalities.

Our paper analyses the willingness and commitment of municipalities in eastern Ontario to implement energy conservation through land use planning.

## 1. INTRODUCTION

To date, the Province of Ontario's concern for the efficient supply and use of energy has not resulted in legislation which would require municipalities to implement energy sensitive land use planning. Rather, the Province has attempted to change the attitudes of planners and municipal officials towards energy conservation in the hope that the appropriate actions (e.g., energy policies and plans) will follow. As long as energy planning remains permissive rather than mandatory, municipalities must be willing to implement energy conservation through land use planning. Survey research can determine the willingness of municipalities to implement energy planning and to guage the motivation of this willingness.

Understanding the source of motivation is important for two reasons. First, it has been demonstrated that where a behaviour is extrinsically motivated, that is, by rewards or sanctions beyond the control of the actor, the behaviour will cease as soon as this source of motivation is removed. (1-3) Second, compared with intrinsically motivated behaviour, the quality of performance of extrinsically motivated behaviour tends to be lower. (4, 5)

Achieving energy conservation through land use planning is only possible by the conscientious application of energy considerations in municipal planning. If this goal is intrinsically motivated, (i.e., by local public and political support), the Province need only play an advisory role. If, however, there is little evidence of intrinsic motivation, the Province must seek to change attitudes or use its fiscal and legislative powers to provide extrinsic motivation.

## 2. PROCEDURE

A questionnaire was devised to collect data on the behaviour and attitude of municipalities with regard to energy conservation through land use planning. The questionnaire was pre-tested at the Canadian Institute of Planners Annual Conference in Kitchener-Waterloo, July 1980, in order to ensure clarity and variance of response.

The questionnaire was administered to all municipalities in the eastern Ontario Region (Fig. 1). The respondent was either the Planning Director or Municipal Clerk (where the municipality had no permanent planning staff) of each municipality. A return rate of 30%, which represented 52 valid responses, was achieved.

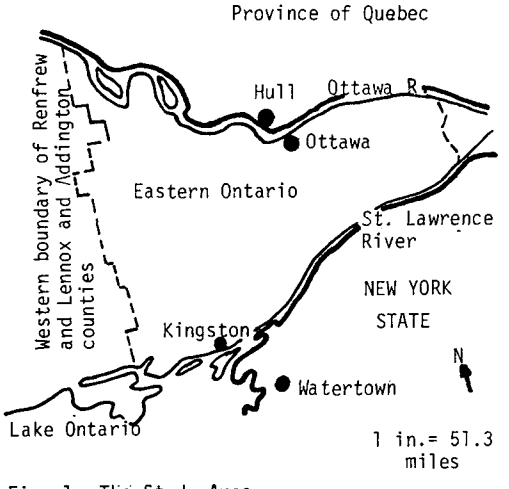



Fig. 1. The Study Area

The results are shown in three categories: townships with a population less than 10,000 (n = 26); towns and villages with a population less than 10,000 (n = 20); and cities with a population of more than 100,000 (n = 6). The sample size of the latter category is small, and these results should only be considered as indicative of general trends.

## 3. SURVEY RESULTS

### 3.1 Legislative Competency

To implement energy conservation strategies through land use planning the municipality must have the authority to control the location, density and type of land use, specific site features of new developments, and the manner in which properties are maintained and occupied. (6) A full range of statutory planning instruments - Official Plan (which is a prerequisite to site plan control), zoning by-laws and property standard by-laws - are necessary to achieve this degree of control. (7)

Municipalities were asked which statutory planning tools were adopted or expected within the next five years. Table 1 shows that the majority of municipalities have or expect to adopt a full range of planning tools within five years. The only exceptions appear to be small towns and villages, and rural townships.

TABLE 1

STATUTORY PLANNING TOOLS ADOPTED OR EXPECTED WITHIN FIVE YEARS

| | Cities* | |
|---|---|---|
| | Adopted % | Expected % |
| Official Plan | 100 | 0 |
| Zoning By-Law | 100 | 0 |
| Property Standards | 83 | 17 |
| | **Townships and Villages*** | |
| | Adopted % | Expected % |
| Official Plan | 80 | 20 |
| Zoning By-Law | 85 | 10 |
| Property Standards | 65 | 10 |
| | **Townships*** | |
| | Adopted % | Expected % |
| Official Plan | 69 | 27 |
| Zoning By-Law | 46 | 30 |
| Property Standards | 50 | 19 |

* Percentage of respondents. Totals may not add up to 100%, in some instances, because a few respondents were uncertain.

### 3.2. Resource Constraints

Municipal support and resources are addressed as potential constraints for implementing energy conservation strategies. Municipalities were asked to rate the three major constraints to implementing energy conservation from a list (shown in Table 2.) The responses are consistent across all sizes of municipalities. The three major obstacles are lack of expertise, lack of funds and higher priority activities.

TABLE 2

OBSTACLES TO THE IMPLEMENTATION OF ENERGY CONSERVATION LAND USE STRATEGIES

| | Cities* | Towns and Villages* | Townships* |
|---|---|---|---|
| Expertise | 83 | 100 | 100 |
| Funds | 50 | 73 | 89 |
| Higher priority activities | 50 | 50 | 83 |
| Manpower | 33 | 40 | 56 |
| Public resistance | 20 | 29 | 28 |
| Political resistance | 17 | 16 | 4 |
| Other | 17 | 0 | 0 |

* Percentage of respondents. Totals will exceed 100% because of multiple answers.

To determine where municipal planning priorities lie, municipalities were asked to indicate the three major planning concerns in their municipality. The data are shown in Table 3. In cities, the primary concerns are industrial and commercial development, redevelopment, and rehabilitation of the existing housing stock. Towns and villages rank as their highest priorities, industrial and commercial development, sewage treatment and new housing development. The townships' priorities are preservation of farmland, industrial and commercial development and the natural environment. Energy is a very low priority with all municipalities at the present time.

Some public and political resistance to a program of energy conservation is inevitable (8), but these factors are not as constraining as the logistics of implementation. However, public resistance is consistently suggested as a greater constraint than the resistance of municipal councils.

TABLE 3

PLANNING PRIORITIES OF MUNICIPALITIES

| | Cities* | Towns and Villages* | Townships* |
|---|---|---|---|
| Industrial/Commercial Development | 67 | 75 | 55 |
| Sewage Treatment | 17 | 50 | 33 |
| New Housing | 17 | 45 | 32 |
| Preservation of Farmlands | 17 | 0 | 77 |
| Recreation | 0 | 25 | 37 |
| Natural Environment | 17 | 15 | 37 |
| Transportation | 17 | 5 | 19 |
| Energy | 17 | 15 | 18 |
| Redevelopment | 50 | 30 | 32 |
| Water Supply | 17 | 10 | 10 |
| Heritage Preservation | 17 | 0 | 0 |
| Housing Rehabilitation | 33 | 25 | 14 |

* Percentage of respondents. Totals will exceed 100% because of multiple answers.

3.3. Willingness and Motivation

Three questions were used to gauge the willingness of municipalities to implement energy planning. These represent different degrees of commitment. As a minimum level of commitment, municipalities were asked whether they would implement provincial guidelines on energy conservation: 100% of cities, 86% of towns and villages, and 80% of townships indicated that they would. This was considered a minimum level of commitment because the initiative for implementation and the effort of developing guidelines would be undertaken outside the municipality; the municipality must still decide to implement these guidelines. At a higher level of commitment, municipalities were asked if they saw a role for the municipality in promoting energy conservation: 100% of cities, 82% of towns and villages, and 74% of townships indicated that they did. The final question asked whether the municipality intended to consider energy issues in development approvals or future Official Plan and zoning by-law amendments: 100% of cities, 74% of towns and villages, and 69% of townships affirmed this intention.

These figures indicate a fairly high level of concern and commitment in municipalities, but is this finding a result of intrinsic or extrinsic motivation? Municipalities were asked which groups (internal or external to the municipality) have effectively encouraged municipal concern for energy conservation. Table 4 displays these data. In all cases, external groups were indicated as providing the greatest encouragement.

TABLE 4

AGENCIES WHICH HAVE EFFECTIVELY ENCOURAGED CONCERN FOR ENERGY CONSERVATION AMONG PLANNING DIRECTORS

| | Cities* | Towns and Villages* | Townships* |
|---|---|---|---|
| Federal Govt. | 33 | 50 | 74 |
| Prov. Govt. | 50 | 70 | 95 |
| Professional Associations | 17 | 25 | 34 |
| Municipal Council | 33 | 50 | 47 |
| Local Residents | 17 | 30 | 30 |

* Percentage of Respondents. Totals will exceed 100% because of multiple answers.

Finally, it was reasoned that if municipalities were intrinsically motivated to implement energy conservation, they would be engaged in an active search for information. Municipalities were asked which groups they had contacted for information on energy conservation. Table 5 displays these data. The cities show the most active search with towns and villages, and especially townships, inactive by comparison.

TABLE 5

GROUPS WHICH MUNICIPALITIES HAD CONTACTED FOR INFORMATION ON ENERGY CONSERVATION

| | Cities* | Towns and Villages* | Townships* |
|---|---|---|---|
| Federal Government | 50 | 30 | 12 |
| Provincial Government | 83 | 56 | 15 |
| Professional Associations | 50 | 6 | 0 |
| Municipal Council | 33 | 6 | 4 |
| Consulting Agency | 0 | 11 | 4 |
| Universities and Colleges | 33 | 0 | 0 |
| Others | 17 | 6 | 4 |
| None | 17 | 30 | 77 |

* Percentage of Respondents. Totals will exceed 100% because of multiple answers.

## 4. DISCUSSION

In general, municipalities have the legislative authority to implement the energy conservation land use planning strategies. Many municipalities, however, are reticent to use legislation which was not expressly enacted to implement energy planning for this purpose. A comment of many respondents was that they would consider energy conservation in land use planning if it was backed by legislation (9) In addition, the use of planning legislation for energy conservation has not been tested in the courts and some uncertainty exists whether this use will be upheld. (9,10)

Municipalities which do not currently have a full range of planning tools are predominantly small and rural. For example, 46% of those municipalities without zoning by-laws have a population less than 1,000 and 83% have a population less than 2,000 (1976 census data). However, the majority indicate that they will adopt a full range of planning tools within five years. This finding is consistent with the rate at which municipalities in eastern Ontario have been adopting these tools. For example, 54% of municipalities in eastern Ontario have adopted an Official Plan within the last five years.

Three constraints are consistently reported by municipalities as the major obstacles to implementation of energy planning: lack of expertise, lack of funds and higher priority activities.

The lack of expertise was a major constraint to implementation. This is particularly true of small municipalities. The same pattern of response may be seen for lack of funds and higher priority activities. Energy planning is largely seen as ancillary to the land use planning function of municipalities and as the size of the municipality, and municipal staff, decreases, planning efforts are increasingly restricted to those activities required by provincial fiat or those essential to municipal functioning. The ranking of planning priorities indicates that energy ranks lower in smaller municipalities than in larger municipalities.

Consistent with those observations, the willingness of municipalities to engage in energy planning declines from cities to towns and villages to townships. This pattern is most notable when municipalities were asked if they intended to implement energy considerations in their planning practice. All municipalities have received primary encouragement to develop a concern for energy conservation from the province. The Province has used an identification strategy (5) to attempt to change municipal behaviour. The primary emphasis has been on creating attitudes favourable to energy conservation. The effectiveness of this strategy varies across types of municipalities. If municipalities had developed such an attitude, it would be expected that they would be actively engaged in a search for means of implementing energy conservation in their planning practice. In fact, 17% of cities, 30% of towns and villages, and 77% of townships had not contacted anyone in search of information.

## 5. CONCLUSIONS

Municipalities have the legislative authority to implement energy conservation land use planning strategies. Municipalities must, however, be given encouragement to use legislation innovatively and be supported if this use is challenged in court.

The major constraint to implementation of energy conservation in land use planning is a lack of technical expertise among municipal planners. Municipal planners look to all levels of government and the planning profession to provide the educational programs which are necessary. (8) Many universities may also be able to contribute to the continuing education of planners, for example, by sponsoring conferences and preparing Proceedings as educational materials. (11)

A second constraint to implementation is the lack of funds. If energy conservation is seen as an ancillary activity of the planning profession then fiscal and manpower resources may be real constraints; however, as will be suggested below, this need not be so.

Municipalities currently face higher priority issues on their planning agenda and cannot undertake energy planning at the expense of these issues. Energy planning is not a distinct function which can be implemented as an isolated policy. Energy efficiency is a situation which must be applied in all phases of the planning function. A fundamental failure of efforts to encourage energy conservation has been to ignore the current planning priorities of municipalities. It can be shown that energy considerations are complementary with these priorities. For example, rural municipalities concerned with the preservation of farm land can use energy policies to require the development of new housing in dense-centered nodes rather than scattered across valuable farm land. Cities, towns and villages concerned with industrial/commercial development may use energy considerations to identify and assemble land which is optimally located for such development. Industrial parks may be assembled and explicitly designed for energy cascading and other energy conservation technologies.

Municipalities are willing to implement energy conservation measures in their land use planning practice. The level of willingness varies across types of municipalities and depends on the level of commitment required of them.

Energy conservation is such a fundamental and vital aspect of planning for the future that the success of its implementation cannot be left to chance. The data presented in this paper suggest that different approaches are required in large and small municipalities. Larger municipalities have accepted the challenge of conserving energy through land use planning, but require the expertise and funds to implement the available strategies and technologies. Smaller municipalities have yet to recognize the benefits of a program of energy conservation. This situation requires further education and also a change in the manner in which energy planning is promoted. (10) Rather than a separate function of municipal planning, energy conservation through land use planning should be integrated with other planning priorities which currently dominate the agenda of all municipalities in eastern Ontario.

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# ASSESSING SOLAR AND CONSERVATION RETROFITS IN HOME REHABILITATION PROGRAMS FOR LOW AND MODERATE INCOME PEOPLE

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## ABSTRACT

A two year study was conducted by the Ann Arbor Energy Office where five solar/conservation demonstrations were conducted on the homes of low income clients in the city's Community Development Department's Home Rehabilitation Program. This paper summarizes the results of that study.

## I. INTRODUCTION

As fossil fuel prices continue to rise, families with low or moderate incomes are continually pressed to make a choice between heating and eating. In Ann Arbor, Michigan approximately 37 percent of the city's households have low or moderate incomes.[1] These families currently spend over $17 million for nonrenewable energy sources; an average of $995 per household. If no further energy efficiency measures can be afforded by these households this annual expenditure could rise to over $50 million by the year 2000; $2816 per household.[2] Not only can these rising prices decrease the amount of spendable income of those who currently have *low incomes they can actually increase the size* of the city's low income population. As fuel prices rise the proportion of local residents' incomes that must go to pay for fossil fuels also rises. Clearly, there is a need to insulate this population from these rising costs. Not only will it improve their quality of life but it is a wiser investment for government when compared to the millions of dollars expended in Michigan alone for fuel payment assistance.

Over the past six years of the city of Ann Arbor's Community Development Department has operated a Home Rehabilitation Program (HRP) to upgrade the structural quality of low and moderate income family residences. Over the past two and a half years the program has expanded its energy component. A client may receive a deferred loan[3] or a low interest loan of up to $6000 for energy improvements and up to $15,000 per project in total.

Two and a half years ago the City received a Midwest Appropriate Small Grant from the U.S. Department of Energy to explore methods of retrofitting solar and conservation measures to the homes of low and moderate income people through the HRP. The goals of the project were:

- To identify feasible solar/conservation options for Ann Arbor's low income housing stock;
- To develop methods to analyze and design solar/conservation for these homes;
- To execute construction of solar/conservation demonstration in the context of the existing HRP;
- To establish a site evaluation method, model *solar/conservation measures and a means of* administering them.

The University of Michigan's School of Architecture was subcontracted to perform certain aspects of the project. But, only one of the demonstration retrofits was implemented as orginally recommended by the University due to cost considerations. The University's ARL is currently completing the monitoring aspect of the project and will soon have detailed information on the performance of each solar energy system installed as well as actual data on the level of energy savings achieved at each demonstration site.

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[1] Ann Arbor Housing Survey, 1982. Low and Moderate income is defined for the purposes of the Home Rehabilitation Program as 80 percent of the City's median income.

[2] Ann Arbor Community Energy Profile, 1983. Dollar projections assume annual fuel escalation rates in 1982 dollars (not including inflation) as follows: natural gas: 8.4 percent; electricity: 4.5 percent; fuel oil 2.5 percent.

## 2. DESCRIPTION OF DEMONSTRATIONS

The six demonstrations that comprise this project are summarized in Appendix A. Total conservation/solar retrofit costs ranged from $850 to $14,000, with total estimated energy consumption reductions ranging from 20 to 76 percent, and project payback periods ranging from 2.5 to 6.5 years.

## 3. DEMONSTRATION ANALYSIS

In analyzing the applicability of the solar conservation items used in these demonstrations as ongoing additions to the HRP several criteria were developed. The options would need to:

- Utilize conservation/solar measures that are simple to apply;
- Cost less than $6000, preferably in the $2,000 to $4,000 range, and have a reasonable payback period (2 to 7 years);
- Include measures/designs for clients with limited mobility;
- Include options for sweat equity clients;[3] and
- Include methods for considering more sophisticated solar projects as components of larger rehabilitation projects.

Of the demonstrations completed six basic design options were considered as they related to these criteria:

- Thermosiphoning air panels
- Sunspace/greenhouse
- Direct gain/night insulation
- Major conservation measures

### 3.1 Thermosiphoning Air Panel Systems (TAPS)

This measure is simple to specify and install, and can be adapted to a variety of situations. It is inexpensive and performs well. Clients with limited mobility do not have to concern themselves with night insulation or any other special considerations on a daily basis. Maintenance tasks are infrequent enough to be easily provided by an outside service organization or a paid handyperson (i.e., cleaning glazing, checking vents). While there are certain TAPS designs that can be easily built by the sweat equity client, this technology can best be provided through the HRP by a competitive bidding process for contractor installation.

Solar distribution and contracting specialists are using primarily fan-assisted dual duct TAPS that are guaranteed and installed by trained, experienced personnel. These features are assets to the HRP where most work must be contractor installed by competitive bid. When this option is selected it will be important, however, to contract directly with these specialists or provide a list of certified solar installation specialists that general contractors must work with. This may assure better quality work than was achieved with the site built demonstration projects. The difference in cost between site built systems and those installed by solar installation specialists is insignificant. General contractors have quoted prices of $25-35 per square foot-installed for repeating the construction of the TAPS specified in the demonstration project and local solar TAPS distributors/installers are quoting similar prices.

### 3.2 Sunspace/Greenhouse

The sunspace/greenhouse design utilized in Demonstration #6 was a simple 6-section modular structure which would be easily specified for contractors. It is also a simple enough building to be site built by a qualified sweat equity client. The design also lends itself to being premanufactured in six sections that could be assembled on site in about half a day. Demonstration #6 was a rental property where the occupants preferred not to invest in wall insulation and other permanent conservation features since they did not own the home. This option was especially attractive to the tenants since the sunspace/greenhouse can be disassembled and moved if need be. This option requires a high level of user participation.

### 3.3 Water Wall

This design was unique to this residence and could not be replicated simply. The project was expensive, and the components used were not readily available. More research would be needed to identify a model water wall option for the HRP.

### 3.4 Direct Gain/Night Insulation

In many homes there is currently a significant amount of south facing glass. In these cases a good conservation approach and night insulation

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3 Sweat equity clients borrow money for materials and provide the labor aspect of their home rehabilitation project themselves.

on all windows, used effectively, can offer substantial energy savings. The operation of this night insulation, however, will require a moderately active user.

Where south facing glass would be added the costs of this option are more of a concern. Such projects would be best implemented where substantial rennovation was already being considered. Such projects would require contractor installation in most cases.

### 3.5 Major Conservation

Where solar site access is inadequate or where there is a substantial need for conservation measures before solar can be considered. the HRP is likely to recommend that the project focus on the conservation measures that can be implemented. Study is currently being conducted by the HRP on door fans and hand held infrared scanners as tools to assess the quality of conservation in a home before specifying any measures.

## 4. PROGRAM METHODOLOGY FOR ASSESSING/IMPLEMENTING SOLAR/CONSERVATION OPTIONS

There are changes needed in the Home Rehabilitation Program from the point of the initial to the point of the final inspection if additional conservation and solar measures are to be included as a regular feature in HRP. A proposed format for these changes is described below and is currently being considered by the department.

### 4.1 Solar Site Analysis/Home Conservation Inspection

A residential conservation service audit (RCS)[4] from the local/utility company is currently requested for each program client. A rehab inspector visits the home to determine what conservation recommendations from the audit actually need to be implemented. To improve the solar/conservation component of this inital inspection four additional tasks would be accomplished by the inspector:

- The inspector would conduct a solar site reading using one of the many solar access measuring devices currently on the market.
- The inspector would complete a checklist of solar considerations which would include information about the users and options applicable to that location.
- A door fan[5] would be employed to determine the air changes per hour and the main sources of infiltration, and would be followed up with appropriate measures to reduce this infiltration by an Home Energyworks Team.[6]
- A hand held infrared camera would be employed to locate hot spots in existing insulation jobs and to aid in the identification of other heat loss area in conjunction with the door fan.

### 4.2 Determining Options

The solar/conservation options to be considered would be approved, simple, low cost systems unless special circumstances can be identified. A final set of solar/conservation options would be submitted to the client for approval. Specifications would then be written for the bidding process (except in the case of sweat equity projects). If there is potential for a solar retrofit or for additional conservation items a rehab specialist can complete a simplified version of the solar design analysis methodology as developed by J.D. Balcomb or a similar measurement methodology. This method can be manually completed, and eventually computerized. All the main inputs would be easily available from the RCS utility audit and the solar checklist completed at the initial inspection.

At least one inspector, or some other employee of the program, would need to be trained to perform this task. This inspector should keep up with changing product lines (i.e., glazing, materials, insulation products) on the market to improve standard specifications for solar and conservation options.

### 4.3 Retrofit Installation

The majority of solar/conservation retrofits will be installed by general contractors. The results of the demonstrations indicate, however, that solar projects should be directly contracted to solar specialists when possible.

### 4.4 Final Inspection

Final inspections by the rehab inspector are the basis for payment to the contractor for work completed. The door fan and infrared scanner can again be used to check the quality of the work completed before payment.

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4 The Residential Conservation Service audit is a home energy analysis conducted by the large utility companies.

### 4.5 Client Education

Each client will have a different level of interest in the solar/conservation retrofit design for her/his home. No matter how little participation is required each client will need to be educated about its operation. Information about changes in behavior that can save energy (i.e., turning down the thermostat at night, resetting a clock thermostat, closing off rooms in the winter, etc) as well as operating and maintaining conservation and solar measures must be provided. Standard pamphlets have been developed and used as a part of the demonstration project. In using them the importance of one-to-one educational sessions with the clients was observed. The educational component of the City's Home Energyworks Program could be modified to take care of this need.

### 4.6 Monitoring

An ongoing monitoring element is needed to assure that energy savings are being achieved and to improve the program over time. This can be done using an annual analysis of energy savings and cost-effectiveness of each project, and consistant follow up with clients. This will be especially important during the first few years to assure that maintenance, ongoing performance and any needed repairs are given adequate attention.

Additional demonstrations should also be staged over a two to three year period to determine the relative savings of various solar/conservation measures. The stages would consist of:

Year 1: Furnace improvements/replacements, clock thermostats and general educational program.
Year 2: Conservation Improvements.
Year 3: Solar Improvements.

The effectiveness of the first 6 demonstrations is currently being monitored by the ARL.

Once this analysis is completed the HRP can refine their ongoing monitoring methodology based on the results of this initial analysis.

## 5. CONCLUSIONS

The majority of energy weatherization programs currently operated by local governments are aimed at achieving the first 20 to 30 percent savings in an average home. While these programs are vitally important to protect the short term needs of low income people this approach will not protect these people for long. Natural gas prices in Michigan are currently rising at a rate of over 20 percent per year. If we are to actually dissolve the need of low income people to make a choice between heating and eating greater savings are needed. Fifty to 75 percent savings, as are projected from the demonstration projects, and provide a much greater degree of energy self sufficiency for these people so that in a few months or years they are not faced with the choice.

## 6. ACKNOWLEDGEMENTS

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- Ecology Center of Ann Arbor, Home Energy Works Program, with special assitance from James A. Frey, Program Coordinator.
- Fred Gerow, Consultant in Appropriate Technology, responsible for the design Demonstration #2 and design assistance on Demonstations #3 and #4.
- Princeton Energy Partners, with special assistance from Don Nelson in demonstrating the use of the door fan and hand held thermoscanner.

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[5] A door fan is a tool which creates either a "suction effect" within a house, either drawing all the air out of the house or pushing air into the house. Utilizing a calculation based on the speed of the fan and the pressure differential between the inside and outside of the house this fan measures air changes per hour of the structure. It exaggerates existing leaks so that they may be easily found utilizing a thermoscanner or a smoke gun. A thermoscanner is a hand held device which photographs heat as it lost from the structure.

[6] The Energy works Home Visit team is a non-profit weatherization program funded by the City's Community Development program. Utilizing approximately $100 to $150 in low cost materials they are able to achieve anywhere from a 15 to 30 percent reduction in energy consumption in residential structures. These crews were employed at most of the demonstration sites.

- University of Michigan - Architectural Research Laboratory, with special assistance from the late Dr. Willard Oberdick, and Dr. HoFu Wu.

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## 8. APPENDIX A: TABLE OF SIX RESIDENTIAL SOLAR/CONSERVATION DEMONSTRATIONS

### 8.1 Demonstration #1: Stoneybrook Neighborhood

Existing Conservation Measures
Furnace improvements, flue damper, clock thermostat, wall insulation, attic insulation, storm windows.
Added Conservation Measures
Insulating window treatments on all windows, floor insulation, Energyworks Home Visit, additional attic insulation.
Added Solar Measures
80 square feet of dual duct type thermosiphoning air panels. Night insulation on existing south facing windows.
Client Profile
Head of household cannot lift arms over head due to heart condition.
Administrative Concerns
Problems with contractor quality relating to window treatments.
Performance
Solar Savings Fraction: .3; total annual savings: 70.9 GJ (67.19 MMBtu ); reduction in annual energy consumption by 76 percent.
Cost Effectiveness
Total Cost: $4,330; simple payback: 6.5 years.
Comments
Due to client's health condition all window treatments required use of pulley systems at easy access. TAPS required minimal maintenance and were, thus, chosen as a suitable measure.

### 8.2 Demonstration #2: Spring St. Neighborhood Home

Existing Conservation Measures
Storm windows, attic insulation, furnace improvements.
Added Conservation Measures Energyworks Home Visit
Wall insulation, inside storm windows, perimeter/basement insulation treatment, additional attic insulation.
Added Solar Measures
110 square feet of thermosiphoning air panels consisting of 45 square feet of U-tube collectors and 56 square feet of dual duct collectors. A small ceiling fan was installed on the second story of the stair well to improve air/heat circulation.
Client Profile
Four member family - Willing to actively participate with solar project.
Site Limitations
Second story solar access only.
Administrative Concerns
Problems with contractor quality relating to solar system.
Performance
Solar Savings Fraction: .16; total annual energy savings: 204.6 GJ (193.9 MMBtu ) annual fuel consumption by 75 percent.
Cost Effectiveness
Total Project Cost: $4,769 simple payback period: 3.5 years

### Demonstration #5: Wall St. Residence

Existing Conservation Measures
Attic Insulation
Added Conservation Measures
Wall insulation, additional attic insulation, perimeter/basement insulation improvements, Energyworks Home Visit, insulating window treatments on all windows.
Solar Measures
Night insulation on existing south facing windows
Client Profile
Senior citizen with limited mobility.

### 8.4 Demonstration #4: Fountain St. Residence

Existing Conservation Measures
Attic insulation, storm windows, new furnace, clock thermostat, flue damper.
Added Conservation Measures
Wall insulation, additional attic insulation, perimeter/basement insulation improvements, Energyworks Home Visit.
Added Solar Measures

110 square feet of dual duct thermoisphoning air panels. Ceiling fan installed for improved heat circulation.

Site limitations
Second story solar access only.
Client Profile
Single senior citizen with limited mobility living with a son who works nights.
Administrative Concerns
Contractor quality concerns relating to solar component.
Performance
Solar Savings Fraction: .15; total savings: 118 GJ (111.89 MMBtu) ; reduction in annual energy consumption by 66.3 percent.
Cost Effectiveness
Total Cost: $2,970 simple payback period: 3.5 years.

8.5 Demonstration #5: Old West Side Historic District Duplex

Existing Conservation Measures
Attic insulation, storm windows furnace replacement
Added Conservation Measures
Additional attic insulation, basement/perimeter insulation treatment, floor insulation, Energyworks Home Visit.
Added Solar Measures
Sunspace addition (4 ft wide) with water wall and moveable night insulation. 120 square feet of glazing area.
Client Profile
Single occupant/owner and one tenant in adjoining apartment. She regulates the amount of direct gain and stored energy by adjusting the moveable insulation depending upon her schedule and heating needs.
Administrative Concerns
This system is prohibitively expensive for consideration as part of the ongoing Home Rehabilitation Program. Guidelines require that the expensive per home be under $6000.
Performance
Solar Savings Fraction: .17 total project energy savings: 200.5 GJ (190 MMBtu ); reduction in annual consumption by 59.9 percent.
Cost Effectiveness
Total project cost: $13,997; simple payback period: 6.5 percent.
This system is located in an historic district and demonstrates that solar systems can be tastefully applied without inhibiting the historical value of the home. In this case it was added to the back portion of the home.

8.6 Demonstration #6: Rental Demonstration

Existing Conservation Measures
Storm windows, attic insulation, perimeter insulation
Added Conservation Measures
Floor insulation over crawl space, low cost/no cost techniques such as provided by the Energyworks Home Visit program, including a third plastic glazing on all windows.
Solar Measures
Modular solar green house with 144 square feet of glazing area used for space heating and food production.
Administrative Concerns
This project was not formally part of the demonstration project. It has added to the analysis, however, so that another system design might be considered.
Performance
Solar Savings Fraction: .11; total project energy savings 36.3GJ (34.43 MMBtu); reduction in annual consumption by 20 percent.
Cost Effectiveness
Total project cost: $567.50 after tax credit; simple payback period: 2.5 years.
Comments
The price of the sunspace/greenhouse includes night insulation. Food production aspects were not considered in the cost effectiveness analysis, although they can be substantial.

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# COMMUNITY ENERGY PLANNING AND MANAGEMENT: GRASS ROOTS STRATEGIES FOR IMPLEMENTING SOLAR AND CONSERVATION PROJECTS

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## ABSTRACT

This paper provides an overview of community energy plans and their implementation, focusing primarily on efforts in the north central United States. It includes case studies and a proposed methodology for instituting a successful community energy plan.

## 1. INTRODUCTION

What do conservation and solar professionals have in common with local governments? There seem to be many mutual interests: building codes and inspections, site plan approvals, zoning regulations, improving the local economic climate, an interest in desirable financing terms for energy projects, the provision of least-cost energy resources...to name a few. Over the past few years cities and counties have begun to take their responsibility for protecting the economic climate of their communities more seriously, and in doing do they have begun to seek ways of encouraging the use of energy efficiency and renewable resource technologies. They have established energy offices, conducted studies to assess local energy consumption patterns, developed long and short range energy plans to improve local energy self sufficiency, and have implemented a host of programs to demonstrate, finance and monitor the use of energy efficiency and renewable energy technologies. Since the early 1970s hundreds of communities have used numerous approaches for encouraging energy efficiency improvements within their communities, and they have found good reasons for continuing to do so.

This paper is an attempt to outline one workable methodology for successful community energy planning and management, and to provide examples of workable community energy projects. It draws extensively from the experience of Ann Arbor, Michigan where I have had the most direct experience as well as from other North-Central U.S. communities and from communities from across the country.

As with any planning or problem solving effort there are five major components to developing and implementing a community energy strategy:

- Assessment of the Local Energy Problem;
- Development of an Energy Planning/Policy Framework;
- Identification/Implementation of Specific Energy Programs; and
- Maintaining/Evaluating/Modifying Energy Programs

### 1.1 Assessment of the Local Energy Problem

In order to develop an effective energy strategy a community must first determine:

- Where energy is used (i.e. residential, commercial, municipal institutional, industrial and other sectors);
- What type of energy is used (natural gas, coal, fuel oil, etc.);
- What the main end uses of energy are (i.e., space heating, water heating, etc.);
- How much energy resources cost;
- What the potential is for local use of energy efficiency and renewable energy technologies;
- What the patterns of energy use and price will look like over time if no efficiency measures are taken; and
- What these patterns would look like given various levels of committment to energy alternatives.

In Ann Arbor, Michigan, a community of

100,000 residents, over $184.24 million will be spent for fossil fuels this year. If no further energy efficiency measures are implemented this annual figure will increase to over $406.1 million by the year 2000. With this rate of fuel escalation Ann Arbor citizens will spend a total of $5.25 billion for fossil fuels by the year 2000. This $5.25 billion is equivalent to about 46 percent of the current expenditure for all heating fuels in the entire state of MI.

It is estimated that approximately 80 percent of the fossil fuels used in the state of Michigan come from other states and countries. That is, for each dollar spent of fossil fuel 80 cents leave the state and a significant portion leaves the nation. For each dollar spent on energy efficiency improvements not only does the dollar stay in the local/state economy, it provides jobs, economic growth and energy self sufficiency. We know that, in Michigan, this dollar turns over at least twice. A dollar used to purchase insulation is used to pay an insulation contractor. That insulation contractor may use it to buy groceries, and the grocer to pay off his car, thus paying the wages of an auto worker. The more times this dollar turns over within a specific community the healthier the local economy.

Analysts in Minnesota have determined that in their state solar/conservation dollars turn over at least 2.43 times as compared to 1.4 for natural gas and even less for other nonrenewable energy resources. Studies in the District of Columbia, population 620,000, and Carbondale, IL, population 30,000, have traced the path of dollars spent for energy within a community and have concluded that only 15 cents of the energy dollar return to benefit the local economy in any manner. That is, only 15 cents is re-spent in the form of salaries and wages to local residents, as profits and dividends to local businesses or as tax revenues to local government.

These statistics and arguments can be startling as well as convincing to local government officials, local developers, and financiers. The development of a community energy profile, as conducted in the cities and counties mentioned above, is often the catalyst for local energy planning, projects and programs. Early efforts to develop these statistics involved an extensive research effort. However, more recent efforts have relied on the work of previous communities. In the past two years a number of reliable studies have been completed which provide national or state-wide statistics that can be stepped down to the locality. State energy offices often have statistics that can be useful as do local utility companies. The generation of these profiles is easily computerized which provides a simple way to update this information at a low expense. The community energy profile can tell us where to focus our efforts to achieve the greatest energy and dollar savings, and can be indispensible in educating decision makers and community members on the importance of a grass roots community energy planning and management strategy.

### 1.2 Development of an Energy Planning and Policy Framework

To achieve the reductions identified in the community energy profile most successful cities and counties have developed some type of community energy plan or strategy. Some of the most successful of these plans have been based on a model that maximizes citizen participation. In Ann Arbor, MI over 100 people were involved in one of five task forces or a steering committee in the development of the Ann Arbor Energy Plan. A current advisory committee oversees its implementation. St. Paul, MN created the St. Paul Energy Committee of 100+ to develop a series of sub-committee reports and recommendations for their local government. Portland, OR, Carbondale, IL, and many other communities have developed citizen committees to focus the development of a community energy plan. This approach assures that there is a constituency in the locality willing to support the resulting program recommendations, and also assures that its direction is in line with community wants. A counterpart to these committees, in most cases, is a professional staff to coordinate efforts and provide technical expertise.

While a number of approaches to energy plan development have been taken the resulting policies and programs from most of them have had two main consequences:

- They modify/add/delete existing policies or activities of local governments in an attempt to alleviate barriers and provide opportunities to encourage energy

efficiency (i.e., building code or zoning ordinance revisions).
- They lead toward what might be called a "municipal energy service authority," or a "local energy efficiency network."

While the names and responsibilities that describe examples of this second result may vary, the function is one of coordinating ways to provide energy conservation measures, energy efficiency equipment, and renewable energy technologies to appropriate places within the community. While some communities may operate one project or a few simple programs the fact remains that they are providing an alternative energy resource. Just as a public utility might generate electricity to meet local needs these new services encourage or provide an alternative form of energy service delivery.

This second consequence is often the more potent of the two, and can by its implementation serve as a catalyst for implementing those revisions needed by the city legislation/policy. As with any company, utility or public authority there are 5 main elements to a successful operation: monitoring/forecasting/planning, technical assistance, financing, promotion /marketing/education, and service delivery/coordination. The number of projects that can fall within these five areas is more than can be achieved by any one community. Yet, in identifying one or more projects within each of these five elements a more balanced approach toward reaching long range goals can be had. Technical assistance programs will not operate well without financing. No programs will run effectively if they are not carefully coordinated. No program will operate well if the public is ill-educated. These 5 elements can be used as a bench mark to evaluate the effectiveness of any program package.

1.2.1 Monitoring/Forecasting/Planning

This element can include efforts to:
- Forecast and assess long and short term energy supply and price;
- Identify community energy flows by sector;
- Assess the impact of energy efficency technologies and alternatives;
- Compare investments based on their energy impacts; and
- Identify programs which will achieve community energy efficiency.

1.2.2. Technical Assistance

This element can include the following four components:
- Development of a system to assess/rate buildings, alternative energy projects and other energy intensive processes;
- Development of the ability to provide design assistance for energy projects;
- Assure the availability or residential and commercial energy audits, consumer protection services and technical information; and
- Provide updated codes, ordinances and other regulations as needed to assure energy efficiency in buildings.

1.2.3 Financing/Revenue Generation

An inability to finance energy improvements within the community is probably the greatest barrier to achieving community energy self sufficiency. The objective here is simple:
- To identify and implement arrangements which will lever dollars for energy efficiency improvements in buildings, alternative energy production projects and other energy intensive processes. Possibilities to explore include tax shelters, lease agreements, power sales, investment financing and tax exempt financing.

1.2.4 Education/Promotion/Marketing

Whether it is called promotion, education or marketing, this is the element which brings the information we wish to share into the eye of the public. It may be focused on a particular group of decision makers or may involve wide spread disemination of energy information to the general public. Four key components of an education/promotion/marketing element include:
- Educational services within the community (i.e., lectures, conferences, displays, individual counseling, etc.); and
- Promotion strategies to encourage community energy efficiency (i.e. displays, media campaigns);
- Forums on energy issues with decision making groups (i.e., planning commissions, city/county commissions, the finance community, developers, economic development corporations, downtown businesses, etc.)

1.2.5 Coordination of Services/Service

There are many areas of energy service delivery. Any program that assists the public ultimately results in

some type of service delivery. A local government may act as a coordinating agency for programs that are provided by utilities, private agencies, public groups, etc., or they may actually deliver the service. In any case this element consists of:

- Assuring that existing energy programs are adequately coordinated and promoted;
- Assuring that a referral functionis available to put people in touch with existing services; both private and public, they may need; and
- Identifying services that need to be fulfilled.

## 1.3 IDENTIFICATION/IMPLEMENTATION OF SPECIFIC ENERGY PROGRAMS

The field of community energy management relates to energy improvements in buildings, transportation systems, industrial processes and all other energy related aspects of the community. This section describes a variety of programs currently being used in communities to encourage or implement building energy conservation and the use of renewable energy resources that creatively blend the elements described above.

### 1.3.1 The Minneapolis Energy Bank

The city of Minneapolis issued $2.75 million in tax exempt revenue bonds for the soTe purpose of providing loans to homeowners. They have more recently issued an additional $6.8 million in formal revenue bonds, and have provided over 2000 loans so far. In addition they are currently developing a Rental Energy Bank to provide low interest money to rental properties of up to 4 units per structure, using taxable bonds. The interest rate will be written down using federal dollars in the form of an Urban Development Action Grant (UDAG). The Minneapolis Energy office provides audits, client screening and promotion to assure program success. They plan to add a service designed to protect clients from unqualified local contractors. The two energy bank programs are capable of making loans simple to obtain and provide loans at about a 10 percent interest rate.

### 1.3.2 Massachusetts Home Energy Rating System

A non-profit institution, Mass-Save, has been providing home energy ratings to individuals in several counties in Massachusetts including Plymouth, Hampshire and Franklin. The rating is a unique approach to providing the Residential Conservation Service Home Energy Analysis (RCS). (RCS is a program where all major utility companies in the U.S. must provide an energy audit to their residential customers under current federal legislation.) There are four types of information provided: the heating efficiency score, the estimated annual heating cost, energy features and estimated improvement costs for the dwelling unit. Values are given for the house at the time of the rating and what the house would be like in an energy improved state. The rating is used by homeowners, sellers and buyers to understand their home's current energy efficiency; how it can be improved; likely costs and savings; and to market the property or obtain a more desirable rate on a home improvment loan. Real estate brokers can more quickly assess building energy efficiency and use that information to more easily answer buyer's questions, improve marketing and obtain the best house selling price for both buyers and sellers. Mortgage lenders who sell mortgages to the secondary mortgage market can qualify purchasers of energy efficiency homes with a higher debt to income ratio. When a mortgage customer has an energy rating on the home the lender knows that the customer has considered the cost to heat the home. Some MA lenders are increasing mortgage loans to cover the energy improvements covered in the rating. This can result in a small additional profit and will cushion the borrower from the shock of ever increasing heating bills.

Real estate appraisers can judge building energy efficiency in order to extract the energy value from sales and to use it in the adjustment process. An energy efficiency rating system can be an excellent technical assistance project for a community. The audit/rating is computerized and simple for the user to understand. It easily dovetails into available financing and education programs within a community, and provides a strong market mechanism for encouraging building energy efficiency in the residential sector. With commercial energy audits currently being developed by utility companies across the country a similar rating system could also be attached and utilized in the commercial sector as well.

### 1.3.3 Oceanside, California: A Municipal Solar and Conservation Utility

In 1979 the city of Oceanside, CA developed a Municipal Solar and Conservation Utility. Program elements included: a street lighting conversion project, the retrofit of municipal fire stations with solar water heating systems, a solar loan program for low income residents, development of an energy efficient mobile home park design, development of solar access and other relevent local energy ordinances, establishment of a solar leasing program and the operation of an energy hotline service as an energy information program. One of the more innovative aspects of their effort was a solar/conservation leasing program.

The solar leasing program is a combination of private sector capital investment and public sector consumer protection and information dissemination. The private capital is used to purchase and install the solar systems for lease to clients. In this way a locality can initiate the program with fairly limited funds. Likewise, consumers who participate in a solar leasing program do not have to pay out the up-front capital that is needed to purchase the solar system. They only need sufficient funds to pay relatively low monthly lease payments. The market that can take advantage of solar technologies is, therefore, greatly expanded. The local government role is also substantial:

- To ensure that the solar systems available for lease are good quality;
- To assure that leasing companies who are permitted to participate are, in fact, sound companies;
- To require that leases specify full service and maintenance at no cost to the customer along with other pro-consumer protection lease provisions; and
- To ensure that installers are appropriately licenced and competent.

The private sector provides capital and labor, and the local government provides consumer protection services. The private investor receives a return on investment the contractor provides jobs and enjoys profits; the client receives lower utility bills; and the city has done its jobs to encourage the use of alternative energy resources.

### 1.3.4 Residential Energy Conservation Action Program (RECAP): The Conservation Utility

In many climates there are much more significant conservation needs where a utility concept is useful in encouraging building energy conservation. The RECAP program conducted in New Jersey by the General Public Utilities Corporation (GPU) is a good example of one way such a utility can work. This program provides guaranteed energy conservation in individual homes -- totally free to the homeowner. In RECAP a contractor, under an agreement with GPU, conducts free energy audits, determines which conservation measures are cost effective for each home, and then installs the measures free of charge. For the contractor is paid by the utility for these conservation measures, but not directly, Instead, the utility pays the contractor based upon actual measured energy savings each year for several years.

Paying only for actual measured savings assures the utility that the contractor will install only cost-effective improvements and provides the contractor with the incentive for high quality materials and work. This system also provides the customer and the utility with the strongest guarantee possible: if there are no savings there are no payments to the contractor. Most importantly, however, RECAP provides GPU with a stable, cheaper source of energy: conserved energy. Those btus that are saved by the contracted measures are just as valuable as if they had been mined from the ground.

Municipal utilities could use this concept, while other cities can encourage its use by regional, private utility companies.

### 1.3.5 Muskegon County, MI Shared Savings Project

Officials in the County of Muskegon, MI are experimenting with the concept of shared savings as the basis for financing residential energy improvements. Investment capital is being provided up front to retrofit low income residential dwellings by an investor who then recoups his investment and an additional return by taking a percentage of the energy savings attained by the client. Accurate auditing and monitoring techniques are essential in using private capital for these arragements. However, Muskegon County is using public sector county funds to experiment with the shared savings mechanism to open up yet another avenue for energy improvement financing.

### 1.3.6 Ann Arbor, Michigan: Programs to Encourage Residential Sector Conservation and Solar Utilization

The city of Ann Arbor has developed a number of programs relating to the encouragement of solar and conservation in residential structures.

#### 1.3.7.1 Energyworks Home Visit Program

One aspect of Ann Arbor's home energy improvement effort is a program to provide low cost/no cost home energy improvements. The program has three basic components:

- To provide actual low cost materials to be installed by the participants of the program;
- To provide energy conservation assistance where a trained individual assists participants in installing energy conservation devices; and
- To provide written evaluations and explanations on behavior and measures for the household.

The Home Visit Program was planned in order to provide extensive personal interaction with the occupants, provide individualized recommendations for each household, and direct specialized technical information geared toward the needs of each family. Each home visit involves a 2 person crew spending 3 or more hours in the home and using $75-150 in materials. A comparative analysis of energy consumption data of the participants showed a

10 to 40 percent savings as a result of the visit, with an average of 15 percent. At this rate the program will pay for itself in collective energy savings in less than two years.

1.3.72 Home Rehabilitation Program: Solar/ Conservation Component

Over the past six years the city of Ann Arbor's Home Rehabilitation program has included an energy component in addition to its efforts to upgrade the overall quality of the low and moderate income housing within the city. As of 2 years ago low and moderate income clients have been able to receive deferred or low interest loans for approved major conservation items and solar retrofits for up to $6000. Six solar demonstrations were completed and are being monitored to better determine the most effective conservation/solar retrofit packages for the city's housing stock. Average costs for these retrofits were in the range of $2000-$4000 and savings ranged from 20 to 76 percent. Program funding is a combination of U.S. Dept. of Housing and Urban Development Community Development block grand dollars, State of MI housing improvement loan monies and private bank financing. It is structured as a revolving loan fund.

1.3.7.3 Ongoing Efforts

As in many U.S. cities the city of Ann Arbor has a number of projects to encourage energy efficiency in the larger residential and commercial buildings. Special educational programs and conferences have been sponsored; research on solar access has been completed with an educational program curently being planned; a mandatory retrofit ordinance for residential rental properties was considered on a recent voter ballot, which led to a City Council mandate to develop a comprehensive building energy conservation ordinance/ service package; and many other projects are underway.

## 1.4 MAINTAINING/EVALUATING/MODIFYING ENERGY PROGRAMS

Once a local community energy strategy has been put in place, the number and range of program possibilities is endless. The effectiveness of these programs, however, is only as good as the monitoring of them. The development of a community energy profile is an important first step in this process. as it allows you to monitor the actual extent of savings to the community. Determining actual energy savings relating to specific projects is also essential to justify their funding, improve their usefulness and generate public interest.

In addition to this there must be a mechanism in place for continued community/decision maker input and support. A local commission of citizens and a second committee of government officials are often essential to move energy programs into the implementation stage. The local energy commission can take responsibility for proposing energy programs, and the task force of local government officials can take responsibility for technical research, funding and implementation. This support assures successful programs and allows participation from those who will be involved in the decision making process as it happens instead of after a program proposal is totally researched and completed.

## 2. CONCLUSION

Communities are the stage for larger, more vital markets for energy products, designs, and construction. They are paving the way for more appropriate regulation, information and education that will create a more informed public on energy efficiency possibilities. They are providing consumer education and protection programs that will protect the industry in its development. What do solar and energy efficiency professionals have in common? Lots!

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# RESULTS OF THE MISSOURI PASSIVE COMMERCIALIZATION PROGRAM

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## ABSTRACT

The Missouri Department of Natural Resources, Division of Energy has been conducting a sixteen county pilot passive commercialization program from fall, 1979 to the present. The pilot region composes 9% of Missouri's total population according to 1980 census data. The unique approach to this program was to include all sectors of the commercialization process; builders, bankers, realtors and consumers to name a few. The basic philosophy and program design were outlined in a ASES paper at the 4th Passive Conference. A follow-up paper at the 6th Passive Conference explained the type of home being promoted. The basic goal of the program was to determine what promotional approaches would prove the most useful. A secondary goal of 60 new solar efficient homes did not happen due to the housing slump occurring coincidental to the program.

## 1. INTRODUCTION

Missouri is not an energy producing state; however, it is blessed with large stands of hardwoods and generous solar gain. With rising fuel prices many Missouri residents made the transition from nonrenewables (gas, electricity and oil) to wood heat. This relieved the monthly energy cost burden on many homeowners; yet, it placed a burden on the state's forests. It is easy to see that heating with wood is not always practical, for example, in the larger cities like Kansas City and St. Louis. The job of the State Solar Program has been to enlighten Missouri residents about solar energy and solar applications. The passive solar market, however, was not getting the attention it deserved, so commercialization of passive solar applications was determined to be a useful addition to the solar program. With this in mind the state of Missouri began a program to evaluate promotional techniques and increase awareness in passive solar housing.

## 2. REVIEW OF THE PASSIVE COMMERCIALIZATION PROGRAM

### 2.1 Program Background

It may be beneficial at this time to review some of the background and philosophy of this program. The basic philosophy was to present an accurate picture of passive solar housing to the target audience. This involved dispelling some common misconceptions. First was the need to show that all passive housing was not expensive and that designs were not always contemporary or "far-out." Second was to assure that the homes did perform as advertised and that passive design tools were indeed available to buyers and builders.

Passive housing promotion has been tried by other groups and agencies. However, in most cases the promotion effort was aimed at only one segment of the market either the buyer or the builder. The Missouri Passive Commercialization Program deviated from this approach by addressing all segments of the passive housing market. It does not help to excite home buyers if qualified passive builders are not available to build solar efficient homes. Also, if the builders are informed and ready, but the buyers are unaware of the benefits, passive homes will not be built. Similar results occur if both the builder and buyer are thinking passive housing but the lenders, realtors and appraisers are unaware of how to handle the financing, selling and appraisals.

### 2.2 Program Design

Table 1 is a summary of the different promotional techniques studied and the target groups for each one.

TABLE 1. SUMMARY OF PROMOTIONAL APPROACHES AND THE TARGET AUDIENCES

P - Primary S - Secondary T - Tertiary

| | Technical Assistance | Seminars | Individual Visits | Open Houses | Television Advertising | Brochures | Energy Fairs | Plan Approval |
|---|---|---|---|---|---|---|---|---|
| BUILDERS | P | P | S | P | P | P | S | P |
| LENDERS | P | P | P | S | S | P | T | P |
| REALTORS | P | P | S | P | S | P | T | P |
| APPRAISERS | P | P | P | S | S | P | T | P |
| SUPPLIERS | P | P | S | S | S | P | S | T |
| CONSUMERS | P | S | T | P | P | P | P | P |
| VO-TECHS | P | S | P | P | S | P | T | S |

## 3. RESULTS & DISCUSSION

### 3.1 Results

Taking into account the poor housing market that occurred during the program, the number of new houses built as a result of the Passive Commercialization Program was not a significant indicator of success or failure. However, by looking at each promotional approach and evaluating its relative merit we hope to gain valuable insight into the most effective approaches for future expansion as the housing market improves.

The data accumulated cover the program from fall, 1979 until June, 1983. The major program activities were accomplished between fall, 1979 and September, 1981 at which time the DOE grant was completed. The work accomplished from September, 1981 to the present was mostly follow-up seminars requested by builders. The Passive Commercialization Program was coined "Sun-Way" in 1981 for the television advertising campaign and also with the expectation that Home Builder Associations (HBAs) would pick up the program and continue promotion in the private sector with the State Solar Program acting as an advisory agent only. This has not happened to date.

Table 2 has been prepared as a summary of the results. This is a table of the actual recorded participants for some of the

TABLE 2. SUMMARY OF RESULTS

| | Builder Seminars | Realtor Seminars | Individual Visits | Television Response | Open Houses | "Sun-Way" Brochures |
|---|---|---|---|---|---|---|
| Builders | 310 | | 8 | 95 | 3 | 413 |
| Lenders | 9 | 6 | 22 | | | 37 |
| Realtors | 4 | 88 | 4 | | | 96 |
| Appraisers | 3 | 3 | 12 | | | 18 |
| Suppliers | 57 | | | | | 57 |
| Consumers | 19 | | 6 | 1,001 | | 1,026 |
| Vo-Techs | 14 | | 15 | | 12 | 29 |
| City and Government | 21 | | | | | 21 |
| TOTAL | 437 | 97 | 67 | 1,096 | 15 | 1,697 |

promotions. Some other approaches are not listed due to inaccurate recording. All the approaches are discussed below.

3.2 Discussion

The builder seminars were well received by the builders groups. A total of 21 seminars were completed with an average attendance of 21 participants. This is an ideal size for the type of training seminar that was offered the builders.

Getting the word out, as always, was the major handicap. By working through home builder associations and mailing to every builder listed in the yellow pages, an adequate sampling was assumed. This was not always the case since some HBAs are not popular in some areas and many builders do not list in phone books but work mostly on referrals. A better method to reach this target group would be to utilize an agency or individual from the area that is well received by the builders. This may be a vo-tech school or instructor in some cases or a building materials supplier in others. This does take some time and research of the target area prior to the seminar. All seminars presented now require a minimum number of attendees and an individual or group to publicize and arrange the meeting.

The individual visits to lenders and appraisers were accomplished prior to setting up the realtor, lender and appraiser seminars. Most bankers and loan officers visited were at least somewhat familiar with solar housing and felt that loans on the solar efficient homes would have no trouble being approved. The greatest response during these visits (summer, 1981) was about the economy and that home loans were nonexistent. This situation did not add to the interest level of the people visited. The visits were somewhat time consuming; requiring travel to and from the areas and a visit to each bank, savings and loan and appraiser. From the responses obtained this method was one of the least productive; This may have been entirely due to the existing economic atmosphere.

Five seminars were given for this target audience with an average attendance of 19 participants. This was a slight smaller turn out than anticipated with mostly realtors, who in many cases are also appraisers, attending. The lender group was not in great attendance. The realtor seminars were arranged by local realtor associations and these organizations did a good job of publicizing the sessions.

The open houses were intended to show off the solar efficient or "Sun-Way" home. With the housing slump experienced during the program only three builders held open houses. An additional 12 vo-tech open houses were conducted during the program. The open houses drew large crowds, averaging 100-200 attendees, of curious people and did a very effective job of sparking interest and bringing out the passive concepts in three dimensions. Since housing starts were down not enough homes were built and this method was not as effective as it would have been during a normal housing market.

The concept behind plan approval was to offer the state's moral support to contractors who built solar efficient homes. Similar to the "Gold Medallion" homes of the 60s the "Sun-Way" stamp was intended to be used by consumer, lender and appraiser groups to assure them that the plan had been evaluated and can be expected to perform adequately. Only four plans were submitted for approval and it was determined that this was not an important item to the builders or consumers, thus was not taken advantage of.

A follow-up brochure was supplied to everyone interested in the program. This included pictures, a short description of the "Sun-Way" home concept, perspectives and floor plans. A list of builders, realtors and other attendees of the passive seminars was also included in the brochure. This means of promoting the program proved very useful giving everyone something to study and digest after the initial contacts were made.

The builder and home buyer groups took advantage of the technical assistance offered. This proved a valuable service since those who called or visited the office usually had plans in hand, were planning to build soon, and were indeed interested in the concepts. Most of the plans reviewed showed a definite concern for conservation and in many cases a good understanding of passive solar applications. The technical assistance was in most cases a follow-up after the initial contact by one of the other approaches.

The energy fairs and expos attended usually produced a few prospective "Sun-Way" customers. However, most people were just curious onlookers filling a Saturday or Sunday afternoon with something to do. Many of the people contacted at fairs and expos utilized one of the other services as a follow-up. This approach usually required two to four man-days and travel expenses for that period.

The last promotional approach was the most productive and also the most costly. The production cost for the television commercials was quite high as was the air time

to run them. The response from the television spots was very good considering the economic times. This approach helped to get interest from individuals who would not have been reached by any of the other methods. It was effective at making the initial contact with seminars and technical assistance as a follow-up. Brochures were mailed to all persons responding to the ads.

## 4. CONCLUSION

Listed below are the promotional approaches covered in this paper. These are rated in order of importance as evaluated by the Division of Energy Solar staff.

* Television advertising - Greatest number of people reached, media that most people follow, most costly in terms of production and air time.
* Brochures - Good visual reference material for all target groups, copies of brochures can be run off as required so cost is low.
* Technical assistance - The people that respond are interested and the time spent is well worth the while, low cost.
* Seminars - Effective for getting educational material out to a select audience, fairly inexpensive.
* Energy fairs - Attract large crowds but fewer truely interested people, can be costly in terms of man-hours and travel expenses.
* Open houses - Good means of visualizing concepts, good crowds of interested folks, more effective in more prosperous times.
* Plans certification - Response poor, hard to guarantee construction and difficult to assure performance by plans alone, low cost.
* Individual visits - Not as effective as anticipated, lenders too busy to converse, moderate cost in man-hours and travel.

The State Solar Program plans to utilize this evaluation to continue the "Sun-Way" program with a possible expansion to the population areas of Kansas City and St. Louis. The impact should be substantial if these areas are worked properly and since the economy and housing market are showing signs of recovering. This fall a survey will be mailed to all participants in the program to evaluate what action has been taken since the initial contact.

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# THE CALIFORNIA TRIANGLE

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## ABSTRACT

Public Housing in California faces new choices in achieving energy efficiency. Should housing agencies fund/develop units which are superinsulated and the easiest for construction trades, but are not passive or active designs? Or, will Public Housing agencies take a leadership role and create an atmosphere for architects, developers and builders to grasp the situation and produce innovative energy efficient housing?

## 1. INTRODUCTION

The California Department of Housing and Community Development (HCD) ( in conjunction with Federal Highways Administration), in attempting to implement California's new residential design standards, is constructing 3700 new homes in Los Angeles, for the Century Freeway Housing Replenishment Program.

HCD is proposing that the designs of these projects be created to comply with the passive or active component of the states standards, versus super insulated designs. This innovative approach has created concerns & resistance in both public and private sector groups involved in this program.

The concerns raised consist of: reliance on pre-conceptions of design; lack of technical expertise; time and money expended to redesign; dollar cost of compliance, market impacts of solar design.

HCD staff is mitigating these concerns and stumbling blocks. This will be accomplished through the development of: case studies exploring the track record of existing solar projects; simplified technical approaches; governmental encouragement and creative financing.

## 2. COST TO DEVELOPERS

The major concern raised by developers in HCD's program, focuses on the perceived increased costs for building a passive or active solar building. The following case study reviews these perceptions.

### 2.1 Case Study

HCD's housing projects must comply to California's Title 24 residential energy code. Within the code, are various methods of compliance, called packages.

The majority of proposals are submitted using "B" package. This consists of a super insulated building. It does not include solar water heating. "C" package requires solar water heating and standard building insulation.

The typical unit submitted to HCD of 2 - 3 bedrooms will cost developers less to use "C" package (solar water) instead of "B" package . Developers, however consistently submit using "B" package. This is due to their general misunderstanding toward solar water heating.

THE CHARACTERISTICS OF EACH PACKAGE ARE:

| | B | C |
|---|---|---|
| Ceiling Insulation | R-30 | R-30 |
| Wall Insulation | R-19 | R-11 |
| Raised Floors | R-19 | R-11 |
| Perimeter Slab Insulation | R-7 | R-7 |
| Glazing | Double | Single |
| Water Heating | Gas | Solar |

The actual costs and benefits of using "B" or "C" to the program and the developer were analysed using a 10 unit development. The costs to HCD for "B" are estimated at $32490, while "C" is estimated at $36410. However, the net cost to the developer is lower for "C" than "B", as shown in the following table:

| | "B" PACKAGE | "C" PACKAGE |
|---|---|---|
| First cost to HCD | $32490 | $36410 |
| Unit cost to HCD | 3249 | 3641 |
| 55% solar tax credit | 0 | 11,000* |
| Net cost to developer | 32490 | 25410 |
| % difference | + 22% | |

If the unit is built with "C" and the developer takes the tax credit, he saves $7000. HCD's cost per unit is $392 more than if constructed to "B" criteria.

If the costs were equal for HCD, the agency would have no financial question in requiring solar DHW. Since this option cost almost $400 more per unit, HCD is establishing a process to recover the difference.

3. MAINTENANCE FEE

Each development project financed by HCD, which uses "C" versus "B" will contribute $400 (or the construction cost difference per unit, after tax credits). This fee we bill used to offset property maintenance costs.

The use of the maintenance fee will allow HCD to recover the difference between financing solar DHW projects and super insulated building.

* $11,000 is the 55% tax credit on $20000 for solar DHW in 10 units.

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# ENERGY EDUCATION FOR A MAJOR BUILDER

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## ABSTRACT

This paper presents a summary of an energy conservation and passive solar training program provided during 1982 for one of the largest homebuilders in the Denver area. The interaction between the energy design consultants and the builder staff--both past and ongoing--is described. Cost and predicted performance information for several home designs are summarized. The limited developments achieved through the program to date are reported.

## 1. INTRODUCTION

Despite the fact that Denver's market for passive solar homebuilding is strong enough to earn it a "trendsetter" cover story in SOLAR AGE magazine (Sept. 1982), there is still resistance on the part of large homebuilders in the city to incorporate solar in their product lines. In fact, none of the ten largest builders yet offers standard or optional passive solar in their developments.

When measured by the standards of small, innovative solar builders, the large Denver developers continue building energy anachronisms. The results from two performance monitoring programs in the region clearly illustrate this point.

In the 12 homes with class-B monitored data generated through the Denver Metro Homebuilders Program—held in cooperation with the Solar Energy Research Institute (SERI) and Western SUN, during 1980-81--auxiliary energy consumption averaged 1.85 BTU/ft$^2$- DD (1). In a parallel monitoring program, conducted by Public Service Company of Colorado (PSCo), metered auxiliary energy consumption in 21 homes averaged 1.74 BTU/ft$^2$- DD (2). By contrast, a comparison group (in the PSCo study) of 325 convential homes built in developments between 1977 and 1979 consumed an average of 7.37 BTU/ft$^2$- DD for auxiliary space heating. Building practices used by large production builders for energy efficiency do not appear to have changed significantly since 1979.

In an effort that would hopefully move at least one major Denver builder towards more energy efficient practices, SUNRISE Solar Design and Assistance Company provided Wood Bros. Homes with a comprehensive passive solar and energy conservation training program during 1982. This technical assistance program was conducted at the request of Wood Bros. and was funded solely by Wood Bros. (Wood Bros. was the fourth largest home builder in Denver during 1982, and its parent company City Investing Corporation was the third largest residentia builder nationwide during 1982.)

## 2. ENERGY PROGRAM: GOALS AND OBJECTIVES

The principal goal of the program was to provide sufficient training to allow Wood Bros. to alter their current building practices so that in the future they could develop land with adequate solar access and design, build and market much more energy efficient housing on it.

The key objectives of the training were as follows:

--Involve and inform the key decision-makers in the organization. Make certain they all gained a solid grounding in the main energy issues: conservation, land planning for solar access, sun tempering, and the range of passive solar options.

--Convince key management personnel that energy efficient passive solar designs could be both cost-effective and marketable.

--Transfer specific skills--from air infiltration strategies to computer design and analysis tools--to the design staff to provide them with sufficient in-house passive solar design capabilities that they needn't rely in the future on outside design and

consulting services.

--Ensure that the builder's staff learned the preeminent merits of energy conservation improvements first, then proper orientation for sun-tempering of all existing designs, prior to any other passive solar strategies.

--Through the training process, develop with the Wood Bros. staff at least 9 energy efficient redesigns from existing, proven product lines (which ranged in price from $70,000 to $140,000).

--While no specific figure was stated, SUNRISE felt that a 50%-75% reduction in production home energy consumption through both passive solar and improved energy conservation measures was readily obtainable at moderate cost increases.

## 3. ENERGY TRAINING PROGRAM PHASES

### 3.1 Proposal Phase

The initial meeting between SUNRISE and Wood Bros. Homes was held in mid-October of 1981. The proposal for a comprehensive conservation and passive solar training program was submitted in November, was then revised during the next month, and was accepted and signed in early January. Several delays were encountered prior to the start of the program in April, due to the builder's production schedule.

### 3.2 Preparation Phase: Design and Cost Analysis

The objective during this phase was for SUNRISE to develop three passive solar designs from existing plans and elevations which were acceptable to the Special Projects Director and the Staff Architect at Wood Bros.

Very important to the success of this phase was the close involvement of these two Wood Bros. staff. They helped to ensure that the three designs which were modified by SUNRISE would be acceptable, from a marketing and cost perspective, by the final decision makers within the organization. Limiting constraints were clearly established by management for the entire assistance program. For example, all three of the initial designs had to be located on rear elevations only.

Once SUNRISE modified the designs, the builder's staff and sub-contractors determined the added costs of the energy conservation and passive solar improvements. SUNRISE also conducted a detailed computer analysis of the three designs. This cost and predicted performance information served as the cornerstone of the training which followed.

Because the designs, cost and predicted performance were for "their homes," the information was far more relevant to them than any other illustrative examples.

The base prices, incremental cost increases for solar and conservation upgrades, and projected energy savings for the three designs selected are presented in Table 1. Cost increases for conservation upgrades and the added passive solar elements averaged 2.8% ($3066) for materials, exclusive of markup. For an average square foot cost of $57.43, solar and conservation increased the cost by $1.67 to $59.10. Projected first year savings for this investment averaged $289 (1982 gas costs, assuming a 70% efficient furnace).

The principal features included in the retrofit of the 109 design (see Figures 1 and 2) included replacing a covered semi-enclosed deck with a sunspace; converting all three of the sunspace commonwalls to 8" corefilled brick; adding a fan to duct solar heated air from the sunspace down to the basement; replacing the insulating board sheathing with a 1" extruded polystyrene sheathing product; insulating outsides of basement walls to four feet below grade; and adding a vapor barrier to the ceilings (previously only located in the walls, as code requires). These improvements would cost $4757.

Computer analysis of the 109--using SERI.RES, an hourly-simulation design tool developed by Larry Palmiter and the Ecotope Group for SERI--indicated the redesign measures would provide a satisfactory comfort level while reducing auxiliary energy use by 51% compared to the "as is" 109 with the same orientation.

The initial 524 retrofit incorporated the same conservation features as the 109, plus some interior brick veneer for mass, a destratification system to the basement, improved overhangs, and a small increase in south glass area. Combined conservation and solar upgrades cost $2053. Since this model already was glazed to the point of overheating, the projected energy savings--24%--were less dramatic than with the other two designs.

The 1040 retrofit (Figures 3 and 4) incorporated the same conservation features as both the 524 and the 109, plus a 42" high thermal storage wall with direct gain in the living area, a two story north-south 8" brick partition wall for the bedroom areas, and improved overhangs. The upgrades for this home cost a total of $2388, with a predicted auxiliary energy reduction of 55%. Hourly simulations indicate no serious

overheating in Denver.

During both the preparation and presentation phases, the specific information which had the most dramatic impact on Wood Bros. staff was the dramatic savings potential offered by high efficiency furnaces (see Table 2). Since half of the new Denver homes monitored under the class-B program had furnace efficiencies under 50% (1), the potential for savings in this area was easily understood by all.

3.3 Presentation Phases

A total of five presentations and two extended working sessions for the builder were conducted over a two-month period. The content highlights of each session are summarized below:

Presentation #1: Conservation Upgrades and Introduction to Solar Concepts (1/2 day, for division managers plus the key design and drafting staff)

--Introduction: heat flows, passive system ingredients.
--Conservation: furnace efficiency, zoned auxiliary systems, infiltration, vapor transmission, basement insulation, exterior sheathing, insulation levels, destratification, role of internal gains.
--Orientation and solar access.
--Passive collection: greenhouse effect, transmission, movable insulation, shading, ventilation, glazing details, rules of thumb for sizing glass.

Presentation #2: Thermal Mass and Passive System Types (1/2 day, same target audience)

--Thermal Mass: definitions, thermal characteristics, benefits, types, factors altering effectiveness, "free mass," dual functions.
--Direct Gain Systems: how they work, suntempering, moderate glazing strategies, sizing glass and mass; advantages and disadvantages of the system type, proposed Wood Bros. design with cost and predicted performance information.
--Thermal Storage Walls: how they work, materials, time lags, selective surface, system sizing issues, advantages and disadvantages of the system type, proposed Wood Bros. design with cost and predicted performance information. --Sunspaces: how they work, the case for isolation, common mass walls, sizing glass and mass, advantages and disadvantages, proposed Wood Bros. design with cost and predicted performance information.
--Hybrid Designs: fans, isolated storage systems, passive discharge.

Presentation #3: Thermal Performance Estimation (1/2 day, same audience)

--Introduction: furnace sizing issues, computer design tools.
--Simplified heat gain and heat loss: manual calculation systems, internal gains.

--SERI's S.H.E.D. Study (3): design variations and associated savings.
--The Load Collector Ratio calculation procedure.

Presentation #4: Solar Access--Design and Protection (1/2 day, for land planners only)

--1 hour overview of passive solar.
--Solar access design and protection: negative solar easements, height and bulk controls, site planning, vegetation, aesthetics.
--Design tools.

Working Session #1: Passive Solar "Retrofitting" of Existing Plans (3 days, design and drafting staff)

--Developed 6 additional designs.

Working Session #2: Design Tool Instruction (3 days, same group)

--Provided instruction in the use of SERI.RES, an hourly simulation code. --Wood Bros. staff modeled the energy consumption of the 6 additional designs.

Presentation #5: Management Summary and Market Approach (1/2 day, for company president, marketing staff, division managers and design staff)

--Introduction: review Wood Bros. position on solar.
--Ideas to consider: testing existing buildings for baseline data, for quality control and for marketing.
--Home energy rating systems and the automobile MPG analogy.
--Passive solar overview: conservation first, sun tempered designs, passive system types.
--SUNRISE recommendations: offer improved energy conservation features as standard features, and build passive solar model homes, with an eye towards offering solar as an option.
--Market approach: build models, develop a knowledgeable sales and marketing staff, test buildings and use the data for marketing, use rating system to help the buyer differentiate Wood Bros. solar product line from conventionally built homes.
--Internal policy decisions: expand beyond rear-elevation-only approach; markup for solar options; move beyond "retrofitting" existing plans; consider expanding passive solar to the townhome market; will Wood Bros. provide movable insulation and shading products.

## 4. PROGRAM RESULTS

While there has not been any rapid movement by Wood Bros. to incorporate passive solar in their current product lines, small steps are being taken in that direction.

There were two different initial reactions at the completion of the training program. First, several of the design and marketing staff were immediately sold on the feasibility and marketability of passive solar energy efficient housing. One marketing VP seriously asked the design staff, "what could we implement tomorrow?" The more conservative participants, including the company president, were skeptical about the affordability issue: in the depths of a severe housing recession, could the homebuyer afford the higher mortgage costs related to the conservation and solar upgrades? How long until the solar improvements "paid for themselves?"

Any immediate "go or no-go" decision was delayed while solar access on land currently under development was analyzed. When it was determined that less than 20% of the developed lots provided solar access in a manner acceptable to Wood Bros., solar options were put on hold. There existed a great reluctance to stimulate the homebuying public about passive solar when it could be offered on so few sites. However, a significant step for the future has been taken in that future developments are being laid out for maximum solar access.

One of the key objectives of the energy training process--that of providing the key decision-makers with enough knowledge to allow them to continue discussing the critical design issues on their own--was met successfully and continues to have an impact. As a result of that on-going in-house dialogue, several basic issues are currently being addressed:

A. Limited testing to establish a baseline of air infiltration rates has been conducted. Three new homes averaged 1.4 air changes per hour (no taping of flu vents or outside air vents for combustion; .9 when vents were taped).

B. Several buyers have expressed an interest in having the proposed conservation upgrade package--high-R sheathing, continuous vapor barriers, and exterior basement insulation--installed on townhomes for side-by-side comparison of energy consumption. They have also expressed a desire to have their homes tested for air infiltration and are considering either zoned heating systems or high efficiency units.

C. Several buyers are also interested in having either an active or passive solar system included in the initial purchase price. Wood Bros. has indicated some willingness to work with these clients' requests. (Movement on these last two points will be reported during the presentation of this paper at the conference.)

## 5. SUMMARY AND CONCLUSIONS

--It did not come as a surprise to us that Wood Bros., like most large homebuilders, is adapting very slowly to the energy and design strategies which innovative builders and designers have taken for granted for several years. While there is a market for solar design teams interested in working with large builders, our experience is that those designers will need to bring both patience and persistence to their task.

--The strategy to transfer a "critical mass of knowledge" to as many players on the builder's team as possible worked well during this program. Our feeling remains that the larger the core of individuals in a builder's organization that are informed about the important energy issues, the more comprehensively those issues will be addressed in new product lines.

--Problems with limited solar access for a vast majority of the builder's currently developed land turned out to be a major "threshold issue" delaying any rapid move towards widespread use of passive solar designs. However, the solar orientation/access issue did not account for "non-adoption" of improved energy conservation measures. (Perhaps the staff picked up on the point that was made during the market approach presentation that passive solar has "pizzaz" and that conservation, while more cost effective, is "just there.")

--As previously stated, improved energy conservation measures were recommended as a new standard for all Wood Bros. homes. It was shown that improved energy conservation and a modest improvement in furnace efficiency could result in 50% energy savings.

--A close working relationship with a builder's design staff minimized the need for redesign, which built mutual confidence in the whole approach of the program.

--"Retrofitting" existing plans and elevations is an easy place to begin incorporating conservation and passive solar upgrades in a builder's product line. This strategy worked here because the builder had direct cost, construction and market experience with the "pre-solar" home.

--Given a second go-round with this training

program, the issue of economic affordability of conservation and passive solar upgrades would be answered more effectively through thorough cash-flow analysis in order to avoid the somewhat misplaced concern with payback analysis.

--There is some question as to the merits of transferring a complicated hourly-simulation design tool to a builder prior to his firm commitment of his company to a passive solar product line. Given the current rate of change at Wood Bros., the design tool instruction appears to have been premature.

--Despite some of the frustrations inherent in working with large builders, the potential impact represented by their adoption of comprehensive conservation and passive solar building practices justifies the effort. Besides, this large builder paid their bill—an indication of serious intentions (hopefully).

## 6. REFERENCES


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Table 1. PRICE INFORMATION

| MODEL* | CURRENT PRICE | SOLAR + CONSERV. MATERIALS | % INCREASE |
|---|---|---|---|
| 109 | $138,000 | $4010 + $747 | 3.4% |
| 524 | $102,500 | $1453 + $600 | 2.0% |
| 1040 | $76,000 | $1906 + $322 | 3.0% |

Ed. Note: A metric-English-metric conversion value list appears immediately preceding the Author Index.



Fig. 1. Wood Bros. Model 109 south elevation "retrofitted" with solar

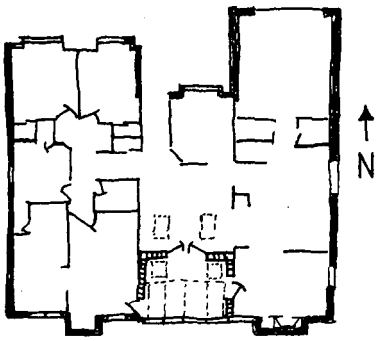



Fig. 2. Wood Bros. Model 109 floor plan "retrofitted" with solar

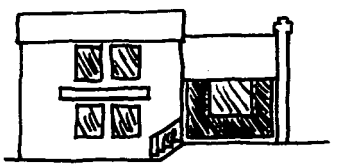


Fig. 3. Wood Bros. Model 1040 south elevation "retrofitted" with solar

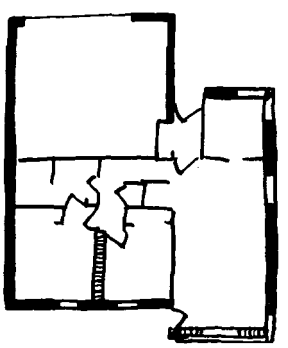


Fig. 4. Wood Bros. Model 1040 floor plan "retrofitted" with solar. North-south axis mass partition wall is 2 stories high.

Table 2. AUXILIARY HEATING ENERGY USAGE AND FURNACE EFFICIENCY EFFECT (in Denver)

| MODEL* | Annual MMBtu | CCF of** Gas | $ at 90% eff. | $ at 70% eff. | $ at 50% eff. | $ at 35% eff. | Aux, Btu/ $ft^2$/DD |
|---|---|---|---|---|---|---|---|
| 109 As Is | 114.30 | 1362 | $756 | $972 | $1362 | $1944 | 8.3 |
| 109 Solar | 55.54 | 661 | $367 | $472 | $661 | $944 | 4.0 |
| 524 As Is | 58.68 | 699 | $388 | $500 | $700 | $1000 | 5.5 |
| 524 Conserv | 41.74 | 497 | $276 | $355 | $497 | $710 | 4.0 |
| 524 Solar | 34.89 | 415 | $231 | $296 | $415 | $593 | 3.3 |
| 1040 As Is | 38.95 | 464 | $258 | $331 | $464 | $663 | 4.5 |
| 1040 Solar | 21.59 | 257 | $143 | $184 | $257 | $367 | 2.5 |

*-The 109 has 2298 $ft^2$ of conditioned space, with a 1830 $ft^2$ partially conditioned basement. This model has 284 $ft^2$ of south glass.

-The 524 has 1758 $ft^2$ of conditioned space with a 671 $ft^2$ partially conditioned basement. It has 163 $ft^2$ of south glass.

-The 1040 is a 1456 $ft^2$ trilevel with no basement. It has a south glass area of 140 $ft^2$.

-All "as is" cases assume R-11/R-30 walls/ceilings with approximately 1.1 AC/Hr for air infiltration, plus south orientation.

-All "solar retrofits" assume R-16/R-30 walls/ceilings with approximately .75 AC/Hr for air infiltration, but no night insulation.

**-Assume one CCF in Denver equals 84,000 Btu and costs $.50 (fall, 1982).

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# COMMON ERRORS IN DESIGN AND CONSTRUCTION OF PASSIVE SOLAR HOMES: RESULTS OF A REVIEW OF NMSEI TECHNICAL ASSISTANCE PROGRAMS

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## ABSTRACT

One of the state-funded programs of the New Mexico Solar Energy Institute (NMSEI) at New Mexico State University provides citizens of New Mexico with a limited amount of free technical advice on the design, construction, and operation of solar systems. Requests for assistance are now averaging 40 to 50 per month in the solar thermal field alone.

Increased efforts to inform the public (especially home builders) through passive solar workshops and through the news media have increased the number of requests concerning the design and construction of solar homes. Most requests for technical assistance fall into this category.

Experience in the technical assistance program has identified common areas in which help is needed and identified common errors made in the design and construction of solar homes. Many of the potential owners and/or builders who contact the institute can be divided into two major categories. The first category consists of those that have little or no knowledge of solar essentials but want to build a solar home. They believe that this solar home must be mechanically equipped with collectors, isolated storage systems, and various fluid handling components. The other category is conversant with solar essentials and elects (for personal, aesthetic, or economic reasons) to build a frame house. People in this group often assume incorrectly that they cannot incorporate an adequate amount of thermal mass for heat storage in a frame house.

Other common errors will be discussed, such as incorrect orientation of houses (this can have some surprising effects) and inappropriate use of what would otherwise be adequate insulation. Proposed methods of providing information to designers and builders to counteract these (and other) common errors will be described.

## 1. INTRODUCTION

As a service to residents of New Mexico, NMSEI provides technical advice on solar design to persons contemplating the construction of a solar home. This service is in the form of a scheduled meeting at the institute between the visitor and an NMSEI staff member for the purpose of reviewing plans. These plans may be in different stages of completion varying from initial conceptual sketches to the final construction drawings. A similar service is provided by mail for the owner and/or builder who is unable to appear in person at the institute and plans mailed in are reviewed and returned with the appropriate comments. Brief questions which do not require in-depth answers are also handled by telephone whenever possible. A review of the Technical Assistance Information Reports indicated several repetitive errors. Information designed to minimize these mistakes is being disseminated through the news media, technical notes, and inclusion in the NMSEI conducted workshops. Some of the more frequently occurring errors are discussed in the following sections.

## 2. ORIENTATION

As part of the design stage we might take a look at some common errors in the initial site selection: choosing a site for a solar home with nearby mountains, trees (both evergreen and decidous), and nearby buildings which may not appear as a problem during the high sun angle seasons may indeed partially obscure the solar aperture during the low sun angle heating season (1). New Mexico Solar Energy Institute (NMSEI) has two site survey tools (2) available for loan to passive solar home builders so that they can ascertain if any obstructions will interfere with the receipt of solar radiation and if so by how much.

The determination of true south is frequently left to chance. Potential solar

homes builders frequently intend to use magnetic (or compass) north/south rather than true north/south. There is also ample confusion on the meaning of magnetic variation, on the method for applying magnetic variation, and on which magnetic variation is applicable in a given area. Five calls to offices which deal normally with maps and/or surveys confirmed that this ignorance is more widespread than we might imagine. The person answering the telephone was asked what the local magnetic variation is. The following were the five answers:

1. 3° 57'
2. 11° 5' (east or west not stated)
3. 32° 51' north 106° west
4. 11½'
5. 12°W

If one overcomes the initial difficulty in obtaining the correct magnetic variation, then the next obstacle is applying it correctly. Applying 12° magnetic variation in the wrong direction will result in the house misoriented 24°. Twenty-four degrees off south orientation will not only reduce the available solar gain by appproximately 9 percent but will induce some surprising results. On June 21, at 6:00 a.m., the sun azimuth angle is 20° north of an east-west line so that the sun will be shining in the north windows at an angle of 44° creating considerable unwanted solar gain. At the NMSEI, we are now setting the correct variation in the compasses attached to the solar site survey tools and instructing on the correct use of the compass.

## 3. SHADE

Frequently the basic solar design has provided for ample glass, mass, correct orientation, and ventilation but allows the house to get in its own way by building wings off the south wall. Often two wings are designed which shade the solar glazing in the morning and afternoon, allowing only a short period of solar radiation on either side of noon. A variation of this design error is placing of the garage on the south side, which is frequently desired because it may provide easy access to the street. This not only blocks the sun, but negates the potential benefit of a buffer from a garage on the north side. A related early error occurs in the orientation of the solar house along the north-south axis rather than the east-west axis restricting the available south wall glazing aperture. In the cases where the shape of the lot dictates the north-south orientation, the insufficient south wall space can be overcome with single or multiple clerestories; however, this usually adds to the building cost.

Overhangs to shade south facing windows are often ignored or, if treated, not enough overhang is provided, causing overheating conditions in the summer. Just as often, too much overhang is used, inhibiting the available solar gain in the winter. Additionally the overhang is often placed too close to the glazing, which prevents the upper portion of glazing from being utilized as a solar window and also increasing the house heating load.

## 4. HEAT REGULATION

Perhaps the greatest number of errors occur in the construction of sunspaces/greenhouses. Glazing the roof seems like the conventional thing to do for the first time solar builder, but by late spring in climates as rigorous as Cuba, New Mexico (with 7,500 degree days), the overheating condition can become uncontrollable without taking corrective action. Some of the remedial suggestions offered at NMSEI are: the use of movable shading devices, such as rigid urethane panels or woven mesh screen; increased ventilation with ventilator stacks, operable windows and doors, or evaporative coolers; and replacing the glass roof with a solid insulated roof. A frequent adjunct to the glass roof is east and west glass walls, which compound the problem by adding unwanted heat in the summer mornings and afternoons, contributing solar heat gain upwards of 1,800 Btu/square foot per day. The use of tilted glazing for sunspaces is generally discouraged for several reasons. It is difficult to control overheating in the summer, it is difficult and more costly to construct, it has a greater tendency to leak than does vertical glazing, is not as self cleaning as vertical glazing and contributes little to the solar aperture (3).

Many plans are submitted for review with little or no provision for ventilation at the clerestory or upper level or with inadequate operable windows at the ground floor level. Operable windows frequently exist only to satisfy code requirements for egress through bedroom windows. Often no provision is made to move stratified warm air in high ceiling homes to a lower level where it can contribute. Low speed ceiling fans would help to alleviate this condition.

## 5. THERMAL STORAGE MASS

Dealing with thermal storage mass probably causes the greatest number of problems, and many frame home builders abandon the idea of a solar home because they believe that adequate thermal storage mass in a frame house is unachievable. Through the technical assistance program and workshops, we emphasize the fact that a carefully designed frame house with south-facing glazing and a concrete slab floor provides some of the major essentials necessary for a passive solar home. The next step is to

convince the prospective homeowner, generally the wife, that there are other alternative floor coverings than wall to wall carpeting. Some of the alternatives are quarry tile, ceramic tile, brick, pressed cement tile, and if all else fails, vinyl tile. If the homeowner insists on carpeted floors (generally bedrooms), then we encourage the use of masonry divider walls or Trombe walls in those areas that have carpeted floors.

More often than not, potential solar homeowners try initally to design an active solar system for home heating rather than a passive solar system. The principal concepts of an active system with its ductwork, pebble bed storage, and blowers are more readily understood than the passive system which relies on few or no moving parts and operates predominantly on a diurnal exchange of heat through radiation, conduction, and convection. The NMSEI Passive Solar Workshops and Solar Survey Courses in the university nontraditional program have made some inroads in creating interest in initial passive solar home design.

## 6. INSULATION

While adequate and appropriate quantities and types of insulation are sine qua non for all types of building construction, it has special significance in passive solar homes. The solar gain obtained through careful design and sometimes with additional initial expenditure needs to be conserved. Most homebuilders are still not aware of the advantages of extruded polystyrene for footing and stemwall insulation rather than other forms of rigid insulation, because of its greater resistance to ground moisture and therefore its greater tendency to retain its original R value. We also suggest (with infrequent success) to builders of masonry homes that they place the insulation on the exterior of the masonry home rather than the interior so that the thermal storage mass of the masonry walls is inside the insulating envelope. Convincing homeowners who want a brick or adobe home for its exterior appearance to wrap the building in insulation is a difficult task. However, we have made some headway in encouraging adobe home builders to apply insulation to the exterior. The myth that adobe is a very good insulator is still prevalent. Adobe, of course, has a value of about R-3 for 10 inches and although it is a very fine thermal storage material with appropriate esthetic qualities for home building in the southwest, it needs to be insulated on the outside. We encourage people to do this in one of two ways: build a load bearing wall of adobe blocks and add exterior insulation with or without furring strips, fiberglass bat and/or rigid insulation; or build a frame bearing wall with insulated fiberglass bat and use a veneer adobe block wall interior to it.

## 7. ADOBE CONSTRUCTION

Since adobe is a popular building material in the southwest because of its traditional and thermal mass qualities, we will discuss some frequently occurring construction errors in adobe building. One that often occurs is the visible concrete bond beam and lintel on the interior of an adobe home that was intended in the design stage to be left in a natural adobe finish. The appearance of the concrete bond beam generally dictates a change in wall finish from adobe to plaster. There are at least two good ways to avoid this. One is to use a wood bond beam in place of the concrete, or if concrete and steel is preferred, then this can be acieved in an esthetically pleasing way by forming the bond beams with left-in-place rough sawn 2 x 6s. The concrete bond beam is there but not visible.

Another frequent error in adobe construction is starting the adobe courses at interior floor level. This of course exposes the lowest level adobe block to erosion during normal mopping up, and the onset of deterioration will occur usually long before the home is complete. One way to avoid this problem is to use a course of concrete block. However this poses the problem of concealing the six or eight inches of concrete block. One method of concealing the concrete block at floor level is to lay ceramic tile as a baseboard.

Many adobe homes are constructed with brick floors laid in sand. We suggest a thorough insect spraying on the ground, then a covering of 6-mil polyethylene and the layer of sand and bricks in turn. We also encourage builders to place a vapor barrier between the adobe wall and the exterior insulation to diminish the opportunity for moisture from the adobe wall penetrating the insulation.

One final note which applies whether the house is adobe, some other masonry, or frame; we encourage people to place their masonry fireplaces inside the house and insulate the exterior so that the intrinsic thermal storage mass can perform a dual function of storing solar heat and fireside heat.

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# NEW MEXICO SOLAR ENERGY INSTITUTE WORKSHOP SURVEY

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## ABSTRACT

During the summer and fall of 1982 the New Mexico Solar Energy Institute conducted an extensive survey and analysis of its information and education activities, primarily the solar workshop program. This paper presents an evaluation of the workshop survey methodology, the survey findings, and an assessment of program directions based upon these findings.

## 1. METHODOLOGY OF THE WORKSHOP SURVEY

The New Mexico Solar Energy Institute (NMSEI) workshop survey was designed and conducted according to the survey methodology prescribed in the Total Design Method by Dr. Don Dillman. This survey methodology is nationally recognized and widely used. The Dillman design criteria and survey procedures were rigorously followed.

Using systematic sampling, 300 respondents were chosen from a mailing list of the approximately 1,600 people who had attended workshops in the past 18 months. Three questionnaires were sent to respondents over an eight-week period. Each respondent had an identification number stamped onto the top right corner of the questionnaire sent to him. As the first questionnaires sent were returned, the numbers were marked and removed from the original list of 300. The second mailing went to those who had not responded. The third followed 3 weeks later.

The response after the three mailings is as follows:

| | No. | % |
|---|---|---|
| Completed returned questionnaires | 221 | 74 |
| Addressee unknown or no forwarding address | 52 | 18 |
| Moved to another state | 7 | 2 |
| Did not attend workshop | 13 | 94 |
| TOTAL | 293 | 98 |

From the sample, those respondents who did not respond either because they should not have been in the universe at all (out-of-state residents; people whose names were on the mailing list despite their not having taken a workshop) or who could not be reached (returned addressee unknown), one obtains a set response rate of 98 percent. Approximately 10 percent of the respondents were disqualified because they no longer resided in New Mexico or did not attend an NMSEI workshop. Added to those who responded, this accounts for more than 81 percent of the survey group. Such a large response rate clearly indicates we have fully representative survey results from which we can accurately analyze the NMSEI information and education program activities.

## 2. CHARACTERISTICS OF WORKSHOP ATTENDEES

Demographic information about users of NMSEI educational and informational program was sought in the survey through a series of 10 questions. Responses revealed that NMSEI workshop attendees are predominantly homeowners (70 percent), with more than two-thirds living in urban areas. They are evenly spread across the state geographically ( 27 percent central, 28 percent south, and 14 percent north), in accordance with the population of the state.

The vast majority of workshop attendees are employed full-time (53 percent), with only 1 percent unemployed and 11 percent students or retired. While a wide range of occupations were represented at the NMSEI workshops, the predominant group are professionals. Consistent with this employment status are the data showing 75 percent of attendees with a college-level education and a median family income of approximately $25,000. The average age of solar workshop attendees is 45-55 years, and attendees are predominantly anglo (62 percent). In short, the workshops attract middle-class homeowners who are employed in professional careers (construction, teaching, real estate, to name a few).

## 3. OVERALL RATINGS

The respondents were asked to evaluate the NMSEI workshops through a series of questions. These questions are distinct from "the economic benefit" questions that follow in the next section of this analysis.

In brief, here are the questions as asked with the aggregate responses shown as percentages:

Question #3: Would you participate in other NMSEI workshops if the topic was of interest to you?
Yes--97 percent.

Question #4: Would you recommend NMSEI workshops to others who show interest in solar/wind energy?
Yes--99 percent.

Asked questions involving the future directions NMSEI's should follow, respondents gave the following answers.

Question #9: Are you interested in "hands-on" construction workshops?
Yes--75 percent.

Question #27: Do you feel the state budget for alternative energy sources should be increased?
Yes--63 percent.

Other information gathered in questions #31 - #33 shows that the majority of respondents believe energy is a serious state and national problem, that the energy tax credits should be expanded, and that building codes and lending practices should further encourage energy efficiency. Answers showed respondents prefer to rely on state energy programs rather than federal. The exact question wordings and percentages follow.

Question #31: Some people feel that energy is a serious national and state problem, but other people feel it is not. We would like to know your opinion. Do you consider meeting the United States' energy needs during the next 10 to 20 years to be a serious problem?
33 percent said it was a serious problem.

45 percent said it was a very serious problem.

Respondents asked to give their perferences on the following questions:

Question #33.1: Providing larger tax credits from improving home energy efficiency, strongly favor--60 percent, neutral--24 percent.

Question #33.3: On changing building codes and mortgage requirements to encourage new types of energy saving homes, strongly favor--73 percent, neutral--9 percent.

Question #33.6: To rely on state instead of federal programs to encourage energy conservation, strongly favor--44 percent, neutral--41 percent.

## 4. ECONOMIC IMPACT OF NMSEI SOLAR WORKSHOPS

In order to estimate the potential economic benefits of these workshops, we posed survey questions seeking "economic benefit" answers. We find when asked:

Question #19: With which energy conservation solar projects did the New Mexico Solar Energy Institute workshop program assist you?
Responses are shown in Table 1.

The figures in the next-to-last column of Table 1 show the economic benefit to New Mexico of the NMSEI workshop program for the 300 people in the survey group. Because this was a random sample, we can extrapolate these figures to the entire population sampled. That is, if our survey group of 300 produced solar retrofit construction activity ("yes" or "in progress") valued at $734,200, then we can estimate that the 1,600 total workshop attendees produced solar retrofit activities with value of approximately $3,900,000.

The same analysis would apply to the new solar home construction valued at $1,529,000 for the survey group of 300 people. If we extrapolate to the entire 1,600 workshop attendees, we estimate about $8,103,700 in new solar home activity. The reasonableness of these estimates can be seen from their correspondence with the results of an independent analysis referenced in Table 1.

Extrapolating one step further, we can estimate the indirect economic impact of the NMSEI program by accounting for the solar construction activities "planned or considering" as a result of attending a NMSEI workshop (see Table 2).

If all of these 224 "planned or considering" solar projects were actually built in the next 12 months, we would see an additional $2,591,200 in solar construction activities from the survey group alone. Again, we can extrapolate to estimate that the 1,600 person workshop group would produce approximately $13,733,360 in solar construction activities assisted by the NMSEI workshop program.

TABLE 1. ECONOMIC VALUE OF SOLAR PROJECTS EITHER BUILT BY NMSEI WORKSHOP ATTENDEES OR IN PROGRESS

| Solar Project | Number Stating "Yes" or "In Progress" | Number Stating "Planned/ Considered" | Project Value (1981 Dollars) | Estimated Value to Participants (1981 Dollars) Sample Group | All Workshop Attendees |
|---|---|---|---|---|---|
| | | | Ave. Cost* | | |
| Attached Greenhouse | 37 | 56 | 4,000 | 152,000 | 805,600 |
| Solar DHW System | 39 | 60 | 3,100 | 120,900 | 640,770 |
| Active Solar System (Space heating with storage) | 24 | 19 | 8,000 | 192,000 | 1,017,600 |
| Small Wind System | 34 | 18 | 12,000 | 48,000 | 254,400 |
| Thermal Storage Walls | 27 | 29 | 1,500 | 40,500 | 214,650 |
| Home Insulation Package | 113 | 17 | 1,600 | 180,800 | 958,240 |
| Solar Retrofit Construction Subtotal | | | | $734,200 | $3,891,260 |
| New Solar Home Construction | 22 | 25 | 69,500 | 1,529,000 | $8,103,700 |

*Table 1 references:

(1) "Starting a Local Conservation and Passive Solar Retrofit Program" by Virginia Barber and Rick Mathews. LA-8992-EPS UC-58C February 1982, pp.259-60, pp.267-68

(2) "Solar Products Specifications Guide," Solar Age Magazine, 1979. Yearly updates 1980, 1981, and 1982.

(3) New Mexico State Department of Taxation and Revenue, 1977 to 1981 Solar Tax Credit Claims.

TABLE 2. ECONOMIC VALUE OF SOLAR PROJECTS EITHER PLANNED OR UNDER CONSIDERATION BY NMSEI WORKSHOP ATTENDEES

| Solar Project | Solar Projects Being Planned/ Considered | Project Value 1981 | Estimated Value to Participants (1981 Dollars) Sample Group | All Workshop Attendees |
|---|---|---|---|---|
| | | Ave. Cost | | |
| Attached Greenhouse | 56 | 4,000 | 232,000 | 1,229,600 |
| Solar DHW System | 60 | 3,100 | 186,000 | 985,800 |
| Active Solar System | 19 | 8,000 | 152,000 | 805,600 |
| Small Wind System | 18 | 12,000 | 216,000 | 1,144,800 |
| Thermal Storage Walls | 29 | 1,500 | 40,500 | 214,650 |
| Home Insulation Package | 17 | 1,600 | 27,200 | 114,160 |
| Solar Retrofit Construction Subtotal | | | 853,700 | 4,494,610 |
| New Solar Home Construction | 25 | 69,500 | 1,737,500 | 9,208,750 |
| TOTAL | | | 2,591,200 | 13,703,360 |

This line of analysis (NMSEI assistance with solar construction activities) could be continued by looking at the economic impact of the workshop program through such benefits as energy savings from solar projects, increased resale value from solar projects, and an analysis of other direct and indirect economic impacts of the NMSEI workshop program.

## 5. WORKSHOP IMPACT ON OTHER SOLAR-RELATED ACTIVITIES

Question #12 on the workshop survey asked "Has attending an NMSEI workshop led you to greater involvement in any of the following solar related activities?" These data on solar-related activities of workshop attendees are very important as indicators of a person's gradual movement to adopt a new technology in the near future (three to five years). From the solar activities listed, the answers indicate 52 percent are buying solar books, 33 percent are buying or planning to buy solar products, 48 percent are visiting or planning to visit solar businesses, 38 percent are visiting solar installations, and 46 percent are designing/constructing or planning to design or construct a solar project. All of these activities (for example the percentage of workshop attendees visiting solar businesses after attending a workshop) are an indication that the attendees have moved much closer to a solar adoption decision.

## 6. NMSEI PUBLICATIONS AND INTERNAL SERVICES EVALUATION

Another category of analysis in the survey was the assessment of NMSEI's written publications and graphic materials, both in production and dissemination. Two items are most pertinent in making this assessment.

In general, our survey indicates the effectiveness of NMSEI-generated photographic slides, consumer fact sheets, professional manuals, and other information/educational materials. For example, NMSEI consumer fact sheets were rated "very necessary" or "necessary" by 64 percent, "helpful" by 30 percent, and "not necessary" by only 1 percent. A similar pattern is found for NMSEI-generated professional manuals and related publications, where 59 percent found these publications "necessary" or "very necessary."

Another area of Information and Education Division activities, internal services, was also surveyed (Question #8). Internal services (graphic arts, editing, workshop coordination, publicity, etc.) make the publications and workshops possible. While NMSEI staffing for internal services is very small, the survey assessment indicates that the NMSEI "slides (93 percent), films (76 percent), viewgraphs (82 percent), etc." were all rated "very effective" or "effective."

## 7. CONCLUSIONS

Findings from the NMSEI solar workshop survey can be summarized as follows:

- °The workshops are very effective at transferring solar-related technologies to a substantial number of New Mexicans.
- °Survey respondents strongly favor expanding the NMSEI workshop program as well as the entire state budget for alternate energy.
- °Workshop attendees are evenly distributed statewide, are homeowners (70 percent), employed full-time (primarily in professional positions), have an median age of about 48, have an income above the median, and the vast majority have at least some college education. Most workshop attendees were homeowners and had little or no experience with solar energy applications before attending one of the workshops. Approximately 30 percent of the workshop attendees are, however, employed in solar-energy-related sales, installation, manufacturing, or servicing. This illustrates the technical training function NMSEI offers the solar industry in New Mexico.
- °The economic benefit of the NMSEI workshop program to New Mexicans attending workshops during an 18-month period is estimated at $3,891,260 in solar retrofit construction activities and approximately $8,103,700 in new solar home construction. Similarly, those workshop attendees responding that they are "planning or considering" a solar retrofit are estimated at $4,524,610 and new solar home construction at $9,208,750 (see table 2). No accounting of economic benefit is made of increased resale value, energy/dollar savings from these solar projects, nor all the New Mexicans currently pursuing solar activities because of the NMSEI workshops. All of these economic benefits were obtained at a workshop program cost of approximately $149,500.

Our analysis indicates that benefits exceed costs by a very large margin, resulting in a very favorable cost-benefit ratio. It is clear from this analysis that the NMSEI workshop program, as well as its related publications program and supporting internal services, is of clear economic benefit to the state of New Mexico.

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# PASSIVE SOLAR
# DESIGN GUIDELINES AND EVALUATION CRITERIA
# FOR BUILDERS

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## ABSTRACT

This paper describes the New Mexico Showcase of Solar homes, a 1983 project featuring two model solar villages. Key features of the project are emphasized including the private sector character and marketplace considerations. To assure integrity and quality in solar design, the Showcase Advisory Board set guidelines using a balance of conservation and passive solar and addressing the issue of occupant comfort. The guidelines, based on research and methodology developed at the Los Alamos National Laboratory (LANL), were then used to establish criteria and worksheets for builders seeking entry into the Showcase project. Designs accepted for the Showcase met the criteria and have become examples of the transfer of research to practice. Another significant aspect of the project is that it makes accessible very usable and reliable design information to builders, real estate lenders, mortgage lenders, and homebuyers. The worksheets bring the laboratory into the marketplace.

## 1. PROJECT DESCRIPTION

The New Mexico Showcase of Solar Homes project was designed to present model solar homes by various solar builders in two solar village locations in New Mexico: Eldorado at Santa Fe and Rio Rancho. These two sites are among the fastest growing areas in the state. The purpose of the Showcase project is to demonstrate that solar homes are affordable and attractive, hence the theme "Affordable Solar Living, Today." Twelve homes at Eldorado and eight homes at Rio Rancho will be open for public tour during the Fall 1983. Builders will be preselling additional homes from the models.

An Advisory Board was formed of leading solar advocates throughout the state, and includes key people from Public Service Company of New Mexico, the New Mexico Homebuilders Association, the New Mexico Energy Research and Development Institute, the Solar Industry Development Corporation, the Department of Energy and Minerals, the Solar Industries Association, the Solar Energy Association, the Commerce and Industry Department, the New Mexico Solar Energy Institute, leading bankers and executives, a marketing director, legal counsel, and a coordinator. The Project Manager is Mark L. Conkling, Ph.D.

Each Advisory Board member has contributed time and expertise in the interest of a successful project. One of the important aspects of this project was the creation of passive solar design guidelines and standards which were put together by the authors of this paper using LANL methodology.

Each builder is expecting to sell additional homes from models, and each participant in the project from landowners to builders to suppliers to bankers to the mortgage lender is expecting to turn a profit on their efforts. The motor for the project is private enterprise.

The prices established for the Showcase homes are competitive for homes in the area. Prices at Eldorado will range from $85,000 to $105,000 and at Rio Rancho from $72,000 to $90,000. The homes are in the 1,100 to 1,500 square foot range. The 16 designer/builders contribute variety in design, site location, and landscaping. Each builder has secured his own interim construction financing based upon a permanent mortgage commitment for the entire project from Southwest Mortgage Company, a leading Solar housing lender in New Mexico. They designed a permanent mortgage commitment that will set entry level interest rates in the 9.25% to 9.75% range if rates remain relatively stable. The key was to enable the most people possible to qualify for a mortgage.

Two Solar Villages were created with contract and deed restrictions to protect the builders in solar marketing. The neighborhoods involved will be all solar.

The Advisory Board was concerned about uniform product quality. Evaluation Criteria were established including conservation, solar performance, occupant comfort, aesthetics and livability, and builders were invited to enter the project based upon these criteria.

## 2. PASSIVE SOLAR DESIGN CRITERIA

There is still considerable confusion about "solar homes" in the marketplace. The range includes "solar" homes with only one south window to "solar" homes with acres of glass, a roof full of collectors, and a control room full of valves, pipes, bells and whistles, and the promise of a lifetime of maintenance. The solar homebuyer is often forced to make a significant judgement with inadequate information. The solar home builder is in a similar position, wanting to design and build good solar homes, but lacking the information needed to assure the performance of the design. If solar homes are to compete in the marketplace, they must be reliable and comfortable and the buyer must have some assurance that they will work. In addition, they must be mainstream homes that are affordable, attractive, and competitively financed.

Accordingly, the Advisory Board in establishing criteria, chose the combination of conservation and solar performance and occupant comfort as the touchstone. Builders and homeowners can easily understand a blend of good conservation strategies combined with good solar contributions to achieve the goal of energy conservation. The LANL methodology, translated into workable guidelines for the various climates and locations integrates easily into standard building trades and practices.

The Passive Solar Design Criteria can be categorized into two main components 1) Guidelines, and 2) Standards--A mandatory requirement for plans accepted into the Showcase by the Advisory Board was that each design had to meet the established project standards. Guidelines on the other hand were optional and simply offered to the designer/builder as a design tool to assure that the standards would be met. Both Guidelines and Standards used in this project were determined specifically for Santa Fe and Rio Rancho, New Mexico, based on LANL methodology according to the climate characteristics of these two cities.

### 2.1 Standards

The passive solar design standards translate into bottomline performance indicators that the home must meet. The standards are further divided into the following three categories: 1) Conservation Performance, 2) Solar Performance, and 3) Occupant Comfort.

- Conservation Performance--Establishes a maximum level of space heating energy the home may consume assuming no solar contribution. This is the total building heating load, the majority of which will be satisfied by the passive solar design. In this project the conservation standards are:

Santa Fe: 5 Btu/DD $ft^2$
Rio Rancho: 5 Btu/DD $ft^2$

- Solar Performance--Indicates the maximum amount of backup space heating energy the home may consume once the passive solar contribution is taken into account. This is the total building heating load minus the passive solar contribution, or in other words, the auxiliary space heating load. The values established for this load in this project are:

Santa Fe: 1.5 Btu/DD $ft^2$
Rio Rancho: 1.8 Btu/DD $ft^2$

- Occupant Comfort--Sets a limit on the maximum allowable clear-day temperature swing (CDTS) within the home. The CDTS is a good indicator of occupant comfort and is defined as the difference between the maximum and minimum temperature experienced in the house over several clear sunny winter days. The occupant comfort levels (CDTS) established for this project are:

Santa Fe: 12°F
Rio Rancho: 12°F

### 2.2 Guidelines

The guidelines used in this project provide the builder with a simple means of designing a home that will satisfy the above standards while minimizing building costs by balancing the costs of conservation and passive solar. Standards are much easier to establish than guidelines when the intent is to balance conservation costs with passive solar costs. The guidelines are divided into two categories: 1) Conservation, and 2) Solar.

- Conservation Guidelines--Are suggested insulation levels that will assure the home of meeting the conservation standards. Suggested R-values are made for walls, ceiling, floor, and windows. The builder is free to under-insulate in some areas and over-insulate in others provided the conservation standard is still met.

The purpose of these guidelines shown in Figure 1 is to help the builder meet the Conservation Standard.

Conservation Guidelines (±20 Percent)
The purpose of these guidelines is to help you meet the Conservation Evaluation Criteria listed on the following page. Decreasing one components's R-Value may be made up by increasing others.

| | Albuquerque | Santa Fe |
|---|---|---|
| Opaque Walls: | R-19 | R-21 |
| Ceiling: | R-30 | R-38 |
| Perimeter: | R-12 | R-15 |
| Frame Floor: | R-18 | R-21 |
| N.E.& W. Windows: | 2 panes | 2 or 3 panes |
| S. Glazing: | 2 panes | 2 panes |
| Infiltration: | ½ ACH | ½ ACH |

*R-value indicated is added to slab perimeter (No insulation required under slab.)

Fig. 1. Conservation Guidelines

- Solar Guidelines--Suggest to the designer the total solar glazing area and the amount of direct and indirect gain necessary to meet both the solar performance and occupant comfort standards. Since the occupant comfort standard deals with temperature swing, and temperature swing is related to the amount of thermal mass in the building, this guideline is different for each house. In order to determine this guideline the builder completes a worksheet titled the "Quick and Dirty Reference Design" which takes into account 1) house size, 2) room sizes, and 3) building materials. The result of the worksheet is the suggested area of direct gain and indirect gain passive solar components that will satisfy the solar performance and occupant comfort standards.

## 3. OTHER CRITERIA

In addition, builders were asked to subscribe to the New Mexico Solar Energy Industry Association's Code of Ethics. Good warranties were sought, and energy efficient appliances and water conservation techniques were strongly encouraged. Either an active or passive solar water heater was required as part of each home design, and both airflow and shading techniques were asked to be called out on the plans. If electricity was to be used as the primary backup heating source then the builder was required to isolate the heating circuits and to provide a separate meter base for the heating load. This, of course, enables the homebuyer, the builder, and the utility to track the actual consumption over time.

## 4. THE WORKSHEETS

The purpose of the worksheets is to provide a simple means of designing and evaluating a passive solar home. The worksheets are divided into three separate categories, 1) Quick and Dirty Reference Design, 2) Energy Requirements, and 3) Clear-Day Temperature Swing.

### 4.1 Quick and Dirty Reference Design Worksheets

These worksheets determine the amount of direct and indirect gain the design should have in order to meet the standards described previously. As indicated in Figure 2 in a partial reproduction of the worksheet, the designer must first assign each room in the home into either category A or B and enter the appropriate room area in the space provided. Category A is for rooms having direct gain windows, clerestories, or skylights. If a room does not have one of the above passive solar components but is connected to a room that does, the room area is entered under category B. Also included in category B are rooms adjacent to vented Trombe walls or greenhouses. Indirect gain components including unvented Trombe walls are ignored in this procedure.

QUICK AND DIRTY REFERENCE WORKSHEET

This worksheet will tell you how much direct gain you can use to maintain a comfortable temperature swing (12°F) and ensure a high solar savings fraction.

What you need to know:

1. Square footage of the home, excluding sunspace and garage. Use outside dimensions and enter here:

Total Square Footage_____.

You will need this number later.

2. Square footage of each room entered in the appropriate category.

Category A: Floor area of each room with direct gain. This includes South facing glass, clerestories, and skylights.

Category B: Floor area of each room without direct gain that connects to direct gain rooms by operable doorways. Also, include in this category the floor area of rooms with vented Trombe Walls, and those rooms adjacent to rooms with vented Trombe Walls.

Enter square footage below.

| | Category A | Category B |
|---|---|---|
| Living | | |
| Dining | | |
| Kitchen | | |
| Bedroom 1 | | |
| Bedroom 2 | | |
| Bedroom 3 | | |
| Bath 1 | | |
| Bath 2 | | |
| Entry Room | | |
| Study/Library | | |
| Den/Family Room | | |
| Other. | | |
| | | |
| | | |
| Line T: Totals | A:_____ | B:_____ |

Write these totals on line W, (page 5).

Fig. 2. Quick and Dirty Reference Worksheet

The next step is to do an inventory of building materials used in construction. The designer simply circles the appropriate building material in Figure 3 and totals the numbers in the two columns labeled Category A and Category B.

**Direct Gain Limit Calculation**

Instructions:

1. Circle the appropriate numbers in the points columns below corresponding to Category A and Catagory B. Refer to Page 3 for description of Catagories A and B. Simply underline your materials used and circle the number for each.

2. Then add up the circled numbers and enter on line U. Then go to step 3. You may need to average the numbers if your design uses a mixture of materials.

| | | Points Catagory A | Catagory B |
|---|---|---|---|
| Exterior Walls | Massive (6 in or more) | 8.1 | 3.1 |
| | Massive (2 in) | 3.6 | 2.6 |
| | Frame/Sheetrock | 0.3 | 0.3 |
| | Adobe | 4.7 | 2.5 |
| | Brick (4 in) | 5.3 | 2.7 |
| Interior Partitions | Massive (6 in or more) | 7.6 | 3.6 |
| | Brick (4 in) | 4.1 | 3.0 |
| | Frame/Sheetrock | 0.4 | 0.4 |
| | Adobe | 5.8 | 3.2 |
| Floors | Thick Slab (4 in or more) | 6.0 | 0 |
| | Thin Slab (2 in) | 3.4 | 0 |
| | Hardwood (1 in) | 1.1 | 0 |
| | Brick Pavers (1.5 in) On Wood | 2.9 | 0 |
| Ceilings | Massive (3 in) | 8.7 | 5.3 |
| | Frame/Sheetrock | 0.4 | 0.4 |
| | Wood (1 in) | 1.0 | 1.0 |
| | Acoustic tile | 0.2 | 0.2 |
| Furniture | | 2.6 | 2.6 |
| Line U: | Total Points | ____ | ____ |

Fig. 3. Direct Gain Limit Calculation

The last steps utilize the previous worksheet results to determine two important solar design guidelines: 1) the maximum total area of direct gain windows, clerestories, skylights, and vented Trombe wall the home should have in order to assure a clear-day temperature swing less than 12°F (Occupant Comfort Standard), and 2) the minimum area of unvented Trombe Wall and greenhouse the home must have to assure a low backup heating usage (Solar Performance Standard).

Step 3, Line Z in Figure 4 below indicates the suggested maximum direct gain area the builder should use in his design.

Step 3.

| | | | |
|---|---|---|---|
| Line V: | Enter total of Circled Points From columns A and B Line U. | (Points A) | (Points B) |
| Line W: | Enter total room Square Footage From line T. | (Sq.Ft. A) | (Sq.Ft. B) |
| Line X: | Multiply total points times total areas (line V times W) for each column separately. | | |
| Line Y: | Add the two numbers in line X together. | | |
| Line Z: | Divide line Y by 100 and enter here: | | sq.ft. |

Fig. 4,

Step 4, Line 5 in Figure 5 indicates the suggested minimum area of unvented Trombe wall and greenhouse the builder should use in his design.

Step 4.

**Balancing Direct and Indirect Gain Areas**

1. Enter total square footage of the home, excluding sunspace and garage (from page 3). _____ sq.ft.
2. For Santa Fe location, multiply the total square footage times 0.24 and enter here. _____.
3. For Albuquerque location, multiply the total square footage times 0.19 and enter here. _____.
4. From the previous table, enter the maximum direct gain square footage allowed (line Z): _____.
5. Subtract the answer found in (4) from the answer found in either 2 (Santa Fe) or 3 (Albuquerque) and enter here. _____ sq.ft.

Fig. 5. Balancing Direct and Indirect Gain Area

The Quick and Dirty Reference Design Worksheets provide the designer with a suggested passive solar design. From this point, the designer finalizes his plan and then makes a detailed check against the passive solar standards using the Energy Requirements Worksheets and Clear-Day Temperature Swing Worksheets described next.

## 4.2 Energy Requirements Worksheets

These worksheets indicate the total space heating requirement and auxiliary backup heating requirement of the home. They are based on the conservation levels and passive solar design used in construction. Through a series of simple calculations the builder can check his design against the conservation and solar performance standards. These worksheets consist of four calculation pages and three reference pages.

## 4.3 Clear-Day Temperature Swing Worksheets

These worksheets indicate the clear-day temperature swing the design will have based on the materials used for construction. If the Quick and Dirty Reference Design process has been followed the result of these worksheets will indicate a temperature swing less than 12°F in accordance with the Occupant Comfort Standard. These worksheets consist of one instruction page, one calculation page, and one reference page.

## 5. SIGNIFICANCE OF GUIDELINES, STANDARDS, AND WORKSHEETS

The significance of the Solar Guidelines and Standards Worksheet is far-reaching. As the Solar Industry matures, so do questions about standards and certification. Clearly, the topic deserves attention if

solar homes are to become mainstream homes of the future, and both the incentives and guidelines have to be widespread.

The worksheets are straight forward and simple to use and are based upon recognized research and proven performance. They can be altered for use in any climate and location. They can help the building profession bring passive solar into the mainstream marketplace.

The worksheets' greatest advantage may lie in their use in the self-education and design-evaluation process. A builder need not hire an outside consultant to determine how well his solar design will work, or what effect a design change will have on performance. The worksheets are a tool, permitting the builder to track quickly and easily the results of design decisions on performance, or to decide what design changes might be utilized to increase solar gain, reduce temperature swing, or achieve whatever performance change is required. The fact that this process can be completed by the designer/builder in the privacy of his or her own office, using only simple arithmetic, requiring no special tools or training, is a major breakthrough. Furthermore, this simple method does not dictate design but is applicable to any passive solar system, and by allowing the alteration of design and the incorporation of buyer preference, actually encourages creativity.

The authors believe that the worksheets provide a lure for builders, and that this process could help solve the problem of regulation. The solar industry needs to regulate itself not to have stifling, inhibiting regulations imposed upon it. These guidelines and standards could provide the key to such self-regulation.

The Solar Criteria Worksheets could become a breakthrough for real estate appraisers and mortgage lenders. Heretofore, appraisers have had only the slowly growing file of "comparables" to work with. They have had to factor hype against high quality solar performance, and they have had to hedge in favor of the marketplace, rather than "future savings" in order to accommodate the criteria of the secondary mortgage market investors. Mortgage lenders, although more alert to the long-term value of a solar home, have had problems with solar loans, and unfortunately, the problems are easily remembered. The mortgage lender really needs a simple way of knowing about: 1) The likely home heating requirement, 2) The likely solar contribution to the home heating needs, 3) The back-up heating needs and how this will relate to the borrower's monthly expenses, and 4) The assurance that the home will be comfortable, easy to maintain, and have a low probability of occupant complaints.

At best, the Solar Criteria Worksheet could be seen as charting a course toward workable and self-imposed standards for the solar housing industry nationwide. The standards would be imposed by the marketplace and consumers' lively search for quality in the products they buy. The consumer would soon learn that the transfer of theory to practice has actually been accomplished and that reliable solar homes are available and affordable and attractive.

A potential buyer could then be relieved of the judgment regarding the solar design, and could focus on the items most thought to influence a buyer's decision: floor plan, amenities, location, kitchen, closet space, and the like. The homebuyer wants to choose a home that is also solar rather than a solar home.

In the interest of applying the Solar Criteria Worksheet to other climatic conditions, plans for a possible American Showcase of Solar Homes are being formulated for 1984.

## 6. ACKNOWLEDGMENT

Like many technical papers, this one was put together at the last minute. We wish to acknowledge Sally Kinsey and the Graphic's Department of the Public Service Company of New Mexico. The typing services and general support they provided on such short notice helped the authors of this paper finish on time.

We also acknowledge Doug Balcomb of LANL for supporting the project and providing the necessary LANL methodology we needed to create the Showcase guidelines and standards.

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# TEST BOXES FOR COMPARATIVE AND COMPETITIVE EXPERIMENTS IN TEACHING PASSIVE SOLAR DESIGN

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## ABSTRACT

Two types of experimental projects were assigned to the author's passive solar course for Miami University students. Students constructed identical foam test boxes. These were used in teams to experimentally compare the performance of various assigned passive solar configurations. Each student, using data monitored collaboratively by the team, independently analyzed the results and presented conclusions. In a separate project, each student designed and constructed a liquid solar collector (active or passive). These were competitively tested and the results presented by each student in a technical paper.

## 1. INTRODUCTION

Passive solar test modules have been used extensively for the purpose of directly and indirectly comparing thermal performance of competing configurations. In addition, they have been used for computer code validation (Moore, 1982). Most researchers have employed full-height test rooms, in order to permit the effects of internal convection to be approximated. Less expensive, small test boxes have been used satisfactorily for experiments where the effect of convectional was negligible (Grimmer, et.al., 1979).

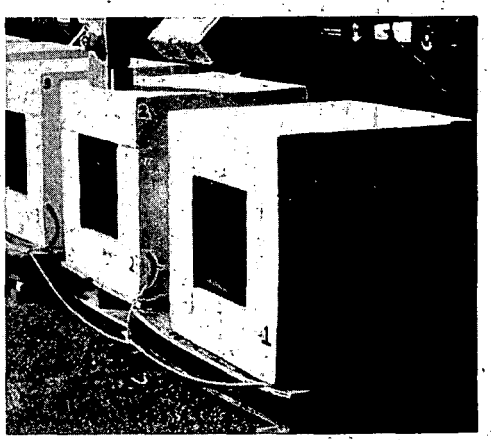


Fig. 1. Passive solar test boxes in use at Los Alamos National Laboratory.

## 2. STUDENT TEST BOXES

In a Saturday afternoon work party, the author's students constructed a total of 30 "beadboard" passive solar test boxes. The parts were cut from 3.25" thick foam sheets using a nichrome "hot wire" attached to a "Variac" transformer (borrowed from the Chemistry Department) in a temporary "jigsaw" configuration. The sides, top, and bottom were assembled using 6" "coat-hanger" staples followed by a tight wrap of duct tape. The front was left loose, and back was hinged with a wipe of silicone caulk across one side joint. Each student received eight concrete bricks, which could barely fit stacked in the box leaving only the black painted ends exposed to the glazing opening. This allowed configuring an 8" thick Trombe wall or direct gain mass. Glazing was a single layer of Saranwrap™. The loose front was covered on one side with aluminum foil to allow use as a shading overhang, night insulation, or horizontal reflector.

### 2.1 TEST BOX EXPERIMENTS

The objectives of assigned project experiments using these boxes were:

a) to gain an understanding of controlled experimental procedures.

b) to demonstrate the difference between temperature and heat.

c) to demonstrate the difference between radiation, conduction, and convection heat transfer.

d) to demonstrate the performance of various passive solar configurations.

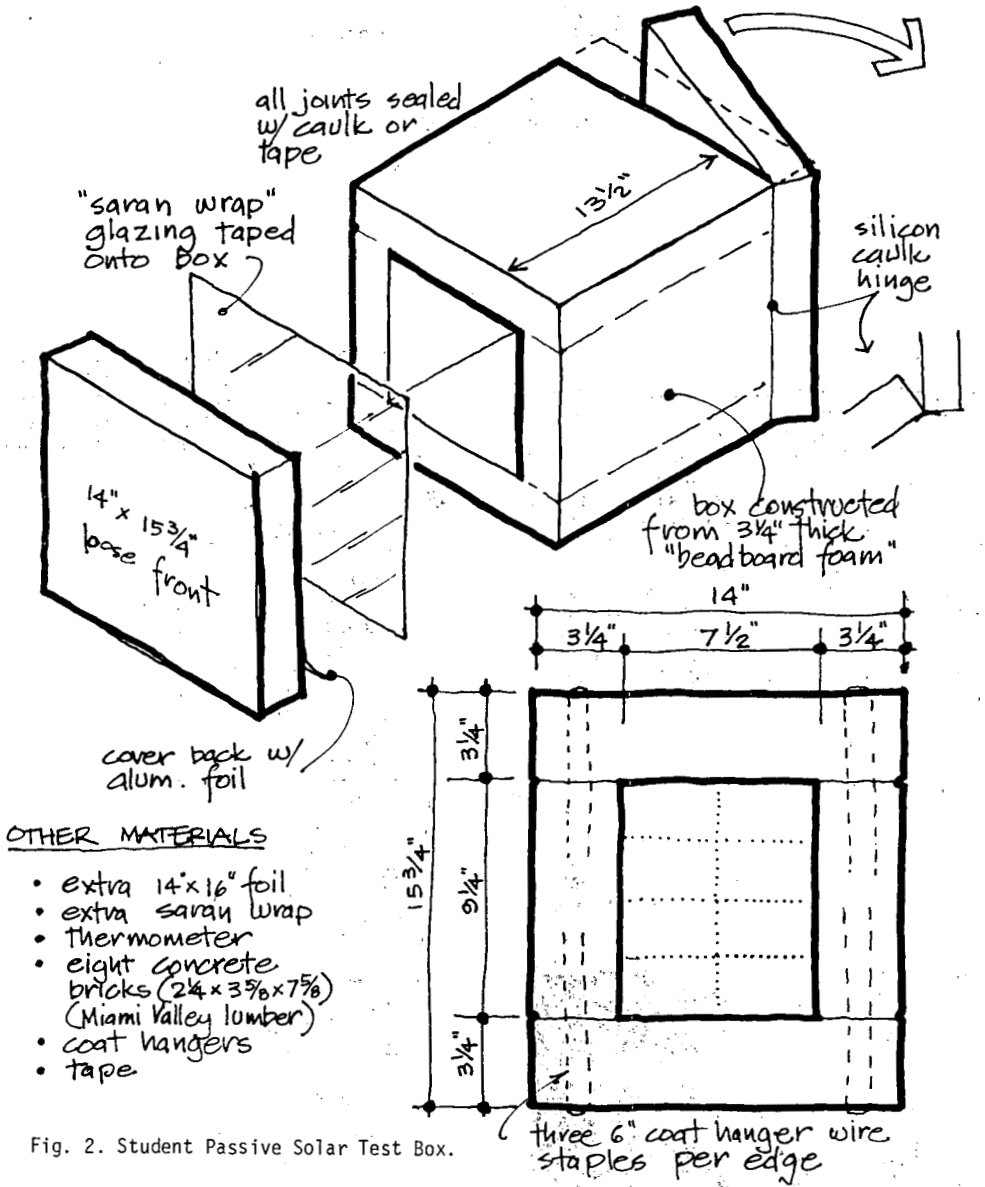



Fig. 2. Student Passive Solar Test Box.

e) to present and interpret data graphically.

f) to analyze data in terms of temperature differences, lag, swing, maximum, minimums, and means.

g) to explain performance differences specifically in terms of types and quantity of heat transfer.

Students worked in teams of two or four to monitor side-by-side experiments comparing an "experimental" vs. "control" configuration. After a 48-hour stabilization period, data weretaken over a 24-hour period manually at two hour intervals, using a bulb thermometer. The students recorded, graphically presented, and analyzed data on a standard "fill-in-the-blank" form. This was accompanied by a one-

page written discussion of conclusions. A total of six such experiments were conducted.

This series of projects were generally successful from an educational standpoint. However, the lack of an automatic data acquisition system (DAS) and a convenient, secure common outdoor location was a handicap. The logistics of gathering manual data were such a burden as to overshadow the learning process. An Aeolean Kinetics (1982) PDL 24 DAS will be available next year in conjunction with a fenced location. Finally, several of the mercury thermometers were broken (much to the dismay of the campus safety officer). This required a rather involved clean-up procedure of the spilled mercury droplets by university personnel in student dormitories, apartments, etc.

## 3. THE GREAT SOLAR COLLECTOR RACE

Near the end of spring semester, students individually designed and built a liquid solar collector. These were all tested simultaneously during a spring campus festival. The objective was to heat one gallon of water (from a common cold supply) as much as possible in one hour using a maximum of one square foot of collection area. Water lost due to leakage (or left trapped in the collector) had to be replaced with cold water from the common supply.

Reflectors and concentrating lenses were allowed, but the total projected insolation collection area was limited to the one square foot. Muscle power could be employed to make the system "active", except that friction heating was not permitted. Pre-heating of intrinsic collector mass was not permitted, and the minimum allowable reflectance of non-collecting surfaces was 40%. The collector could be re-oriented or reconfigured (i.e., add glazing layers as temperature increased) twice during the test period.

Students were started at staggered three minute intervals by a graduate assistant. During the test period, the instructor inspected evaluated, and discussed the design of each collector with the student.

At the end of the test period, the water was emptied into a measuring container, make-up cold water added if necessary, and the temperature taken by the instructor.

Evaluation was based on water temperature rise, innovation, craftsmanship, and "style". Each student submitted a final report on the project describing the design, thermal operation, test procedure, temperature rise, and collection efficiency (based on a common normal pyranometer reading). Graduate students were required to use the format of these proceedings, preparing the paper on 11in x 14in mats" and submit it in the form of photocopy.

This project has evolved over a period of five years and is very popular with the students. The testing is a festive event, is typically cheered by non-participants, and covered by the campus press and radio.

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Fig. 3. The Great Passive Solar Collector Race, 1982.

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# SOLAR ARCHITECTURE IN SCHOOLS: AN INNOVATIVE COMMUNITY APPROACH

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## ABSTRACT

An Architect-in-Schools program has completed its second year with a unique emphasis on solar architecture under joint funding from the New York Foundation for the Arts and the Schalmont Central School District. The program supported 84 sessions of an architect in residence. Hands on experimentation with solar design parameters culminated with the actual construction of solar greenhouse additions to two schools. These greenhouses were designed by students in grades 4 and 5 and were constructed as workshops involving the entire community. The program not only provided solar architecture as a synthesizing academic exercise for the school children, but also provided community consulting time and lectures on energy conscious design. The establishment of an annual Energy Fair further involved the community.

## 1. INTRODUCTION

One of the promising young solar architectural firms in the country is composed of elementary school children near Schenectady, New York. These young designers have already designed and constructed two permanent solar additions to their schools and have stimulated a community interest in solar and energy conscious design.

## 2. BACKGROUND

Starting in 1981, the Schalmont School District, under the direction of Ross Stagnitti and Laurence Weidler, received a grant for the Artists in Schools Program of the National Endowment for the Arts, administered through the New York State Foundation for the Arts. The school district chose to center their program around architecture with a unique emphasis on solar energy. The school district contacted RPI's School of Architecture for potential candidates for the Architect in Residence position. The author, a member of the RPI faculty, was selected to join the effort. The program accepted the premise that while the thrust of the activities would relate directly to children in grades four and five, educational opportunities should be presented to the entire community.

## 3. SOLAR ARCHITECTURE AS A VEHICLE FOR THE BASICS IN EDUCATION

The hands on architectural projects were quite simply fun for the students. Yet, the solar architectural design process tied itself directly to applications of math, research, public speaking in mock town meetings and public reviews, art, principles of physics and earth science, and social studies. Integrated meaning of the diverse curriculum was provided by the architecture program and the students responded with enthusiasm.

## 4. GETTING READY FOR SOLAR DESIGN

The program started with bi-weekly sessions with classes in two elementary schools. The students were given exploratory activities to introduce the tools and vocabulary of architecture. Solar design with little considerations for other architectural parameters was unacceptable. Thus, collage assemblies of all the elements that influence human reaction in spaces explored light, temperature, feelings, privacy, materials, acoustics, circulation and other components of architecture. Structure was explored through bridge and tower building using newspaper and masking tape or straws and pins. Introductory lessons to drawing, scale, and model building were given.

Exploring the basic design parameters of solar design was the next step. Controlled experimentation resulted in graphic data displays combined into a design resource notebook. The data were collected utilizing a home made device called an STM (solar testing module). Students constructed STMs using gallon cans from the school cafeteria, clear plastic as the collector, milk cartons

as a receptacle for thermal mass, and black paper as an absorber. The students then systematically varied interior color, exterior color, thermal mass, orientation, tilt, and envelope characteristics to provide themselves with solar design concepts and data.

The students then tackled two design experiments to extrapolate information and integrate conclusions from the STM data. First, they were assigned to design an enclosure to keep an ice cube as long as possible. Next, they designed another enclosure to melt an ice cube as fast as possible, outside on a clear winter day. The dialogue created in choosing among alternatives, testing and comparing results produced some polished young designers ready for the next design stage.

## 5. SOLAR ARCHITECTURAL DESIGNS

Students began to explore solar design within an environmental context by designing solar homes and solar fantasy schools. The designs were rendered through scale models, a media quite appropriate and exciting for the age group.

## 6. GREENHOUSE DESIGN AND CONSTRUCTION

The students formed mock architectural firms to proceed with the culminating project for the first year--the actual construction of solar greenhouses for each school. The complete architectural process was undertaken by the students. A research/programming phase collected data as to how the greenhouse might be used, necessary size, and acceptable microclimate variations.

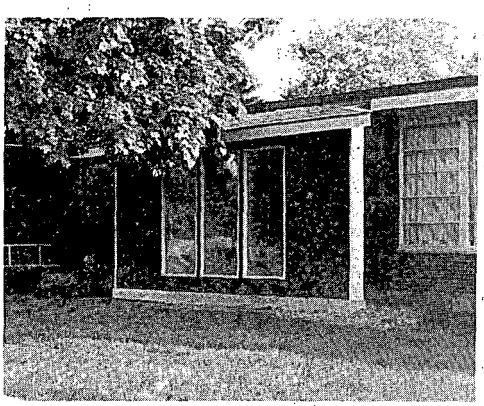


Fig. 1. Jefferson School Greenhouse



Fig. 2. Mariaville School Greenhouse

Students then analyzed and selected possible sites, built site models of existing conditions and individually proposed solutions via models. Public reviews of all solutions were held and several designs were synthesized by the architect into working drawings. Volunteers from the community then met with the students and proceeded to construct the greenhouses under student supervision. Material donations came from the community and the construction became a community workshop in itself.

## 7. THE SECOND YEAR

Monitoring equipment, complete with a program to store and display data on the schools' microcomputer, was installed in the completed greenhouses during the second year of the program. The greenhouses are used for science experiments on solar energy, plant growth and microclimate; and flower growing for both fund raising and Mothers Day presents.

The second year of the program added a third elementary school and further tapped the resources of RPI's School of Architecture. The author offered an independent study course to upper level and graduate architecture students to participate in Schalmont's program. The students provided additional interaction time and exemplified an excellent integration of university resources and community endeavors.

Design of classroom micro-environments that responded to identified classroom needs (e.g., craft center, quiet area, computer area) explored the ability to creatively use natural light and architectural space.

The primary thrust of the second year was a year long project whereby each school designed a community with the charge of

making it self sufficient. The land form was given, yet each school developed alternative solutions including examination of the use of solar energy on the building and community scales, wind power, waste recycling and generation, water power, and community planning. The students used role modeling to identify issues, advocacy groups to provide debate on alternative zoning directions, mock town meetings to decide issues, and several stages of design culminating in a large community scale model, complete with running water and electric lights.

## 8. A COMMUNITY PROGRAM

There is no question that the program in the school itself was successful. Several youngsters now want to be architects, but many at least have a clear awareness about solar design alternatives and energy conscious design methods. The program extended beyond the children, however. Elementary school children are often from families that are ready to expand, buy, or build their house. In response, the program elected to offer free consulting hours with the architect concerning building or energy matters to anyone in the community. Several dozen community members took advantage of the offer with projects ranging from recommendations for thermal draperies to residential addition concepts, to energy retrofit strategies for a church.

The consulting hours were supplemented by public displays of the architect's private work relating to solar design and retrofit. Two Energy Fairs were held with excellent community participation. Products of the residency were displayed and the community met in workshop fashion to plan the building of the greenhouse. The community also provided the basis for student field trips including the State University of New York at Albany's Solar Alumni Center, the RPI Passive Solar Visitors' Information Center in Troy, NY, and local passive solar homes. Furthermore, trips to the RPI's Center for Architectural Research and School of Architecture allowed students to see that their own design processes are paralleled in the "real" world and to explore some of the state of the art research being conducted at the university.

## 9. CONCLUSIONS

Beyond the construction of the greenhouses, the development of student skills and the community programs and consulting, lies the true test of the program's success--increased community awareness and pride. The program received excellent publicity in both local and national publications. This publicity provided a tremendous boost to the students' concept of self worth. The community and the students were recognized, and they are involved with solar architecture, now as fundamental to them as math, reading, and writing.

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# CURRICULUM FOR THE LOS ALAMOS METHOD

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## ABSTRACT

A curriculum for teaching the Los Alamos passive solar analysis method has been developed. The Los Alamos method is a quick and fairly accurate tool for estimating the perormance of a wide variety of passive solar configurations. However, the method as presented in Volumes 2 and 3 of the Passive Solar Design Handbook is not easily accessible to many people. We have developed a curriculum for a community college course in solar home design that presents the Los Alamos method in a coherent fashion. The curriculum has been tested and improved over three semesters. The performance of the students proves that the Los Alamos method can be taught to both professionals and novices with limited math background if the presentation is greatly clarified. This paper describes our curriculum and the steps taken to develop it.

## 1. INTRODUCTION

In this paper the authors will introduce the *Passive Solar Design Handbook* (1), hereafter known as the Handbook. We will describe the solar home design curriculum that utilizes the Handbook, discuss the advantages and disadvantages of using the Handbook to teach passive solar building design, and draw conclusions.

Solar home design classes that are taught at community colleges usually must meet a wide variety of needs: professional designers and builders wishing to integrate solar into their designs, undergraduates wishing to make solar energy their career, and homeowners wishing to design an energy-efficient home for themselves. Since buildings are too expensive to experiment with, a course purporting to teach solar home design must present a reasonably coherent design process that will result in a well-functioning solar building. The course must be a balance of qualitative design methods and quantitative analysis methods.

To meet these goals, a course must cover the following:

- building functional design
- building heat loss calculations
- solar energy basics
- passive solar types and variations
- climate
- sizing of solar components
- analyzing the effect on performance of design variations
- cooling

During the fall of 1981 we were challenged to develop a new curriculum for the solar home design class we were to teach in Spring 1982 at Cabrillo College in Santa Cruz, CA. Having previously used The Solar Home Book (2) and The Passive Solar Energy Book (3) as texts for the classes, we wanted to use something new and up-to-date. There was no single book that covered all of the above material with sufficient depth for the course. Particularly lacking were easy-to-use quantitative analysis methods. The (then) recently released versions of the Passive Solar Design Handbook: Volumes 1 and 2 by the Los Alamos National Laboratory represented the most up-to-date publication on passive solar design, and in particular, solar heating calculations.

Although the Handbook was not written as a textbook, and often was very clumsy to use as such, it was adopted as the primary reference material for the class the next semester. The course has been revised over three semesters now so that the following combination of texts provides the balance needed:

Designing Homes (4) by Les Walker and Jeff Milstein (to introduce building functional design),

The Passive Solar Energy Book by Edward Mazria (to introduce passive solar concepts and design options, and to provide rule-of-thumb sizing of solar components),

Passive Solar Design Handbook, Vol. 3, with supplementary material from Volume 2. (to provide a quantitative analysis tool for estimating heating performance).

## 2. THE HANDBOOK

The Passive Solar Design Handbook represents the results of a computer model that was developed at Los Alamos National Laboratory (LANL) to predict the performance of passive solar buildings in a variety of conditions. The researchers studied three types of passive solar buildings: Direct Gain, Thermal Storage Wall, and Sunspace. The computer similations were summarized into a set of hand calculation methods that should approximate (within 10%) the results of the detailed computer simulations, without the need for a computer.

There are two different methods in the Handbook to make heating estimates. Both methods give you the Solar Savings Fraction (SSF) for the building, which can then easily be used to determine the real figure-of-merit: the auxiliary energy use.

The "annual method" (using LCR tables) allows very quick estimates of performance. The speed comes from contraining the choices to 97 reference designs, in any of 200 cities. A ratio of the building heat loss to the solar glazing area is used in a table to estimate Solar Savings Fraction for the entire year. Variations from the reference designs are accounted for with Sensitivity Graphs. These allow you to adjust the SSF when certain design parameters, such as the amount of thermal mass, are varied. This method is appropriate even for beginners and those that do not have a facility for mathematics.

The "monthly method" (using monthly SSF calculations) requires stepping through a complex series of graphs, tables and calculations to determine the Solar Savings Fraction for each month. Again, the reference designs are used to get started, and sensitivity graphs allow for variations.

In the present one-semester course, only the annual method is presented. This method allows the designer to quickly select from a wide variety of system types and sizes, in almost any climate. The monthly method is a cumbersome gauntlet of equations and graphs, and is worth the effort only when the glazing configuration differs radically from the reference designs. It is very difficult to teach the monthly method because the material is so scattered throughout the Handbook.

## 3. THE CURRICULUM

We divided the solar design process into three main parts. The first is Prelimianry Design, in which the needs of the occupant are assessed, floor plan ideas are sketched, and passive solar system types are chosen. This stage emphasizes designing a livable home rather than a "solar" home. The second stage is Schematic Design, in which the floor plan is firmed up, the insulation levels are specified, and the solar components are sized by rules-of-thumb and located in the building. This stage emphasizes the various solar design options and their effect on thermal comfort. The third stage is Final Design, in which the performance of the building is calculated using the "annual method", and modifications are made to improve the performance.

### 3.1 Weekly Course Outline

Preliminary Design

1. Introduction to passive home design
2. Building functional design
3. Human comfort
4. Building heat loss calculations
5. Insolation and siting

Schematic Design

6. Direct Gain
7. Thermal mass sizing and locations
8. Thermal storage walls
9. Sunspaces
10. Cooling Design

Performance analysis

11. Direct gain--annual method LCR
12. Direct gain--sensitivity analysis
13. Thermal storage walls analysis
14. Sunspace analysis
15. Mixed systems
16. Review

### 3.2 Handbook Curriculum Details

-Introduce concept of computerized simulations.
-Demonstrate Building Load Coefficient calculations (using Volume 2 material).
-Solar Savings Fraction defined, and used to calculate auxiliary heat.
-Load Collector Ratio defined and calculated.
-Reference designs in Handbook are reviewed.
-Choosing the reference design and climate closest to your situation.
-Drawing LCR vs. SSF graphs using Appendix F.
-Using LCR/SSF graphs to performance trade-offs between different reference designs, different building heat losses, and different solar apertures.
-Introduction to sensitivity graphs (identifying what they are, where they are in the books, what the parts of the graph mean).
-Qualitative use of sensitivity curves as indicators of performance changes.
-Quantitative use of sensitivity graphs:
  -choosing the graph closest to your situation.
  -tracing a sensitivity curve that passes through the SSF for your reference design.

-Using particular and odd sensitivity graphs:
  -direct gain mass thickness
  -temperature bounds
  -sunspace storage volumes
  -sunspace glazing tilts
-Changing more than one design parameter at a time.
-Mixed systems (i.e., direct gain and sunspace) as a weighted average.
-Temperature fluctuations within solar buildings (from Volume 2).

A great deal of time was spent clarifying definitions of terms and outlining step-by-step procedures to enable beginning students to use the Handbook. These procedures were handed out in class, along with worked examples and assignements that closely follow the examples. This hand holding is necessary the first time through because the Handbook can be overwhelming, even for professionals.

Other supplementary material was prepared to enable students to easily manipulate thermal mass quantities such as density, volume, thickness, specific heat, heat capacity, mass-to-glazing area ratio.

## 4. ADVANTAGES AND DISADVANTAGES

The following are some advantages and disadvantages to weigh when considering using the Handbook for teaching a solar design class.

Advantages:

1. Up-to-date research and data. The LANL methods are referred to often in the solar literature and media.

2. Simple performance analysis method that can be done without a computer.

3. Methods quickly show how design changes affect performance.

4. Emphasis on only three basic types of passive solar: direct gain, thermal storage wall, and sunspace. It was easier to teach a few things in detail than many in general, especially such technical material.

5. Large volume of data and graphs to study. Much material to choose from for classes.

Disadvantages:

1. Handbook is poorly organized, and so may be inappropriate as a textbook. We spent a lot of time ourselves sorting out the information and developing clear procedures.

2. Handbook not introductory level, and so many of the terms and calculations needed clarification for community college students.

3. Lots of supplementary material required to round out the course:

   a. Superinsulated, underground, double-envelope, and other innovative designs are not discussed.

   b. Cooling is not covered and no method is prescribed to protect buildings from overheating.

4. Tables and graphs poorly labelled, and the technical vocabulary is inconsistent and confusing.

5. Methods are not quite complete enough. For example, there are no sensitivity graphs to deal with glazing that is tilted or off-south.

## 5. CONCLUSIONS

It is possible to teach a community college solar home design class that makes use of the Los Alamos methods. Most of the students were able to develop good solar designs and carry out the performance analysis on them. However, a great deal of supplementary material was needed to explain and round out the Handbook, and the poor organization and confusing terminology used in the Handbook make the teacher's job very difficult. The material is important and useful enough for someone to write a solar design textbook that: 1) presents the methods in a more coherent fashion, and 2) integrates the analysis methods into an overall design process. As an interim solution, William Shurcliff has produced a Simplifying Guide to Volume 3 (5) that provides more precise terms and clarifies many misleading concepts.

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# YOUR SOLAR HOUSE

## THIRTY-FIVE YEARS LATER

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ABSTRACT

The following study re-examines a 1947 book of passive solar house designs, the results of a project sponsored by a leading U.S. glass company. From interviews with people involved in solar research and energy-conscious design and using computer studies, an analysis of the reasons for the rise and fall of post-war solar design was conducted. It was found that net energy gained from solar proved to be a less significant influence on later developments than the aesthetic qualities for which these houses were also designed.

## 1. INTRODUCTION

In 1947, Simon and Schuster, in conjunction with Libbey-Owens-Ford Glass Company, published Your Solar House. This book compiled and discussed the plans for 49 passive solar houses, each designed for a particular state (and the District of Columbia) by one of its noted architects. Some of the better known contributors included Pietro Belluschi (Oregon), Louis Kahn (Pennsylvania), Hugh Stubbins (Massachusetts), John Lloyd Wright (Indiana), Albert Harkness (Rhode Island), and George Fred Keck (Illinois). The only limitation imposed on these architects was that the construction costs should not exceed $15,000 by pre-war standards.

This study chose four of these designs, and simulated their thermal performance using computers. The results were analyzed and interviews were conducted with several architects and building technology experts of the time, some of whose own designs were published in Your Solar House. It is hoped that this study will shed some light on an overall assessment of the period, the state of "solar" design in the 1940s , the context from which it emerged and the factors leading to the decline, until recent times, of energy conscious design.

## 2. APPEAL OF SOLAR

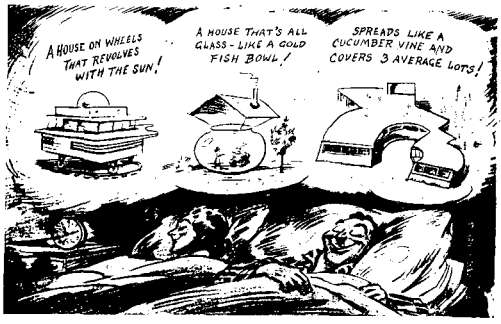
"If you say any one thing about a solar house, it's the fact of its livability. It's a grand place to live."(1)

In the United States, residential construction increased dramatically in the years following the second World War. After years of planning, people across the country were beginning to build their "dream houses" creating a market which was addressed by great activity in the commercial and building industries. It was this rapidly growing consumer public that the book, Your Solar House, tried to reach. Published in 1947, it attempted to articulate and encourage extensive use of Libbey-Owens-Ford's new invention, hermetically sealed, double pane insulating glass, called "Thermopane".

The desire to use more glass was certainly promoted by more than only those marketing the material. It was a characterstic of the times; the post-war era was marked by the availability and extensive use of glazing

(All quotes are from Your Solar House, Libbey-Owens-Ford Glass Company and Simon and Schuster, New York, 1947.)

(1) Lambert Ennis, Professor of English, Northwestern University, Evanston, Illinois, YSH, p. 22.




**Will your post-war Dream House be a Pipe Dream?**

of all kinds, conventional single pane as well as the new Thermopane. The "modern movement" was taking the pre-war picture window to an extreme, employing walls of glass in an attempt to merge the indoors with the outdoors. This increased spaciousness had great appeal for the new homeowners, as costs per square foot were becoming prohibitive. Adding visual space was an economical manner of virtually enlarging the residence.

Furthermore, great amounts of natural light were perceived as being especially beneficial to people's physical health as well as uplifting to their spirits. Those architects who studied or worked with Gropius at Harvard recall his dictums for exposing people to at least two hours of direct sunlight per day. Wright, Schindler, and others published similar advice. An ability to grow plants indoors and, indeed, to design with them, contributed further to the appeal of light, open, cheerful interiors.

The increased amount of daylight entering through south windows radically reduced the amount of artificial illumination required, diminishing electrical consumption and bills. Potential savings in heating costs were considered, but "savings on light and fuel [were] the smallest advantages of such a house." (2)

And, of course, solar houses had the appeal of most fashions, of being new, fresh and different.

> You wouldn't buy a 1912 car today if you could get a 1947 model, would you? Houses are just like cars. The new models are better. Better design ideas, better construction methods. It's just a better way to live than we knew in 1912.(3)

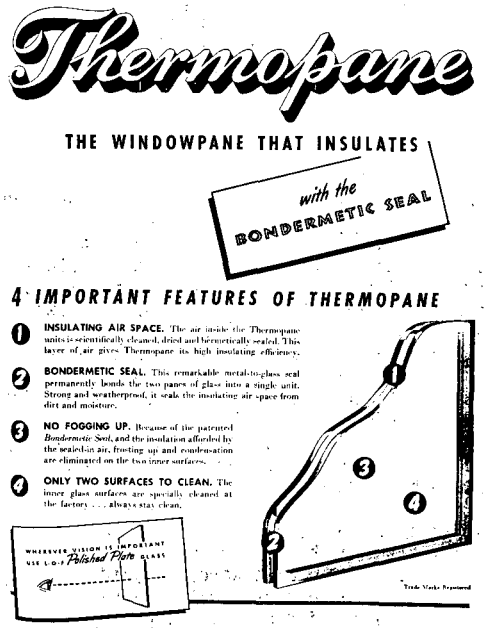
(2) Robert Sidney Dickens, Industrial Designer, Glenview, Illinois, YSH, p. 22.

3. EMERGENCE OF SOLAR BUILDINGS

These characteristics led to an emerging interest in solar homes. In 1942, "Solar Park," a very successful subdivision of 30 solar homes, was constructed with the foresight of developer Alfred Sloane, one of George Fred Keck's satisfied clients. After the war, more subdivisions were built in Massachusetts, Illinois, and elsewhere. A study done in 1941 (Peebles and Knopf, Illinois Institute of Technology) of Keck's Duncan house exposed classic difficulties in quantifying energy use in homes. After a year spent deciding which variables were known and which were indeterminate, Peebles and Knopf concluded that "the incoming solar energy offset most and probably all of the energy lost through the glazing." This dubious result was greeted favorably by the press in Progressive Architecture, Ladies' Home Journal and others; it seemed to prove that solar buildings "worked."

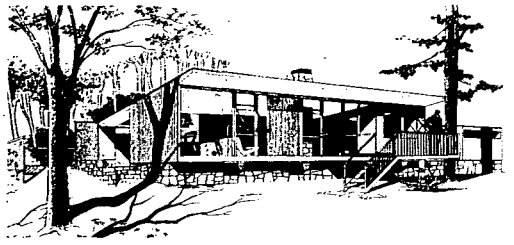
4. SOLAR DESIGN KNOWLEDGE: 1940's

What was meant in 1947 by a "solar house"? The original use of the term is most often attributed to the Chicago press, who employed it in reference to George Fred Keck's Sloane house, which received much publicity in the early '40's.




(3) Rudolph Teichner, Mechanical Engineer, Roslyn, New York, YSH, p. 21.





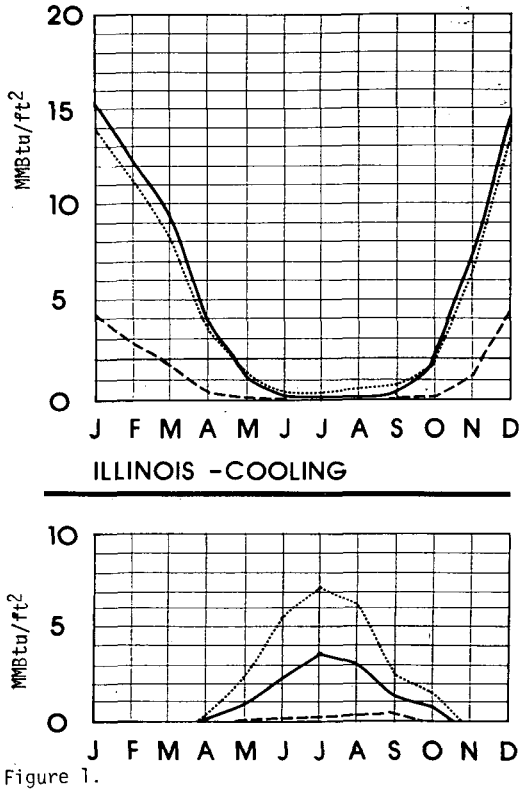



Figure 1.

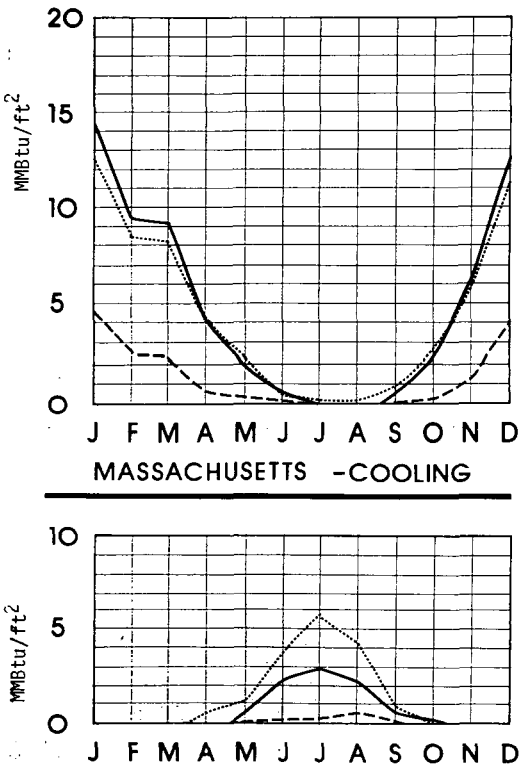
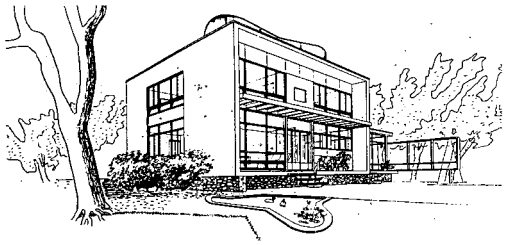



Figure 2.

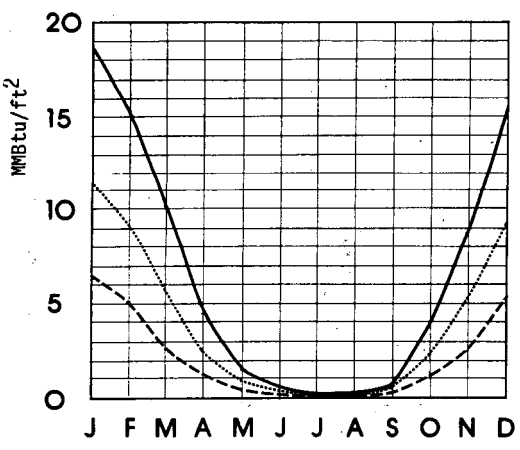
Although solar domestic hot water systems were well known, especially in the Southwest and in Florida, and solar collectors had been used to heat experimental buildings, the 1947 "solar house" was a passive, climate-influenced building. The designs in Your Solar House follow this pattern, and represent the spectrum of environmental concerns of architects of the day.

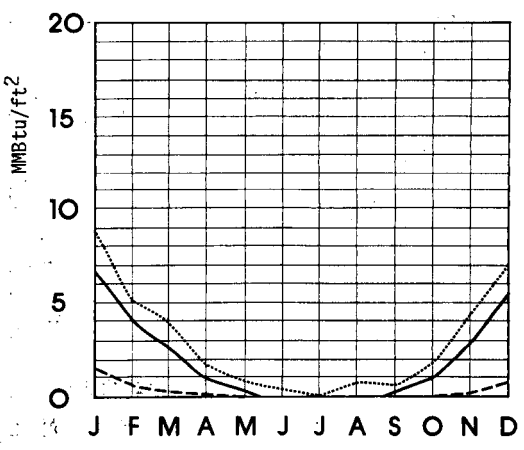
Most of the designs acknowledge the advantages of southern orientations. Methods of shading the great areas of southern glass, including the use of overhangs, awnings and deciduous plants were well-developed and clearly understood. Although benefits in energy consumption which accrued from the use of insulating Thermopane had to be balanced with the additional expense, the use of double glazing was considered fundamental to any solar design.

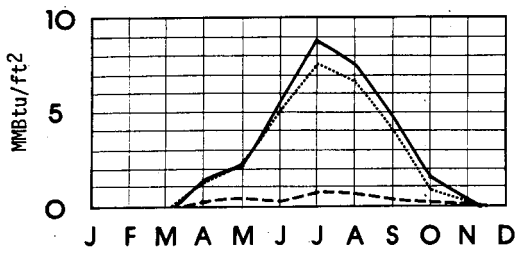
Attempts to store the sun's heat for night use (using thermal mass) were uncommon. Despite a wartime ethic of frugality, measures to conserve energy were not given high priority, nor was the potential effectiveness of energy conservation appreciated. Insulation was minimal in walls and ceilings. Drapes







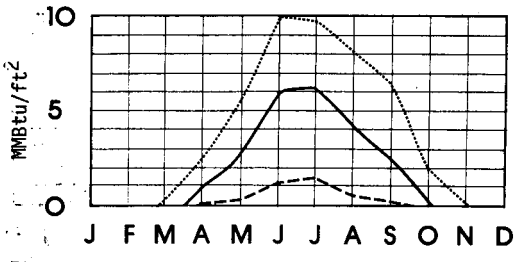




Figure 3.

Figure 4.

were customarily used, but their role as insulators was not further developed. Heat loss due to air infiltration, while an obvious problem, was not combatted effectively.

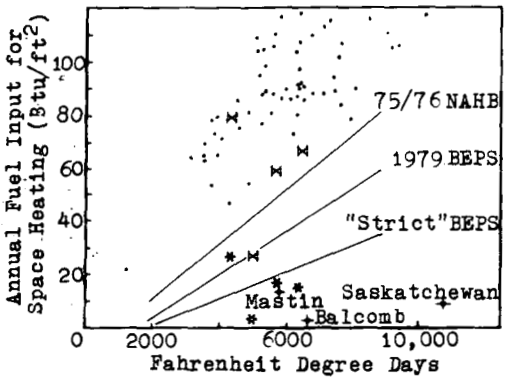
## 5. COMPUTER SIMULATION

Our study attempted to approximate the way these houses would have performed, and to see if the results from these studies would show first, how effective the houses were, according to various standards, and second, to what extent their (possibly poor) performance influenced the eventual lack of interest in "solar" design. Houses were modeled using Berkeley Solar Group's CALPAS 3 hourly simulation computer program. Four designs from Your Solar House were selected from climatically different geographic regions, and parametric studies were run. [Refer to Figures 1 to 4 ].

First (solid lines) the houses were run as they were designed in the book. Walls and ceilings were generally assumed to be insulated to a value of R-11 (the exception was New Mexico, where the adobe walls were specified to be insulated; a thermal resist-

| LOCATION | HEATING Btu/ft$^2$ | COOLING Btu/ft$^2$ | TOTAL Btu/ft$^2$ |
|---|---|---|---|
| MASSACHUSETTS | 5791 Degree Days | | |
| 1947 Standard | 56,451 | 16,055 | 72,506 |
| 1947 Solar | 60,582 | 8437 | 69,019 |
| 1983 Solar | 16,206 | 535 | 16,741 |
| ILLINOIS | 6310 Degree Days | | |
| 1947 Standard | 61,133 | 24,142 | 85,275 |
| 1947 Solar | 65,901 | 11,349 | 77,250 |
| 1983 Solar | 14,690 | 476 | 15,436 |
| WASHINGTON, D.C. | 4539 Degree Days | | |
| 1947 Standard | 46,758 | 27,731 | 74,489 |
| 1947 Solar | 79,033 | 32,101 | 111,134 |
| 1983 Solar | 24,900 | 2,801 | 27,701 |
| NEW MEXICO | 5138 Degree Days | | |
| 1947 Standard | 32,455 | 45,119 | 77,547 |
| 1947 Solar | 23,747 | 22,477 | 46,224 |
| 1983 Solar | 3,389 | 3,942 | 7,331 |

Figure 5. ANNUAL ENERGY CONSUMPTION




KEY

* = 1983 Solar Buildings Modeled
× = 1947 Solar Buildings Modeled
· = U.S. Building Stock

Figure 6. COMPARISON: ANNUAL ENERGY CONSUMPTION

ance of R-14 was assumed) with two air changes per hour. Overhangs and other kinds of shading devices, where appropriate, were modeled, as were concrete slabs, tile floors, and interior mass walls.

Second (dashed line) the houses were modeled at 1983 insulation and air infiltration standards and night insulation (R-5) was introduced. Third (dotted line) each house was compared with a "non-solar" house in the same region, the latter with random orientation and window placement, and with the assumed 1947 infiltration and insulation levels.

## 6. INTERPRETATION

When compared to a typical house in the same region, the solar house generally did not perform substantially better. While the designs were quite successful in addressing cooling needs, energy consumption for heating the houses was generally as great or greater than that of the typical 1947 house [Fig. 5].

The New Mexico house was an exception; in both heating and cooling, the solar design performs substantially better than the "typical" house. Residential mechanical cooling (through the use of "evaporative coolers") was only in use in arid climates, while heating systems were sufficiently well developed to meet heating needs of most climates. Therefore it is reasonable that architects were successful in addressing what was likely to be their first priority, reducing the cooling load, and less concerned with using solar design to lower the amount of energy needed for heating.

Finally, each design, when modeled using current passive solar building practices, consumed from one-sixth to one-third of the energy consumed by the typical 1947 house, bringing them into the range of today's best energy conserving houses [Fig. 6].

## 7. DECLINE OF SOLAR DESIGN

What led to the demise of energy-conscious design? Work on solar processes in academic circles stopped in the late 1950s and in commercial architecture designing with and controlling for the sun was no longer a central or even ancillary concern.

The energy effectiveness of solar design without conservation was (and still is) questionable. There were difficulties in quantifying how much energy buildings used, but by most common measures there was a lack of dramatic difference in overall energy consumption between solar and non-solar buildings. In addition, solar buildings often subjected their occupants to extreme temperature fluctuations; the lack of consideration of thermal storage meant buildings would often overheat on sunny winter days, necessitating venting which would waste the solar energy that had been collected.

There is some debate concerning how great the market's demand for solar houses really was, but the negative impact of the many misapplications cannot be ignored. Use of the term "solar house" became liberally applied to any "modern" house, those exhibiting large areas of glass but often with questionable orientation. These imitation solar houses performed much worse than conventional houses, baking people in the summer, and suffering

huge heat losses during the winter.

While an early characteristic of solar design was its ability to work with nature, it became increasingly allied with other trends to systematize building design (prefabricated homes, modular building systems). Passive principles were superceded by more marketable devices. Indeed, when a contest to design a solar heated residence was conducted in 1950, virtually every entry employed an active solar system. The development of sophisticated mechanical systems for residential central air conditioning and heating allowed the climatic comfort merits of solar design to be neglected in favor of other concerns. Environmental factors ceased to be significant influences on architectural designs.

The costs involved in site specific design, thermopane, and relatively large areas of glass made the investment in a solar house initially more expensive than a conventional design and less accessible to the general public concerned with high first costs. And of course, the constantly increasing availability of cheap fuel further led to the diminished importance of energy conscious design.

## 8. CONCLUSIONS

The designs which emerged in the 1940s for solar buildings displayed a crucial recognition of some fundamental principles of current passive solar design. The economic conditions of the late 40s and 50s discouraged sufficient development of knowledge and technology to make solar energy an effective source for space heating. Passive design was used as a way to maintain summer comfort levels and allow more daylight to penetrate. The greater use of glass led to aesthetic experimentation, providing amenities which had never before been possible.

While concern with the consumption of energy has varied with the tides of consumer economics, the inherent strengths of passive solar design remain. The liveablility, the struggle for light and the other aims of 1940s designers, are the qualities which lie at the core of current interest in passive solar design.

## 9. ACKNOWLEDGEMENTS

Our thanks to Harvey Bryan, Assistant Professor, Department of Architecture, Massachusetts Institute of Technology, for his never-ending help, advice, and encouragement. We would also like to thank the following people for generously taking the time to discuss with us their own positions in and assessments of the period:

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Robert Woods Kennedy, Author, Architect, Cambridge, Massachusetts;
Hugh Stubbins, Principal, Hugh Stubbins and Associates, Cambridge, Massachusetts.

The houses modeled in our computer simulations were attributed as follows:

New Mexico: John Gaw Meem
Washington, D.C.: Alfred Kastner
Massachusetts: Hugh Stubbins
Illinois: George Fred Keck

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"Two Developments...," Architectur l Forum, Vol 80, March 1944, p. 85.

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*Progress in Passive Solar Energy Systems.* Copyright 1983 by American Solar Energy Society, Inc. Printed in U.S.A.

0731-8626/83$3.00

# EDUCATIONAL TOOL FOR QUICK AND ACCURATE DAYLIGHTING ANALYSIS

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## ABSTRACT

An educational/design tool using a microprocessor based, multiple-cell photometer has been developed by the ENSAR Group for the analysis of daylighting schemes in both physical models and actual buildings. Unique aspects of the system are its ability to produce instantaneous CRT display and hard copy graphic output which provide the student/designer with quick feedback concerning the light distribution in the space.

A physical model of a building design can be tested and then modified to learn the effects of any number of building parameters on the daylight level and distribution in the space. This is perhaps the most effective way to learn about daylighting design concepts because it instantly shows the cause and effect relationship between building design parameters and daylight levels.

The system can also be programmed to act as a data-logger in order to monitor light levels over long periods of time (i.e., days or weeks) and store the data on magnetic tapes for later retrieval, plotting and analysis.

This paper describes the ENSAR Daylighting Analysis System, as well as illustrating its application with an example design problem.

## 1. INTRODUCTION

Physical models are often the best way to learn about the quantitative and qualitative aspects of daylighting schemes. Unfortunately, much of the student/designer's time and effort is often expended manually measuring and recording quantitative data using a lightmeter, leaving little time for studying the qualitative aspects of light in the space or even careful data analysis. Often when there is time to study the data, the designer realizes that mistakes or ommissions were made in his recording, necessitating that tests must be repeated. This is a time consuming and frustrating process. At best, it is often a matter of hours before the data can be plotted for easy study.

In contrast to the manual method, the ENSAR Daylighting Analysis System provides the student/designer with a quick, accurate and organized method for obtaining and recording data in a graphic format, easily understood by design professionals. This system not only allows for the investigation of more options in a shorter period of time, but also leaves much more time to study the qualitative aspects of light in the space.

## 2. SYSTEM DESCRIPTION

The ENSAR Daylighting Analysis Program consists of a computer and a data acquisition system (1) (Fig. 1 & 2).

An array of photometers is used in the physical model to measure the light at several locations. Generally, the light is measured along a line perpendicular to an exterior wall. The photometric sensors are placed along this line at regular intervals. Two exterior photometric sensors also measure the vertical and horizontal daylight available outside the model. All sensors are connected to a microcomputer through custom-built scanning equipment.

The software for the microcomputer is designed to interpret the light measurements in various forms. Generally, the light distribution in the space is displayed in graphic format on a CRT display, and recorded on hard copy. Light distribution curves which plot location in the space vs. illumination, are generated for various schemes and printed for future evaluation, comparison and presentation.

The student/designer can modify aperture locations, sizes, and shapes, as well as surface reflectivities, space geometry, glazing light transmittance, light, diffusing techniques, and other design considerations. With each modification of the physical model, the student can promptly generate an updated

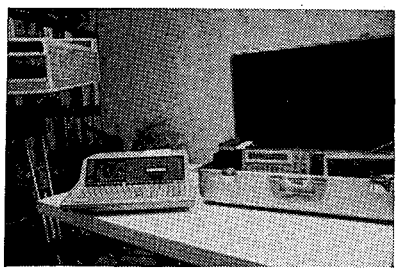


Fig. 1. ENSAR Daylighting Analysis System, L to R, model, HP-85, instrument case containing calibration connectors, A to D converter and scanner.

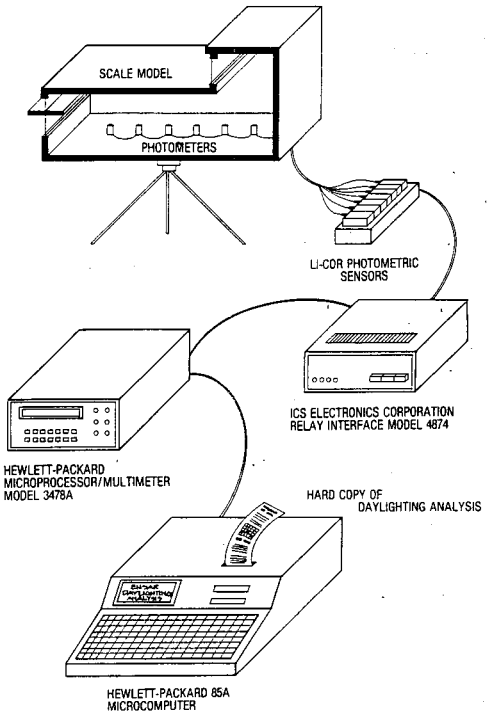



Fig. 2. System schematic

light distribution curve, which relates the modification directly to lighting performance. The out-put of the analysis system also includes the following information:

Project title
Test identification
Time of test
Available light outside model:
  Horizontal plane (footcandles)
  Vertical plane (footcandles)
Interior Light Levels:
  Sensor #
  Sensor Location (distance from wall)
  Illumination (footcandles)
  Coefficient of utilization*

Sample outputs are illustrated in Figures 3 through 6.

## 3. EXAMPLE DESIGN EXERCISE

In order to illustrate the application of the ENSAR Daylighting Analysis System, a recent project will be presented in the following text. The project is a multipurpose gym/auditorium/cafeteria for the Saint Mary School, located in Derby, Kansas. ENSAR Group assisted the architectural firm of Eldon B. Swensson, AIA, Witchita, Kansas, with the elvaluation of daylighting application for the building design. After a preliminary design was selected, a scale model was constructed at the scale of 1/2" = 1' 0". Photometers were installed in the model at the positions indicated in the schematic section (Fig. 3).

A series of tests were performed using the model out-of-doors in order to evaluate the daylighting design. The first test, as documented in Figure 3, confirmed that there was adequate light levels in the space. Note that the average of 200 footcandles across the section on a clear February afternoon does not account for losses due to mullions or glass transmission, so levels in the actual building would be a bit lower. Once it was determined that the design was in the proper range of light quantity, the quality and uniformity of lighting the space was analyzed.

A series of tests (Fig. 4 - Fig. 6) illustrates the amount of light from each source by selectively closing apertures so that each run only measures the light coming from one aperture. This allows for evaluation of light distribution from each aperture. For

* The coefficient of utilization at a point is defined as the ratio between interior and exterior illumination levels. Vertical or horizontal plane exterior illumination levels are used, depending on aperture arrangement.





ST MARY ACTIVITY CENTER
FEB 2PM ALL OPEN
TIME 13:52

| OUTDOOR SENSORS | FC. |
|---|---|
| Horizontal | 5065 |
| Vertical | 8474 |

INDOOR SENSORS

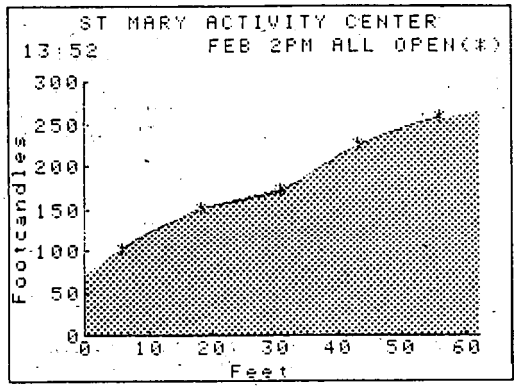
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| 3 | 31.0 | 173 | .020 |
| 4 | 43.5 | 226 | .027 |
| 5 | 56.0 | 258 | .030 |

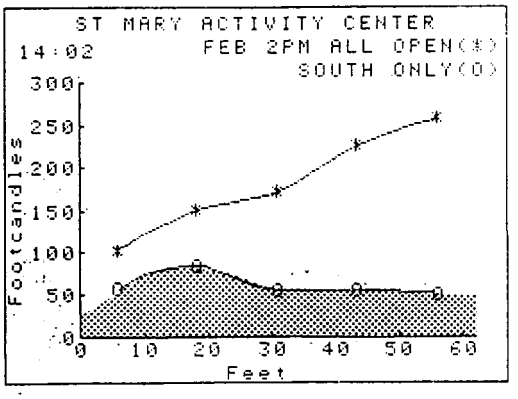
ST MARY ACTIVITY CENTER
SOUTH ONLY
TIME 14:02

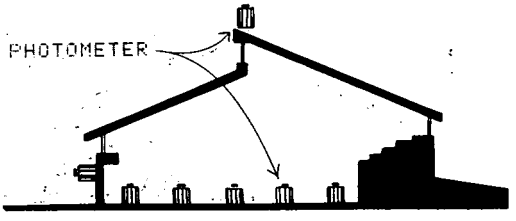
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|---|---|
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| Vertical | 7817 |

INDOOR SENSORS

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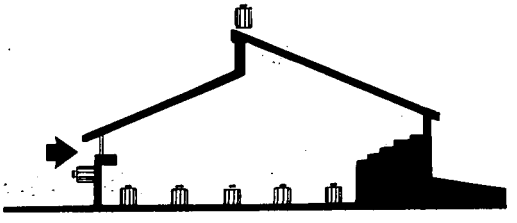



Fig. 3. Preliminary scheme, all apertures contributing, February, clear sky, 2:00 pm.

Fig. 4. Preliminary scheme, only south transom contributing, February, clear sky, 2:00 pm.

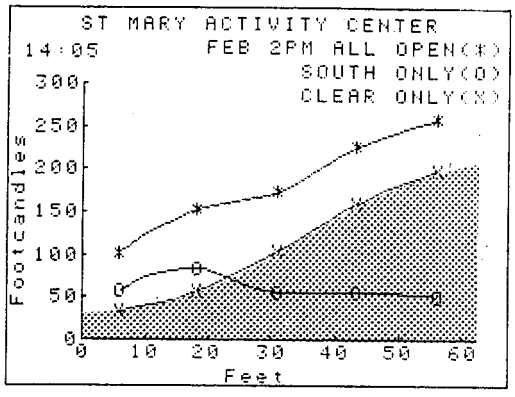


ST MARY ACTIVITY CENTER
CLEAR ONLY
TIME 14:05

| OUTDOOR SENSORS | FC. |
|---|---|
| Horizontal | 4802 |
| Vertical | 8347 |

INDOOR SENSORS

| # | Dist | FC. | C.U. |
|---|---|---|---|
| 1 | 6.0 | 35 | .004 |
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| 3 | 31.0 | 104 | .012 |
| 4 | 43.5 | 160 | .019 |
| 5 | 56.0 | 199 | .024 |



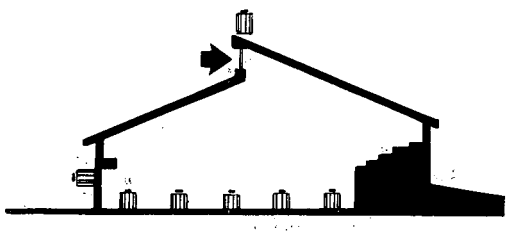
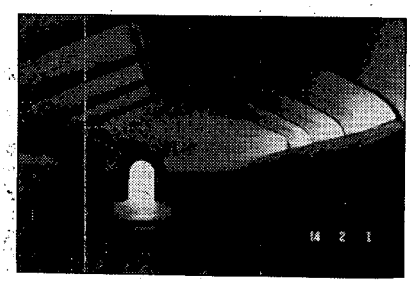



Fig. 5. Preliminary scheme, only clerestory contributing, February, clear sky, 2:00 pm.

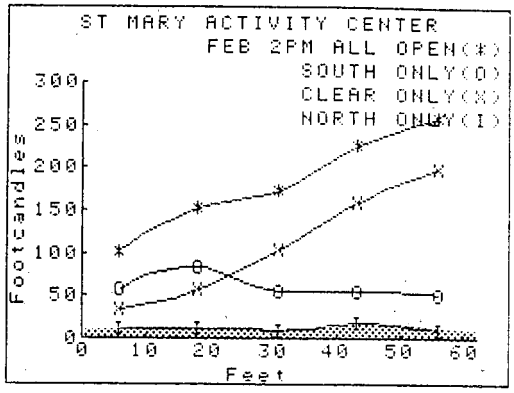


ST MARY ACTIVITY CENTER
NORTH ONLY
TIME 14:05

| OUTDOOR SENSORS | FC. |
|---|---|
| Horizontal | 2374 |
| Vertical | 8327 |

INDOOR SENSORS

| # | Dist | FC. | C.U. |
|---|---|---|---|
| 1 | 6.0 | 11 | .003 |
| 2 | 18.5 | 12 | .004 |
| 3 | 31.0 | 10 | .003 |
| 4 | 43.5 | 18 | .005 |
| 5 | 56.0 | 8 | .003 |



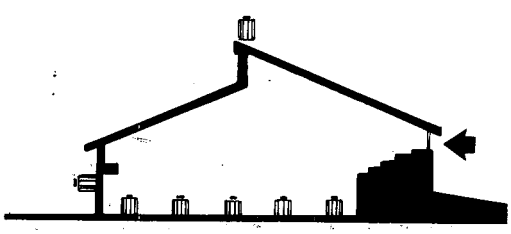



Fig. 6. Preliminary scheme, only north aperture contributing, February, clear sky, 2:00 pm.

example, Figure 4 only considers the light from the south transom aperture.

Note that the system is capable of overlapping contours to facilitate easy comparison. This is illustrated in Figure 4 where the contour from Figure 3 is still visible.

This entire sequence of four contours (Fig. 3-6) was generated in fifteen minutes by one individual. This included the time required to modify and photograph the model. This is many times faster and much more accurate than would have been possible had the test been manually conducted with a single photometer.

After studying this first series of data, it was decided that a baffle would be added in front of the south transom window in order to eliminate glare which would hamper the view of spectators in the bleachers area.

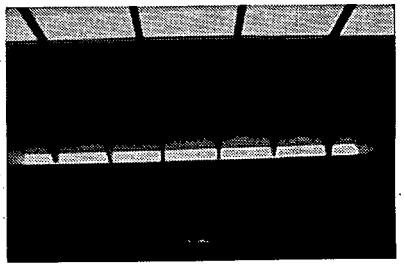


Fig. 7. Interior view looking from bleacher area towards south wall. Photo shot with camera in automatic mode. Note high contrast.

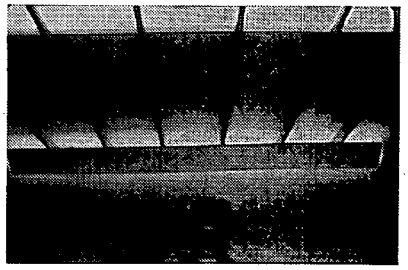


Fig. 8. Similar to Fig. 7 only with addition of opaque baffle in front of south transom window. Note lower contrast, photometers are clearly visible.

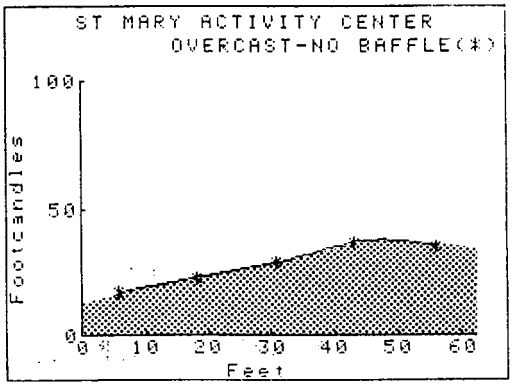
The baffle proved to be desireable not only from the standpoint of reduced glare (Fig. 7 & 8), but also in terms of uniformity. As is evident in the comparison between Fig. 9 & 10, the baffle tended to produce a more uniform light in the space. Thus, the resulting design has improved the quality of daylighting due to the reduced glare and better uniformity.

ST MARY ACTIVITY CENTER
OVERCAST-NO BAFFLE
TIME 14:31

| OUTDOOR SENSORS | FC. |
|---|---|
| Horizontal | 1604 |
| Vertical | 1131 |

INDOOR SENSORS

| # | Dist | FC. | C.U. |
|---|---|---|---|
| 1 | 6.0 | 17 | .015 |
| 2 | 18.5 | 23 | .020 |
| 3 | 31.0 | 29 | .025 |
| 4 | 43.5 | 37 | .033 |
| 5 | 56.0 | 35 | .031 |



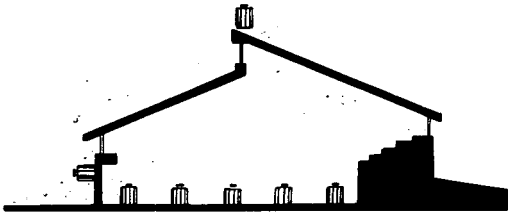



Fig. 9. Preliminary scheme, all apertures contributing, overcast sky.

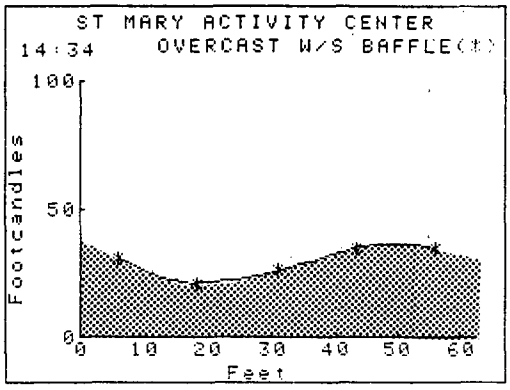


ST MARY ACTIVITY CENTER
OVERCAST W/S BAFFLE
TIME 14:34

| OUTDOOR SENSORS | FC. |
|---|---|
| Horizontal | 1773 |
| Vertical | 1372 |

INDOOR SENSORS

| # | Dist | FC. | C.U. |
|---|---|---|---|
| 1 | 6.0 | 31 | .022 |
| 2 | 18.5 | 21 | .015 |
| 3 | 31.0 | 26 | .019 |
| 4 | 43.5 | 35 | .025 |
| 5 | 56.0 | 35 | .025 |



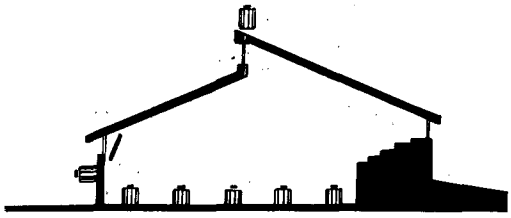



Fig. 10. Modified scheme with baffle, all apertures contributing, overcast sky.

## 4. CONCLUSION

The ENSAR Daylighting Analysis System provides a powerful tool for the education of design professionals regarding the relationship between building form and daylight distribution in a space. It is particularly useful because of its ability to generate graphic daylighting contours in the field as modifications are made to a model. This allows the designer to develop an intuitive cause and effect relationship for future reference.

The ENSAR Daylighting Analysis System has been successfully used as an educational tool in "Energy in Architecture" seminars conducted by the American Institute of Architects. Present plans call for using the system in educational programs at Harvard, MIT, and the University of Colorado - Denver.

## 5. ACKNOWLEDGEMENT

The authors would like to acknowledge the assistance of Peter Mullineaux, Allan Mitchell and John Ehlers in the development of this instrumentation package.

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# A GAS-FIRED HEAT PIPE ZONE HEATER FOR PASSIVE SOLAR BUILDINGS

C. Byron Winn • Allan Kirkpatrick **

Francis deWinter++

## ABSTRACT

A heat pipe zone heater for backup heating in passive solar buildings is described. The gas-fired zone heater has lower operating costs than alternative zone heaters. It also has the boiler outside the building envelope and the condenser inside so that combustion products are not generated inside the conditioned space. Energy conserving features of the zone heater include a low thermal capacitance boiler, low flue gas temperature due to the self-regulating effects of the heat pipe, the use of outside combustion air, and elimination of vent penetrations of the heated envelope (only a small diameter, easily sealed transport section of the heat pipe will penetrate the envelope).

The use of the zone heater with a passive heating system results in reducing life cycle costs for heating and also affects the Conservation Factor for the various passive system types and locations. The conservation factor gives the optimal combination of energy conservation and passive solar design for a building. The conservation factor is modified in this paper to account for the use of a zone heater in a given zone in an energy conserving passive solar building. Analytic solutions to constrained and global optimizaton problems are also presented.

## 1. INTRODUCTION

The use of a zone heating device can lead to a reduction in the annual heating energy requirements for a building while still maintaining comfort conditions in any given zone of the building when desired. The sizing of the zone heater can affect the energy savings realized. An analytic solution to the zone heater sizing problem is presented in this paper.

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## 2. GENERAL HEAT PIPE CONFIGURATION, MATERIALS AND WORKING FLUID

A copper/water heat pipe is the most attractive material combination for the two phase heat exchanger. Water is ideal since it possesses superior heat transfer characteristics to any other potential fluid. At the operating temperatures of a space heater (180-220°F), water does not have excessive vapor pressure, making it safer than other fluids, such as Freons, which would operate in excess of 100 psig. Also, perhaps more importantly, the vapor density and heat of vaporization of water result in low enough vapor velocity so as to permit counter flow of vapor and condensate in a single, reasonably small diameter pipe. With other working fluids, a separate condensate return would probably be necessary. With water selected as the working fluid, copper or cupro-nickel is necessary for the heat pipe container so as to avoid non-condensible gas generation.

### 2.1 CONDENSER

The condenser required for the space heater is of the convector/radiator variety. To minimize liquid hold up, vapor passages need to be kept to a minimum. A geometry which minimizes the length of condenser tube passages is a finned tube of the type used in conventional hydronic baseboard heaters. A commercially available unit has been selected for the prototype zone heater. It employs two 24-inch long, 1/2-inch diameter copper flow passages with radial aluminum fins. The heat exchanger is housed in a 24 " x 14" x 4-1/2 " sheet metal enclosure which promotes convection and serves as the "radiator."

### 2.2 EVAPORATOR/ADIABATIC TUBE

With the zone heater constructed as a single pipe heat pipe, the evaporator should be an integrated extension of the adiabatic tube. The preliminary evaporator design is a 6-inch long copper-finned tube of the type used currently for constructing gas-fired boilers. Dimensions of the evaporator tube are 7/8 " ID x 1-7/8" fin OD x 7 fins/inch x .072 " wall thickness.

With the low mass flow rates associated with the design, erosion should not be excessive with a copper evaporator tube. However, this can only be determined conclusively after many hours of actual operation. The prototype heater uses a copper evaporator. If at some point it is concluded that erosion is excessive, a copper/nickel alloy tube can be substituted without significant performance penalty.

An adiabatic tube of approximately 3/4-inch diameter extends from the end of the evaporator and slopes up to the condenser. With a single pipe system the condenser does not need to be more than several inches higher than the evaporator.

## 2.3 BURNER/FIREBOX

The burner for the space heater is a drilled port atmospheric pipe burner. A 3/8-inch diameter pipe with a series of drilled holes is suspended below the evaporator tube. Gas and primary air are supplied to the burner through a mixer at the pipe inlet. The burner and evaporator are integrated into a firebox which directs hot combustion products past the evaporator and then to the flue. The current firebox design uses a stainless steel box insulated with ceramic fiber.

## 2.4 USE IN BUILDING

The use of the zone heater in a two zone building is described next. Consider a building comprised of two zones, 1 and 2. Zone 2 is maintained at some nominal baseline temperature, say 15.6℃ (60℉), whereas the temperature in zone 1 is to be maintained at certain time periods at a higher temperature, say 20℃ (68℉). A zone heater provides the additional energy required for the higher temperature in zone 1. In addition, we may consider the use of a passive solar heating system to provide some portion of the baseline energy required and energy conservation to lower the overall energy requirement.

The cost of passive solar may be written as

$$C_{PS} = a\, A_P + e \qquad (1)$$

where $A_P$ is the projected collector area and a is the incremental cost for passive solar. The cost of energy conservation is [1]

$$C_{EC} = \frac{b}{L_T} - c \qquad (2)$$

and the cost of the zone heater is

$$C_{ZH} = d\, A_{ZH} + f \qquad (3)$$

where d is the incremental cost for the zone heater and $A_{ZH}$ is the zone heater area. The purchased energy required is

$$AUX = (1\text{-}SSF)\, L_T * DD_{LB} + Q_{ZH} \qquad (4)$$

where SSF is based on maintaining the entire building at the lower temperature, $L_T$ is the total building load coefficient, and the degree-days are based on the lower base temperature.

The energy supplied by the zone heater is given by

$$Q_{ZH} = (L_1 + L_i)\, \Delta DD = L_1\, (1 + F)\, \Delta DD \qquad (5)$$

where $L_1$ is the building load coefficient for zone 1, $L_i$ is the interzonal load coefficient between zones 1 and 2, F is $L_i/L_1$, a nondimensional load coefficient, and $\Delta DD$ represents the difference between the degree-days to the higher and lower bases.

From basic heat transfer analysis, the area of the zone heater, $A_{ZH}$, is related to its power output by

$$\dot{Q}_{ZH} = k\, A_{ZH} \qquad (6)$$

where $k = h_{ZH}\, (T_{ZH} - T_1) \cong h_{ZH}\, T_{ZH}$, the product of the zone heater heat transfer coefficient and temperature. Also, expressing equation (5) as a rate equation:

$$\dot{Q}_{ZH} = \frac{1}{24}\, L_1\, (1+F)\, \Delta T \qquad (7)$$

where $\Delta T$ represents the temperature difference between zones 1 and 2. The factor of 24 is required since $L_1$ is given in terms of kJ/degree-day (Btu/DD). Hence

$$A_{ZH} = L_1\, \frac{\Delta T}{24k}\, (1 + F) \qquad (8)$$

## 3. CONSTRAINED OPTIMIZATION PROBLEM

The constrained optimization problem is to minimize the purchased energy, AUX, subject to a constraint on the initial amount of money , $C_I$, to spend on energy conservation, passive solar, and the zone heater. Using LaGrange multipliers, the function J is to be minimized.

$$J = AUX + \lambda\{C_I - C_{PS} - C_{EC} - C_{ZH}\} \qquad (9)$$

Upon substitution

$$J = (1-SSF)\ L_T\ DD_{LB} + (L_T - L_2)\ (1+F)\ \Delta DD + \lambda \{C_I - (a\ A_p + e) - (\frac{b}{L_T} - c) - \left[d\ \frac{\Delta T}{24k}\ (L_T - L_2)\ (1 + F) + f\right]\} \quad (10)$$

Now we wish to find $A_p$, $L_T$ and $\lambda$ to minimize J. The necessary conditions are:

$$\frac{\partial J}{\partial A_p} = - L_T\ DD_{LB}\ \frac{\partial (SSF)}{\partial A_p} - \lambda a = 0 \quad (11)$$

and

$$\frac{\partial J}{\partial L_T} = (1-SSF)\ DD_{LB} - L_T\ DD_{LB}\ \frac{\partial (SSF)}{\partial L_T} + \Delta DD - \lambda d\ \frac{\Delta T}{24k} + \frac{\lambda b}{L_T^2} = 0 \quad (12)$$

From the first necessary condition,

$$\lambda = -L_T\ \frac{DD_{LB}}{a}\ \frac{\partial (SSF)}{\partial A_p} \quad (13)$$

But

$$\frac{\partial (SSF)}{\partial A_p} = \frac{1}{L_T}\ D \quad (14)$$

where

$$D \triangleq \frac{\partial (SSF)}{\partial (1/LCR)} \quad (15)$$

and LCR is the load collector ratio, defined by

$$LCR \triangleq \frac{L_T}{A_p} \quad (16)$$

Hence

$$\lambda = - \frac{D * DD_{LB}}{a} \quad (17)$$

Substituting into the second necessary condition gives

$$(1-SSF)\ DD_{LB} + \Delta DD + DD_{LB}\ \frac{A_p}{L_T}\ D + (\frac{b}{L_T^2} - d\ \frac{\Delta T}{24k})\ (\frac{-D * DD_{LB}}{a}) = 0 \quad (18)$$

where we have used

$$\frac{\partial (SSF)}{\partial L_T} = - \frac{A_p}{L_T^2}\ D \quad (19)$$

The above equation may be solved for the optimal building load coefficient, $L_{T_o}$. The result is

$$L_{T_o} = \left\{ \frac{b * LCR/a}{1 + \frac{LCR}{D}\left[1 - SSF + \frac{\Delta DD}{DD_{LB}}\right] + \frac{\Delta T}{24k}\ \frac{d}{a}\ LCR} \right\}^{1/2} \quad (20)$$

This reduces to equation (16) in Ref. [1] for the optimal building load coefficient if $\Delta DD$ and d are set to zero.

## 4. GLOBAL OPTIMUM

The life cycle cost may be written as

$$LCC = (e + a\ A_p + \frac{b}{L_T} - c + d\ A_{ZH} + f)\ E_1 + [(1 - SSF)\ L_T\ DD_{LB}\ C_f + Q_{ZH}\ C_f]\ E_4 \quad (21)$$

where $E_1$ and $E_4$ are economic factors and $C_f$ is the initial cost of fuel[3]. In Ref. [1], $E_1$ is unity and $E_4$ is equal to the fuel cost levelizing factor divided by the fixed charge rate. In the notation of Ref. [1], let

$$h = C_f\ DD_{LB}\ E_4 \quad (22)$$

and

$$E_1 = 1$$

Then

$$LCC = e + a\ A_p + \frac{b}{L_T} - c + d\ A_{ZH} + f + (1-SSF) L_T\ h + Q_{ZH}\ C_f\ E_4 \quad (23)$$

Upon substitution of (7) and (8),

$$LCC = e + a\ A_p + \frac{b}{L_T} - c + d\ \frac{\Delta T}{24k}\ (L_T - L_2)(1 + F) + f + [(1 - SSF)\ L_T\ h + (L_T - L_2)\ \tilde{h}] \quad (24)$$

where

$$\tilde{h} = C_f\ E_4\ \Delta DD. \quad (25)$$

The independent variables in the LCC expression are the collector area, $A_p$, and the total building load coefficient, $L_T$. The necessary conditions for a minimum value of

LCC are

$$\frac{\partial(LCC)}{\partial A_P} = 0 \text{ and } \frac{\partial(LCC)}{\partial L_T} = 0 \qquad (26)$$

One obtains

$$\frac{\partial(LCC)}{\partial A_P} = a - h L_T \frac{\partial(SSF)}{\partial A_P} = 0 \qquad (27)$$

and

$$\frac{\partial(LCC)}{\partial L_T} = -\frac{b}{L_T^2} + d\frac{\Delta T}{24k} - h L_T \frac{\partial(SSF)}{\partial L_T} + (1-SSF)h + \tilde{h} = 0 \qquad (28)$$

Substituting for the partial derivatives the expressions presented earlier (Equations (14) and (19)) one obtains, from Equation (27), that

$$a - h D = 0,$$

or

$$D = \frac{a}{h} \qquad (29)$$

at the global optimum. Substituting this into Equation (28) and solving for the optimal building load coefficient, one obtains

$$L_{T_o} = \left\{ \frac{b}{(1-SSF)h + \frac{a}{LCR} + d\frac{\Delta T}{24k} + \tilde{h}} \right\}^{1/2} \qquad (30)$$

This equation reduces to equation (24) given in Reference [1] when d and $\tilde{h}$ are set equal to zero.

The following design procedure leads to the optimal building load coefficient, the optimal collector size, and the optimal size for the zone heater, as well as the life cycle costs (and life cycle savings).

1. Given a and h, solve for D.
2. Knowing D and the variation of SSF with respect to LCR for a given system type and location, determine SSF and LCR. [2]
3. Solve for $L_{T_o}$ from the above equation.
4. From $L_{T_o}$ and LCR, solve for $A_P$.
5. Determine $L_{1_o}$ and $A_{ZH}$ as before from $L_{1_o} = L_{T_o} (L_1/L_T)$ and $A_{ZH} = L_{T_o} \Delta T/24k$
6. Determine life cycle costs.
7. Determine life cycle savings.

The following example will serve to illustrate the constrained and global optimization methods.

## 5. EXAMPLE

This example is based on the example presented in Ref. [1] and concerns a hypothetical single family residence in Dodge City, Kansas. The baseline building load coefficient is 11966 Btu/DD. Consider the same building but include a zone heater that heats one-third of the building from 60°F to 70°F. Assume that the corresponding base temperatures for degree-day calculations are 55°F and 65°F respectively. Then, $DD_{65}$ = 5046 and $DD_{55}$ = 2980; hence $DD_{LB}$ = 2980 and $\Delta DD$ = 2066. The energy conservation coefficients are: $b=3.18 \times 10^7$ \$ Btu/DD, c = \$2470. The passive solar system selected was a Trombe Wall with night insulation costing \$7.44/ft$^2$ and e = 0. The cost of the zone heater is assumed to be d = \$45.50/ft$^2$, and f = 0. The value of the parameter k is assumed to be 200 Btu/hr ft$^2$ and the value of the parameter F is assumed to be zero.

Using the values for SSF and LCR extracted from Ref. 1, the constrained optimal values of $L_T$ and $A_P$, and the corresponding conservation, passive solar, and zone heater costs are calculated and tabulated in Table 1. The constrained optimal cost fractions for conservation, passive solar, and zone heater as a function of the initial cost constraint are plotted in Figure 1. If the cost constraint is \$5000, the optimal fractions are 0.72 for conservation, 0.25 for passive solar, and 0.03 for a zone heater.

The global optimum with no zone heater was determined from equations (29), (30) and Table 1 (assuming the fixed charge rate is 0.0831 and the fuel cost levelizing factor is 1.50) to be D = 4, $L_{T_o}$ = 6068 Btu/DD, SSF = 0.816, and $A_P$ = 424 ft$^2$. The life cycle cost was found to be \$8051, resulting in a life cycle savings of \$14,325.

For the global optimization with a zone heater, assume that the present cost of fuel is \$0.07/kWh. Then

$$h = \frac{1.5}{0.0831} \times \frac{0.07}{3413} \times 2980 = 1.1$$

Also

$$D = a/h = 7.44/1.1 = 6.76$$

and, by linear interpolation in Table 1, one finds

$$LCR = 19.2$$

and

$$SSF = 0.72$$

Hence

$$L_{T_o} = 4518 \text{ Btu/DD}$$

and

$$A_P = \frac{4518}{19.2} = 235 \text{ ft}^2$$

The cost of the passive system is

$$C_{PS} = (7.44)(235) = \$1751$$

and the cost of energy conservation is

$$C_{EC} = \frac{31.8 \times 10^6}{4518} - 2470 = \$4569$$

The optimal building load coefficient for zone 1 is

$$L_{1_o} = L_{T_o} \frac{1}{3} = 1506 \text{ Btu/DD}$$

so the size of the zone heater is

$$A_{ZH} = L_{1_o} \frac{\Delta T}{24k} = (1506)(\frac{10}{24 \times 200}) = 3.1 \text{ ft}^2$$

and

$$C_{ZH} = \$141$$

The life cycle cost is therefore \$7872 and the value for life cycle savings is \$14,504.

The effect of the zone heater has been to reduce the annual energy requirements and to increase the life cycle savings.

## 6. CONSERVATION FACTORS

A conservation factor (CF) was developed based on the material in Ref. [1] and was presented in Ref. [2]. The conservation factor is used to determine the optimal conservation levels for each component of the building envelope and forms the basis of the design procedure presented in Ref. [2]. A modified conservation factor that takes into account the zone heater is derived as follows.

It is known from [1] that the optimal insulation (R-value) for the $i^{th}$ component of the building envelope is

$$R_i = \frac{1}{L_{T_o}} \sqrt{24 \frac{b}{r_i}} \qquad (31)$$

where $r_i$ is the incremental cost for insulation. Substituting for $L_{T_o}$ gives

$$R_i = \{ 24 \, (\frac{a}{r_i}) \{ \frac{1}{LCR} + [1 - SSF + \frac{ADD}{DD_{LB}}] \frac{1}{D} + \frac{\Delta T}{24k} \frac{d}{a} \} \}^{1/2} \qquad (32)$$

Define the conservation factor as

$$CF \triangleq R_i \sqrt{\frac{r_i}{a}} \qquad (33)$$

Then

$$CF = \{ 24 \, \{ \frac{1}{LCR} + [(1 - SSF) + \frac{ADD}{DD_{LB}}] \frac{1}{D} + \frac{\Delta T}{24k} \frac{d}{a} \} \}^{1/2} \qquad (34)$$

The conservation factor can be tabulated as a function of SSF and degree-day and cost data for each passive system type and each location, similar to the data presented in [2]. In fact, the relationship between the conservation factor presented in [2], $CF_P$, and that presented here is

$$CF_{ZH}/CF_P = \left[ 1 + 24 \left[ (\frac{ADD}{DD_{LB}} \frac{1}{D} + \frac{\Delta T}{24k} \frac{d}{a}) \right] \frac{1}{(CF_P)^2} \right]^{1/2} \qquad (35)$$

Hence, for each passive system type and location for which $CF_P$ has been determined, one can modify the conservation factor in [2] by this equation to account for a zone heater.

Graphs of the conservation factor ratio as a function of SSF for two different system types in Dodge City, Kansas, are shown in Figures 2 and 3. The values for $CF_P$ and LCR for each value of SSF were taken from the tables in Ref. [2]. Similar graphs may be constructed as a function of system type and location. Note that the variation in the conservation factor ratio with respect to changes in the solar savings fraction increases rapidly as SSF approaches unity. Also, the sensitivity of the direct gain system is greater than that of the Trombe wall system.

## 7. SUMMARY AND CONCLUSIONS

An analytical solution to the optimal sizing of the zone heater, as well as the optimal sizing of a passive solar system and the energy conservation features in the building, has been presented. A method of developing

design charts has been presented, along with some representative design charts.

The use of a zone heater has been shown to reduce the annual energy requirements for space heating and to increase the life cycle savings.

## 8. ACKNOWLEDGMENT

This work was partially supported by the Gas Research Institute. This support is gratefully acknowledged.

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(3) J. D. Balcomb, et. al, "Passive Solar Design Handbook, Vol. II," DOE-CS-0127/2, Jan. 1980.

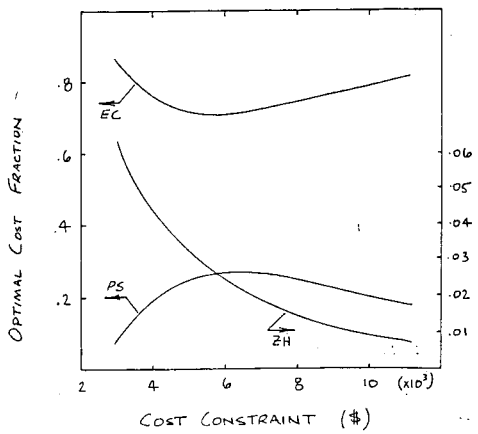



Fig. 1. Optimal Cost Fractions.

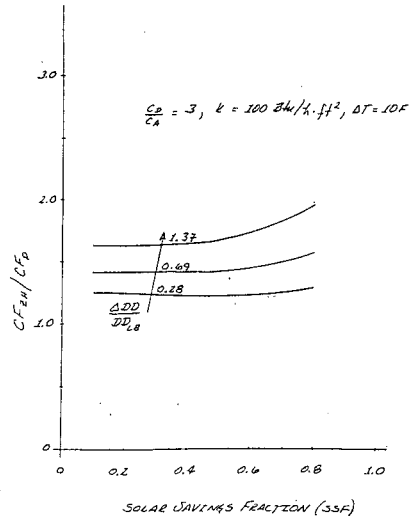



Fig. 2. Conservation Factor Ratio, Trombe Wall (RWD3), Dodge City, Kansas.

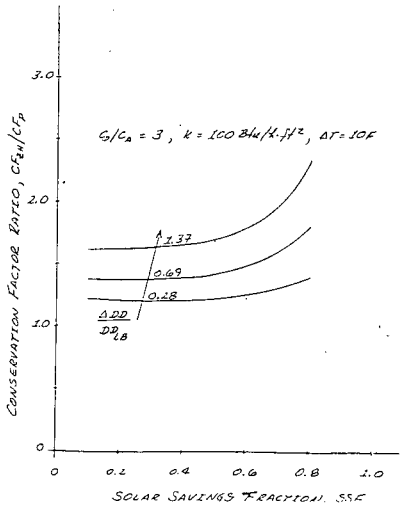



Fig. 3. Conservation Factor Ratio, Direct Gain (DGA2), Dodge City, Kansas.

TABLE 1. SOLAR SYSTEM PERFORMANCE (SSF, LCR, AND D ARE ABSTRACTED FROM REF. (1))

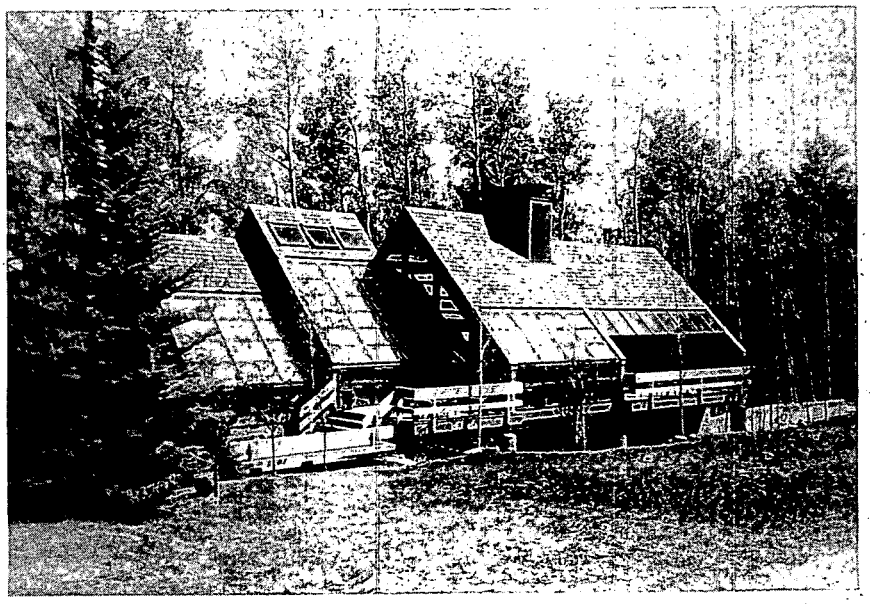
| SSF | LCR ($BTU/ft^2 \cdot DD$) | D | $L_{T_o}$ (Btu/DD) | $A_{ps}$ ($ft^2$) | $C_{EC}$ | $C_{ps}$ ($) | $C_{ZH}$ |
|---|---|---|---|---|---|---|---|
| 0.10 | 215 | 19.7 | 6208 | 28.87 | 2658 | 215 | 196 |
| 0.20 | 100 | 17.8 | 5987 | 59.87 | 2847 | 445 | 189 |
| 0.30 | 63 | 16.0 | 5772 | 91.61 | 3045 | 682 | 182 |
| 0.40 | 45 | 14.6 | 5603 | 124.51 | 3211 | 926 | 177 |
| 0.50 | 34 | 12.7 | 5361 | 157.68 | 3467 | 1173 | 169 |
| 0.60 | 26 | 10.2 | 5000 | 192.3 | 3896 | 1431 | 158 |
| 0.70 | 20 | 7.2 | 4477 | 223.9 | 4640 | 1665 | 141 |
| 0.80 | 15 | 4.4 | 3807 | 253.8 | 5891 | 1888 | 120 |
| 0.90 | 10 | 1.8 | 2749 | 274.9 | 9109 | 2045 | 87 |

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# OVERHEAD GLAZING AND THERMAL COMFORT CONTROL

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## ABSTRACT

Thermal comfort is uniquely controlled in this well-oriented and insulated mountain home with extensive overhead glazing. The fully automatic system reduces window heat loss and gain by multiple layers of flame-retardent fabric that rolls up into a compact tube assembly. In addition, a vinyl-coated fiberglass screen assembly on a separate track provides sun control while maintaining views to the exterior. The overall sloping to vertical system provides for both effective energy control and a pleasing interior environment.

## 1. INTRODUCTION

The challenge in the design intent of an integral living/sunspace was to provide a method of window energy management that both satisfied particular client requirements and optimized thermal control on overhead sloping to vertical glazing.

The dual insulating shade and sunscreen motorized roller assembly allows adaptation to outside climatic changes in a sunny, dry and cold environment through homeowner control.

## 2. PROJECT DESCRIPTION

The Finger Residence is located in Snowmass Village, Colorado, a ski resort community with strict building energy code requirements. Unlimited south-facing glass is allowed within 30° east or west of due south. Allowable area of east, west and north glass is limited to 12.5% of heated floor area. If site orientation does not relate to the above proscription,

then the total glass area cannot be more than 14% of the heated floor area.

The home at present is used for extended winter and summer vacations for a family of five and numerous guests. The site afforded excellent orientation $16^{o}$ east of south. It is well-insulated but of low-mass construction. Integral sunspaces were incorporated into the master bedroom, sitting and living room areas at the upper level. The lower level has two bedrooms, a laundry, the entry and a two-car garage. Total square footage is 3,400 and that includes the minimally heated garage.

Exposed glulam beams support 443 $ft^2$ of insulating tempered glass set into an extruded aluminum glazing system. 196 $ft^2$ of vertical glass is divided between operable awning windows below the sloped glazing and sliding door assemblies at the kitchen and dining room. Three operable skylights at the loft above the guest bath allow for very efficient ventilation but did not get treated thermally. A large expanse of west-facing window area in the master bedroom with good views utilizes just the insulating shade. Each space was analyzed for its particular view, lighting, thermal and aesthetic need.

## 3. SYSTEM COMPONENTS

The dual-shade motorized assembly consists of one electric motor (12 volts) and geartrain per shade. This is then fitted into a high-strength steel tube. One motor is capable of pulling 18 pounds of fabric up into a roll that is less than 4". Wiring for the system is low voltage, and this enables a variety of control modifications. The manual switches are small red buttons on an acrylic switchplate. The dual assembly can be operated in tandem or individually. In this particular design, when the insulating shade comes down, so does the sunscreen.

The motor and tube are then bracketed to the glulam beams. Upon activation of the motor, gravity slides the bottom-weighted units down their respective guiderails to the vertical track.

### 3.1. Insulating Shade

The insulating shade in this design is a polyethylene foil reinforced with fiberglass. By increasing layers the R-value against glass is raised. In other projects a polyester aluminized weave on mylar has been used. The polyester is stronger and more aesthetic. The R-value of the system in the

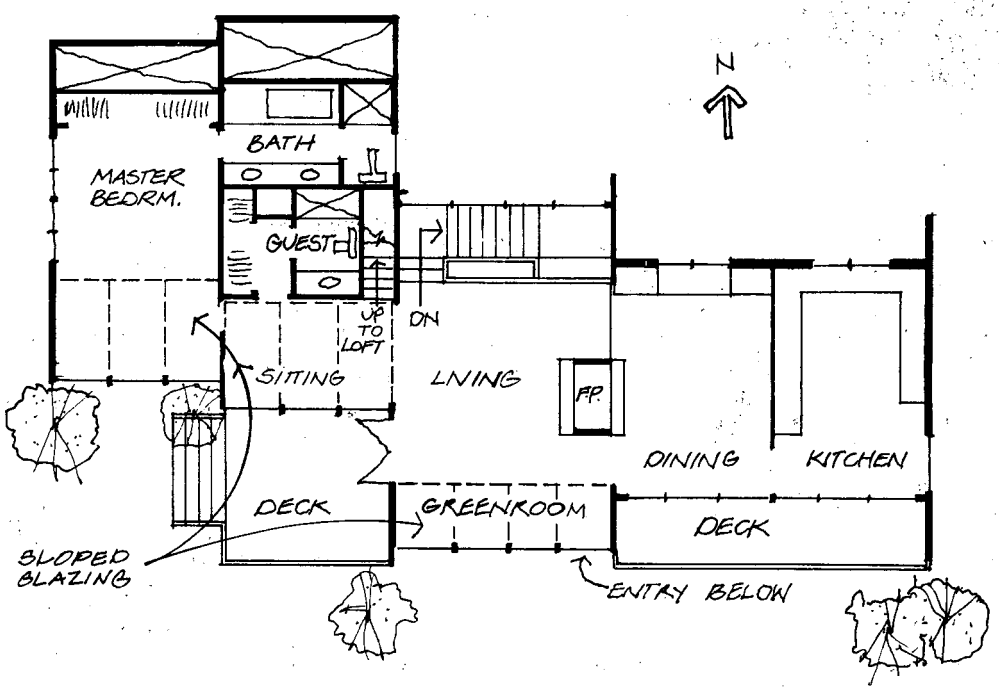



Fig. 1. Upper Level Floor Plan.

Finger Residence is approximately calculated at 6. The foil faces inward with the added possibility of laminating fabric on the outside. Aluminum battens sewn between the layers create a patent-pending long-life edge seal.

### 3.2. Sunscreen

The sunscreen used in this system was a vinyl-coated fiberglass, although a vinyl coated polyester would be heavier and allow for a wider range of colors. What is important about both these materials is that they can be cut without fraying and that they maintain views to the exterior.

## 4. KEY OPERATIONAL ASPECTS

One of the key operational aspects of the system is the design of a dual guiderail track that enables both the shade and the sunscreen to make a continuous transition from the sloping to the vertical condition. After exploring the option of using clear acrylic channels, 2"xl"x 1/8" unfinished aluminum angles were installed. Referring to Figure 2., two 5/8" diameter steel rods with nylon bearings supported by brackets were attached to the glulam beams. The weighted bottoms of both the shade and sunscreen then can rotate past the angle. No guiderail is necessary for the sunscreen at this section.

One problem worth mentioning at this point was the coefficient of friction of the aluminum angle. To solve the problem of a balky slide a polyethylene tape was applied to the surface.

Although the Fingers have the option for automatic operation by either setting a timer or adjusting a thermostat located next to the heating system thermostat, they prefer to operate the system manually. Avoiding the negative effects of intense sunlight on their furnishings and carpet are particular requirements.

## 5. PERFORMANCE AND FUTURE STRATEGIES

The Fingers are not only very pleased with the dual-shade/sunscreen assembly and operation, but their upstairs heating system rarely turns on. Heat accumulation in the high-volume space could be better controlled in the wintertime by ducting excess heat down to the lower-level bedrooms. As it is now, the lower level stays cooler.

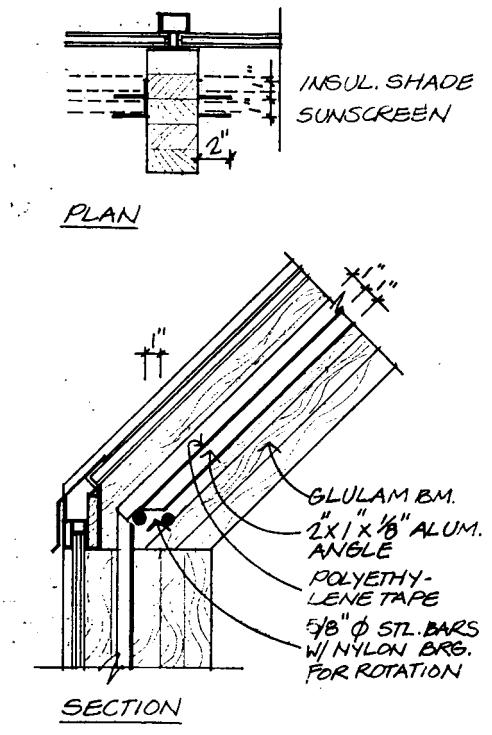



Fig. 2. Vertical to Sloping Transition Detail.

Less fluctuation in temperature within the upper living areas results in less expansion and contraction of the woodwork. At the west bedroom window, some condensation buildup has occurred at the sill. This is due, in large part to the wider wood-track detail which can easily be corrected.

There is some noise generation through assembly vibration that can be controlled by isolation of the bracket holding the steel tube. Lowering the speed of operation and wrapping the steel tubes with foam and lead foil are other easily correctable measures.

## 6. ECONOMICS

Any economic analysis for this project would have to balance not only the cost of the system and the energy saved, but the enhanced quality and comfort of the space. The displaced wall and ceiling assembly and decorative window treatments are other factors.

The actual raw costs of power, switches and controls, motors, steel tubes, brackets, sizing and handling of the

fabric and installation amounted to approximately $9.10 per square foot. Approximately $4.75 can be attributed to the insulating shade part.

The above price does not include the metal guiderails nor the wood track and trim finishes at the vertical glass. Nor does it include decorative drapery swags at all vertical areas.

## 7. CONCLUSION

The success of this project illustrates a unique merging of the design professional and product development in providing human comfort, energy conservation and visual delight.

## 8. ACKNOWLEDGEMENTS

The author wishes to acknowledge Raymond Auger of Solar Power West for his essential contribution to this project and this paper. Solar Power West now uses products from the Solar Roller Corporation of Aspen, Colorado, for its motorized rollers.

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# A PASSIVE SOLAR WATER PUMP

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## ABSTRACT

In the early 1970s a novel pumping apparatus was researched in England that incorporated a liquid piston in a Sterling Cycle heat engine. However, due to the arrangement of the actual pumping mechanism the heat requirements, i.e., the flux density and quality of heat, were only satisfied by an electrical resistance heat source. Even with this restriction, the pump showed great promise for wide application since it was easily constructed.

In the latter 1970s the machine came to my attention. Through extensive research and development, a novel pumping mechanism has been constructed that profoundly affects the entire function of the original pumping apparatus. The new machine operated with only one moving part. The major advantage of this latest design is the requirement for low grade thermal input, easily converted from a solar collection system. An input of 250 watts at 60° C (143° F) can now pump one gallon of water in two minutes through a lift head of 2 meters (6.5 ft).

## 1. BACKGROUND HISTORY

In 1971, the United Kingdom Atomic Energy Authority Research Group, Electronics and Applied Physics Div. at Harwell, Berkshire, England, published the first document on "The Fluidyne Heat Engine" by C. West. This document is an overview of the liquid piston Stirling Cycle heat engine. Although many ideas and ramifications are discussed in this document, it is not possible to construct an operational machine due to many missing parameters. The document does speculate upon scale, configuration and heat source variables.

In 1974, the Office of Naval Research, London, England, published a further document titled, "The Fluidyne Heat Engine: How To Build One and How It Works," by Harold G. Elrod. This particular document does supply the reader with sufficient information to construct an operational pumping machine. While pertinent dimensions are given, materials for construction are not always clearly delineated. Also, only one size and configuration is depicted. Dimensional sensitivity of key components is not addressed, and only a dual valve "ratchet type" pumping configuration is shown.

In 1978, the University of New Mexico's Center for Environmental Research and Development performed basic research under a grant from the U.S. Dept. of Energy on the liquid piston Stirling Cycle heat engine. The basic research performed under this grant included sensitivity studies of key components. By varying the dimensions of these components, performance curves were plotted showing pump rate in sec/liter vs. power input to heater in watts.

Results included but were not limited to: 1) Insensitivity of certain components to performance, 2) Identification of new components with large sensitivities to performance, 3) Very low efficiencies when compared to Carnot Cycle, 4) High temperature thermal inputs to drive the pump, 5) Narrow band of operation when compared to source temps, i.e., minimum and maximum temperatures of input, 6) Extreme sensitivity to temperature of sink temps, i.e., cooling jacket temperatures.

A copy of this research is available from N.T.I.S. #ALO/1894/1 "Solar Powered Liquid Piston Sterling Cycle Irrigation Pump" by Geoffrey C. Bell, April 10, 1979.

## 2. A NEW, IMPROVED CONFIGURATION

Enthusiasm for the liquid piston pumping concept continued after the termination of the research grant. A component (the dual valve "ratchet type" pumping configuration) was idendified during the research grant as having a large impact upon performance. Through a great deal of time, effort and "lateral thinking" an alternative pumping configuration was later discovered. Its arrangement is unique to the liquid piston heat engine.

Two major improvements have been attained with the new pump configuration: 1) The band of operation when compared to source, i.e., heater temperature is broader; 2) The necessary temperatures of the heat source are reduced. To a lesser degree, the extreme sensitivity to the temperature of the sink (cooling temp.) is reduced. Consequently the efficiency, when compared to the Carnot Cycle, is improved.

The actual pumping configuration is simply a very long coil of outlet tubing which is open at one end and connected to the heat engine on the other end (see Fig.1). A single inlet valve is positioned between this outlet coil and the heat engine, i.e., the driver. The inlet valve is positioned in its own tubing branch and is immersed into the lower water level to be pumped. The inlet value at present is a poppet-type foot valve for a well.

There is now a strong reciprocity between the outlet coil and the driver. During operation, oscillations occur throughout the complete machine that are contingent upon 1) The momentum in the outlet coil, i.e., the water mass multiplied by its velocity; 2) The volume, pressure and temperature of the working fluid, i.e., air-water vapor mixture in the driver acts as a spring; 3) The mass of water in the driver; 4) The position and length of inlet tube.

## 3. PRINCIPLES OF OPERATION

The start-up sequence is quite difficult to describe. Initially, water at the top of the hot piston is evaporated when heat is supplied to the driver. This evaporation causes an instantaneous difference in heights above a datum between the water in the hot and cold pistons. Since the pistons are connected through the driver, they seek to re-establish equal heights above the datum. However, with continued heating, this does not occur. The water heights "over-ride" equal levels and begin to transfer the working fluid, i.e., air-water vapor mixture from hot piston to cold piston and vice versa through a cross-over tube. The alternate heating and cooling of the working fluid causes it to expand and contract. This expansion and contraction of the working fluid now transfers its motion to the open ended outlet coil. As oscillations increase in magnitude, momentum is being "stored" in the outlet coil. The frequency or period of these oscillations in the outlet coil is partly determined by the volume and temperature of the working fluid in the driver. The working fluid is essentially the "spring" for the "mass," i.e., the "mass" is the water in the outlet coil, in the "text book" vibration analysis. The machine pumps the most water when the spring-mass system reaches its natural frequency. Obviously the reciprocity between the outlet coil and the driver is quite pronounced.

The oscillations occuring in the machine cause a change in internal pressure that swings between approximately 6 psi to approximately 5 inches of mercury vacuum. With the proper positioning of an inlet valve between the outlet coil and the driver, water can be drawn into the machine while at the same time discharge water from the open end of the outlet coil. The pumped water is actually drawn into the driver where the vacuum is being developed by the oscillations of the output coil. It then travels through the outlet coil where it is discharged from the open end of the outlet coil.

## 4. COMPONENTS

Even though the machine functions as unit with the pumping system inexorably linked and tuned with the driver, it is convenient to discuss the construction of these two components separately with the solar input reviewed in the following section.

The pumping system construction includes an inlet and outlet for the pumped water. The tubing in the prototype is one inch diameter vinyl. A "tee" fitting connects outlet tube the inlet tube and the driver. The inlet valve at present is a poppet-type foot valve with a Buna-N seal. The inlet valve is immersed into the reservoir of water to be pumped.

The driver is a conglomeration of P.V.C. household plumbing fittings, 2 1/2" acrylic pipe, 1 1/2" diameter copper tubing for hot and cold pistons, smaller diameter copper, stainless steel and plastic tubing for the crossover connection. A pressure/vacuum

gauge is mounted. Attachments for temperature gauges are also provided. The pumped water cools the cold piston, therefore, a coolant jacket must be fabricated and piped into the circuit. Graduated tubing is mounted beside the hot and cold pistons to show internal water levels as they rise and fall during operation. A fill valve is installed to put air into the driver. This air becomes the working fluid.

Although the materials used in construction are easily acquired in the industrialized nations, the proper mix of metals and plastics is not as easily attained. Metals are used in components that transfer heat in and out of the machine. Plastics are used in parts that must isolate heat conduction between hot and cold sections of the machine. Plastics also simplify the manufacturing process and reduce cost. Only simple hand tools are necessary to build the pump. A complete materials list and dimension outline are available through the author's company.

## 5. SOLAR INPUT

The solar input has been reviewed in only a few areas of collection systems. The requirements of a high flux density of Btu per unit area per unit time to the hot piston restrict the solar input to a few solar collection systems. The first system employs a stagnated flat plate collector of either aluminum or copper. The plate is mounted directly to the hot piston and is enclosed in a glazed, insulated collector box. Selective surfaces as well as black paint have proved effective. However, the thermal resistance between the collecting surface and the working fluid in the driver can be quite high. Time delays in warm-up mode are 20 to 40 minutes. Intermittent clouds have minor impacts upon heat collection.

An alternative to the flat plate collector is the higher performance, but more complicated, heat pipe. The heat pipe, an evaporation/condensation heat transport device, is enclosed in a glazed, insulated collector box. Thermal resistance in this device is minimal due to heat exchange which occurs at the vaporization temperature of the heat pipe's working fluid. The heat pipe can also be tuned to transfer heat at a predetermined temperature. The rate is determined by the heat pipe's collection area and the isolation available on site.

Concentrating collectors such as parabolic troughs, compound parabolic troughs, Fresnel Lenses and point focus units have not yet been thoroughly reviewed. Direct illumination of the hot piston or use of a heat pipe are possible with the concentrating collectors. However, all of these devices will require some tracking which will complicate the machine.

## 6. PROTOTYPE EFFICIENCY AND LIMITATIONS

Efficiency of prototype units to date have been quite low. With Carnot efficiencies ranging from 12 to 15 percent, the pump has been operated at 1.5 to 2.5 percent of this Carnot range -- a discouraging efficiency if fuel to operate must be purchased from a centralized source. Even at this low efficiency, however, the prototype can pump 30 gallons of water per hour through a lift head of 2 meters.

There are many factors that can be easily identified as causing the low efficiency. These areas include but are not limited to 1) Cold piston heat removal, extending heat transfer surfaces, internal and external, of the piston can help to improve the heat removal; 2) The inherent heat loss, i.e., transfer throughout the machine, is most pronounced to the water contained in the driver; 3) The working fluid vapor and the piston itself are of the same material causing "vapor lock" at high temperatures. A membrane or film to isolate the piston's free water surface from the working fluid could help rectify this situation. A different working fluid material from the water piston is also suggested. 4) The inlet valve is quite inefficient.

A few limitations of the liquid piston machine are also reviewed. During extended operation, the machine can "over heat", i.e., go through a phase of vapor lock, when the cold piston is incapable of condensing enough water to adequately reduce the working fluid's volume to induce oscillations in the outlet tube. The band of operation should be increased even further to allow a broader range of heat inputs for a fixed volume of air. Likewise, if the volume of air could be varied during operation, a wider band of temperature inputs could be accommodated. Also a need for some capacitance in the solar input would reduce sensitivity to passing clouds.

## 7. APPLICATIONS

Because the machine is so easily constructed a few immediate applications can be accommodated in spite of the present low efficiencies. Drip irrigation, hydroponics, pond aeration and water distribution seem likely. It is believed water

distribution could be the biggest application of the machine. The very long outlet tube depicted as a coil could easily be unwound to move the water over long horizontal distances.

After showing the machine to engineers at Princeton University, larger scale applications to Solar Ponds and Ocean Thermal Energy Conversion (OTEC) were suggested. Major competition from photovoltaic systems seems assured in the residential markets. Heat input by other means such as burning peat, dung or wood could be employed in lieu of the sun.

## 8. THE FUTURE

After six years of intermittent private research, with a bit of help from the U.S. Dept. of Energy, future refinements and development of the machine are very much in doubt. Perceiving some of the information and insights discussed in this report as an "invention," I have been waging a battle with the U.S. Patent Office as well as with my attorneys and with the "exploiters" and "opportunists." The price for a little protection is truly exorbitant for the private inventor.

The next logical step is to attain venture capital to conduct an optimization study of the machine. This will involve building a series of models and taking the data gleened from the models to construct a computerized sizing model. The computer model will predict optimal dimensions, attainable pump rates with particular solar inputs, and improved piping configurations.

LEGEND

1. OUTLET
2. COOLANT JACKET
3. CROSSOVER TUBE
4. COLLECTOR
5. STAGNATED PLATE
6. HOT PISTON
7. WORKING FLUID
8. COLD PISTON
9. FILL VALVE
10. GRADUATED TUBING
11. TEE FITTING
12. DRIVER
13. PRESSURE GAUGE
14. OUTPUT COIL
15. INLET
16. INLET VALVE

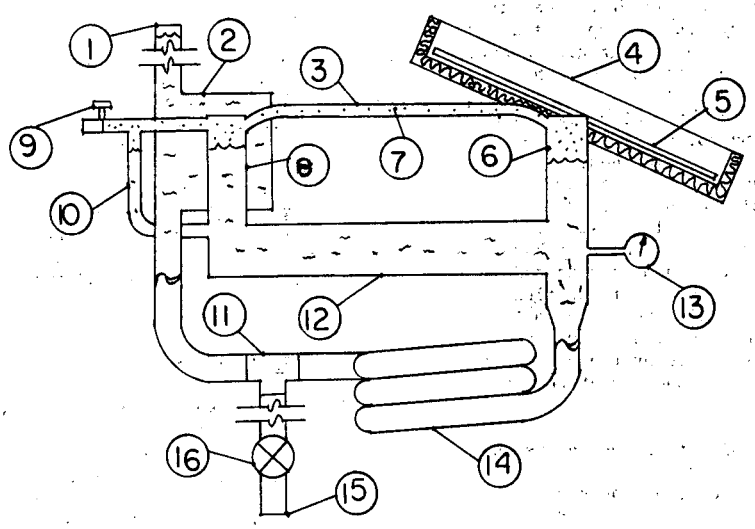



FIG. 1

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# RETROFIT TAPs FOR THIRTEEN PENNSYLVANIA SCHOOLS

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## ABSTRACT

Relatively inexpensive, however commercial quality, retrofits were made to a variety of Pennsylvania schools varying from elementary schools, to high schools, to university facilities. The south, southeast, and southwest facades of each building were treated with a commercial insulated panel system that was designed as a Thermocirculating Air Panel (TAP). The TAP-FLOW computer program was used to estimate the appropriate vents, and collector proportions. A computerized analysis based on Balcomb's Solar Load Ratio was used in order to determine the effectiveness of the TAP.

This paper reports on the diverse problems encountered during the design and execution stages of the retrofits. Because of client requirements, each application used different construction and management styles. A variety of reverse circulation damper stops were used with varying degrees of acceptance and success. At the request of the client, certain TAPs were outfitted with internal shading devices that would control the gain. The TAPs have had great acceptance by the users and are presently being used as examples of solar energy heating by the diverse educational institutions. This paper concentrates on the constructional and client acceptance aspects of the large scale TAP installation (over 12,000 square feet of TAPs to date).

## 1. INTRODUCTION

During technical analysis of possible energy conservation methods for existing educational buildings, including use of a modified version of Balcomb's LASL Method (1) to evaluate various solar heating methods, direct-gain thermocirculating air collector panels were seen to have attractive energy-savings potential when used to retrofit south-facing areas of glazing. Thermocirculating Air Panels have been defined and performance tested both experimentally and analytically in numerous previous publications, see references 2 , 3 , and 4 as examples. TAPs have the advantage of supplying solar heat when available, yet provide insulation during night and low-gain periods. This particular application has the additional appeal of providing a remedy for the excessively large areas of single glazing in so many schools built during the '50s and '60s which account for substantial envelope heat loss both by conduction through the glass, and by infiltration through loose frames and glazing.

TAPs have been classified as back-pass and front-pass circulation - see reference 2 . Front-pass circulation has been found to be relatively more efficient in promoting thermocirculation and net gain; see references 2 and 4 . This particular application makes use of front-pass circulation TAPs for reasons of cost control and ease of assembly.

The use of TAP retrofits to South-facing existing glass has a number of advantages, including:

1. The more expensive collector component, the glazing, is already installed.
2. No weatherproofing is necessitated since the exterior glazing design has already accomplished that.
3. In most situations, the window sills and mullions provide an ideal structure to which the TAPs retrofits can be affixed.
4. The existing architectural character of the facade is substantially unaltered.

It was clear at the analysis stage that the economic success and "payback" of the TAPs retrofit was dependent on development of a low-cost, thermally-efficient construction. During design and construction, it became increasingly clear that success is also strongly affected by the involvement and acceptance by clients - teachers, students and maintenance staff as well as administrators.

Retrofit TAPs are in operation in two elementary schools, one intermediate school, two high schools, one college classroom building, and one college dining hall. TAPs are now under construction in two elementary schools, one intermediate school, and three high schools, and in design stage for two other schools.

The original concept underwent major design and detailing modifications before the first installations were made, with several refinements developed subsequently.

## 2. GENERAL DESIGN CRITERIA

The following criteria were established for TAPs materials and construction:

1. Low Cost. In part, this could be effected by developing a system which could be installed quickly, with little detailled finishing work, since all of the projects were funded as part of a DOE energy grant program and were required to use federal wage rates for on-site labor.
2. Low Maintenance. Generally, school district and college maintenance resources are stretched to the limit. Any renovations must utilize durable materials and construction which require only limited maintenance. The panels must be demountable for periodic cleaning of the interior surfaces of the glass.
3. Temperature. Analysis of solar loads indicated that materials used for the collector surface might be subjected to temperatures as high as 300° F.
4. Fire resistance. Any materials selected must comply with the necessary fire ratings for use in educational buildings, for flame spread, smoke, and gasses.
5. Simple operation. Any routine manual control of dampers must be possible for teachers or custodians to perform simply and quickly.

## 3. DESIGN I

The original system detailling featured a relatively high-technology, specialized construction (see Fig. 1): A heavy stud panel, faced with a corrugated black metal panel as collector surface, $\Delta t$-actuated mechanical dampers at top and a one-way hinged diaphragm at the bottom to prevent backdraft of cooled air. The entire collector assembly was to be sealed in the window opening so as to be removable for cleaning of glass and collector surface every two or three years.

### 3.1 Comments

This design was never fully developed or implemented, primarily because of prohibitively high cost in both materials - the sophisticated dampers, metal collector surface and stud construction - and in labor - damper installation, and extensive finishing work. Slightly less costly wood-stud construction was rejected because of possible difficulties withstanding high temperatures.

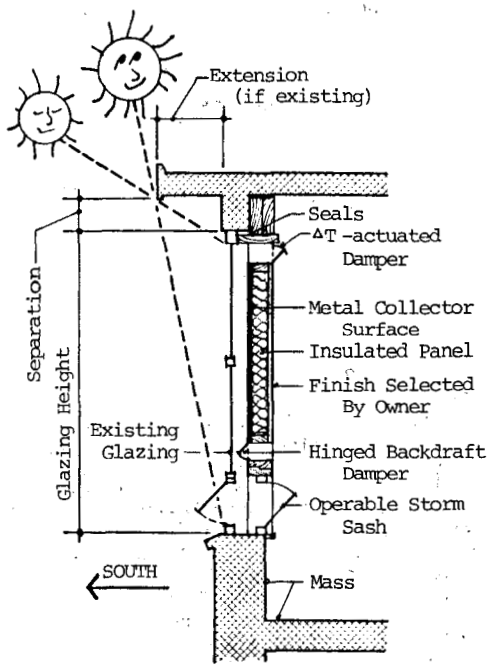



Fig. 1. TAPs Design I.

## 4. DESIGN II

At this time, a light-weight fiberglass-core panel system appeared on the market for retrofit window insulation. This was a relatively low cost system, using non-combustible materials capable of withstanding high temperatures, and requiring little time or experience to install. This system has remained the base construction for all our retrofit TAPs installed to date, the lower cost compensating for the lower R- value.

A backdraft damper was developed as the only "working" component in the system at this stage, using a thin (½ mil) flexible polyethylene flap mounted at the base of the air cavity, and the top damper was eliminated. The TAP-FLOW (5) program determined the clear opening area for the bottom dampers and for an open strip running along the top of the entire panel. The top opening allows circulation of warmed air into the room; however, during low-gain periods the bottom damper is closed by reverse flow of air being cooled by the glass surface (See Fig. 2). Cool air pools in the cavity, below the level of the top opening (similar to a chest-type freezer), and does not tend to mix with room air. A temperature-resistant paint was applied to the exterior surface of the panels to provide the collector surface.

Although the TAP-FLOW program was used to determine the effects of overhangs, optimum collector area, and proper location, the actual placement of TAPs in each case was determined equally by the needs of the occupants - teachers, students, and staff. Most or all vent windows were left operable, with special attention given to the sensitive issues of maintaining adequate daylight and view (generally at least one full-height classroom window left exposed in addition to vent windows). No TAPs were installed in corridors or rest rooms, since these areas are not significant in terms of comfort level heating, and school administrators indicated vandalism was a potential problem in uncontrolled areas.

### 4.1 Comments

At intervals after TAPs were installed in each building, teachers and staff were interviewed and invited to express comments or problems. Design II was installed in three schools in northwestern PA. As is frequently the case with retrofits involving reduction of glazing areas, teachers were initially disturbed by the loss of windows. However, once installed, the system tended to approximate the traditional use of window blinds and after a period of adjustment, they did not view this as a concern. By far the most common problem expressed was overheating in spring and fall, there being no method of controlling the circulation of collected warm air when the rooms were warm enough. However, the overall reaction of teachers was quite positive - some indicating that this was the first winter they had been able to maintain classrooms at a $\pm 68^{o}$ temperature.

The only construction problem encountered concerned the anchorage of damper flaps to their supporting frame, a problem which was easily solved with additional Tedlar tape.

## 5. MODIFIED DESIGN II

The next group of TAPs featured one significant revision: to control absorption of radiation by the black collector surface and reduce problems with overheating in the rooms, white shades were installed in the collector cavity, with cords mounted so that they could be controlled from within the room. With the blinds extended and the white surface screening the black collector surface, most of the absorption of radiation was eliminated. With the blinds retracted, there was no reduction in the amount of radiation absorbed when the collector surface was exposed (See Fig. 2).

### 5.1 Comments

The modified TAPs were installed in two schools and two college buildings. It was observed that where teachers and staff were consulted, or at least kept informed during the design process, there was no initial negative reaction to the retrofits.

Because of the space required to mount blind hardware at the top of each window, the top opening could not be completely blocked off by the blind, so the blind could not be used as a top damper in addition to screening the collector surface.

In most cases, the teacher controls the operation of the blinds. The college classrooms and dining-hall, however, presented a different situation, with no individual "in control" throughout the day; and adjustment of blinds is generally performed by custodial staff seasonally.

An interesting condition was observed in one building where the treated facade was oriented south - southwest. The TAPs contributed heat early and mid-afternoon, after the building heating system had come up to temperature and only a short time before the building is vacated for the night. This seems to suggest that a southeast orientation, although contributing less total Btu gain, may be somewhat more valuable for TAPs retrofit in cases where the building is not normally occupied in late afternoon.

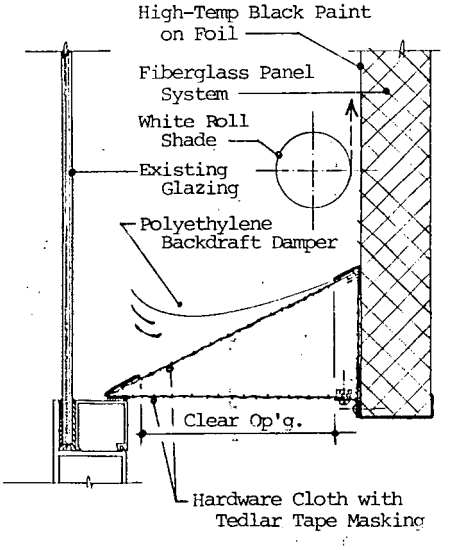



Fig. 2. TAPs Modified Design II. Detail of Backdraft Damper and Shade.

## 6. DESIGN III

For the group of installations which are currently in construction, the black-painted fiberglass panel system is again used. The major changes were made to the dampers, in attempt to afford room occupants greater control (and greater comfort) of heat contributed by TAPs and also of summer shading and insulation.

Top and bottom openings are as determined by the TAPFLOW program, but this time both are fitted with insulated dampers using the fiberglass panel material. Both dampers are hinged and will be manually operated. Generally, the top damper will be left open for the duration of the heating season, while the bottom damper may be easily opened for air circulation and closed for night insulation. During warm months, top dampers may be left closed (and bottom dampers left open to prevent overheating of the materials in the cavity), providing shading and summer insulation. (See Fig. 3).

### 6.1 Comments

This design is currently under construction in six schools, and is being refined for use in another school.

Although it is too early to evaluate the performance of these TAPs, it is evident that their efficiency is still dependent on the willingness of the users to control the dampers.

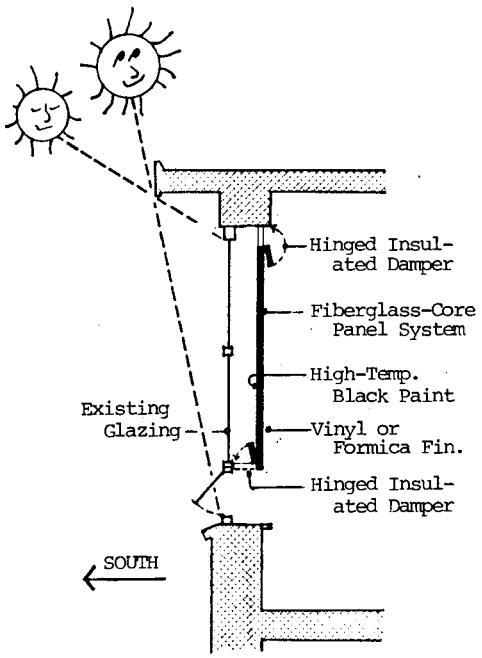



Fig. 3. TAPs Design III.

## 7. CONCLUSIONS

Generally, the TAPs retrofits have been well accepted and utilized by administration, teachers, and staff. For as long as the TAPs are detailed with damper systems which require operation by users, part of the effectiveness will depend on the degree of involvement those users maintain. To maximize their potential as passive solar retrofit, it may be desireable to develop a thermostat-activated damper system which responds to temperature conditions in the room, in the collector cavity, and outside.

TAP retrofits should be coupled to modifications to the Automatic Temperature Control system. Normally, a wall thermostat will control the ventilation (unitvent) of a classroom; but not the perimeter radiation (fin tube convectors). The added window insulation provided by the TAPs, coupled to both decreased infiltration and increased thermal gain make the south-facing classrooms overheat. It has been observed that during periods of high gain in some installations, all the solar control devices (shades) were in use due to overheating. A solution would be to install thermostatically actuated flow valves and an interlocking of the temperature sensor in the TAP with the Automatic Temperature Control system.

Although teachers initially resented the loss of glass, after the TAP installation they are delighted with the added wall area for display and with the increased comfort of the rooms.

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# ASSESSMENT OF THE BENEFITS AND IMPLICATIONS OF RETROFIT OPTIONS FOR EXISTING WINDOWS IN THE UK

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## ABSTRACT

The various options available for retrofitting windows are described and their performance simulated in a domestic situation using the thermal simulation model SUNCODE . Predicted energy savings are presented for each treatment and certain combinations of treatments. The performance of each treatment in terms of solar gain versus heat loss, ability to reduce air infiltration and other characteristics is illustrated. Conclusions are drawn as to the most appropriate applications for the various window treatments.

## 1. INTRODUCTION

Windows are key elements in both energy conservation and passive solar design. They also require regular maintenance and frequent replacement. Upgrading or replacing windows could be a significant step towards optimizing passive solar gain in existing housing.

## 2. OPTIONS

Two main retrofit options exist:
1. Additions
2. Substitutions

### 2.1 Additions

Additional systems comprise secondary glazing and movable insulation.

Secondary glazing is available in many forms; fixed or openable, with glass or plastic sheet, DIY or professionally installed. Secondary glazing can be an inexpensive means of upgrading sound existing windows and is growing in popularity, especially in the DIY field.

Movable insulation has only recently begun to appear on the UK market although the benefits of shutters and heavy curtains have been appreciated for some time. The passive solar benefits of movable insulation are obvious: allowing maximum solar gain on winter days and reducing heat losses through the long winter nights. Roller blinds, now widely accepted for covering windows, can also be a form of movable insulation. Unfortunately at the present time there are few proprietary products available and the would-be installer must in the main resort to DIY methods.

### 2.2 Substitutions

Replacement windows represent some 40% of all windows produced in the UK. They come in different forms usually double glazed with frames of timber, aluminium and plastic, some containing insulating thermal breaks . Although sealed double glazing units are the most common, there are several other options: evacuated sealed units, units filled with special gases, heat reflecting coatings or plastic films, highly transparent films introduced to create multiple airspaces, triple and quadruple glazing. All these systems will incur large expenditure as they will almost certainly be professionally installed. It should be recognized that as well as reducing heat loss these systems generally reduce the amount of available solar radiation transmitted by the window.

## 3. QUANTITATIVE ANALYSIS

In order to assess the overall energy saving and passive solar potential of the various forms of window treatment a thermal simulation model SUNCODE , developed by the Ecotope Group, Seattle, was used. House type c, a three bedroom, 1930 s Semi-D, with 80 $m^2$ floor area and 21 $m^2$ window area, was chosen from the range available to the design studies (see Fig 1). Each simulation

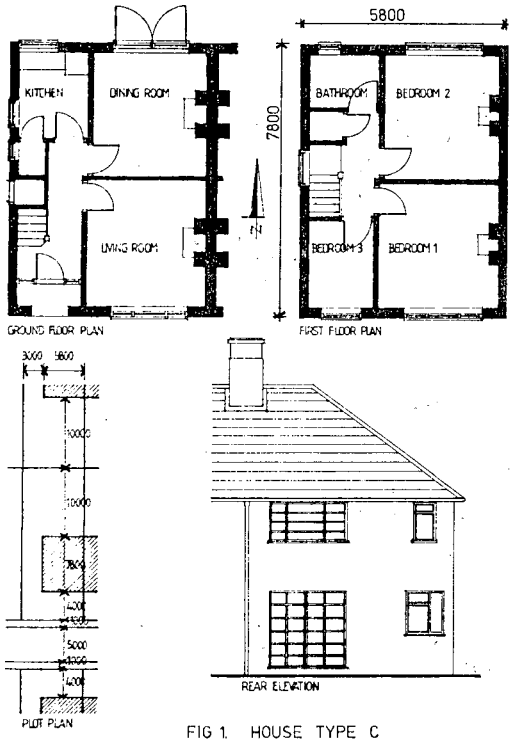



FIG 1. HOUSE TYPE C

was performed at both low and high occupancy levels. Low occupancy being evenings only on weekdays and all day at the weekend. High occupancy being all day, every day. The heating system was assumed to be off during the night.

Simulations 2 to 12 had the window treatments described in the Table 1 applied throughout the house. The various treatments affected both the U -value of the window and the air leakage rate around it, this second factor is reflected in the infiltration rate of the whole house. Simulation 13 was performed to show the effect of reducing the infiltration rate only, by draught-stripping the existing windows. Where movable insulation was simulated the window U -values were only reduced during the periods of use.

Simulations 14 to 17 were performed to show several different approaches to upgrading the windows based on cost and practical consideration of the individual rooms. In each case the air change rate has been averaged out between the various treatments. The numbers in ( ) refer to window treatments 2 to 12 from Table 1.

Simulation 14: -1- All windows in the north and west elevations were replaced with double glazed units (3). It would be economical to do two whole elevations together; also the risk of condensation in the bathroom and kitchen was greatly reduced. All the rooms affected except bedroom 2 are likely to be intermittently occupied during the day.

-2- High performance movable insulation was added to the main windows on the south elevation; this maximizes the benefit of solar gain in a high occupancy household and insulates during the critical period in the low occupancy case. All these rooms have a low risk of daytime condensation.

-3- Fixed secondary glazing (2) was applied to the sidelights in the hall for reasons of economy.

Simulation 15: -1- Replacement double glazing (3) was applied to the dining room, kitchen and bathroom. The reasons for this action are the high risk of condensation and the intermittent occupancy pattern of these rooms.

-2- High performance movable insulation (6) was added to all the bedrooms because this was considered an effective solution to rooms only occupied during the night.

-3- Secondary glazing (2) was added to the windows in the hall and living room as a low cost answer.

Simulation 16: -1- Secondary glazing (2) was applied throughout except for the bedrooms. If the existing window frames were sound this would be a cheaper alternative to replacement windows, and the careful positioning of fixed panels could help prevent condensation.

-2- All bedrooms were upgraded with medium performance movable insulation (5) since this was a low cost solution to rooms only occupied at night.

Simulation 17: -1- High performance movable insulation (6) was applied to the living, dining and bedrooms only. This installation could be performed with the minimum of disruption and at a reasonable cost. This approach would give the benefits of maximisiing solar gain on the south elevation and insulating the bedrooms only when necessary.

Table 1 summarizes the inputs and predictions of the SUNCODE simulations. The energy saving potential of each system is described in $kWh/m^2$ of glazing saved, compared to the base case (1) single glazing. Table 2 shows the performance characteristics of the main options. The energy balance for the south facing window is derived from the SUNCODE simulations. Table 3 illustrates the benefits of specific systems in the living spaces and bedrooms of house type C.

## 4. PRACTICAL CONSIDERATIONS

| TABLE 1 SUNCODE INPUTS & PREDICTIONS HOUSE TYPE C 21m² GLAZING WINDOW TREATMENT | SOLAR TRANS. | SYSTEM U-VALUE W/m²°C DAY | SYSTEM U-VALUE W/m²°C NIGHT | HOUSE AIR CHANGE RATE H⁻¹ DAY | HOUSE AIR CHANGE RATE H⁻¹ NIGHT | LOW OCCUPANCY ANNUAL AUXILLARY HEAT KWh | LOW OCCUPANCY SAVING KWh/m² GLAZING | HIGH OCCUPANCY ANNUAL AUXILLARY HEAT KWh | HIGH OCCUPANCY SAVING KWh/m² GLAZING |
|---|---|---|---|---|---|---|---|---|---|
| 1 SINGLE GLAZED | .85 | 5.7 | 5.7 | 1.5 | 1.5 | 10265 | — | 16592 | — |
| 2 AS 1 + OPENABLE SECONDARY GLAZING. | .72 | 3.2 | 3.2 | 1.5 | 1.5 | 8390 | 80 | 13500 | 157 |
| 3 REPLACEMENT DOUBLE GLAZING. | .72 | 2.8 | 2.8 | 1.1 | 1.1 | 7720 | 121 | 12145 | 212 |
| 4 AS 1 + SINGLE LAYER REFLECTIVE BLIND, NO EDGE SEALS. | .85 | 5.7 | 2.8 | 1.5 | 1.5 | 8775 | 71 | 14971 | 77 |
| 5 AS 4 + 50% EFFECTIVE EDGE SEALS. | .85 | 5.7 | 2.3 | 1.5 | 1.2 | 8078 | 104 | 14240 | 113 |
| 6 AS 1 + DOUBLE LAYER REFLECTIVE BLIND, 80% EFFECTIVE SEALS. | .85 | 5.7 | 1.0 | 1.5 | 1.0 | 7075 | 152 | 15130 | 165 |
| 7 AS 1 + INSULATING SHUTTERS, 80% EFFECTIVE SEALS. | .85 | 5.7 | 0.6 | 1.5 | 1.0 | 6889 | 161 | 12855 | 176 |
| 8 AS 3 + 2 Nº LAYERS OF HIGHLY TRANSPARENT PLASTIC FILM. | .71 | 1.5 | 1.5 | 1.1 | 1.1 | 6760 | 167 | 9536 | 356 |
| 9 AS 3 WITH PILKINGTON'S 'KAPAFLOAT' GLASS. | .69 | 2.0 | 2.0 | 1.1 | 1.1 | 7245 | 144 | 11368 | 245 |
| 10 AS 3 + 1 Nº LAYER 'HEAT MIRROR' ™. | .64 | 1.4 | 1.4 | 1.1 | 1.1 | 6845 | 163 | 10651 | 281 |
| 11 REPLACEMENT TRIPLE GLAZING. | .61 | 1.5 | 1.5 | 1.1 | 1.1 | 7204 | 146 | 11281 | 255 |
| 12 AS 1 + HEAVY CURTAINS. | .85 | 5.7 | 3.5 | 1.5 | 1.5 | 9136 | 54 | 15366 | 58 |
| 13 AS 1 + DRAUGHT STRIPPING. | .85 | 5.7 | 5.7 | 1.1 | 1.1 | 9486 | 37 | 15208 | 66 |
| 14 — SEE TEXT FOR DESCRIPTION | | — | | 1.1 | 1.1 | 7849 | 115 | 12752 | 183 |
| 15 — SEE TEXT FOR DESCRIPTION | | — | | 1.2 | 1.2 | 8404 | 80 | 13561 | 144 |
| 16 — SEE TEXT FOR DESCRIPTION | | — | | 1.3 | 1.3 | 7848 | 115 | 13715 | 137 |
| 17 — SEE TEXT FOR DESCRIPTION | | — | | 1.3 | 1.3 | 7453 | 188 * | 12553 | 283* |

* - ONLY 15 M² OF GLAZING TREATED

4.1 Secondary Glazing

Installation and Availability

If existing windows are in a bad condition then a replacement system should be considered. If the existing windows are sound then secondary glazing may be installed professionally or by using one of the many DIY kits available. Professional installation is more expensive but is probably preferable when dealing with non-standard windows or difficult situations such as angled bays. The DIY kits available range from sliding sash units to heat shrink films which must be replaced each year, and most are within the realms of the competant handy-person'. It should be noted that legislation is proposed in the UK to restrict the use of fixed secondary glazing as it has recently prevented escape in cases of fire.

Operation

Only the sliding systems will give similar flexibility in terms of operation to the existing windows for the purposes of cleaning and ventilation. Hinged systems are convenient for cleaning but rarely useful for ventilation. Fixed systems are really only suitable for existing windows which are permanently fixed.

Appearance

Very few available systems have a satisfactory appearance. The cheaper products with clip-on frames invariably look cheap, whereas more sophisticated systems may create such anomalies as staggered glazing bars or partially covered architraves.

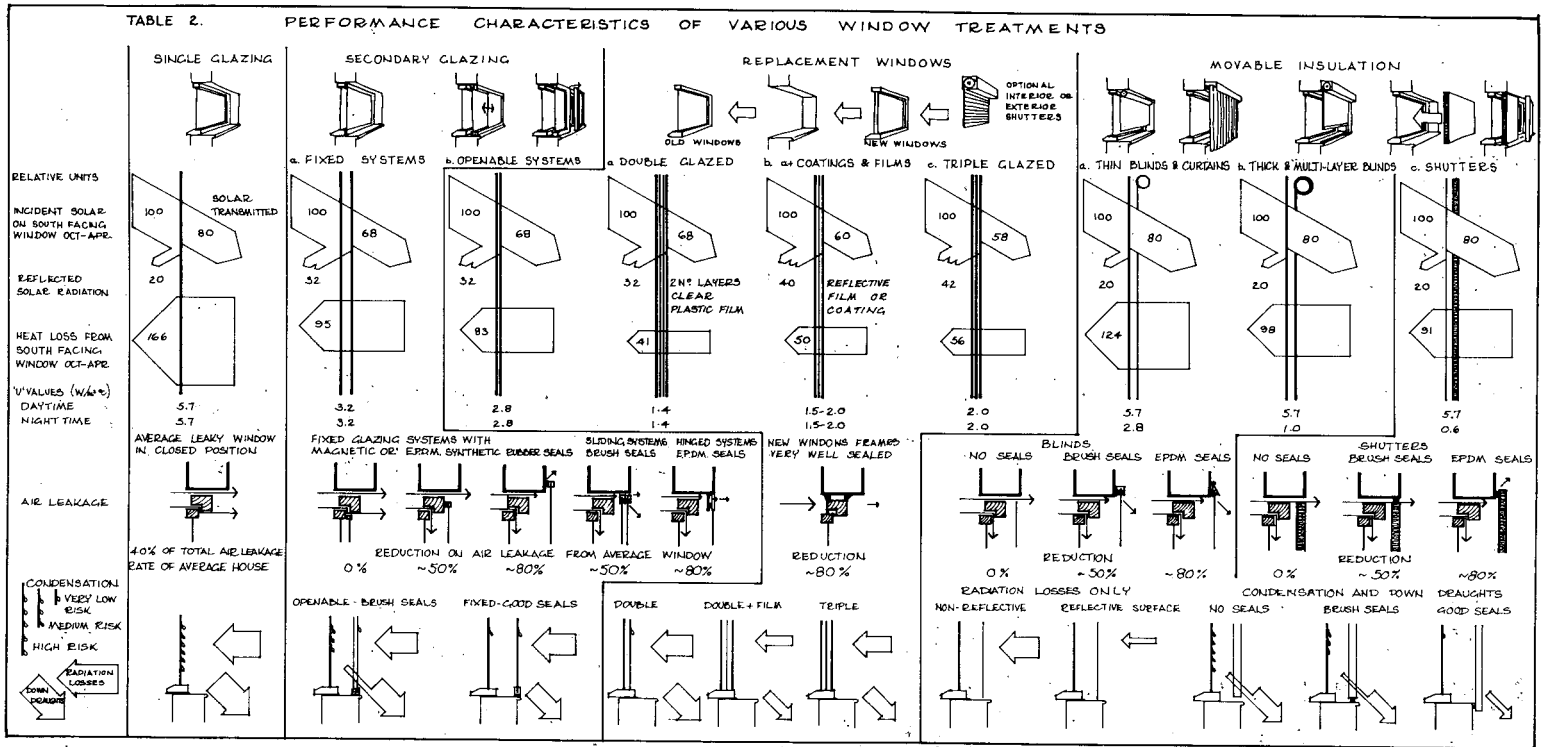
View

The view fom the window is rarely affected unless one of the very cheap plastic film type systems is employed which may cause a certain amount of visual distortion. Another possibility is that certain plastics which may be used in place of glass are degraded by ultra violet light and scratch easily.

Maintenance and Life

Apart from cleaning the available systems should be maintenance free as they are mainly uPVC or aluminium. Unless the product is very cheap it could last as long as the existing windows as it is not exposed to the elements. One important consideration is whether the secondary glazing would add value to a property in a future sale and therefore offset the initial cost.

TABLE 2. PERFORMANCE CHARACTERISTICS OF VARIOUS WINDOW TREATMENTS




| TABLE 3. | 2. SECONDARY GLAZING | | | | 3 REPLACEMENT DOUBLE G. | | | | 6 DOUBLE BLIND | | | | 7 INSULATING SHUTTERS | | | | 9 AS 3+ 'KAPAFLOAT' | | | | 13 DRAUGHT STRIPPING. | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OCCUPANCY LEVEL | HIGH | | LOW | | HIGH | | LOW | | HIGH | | LOW | | HIGH | | LOW | | HIGH | | LOW | | HIGH | | LOW | |
| ORIENTATION | S | N | S | N | S | N | S | N | S | N | S | N | S | N | S | N | S | N | S | N | S | N | S | N |
| % SAVING ON ANNUAL AUXILLARY HEATING IN LIVING SPACES OF HOUSE TYPE C | 19 | 19 | 19 | 17 | 26 | 25 | 24 | 23 | 20 | 20 | 35 | 29 | 21 | 21 | 35 | 31 | 30 | 29 | 30 | 27 | 8 | 7 | 8 | 6 |
| % SAVING ON ANNUAL AUXILLARY HEATING IN BEDROOMS OF HOUSE TYPE C | 28 | 27 | 24 | 23 | 39 | 37 | 33 | 31 | 32 | 29 | 39 | 37 | 33 | 31 | 41 | 39 | 45 | 45 | 38 | 37 | 15 | 14 | 12 | 11 |

Cost per square meter

| | |
|---|---|
| DIY fixed systems | $16 - 24 |
| DIY openable systems | $24 - 40 |
| professionally installed systems | $80 - 128 |

## 4.2 Replacement Windows

Installation and Availability

Replacement windows are unlikely to be a DIY job and there are many companies specialising in this area. If all the windows in a property are to be replaced this could cause major disruption. Usually the windows will have to be tailor made to suit the openings and this may involve the use of sub-frames; in any event a good fit is important to enable effective sealing.

Operation

This will depend entirely on the type of windows chosen.

Appearance

This is a very subjective field. Aluminium windows may possibly be acceptable in place of timber, but the random placement of transoms and mullions often ruins the proportions of the opening. To maintain the traditional appearance or even pre-date a building some windows are now available with plastic leaded lights, at substantial extra cost and reduction in solar transmission. The local joinery firm may well be more appreciative of the subtle qualities of the existing windows.

View

The veiw should not be affected unless the new frames occupy a significantly larger area than the previous ones.

Maintenance and Life

Cleaning apart, plastic and aluminium frames should be maintenance free. Timber will be much easier to preserve if it is stained and varnished rather than painted. The life of a new window will depend on its exposure but it may be as long as the remaining life of the building. The increased value of the property due to replacement double glazing should not be over estimated in view of the large initial expenditure.

Cost per square meter

| | |
|---|---|
| replacement double glazing | $320-400 |
| ditto with 2 layers 3M film | $416 |
| ditto with Pilkington's Kapafloat | $368-448 |
| ditto with 1 layer Heat Mirror | $352-432 |
| litto with leaded lights | $352-432 |
| replacement triple glazing | $400-480 |

## 4.3 Movable Insulation

Installation and Availability

The availabilty of products in the UK is limited to one company producing plastic insulating shutters and several companies producing roller blinds with heat reflecting coatings, only one of which is aimed at the domestic market. The shutters may be professionally installed or supplied as a DIY kit. The roller blinds available are supplied for easy self-assembly. The other option available is heavy insulating linings for curtains which have a limited effect especially if they are allowed to drape in front of radiators. There are a variety of systems, from the very simple to the sophisticated, which could be constructed by the home owner based on the information to be found in books such as MOVABLE INSULATION [1].

Operation

Curtains are simple to operate as are most forms of roller blind; both these systems can be easily automated on a time basis or to react to changes in temperature or solar radiation. The simplest form of shutter is the push-in panel; the main disadvantage with this system is the need for daytime storage space. Shutters which bi-fold back can be easy to operate but may sterilize useful wall space. Blinds however occupy a minimum of storage space when not in use.

Appearance

It is assumed that curtains will be used in conjunction with the manufactured shutters therefore appearance is not considered important. One of the manufactured heat reflecting blinds has a range of attractive surface finishes comparable with most other roller blinds. Obviously the appearance of the DIY devices will depend upon the skill and design ability of the individual.

View

The view will not be affected during the day as the insulation is only in place at night. With shutters and roller blinds there may be the added advantage of reducing unwanted solar gain in the summer.

Maintenance and Life

The maintenance involved with movable insulation would most likely be limited to replacing faded or damaged surface material or the oiling of hinges. The average life of a roller blind or curtains might be 10 to

12 years, but well-built shutters could last considerably longer. There may be an increase in the value of a property with movable insulation; if not blinds and curtains may be transfered to a new property.

Cost per square meter

| | |
|---|---|
| DIY kit reflective roller blind | $13-20 |
| multi-layer blind with seals | $32-48 |
| DIY push-in shutters | $8-16 |
| DIY bi-fold shutters | $40-56 |
| professionally installed shutters | $80-96 |

## 5. CONCLUSION

Movable insulation performs better in low occupancy dwellings/rooms and rooms with winter solar gain. Replacement double glazing systems are more beneficial in high occupancy dwellings and are particularily applicable in rooms with a high risk of condensation. Secondary glazing may be a cheaper solution than replacement double glazing if the existing windows are sound and if there is little risk of condensation. It is evident that no one treatment has universal application throughout a dwelling. However judicial use of certain window treatments in the various rooms of a house, as illustrated by simulations 14 to 17, may result in a cost effective solution to many practical problems.

## 6. ACKNOWLEDGEMENTS

This paper is based on a Passive Solar Design Study for the UK Department of Energy carried out by the sub-contractors Energy Design Group in colaboration with the Polytechnic of Central London.

## 7. NOMENCLATURE

$1.00 = £0.63

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0731-8626/83$3.00

# RESEARCH ON SOLAR FOOD DRYING AT THE UNIVERSITY OF CALIFORNIA, SANTA CRUZ

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## ABSTRACT

Research at the University of California, Santa Cruz farm has examined small-scale solar cabinet food dryers. Sun drying and direct and indirect solar convection dryers have been monitored for operating temperturés, drying times ,and solar insolation. Each dryer has been evaluated with respect to ease and cost of construction, utility, operating temperatures, and quality of their respective dried products. The relative vitamin C content of spinach and cantaloupe before and after drying has been examined to determine the product quality of the tested units.

## 1. INTRODUCTION

The UCSC Farm was started in 1972 when 17 acres were designated by the then Chancellor of the University of California ,Santa Cruz (UCSC), to further work begun by Alan Chadwick on a smaller scale at the UCSC biodynamic organic garden. Since then the Farm has been the location of many student-initiated projects in appropriate technology. It is now the site of many experiments in a new program of Agroecology located at UCSC.

## 2. SOLAR DRYING PROJECT

The present solar drying research project started in the fall of 1982. Solar food drying has been generally acknowledged as superior to sun drying, but there has been little examination of the various types of solar dryers in comparison with each other over a meaninful set of evaluative criteria (1). It is the overall goal of this project to perform some of that evaluation and comparison. Specfically, we wanted to complete a series of comprehensive performance evaluations of solar dryer designs begun by the Energy Center, a local resource center for appropriate technology(2), to identify the most promising designs in terms of overall dryer utility, and to work toward a model of dryer performance in the context of work reviewed by Mallan, et al. (3).

### 2.1 Evaluative Criteria

The criteria used for the evaluation of the dryers were: 1.Operational temperatures ,2.Drying times, 3.Cost, 4.Ease of Construction, 5. Utility, and 6.Vitamin loss of the dried food. Temperatures were taken with a Cambell Scientific Micrologger and an Omega thermocouple meter at three points in each dryer, close to the collector exhaust, at the middle of the cabinet, and at the top of the cabinet. Solar insolation was determined with a Li-Cor pyranometer positioned horizontally. Cost for each dryer is given in present U.S. dollars as determined by building each unit. A cost per tray area is given in Table 2 to normalize the differences in size of the units. Ease of construction was determined by consensus of the construction crew,i.e., ourselves representing the not too skilled do-it-yourselfer. Utility encompases ease of use, identifying problems that the dryer design creates in the dryer's use. It is reflected to some extent in the tray space available in the dryer. In practical terms, a dryer needs to be able to handle certain peak loads during the harvesting season as a delay in drying will result in food spoilage.

Vitamin loss was measured by assaying for vitamin C in samples of spinach and cantaloupe before drying and after drying in several of the dryers. Ascorbic acid was used for a measure of nutrient and vitamin breakdown during the drying process because many

other vitamins and nutrients are neutralized by the same effects but to a lesser degree. We hypothesized that food from those dryers that exposed the vitamin C to the most light, i.e. direct dryers, would show the largest vitamin C loss. However, vitamin C is also sensitive to heat and the length of the drying process which might be increased in the indirect dryers. Some work has been done on the relative vitamin loss in direct and indirect dryers(4), but not in a variety of designs.

The titration method for measuring ascorbic acid is based on an oxidation-reduction reaction in which ascorbic acid is oxidized to dehydroascorbic acid using 2,6-dichloroindophenol (DCP). Both ascorbic acid and dehydroascorbic acid are colorless. DCP is red below pH 3 and is reduced to a colorless product by ascorbic acid. Therefore, the pink endpoint of the titration is measured by the lack of ascorbic acid available to reduce the red DCP.

2.2 Dryer Describtions

We monitored 6 dryers in this stage of the project. The indirect dryer designs we tested were :

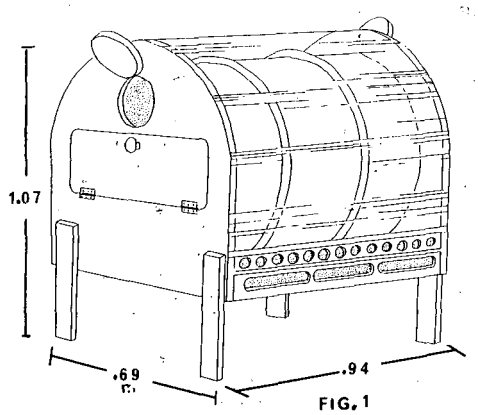


FIG. 1

Dryer 1, Fig.1. The Solar Survival dryer, with slight modifications of the unit. This dryer has a chamber inside of a sheet metal surface curved above it. The first models used a 55 gal drum as the metal surface. Air enters on one side of the dryer and is heated up between the metal and the fiberglass glazing, drawn down into the chamber from the bottom and up through the trays of food and out the vents on each end.

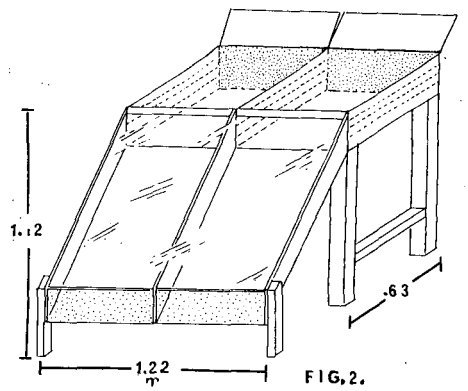


FIG. 2.

Dryer 2, Fig. 2. This is a dryer already in use at the Farm. It has a conventional air collector convecting heated air into the front of a chamber passing over the trays horizontally and out the back of the unit.

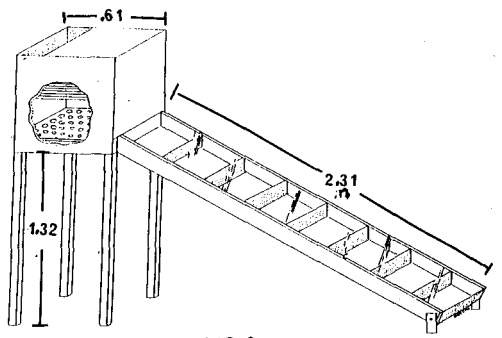


FIG. 3.

Dryer 3, Fig.3. This design is similar in many respects to common solar dryers. An air collector supplies heated air to the bottom of the drying cabinet and flows vertically to an exhaust vent at the top of the cabinet.

Dryer 4, Fig.4. This dryer is similar in design to dryer 3, but the collector has a matrix of metal turnings added to the plate and the overall dimensions of the collector and the cabinet are slightly different.

The direct dryers that we tested were:

Dryer 5, Fig.5. The New Mexico Solar Energy Association Dryer. This dryer has a glazed face in addition to a small collector at the bottom of the cabinet. All of this face is included in the area given as collector, though

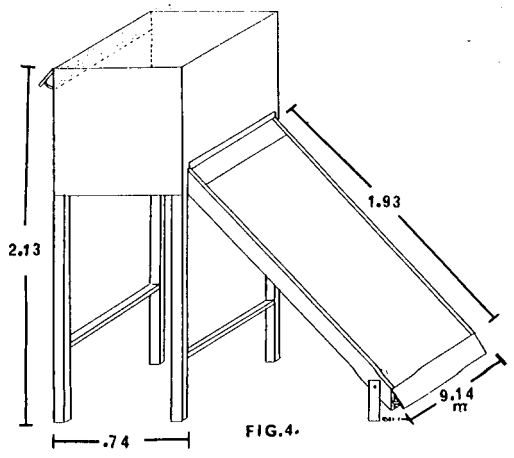


FIG.4.

the vertical surface of the dryer does not fuction well as a collector during the months when the sun is high in the sky.

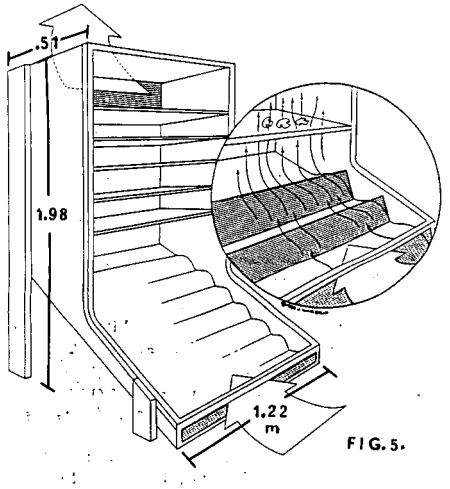


FIG.5.

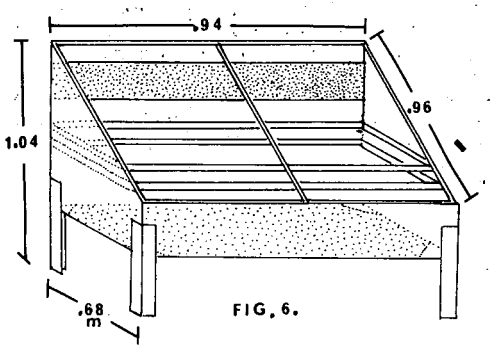


FIG. 6.

Dryer 6, Fig.6. This dryer was inspired by one developed by the Brace Research Institute and is possibly the simplest of the units. The cabinet and the collector are combined into one unit, looking somewhat as a solar oven with large vents.

Table 1 summarizes some of the characteristics of each unit.

TABLE 1.

Dryer Characteristics

| Dryer no. | Collector Area $m^2$ | Intake Vent $cm^2$ | Exhaust Vent $cm^2$ |
|---|---|---|---|
| 1 | 1.33 | 123 | 368 |
| 2 | 1.40 | 256 | 2670 |
| 3 | 1.13 | 613 | 774 |
| 4 | 1.47 | 542 | 697 |
| 5 | 2.45 | 871 | 2122 |
| 6 | .91 | 5418 | 1354 |

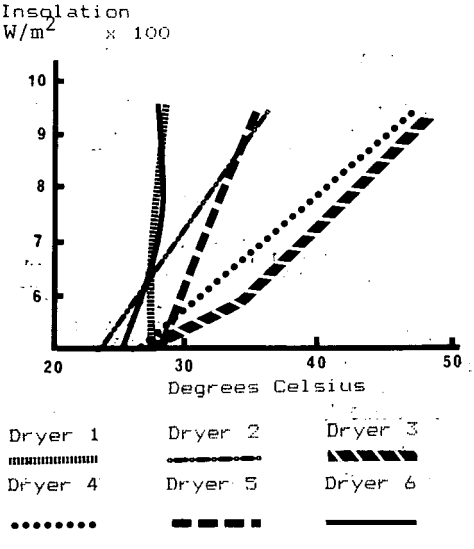
## 3. RESULTS

### 3.1 Temperatures

The performance of the dryers is reflected in Table 2. Dryer temperatures are plotted against insolation. The temperatures were measured at the middle of each dryer's cabinet.

TABLE 2.

Cabinet Temperatures



### 3.2 Drying Times

Weight per time is shown in Table 3 for four of the dryers and sun drying strawberries. All the dryers started with 566 grams of strawberries, and they were dried for 70 continuous hours.

TABLE 3.

Strawberries' Dried Weight

| Drier | Type | Grams |
|---|---|---|
| 1 | indirect | 52.5 |
| 2 | indirect | 44.4 |
| 4 | indirect | 40.5 |
| 5 | direct | 39.3 |
| | open sun | 49.4 |

### 3.3 Cost and Utility

From our past experience, it seems that at least 10 kilograms of produce should be accommodated by the dryer. That is the approximate weight of a lug box of fresh fruit. At an average rate of 7.32 kilos to the square meter of tray space, that implies dryer tray space of 1.37 square meters.

Table 4 gives some of the values relevant to our evaluation of these units.

TABLE 4.

Convenience and Cost

| Dryer | Tray Space (sq meter) | Cost/ Unit | Cost/ Tray |
|---|---|---|---|
| 1 | 1.12 | $65. | $58.04 |
| 2 | 1.49 | 90. | 60.40 |
| 3 | 1.30 | 75. | 57.69 |
| 4 | 3.16 | 115. | 36.39 |
| 5 | 2.88 | 175. | 60.76 |
| 6 | 1.21 | 50. | 41.32 |

### 3.4 Ease of Construction

The ease of construction varied somewhat. Dryer 1 has close tolerances that might be frustrating to the not too experienced builder. Dryers 2 and 5 were also judged more difficult to build than dryers 3 or 4. The dryer 6 is one of the simplest to build.

### 3.5 Vitamin Loss

Table 5 shows the results of the vitamin testing. The percentages are relative to the amount of vitamin C present in the sample of fresh product. The table shows data for two separate tests, one of cantaloupe and one of spinach. For the cantaloupe, there were one direct and two indirect dryers and a sample dried in the open sun. For the spinach, there were one direct and one indirect. The dryers are distinct in the two tests.

TABLE 5.

Vitamin C Loss Measurements

| Dryer | Type | Food | Percentage Retained |
|---|---|---|---|
| 1 | indirect | cantaloupe | 70.4 |
| 2 | indirect | cantaloupe | 51.0 |
| 5 | direct | cantaloupe | 53.6 |
| | open sun | cantaloupe | 39.5 |
| 3 | indirect | spinach | 35.9 |
| 6 | direct | spinach | 22.4 |

## 4. CONCLUSIONS

Review of the results of this monitoring and comparison seem to us to make a strong case for the advantages of an indirect dryer over either a direct dryer or open sun drying. For the most part, there is less vitamin loss, for instance. One exception to this is the New Mexico dryer, dryer 5. The anomalous vitamin loss in this dryer is probably explained by the fact that during our tests, direct sunlight was not shining into the transparent front. The only direct solar load was on the small collector at the bottom of the dryer, and so it was functioning more as an indirect unit, or one on the boarder. This is relected in other results for the dryer. It performed very much like dryer 2. All the dryers seemed to pair off, in fact. Dryers 3 and 4 were similar in most respects, as are their designs and dimensions. Dryers 1 and 6 also performed similarly. In this case there is less obvious reason as they are not similar in any respect. More work will be required to determine the causes for these strange results. It may be that either one or both of these dryers were behaving abnormally for reasons unrecorded by us. We have used both of these dryers previously with better results but with a different monitoring system.

## 5. FUTURE WORK

We need to take these data during the drying process when the dryers are fully loaded. We want to be able to

predict the most successful amount of tray space for each dryer design. We intend to extend our montoring to include relative humidity, air flow, and ambient air speed. These are the measurements that are needed to verify the various models that are being proposed for dryer design. We hope to run several more vitamin tests as well. Our project is scheduled to continue with this monitoring.

## 6. ACKNOWLEDGEMENTS

We would like to thank the UC Program in Appropriate Technology who funded a large part of this work and Kathy Ginetti who did the drawings.

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# WOOD FRAME SUPPORTED THERMAL MASS FLOORS

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## ABSTRACT

The direct gain passive solar concept employing a mass floor is quite common and easily constructed in slab-on-grade residences. Often, however, certain design decisions or constraints may require an above grade solution to thermal mass floors for optimum solar performance.

Above grade, wood frame supported, thermal mass floors, which can be low-cost, low maintenance, and attractive, have been developed in two residences designed and constructed by SUNSTRUCTURES. The finished result is a mass floor with a dark color added to the concrete with a tile pattern of oak strips set in the floor in one house and a dark slate tile finish in the other. Both of these floors will have good passive thermal storage and sound control characteristics. They are relatively simple to build and are amazingly effective when the need arises to utilize them in the upper story of wood framed residences.

## 1. INTRODUCTION

The use of wood frame supported direct gain thermal mass floors in two new residences by SUNSTRUCTURES has proven to be quite successful. These floors are a relatively simple solution to upper story thermal mass needs in a passive solar residence. They are especially useful when utilized to gain better solar exposure for residences on small intercity lots in traditional neighborhoods where ground level shading is a problem due to either other residences, garages, or trees, or as a way to provide upper floor mass in a two story wood framed residence.

## 2. BENEFITS

The inherent benefits of such a design/construction approach are that these floors are low in initial installed cost when compared to the installed cost of indirect gain thermal mass Trombe walls or isolated gain attached solariums; they provide good solar performance as the thermal mass is distributed throughout the living space; they are low in maintenance cost as they are strong, durable, and easily cleaned; and they are good in sound control attenuation between floor levels due to the presence of the thermal mass in the floor.

## 3. CONSTRUCTION TECHNIQUES



Fig. 1. Southwest View of Evich Residence
Ann Arbor, MI.

For the Evich Residence (Figure 1.), we designed and constructed an adequately engineered [1] living, family, and kitchen floor deck [2] of double 3.810 cm x 23.495 cm (2x10 s) floor joists at 40.640 cm (16 inches) on-center with 1.905 cm (3/4 inch) tongue and groove plywood glued and nailed on top (Figure 2.). To allow for different floor finishes that butt up to the thermal mass floor, we utilized extra sill plates as necessary to achieve the desired height in those areas with the different floor finishes (i.e. carpeting on plywood decking). A 6 mil poly vapor barrier was installed on top of the plywood decking and then the desired wood grid pattern was installed to create the individual tile effect. This grid pattern was made of 3.810 cm x 6.985 cm (1 1/2 inches x 2 3/4 inches) rough wood members ripped out of 3.810 cm x 13.970 cm (2x6 s) wood studs. With this operation completed, 6x6 10/10 welded wire mesh was then cut to size

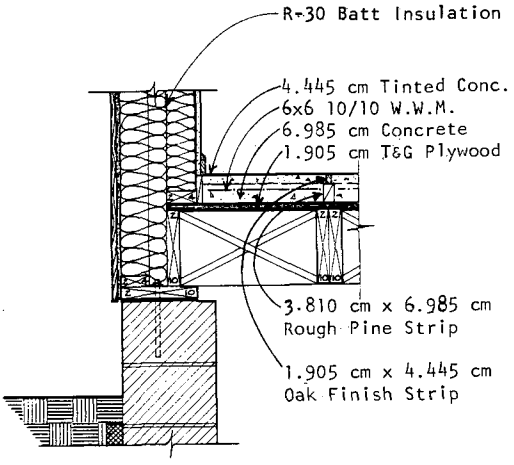



Fig. 2. Detail of Wood Frame Supported Thermal Mass Floor.

and layed within the rough wood grid pattern as temperature reinforcing for the individual concrete slabs. A rough pour of 6.985 cm (2 3/4 inches) of concrete was then made and screeded off at the top of the vertically installed rough wood grid pattern. As the concrete was delivered to the job site in a standard concrete truck, we utilized a front loading tractor to lift small loads of fresh concrete up to the second floor through the still open rough framed large south window openings, where it was carefully dumped to avoid exceeding the load bearing capabilities of the small area of floor underneath these window openings. The surface of this slab, which is actually a series of small slabs contained within the rough wood grid pattern, was purposely left rough to allow for a good bonding surface for the final pour of tinted concrete. However, before the final pour of tinted concrete, a second finish wood grid of 1.905 cm x 4.445 cm (3/4 inch x 1 3/4 inch) oak strips was fitted and nailed vertically to the rough wood grid pattern with stainless steel finish nails. This finish oak grid pattern was then well sealed with three coats of polyurethane sealer to prevent any absorption of water during the final pour of 4.445 cm (1 3/4 inch) thick tinted concrete. A site-mixed recipe of small batches of integrally tinted concrete was then poured to the top of each oak strip grid pattern and then troweled smooth by hand (Figure 3.). Extra care should be taken during this step to keep the tops of the finish oak strips as clean as possible of excess concrete. Upon proper curing of the finish slabs, the tops of the oak strips were then cleaned with a putty knife, water, and rags. An alternate method, which we have not tried yet but may, would be to coat the tops of the oak strips with a thin layer of removeable floor wax. Stripping off this floor wax with a suitable floor wax remover after the tinted floor slab was in-place might then allow for easy removal of any excess



Fig. 3. Installation of Tinted Concrete in Finish Oak Strip Grid Pattern.

concrete particles and concrete dust adhering to the tops of the oak strips. The final finishing step is the application of two coats of a quality acrylic semi-gloss concrete sealer over the entire surface of the finished slabs.

The end result of this effort is a 11.430 cm (4 1/2 inch) thick wood framed supported thermal mass floor with the appearance of a dark quarry tile/marble type finish, as we used a dark brown tinted concrete.

For the Downen Residence (Figure 4.)[3], similiar first steps were followed, except that the rough and finish wood grid patterns were not installed in the living and dining room thermal mass floor slab. The initial rough pour of concrete was 7.620 cm (3 inches) thick. The top pour of concrete was actually a 2.540 cm (1 inch) thick concrete bed for the thick setting of a 0.635 cm (1/4 inch) thick black slate tile. Upon installation of the black slate tile and proper curing of the concrete bed, a site-mixed recipe of small batches of integrally tinted concrete grout was applied between the individual black slate tiles. A dark grey tinted concrete grout was installed to help set off the black slate tiles in a pleasing effect. When the grout had sufficiently cured, the entire floor surface was thoroughly wetted and then washed with a weak solution of muriatic acid to remove any grout stains on the black slate tiles. The surface was then



Fig. 4. West View of Downen Residence Ann Arbor, MI.

mopped clean and left to dry, completing the final step in the finishing process.

The end result of this effort is a 10.795 cm (4 1/4 inch) thick wood frame supported thermal mass floor with an appealing black slate tile finish.

## 4. CONCLUSION

Both of the above described construction techniques for wood frame supported thermal mass floors were found to provide good thermal performance while being low in cost, easily constructed, and aesthetically pleasing.

Another construction technique for wood frame supported thermal mass floors we have also yet to try but merits exploration would be one where a tinted concrete floor would be poured and smooth troweled and then saw cut in a grid pattern with approximately 1.270 cm (1/2 inch) wide cuts, and finally these saw cuts would be filled with a lighter colored grout, the slab cleaned and sealed with a suitable concrete sealer. A tiled effect would again be achieved at an even lesser cost than either of the above two techniques described in this paper.

As part of our continually evolving and improving passive solar design and construction techniques, it is important to us that each solar application, such as those described herein, be at once pleasingly functional, readily buildable, and easily maintainable while being low or moderate in cost to install. Only through such an approach will the passive solar industry mature and grow to its fullest potential as one key energy/lifestyle component in a safe energy future.

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# VAPOR CONTROL IN SITE-BUILT GLAZING SYSTEMS

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## ABSTRACT

Site-built multiple glazing systems as an alternative to movable insulation offer a cost-effective method for enhancing energy performance in cold climates. Combining various glazing materials and especially high transparency films allows increased R-values without unacceptable losses in net energy gain. This approach is very attractive for horticultural greenhouses where movable insulation is not only expensive but difficult to implement over large areas and on overhead surfaces. One obstruction to the development of techniques in this area is the control of vapor migration into the glazing space. This paper discusses the results of an experimental test room constructed to evaluate the performance of five possible solutions to this problem. The approaches tested include the use of wicks, desiccant vent holes, a combination of sealed insulating unit with a storm glazing added, and a control.

## 1. INTRODUCTION

On two separate occasions, I have used a high transparency film in conjunction with fiberglass-reinforced polyester glazing to provide triple glazing for greenhouses. In one installation, condensation on the interior surface of the exterior glazing has been a reoccurring problem. In the other installation, condensation between the glazings has not occurred during the two years it has been in place. In an effort to determine the reason for this difference in performance and also to evaluate different methods for the control of water vapor in site-built multiple glazings that have been used and/or suggested by others, I have conducted a relatively simple experiment. A shoestring budget pre-determined my approach to a great extent. Necessary equipment to conduct an accurate quantitative analysis was simply out of the question. A qualitative comparison of different methods on the other hand was a realistic goal.

To accomplish this, I constructed a small test room. The glazed wall is framed with two by fours to create five separate spaces. No effort was made to paint or treat the framing lumber, and the stud to plate junctions were sealed with caulk. The remaining surfaces of the test room were insulated and a 6 mil polyethylene vapor barrier applied. Some water containers were added to provide thermal storage. All five glazed spaces were triple glazed and constructed as follows: Space number 1 consisted of a sealed double pane insulated glazing unit set against nailed in wooden stops with typical butyl glazing tape. A single glaze was then added on the outside and held in place with screwed in place wooden battens. The battens were set loose enough to allow a very slight ventilation of the space. Spaces 2, 3, 4, and 5 were all glazed on the exterior with fiberglass-reinforced polyester held in place with screwed on wooden battens. Silicone caulk was used to seal the battens to the glazing on the exterior only. The interior glazings in these four spaces were clear 2 mil films applied with wooden strips nailed over the film. Space #2 contained a cotton wick which ran the full height of the space and through a hole to a soffit area exposed to ambient air. Space #3 contained two holes approximately 8 mm in diameter each, one drilled in the bottom plate and one drilled in the top plate, and both were exposed to ambient air. Space #4 was left as a control. Space #5 received 50 grams of a commonly used desiccant (60% molecular sieve, 40% silica gel) between the center and the exterior glazing.

## 2. RESULTS

On the days that I built the test room, temperatures averaged around freezing, and it rained and snowed intermittently. My efforts to keep things dry were easily out-maneuvered by the high relative humidity. Large amounts of condensation formed on the inside surface of the exterior glazing immediately. Figure #1 illustrates the occurrence of visible condensation for the first twenty-one days

Fig. 1. Initial 21 days after construction.

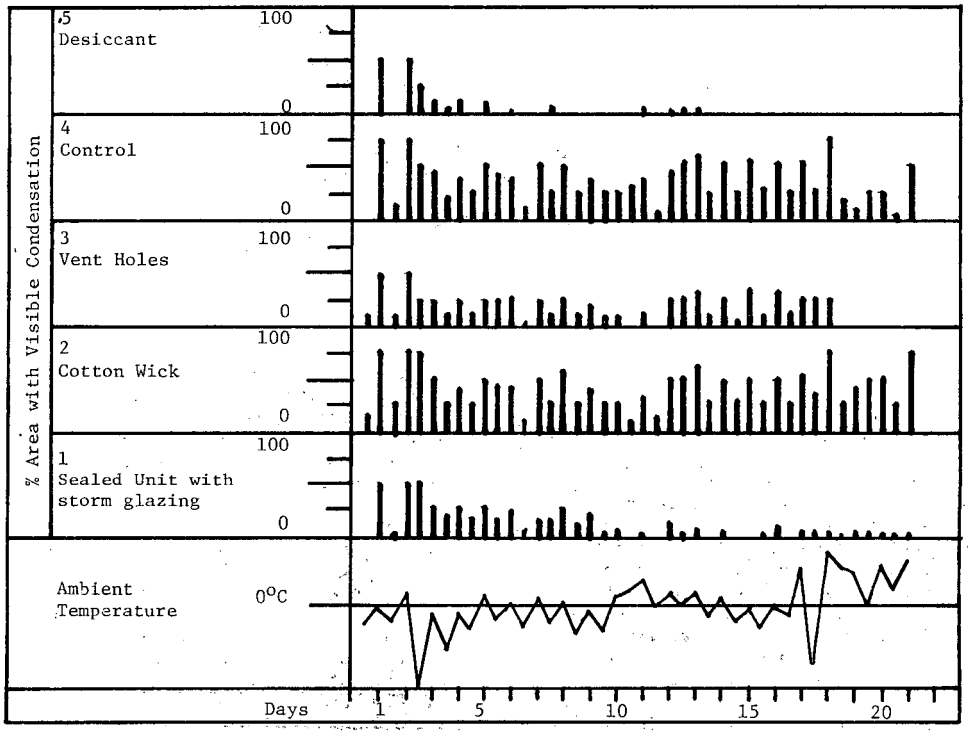
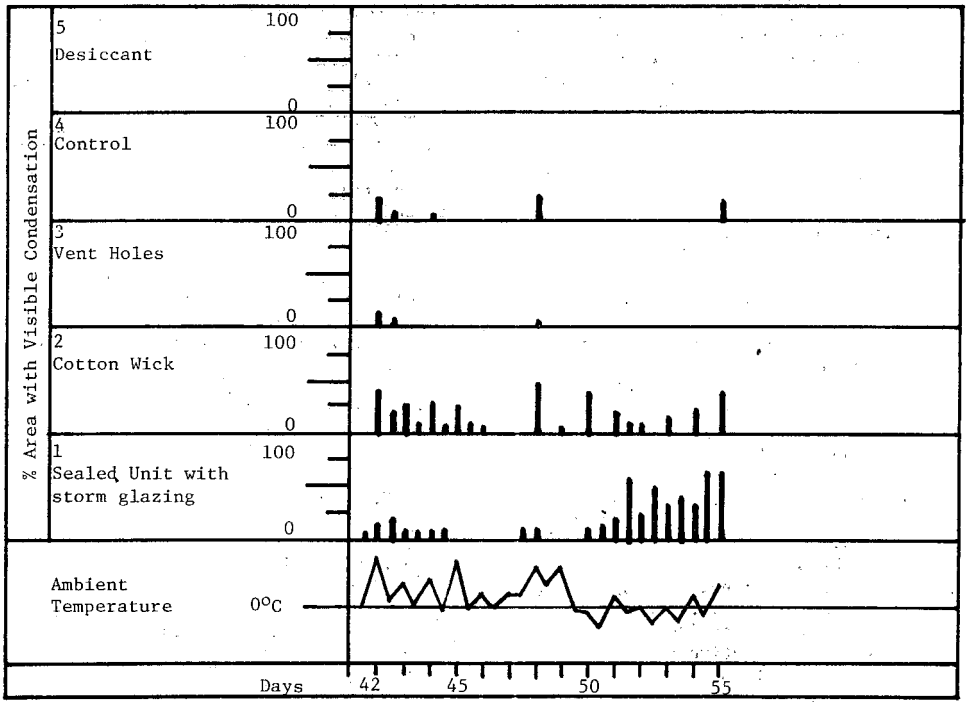



Fig. 2.



after construction. Observations were made every morning and evening, and visible condensation was recorded by the area of the glazing it occupied as a percentage of the total area of glazing for each space. No effort was made to induce high levels of humidity in the test room at this time. The large amounts of visible condensation left in the glazing spaces during construction was sufficient to test the individual methods of control.

The exterior glazing in each space showed severe condensation build-up on the first day. The area covered varied each day with the most condensation occurring in the late afternoon. The space with the desiccant showed the best performance. Visible condensation disappeared rapidly with only trace amounts showing after five days. After two weeks and throughout the balance of the experiment no visible condensation occurred in this space. The sealed unit with storm glazing reduced visible condensation rapidly. However, trace amounts persisted throughout the initial 21 days. The vented space was the third most effective during this initial period. Condensation persisted until clear skies and warmer weather with temperatures above freezing eliminated visible condensation on the eighteenth day. The wicked space and the control space showed very similar performance and no significant reduction of condensation during this initial period.

Figure #2 illustrates a period of 14 days which begins on day 42 after construction. Average ambient temperatures were warmer, but all other conditions remained the same. On days #50 through #55, the relative humidity in the test room was increased by simmering a bucket of water on a hot plate. Ambient temperatures remained below freezing during most of this period, and the interior surfaces of the inner most glazings were completely fogged, with excess moisture running down and pooling on the floor. The spaces with 2 mil films for inner glazings were not affected during this period. In each of these spaces, no additional condensation occurred between the glazing layers. However, the sealed unit set against butyl tape on wooden stops proved very susceptible with an immediate increase in condensation on the exterior storm panel.

## 3. DISCUSSION

This experiment is not sufficient in itself to define conditions for the migration of vapor into site-built glazings. Much greater vapor pressure can be expected with normal greenhouse conditions during extreme cold weather. It is also necessary to approach this problem with preventive measures as well as methods to eliminate or control the moisture that finds its way between glazing layers. However, certain characteristics of moisture in site-built glazing systems become evident in this experiment.

The greatest amount of condensation was visible during late afternoon and evening and not in the early morning when ambient temperatures were lower and relative humidity higher. Visible condensation also increased after sunny days. It would appear that warmer temperatures between the glazing layers acted to release moisture that was held in the wood framing. Even though the air between the glazings could hold more moisture as vapor at higher temperatures, the amount of moisture released from the framing as vapor was sufficient enough to produce larger areas of condensation. The fluctuation in temperature and the consequent change in the relative humidity in the space varies the equilibrium moisture content of the wood, causing water vapor to be absorbed or released (1). This condition was not observed with the desiccant, presumably because of its much greater capacity for moisture absorption. The relatively poor performance of the wicked space on the other hand may be the result of the greater surface area it affords for water vapor absorption. It held moisture available for this cycle while it was only marginally successful at wicking it to the outside.

Migration of water vapor into the glazing space depends largly on the particular details of construction and materials used. Moisture may enter the space from either the exterior or interior. In either case the primary mechanism for the transportation of water vapor into the glazing space is by air infiltration. Vapor migration by diffusion in glazing systems can be assumed to be very slight, the reason being the typically low permeability of glazing materials (1).

## 4. CONCLUSION

Controlling condensation in site-built glazing systems is feasible. The most important consideration is during actual construction, since moisture absorbed in the framing material and trapped humid air proved to be critical factors. Aluminum framing is advisable. If wood framing is used, care should be taken to use dry wood which is properly primed and painted to reduce its ability to absorb moisture. It is also important to assemble or install the glazings during dry sunny weather. In addition, some method to control the moisture trapped during construction or which may migrate into the glazing space should be incorporated. A small amount of desiccant will

afford the greatest insurance, and ventilation of the most exterior glazing space also is effective. A combination of these two is probably the best insurance. The desiccant can control moisture build up when necessary, holding it untill it can be ventilated during periods of low relative humidity.

The combination of wood stops and butyl tape are not sufficient to prevent vapor migration from the interior. Caulking at all joints on the interior of fixed glass is required. The use of cotton wicks was shown to be counter productive with that space experiencing more condensation than the control space.

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# ADVANCED PHASE-CHANGE STORAGE FOR PASSIVE SOLAR HEATING: ANALYSIS OF MATERIALS AND CONFIGURATIONS

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## ABSTRACT

In this paper we discuss the performance of phase-change materials (PCMs) as thermal storage in passive solar heating systems. We discuss factors, other than material properties, that affect storage performance and optimization. We also briefly describe solid-state phase-change materials (SS PCMs) and list typical material properties. We give results from a parametric analysis of PCM Trombe walls and discuss the factors that limit performance. We present configurations for enhanced PCM performance and give simulation results for an idealized case.

## 1. INTRODUCTION

The effectiveness of thermal storage in passive solar systems depends on a number of factors, the most obvious being the thermophysical properties of the storage material. Parametric analysis can identify optimum properties and sensitivities to suboptimum properties. However, such analysis is complicated by the number of properties (and system parameters) of interest and by the fact that the optima and sensitivities for a particular property depend on other properties and parameters that may have suboptimum values.

Storage effectiveness also depends on context, i.e., the details of the passive system and the building. For instance, the addition of highly insulated glazing to a passive system alters the effectiveness of the system (Trombe wall or direct gain) and is likely to alter the effectiveness of different storage materials. Similarly, increasing building insulation levels alters the seasonal heating load patterns and the daily load profiles and is likely to favor one storage material over another. For near-term applications it is reasonable to evaluate storage materials in the context of typical current passive solar systems, and building types. For future applications, assumptions are not as well defined, and additional system and building types must be considered, but preliminary analysis of typical system and building types may serve as a point of departure. It should be emphasized, however, that a stated storage equivalence (e.g., a given PCM has four times the volumetric heat storage capacity of concrete) is situation specific. Such an equivalence is useful for comparison but is not necessarily general and should not be interpreted as an absolute limit on performance for that material except in the situation evaluated. It may be useful to determine maximum theoretical performance as an idealized situation by placing an upper bound on performance for a particular class of materials.

To date, storage material performance in passive solar systems has been analyzed to predict overall system performance and storage component heat transfer. The system performance studies (1,2) have been based on computer simulations for a limited number of typical storage materials, solar systems, building types, and locations. The heat transfer studies (3,4) have been more detailed including optimization, but have been based on analytical solutions with simplified boundary conditions or numerical simulations with limited building models.

## 2. SOLID-STATE PHASE-CHANGE MATERIALS

A solid-state phase-change material is any material that absorbs or releases energy when changing from one solid phase to another solid phase. The Solar Energy Research Institute (SERI) has studied the properties of such materials for possible use as thermal storage in various solar applications. The organic SS PCMs, which we are now studying for passive solar applications, were first considered for use in the passive temperature control of earth satellites. Under National Aeronautical and Space Administration (NASA) sponsorship, numerous such SS PCMs were evaluated ten years ago (5). At SERI, we have extended the earlier NASA research and discovered organic solid solutions that lower the useful temperature range of SS PCMs to where the passive solar system designer would be interested (6).

The most promising materials are solid solutions of pentaerythritol ($C_5H_{12}O_4$), pentaglycerine ($C_5H_{12}O_3$), and neopentyl glycol ($C_5H_{12}O_2$). Solid-solution mixtures of these compounds can be tailored so they exhibit solid-to-solid phase transformations at any desired temperature within a range from less than 25°C to 188°C. Table 1 lists some of the characteristics of the three compounds and an example of the solid solutions that are the focus of this work. From the table it is

**Table 1. Comparison of Phase-Change Thermal Energy Storage Materials**

| Constituents | Latent Heat of Transition | Transition Temperature | Solid Material Density | Raw Materials Cost* |
|---|---|---|---|---|
| | kJ/kg (Btu/lb) | °C (°F) | kg/m$^3$ (lb/ft$^3$) | $/kg ($/lb) |
| Solid-State PCMs | | | | |
| Pentaerythritol (PE) | 269 (115.7) | 188 (370) | 1390 (86.7) | 1.56 (0.71) |
| Pentaglycerine (PG) | 139 (59.8) | 89 (192) | 1220 (76) | 1.61 (0.73) |
| Neopentyl-glycol (NPG) | 119 (51.2) | 48 (118) | 1060 (66) | 1.30 (0.59) |
| Solid-solution mixture of 60% NPG plus 40% PG | 76 (32.7) | 26 (79) | 1124 (70) | 1.46 (0.66) |
| Solid-Liquid PCMs | | | | |
| Sodium sulfate decahydrate | 225 (96.8) | 32 (90) | 1464 (91) | 0.10 (0.045) |
| Calcium chloride hexahydrate | 190.8 (82.1) | 27 (81) | 1802 (112.5) | 0.145 (0.066) |

*Chemical Marketing Reporter 223, No. 7, Schnell Publishing Co., New York.(14 Feb. 1983).

apparent that the latent heat of transformation is typically lower for SS PCMs with lower transition temperatures. Currently, we are investigating the reasons for this relationship in an effort to develop materials that do not suffer from reduced latent heats of transformation.

One of the concerns with using PCMs for thermal energy storage is the stability of the material and its retention of full, reversible latent heat of transformation after several thermal cycles. The solid-state phase-change process is quite different from the salt hydrate solid-to-liquid PCMs and is not expected to suffer any changes during cycling because there is so little migration of material in the solid even above the transformation temperature. Preliminary experiments support the contention that the SS PCMs are basically stable to thermal cycling.

Another common problem with PCMs is undercooling; i.e., when the PCM is cooled from above the transition temperature, the reverse transformation that liberates the stored heat occurs at a lower temperature than the forward transformation. This undercooling effect is particularly great in SS PCMs. Experiments have shown that the kinetics of the transformation can be changed by adding a nucleating agent that lowers the activation energy for the nucleation of the phase transformation. For instance, adding 0.1% fine graphite powder reduced the undercooling significantly, particularly at low heating and cooling rates. Further experiments are needed to determine minimum achievable undercooling at the lower heating and cooling rates typical of passive systems.

## 3. PARAMETRIC ANALYSIS OF PCM TROMBE WALLS

In this section, we give assumptions and results for a parametric analysis of PCM Trombe walls and discuss the factors that limit performance.

### 3.1 Assumptions

The properties of neopentyl glycol were used as a starting point for the parametric analysis. Thermal conductivity and the phase transformation temperature were varied as parameters to evaluate the performance for modified neopentyl glycol or other PCMs. Enthalpy of transformation, density, and specific heat were held constant at the nominal values of neopentyl glycol. In these preliminary analyses, we did not include the effect of undercooling.

Thermal analysis was based on simulations using the SERIRES computer code (7) and ersatz ETMY (8) weather data for Denver, Colo. The thermal network model for the building and the Trombe wall were solved by forward finite differencing with time steps of 6 min or less. Solar savings fractions were based on annual simulations with and without the Trombe wall.

Table 2 lists characteristics of the building model, which was based on the SERI test house, a single-story, three-bedroom house that has been extensively monitored (Class A). We determined a base annual heating load of 3430 kWh (11.7 X 10$^6$ Btu) from a SERIRES simulation assuming an adiabatic south wall (for calculating solar savings fractions).

**Table 2. Building Characteristics***

| |
|---|
| Floor area = 100 m$^2$ (1080 ft$^2$) |
| Windows = double glazed |
| Ceiling = RSI 5.3 (R30) |
| Walls = RSI 1.9 (R11) |
| Crawlspace walls = RSI 3.3 (R19) |
| Infiltration = 0.5 ACH |
| Internal gains = 56,000 kJ/day (53,000 Btu/day) |
| Heating setpoint = 20° C (68° F) |
| Venting setpoint = 24.4° C (76° F) |
| Cooling setpoint = 25.6° C (78° F) |

**Table 3. Trombe Wall Characteristics**

| |
|---|
| Area = 18.6 $m^2$ (200 $ft^2$) |
| Glazing = double |
| Vent area = 3% |
| Concrete |
| Thermal conductivity = 1.31 W/m °C (0.7576 Btu/ft° F h) |
| Density = 2243 kg/$m^3$ (140 lb/$ft^3$) |
| Specific heat = 0.837 kJ/kg°C (0.2 Btu/lb °F) |
| Phase-change materials |
| Density = 1066 kg/$m^3$ (66.55 lb/$ft^3$) |
| Specific heat = 2.5 kJ/kg°C (0.5996 Btu/lb °F) |
| Heat of transformation = 121 kJ/kg (52.03 Btu/lb) |

Table 3 lists characteristics of the Trombe wall. Thermal storage was modeled with multiple nodes to account for the effect of thermal conductivity and the resulting temperature gradients in the wall.

### 3.2 Results

Figure 1 shows the results of a series of simulations with the phase transformation temperature as a parameter and with a wall thickness of 5.1 cm (2.0 in.). For the nominal PCM thermal conductivity, the optimum phase transformation temperature is 29°C (84°F). For a PCM with thermal conductivity increased by a factor of five, the optimum transformation temperature is 27°C (80°F).

Figure 2 shows results with thermal conductivity as a parameter. For a transition temperature of

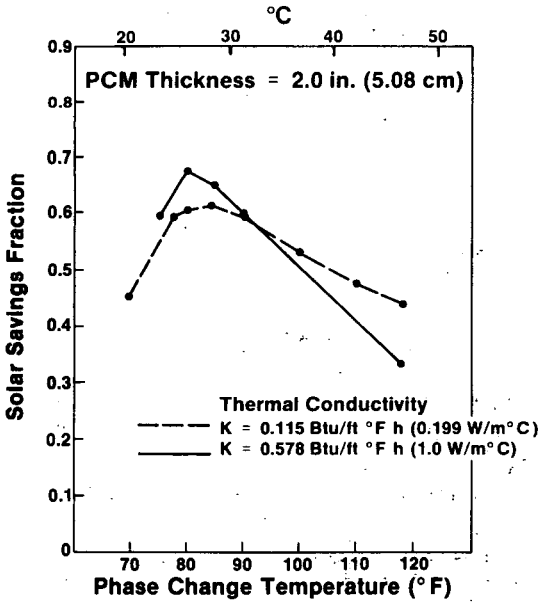



**Fig. 1. Solar Savings Fraction as a Function of Phase-Change Temperature in a PCM Trombe Wall**

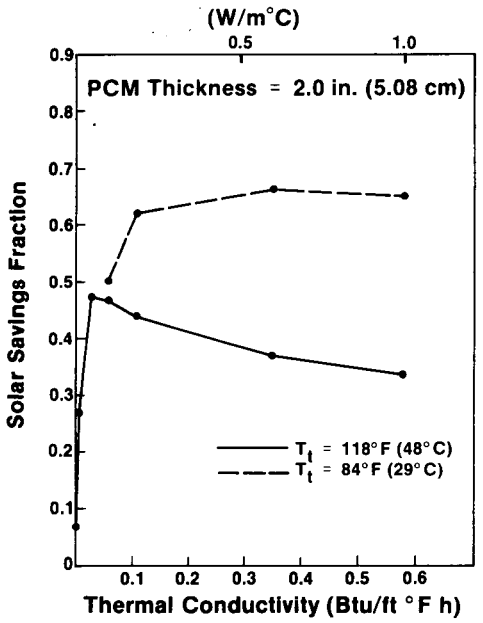



**Fig. 2. Solar Savings Fraction as a Function of Thermal Conductivity in a PCM Trombe Wall**

48°C (118°F), performance is optimized when the thermal conductivity is about 0.05 W/m °C (0.03 Btu/h ft °F) and declines rapidly for lower values. For a transition temperature of 29°C (84°F), performance is relatively insensitive to thermal conductivity, except for conductivity values below 0.17 W/m °C (0.1 Btu/h ft °F) where performance declines rapidly.

Figure 3 shows Trombe wall performance as a function of wall thickness for parameters listed in Table 4. Curve A gives results for an idealized PCM Trombe wall discussed in Sec. 3.3. Curve C gives results for a concrete Trombe wall for comparison. The remaining curves give results for PCM Trombe walls with various material properties.

For concrete Trombe walls, thickness is shown along the abscissa at the top of the graph. For the PCM walls, thickness is shown along the lower abscissa, which is scaled one-fourth the thickness of concrete.

### 3.3 Discussion of Results

The optimum phase transformation temperatures for PCM Trombe walls (Fig. 1) are caused by trade-offs between storage heat delivery rates and storage heat loss rates during the heating season. For transition temperatures below the optimum, perfomance is limited by heat delivery rates that are inadequate relative to hourly heating loads. For transition temperatures above the optimum, storage losses are increased owing to backlosses through the glazing and losses caused by unnecessary heating of the building.

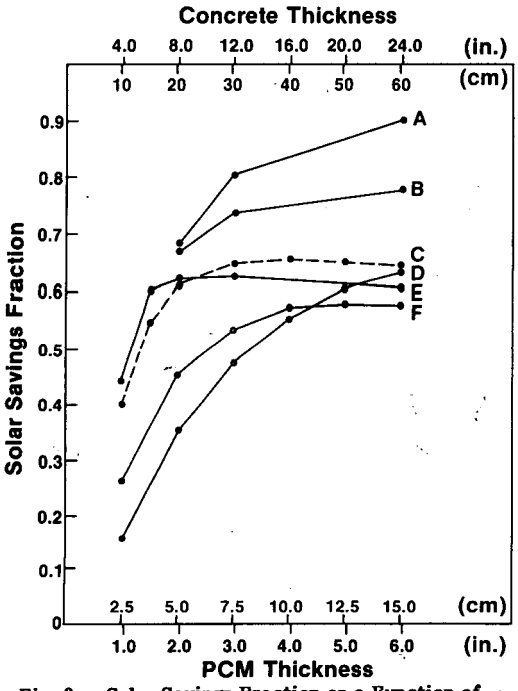



**Fig. 3. Solar Savings Fraction as a Function of Trombe Wall Thickness for SS PCMs and Concrete.** (See Table 4 for parameter values.)

The sensitivity to thermal conductivity for PCM Trombe walls (Fig. 2) depends on the phase transformation temperature. For a transition temperature of 29°C (84°F), the results indicate that performance will be near optimum if the thermal conductivity of the PCM is large enough so the interior surface temperature of the Trombe wall is near the transition temperature even when the phase transition boundary is near the center of the wall. For a phase transformation temperature of 48°C (118°F) and a large thermal conductivity, performance is low because: (1) during charging, heat is conducted to the interior surface and into the room at such a rate that less of the wall is heated up to the phase transformation temperature, and (2) once charged, the wall discharges and loses heat at an excessive rate. For a phase transformation temperature of 48°C (118°F) and a lower thermal conductivity, performance is somewhat improved. The improvement is limited because a trade-off exists between the discharge and heat loss rates and conduction of heat into the wall during charging.

Performance of PCM Trombe walls (Fig. 3) varies over a wide range depending on material properties. For case E, performance is approximately equivalent to the performance of a concrete Trombe wall four times as thick. For higher transition temperatures (cases D and F), performance is lower. In case B, transition temperature and thermal conductivity are optimized, and solar fractions are 10%-20% higher than solar fractions for a concrete Trombe wall. Note that the transition temperature and thermal conductivity have been optimized for a 5-cm (2-in.) thick wall and that solar fractions for thicker walls may increase if these properties are optimized for those thicknesses.

**Table 4. Parameter Values for Fig. 3**

| Case* | Transformation Temperature °C (°F) | Thermal Conductivity W/m °C (Btu/ft °F h) | Heat-Transfer Coefficient W/m² °C (Btu/ft² °F h) |
|---|---|---|---|
| A | 20.3 (68.5) | 1728 (999) | 567 (99.9) |
| B | 27 (80) | 1.00 (0.578) | 8.29 (1.46) |
| C | Concrete | 1.31 (0.758) | 8.29 (1.46) |
| D | 48 (118) | 1.00 (0.578) | 8.29 (1.46) |
| E | 29 (84) | 0.20 (0.115) | 8.29 (1.46) |
| F | 48 (118) | 0.20 (0.115) | 8.29 (1.46) |

*All cases are for SS PCMs except for C.

PCM heat storage capacities are often quoted relative to concrete, assuming operation over a particular temperature range. A relative heat capacity implies an equivalent thickness; i.e., if the relative heat capacity of a PCM is stated to be four times that of concrete, then the implication is that a quantity of the PCM will perform equivalently to four times as much concrete.

Performance comparisons for PCM and concrete Trombe walls (Fig. 3) can be used to determine the validity of equivalent thicknesses and relative heat storage capacities. The results presented in Fig. 3 indicate that an approximate equivalence can be stated in some cases, e.g., curve E. In other cases, however, PCM solar fractions exceed the maximum solar fraction for the concrete Trombe wall, and a storage equivalence cannot be directly stated. It is nevertheless important to compare storage performance at equal solar fractions, and one way to achieve this is to use PCM and concrete walls with different aperture areas. Such storage and aperture trade-offs will be included in future SS PCM systems analyses.

## 4. CONFIGURATIONS FOR ENHANCED PCM PERFORMANCE

As described in the Sec. 3.3, performance for PCM Trombe walls improves as the phase transformation temperature is reduced to an optimum of approximately 27°C (80°F). To further maximize PCM performance, we now discuss alternative situations that allow lower phase transformation temperatures and reduced storage losses while maintaining adequate heat delivery rates. The objective is to minimize passive system standby losses and uncontrolled delivery of heat when it is not needed. The ideal system is analagous to an active system with well-insulated storage (and very high heat exchanger effectiveness between

storage and load). We discuss three alternative passive configurations which if taken to ideal extremes are essentially equivalent in terms of heat transfer. Some of these alternatives are more theoretical than practical, but serve to determine an upper bound for PCM performance and to identify what needs to be done to approach such idealized performance.

Note that an elevated phase transformation temperature causes not only increased heat losses but also increased sensible heat storage that to some extent offsets the heat losses. This offsetting effect is relatively large for the SS PCM analyzed here because of a high specific heat and relatively low enthalpy of transformation compared to other PCMs. For other PCMs, we expect the offsetting effect to be smaller and the benefits of a lower phase transformation temperature to be correspondingly greater. In the following discussion, we assume that the heat-loss effect is dominant and that a lower phase transformation temperature will result in a net benefit.

### 4.1 Trombe Wall

For the Trombe wall configuration, interior surface area equals aperture area, and heat delivery depends on the storage temperature and the heat-transfer coefficient at the interior surface. If this coefficient increases, then adequate heat delivery can be achieved even with a lower transition temperature, which, in turn, reduces heat losses from storage. The maximum benefit would occur if the heat-transfer coefficient were infinitely large and the transition temperature were equal to the heating setpoint. Then heat would be delivered from storage to the space only if there were a net heating load for the building (unless the latent heat capacity of the storage had been exceeded, in which case the storage temperature would be greater than the phase transformation temperature). This idealized PCM Trombe wall also assumes a high conductivity PCM so the interior surface temperature is not significantly lower than the phase transition temperature.

In practical cases, the surface heat-transfer coefficient can be increased somewhat by forced convection, but the potential for using lower phase transformation temperatures is not great. The concept is described here mainly as a vehicle for using Trombe wall results to indicate other configurations with high performance potential.

### 4.2 Direct Gain

For typical direct-gain configurations, storage within the building is charged during the day and delivers heat at night convectively to the room air and by long-wave radiation to other room surfaces. The heat delivery situation is similar to that for Trombe walls. Note, however, that even though storage surface area is typically larger in direct-gain systems, aperture losses are part of the heating load to be met by heat transfer from the storage surface area (while in a Trombe wall configuration, heat is transferred from the exterior wall surface, and the room is effectively insulated from aperture losses). Further increases in storage surface area in a direct-gain system could allow for use of a lower phase-transformation temperature while still maintaining adequate heat delivery. The benefit would increase as the product of the surface area and the heat transfer coefficient increased and the phase transformation temperature approached the heating setpoint.

In practical cases, additional surface area may be available for storage, but it will be usable only if incoming solar energy can be adequately distributed. In typical direct-gain systems with storage charged primarily by direct beam solar radiation, storage-to-aperture ratios of between 3 and 6 are often assumed (9). Neeper and McFarland (10) have studied convectively charged PCM storage with area ratios between 6 and 12 and a phase-change temperature 1.6°C (3°F) above the heating setpoint. This low temperature was assumed to allow convective charging and discharging within the 5.5°C (10°F) thermostat deadband. The results were promising, but maximum performance for PCM storage was achieved only when the surface heat transfer coefficient was assumed to be three to four times larger than the normal values for natural convection.

### 4.3 Conductively Coupled Storage

In the previously described configurations, system optimization was limited by the need for phase-transformation temperatures above the heating setpoint except in hypothetical idealized cases. We now propose a configuration that avoids this limitation, i.e., a configuration in which heat delivery does not depend on a storage temperature above the heating setpoint. The proposed ideal configuration is one in which the PCM storage is in direct contact with building components through which heat is lost to ambient, e.g., a thin layer of PCM storage on the interior surfaces of exterior walls. The room air is buffered from heat losses by the presence of the PCM storage at the heating setpoint temperature.

In this configuration, heat delivery is by conduction to exterior building components, vis a vis typical passive solar configurations in which heat is delivered from storage to room air by convection. Hence, we refer to this configuration as conductively coupled storage. Note that the benefits of conductively coupled storage depend on the use of a PCM with a phase-transformation temperature at or near the heating setpoint; i.e., a sensible heat storage material that depends on elevated temperatures to store heat will not benefit from the conductively coupled storage configuration. Some portions of the building heating load (infiltration) are not amenable to the conductively coupled storage approach and would require some storage to be at an elevated temperature.

To the extent that PCM storage can be located as described and adequately charged, this configuration will approach ideal effectiveness for PCM

storage. Distribution of solar energy to a large storage area depends at least partially on convective charging, and a low phase-transformation temperature facilitates convective heat transfer. It may also be useful to employ aperture materials or devices that diffuse incoming solar radiation so it is dispersed widely over interior building surfaces.

### 4.4 Results

As an example of a configuration for enhanced PCM performance, we simulated an idealized PCM Trombe wall with a transformation temperature of 20.3°C (68.5°F) and a surface heat-transfer coefficient of 567 W/m °C (99.9 Btu/h ft °F). The results for this case are presented as curve A in Fig. 3. Solar savings fractions for the idealized PCM Trombe wall are approximately 10%-20% higher than solar fractions for the optimized PCM Trombe wall with a typical heat-transfer coefficient (curve B).

The results presented as curve A in Fig. 3 for the idealized PCM Trombe wall are thought to represent an upper bound for the effectiveness of this particular PCM. Preliminary results for the conductively coupled storage configuration are similar to the results presented for the idealized Trombe wall.

## 5. CONCLUSIONS

Solid-state phase-change materials have certain advantageous characteristics, but effective use of these materials depends on an optimum combination of material properties and system design. Further improvements may be possible if materials research provides better SS PCMs.

PCM Trombe wall behavior is functionally different than the behavior of a concrete Trombe wall, resulting in different trends in material property sensitivities and PCM-to-concrete equivalences that are only valid for a specific set of circumstances.

For a typical Trombe wall configuration, performance is optimum for a PCM with high thermal conductivity and a phase transformation temperature that is a seasonal compromise between adequate heat delivery and storage heat loss.

In idealized passive configurations, the phase-transformation temperature equals the heating setpont so storage losses are minimized and performance is maximized.

## 6. ACKNOWLEDGMENTS

I wish to thank David K. Benson, of SERI's Materials Research Branch for his guidance and support of this project and for his careful review of each stage of the work. This work was sponsored by the U.S. Department of Energy, Division of Passive and Hybrid Solar Heat Technologies.

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# HVAC CONTROLS IN PASSIVE/HYBRID BUILDINGS WITH REMOTE THERMAL STORAGE

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## ABSTRACT

The interaction of "solar" and "auxiliary" resources in passive/hybrid solar commercial buildings calls for special care in the design and selection of mechanical systems controls. The author reports difficulties experienced with HVAC controls for an otherwise highly successful project, and offers observations which may help other designers avoid such problems.

## 1. BACKGROUND : PRINCETON PROFESSIONAL PARK

Princeton Professional Park (PPP), one of the major U.S. Department of Energy Passive and Hybrid Solar Commercial Building Program projects, and winner of a Passive Solar Design Award at the 5th National Passive Solar Conference, is now occupied. PPP is a 5760 $m^2$ (64000 $ft^2$) passive/hybrid solar office building complex in Princeton, NJ. Its three buildings combine direct gain heat collection, spray roof cooling, and active thermal storage in a horizontal below-slab rockbed. Daylighting is also an important part of the design. Concepts, design process and additional project details are reviewed in the July 1981 SOLAR AGE. Photos of the completed buildings appear in the April 1983 issue of PROGRESSIVE ARCHITECTURE.
PPP is especially interesting because it is a speculative for-rent office development at the low end of typical construction costs for commercial buildings.

The project has been very successful for the owners and the design team (A Joint Venture: Harrison Fraker, Architects and Short & Ford, Architects, with Princeton Energy Group). It has been built with little variation from the original award-winning design, at a cost only 3.5% above January 1980 estimates prepared for the initial U.S. DOE Grant proposal. Predicted savings for this project are very encouraging, especially at a total solar add-on cost of only \$86/$m^2$ (\$8/$ft^2$). Even against the upgraded base case used in final design evaluations, PPP's total energy consumption is expected to be four times better, achieving a comparative reduction of \$17.22/$m^2$ (\$1.60/$ft^2$) in annual energy expense. These savings, if borne out in operation, give financial returns within the range attractive to most commercial building owners and investors. The design has also been widely acclaimed for effectively handling energy issues within a significant architectural statement and a pleasant working environment. Energy components provide better quality surroundings thermally, visually, and aesthetically. The atrium is more than an oversized corridor acting as a heat and light collector; it's a marvelous space within each building, one of the main features giving this project a competitive advantage over many other less attractive "spec" office environments. The rockbed is hardly more than the normal gravel fill below a concrete floor slab. Yet it represents over 80% of building mass, stores large amounts of heat and "coolth," and provides a more comfortable mean radiant floor temperature in all seasons. The spray roof system not only "wipes away" a big part of daytime cooling load, but is also expected to cool air to below ambient temperature at night. This "coolth" is inexpensively transferred to the rockbed for use the following day. Strong daylighting affects not only the well known double reduction in energy use (less electricity for artificial lighting and less refrigeration to reject excess heat from electric lights), but also the benefits of daylight in visual comfort and satisfaction of building users.

## 2. THE PROBLEM : HVAC CONTROLS

While meeting its overall budget constraints, project costs have shifted in some interesting ways during the process of design and construction. The most significant and frustrating of these shifts has been in the area of mechanical systems controls, which are turning out to be much more costly than the \$500 originally budgeted for each 102 $m^2$ (1100 $ft^2$) office rental unit.

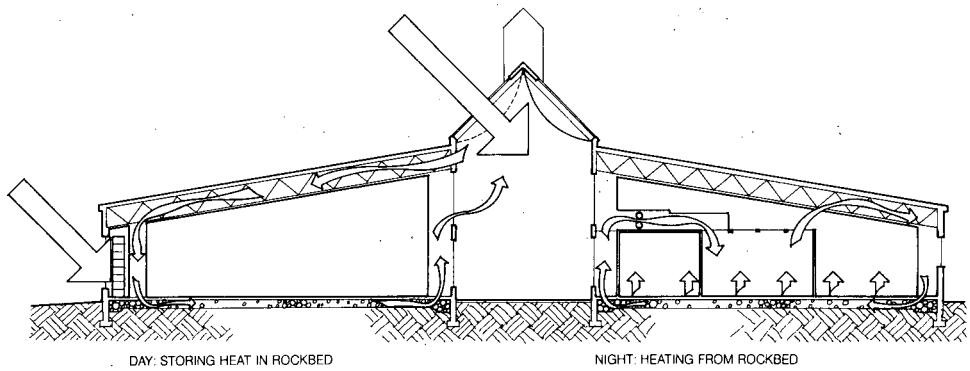



Figure 1. Heating.

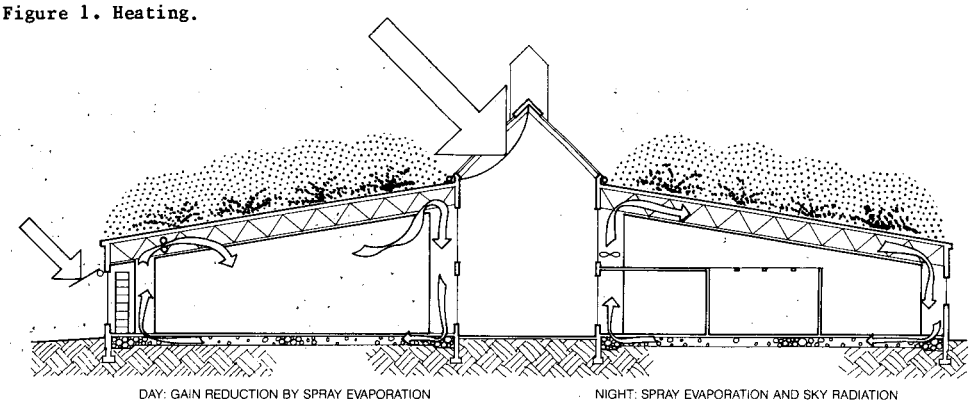



Figure 2. Cooling.

2.1 Complexity Inherent in the Design

One of the chief attractions of passive solar design is the simplicity of concepts and techniques employed. PEG's experience in many commercial building design efforts has shown, however, that occupancy and load patterns, as well as more complicated HVAC equipment than normally encountered in residences, often call for greater complexity and flexibility in both "solar" and "auxiliary" mechanical systems response. The simple, established passive solar techniques have been shown effective in a few commercial building projects. However it is our experience that "pat" answers which give highly satisfactory performance in houses, are severely limited, if not counterproductive, in many non-residential building contexts. We have observed a tendency, both in our own work and that of our clients, to "mix" solar concepts to achieve better dynamic response to commercial building load patterns. There are good reasons for this predilection, indeed it may be argued that an ignorant or lazy avoidance, tacit or conscious reluctance to confront the differences between commercial and residential buildings, is a major barrier to widespread application of passive and hybrid solar techniques in non-residential structures. The tendency to overcomplicate nevertheless deserves tight rein, for the cart may lead the horse to surprising levels of design complexity. In PPP, functional requirements as well as research interests produced a design solution coordinating several alternative energy subsystems. The desired interaction of these elements with conventional HVAC equipment under various conditions of occupancy and weather is unavoidably complex.

Each rented office module in the project has its own semi-independent HVAC system. Backup heat and air conditioning are provided by Bryant 541C split system heat pumps, separately controlled in each of the 53 rental modules. Communal passive collection and heat rejection subsystems (direct gain atrium, roof spray), are centrally controlled. Active heat transfer to and from rockbed thermal storage is accomplished by fans under individual rental unit control. The major passive/hybrid heating, cooling, and daylighting concepts are depicted in Figures 1 through 4.

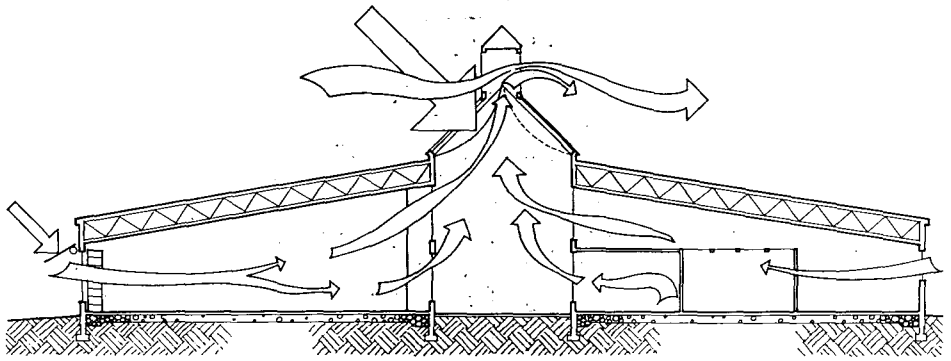



Figure 3. Natural Ventilation.

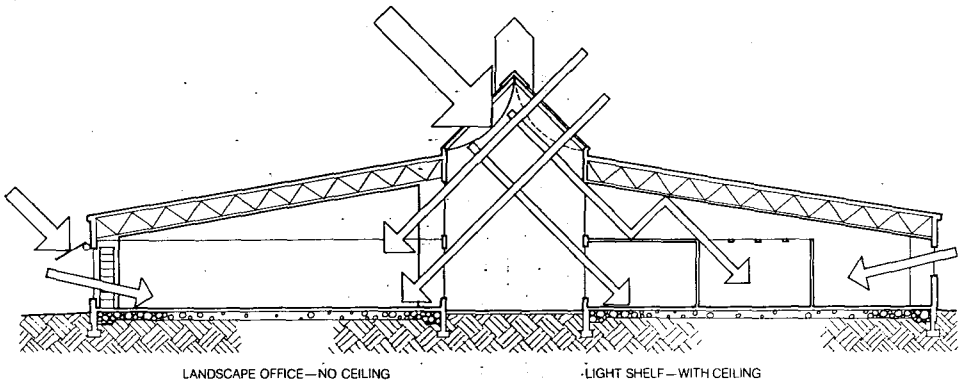



Figure 4. Daylighting.

The HVAC control system is called upon to govern nine distinct operating modes:

Winter: Heating from Atrium. When the first stage of a two-stage office thermostat calls for heat, and atrium temperature exceeds that of the rockbed, warm air is drawn from the atrium into the office air delivery system.

Winter: Storing Atrium Heat in Rockbed. When there is no demand for heat in the office, but atrium temperature exceeds that of the rockbed by 5.6°C, atrium air is circulated in a closed loop through the rockbed.

Winter: Heating from Rockbed . When the first stage of the office thermostat calls for heat, and rockbed temperature exceeds that of atrium air, warm air is drawn from the rockbed into the office's air delivery system.

Winter: Cooling. When the office thermostat calls for cooling in winter, the rockbed loop is activated if its temperature is low enough to provide useful "coolth" (this priority can also be conceptualized as storing excess internal heat gain, if possible, in the rockbed); if the rockbed temperature is greater than that of the office space, an enthalpy controller opens outside dampers to draw cool air from outside into the office air delivery system. Since rockbed distribution can also operate as a closed loop, charging with heat from atrium can occur simultaneously with outdoor air cooling of the office space.

Winter: Backup Heating. When the second stage of the office thermostat calls for heat, heat pumps operate in their normal function, superseding the atrium and rockbed heat collection, storage and retrieval.

Summer: Removing Heat from Rockbed. When temperature in roof ducts is lower than that in rockbed (e.g., during the night with roof spray operating), air is circulated in a closed loop with rockbed to reject heat in preparation for anticipated (next day) cooling needs.

TABLE 1. CONTROL LOGIC.

| MODE NUMBER | DESCRIPTION | SUMMER/WINTER SWITCH | BRYANT CONTROLS | | | | TIME CLOCK (ON=OCCUPIED) | OTHER CONDITIONS | MODES THAT MUST BE OFF | EXTERNAL DEVICES OPERATED (<—> = linked together) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | HEAT STAGE I | HEAT STAGE II | OUTDOOR AIR SET POINT | COOL STAGE I | | | | HEAT PUMP FAN | HEAT PUMP COMPRESSOR | HEAT PUMP ELEC. RESIST. | ROCKBED LOOP FAN | DAMPERS (O=open, C=close, -=not aff.) | | | | | | | | | |
| | | | | | | | | | | | | | | <——————> | | | | <——><——————> | | | | | |
| | | | | | | | | | | | | | | 1 NO | 2 NC | 3 NC | 4 NO | 5 NC | 6 NO | 7 NC | 8 NC | 9 NO | 10 NC |
| 1 | Night Auxiliary Heat<br>Use electric resist. | S/W<br>- | -<br>- | -<br>- | off<br>off | off<br>off | on<br>off | $T_1$ < 50 - 70 °F adj.<br>$T_1$ < 50 - 70 °F adj. | - | on<br>on | on<br>on | off<br>on | -<br>- | O | C | C | O | C | - | - | - | - | - |
| 2 | Daytime Auxiliary Heat<br>Use electric resist. | S/W<br>- | on<br>on | on<br>on | off<br>on | off<br>off | on<br>on | none<br>none | - | on<br>on | on<br>on | off<br>on | -<br>- | O | C | C | O | C | - | - | - | - | - |
| 3 | Heat Office from Atrium | W | on | off | - | off | - | ON when $T_2$ is 9 °F > $T_3$<br>OFF when $T_2$ is 5 °F > $T_3$ | - | on | off | off | fwd | C | O | O | C | C | O | C | O | C | O |
| 4 | Heat Office from Rockbed | W | on | off | - | off | - | ON when $T_3$ is 9 °F > $T_1$<br>OFF when $T_3$ is 5 °F > $T_1$ | 3,5 | on | off | off | fwd | C | O | O | C | C | O | C | C | O | C |
| 5 | Collect Heat from Atrium | W | - | - | - | - | - | ON when $T_2$ is 9 °F > $T_3$<br>OFF when $T_2$ is 5 °F > $T_3$ | 4 | - | off | off | fwd | O | C | C | O | - | O | C | O | C | O |
| 6 | Cool Office from Rockbed | W | off | off | - | off | - | ON when $T_1$ 5-10 °F > $T_3$ adj.<br>and $T_1$ > 70-80 °F adj.<br>OFF when $T_1$ is 5 °F > $T_3$ | 5 | on | off | off | fwd | C | O | O | C | C | O | C | C | O | C |
| 7 | Cool Office w/ Outside Air | S/W | off | off | - | - | - | ON when $T_1$ > 70-80 °F adj.<br>and $T_0$ < 55-70 °F adj.<br>and $E_0$ < set point adj. | 6 | on | - | off | - | O | C | C | C | O | - | - | - | - | - |
| 8 | Store Coolth in Rockbed | S | - | - | - | - | off | ON when $T_4$ is 9 °F > $T_5$<br>OFF when $T_4$ is 3 °F > $T_5$ | - | - | off | off | rev | O | C | C | - | - | C | O | C | O | C |
| 9 | Cool Office from Rockbed | S | off | off | - | - | - | ON when $T_1$ > 70-80 °F adj.<br>and $T_1$ is 5-10 °F > $T_3$ adj.<br>OFF when $T_1$ is 3 °F > $T_3$ | 7,9 | on | off | off | fwd | C | O | O | C | C | O | C | C | O | C |
| 10 | Auxiliary Cooling | S | off | off | - | on | on | $T_1$ > 70 - 80 °F adj. | - | on | on | off | - | - | - | - | - | - | - | - | - | - | - |

Summer: Cooling from Rockbed. When office temperature exceeds that of the rockbed by 2.8 to 5.6°C, and the first stage of the office thermostat calls for cooling, cool air is drawn from the rockbed into the office air distribution system.

Summer: Economizer Cooling. When the first stage of the office thermostat calls for cooling, and an enthalpy sensor indicates outside temperature and humidity conditions suitable for cooling, the office air distribution system uses outside air and fans in the rockbed loop are deactivated.

Summer: Auxiliary Cooling. When both stages of the office thermostat call for cooling, the heat pump compressor and fans operate in their conventional cooling mode, with or without economizer cycle, with rockbed loop inactive.

The control logic for these operating modes was simplified during the course of design, primarily by eliminating some functions responding to conditions shown to be rare, redundant, or of little energy and economic importance. For example economizer "flushing" of rockbed under cool night conditions is rarely feasible in New Jersey summers, although this function might be extremely valuable in other climates. Table 1 shows the control logic on which mannufacturers' bids were based.

While the controls for PPP are complicated by the coordination of several subsystems and operating modes, the complexity of these functions is typical, not exceptional, for designs using multiple passive/hybrid concepts in response to non-residential load patterns. The complexity inherent in this kind of design is also considerably below the level of sophistication normally confronted by building HVAC controls manufacturers, and well within capabilities of current hardware.

## 2.2 Estimated Costs for HVAC Controls

The original budget for electronic controls was based on additive pricing of components known at that time to be required. Table 1 was used as a performance specification to solicit quotations for fabrication, installation supervision, and maintenance during initial operation, from several equipment manufacturers. Table 2 shows initial results of that solicitation, to the extent that quotations from the various bidders can be reasonably compared. The bid list ran the gamut from large firms such as Manufacturers A and B, which are well known for complete system services to big building clients, to very small companies whose primary business to date has been in standard fabrication of simpler devices such as differential thermostats for active domestic hot water systems. Another large supplier declined the opportunity to bid, stating that the limited quantity needed would result in costs too high to be competitive or appropriate for this application.

Our first lesson was that even with an explicit statement of functions and control logic, it is difficult to elicit comparable estimates. One must recognize at least the three cost elements expressed in Table 2; specific on-site tests to verify proper operation may also be itemized, and maintenance policies under warranty vary among suppliers. Although cost is only one consideration in selecting among alternative suppliers, it is at least important that costs be broken down sufficiently to ascertain whether the quotations represent equivalent services.

Most preliminary quotations were well over the original budget, and we doubted the low bidder's ability to provide good technical support. Our second lesson was that basing estimates on individual prices of simpler mass-produced items is dangerous. An HVAC

TABLE 2. MANUFACTURERS' PRELIMINARY QUOTATIONS (EARLY 1982) FOR PPP CONTROLS.

| Manufacturer | Hardware Base Price (per unit) | + preinstallation wiring diagram | + supervision during initial installation |
|---|---|---|---|
| A | fixed price $ 2,628 | fixed price $ 19,000 | fixed price $ 4,500 |
| B | rough estimate $ 3,000 * | unknown * firm quotation never submitted | unknown |
| C | fixed price $ 1,500 * | unknown * initial quotation later withdrawn | unknown |
| D | fixed price $ 1,150 | included in base | included in base |
| E | fixed price $ 500 | $ 30/hr labor + all expenses, no estimate or limit | fixed price $ 400 |

controls package must be looked at as a total entity. For both technical and cost reasons, it is a good idea to seek advice from potential package system suppliers at an early stage in any project involving custom control applications.

### 2.3 Actual Cost of HVAC Controls

Manufacturer D, whose price was near the low end of preliminary quotations received, was selected for final price negotiations. During nearly a year of development and haggling involving the contractor, electrical and HVAC subcontractors, heat pump manufacturer, the design team, and the controls supplier, the equivalent unit price (including wiring diagram and supervision services) rose 41%, from $1150 to $1617 per controller. The increase resulted from minor change orders, arguments over lines of responsibility between "solar" and conventional auxiliary controls suppliers (the latter influencing the heat pump manufacturer's position about equipment warranties), and other jurisdictional disputes among designers, suppliers, and installers. The lesson here is that interfaces between conventional and solar components, and between cooperating roles of various contributors in the design and construction process, should be very clearly defined at the beginning of the project.

## 3. STRUCTURE OF HVAC CONTROLS DELIVERY

In PPP we have encountered a problem not in technical concepts or in limited capability of specific products, rather in the traditional systems by which they are delivered. Successful provision of customized controls requires that project managers recognize some important facts about relationships among engineers, equipment suppliers, HVAC installers, building owners, and tenants. Tenants hold owners responsible if things don't work. With some variations, any complaint moves along a ladder of responsibility that may include any of the other participants, and may fall heavily on any poorly defended rung. Designers, manufacturers, and installers understandably tend to limit their respective roles, and their corresponding levels of risk. The resolution may be that the designer takes the greatest burden of responsibility, in which case a higher design fee can be expected.

What we've observed in the PPP project is a different but equally obvious manifestation of the same principle. The larger and better established mechanical controls suppliers often assume much of the responsibility which might otherwise fall to designers and installers. When adequately involved in critical stages of the project, they may accept limited liability not only for their own components, but also for integration with the HVAC products provided by others. To fulfill this role properly (and to protect themselves), integrated system suppliers tend to provide very strong support to both designer and installer, and the cost of that support is reflected in higher prices for their products. Anyone who has simply added the best individual component prices from manufacturers, then compared the sum with an integrated system quote from a major supplier, is likely to have had a sobering look at the extra cost of support. Some of the difference might also be justified as risk reduction. Opting for the full-service integrated system supplier is a bit like buying insurance, and it's an industry pattern which we mistakenly overlooked in our early estimates.

## 4. CONCLUSION

In PPP, we worked very hard to establish clear and supportive relationships with a low-cost custom controls manufacturer, a conventional HVAC equipment manufacturer, and two reticent installation subcontractors. The effort has, of course, been very costly for everyone involved. But we may yet achieve a control system cost more consistent with the simplicity of, instead of the fear borne of unfamiliarity with, innovative techniques of passive solar construction. Luckily for the cost/benefit ratio that has helped earn PPP an excellent reputation, we overestimated a few other items of solar construction cost.

Total annual energy consumption is still speculative. PPP has received another grant award which provides for extensive monitoring (both quantitative and qualitative) over the coming year of building occupancy. Meanwhile further analyses have indicated probable benefits beyond those documented during the design process. Electrical consumption on a peak summer day is expected to be 55%, and the diurnal peak less than half, of the representative base case. These results indicate strong opportunity for contribution to the load-leveling strategies now adopted by many utilities, in a building type which has traditionally been a major offender. Much is yet to be learned, especially in such theoretically controversial areas as spray roof cooling effectiveness in our humid Mid-Atlantic climate. However our buildings are now up and closed, looking more real, better than we dreamed. Based on successes to date we are confident that PPP will fulfill our expectations as a living laboratory for further development of passive solar concepts, as an excellent energy performer in its own right, and as a comfortable and beautiful place to work.

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# PRODUCT UPDATE ON OPTIONS FOR NORTH-FACING GLAZING

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## ABSTRACT

With careful selection of glazing materials, even north-facing windows can become "net gain" surfaces in passive solar design. Several clear insulating glass products are examined and compared on the bases of net annual energy performance and relative cost. The analysis includes standard insulating glass, as well as high performance glazings utilizing low-emissivity coatings, antireflective coatings, and substitute gas fill. Net heating energy flux is calculated for both moderate and severe winter climates, and glazing performance is compared to typical night insulation systems and to an insulated wall.

## 1. INTRODUCTION

The minimization of north-facing glazing has always been a maxim of "proper" passive solar design. Unfortunately, siting, view, and lighting considerations occasionally pre-empt energy concerns, resulting in substantial north window areas. A familiar example is that of ski resorts, often located on north-sloping hillsides to reduce daytime snow melting. Similar problems arise in the selection of a house site in an area where all of the "good solar sites" have been previously developed. In these and other cases, north-facing glazing materials must be carefully selected to minimize heat loss while maximizing transmitted solar energy and visible light.

In addition to their impact on building energy requirements, north windows have a significant effect on thermal comfort by reducing the mean radiant temperature of the adjacent living space. Since the interior surface temperature of a glazing material is directly related to its thermal resistance (in the absence of direct solar gain), low overall conductance, or U-value, is the most important performance criterion. Solar transmissivity cannot be completely neglected, however, when using one of the high performance window systems available today. Diffuse solar radiation, while trivial compared to direct gains from non-north fenestration orientations, can often provide enough energy gain through north glass to completely offset heat losses (on a seasonal basis).

In this paper, we investigate the various options available to the residential designer for clear-appearing (minimum of 70 percent visible transmittance) north glazing. Products are evaluated on the basis of net energy performance and relative cost and include standard double and triple glazing as well as newer fenestration components, such as coatings that reflect infrared radiation, polyester films suspended vertically in the air space of a double glazed window, and low-conductivity gas-filled insulating units. Typical night insulation and insulated wall data are included for comparison.

## 2. DESCRIPTION OF GLAZING TYPES

All of the options studied are commercially available in the U.S. as of mid-1983. Some of the newer products are limited to a few suppliers at present; availability should expand as the technologies gain public acceptance through proven effectiveness.

### 2.1 Standard Insulating Glass

In most of the colder portions of the U.S., double and triple glazed windows are in widespread use. Whether hermetically sealed into an insulating unit or mechanically attached ("storm windows"), additional lights of glass improve thermal performance by creating an enclosed air layer between the panes. For both double and triple pane units, optimal air-gap width is approximately 12.7 mm (0.5 inch) (1). Though quadruple pane insulating glass has been used in severe climates to provide low U-values, its weight, bulk, and reduced transmittance preclude its practical utility in most applications.

### 2.2 Low-Emissivity Coatings

Since approximately two-thirds of the heat

TABLE 1. TYPICAL GLAZING PERFORMANCE DATA

| Glazing Type | Overall Thickness[a] (mm) | U-Value[b] SI | U-Value[b] Eng | Shading Coefficient[c] | Solar Transmittance (%) |
|---|---|---|---|---|---|
| Standard Insulating Glass | | | | | |
| Double Pane | 15.9 | 3.0 | .52 | .88 | 71 |
| Triple Pane | 25.4 | 2.0 | .36 | .78 | 61 |
| Low-Emissivity Coatings | | | | | |
| PPG Sungate™ 100 | 15.9 | 2.0 | .35 | .80 | 56 |
| Heat Mirror™ 88 | 31.8 | 1.3 | .23 | .70 | 53 |
| Antireflective Coatings | | | | | |
| Weather Shield Tri Pane | 25.4 | 2.0 | .36 | .85 | 66 |
| Weather Shield Quad Pane | 44.5 | 1.5 | .26 | .82 | 63 |
| Argon Gas Fill / Low-E | | | | | |
| Alpenglass™ 88 / Argon | 31.8 | 1.1 | .20 | .70 | 53 |

*Notes: (a) All units using 3.2 mm (1/8 in) float glass*
*(b) U-values calculated for ASHRAE standard winter conditions, SI units: W $m^{-2}K^{-1}$, English units: Btu $h^{-1}ft^{-2}F^{-1}$*
*(c) Shading Coefficients for ASHRAE standard summer conditions*

loss in a double pane window results from radiation heat transfer, thin-film coatings having a high reflectance to long-wave infrared radiation offer substantial improvements in glazing thermal performance. These new selective transmitters, known commercially as "low-emissivity, high-transmittance" glazings, can nearly double the thermal resistance of an insulating glass unit while reducing the solar transmission only slightly (2).

Two classes of products are available: those with the low-emissivity coating directly on one of the inner glass surfaces of an insulating unit and those incorporating a low-e coated polyester film suspended between the lights of glass. The latter typically have lower U-values, since convection heat transfer is reduced by the creation of a partitioned air space.

Insulating low-emissivity coated glass is recently available from PPG Industries (Pittsburgh, PA), Advanced Coating Technology (Franklin, TN), and Guardian Industries (Carleton, MI), among other manufacturers. The low-e film, "Heat Mirror™ 88," is produced by The Southwall Corporation (Palo Alto, CA) and is available in the high performance glazing products of a number of insulated glass and window manufacturers in the U.S., Canada, and Europe.

### 2.3 Antireflective Coatings

For a given overall glazing thickness, the use of one or two thin polyester films suspended vertically in the air space provides a slightly lower thermal conductance than an all-glass window having the same number of layers and weighs significantly less. By using film with an antireflective coating (3), high transmittance can be achieved with convection loss suppression comparable to triple or quadruple glazing. Such windows are available from Weather Shield Mfg. (Medford, WI), with either one ("Tri pane") or two ("Quad pane") film baffles.

### 2.4 Substitute Gas Filling

By using a gas with low thermal conductivity, high viscosity, and low specific heat as the fill gas in a sealed insulating glass assembly, both conduction and convection can be minimized. Such windows are quite common in Europe, where over 500 insulating glass manufacturers utilize substitute gas filling for high performance glazing (4). The combination of a low-conductivity gas fill (such as

argon) with the low-emissivity coating discussed above provides superior thermal performance for clear glazing applications (5). One U.S. insulating glass manufacturer, Alpen, Inc. (Denver, CO), produces argon-filled insulating units equipped with the Heat Mirror™ 88 low-emissivity film.

## 3. THERMAL PERFORMANCE COMPARISON

The prime determinant of north window performance in the heating season is U-value, as noted earlier. Table 1 gives U-values, shading coefficients, and solar transmittances for each of the glazing options investigated, under ASHRAE standard conditions (6). These data are useful for making general comparisons among glazing materials and also for simplified calculations of annual building energy consumption (7).

### 3.1 Net Energy Flux Calculation

To evaluate more accurately the energy flux on an annual basis for the various glazing materials, a detailed building energy simulation program was employed. The SOLPATH computer code, a proprietary program of ENSAR Group (Lakewood, CO), uses average monthly solar radiation and temperature data (8) to calculate hour-by-hour heat gain and loss through building components. For the simulations, a residence with 140 $m^2$ (1500 $ft^2$) of floor area and 9.3 $m^2$ (100 $ft^2$) of north-facing glass was assumed, with climatic data corresponding to Denver, Colorado, and Minneapolis, Minnesota. (Studies have shown that variations in building thermal mass levels have minimal effect on north glazing performance characteristics (3).)

In addition to the glazing options, an insulated wall (U-value 0.3 W $m^{-2}K^{-1}$, or R-19) and night insulation (U-value 1.8 W $m^{-2}K^{-1}$, or R-3.2) were included in the analysis for comparison. Perfect management of the night insulation system was assumed (in place ten hours nightly), and its insulating values correspond to those for Window Quilt® (Appropriate Technology Corporation, Brattleboro, VT).

Results of the simulation runs are presented in Table 2. Many of these calculated data are corroborated by earlier analysis (3). Several interesting conclusions should be noted:

- In both climate types, double and triple glass are the least thermally efficient options among those compared.

TABLE 2. NET ENERGY FLUX RESULTS AND RELATIVE COST DATA

| Glazing Type | Net Energy Flux (North-facing) ($10^6$ J $m^{-2}$) | | Relative Cost* | |
|---|---|---|---|---|
| | Denver | Minneapolis | per $m^2$ | per $ft^2$ |
| Double Pane Glass | -300 | -640 | --- | --- |
| Triple Pane Glass | -110 | -310 | $ 20-40 | $ 2-4 |
| PPG Sungate™ 100 | -89 | -270 | 30-50 | 3-5 |
| Weather Shield Tri Pane | -77 | -260 | 40-80 | 4-8 |
| Weather Shield Quad Pane | +58 | -65 | 70-140 | 7-14 |
| Heat Mirror™ 88 | +51 | -58 | 50-70 | 5-7 |
| Alpenglass™ 88 / Argon | +97 | +9 | 80-90 | 8-9 |
| Window Quilt® Night Insulation | -73 | -300 | 50-70 | 5-7 |
| Insulated (R-19) Wall | -70 | -100 | --- | --- |

* *compared to double pane glass, in 1983 U.S. dollars*

- For Denver, the three north glazing options with the lowest U-values actually provide "net gain" performance on an annual basis; for Minneapolis, only the Alpenglass™/ Argon glazing system provides a net heat gain.

- Of the eight glazing options listed, the night insulation system ranks sixth in Minneapolis, and fourth in Denver.

## 4. RELATIVE COST COMPARISON

Approximate costs (in 1983 U.S. dollars) for each of the glazing options are listed in Table 2, relative to standard double-pane glass. Since these prices are estimates for the glazing only, marginal costs may vary widely among different window manufacturers and in various market regions. Standard patio door sizes may also be greatly discounted.

## 5. SUMMARY

Seven clear insulating glass products have been described and compared on the bases of net annual energy performance for north-facing application and relative cost. Though all of the products have a similar visual appearance, their performance characteristics vary considerably. Several of the glazings can actually provide a net energy gain to the building from north windows in moderate winter climates. The cost and energy performance data presented here can assist the designer in making an intelligent choice of north-facing glazing materials.

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# HIGH PERFORMANCE PASSIVE SOLAR HEATING SYSTEM WITH HEAT PIPE ENERGY TRANSFER AND LATENT HEAT STORAGE

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## ABSTRACT

Preliminary results are reported from a current project on the development of a high performance passive solar heating system. Two special components are introduced:

a. A heat pipe as a thermal diode tube for the efficient transfer of collected solar heat from the absorber plate to behind an insulation layer.
b. A latent heat storage section with high storage capacity at moderate operating temperatures.

Additional advantageous characteristics: the maintenance costs are negligible, and the performance is highly insensitive to unadequate control of the system by the inhabitants.
A first global design of the system showed significantly higher predicted gains than a conventional storage wall at however still high manufacturing costs, although the cost-benefit ratio was already competitive with a similar active solar system.
The project will be concluded at the end of 1983, with an optimized design of the system. First optimization exercises and series of measurements on the single components lead to the expectation that the final optimized design will be characterised by significantly reduced manufacturing costs.

## 1. INTRODUCTION

Within the passive solar approach, the direct gain and convective loop systems are the most simple and therefore cheapest solutions. These kind of systems, however, are characterized by high indoor temperature swings and high solar heat supply on the hours of least demand.
A thermal storage wall has an advantageous accumulation of solar heat which results in low temperature swings and a time delay between the absorbtion of solar energy and the heat supply to the building.
The main disadvantage of a conventional thermal storage wall, however, is the higher temperature of the solar collecting surface which in combination with the high thermal capacity of the wall can lead to considerable heat loss to the outside. Multi-glazing can limit this heat loss to a certain extent, but is costly. Movable insulation is also expensive, has a slow response and needs careful attention for a reliable and effective operation. Furthermore, the extra mass introduced into the building may sometimes lead to extra costs particularly in multi-story buildings, and valuable space within the building is occupied by the system.

## 2. AIM OF THE PROJECT

This project aims to develop a passive solar heating system which has the advantages as mentioned above. This can be achieved by the introduction of two special components:

a. A thermal diode tube, which acts with small temperature difference already as a high performance thermal conductor. It transfers heat from the collector to behind a insulation layer, but does not transfer heat in the reverse direction. With a low capacity collector the system responds rapidly to changes in outdoor conditions, while needing no movable parts or manually or automatically operated control equipment.
b. The latent heat storage. With thermal storage in elements containing phase change material a reduction in storage volume compared with concrete down to 20% can be achieved at a moderate storage temperature level. The thickness and weight of the complete system can then be restricted.

## 3. SYSTEM DESCRIPTION

The design of the passive solar element is based on the following mechanisms (see Fig. 1):

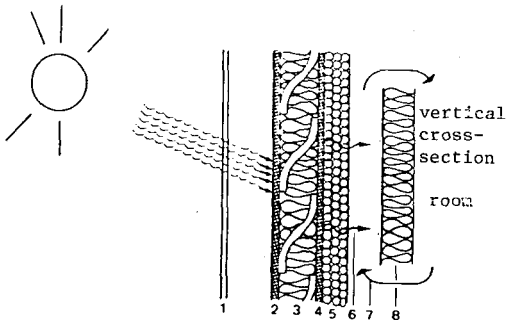



Fig. 1. Schematic drawing of the high performance passive solar heating system.

- One glass pane cover (1)
- Small air gap
- Absorber plate (2) to collect the solar radiation
- S-shaped heat pipes as thermal diode tubes to transfer the absorbed heat through a insulation layer (3)
- A back plate (4) to distribute the heat from the diode tubes to the latent heat storage elements (5)
- A air cavity is formed with a common insulation sheet (8) to separate the system from the room
- When the air cavity is open to the room, air flows under the buoyancy force through the cavity (7), thus transferring the heat from the storage material (6) to the room. The cavity can be closed when there is no heat demand.

The thermal characteristics of a heat pipe in inclined position can be shortly described as follows: the heat pipe is basically a closed hollow tube partially filled with a working fluidum, in equilibrium with its vapor. When the lower end is heated the fluid absorbs this heat by evaporating. At the - colder - upper end the vapor will condense and release the latent heat; the liquid will return to the lower end by gravity force. With reverse temperature difference the upper end will dry out, and no heat transfer takes place in this element (thermal diode effect). The working fluid and the heat pipe tubing are chosen on the basis of the operating temperature and their mutual compatibility.

## 4. A FIRST GLOBAL DESIGN OF THE SYSTEM

### 4.1 Characteristics

A first step in the project was to draft a first global design of a high performance passive system. Table 1 shows the main characteristics.

### 4.2 Net heat gains

The annual heat gains of the first global design have been calculated in preliminart calculations with a steady-state model. The heat demand is taken hourly from a well-insulated living room with consequently quite low annual heat consumption. The calculations have been performed with a average Dutch heating season (Table 2).
For comparison a similar (but unsteady-state) calculation has been performed with an active system under the same climatic conditions.
The heat transfer ornaments of this active system have been designed with extremely great dimensions to maintain a low temperature level. Although this is energeticly the most favorable (but the most expensive) design, the high performance passive system seems to yield competitive results.

TABLE 1. Main characteristics of the first global design, according to preliminary calculations.

| Thermal resistances: | | |
|---|---|---|
| component | description | resistance ($m^2$ K/W) |
| cover | single glass | |
| absorberplate | spectral selective layer ($\varepsilon$ = 0.5) | $R_u$ = 0.25 |
| heat pipes | 5 heat pipes per $m^2$ provided with extra heat exchange surface | $R_{hp}$ = 0.05 |
| air cavity | | $R_{ac}$ = 0.09 |
| Effective absorbtion transmission factor AT = 0.80 | | |
| Overall heat removal factor: $F_r = 0.65$ ($F_r = R_u/(R_u + R_{hp} + R_{ac})$) | | |

TABLE 2. Preliminary calculation of the net heat gain of the high performance passive system and a preliminar comparison with an active and a conventional passive system. Average Dutch heating season.

| system | characteristics | net heat gain kWh/m$^2$ year (south orientation, vertical) | remarks |
|---|---|---|---|
| HP passive system (table 1) | 4 m$^2$ collector area $F_r$ = 0.65 | 85 | room with small heat demand |
| Similar active system | 4 m$^2$ collector area $F_r$ = 0.95 | 105 | room with small heat heat demand; low temperature ornaments |
| Conventional storage wall | 2 x 2 m$^2$ area, single glass, spectral selective ($\varepsilon$ = 0.50) | 50 | ideal control by inhabitants; room with unlimited heat demand |

Moreover it should be emphasized that the presented net heat gains for the passive system should be considered against a (well insulated) normal opaque wall with a annual heat loss of about 50 kWh/m$^2$.
Also a preliminary calculation has been performed with a conventional storage wall. The net heat gains of this system have been calculated assuming ideal conditions: the air cavity between glass cover and wall is always ventilated when the cavity air temperature exceeds the room temperature, and the cavity is always closed when the temperature in the cavity drops below the room temperature. Moreover in this calculation a room has been chosen with unlimited heat demand. Nevertheless the results in Table 2 show that even then a conventional passive system still yields significantly lower gains. These gains can of course be increased by providing the conventional storage wall with night time insulation, which means extra manufacturing and maintenance costs and extra attention needed from the inhabitants. One should realize also, that the performance of a conventional storage wall is highly sensitive to use of the dampers in the air cavity. For the high performance passive design this is not the case, because the dampers in the air cavity of this system only distribute the heat - which already passed the thick insulation layer - between storage and direct gain. More precise, unsteady state calculations are planned for the last step in this project when the high performance passive design will be optimized.

### 4.3 Manufacturing costs

The first global design has been subjected to a detailed analysis of manufacturing costs. In this analysis it has been assumed that this first design would be the basis for the production of a number of systems without a serious attempt to optimize the detailing of the design. From this analysis it was shown that the chosen design principles and details made the system very labor-intensive and therefore a commercial production quite expensive (Dfl. 700 - 900 per m$^2$). With these results the high performance passive system would already be competitive with comparable active systems. Nevertheless it is aimed to bring down the manufacturing costs to a significantly lower level. This can be achieved in three ways:

1. by reconsidering the need for some expensive components which are not essential to the performance. It has e.g. already been concluded that the dampers to the outside, provided in the original design for summer ventilation, should be omitted. When performing unsteady-state calculations on a more definitive design, e.g. the necessity of the thick insulation sheet between cavity and the room air, can be investigated.
2. By redefining the design principle. In the first design the system was provided with separate modular elements consisting of a sandwich with absorberplate, heat pipe with insulation and back plate. Although it was expected that this kind of approach would lead to low manufacturing costs (including assembling), the opposite proved to be the case. A high portion of the costs appears to be in assembling the sandwich modules. It is now expected that other principles can also lead to a design which is flexible enough to be applied under a wide range of conditions, e.g. a design with one or two defined heights and unlimited horizontal dimensions with a repeating pattern for each 0.30 m.
3. By an optimized design of all necessary details. This proces will be started when a new global design has been drafted. The result of this proces will be a prototype high performance passive system with significantly reduced manufacturing costs. The lower limit consists of the bare costs for the materials of which the functional

components of the system are composed. These costs are estimated to be Dfl. 150 - 300 per $m^2$.
A second detailed analysis of the manufacturing costs will be performed during the last step in this project. Finally one should note that from the eventual manufacturing costs one should substract the costs for the conventional wall which has been replaced by the passive system (Dfl. 75 - 100 per $m^2$).

## 5. OPTIMIZATION OF THE COMPONENTS

### 5.1 The heat pipes

Measurements have been performed on the thermal resistance of a few types of heat pipes (Figure 2). In these measurements the heat flow, working fluid, interior surface treatment and inclination were varied. Table 3 shows the main results of this first series of measurements. It appeared that a plain copper tube filled with water has so far the best results. These results also are better than what had been assumed in the first global design of the high performance system (see Table 1).

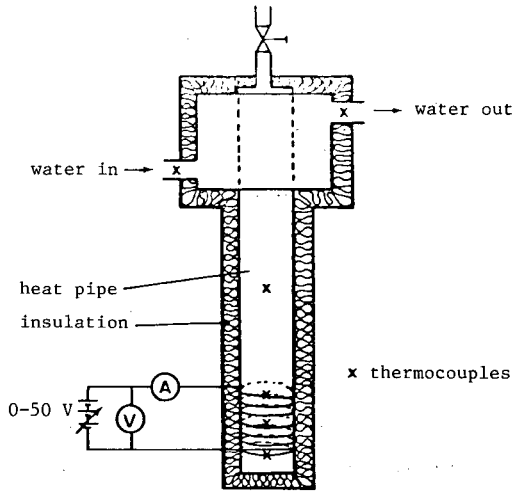



Fig. 2. Schematic view on the measurement of the thermal resistance of the heat pipes.

TABLE 3. Major results of a first series of measurements on the heat resistance of a heat pipe as thermal diode.

Material : copper
Length : total: 0.40 m
vapor zone: 0.20 m
cond. zone: 0.10 m
Diameter : 13 - 15 mm
Assumption : 5 heat pipes per $m^2$

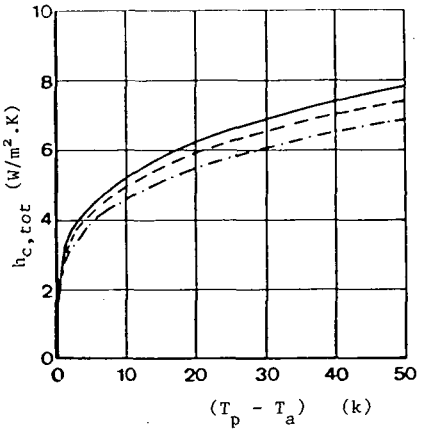
| inclination | working fluid | interior surface treatment | thermal resistance ($m^2$ K/W) measured with heat flow: low (100 W/$m^2$) | high (500 W/$m^2$) |
|---|---|---|---|---|
| vertical | alcohol | copper wick added | 0,060 | 0,020 |
| | water | copper wick added | 0,080 | 0,030 |
| vertical | alcohol | plain copper | 0,046 | 0,040 |
| | water | plain copper | 0,062 | 0,018 |
| 10 degr. from horizontal | water | plain copper | 0,026 | 0,018 |
| 10 degr. from horizontal | alcohol | screw thread tapped in surface | 0,026 | 0,026 |
| | water | | 0,088 | 0,026 |

Alcohol and water are chosen as working fluids because of their compatitiveness with copper. Alcohol is expected to give a better wetting of the surface in the vaporization zone, which indeed leads to better results for the cases in which the interior surface has been treated to increase the fluid surface by capillary forces. However, alcohol has a drawback of having a lower thermal conductivity. Water indeed suffers from bad wetting, but particularly at nearby horizontal position the performance of water indicates a very effective (low resistance) vaporization. This is probably due to boiling effects which let the water spread all over the surface of the heated vaporization zone instead of having the lower end of the heat pipe filled with a water column with a small surface for vaporization. A nearby horizontal position can fit in the systems design very well because the hot respectively the cold end of the heat pipe can be stretched out along the absorber plate and back plate, respectively, thus covering large areas of the plate surfaces.
In additional experiments the results obtained so far will be analyzed more elaborately in order to obtain a better understanding of the mechanisms, which is a condition sine qua non for a further optimization of the heat pipe design.

## 5.2 Heat transfer in the air cavity

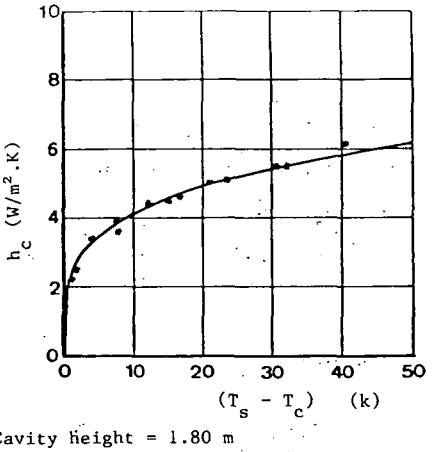
A series of measurements has been performed on the heat transfer in the air cavity, with a experimental set up at the Technical University of Eindhoven. The air cavity is created by an electrically heated hot plate on one side and a thick sheet of insulation material on the other. The heat transfer rate has been measured by metering the electrical supply as a function of the resulting hot plate temperature. The heat balance is checked by measuring the air flow rate at cavity outlet opening and the air flow temperatures at the inlet and outlet openings. Measurements have been performed at heights 1.80 and 0.90 m, cavity depths 0.02 to 0.10 m and heat flow ranging from 5 to 400 W/m$^2$. Also, measurements have been performed with the opposite surface covered with aluminium foil to reduce radiant heating of this plate, in order to examine the effect of a deviating temperature difference between the two plates. An illustration of the results is presented in Figures 3 and 4.
The heat transfer rate at moderate hot plate temperature equals a thermal resistance of $R_{ac} \approx 0.13$ m$^2$ K/W, which already comes close to the value estimated in the first global design for an air cavity provided with extra heat exchange surface ($R_{ac} = 0.09$, see Table 1). Therefore it may be concluded that it will not be difficult to meet the specifications of the first global design of the high performance system.

At this moment, the results are analyzed in order to generate relations for the heat transfer rates which are generally valid for a wide range of cavity dimensions and conditions.




Cavity height = 1.80 m
——— cavity width = 0.10 m
------ = 0.06 m
-.-.-. = 0.04 m
$T_p$ : average hot plate temperature (°C)
$T_a$ : ambient air temperature (°C)
$h_{c,tot}$ : resulting total heat transfer coefficient by convection per m$^2$ hot plate (W/m$^2$K)

Fig. 3. Measurements on the heat transfer rate in the air cavity; heat transfer as a function of plate temperature and cavity width.




Cavity height = 1.80 m
width = 0.06 m
$T_s$ : surface temperature (°C)
$T_c$ : average cavity air temperature (°C)
$h_c$ : heat transfer coefficient by convection (W/m$^2$K)

Fig. 4. Measurements on the heat transfer rate in the air cavity; an example.

### 5.3 The latent heat storage

With the first results of the measurements described above, preliminary calculation have been performed to the thermal storage. The hour by hour performance of the high performance passive element has been calculated for two typical days in spring, with various types of storage materials and dimensions. From these calculations it has been concluded that the best performance is expected from a high performance passive design with a heat storage as one thin layer (few centimeters) directly attached to the back plate at the cold end of the heat pipes: the efficiency of the system when applied with open cavity for direct gain is hardly affected by the resistance of a few centimeters of storage material. So also for midwinter conditions - when storage would not be needed - the performance remains high.
Results have been compared between two types of storage materials which were chosen on basis of 1) commercial availability, 2) well-known characteristics and proven performance and life duration and 3) operating temperatures within the required region. Material A has a melting temperature of 27 °C, material B of 57 °C. Material A has the advantage that the temperature level of the system, thus the threshold value for the solar gain, is lower. The disadvantage, however, is that the heat transfer from storage to air cavity is far too slow to extract the absorbed heat by free convection within the required few hours.
A program of measurements has been initiated to validate these preliminary results. An experimental set up is under construction at the Institute of Applied Physics. Measurements will be performed for unsteady-state conditions with 24 hours cycle, both with 24 hours open cavity and with the cavity closed during strong insolation. The air cavity in this set up is a reproduction of the air cavity from the heat transfer measurements in Eindhoven, the results of which can then be used in the analysis of the storage performance.
As storage materials will be tested:

1. water
2. paraffin ($T_{melt}$ = 52 - 54 °C)
3. a salt hydrate ($T_{melt}$ = 57 °C)
4. optional: PCM with intermediate temperature .

## 7. PRELIMINARY CONCLUSIONS

In this paper first results are reported from a current project on the development of a high performance passive solar heating system. The project is at the moment of writing still in a stage of optimization of the components. The project will be concluded with a optimized design of a prototype high performance system and a performance analysis with a unsteady state model of a dwelling with high performance passive elements in the south facade.
Nevertheless, from the results obtained so far already important conclusions can be drawn:

- A first global design of a high performance passive system has indicated that such a system will have significant higher gains than a conventional storage wall, even if the latter is assumed to operate under ideal conditions concerning heat demand and inhabitants attention.
- The manufacturing costs of this first approach seemed however high, although the cost-benefit ratio was already competitive with a similar active solar system.
- First optimization exercises and series of measurements on the components indicate that with an optimized design the high performance can be maintained at significantly reduced manufacturing costs.
- It is expected that at the end of the project, a optimized prototype high performance passive solar system will be designed which reaches a payback period of 10 to 20 years for the Dutch situation, which is comparable with conventional energy conservation measures (e.g. double glazing).

## 8. ACKNOWLEDGEMENTS

The project is financed by the Commission of the European Communities and by the Dutch National Solar Energy Programme.
In this project the following organisations are co-operating in the research: the Institute of Applied Physics TNO-TH, the Technical Universities of Delft and Eindhoven and the B.V. Koninklijke Maatschappij "De Schelde".

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# A SIMPLE PROCEDURE FOR ESTIMATING THE ENERGY SAVINGS DUE TO NIGHT TEMPERATURE SETBACK

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## ABSTRACT

A simple procedure for predicting the savings in heating loads associated with night temperature setback has been developed from a substantial data base of simulation results. Sensitivities were conducted to isolate the influence location, type of home, thermal integrity and window area have on the projected savings. The magnitude or savings is seen to be directly correlated to heating degree days if the savings are expressed as a percentage of the total building load.

## 1. INTRODUCTION

Clearly one of the most effective and popular no-cost/low-cost strategies for reducing residential heating energy use is setting back the thermostat at night. In an attempt to characterize the amount of energy saved by night setback a series of DOE 2.1a computer simulations was conducted using a number of home configurations, levels of thermal integrity and window areas in a representative number of climates. The resulting data base was analyzed in an attempt to extract a simplified procedure for estimating night setback savings.

This work is part of a much larger effort in which the authors, under contract to the U.S. Department of Energy, Office of Conservation and Renewable Energy, are developing a set of simplified energy analysis tools designed to assist the homebuilding industry in selecting cost-effective energy conservation features for new homes. These tools will be published in the early part of 1984 in a set of documents entitled Affordable Housing Through Energy Conservation, A Guide To Designing and Constructing Energy Efficient Homes.

## 2. APPROACH

The amount of heating energy saved by judicious operation of the thermostat will primarily be a function of home location (climate), its configuration, the thermal integrity of the building envelope (ceiling, wall and floor insulation values), the window area, the thermostat settings and schedule of setback. While the last two variables, thermostat settings and schedule of setback, can influence the magnitude of the savings they are generally out of the sphere of influence of the designer and, therefore, considered as constants in this study. For all sensitivities the values selected were: a standard temperature septoint of 70°F with a night setback to 60°F with a setback period from 11 pm to 7 am.

Simulations with and without setback were conducted in climate representative locations using the following prototype home types: manufactured home (single-section), ranch, two story, split level and townhouse. While the absolute data varies the general relationships and conclusions regarding setback benefits are indifferent to house type. To exemplify the results of the work, therefore, the data for only one home type, manufactured homes, is presented below.

### 2.1 Correlating Setback Savings with Heating Degree Days

Simulations of a single-section manufactured home with average insulation levels (i.e. medium thermal integrity) and typical window area (98 square feet or 11% of the gross floor area) were performed in 42 cities with and without the night thermostat setback option. The resulting savings due to the setback was compared to the heating degree days for those locations. Heating degree days provide an attractive climatic indicator for correlating with savings as degree day data is readily available and familiar to most designers. While degree days correlate poorly with absolute heating load savings the correlation improves substantially when the savings are expressed as a percentage of total load.

As shown in Figure 1 a plot of percent savings versus heating degree days (base 55°F - approximately the balance point for the medium thermal integrity home with setback) defines a parabola characterized by the equation:

$$SBS = (x^2 - 100.37x + 3409)/74 \quad (1)$$

where: SBS = Setback Savings expressed as a percent of the load

x = number of degree days (base 55°F)/100

For example a home with a heating load of 50 MMBtu/yr in a city with 3000 heating degree days where the thermostat is setback at night can be expected to save:

$$SBS = ((30)^2 - 100.37(30) + 3409)/74$$
$$= 17.54\%$$

$$\text{Savings} = 50 \text{ MMBtu/yr} \times .1754$$
$$= 8.77 \text{ MMBtu/yr}$$

The correlation coefficient of the data to the curve is 0.909.

To improve the correlation the percent savings were plotted against the ratio of degree days for base temperatures of 60°F to 55°F. The two base temperatures were selected to approximate the homes balance point without and with setback, respectively. The plot of the data for the 44 selected cities is ilustrated in Figure 2.

In this case the data is represented by two straight lines described by the following equations:

$$SBS = 33.81x - 27 \quad (2)$$
where: $x \leq 2$

$$SBS = 11.80x + 18 \quad (3)$$
where: $x > 2$

for:
x = (HDD (Base 60°F))/HDD (Base 55°F))

For equation (2) and (3) the correlation coefficients are 0.952 and 0.944, respectively. The accuracy of the correlation can be further enhanced by adjusting the degree day base temperatures to conform to the change in balance point on a diurnal basis when the temperature is setback at night.

The night time balance point will be decreased from about 67°F to 57° while the daytime balance point is approximately 60°F. Plotting the percent savings against the ratio of the diurnal degree days adjusted for balance point results in the linear relationship illustrated in Figure 3. The setback savings is given by the equation:

$$SBS = 82.6(x) - 2.5 \quad (4)$$

where: x =
1-(Day HDD (Base 60°F) + Night HDD(Base 57°F))
/(Day HDD(Base 60°F) + Night HDD(Base 67°F))

Similar plots were developed for other home types (see Figures 4,5 and 6) and thermal integrity/window area combinations (modifying the Balance Point (BP) in each case). While each house type/thermal integrity/window area combination resulted in a change in line slope and Y intercept the basic linear nature of the data remained unchanged.

The correlation coefficient for equation (4) is 0.991. Although more accurate, the utility of equation (4) is limited by the lack of available day and night HDDs taken to various base temperatures.

## 2.2 Sensitivity of Night Setback Savings to Changes in Thermal Integrity and Window Area

Runs were conducted on the single-section manufactured home in 12 cities in order to isolate the impact that changes in the envelope construction (balance point) have on setback savings. Three levels of thermal integrity* low, medium and high and two window areas 98 and 180 square feet were considered.

The results of this analysis are tabulated on Table 1. Note should be made of the fact that while the changes in envelope characteristics result in substantial changes in both heating load without setback and the absolute savings due to setback option (expressed in MMBtu /yr), the ratio of setback savings to total heating load (expressed in percent) is nearly constant by location. The largest variation in percent savings is in San Francisco where a small change in Balance Point will radically alter the number of degree days that occur during the non-setback period. In addition, note that while the increase in window area results in a small change in percent savings the change is systematic, increasing 1 to 2 percent in all locations.

In effect, and with only a few minor exceptions, a single percentage value can be used per location to represent the magnitude or savings due to the setback option regardless of envelope construction. Suggested average percentage values are listed on Table 2. The average value will, however, vary by building type.

* See bottom of Table 1 for corresponding insulation and infiltration values.

## 3. RESULTS AND CONCLUSIONS

The results of the research on night thermostat setback can be summarized in the following points:

- Absolute savings in MMBtu/yr due to night setback correlates poorly with degree days.
- The savings in heating load due to setback can be expressed as a percentage of the total heating load, the percentage exhibiting little variation by location in insulation level and window area.
- The impact of setback on heating load, if expressed as a percentage of total heating load, correlates well with HDDs. The correlation improves as the data is refined to reflect the actual degree days "seen" by the home as a function of balance point.
- Simple calculation procedures can be developed to provide rough estimates of savings due to setback as a function of heating degree day data. The procedures vary in accuracy as a result of specificity of the data (see Equations 1, 2 and 3 above).

## 4. REFERENCES


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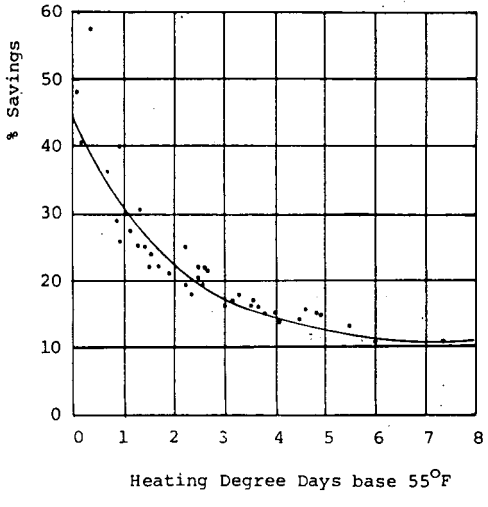




Fig. 1. Manufactured Home.

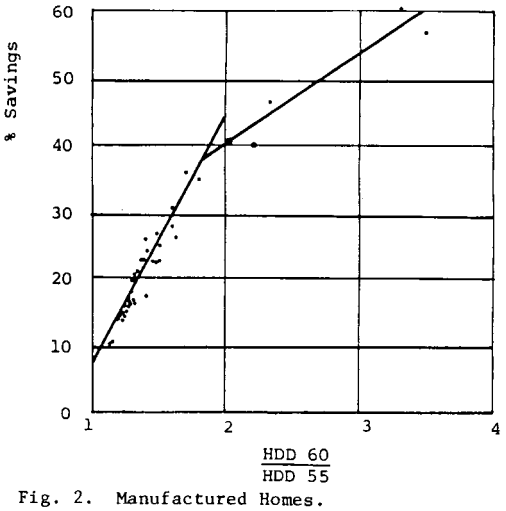



Fig. 2. Manufactured Homes.

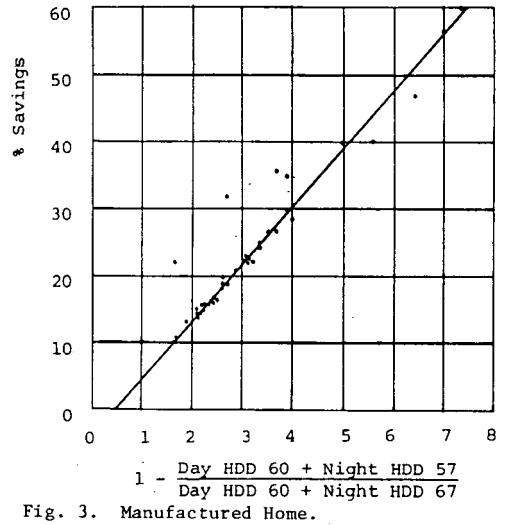



Fig. 3. Manufactured Home.

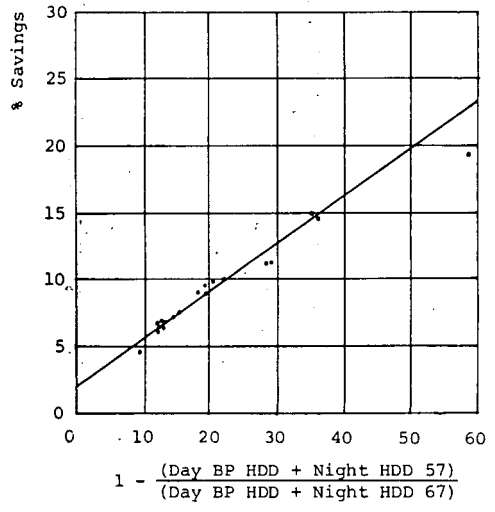



Fig. 4. Ranch House Single Family.

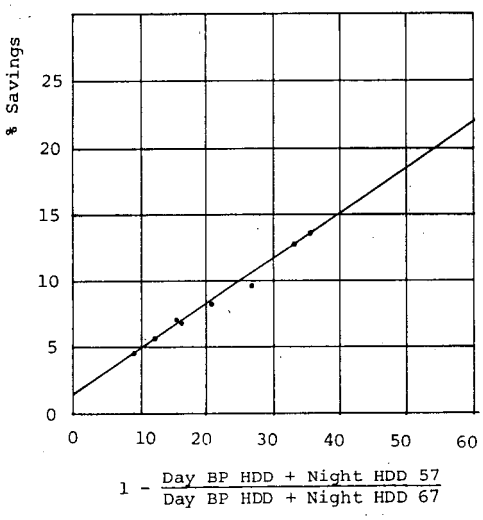



**Fig.** 5. Two-story House, Single Family.

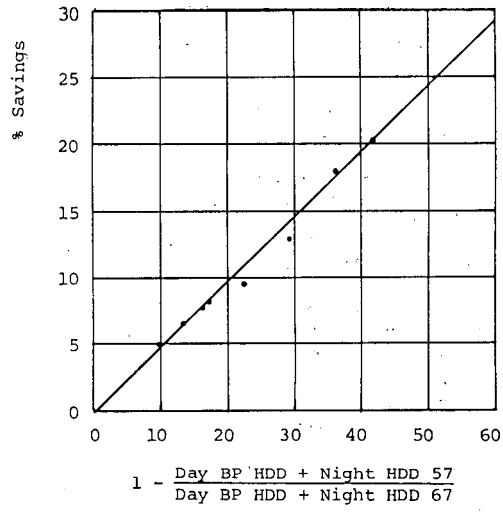



Fig. 6. Townhouse, Single Family.

Table 2.

Manufactured Homes Estimated Percentage Energy Savings Due to Night Thermostat Setback
11 pm to 7 am

| Location | Setback Savings (%) | Location | Setback Savings (%) |
|---|---|---|---|
| Albuquerque, NM | 21 | Los Angeles, CA | 57 |
| Atlanta, GA | 23 | Medford, OR | 23 |
| Birmingham, AL | 24 | Memphis, TN | 22 |
| Bismarck, ND | 11 | Miami, FL | 48 |
| Boise, ID | 18 | Minneapolis, MN | 11 |
| Boston, MA | 17 | Nashville, TN | 21 |
| Brownsville, TX | 41 | New York, NY | 19 |
| Buffalo, NJ | 15 | Oklahoma City, OK | 18 |
| Burlington, VT | 13 | Omaha, NE | 14 |
| Charleston, SC | 27 | Philadelphia, PA | 17 |
| Cheyenne, WY | 17 | Phoenix, AZ | 36 |
| Chicago, IL | 15 | Pittsburgh, PA | 16 |
| Cincinnati, OH | 17 | Portland, ME | 15 |
| Denver, CO | 19 | Portland, OR | 22 |
| El Paso, TX | 26 | Reno, NV | 22 |
| Fort Worth, TX | 25 | Salt Lake City, UT | 16 |
| Fresno, CA | 31 | San Antonio, TX | 26 |
| Great Falls, MT | 15 | San Diego, CA | 60 |
| Jacksonville, FL | 35 | San Francisco, CA | 40 |
| Kansas City, MO | 16 | Seattle, WA | 22 |
| Lake Charles, LA | 29 | Washington, DC | 19 |

Table 1.

Impact of Thermal Integrity and Window Area on Heating Load Reductions Due to Night Temperature Setback for 12 Representative Locations

| Location | Thermal Integrity* | Window Area** ($ft^2$) | Heating Load w/o Night Thermostat Setback (MMBtu) | Savings Due to Night Thermostat Setback (MMBtu) | (%) |
|---|---|---|---|---|---|
| Albuquerque NM | low | 98 | 45.304 | 8.484 | 18.73 |
| | | 180 | 48.345 | 9.514 | 19.68 |
| | average | 98 | 29.634 | 5.891 | 19.88 |
| | | 180 | 21.243 | 6.626 | 21.21 |
| | high | 98 | 16.749 | 3.703 | 22.17 |
| | | 180 | 19.141 | 4.553 | 23.79 |
| Atlanta GA | low | 98 | 34.817 | 7.312 | 21.00 |
| | | 180 | 37.424 | 8.228 | 21.99 |
| | average | 98 | 22.580 | 4.930 | 21.83 |
| | | 180 | 23.902 | 5.556 | 23.24 |
| | high | 98 | 12.507 | 2.912 | 23.28 |
| | | 180 | 14.344 | 3.637 | 25.36 |
| Chicago IL | low | 98 | 68.590 | 9.841 | 14.35 |
| | | 180 | 73.643 | 10.986 | 14.91 |
| | average | 98 | 46.264 | 6.875 | 14.86 |
| | | 180 | 48.850 | 7.689 | 15.74 |
| | high | 98 | 27.632 | 4.357 | 15.77 |
| | | 180 | 31.138 | 5.325 | 17.10 |
| Cincinnati OH | low | 98 | 56.090 | 8.621 | 15.37 |
| | | 180 | 60.161 | 9.679 | 16.09 |
| | average | 98 | 37.419 | 5.970 | 15.95 |
| | | 180 | 39.419 | 6.655 | 16.88 |
| | high | 98 | 21.826 | 3.646 | 16.70 |
| | | 180 | 24.702 | 4.520 | 18.30 |
| Denver CO | low | 98 | 63.673 | 10.872 | 17.07 |
| | | 180 | 68.562 | 12.186 | 17.77 |
| | average | 98 | 42.432 | 7.660 | 18.05 |
| | | 180 | 45.052 | 8.623 | 19.14 |
| | high | 98 | 24.875 | 4.966 | 19.96 |
| | | 180 | 28.537 | 6.113 | 21.42 |
| Lake Charles LA | low | 98 | 21.951 | 5.726 | 26.09 |
| | | 180 | 23.633 | 6.415 | 27.14 |
| | average | 98 | 13.940 | 3.820 | 27.40 |
| | | 180 | 14.863 | 4.324 | 29.09 |
| | high | 98 | 7.338 | 2.164 | 29.49 |
| | | 180 | 8.554 | 2.754 | 32.20 |
| Miami FL | low | 98 | 2.416 | 1.117 | 46.23 |
| | | 180 | 2.676 | 1.300 | 48.58 |
| | average | 98 | 1.338 | .611 | 45.67 |
| | | 180 | 1.483 | .729 | 49.16 |
| | high | 98 | .560 | .253 | 45.18 |
| | | 180 | .712 | .369 | 51.83 |
| Minneapolis MN | low | 98 | 93.665 | 9.725 | 10.38 |
| | | 180 | 100.751 | 10.821 | 10.74 |
| | average | 98 | 64.380 | 6.834 | 10.62 |
| | | 180 | 68.009 | 7.575 | 11.14 |
| | high | 98 | 39.864 | 4.363 | 10.94 |
| | | 180 | 44.723 | 5.271 | 11.79 |

| Location | Thermal Integrity* | Window Area** ($ft^2$) | Heating Load w/o Night Thermostat Setback (MMBtu) | Savings Due to Night Thermostat Setback (MMBtu) | (%) |
|---|---|---|---|---|---|
| New York City | low | 98 | 52.708 | 9.081 | 17.23 |
| NY | | 180 | 56.535 | 10.180 | 18.01 |
| | average | 98 | 34.593 | 6.250 | 18.07 |
| | | 180 | 36.374 | 7.038 | 19.35 |
| | high | 98 | 19.892 | 3.971 | 19.96 |
| | | 180 | 22.505 | 4.878 | 21.68 |
| Phoenix | low | 98 | 21.337 | 6.997 | 32.79 |
| AZ | | 180 | 23.081 | 7.743 | 33.55 |
| | average | 98 | 13.497 | 4.742 | 35.55 |
| | | 180 | 14.597 | 5.295 | 36.27 |
| | high | 98 | 6.839 | 2.652 | 38.78 |
| | | 180 | 8.240 | 3.343 | 40.57 |
| San Francisco | low | 98 | 39.512 | 13.198 | 33.40 |
| CA | | 180 | 42.265 | 14.732 | 34.68 |
| | average | 98 | 24.351 | 9.267 | 38.06 |
| | | 180 | 26.018 | 10.500 | 40.36 |
| | high | 98 | 12.151 | 5.711 | 47.00 |
| | | 180 | 14.684 | 7.239 | 49.30 |
| Seattle | low | 98 | 62.023 | 12.444 | 20.06 |
| WA | | 180 | 66.754 | 13.867 | 20.77 |
| | average | 98 | 40.790 | 8.755 | 21.46 |
| | | 180 | 43.302 | 9.781 | 22.59 |
| | high | 98 | 23.122 | 5.496 | 23.77 |
| | | 180 | 26.624 | 6.771 | 25.43 |

| *Thermal Integrity | Ceiling nominal R-value | Wall nominal R-value | Floor nominal R-value | Infiltration rate Ach |
|---|---|---|---|---|
| low | 7 | 7 | 7 | 1.0 |
| average | 19 | 11 | 11 | .7 |
| high | 33 | 18 | 22 | .4 |

**Windows are single and storm, aluminum sash w/o thermal breaks.

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# AN INTEGRATED APPROACH TO BUILDING DESIGN

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## ABSTRACT

A five story building is to be built in the coastal city of Madras (latitude 13°N) which averages 32°C touching 42°C during summer. To tackle this high temperature and moisture load, several passive features are incorporated and a liquid desiccant open cycle is used to comfort condition the building. Experimental data for a one ton system are presented in this paper.

## 1. INTRODUCTION

In tropical coastal climates like that of Madras, humidity constitutes a major part of the air-conditioning load. In view of the large amount of literature available on passive architectural features, the Murugappa Group of Companies had decided to translate these theoretical aspects into practical applications in a five story building of approximately 500 $m^2$ floor area per floor. Since moisture removal is best effected by desiccant systems (1), this system has been adopted for the five story building that is under construction. Hollow folded plates of trapezoidal cross section not only serve as structural elements but also to conduit the air into the building. Experimental results presented in this paper refer to a one ton system that is in operation at the Murugappa Chettiar Research Centre (MCRC).

## 2. THEORY OF OPERATION

Using the folded plates which are structural elements as ducts does away with the cost of separate ducting and false ceiling. Besides major cost savings, a large amount of time which would be spent in designing and fabricating ducts for the distribution of the conditioned air is saved. The elimination of a false ceiling brings the electrical fittings inside the folded plates. Thus each floor is a self-contained unit needing no further embellishment aside from furniture and partitioning. Since the main air ducts run outside the building considerable space is saved inside the building. Thus apart from a direct saving of almost 4% of building costs, a saving in the lead time for the construction of this five story building is effected. The walls of the building are of sandwich construction with a 25 mm thermocole packing as an insulation medium between a 100 mm (4") thick brick wall on the outside and 50 mm (2") concrete on the inside.

Solar insolation contributes a major heat load from the east-west direction. So windows have been done away with on the western wall, and on the eastern side the windows are in the shadow of an existing building.

A desiccant cycle was sought to combat the moisture laden ambient air. The choice of the desiccant medium was achieved with several considerations in mind. Silica gel crumbles within a few absorption-desorption cycles and offers a high pressure drop to the air flow. Triethylene glycol and lithium halides are very expensive and inventory costs are high. Thus the choice of the desiccant narrowed down to calcium chloride solution which is only mildly corrosive and whose handling problems are within manageable limits.

The thermodynamic cycle of the open desiccant system is as shown in Figure 1.

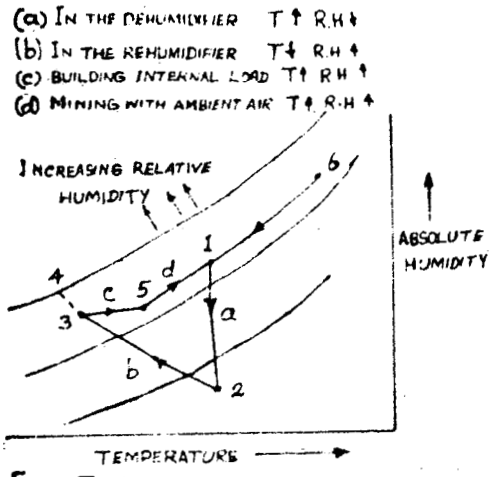



Fig 1. THERMODYNAMIC CYCLE OF THE OPEN DESICCANT SYSTEM

The essence of this cycle lies in the fact that the humidity is brought down well below comfort limits and then evaoprative cooling is utilised to achieve the comfort limits of humidity and temperature (see Figure 2).

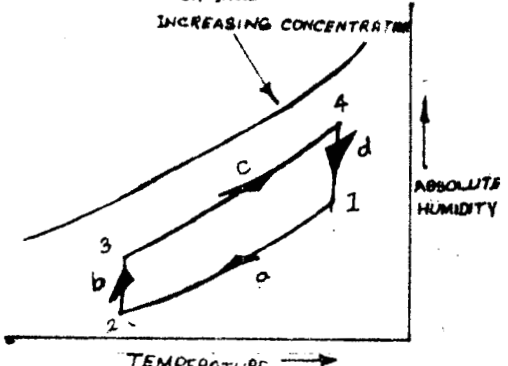



Fig 2. CALCIUM CHLORIDE CYCLE ON PSYCHROMETRIC CHART

To control the temperature rise of the calcium chloride solution when contacted with air in the dehumidifier, a sensible water cooling system is built one with vertical and the other with horizontal aluminium cooling tubes (see Figure 3). Dehumidification performance was not noticeably different.

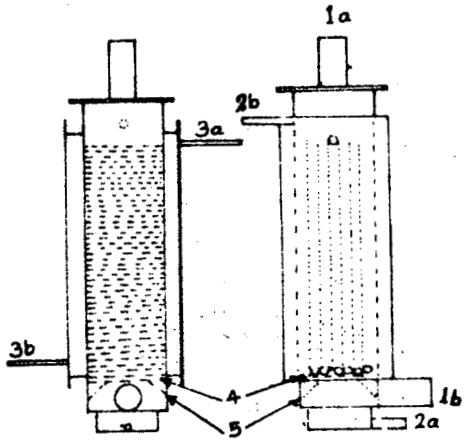



Fig 3. DEHUMIDIFIER CONSTRUCTION ESSENTIALS

## 3. DESCRIPTION OF MAJOR EQUIPMENT

### 3.1 Dehumidifier

This is the heart of the open desiccant cycle where simultaneous heat and mass transfer occur between air, water and calcium chloride solution. When air is dried using calcium chloride solution,

heat is generated. However as the calcium chloride solution temperature rises, the water retention capability of the calcium chloride solution goes down. So while the air is being dried, the temperature of the calcium chloride and air must not be allowed to rise. This is why a heat exchanger is built in the dehumidifier. The cooling tower and this process of moisture removal from the air is maintained at a steady temperature which is a function of ambient wet bulb temperature. (see Figure 4)

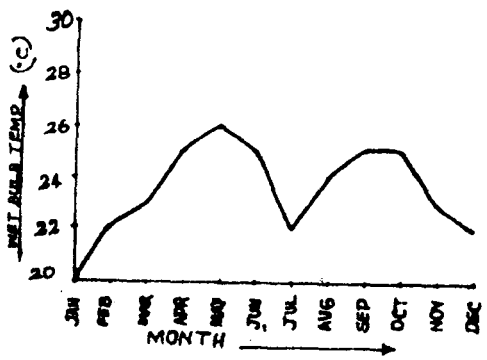



Fig.4 - W.B. Temp. vs months for Madras city

Heat transfer area is provided by the aluminum tubes inside which cooling water flows and mass transfer area is provided by the aluminum tube and a boiling bed of H.D.P.E. balls. The aluminum tubes may be in cross-flow or anti-parallel configuration.

3.2 Regenerator

Calcium chloride solution is regenerated on the plastered roof with a wick type arrangement on the inclined surface and perspex sheets are used as regenerator covers. The calcium chloride solution is pumped from the dehumidifier into the regenerator using an aluminum tube distributor with multiple discharge points.

The regenerator has only one discharge port and the calcium chloride solution flows into the dehumidifier by gravity. While pumping calcium chloride, a tendency for foam to develop in the regenerator was cut down considerably by the addition of lithium chloride in trace quantities.

3.3 Rehumidifier

The rehumidification is achieved by an atomizer which is placed in the air stream. A by-pass with a control valve is provided to attain the desired relative humidity.

4. EQUIPMENT PERFORMANCE

4.1 Dehumidifier

Table 1 - Dehumidifier performance

| TIME | | 2.25 P.M | 4.05 P.M |
|---|---|---|---|
| Air inlet temp. into dehum | | | |
| | db | 42 | 42.5 |
| | wb | 33 | 35 |
| Air exit temp. from dehum. | | | |
| | db | 42 | 41 |
| | wb | 30 | 30.5 |
| Air temp. in rehum. | | 32 | 30.5 |
| Air inlet temp. into room | db | 33.5 | 32.5 |
| | wb | 32 | 30.5 |
| Water temperature | | 40 | 39 |
| Ambient temperature | db | 36 | 35 |
| | wb | 31.5 | 32 |
| $CaCl_2$ density | | 1.4 | 1.39 |

The dehumidifier operates at about 65% efficiency. The efficiency of the dehumidifier is defined as follows

$$n = \frac{\text{dehumidifier inlet R.H - R.H at dehumidifier exit}}{\text{dehumidifier inlet R.H - R.H that is at equilibrium with the given concentration of calcium chloride solution.}}$$

4.2 Regenerator

Table 2 - Regenerator Performance

| TIME | Density (gm/cc) | Temp (°C) |
|---|---|---|
| 9·15 a.m | 1·38 | 45 |
| 10·00 a.m | 1·385 | 57 |
| 10·45 a.m | 1·37 | 59 |
| 11·30 a.m | 1·39 | 57 |
| 12·15 P.m | 1·38 | 57 |
| 1·00 P.m | 1·41 | 58 |
| 1·45 P.m | 1·43 | 60·5 |
| 3·45 P.m | 1·45 | 53 |
| 4·30 P.m | 1·46 | 52 |

It has been observed that 50% concentration can be maintained.

4.3 *One ton system*

One set of readings for the whole day of the system are as follows:

| | a.m. | a.m. | a.m. | noon | p.m. | p.m. | p.m. | p.m. |
|---|---|---|---|---|---|---|---|---|
| Time | 9.00 | 10.00 | 11.00 | 12.00 | 1.30 | 2.00 | 3.00 | 4.00 |
| Ambient db (°C) | 35 | 36 | 37.5 | 36 | 36 | 34.5 | 36.5 | 37 |
| Ambient wb (°C) | 28.5 | 32 | 28 | 31 | 30.5 | 29 | 28 | 30 |
| Dehum inlet db (°C) | 35 | 43 | 42 | 43 | 46 | 43 | 39.5 | 40 |
| Dehum exit db (°C) | 35 | 38 | 39 | 40 | 39 | 40.5 | 39 | 38 |
| Rehum exit db (°C) | 26.5 | 29 | 29 | 29 | 31 | 29 | 28 | 28 |
| Water inlet (°C) | 30 | 34 | 33 | 34 | 34 | 35 | 35 | 33 |
| Water exit (°C) | 31 | 36 | 36 | 37 | 37 | 37 | 37 | 36.5 |
| $CaCl_2$ temp in regen (°C) | 49 | 57 | 60 | 59 | 63 | 64 | 64 | 53 |
| $CaCl_2$ density in regen (gm/cc) | 1.5 | 1.49 | 1.48 | 1.49 | 1.5 | 1.52 | 1.51 | 1.5 |
| $CaCl_2$ temp in dehum (°C) | 39 | 47 | 45 | 48 | 48 | 49 | 47 | 47 |
| Air inlet temp into room (°C) | 28 | 30 | 30.2 | 34 | 32 | 31 | 30 | 30 |

## 5. CONCLUSION

Experimental results so far have been quite encouraging. Room air inlet temperature is 5 to 10°C lower than the ambient during summer. With better equipment matching, one can expect the room inlet air at the desired comfort limits. In addition a 30% electrical energy saving is expected when compared with a vapour compression cycle.

## 6. ACKNOWLEDGEMENTS

This building design has evolved out of the efforts of several engineers of different disciplines, architects, contractors and financiers with a common goal. We thank Dr C V Seshadri (Director, MCRC) for the many ideas that led us in the right direction, M/s Karekar & Sundaram of Bangalore for the folded plate design and Mr B V Umesh for the details of the sandwich wall construction.

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# METAL BUILDING INTEGRATED THERMOSIPHON AIR PANEL

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## ABSTRACT

A low cost thermosiphon air panel has been retrofitted to a metal building used for agricultural and educational purposes. The design, construction and monitoring was carried out by faculty and students of the Colorado Mountain College Solar Retrofit program. Included in this analysis is a design rationale, materials list, construction concerns, monitoring data, a thermal and economic analysis resulting in a simple payback period computation.

## 1. BACKGROUND

Retrofit of existing building stock for energy efficiency presents tremendous challenge as well as opportunity. The retrofit market is immense and is not characterized by a singular solution. Certain solutions which are currently cost effective in new construction are cost prohibitive in a retrofit situation. Appropriate retrofit requires a careful analysis of the existing structure, usage patterns and occupancy. Sometimes daring deviations from standard solutions prove appropriate. Solarization may prove more appropriate than certain conservation strategies(1).

Many buildings in the United States have energy requirements dominated by space heating loads. Small to medium sized commercial and institutional use buildings are often occupied during the daytime hours only. Thermostat setback strategies can significantly lower space heating loads during nonoccupied periods. Since occupancy then coincides with both solar gain and the dominant load, daytime solar space heating can be considered a viable retrofit option.

Throughout the United States metal skinned buildings have taken a significant position in our current building stock. Commercial, industrial, storage and agricultural operations have been attracted to metal buildings because these are relatively inexpensive, quickly constructed, fire resistant, durable, low maintenance and versatile buildings. Mobile homes are sided with metal and other permanent homes have opted for metal roofs and metal siding. In climates with significant heating loads, metal buildings can be fitted with vertical wall passive solar air heaters. These collectors sometimes can be mounted directly to the south wall to utilize the metal skin as an absorber and the existing building wall insulation then doubles as the back insulation and eliminates the need for a weatherproof collector backing. Mounting hardware can be minimized. Wall mounting reduces installation labor and materials. Collector maintenance (e.g., cleaning) is easier. F-CHART predicts thermal performance losses of fifteen percent or less for vertical space heating mounts compared to more optimal angles (i.e., latitude plus fifteen degrees). Thus, the expense of such a system is largely dependent on the following options:

A) passive or active; B) daytime heating or daytime heating with a storage component for nights and cloudy days; and C) glazing material and glazing support mounting.

The lowest initial cost strategy is a passive thermosiphon air panel (TAP) for daytime heating with a plastic glazing. The TAP requires no electrical energy for air moving, thus there is no initial cost for an air mover, wiring and controls. TAP control is automatic, aided by the use of backdraft dampers. Minimal (near zero) operations and maintenance costs for TAP's have proven to be a prime asset when compared to active solar systems. Daytime heating loads are usually 25 to 40 percent of the total

heating load and can be largely met with systems designed for daytime use only. Preheating makeup ventilation air is another such use. Daytime use eliminates the need for more collectors, more control, more wiring, a larger air mover, ductwork, domestic hot water preheating components, insulated storage containers and storage materials. Systems with storage can provide a greater percentage of the load, are often mounted on a tilt and cost more than 2 to 6 times the price of a daytime system. Since a freely operating wall mounted TAP operates at low temperatures, will not stagnate, and absorbs little radiation in the summer, plastics can be used as a glazing material. The 19 square foot TAP constructed costs approximately $4.86 per square foot for materials. The majority of the cost is associated with the sidewalls. Larger collector areas can significantly reduce this figure as can cost cutting in the area of aesthetics. For example, a 170 square foot TAP could cost as little as $3.74 per square foot for both labor and materials with no sacrifice in performance.

## 2. CONSTRUCTION

Dimensional design relied on the work of Mr. W. Scott Morris(2), including careful attention to net free areas of collector cross section, ducts, dampers and grilles. The TAP was integrally retrofitted to a Cuckler Building Systems steel building in December of 1982. A total of ten active and passive vertical wall solar air heaters were installed on the Colorado Mountain College campus at this time. Seven of these collectors (including the subject TAP) measured 35 inches by 77 inches. This allowed for comparison studies.

The actual construction sequence was as follows. First, the outside dimensions were lined out, accounting for purlin location. Duct openings were then cut. The steel siding was cleaned, masking tape applied to the outside dimension and painted with high temperature flat black paint. The box wall, made of 6 inch steel dry wall track was prepainted and riveted to the wall. All joints were sandwiched with high temperature silicon caulk then caulked again from the outside. The box walls were insulated with rigid cellular glass insulation, coated with high temperature black silicon caulk. The inlet and outlet ductwork and backdraft dampers were custom fabricated and installed. The glazing, consisting of 6 mil polyethylene supported by thin pine battens, was laid in place with a prepainted custom steel glazing cap, bonded washers and screws. Again, careful attention was paid to airtight caulking. Standard return air grilles were fastened to the interior sheet rock to finish the job. As in all retrofit, the aspect of custom work must be carefully considered when first viewing a project.

## 3. MONITORING SUMMARY

Data were collected during the winter of 1983. Twelve Colorado Mountain College space heating systems using air as the transport medium were monitored. Four days in February and March were used which include one cloudy day, two sunny days and one partly hazy, partly sunny day. This choice of days resembles the Colorado winter climate. Twelve data points, encompassing the hours of 8:15 AM to 4:30 PM, were used to develop TAP collector efficiency parameters. Data collected includes date, time, general weather conditions, solar radiation, ambient air temperature, inlet air temperature, outlet air temperature, metal building siding or absorber temperature, air velocity and general observations.

Solar radiation was monitored using a Crystal Productions model 430T, 4888 solar radiation meter. Temperatures were measured with Electromedics TM-Series 2 and 3 channel digital thermometers, a Pacific Transducer Corporation model 572 FM magnetic surface thermometer and Universal Enterprizes dial thermometers. Air velocity was measured with an Alnor 6000-P velometer.

Air velocity measurements required the visual reading of a needle display. At such low velocities as encountered in a TAP the measurement accuracy has previously been estimated to be within plus or minus twenty five percent (3). The author considers this to be the weakest link in this monitoring effort. Each of the twelve collector efficiency parameter data points include the average of fifteen separate air velocity readings taken within a two minute period. Measured air flow rates ranged from 0.73 cfm to 4.62 cfm per gross square foot of collector with an average of 2.1 cfm per gross square foot of collector. Measured temperature difference from inlet to outlet peaked at 48°F, averaging a 32°F temperature rise through the collector.

Collector efficiency was calculated simply as actual useful energy delivered into the building divided by solar energy incident upon the collector (4). Energy delivered into the building was computed using equation 1 and efficiency computed using equation 2.

$$q_u = \dot{m} c_p (t_o - t_i) \quad [1]$$

$$\eta = \frac{q_u}{I_t} \quad [2]$$

Collector efficiency was initially plotted against equation 3.

$$\eta \text{ versus } \frac{t_{avg} - t_a}{I_t} \quad [3]$$

The collector efficiency plot was then converted to the standard format (4) as in equation 4 using a method outlined by Beckman, Klein and Duffie (5).

$$\eta \text{ versus } \frac{t_i - t_a}{I_t} \quad [4]$$

Thus, the resultant collector efficiency parameters for the subject TAP are

$F_r (\tau\alpha) = 0.42$

$F_R U_L = 1.18$

### 3.1 Observations

The metal building was factory finished to a flat red color. At six feet from the collector the red steel siding routinely attained slightly higher temperatures than the air cooled absorber. This occurance, usually during periods of high solar gain, enhanced collector efficiency through conduction heat transfer. Wall temperatures peaked at 135°F while absorber temperatures peaked at 130°F. The magnetic surface thermometer was shielded from direct solar radiation.

Reverse thermosiphoning is a concern to be reckoned with. The subject TAP was installed with two backdraft dampers, at inlet and outlet. To ascertain the performance of the backdraft dampers, smoke tests were made. On two cold winter nights a beekeepers smoker and incense sticks were used to visually observe smoke movement. With both backdraft dampers in place absolutely no smoke could be observed moving in or out of the collector. When the outlet (higher) backdraft damper was removed a very small amount of smoke was observed to occassionally be drawn into the collector outlet when room air pressure was essentially constant.

Changes in room air pressure due to wind, combustion heaters and door opening will introduce air movement into the collector. The polyethylene glazing can actually act like a bellows when winds cause movement of the glazing. Though the polyethylene glazing survived the Colorado winter without damage, it is not recommended as a collector glazing.

After six months of operation no visible degradation of the collector is observable. The base of the collector inlet area has accumulated a noticeable layer of dust. The absorber appears clean. The dust is from the sand floor of the building and is inevitable.

Numerous design options exist to improve collector performance or decrease costs. For instance, the TAP outperformed a nearly identical U-Tube design (2) but was outperformed by very similar, though non-integrated designs using matrix or selective surface absorbers.

## 4. ECONOMICS

With experimental thermal performance data available, a modified F-CHART analysis was calculated by hand (6). F-CHART, developed for active solar systems with storage, was modified to reflect daytime heating loads and daytime average temperatures, assuming all solar energy delivered was usable (up to 100 percent of the load). The analysis was conducted for a proposed project consisting of 170 square foot of TAP. This larger TAP has roughly one third the sidewall area to collector area that the experimental 19 square foot TAP has. It has the additional advantage of a 10 foot collector height compared to a 6.33 foot height of the experimental TAP. Thus, thermal performance should be enhanced, though not reflected in this F-CHART analysis. Using a heating season length of October through April (conservative for our locale) the TAP will deliver 9.457 MMBtu per year. This represents seasonal solar heating system efficiency of 28 percent.

When replacing electric resistance heating at $16.88 per MMBtu, the annual savings would be $159.63. When replacing natural gas at $4.86 per MMBtu (with a 55 percent seasonal heating system efficiency) the annual savings would be $83.57.

The cost of materials is $316.56 (see Appendix A). Labor is estimated at 32 person hours at $10 per hour. The total cost for the 170 square foot TAP is $636.56 or $3.74 per gross square foot of collector. Simple payback, excluding all tax considerations, is 3.99 years when replacing electricity and 7.62 years when replacing natural gas.

## 5. CONCLUSIONS

Moderate to large size metal building integrated TAPs are an appropriate and economically viable solar retrofit, especially for day use buildings in climates with a significant heating season. It is estimated that such a TAP can be purchased and installed for $3.74 per square foot yielding simple paybacks in the two to ten year range, depending on heatng fuel costs. More complete monitoring is needed to fully assess the true value of these systems. A final word of advice as metal siding comes in numerous sizes and shapes: be prepared to deal with fabrication details.


## 6. ACKNOWLEDGEMENTS

I wish to thank the students and staff, Johnny Weiss and Ken Olson, of the Colorado Mountain College Solar Retrofit program, who contributed their time and expertise to this project. Colorado Mountain College offers an intensive, vocational course of study that specifically targets appropriate retrofit. The focus of the course work is on the design, construction and installation of solar energy systems.

Solar greenhouses, solar domestic water heating and solar air heating systems are designed, built and installed. Energy auditing and energy conservation techniques are taught in detail. The Solar Retrofit program emphasizes adapting solar systems to existing buildings. It is divided into two areas of study - theory and practice. Students learn about energy efficiency in the classroom, practice construction skills in the "laboratory" and do actual field installations in the community. Classes are scheduled to enable participants to work at part-time jobs. Upon completion of the year long program, participants are certified solar technicians, having installed a variety of solar systems on private, public, non-profit and low-income buildings (7).


## 7. NOMENCLATURE

TAP - thermosiphon air panel
F - degrees Fahrenheit
cfm - cubic feet per minute
$q_u$ - useful energy, Btu per hour
$\dot{m}$ - mass flow rate, pounds per hour
$C_p$ - specific heat, Btu per pound per degree F (at 7000 feet above sea level)
$t_o$ - outlet air temperature, degrees F
$t_i$ - inlet air temperature, degrees F
$\eta$ - collector efficiency, percent
$I_t$ - total solar irradiation incident upon the gross collector area, in one hour
$t_{avg}$ - average collector air temperature, degrees F
$t_a$ - ambient air temperature, degrees F

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

9. APPENDIX A

Material Cost For 170 Square Foot Metal
Building Integrated Thermosiphon Air Panel
(17 feet by 10 feet)

| | | |
|---|---|---|
| 84 feet -6" metal track | $0.291/foot | $24.45 |
| 27 square feet-polyisocyanurate | $0.39/ft$^2$ | $10.53 |
| 8 tubes silicon caulk | $4.00/tube | $32.00 |
| 270-1/4" x 1/8" steel rivets | $0.0114/each | $ 3.08 |
| 270-#8 x 3/4" sheet metal screws | $0.01166/each | $ 3.15 |
| 270 bonded washers | $0.03/each | $ 8.10 |
| 4 cans flat black paint | $3.95/can | $15.80 |
| 170 square feet - Tedlar coated fiberglass reinforced polyester | $0.86/ft$^2$ | $146.20 |
| 54 feet-1 1/2" x 1 1/2" drywall angle | $0.145/foot | $ 7.83 |
| 30 feet-1 1/2" flashing | $0.25/foot | $ 7.50 |
| 8 - backdraft dampers | $1.50/each | $12.00 |
| 8 - 30" x 8" grilles | $4.74/each | $37.92 |
| 8 - 30" x 8" x 7" ducts | $1.00/each | $ 8.00 |
| | | $316.56 |

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# THE EFFECT OF THERMAL MASS IN EXTERIOR WALLS ON ENERGY CONSUMPTION IN COMMERCIAL BUILDINGS

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## ABSTRACT

DOE2.1A building analysis of prototypical office buildings completed for the California Energy Code has shown that increased heat capacity of exterior walls allows equal annual energy performance with reduced thermal resistance. Based on this work, the California Energy Commission has adopted a set of prescriptive standards, in which the required insulation level depends on wall heat capacity. An optional package of conservation measures which allows uninsulated masonry walls by increasing ceiling insulation and reducing lighting energy is also presented.

## 1. INTRODUCTION

The State of California is currently developing a new performance-based Title 24 energy code for non-residential buildings. Compliance with this regulation can be demonstrated in one of three ways: 1) to follow one of three sets of prescriptive building guidelines, 2) to use a simplified calculation method (under development) to allow building component tradeoffs, or 3) to meet the annual energy budget with a certified computer analysis tool.

The annual energy budget is based on the lowest life cycle cost for a prototypical building, such as a low-rise office building. Other building types currently under development are high-rise office buildings, retail and grocery stores. The low-rise office building analyses established the minimum life cycle costs; that is, the point at which the total present value of conservation measure cost and future energy cost is minimum. The measures achieving the greatest savings for the lowest costs were introduced in sequence, until the combination with lowest life-cycle cost was reached.

Compliance can be shown through demonstrating equivalent performance through either of the three methods described above. The energy budget includes energy consumption for heating, cooling, lights, fans and domestic hot water. The energy budgets are based on source energy, so electricity consumption has been multiplied by three (3) in order to account for the 33% efficiency of transporting it to the customer, while natural gas is assumed to have an efficiency of 100%. For the purposes of the non-residential building standards analysis, the 16 climate zones of California have been combined into six climate regions, represented by the weather data from the following six cities: San Diego (south coastal), Santa Maria (mid-state coastal), Oakland (north coastal), Fresno (central valley), China Lake (high desert), and Mt. Shasta (mountainous).

Berkeley Solar Group (BSG) has participated in the development of the new regulations under contract with the Concrete Masonry Association of California and Nevada, in order to develop prescriptive packages which allow credit for the positive thermal contribution made by massive elements in a building. The heat capacity of the construction used in a building's walls significantly affects both the overall performance of the building and the manner in which it reacts to changes in insulation levels. Walls of heavy-weight construction are also sensitive to the location of the insulation within the wall. In general, thermally massive building elements are most beneficial where the dominant load is cooling. In large commercial buildings this is generally the case, due to large lighting and equipment loads.

For this analysis, the base case office building for compliance was a two story building of 20,000 $ft^2$, 10 thermal zones and an aspect ratio of 2.5:1 with the 2.5 building length facing east and west. Roof and wall insulation levels were R-11. Thirty percent of the wall area was glazed with heat-absorbing glass (shading coefficient = 0.6). The lighting power was 1.5 $W/ft^2$ and the equipment power was 0.5 $W/ft^2$. Thermostat settings were 70° F for

heating and 78 °F for cooling. The base case mechanical system was a rooftop package single-zone unit for heating and cooling in each zone. The buildings were conditioned from 8 am to midnight on work days.

## 2. METHODOLOGY

Heat capacity and R-values were selected for typical commercial mass construction. For example:

| Heat Capacity Btu/ft² °F | Generic Wall Type |
|---|---|
| 10 | 8" Concrete Masonry Unit (CMU), Perlite-filled |
| 15 | 8" CMU, Solid-grouted |
| 20 | 12" CMU, Solid-grouted or Adobe |

The methodology used to develop the packages was to define for the low-rise building type a set of wall constructions with varying heat capacities and minimum R-values. Each wall construction was selected and tested to result in an annual source energy consumption equal to the energy budget level required by the standards. A designer may then use any one of these combinations of heat capacity and insulation levels.

For two equivalent prescriptive packages, A and C, two separate generic mass wall constructions were defined. Package A is the base package with a masonry wall construction combined with interior firring and insulation covered by gypsum board. The Package C wall construction assumes that the mass is exposed to the room air so that insulation must either be integral to the wall construction or exterior. Figure 1 illustrates the Package A wall and Figure 2 illustrates the Package C wall construction.

The Package A, as developed by the California Energy Commission (CEC), did not allow uninsulated wall construction. Since this is a common type of construction in commercial development, Package C was developed with the intention that it have required wall R-values low enough so that, in most climate zones, no additional insulation would have to be added to the masonry wall construction. In order to compensate for the lower performance of the Package C wall construction while still maintaining the same annual source energy budget as Package A, lighting power levels were reduced to 1.4 W/ft² and roof insulation was increased from R-11 to R-19, or R-19 to R-30, depending on the particular climate zone.

Using DOE2.1A with custom weighting factors, BSG iteratively found the R-value for each heat capacity which gave equivalent performance for the low-rise office building. Figure 3 illustrates this iterative procedure. The graph is a plot of energy consumption vs. R-value and three wall heat capacity levels are shown for Package C in Zone 13, Fresno. Two runs were used to bracket the actual equivalent wall R-value. It was convenient to use interpolation between close R-values where the error of interpolation was small.

Three heat capacity curves as shown in Figure 3 produced three equivalent R-values for those particular wall constructions. The three points established in this manner were then fit with an exponential equation to locate intermediate points of different heat capacity. Figures 4 and 5 illustrate the equivalent mass wall curves for low-rise office buildings in Climate Zones 13 (Fresno) and 16 (Mt. Shasta).

## 3. RESULTS

The equivalent mass wall curves as illustrated in Figures 4 and 5 are plots of wall heat capacity vs. overall wall R-value. Both the Package A curve and the Package C curve are plotted on the same graph. These curves were then used to generate wall heat capacity vs. R-value matrices for the six target climate zones. Tables 1 and 2 list the equivalent R-values for Package A walls and Package C walls.

For Package A low-rise offices, the results show that the reduction in R-values is significant as the heat capacity increases in mild zones such as Climate Zone 13 (valley) and the coastal zones. For heavy walls, such as a wall construction of heat capacity 20 Btu/ft² °F, no insulation would be required in the milder zones. In contrast, the reductions in R-values for Zone 16 (mountainous) are less significant and for Package A firred interior insulation would be required.

The second set of curves plotted on both Figures 4 and 5 show the equivalent mass walls for low-rise offices for Package C. Again, there is a reduction in R-value due to increased heat capacity. This substantial mass effect is more significant in the milder Zone 13 than in the more severe and colder climate of Zone 16.

## 4. CONCLUSIONS

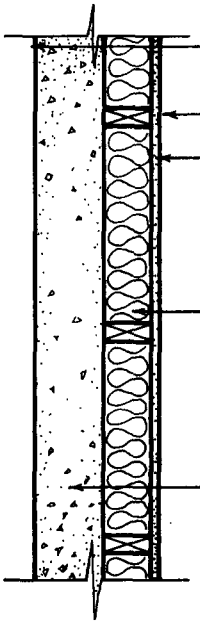
1) Wall heat capacity and thermal resistance can be traded-off for each other to provide equal energy performance in office buildings in California. Walls with low heat capacity need to be well-insulated; walls with high heat capacity need not be.

2) The change in thermal resistance required to compensate for changes in heat capacity is significant. The conductance (1/R) of heavy weight walls can be much higher than light weight walls with the same annual energy performance. In the coldest climate, Zone 16, a heavy weight wall can have a conductance 50% higher than a light weight wall. In the mildest climate, Zone 7, the conductance of the heavy weight wall can be 8 times as high.

3) The heat capacity and R-value trade-offs vary with climate. Zones 3, 5 and 7, which are mild temperature marine dominated climates, receive the most credit for heavy mass construction, while Climate Zone 16 receives less credit due to the high heating loads.

4) The effect of the wall thermal properties on total building energy consumption is small. A seven percent reduction in lighting power can compensate for significant changes in wall properties.

5) The wall matrix presented is a successful approach to implementing mass effects in energy codes and provides a simple way to ensure equal performance without restricting design options.



Outside Film Resistance = 0.17
Solar Absorptivity = 0.70

Inside Film Resistance = 0.68

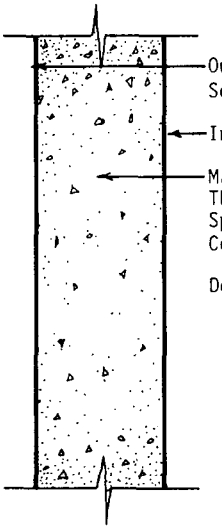
5/8" Sheetrock:
Cond. = 0.0926 Btu-ft/hr ft$^2$ $^oF$
Density = 50 lb/ft$^3$
Specific Heat = 0.20 Btu/lb $^oF$
Sheetrock removed for low R-value wall cases.

Homogenized Insulation and Furring Material:
Cond. = 0.345 Btu-ft/hr ft$^2$ $^oF$
Density = 120 lb/ ft$^3$
Specific Heat = 0.20 Btu/lb $^oF$
Thickness varies with R-value, 0 for low R-value cases.

Masonry Material:
Cond. = 0.70 Btu-ft/hr ft$^2$ $^oF$
Density = 120 lb/ft$^3$
Specific Heat = 0.20 Btu/lb $^oF$
Thickness varies with wall heat capacity:

| Thickness | Approximate Wall H.C. |
|---|---|
| 0.0425 | 1.8 |
| 0.167 | 4.0 |
| 0.417 | 10.0 |
| 0.625 | 15.0 |
| 0.833 | 20.0 |

Fig. 1. Package A Horizontal Wall Section.



Outside Film Resistance = 0.17
Solar Absorptivity = 0.70

Inside Film Resistance = 0.68

Masonry Material:
Thickness = 1 ft
Specific Heat = 0.20 Btu/lb $^oF$
Conductivity varies with R-value.
Density varies with wall heat capacity:

| Density | Approximate Wall H.C. |
|---|---|
| 0.90 | 1.8 |
| 20.0 | 4.0 |
| 50.0 | 10.0 |
| 75.0 | 15.0 |
| 100.0 | 20.0 |

Fig. 2. Package C Wall Section.

Ed. Note. A list of metric-English-metric conversion values appears immediately preceding the Author Index.

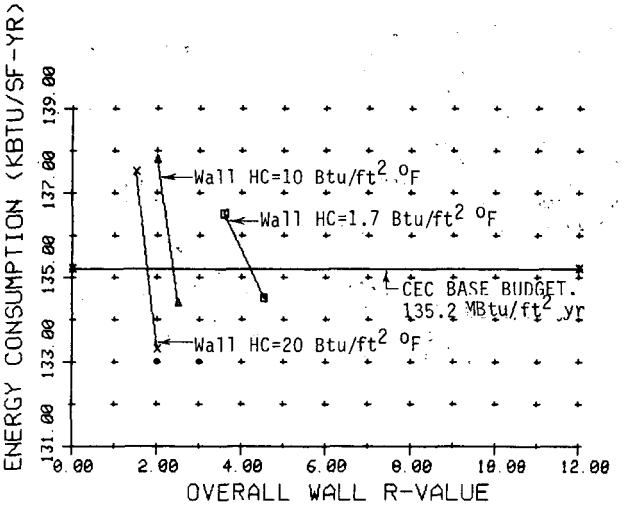



Fig. 3. Package C Mass Walls for Low-Rise Office Building, Climate Zone 13.

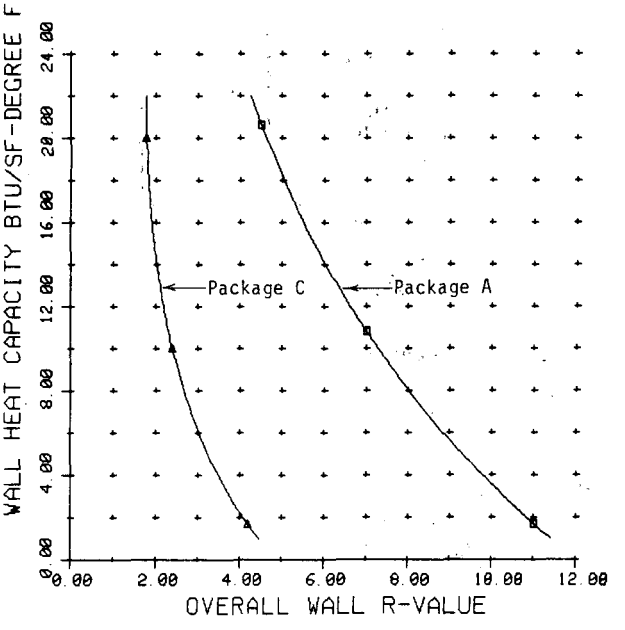



Fig. 4. Equivalent Mass Walls for Low-Rise Office Building, Climate Zone 13.

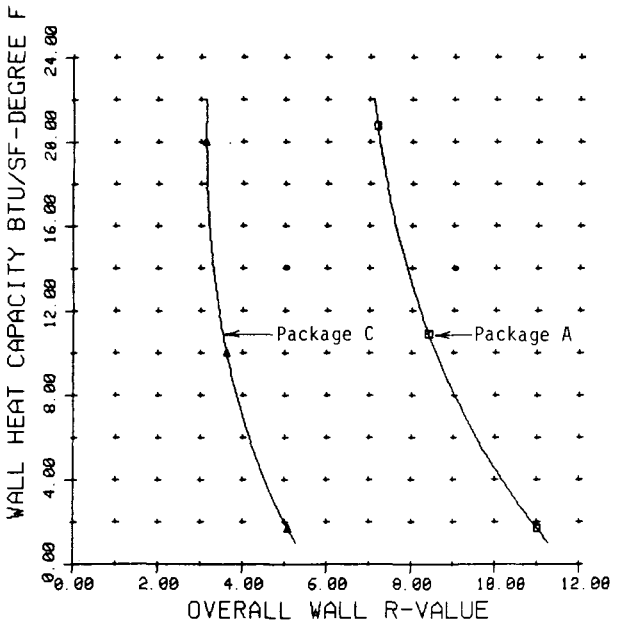



Fig. 5. Equivalent Mass Walls for Low-Rise Office Building, Climate Zone 16.

TABLE 1. PACKAGE A WALL HEAT CAPACITY VS R-VALUE MATRIX FOR LOW-RISE OFFICE BUILDINGS

| Wall Heat Capacity ($Btu/ft^2$ °F) | Wall R-value | | | | | |
|---|---|---|---|---|---|---|
| | Climate Zone | | | | | |
| | 3 | 5 | 7 | 13 | 14 | 16 |
| 1.8 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 |
| 4.0 | 9.9 | 10.3 | 8.7 | 9.8 | 9.9 | 10.2 |
| 10.0 | 7.0 | 7.2 | 4.6 | 7.3 | 7.7 | 8.6 |
| 15.0 | 4.9 | 4.4 | 2.6 | 5.8 | 6.2 | 7.7 |
| 20.0 | 3.2 | 2.3 | 1.4 | 4.6 | 5.1 | 7.2 |

ASSUMPTIONS: Same as CEC Package A runs except wall characteristics. Lights are at 1.5 $W/ft^2$. Roof R-value: R-11 for CTZ 3, 5, 7, and 13; R-19 for CTZ 14 and 16. If walls require insulation they are firred and insulated on the inside and finished with sheetrock.

TABLE 2. PACKAGE C WALL HEAT CAPACITY VS R-VALUE MATRIX FOR LOW-RISE OFFICE BUILDINGS

| Wall Heat Capacity ($Btu/ft^2$ °F) | Wall R-value | | | | | |
|---|---|---|---|---|---|---|
| | Climate Zone | | | | | |
| | 3 | 5 | 7 | 13 | 14 | 16 |
| 1.8 | 2.9 | 3.2 | 8.5 | 4.2 | 4.7 | 5.1 |
| 4.0 | 2.5 | 2.8 | 5.3 | 3.5 | 3.9 | 4.5 |
| 10.0 | 1.9 | 2.0 | 2.1 | 2.4 | 2.6 | 3.6 |
| 15.0 | 1.6 | 1.7 | 1.4 | 2.0 | 2.1 | 3.2 |
| 20.0 | 1.5 | 1.5 | 1.4 | 1.8 | 1.9 | 3.1 |

ASSUMPTIONS: Same as CEC Package C runs except wall characteristics and lighting power density. Lights: 1.5 W/sf in CTZ 7; 1.4 $W/ft^2$ in all the rest. Roof R-values: R-19 for CTZ 3, 5, 7, and 13; R-30 for CTZ 14 and 16. If walls require insulation it is intergral with the wall construction so that wall mass is exposed to room air.

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# ENERGY SAVINGS POTENTIAL FOR ATTACHED SUNSPACES IN DIFFERENT CLIMATES

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## ABSTRACT

Sensitivity analyses were performed using a modified DOE 2.1a code to model sunspace options attached to the south side of a one-story ranch house. Simulations were run in 11 representative cities with different climatic conditions for four sunspace configurations. The sunspace was eight feet in width, and either 12 or 24 feet long and was modelled with a glass or an opaque roof. The sunspace results were compared to a base case house without a sunspace but with similar thermal integrities. Parametric results showed that a sunspace operated under the conditions assumed in this study was able to contribute to the heating loads of the house to which it was attached. An appropriately oriented, designed and operated sunspace will heat itself if one tolerates a sunspace usable only during the day. In a few locations, an attached sunspace will also substantially reduce heating loads for the entire house.

## 1. INTRODUCTION

Interest in passive solar buildings including the isolated gain systems (e.g., attached sunspaces) has increased significantly in recent years as one response to higher energy prices and the widespread popularity of solar technologies. Although a large number of new homes incorporating passive solar design have been constructed and other houses have been retrofitted, little analytical work has been done to determine the effect of these additions on space conditioning loads of residential buildings. In support of a homebuilders' guide for new single-family residences, we conducted sensitivity analyses using a modified version of the DOE 2.1a code to model sunspace options attached to the south side of a one-story ranch house in 11 cities. These results, presented here, are compared to a base case house without a sunspace but with similar thermal integrities.

Ed. Note. A list of metric-English-metric conversion values appears immediately preceding the Author Index.

## 2. APPROACH

The attached sunspace was modelled as an extension to the south wall of the building. It covered as much as 44% of its surface area. The sunspace constituted a separate thermostatic zone, thus allowing heat transfer to the house to reduce the heating loads for the living space. The attached sunspace was modelled for a one-story ranch house prototype with 1540 ft$^2$ of floor area plus the additional sunspace area.

The sunspaces modelled were eight feet in width, and either 12 or 24 feet long (see Fig. 1). Single, double and triple-glazed options corresponding to the glazing levels of the main house were simulated. Side walls and the partition wall between the sunspace and the living space were covered with the same level of insulation as that of the main building.

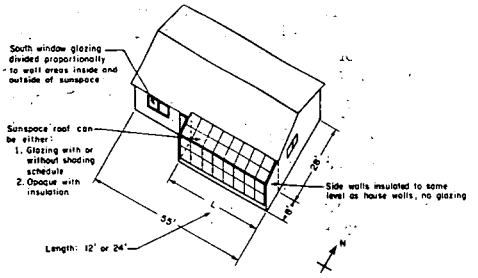



Fig. 1. Sunspace Model.

XBL 836-956

Thermal mass in the sunspaces was provided by a six inch concrete floor slab and by a facing brick wall situated on the sunspace side of the partition separating it from the house. The sunspace roof extended at the same angle as the house roof (tilt: 18.4°) and was modelled in two configurations: glazed and opaque. Glazed roofs were

assumed to have the same glazing as the rest of the sunspace and opaque roofs the same insulation levels as the roof of the main house.

The sunspace was assumed to be a semi-conditioned space representing a compromise between energy efficiency and livability. As operated, the sunspace could be occupied during the day and was not allowed to freeze at night. Therefore, its thermostat settings differ from those of the living space. Temperatures were allowed to drop to 45°F, below which a baseboard heater was assumed to be used. When sunspace temperatures exceeded 80°F, natural venting would equalize the sunspace temperatures with that of the outdoors. During the heating season, night heat loss was reduced by covering the sunspace's front glass wall (and roof if glass) with R-5 movable insulation from 10 pm to 8 am. During the cooling season, movable shading (shading coefficient of .30%) was used during hours when the sun shone on the glass roof and walls.

Heat was transferred from the sunspace to the living space by using a thermostatically controlled fan that allowed reduction of the living space heat load. It was assumed that the fan was activated hourly when the differential between the two areas was greater than 3°F during periods when the living space had a heating load. Forced air was then returned to the sunspace through another set of vents. Convection was not assumed to occur between the two zones through either open doors or windows in the partition.

Certain modifications were implemented into the DOE 2.1a code to account for the forced convection heat transfer from the sunspace to the living space. We calculated and used a set of custom weighting factors to estimate the impact of the thermal mass in the sunspace and to account for the fact that radiative heat losses were different in the daytime (glass only) and the night (glass plus movable insulation). In addition, code changes were made to approximate the impact of the solar gains through the windows in the partition wall between the sunspace and the living space.

## 3. RESULTS

Sensitivity analyses were performed in 11 representative cities with different climatic conditions for four sunspace configurations (12 and 24 ft with glass roof and 12 and 24 ft with opaque roof) and for three thermal integrities (loose, medium and tight). The cities and foundation types that were modelled are shown in Table 1, while Table 2 lists the various thermal integrities by foundation type.

The sensitivity results are presented in Table 3 for the different sunspace configurations and for the various thermal integrities. Since in some climates the cooling loads were increased through the use of an attached sunspace (especially those with glass roofs), the results are reported as net changes (in MMBtu) in the total space conditioning loads of the house.

## 4. CONCLUSIONS

Parametric results, as shown in Table 3, indicate that a sunspace operated under the conditions assumed in this study can reduce the heating loads of a house to which it was attached in many climates. The contribution, however was related to various design factors like the size of the sunspace and the type of roof (glass or opaque), or to the particular space conditioning requirements of the location. The larger sunspace (24 ft. long) with a glass roof usually performed better than the other configurations. For example, it was estimated that such a sunspace could reduce the total space conditioning load of the house by greater than 20% in Albuquerque and San Francisco, and by about 15% in Atlanta and Denver. In other climates the contribution was significantly less and in some instances (e.g., Miami), an attached sunspace actually increased the cooling loads so that the total space conditioning requirements were also substantially increased.

In cold climates like Minneapolis, the use of an attached sunspace, as operated in this analysis, did not contribute much to the reduction of the space conditioning loads (1-2% reduction). Since the inhabitable area of the base house has been substantially increased by the addition of the sunspace (96 $ft^2$ or 192 $ft^2$ depending on the design), we should in this instance consider the energy savings in Btu/$ft^2$ of usable area. This will show a greater decrease on a percentage basis and may, in fact, be more appropriate than absolute savings.

We found in this analysis that, at a minimum, a sunspace was able to heat itself in all climates studied and with proper design and operation contributed to the heating requirements of the house to which it was attached. Since we did not let the sunspace temperature drop below 45°F, the sunspace becomes a usable addition only during the day. Doing this allows even in cold climates a modest decrease in total house energy use and provides a partially conditioned space. It becomes important to consider how usable that space is, i.e., the number of hours during the day (and which hours) the homeowner would be able to live in the space without paying any heating bill for it. In other words, an attached sunspace has more value to the homeowner as a "live-in" device rather than only as a "heating device.

TABLE 1. CITIES AND FOUNDATION TYPES MODELLED.

Albuquerque (slab)
Atlanta (slab)
Chicago (basement)
Denver (basement)
Lake Charles (slab)
Miami (slab)
Minneapolis (basement)
New York (basement)
Phoenix (slab)
San Francisco (slab)
Seattle (basement)

TABLE 2. THERMAL INTEGRITIES AND FOUNDATION TYPES.

Slab Foundation

| Loose | Medium | Tight |
|---|---|---|
| R-19 Ceiling | R-19 Ceiling | R-30 Ceiling |
| R-11 Wall | R-11 Wall | R-19 Wall |
| No Fnd. insul. | R-5(2 ft) slab | R-5 (2 ft) slab |
| 0.7ach infltr. | 0.7ach infltr. | 0.4ach infltr. |
| Single glazing | Double glazing | Double glazing |

Basement Foundation

| Loose | Medium | Tight |
|---|---|---|
| R-19 Ceiling | R-30 Ceiling | R-38 Ceiling |
| R-11 Wall | R-11 Wall | R-19 Wall |
| R-5(4ft) Bsmt wall | R-5(8ft) Bsmt wall | R-10(8ft) Bsmt wall |
| 0.7ach infltr. | 0.7ach infltr. | 0.7ach infltr. |
| Single glazing | Double glazing | Triple glazing |

TABLE 3. SUNSPACE SENSITIVITY RESULTS (NET CHANGES IN TOTAL SPACE CONDITIONING LOAD).

| Location/ Option | OP12 (ΔmmBtu) | OP24 (ΔmmBtu) | GL12 (ΔmmBtu) | GL24 (ΔmmBtu) |
|---|---|---|---|---|
| Albuquerque | | | | |
| Loose | -3.76 | -6.63 | -5.70 | -9.41 |
| Medium | -2.57 | -4.56 | -3.97 | -6.45 |
| Tight | -1.98 | -3.00 | -2.86 | -4.34 |
| Atlanta | | | | |
| Loose | -1.81 | -3.30 | -3.00 | -4.62 |
| Medium | -1.01 | -1.93 | -1.64 | -2.51 |
| Chicago | | | | |
| Loose | -1.26 | -2.68 | -2.53 | -4.44 |
| Medium | -0.56 | -1.32 | -1.50 | -2.51 |
| Tight | -0.07 | -0.27 | -0.67 | -0.97 |
| Denver | | | | |
| Loose | -2.28 | -4.51 | -4.57 | -7.90 |
| Medium | -1.52 | -3.05 | -3.31 | -5.67 |
| Tight | -0.99 | -1.89 | -2.38 | -3.87 |
| Lake Charles | | | | |
| Loose | -1.40 | -2.42 | -2.16 | -2.81 |
| Medium | -0.83 | -1.47 | -0.91 | -1.21 |
| Miami | | | | |
| Loose | -0.06 | -0.09 | +0.27 | +0.77 |
| Medium | -0.06 | -0.09 | +0.31 | +0.81 |
| Minneapolis | | | | |
| Loose | -0.77 | -2.02 | -1.25 | -2.29 |
| Medium | -0.03 | -0.44 | -0.11 | -0.05 |
| Tight | -0.58 | -0.69 | -0.29 | +1.68 |
| New York | | | | |
| Loose | -1.47 | -3.03 | -3.04 | -5.19 |
| Medium | -0.85 | -1.83 | -2.04 | -3.48 |
| Tight | -0.44 | -0.93 | -1.16 | -1.98 |
| Phoenix | | | | |
| Loose | -1.55 | -2.66 | -2.27 | -3.26 |
| Medium | -0.92 | -1.62 | -1.14 | -1.66 |
| San Francisco | | | | |
| Loose | -2.67 | -4.72 | -5.62 | -8.94 |
| Medium | -1.56 | -2.68 | -3.54 | -5.60 |
| Seattle | | | | |
| Loose | -1.22 | -2.55 | -2.67 | -4.78 |
| Medium | -0.57 | -1.29 | -1.67 | -3.01 |
| Tight | -0.11 | -0.34 | -0.96 | -1.60 |

OP 12 = 12 ft. long sunspace with opaque roof
OP 24 = 24 ft. long sunspace with opaque roof
GL 12 = 12 ft. long sunspace with glass roof
GL 24 = 24 ft. long sunspace with glass roof
Loose, medium and tight options defined in Table 2

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0731-8626/83$3.00

# THE OPTIMIZATION OF A COMMERCIAL REFRIGERATION SYSTEM (WITH AMBIENT COOLING, ICE STORAGE AND SUPERINSULATION)

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## ABSTRACT

The proposed system will utilize winter climate as an annual source of cooling by taking advantage of natural ambient temperatures to freeze ice as a source for cooling. A passive freon heat pipe and ice storage system will provide the necessary cooling for refrigeration. The Refrigeration/Economic Loads Optimization Program, or RELOP, explores the various proportions of ice storage and superinsulation to discover the economically-optimized combinations of the two.

## 1. ASSESSMENT OF CLIMATIC RESOURCES FOR PLATTSBURG, N.Y. (44°N. LAT.)

Two direct climatic resources are available: ambient air temperature and effective sky temperature. Indirect climatic resources that could be used with a heat pump include soil and ground water. Wind and evaporation can also be utilized to lower temperatures. However, only ambient air temperature will be discussed in the following pages.

Graph A topographically illustrates the distribution of temperatures for Plattsburg over a twelve-month period. Approximately one-third of all hours during this period have temperatures below 32°F., with the capability for freezing the ice needed for this project. The greatest number of cooling degree days occur in January, as well as the greatest distribution of temperatures below freezing.

Graph B shows the amount of degree days within various temperature bins. The two curves presented describe both refrigeration and space conditioning. 1500 degree days are available for ambient refrigeration, as shown in the lower left-hand corner of the graph. Since the average temperature for the ambient refrigeration season in Plattsburg is 18.3°F, this means that freezers as well as refrigerators can take advantage of this climatic resource.

## 2. POTENTIAL CLIMATIC LOADS FOR BUILDINGS WITH REFRIGERATION

In Figure 1, it is shown that the largest number of degree days occur between the cooler and the conditioned space, suggesting to the designer the benefit in building walk-in coolers exposed more towards the outdoors in climates similar to Plattsburg. The annual difference in cooling degree days between air and soil temperatures is slight, even though air has higher peak demands during the summer.

In this study, the refrigerator and the ice storage container are horizontally connected and both are surrounded by a conditioned air space at 72°F. They are connected to the outside air by an ambient cooling system which is sized to meet all the ice and cooler loads during the annual hours below 32°F, while continuing to freeze the ice. This study assumes an ideal system for loads optimization.

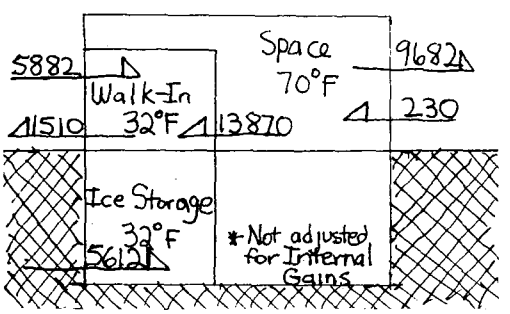



Fig. 1. Building with Refrigeration, Plattsburg.

## 3. REFRIGERATION/ECONOMIC LOADS OPTIMIZATION PROGRAM- RELOP

The purpose of the RELOP Program is to economically optimize the major loads component of the passive/hybrid refrigeration system; that is, the amount of ice vs. the amount of insulation on the ice storage and the cooler.

This process involves parametric analysis of thermal performance, installation costs, and life cycle costs and savings. Insulation thickness is increased incrementally from one to twelve inches by 1" increments. At the same time, ice volume is varied from no ice at all to five times the cooler volume. There are ten increments of 50% the cooler volume each. Until the ice volume exceeds the cooler volume, it expands out from the cooler/ice storage common wall. Once the ice volume exceeds the cooler volume, the ice expands as a cube, exceeding the wall's boundaries.

The program has four types of input variables. First, there are economic variables which estimate life cycle costs or life cycle savings. Second, component costs include incremental costs such as insulation and ice storage as well as fixed costs such as ambient cooling systems costs and electric energy costs. Third, walk-in cooler dimensions are important in determining the thermal loads of the cooler and ice storage, and they also determine the maximum limits of the ice volume.The final type of input variable is the thermal parameters. These include the type of insulation being used, ambient cooling degree hours, hours with cooling needs, winter and summer thermostat settings, air change rates , amount of food to be stored and the incoming food temperatures. (See Appendix 1 for the variables used in this study.)

The program uses ASHRAE refrigeration loads calculations including food loads, infiltration loads, and conduction loads. The ice storage includes latent heat capacity as well as sensible capacity for ice and water in reducing summer cooling loads. The program has summer and winter thermostat settings which determine loads to the inside of a store. Other options include night set-back or connection to the outside air in the summer if the store has no cooling system.

The economic model calculates both net benefit analysis and total life cycle costs. Included in the economic analysis are present values of the energy costs or savings,& the installation costs. An investment tax credit, tax deductions for interest, depreciation and energy costs are included in determining energy and installation present values.

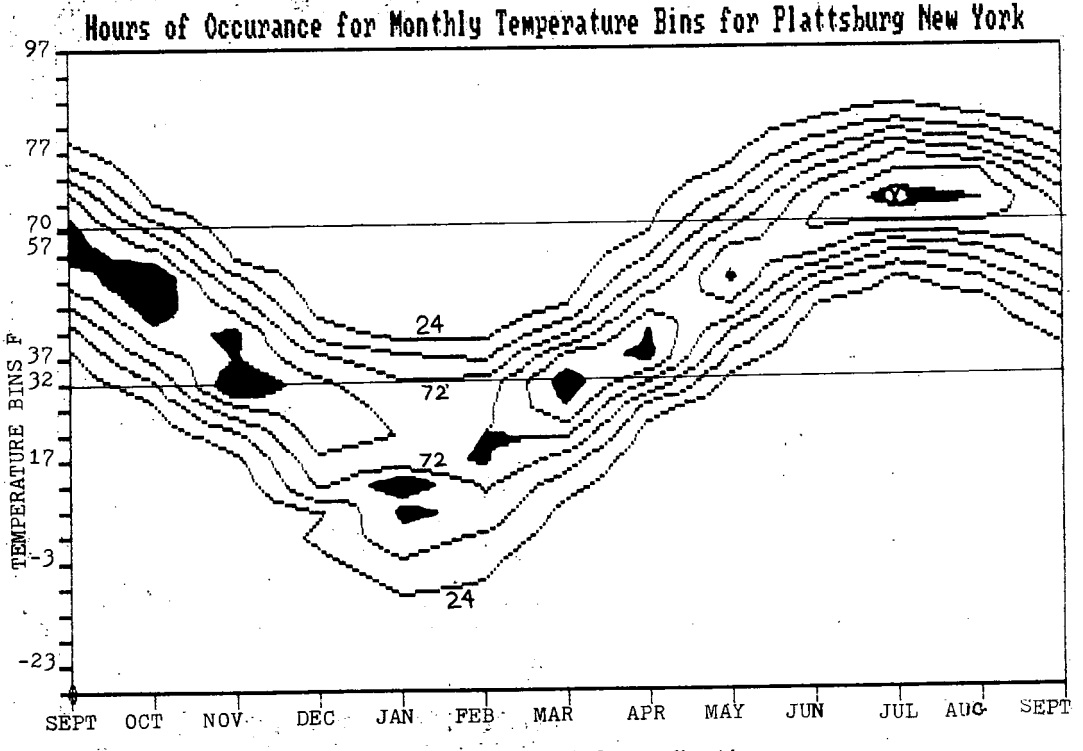
## 4. COMPARISON OF ENERGY-SAVING OPTIONS

There are three economic bases used for net benefit analysis. ECOBASE 1 assumes ambient cooling has already been installed and analyzes the savings and costs of ice only, for given insulation levels (the insulation base case shifts with the insulation thickness of the test case in ECOBASE 1 and 2) ( See Contour Plot 1). ECOBASE 2 examines the effect of ambient cooling alone when ice volume is at zero, as well as the combined effects of ice and ambient cooling for a given insulation level. This allows one to evaluate the energy savings of ambient cooling only compared to increments of ice ( See Contour 2). (The base case is not presented in the plots of ECOBASE 2 and 3). ECOBASE 3 compares the energy savings of insulation, ice and ambient cooling to a two-inch insulation thickness of a cooler without ambient cooling. In this manner one can examine the designs which create the same savings for different combinations of ambient cooling, insulation and ice (See Contour Plot 3).

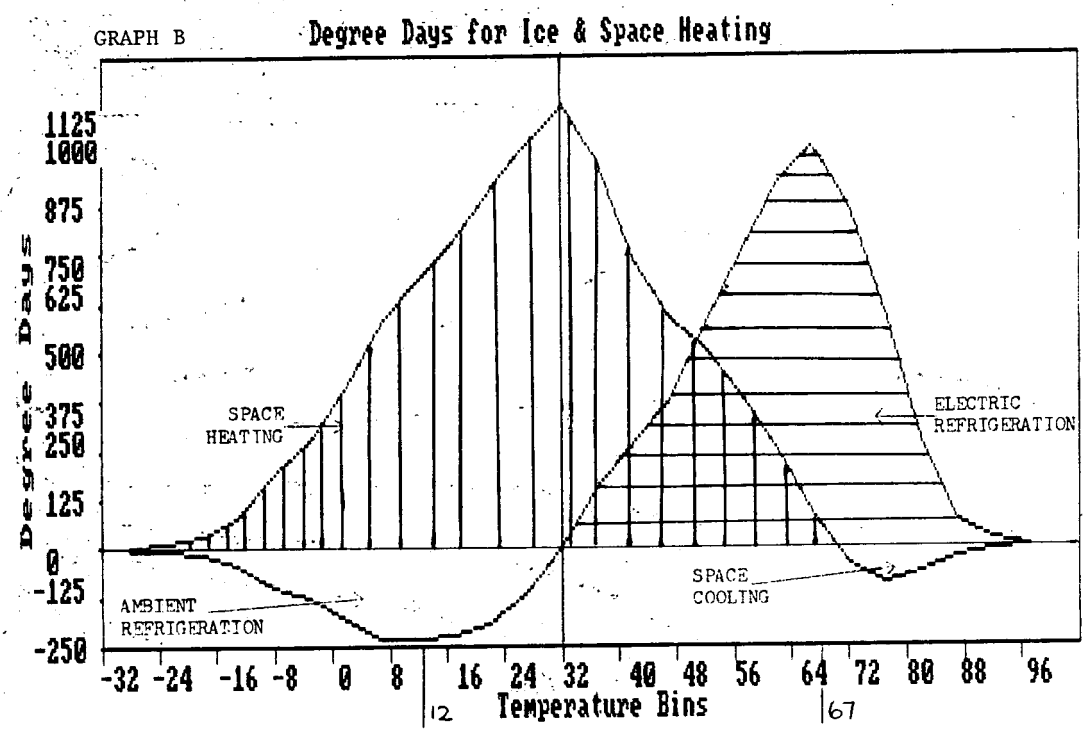
Contour plot 4 shows total life cycle costs (not savings) for the test system configuration. In this case the lowest costs represent the best design.

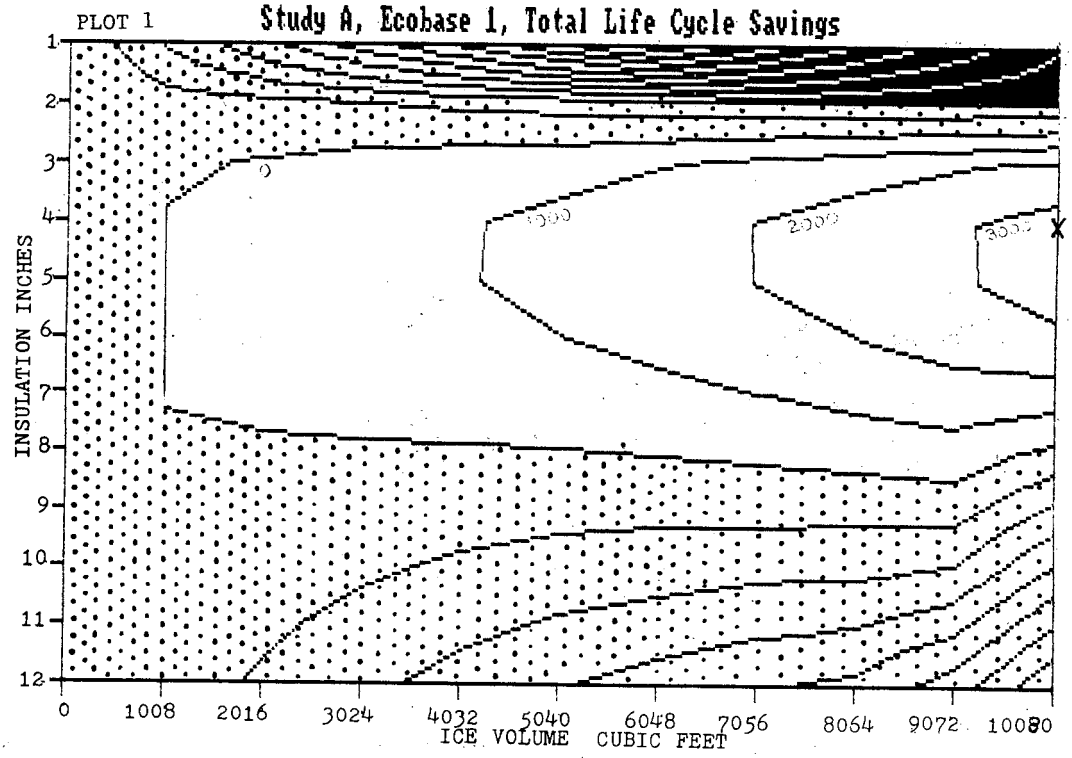
ECOBASE 1 and 2 exhibit similar patterns due to the fact that their savings are contingent upon the amount of insulation being considered. The magnitude of ECOBASE 2 is greater because it takes credit for winter ambient cooling. It also demonstrates that savings due just to ambient cooling for low insulation levels are comparable to savings due to high ice volumes and medium insulation levels. ECOBASE 3's savings pattern is more horizontal, showing the savings to insulation by itself. The total life cycle savings cost plot widens the acceptable range of insulation thickness for near optimum amounts of ice.

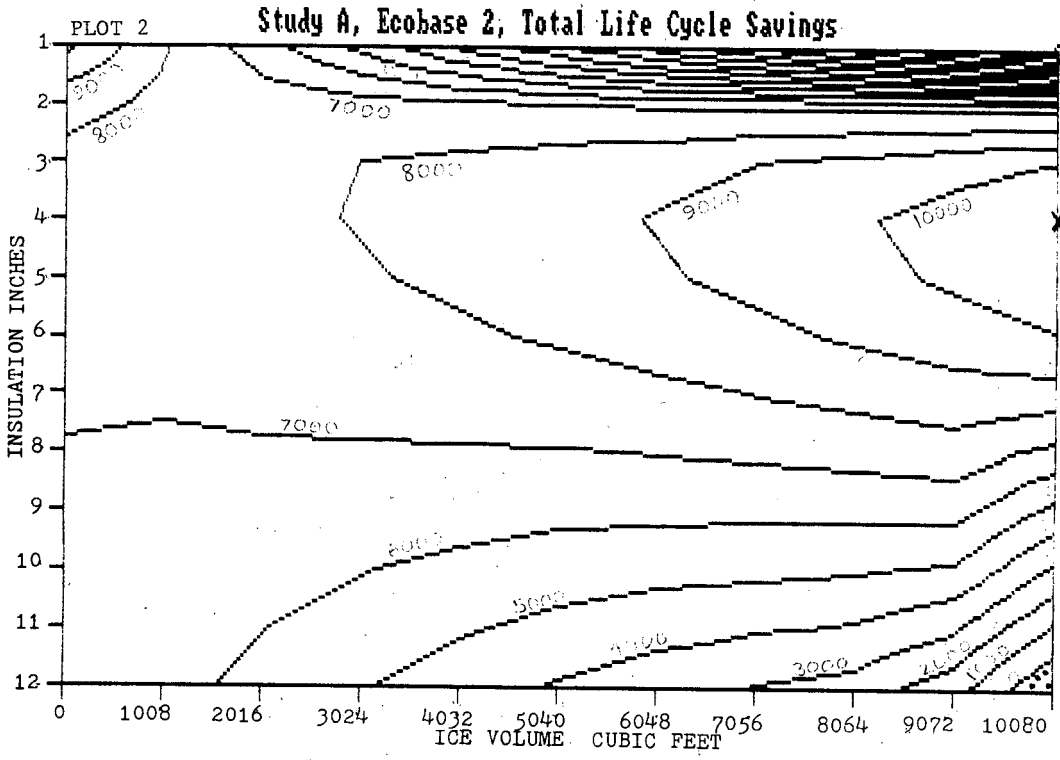
GRAPH A

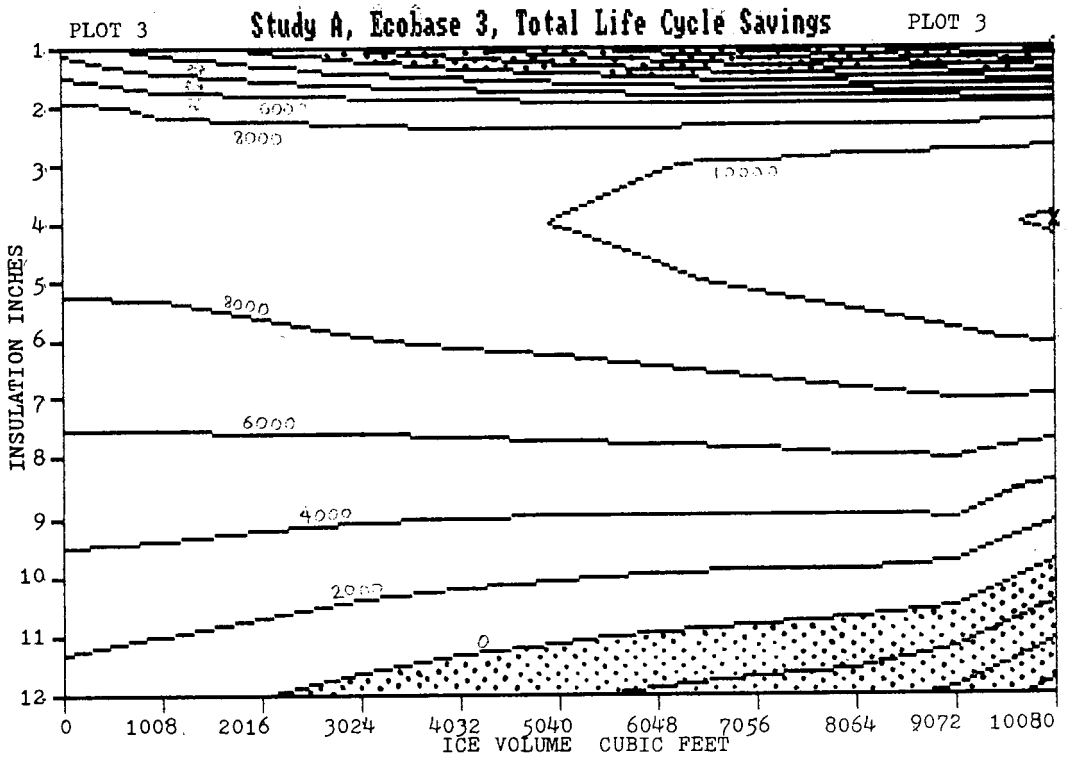


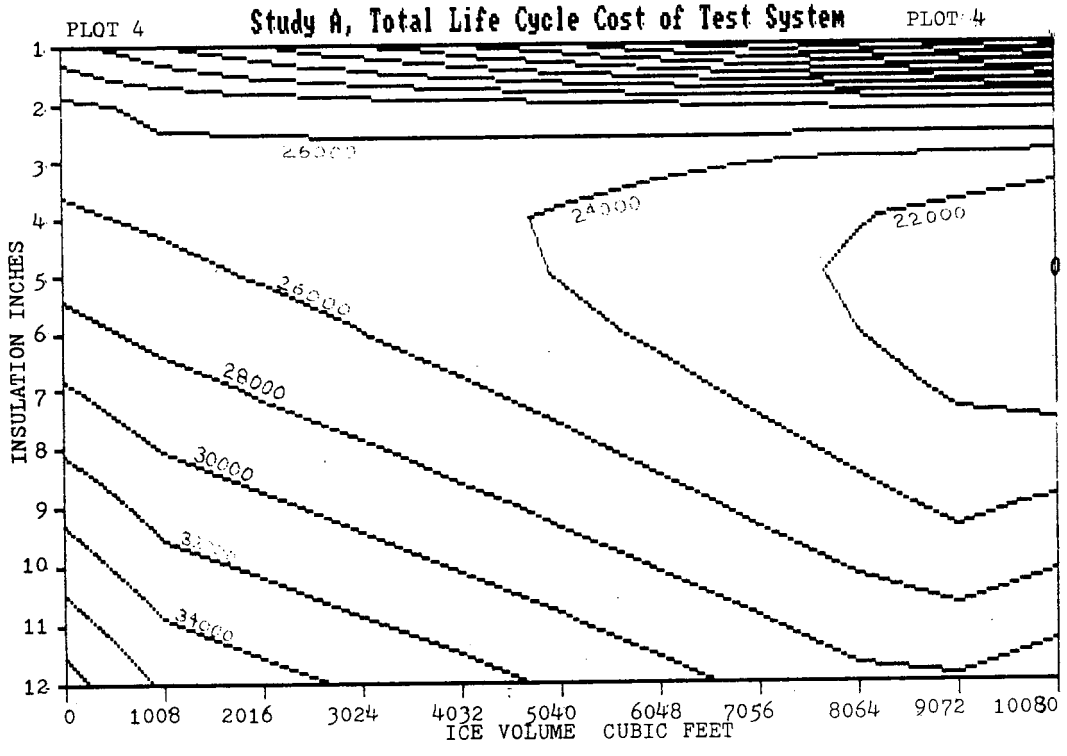

GRAPH B




PLOT 1
Study A, Ecobase 1, Total Life Cycle Savings
INSULATION INCHES
1
2
3
4
5
6
7
8
9
10
11
12
0
1008
2016
3024
4032
5040
6048
7056
8064
9072
10080
ICE VOLUME CUBIC FEET
0
1000
2000
3000


PLOT 2
Study A, Ecobase 2, Total Life Cycle Savings
INSULATION INCHES
1
2
3
4
5
6
7
8
9
10
11
12
0
1008
2016
3024
4032
5040
6048
7056
8064
9072
10080
ICE VOLUME CUBIC FEET
7000
8000
9000
10000
3000


PLOT 3
Study A, Ecobase 3, Total Life Cycle Savings
PLOT 3
INSULATION INCHES
ICE VOLUME CUBIC FEET
0
1008
2016
3024
4032
5040
6048
7056
8064
9072
10080
1
2
3
4
5
6
7
8
9
10
11
12
8000
12000
3000
6000
4000
2000
0


PLOT 4
Study A, Total Life Cycle Cost of Test System
PLOT 4
INSULATION INCHES
ICE VOLUME CUBIC FEET
0
1008
2016
3024
4032
5040
6048
7056
8064
9072
10080
1
2
3
4
5
6
7
8
9
10
11
12
26000
24000
22000
28000
30000
34000

This is because each design is examined separately without being related to any base case insulation.

5. APPENDIX 1

| | | |
|---|---|---|
| ECONOMIC VARIABLES ========== | | |
| ecobase case 1-ice,2-ice&sub,3ice&sub&insul | 1 | |
| period of analysis ---------- | 10 | |
| discount rate ---------- | .0286 | |
| fuel escalation rate ---------- | .1143 | |
| % REAL depreciation by end ---------- | .7 | |
| If Financed Interest rate, Loan Term----- | 0 | 0 |
| COMPONENT COSTS ========== | | |
| base sub-cooling cost ---------- | 1000 | |
| unit cost of insulation $/in sq ft cool,ice | 2 | 1 |
| unit cost of ice stucture in $/sq ft------- | 3 | |
| unit cost of energy in $/kWH---------- | .08 | |
| WALK-IN DEMENSIONS ========== | | |
| height of cooler in ft---------- | 7 | |
| width of cooler in ft---------- | 24 | |
| depth of cooler in ft---------- | 12 | |
| ice container attached to cooler?1=yes,0=no | 1 | |
| THERMAL VARIABLES========== | | |
| R-value of insulation in R-units/in-------- | 7 | |
| hours with cooling needs, sensible deg-hrs- | 6176 | 36254 |
| winter tset , summer tset | 68 | 72 |
| air changes/hour---------- | .7 | |
| food mass /week---------- | 2000 | |
| food temp, refrigeration temp---------- | 55 | 35 |

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0731-8626/83$3.00

# THE WALL REPORT
# A "VALUE INSULATION" APPROACH TO DETERMINING THE COST EFFECTIVENESS OF RESIDENTIAL WALL CONSTRUCTION

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## ABSTRACT

This paper addresses many of the misconceptions associated with superinsulated walls and proposes a "value insulation" approach for determining the cost effectiveness of residential wall systems. The thesis of the paper is that homeowners, builders, and architects often do not clearly understand the benefits and total real costs of superinsulated wall construction. It becomes necessary therefore, to point out that "superinsulation" is not always "value insulation".

"The Wall Report" was prepared by Miami University's Department of Architecture, in Oxford, Ohio. It provides some necessary background information on superinsulated construction, and a simplified worksheet procedure to analyze the cost effectiveness of various wall systems. Through the descriptions given for different wall framing approaches and the use of the worksheets, the most appropriate type of construction and the proper amount of insulation can easily be determined.

## 1. INTRODUCTION

Insulation is one of the best selling, energy saving products on the market today. The main reason for the demand on insulation is the promise of lower fuel bills; but, the actual dollar savings from increasing insulation levels must be looked at closely. The savings depends on many factors, such as the cost of heating fuel, the climate, and the cost of adding insulation. This last factor is often the most difficult to determine, especially when adding greater amounts of insulation will require changes to normal construction practices. While it is true that increasing insulation levels in walls will reduce heat loss and heating bills, the money spent on insulation will not always repay itself in a reasonable period of time.

## 2. SUPERINSULATED WALL EXAMPLE

Many superinsulated walls which have been built in the last few years fall into what could be called a "slow payback" category. Even though they have gained some prominence in Canada,[1] a closer look at the construction costs involved leaves some doubts as to their true cost effectiveness, particularly in U.S. climates. The student researchers on this project began their study by looking at existing examples of superinsulated wall construction. We found that essentially, there are two procedures which have been followed for superinsulating walls. One method is to add rigid board insulation to the outside of the wall studs (see Figure 3, Wall Section #2). The other approach is a double-stud construction method, like that found in the Saskatchewan Conservation House in Regina, Saskatchewan, Canada.[2] This house was designed primarily as a public demonstration of the energy savings possible in residential construction.[3] The major energy conserving features of the house include:

- insulation levels in the ceiling, walls, and floor that are approximately three times the standards in Canada;
- caulked and sealed vapor barriers coupled with a unique air-to-air heat exchanger;

-southern orientation of most of the windows;

-a wastewater heat exchanger that recovers heat from laundry and bath water; and

-an active solar system, with 17.8 square meters (192 square feet) of vacuum tube collectors and a 12,700 liter water storage tank.

The wall construction used in the Saskatchewan house is shown in Figure 1.

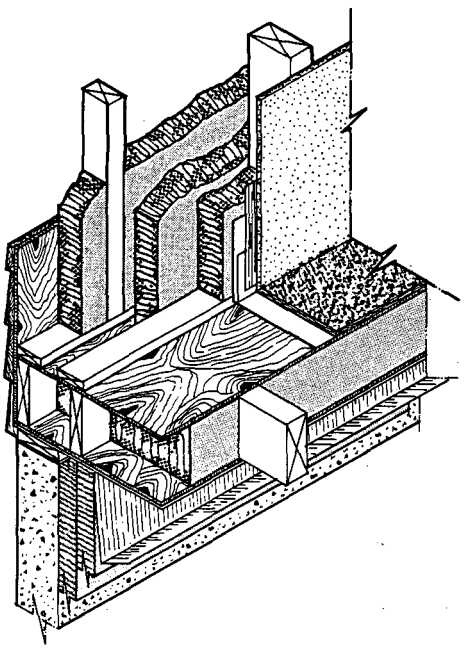


FIG. 1

Two 3-1/2" wood frame walls were built and erected at the exterior wall line of the house. A space was left between the inner and outer walls making a total wall thickness of 12". The double walls and the space allow for three layers of batt insulation.

The actual costs for the Saskatchewan house do not fairly represent the cost that can be expected for this type of construction. The house was built as a demonstration on a cost-plus contract. Final costs included the additional expense of changes that were made to refine construction procedures, and learning costs. It was estimated[4] that a residence with a 100-square meter floor area and unfinished basement can be constructed to the same conservation standards for less than $4000 above standard construction costs. The cost for labor in vicinities not familiar with superinsulation, however, must still be taken into account.

One of the least understood aspects of superinsulated wall construction is the cost of the building square footage lost due to the wall thickness. In the Saskatchewan house, the 12" walls represent a nominal 8" increase in wall thickness or conversely a loss of .67 feet of floor area for each linear foot of wall. Since the perimeter of the house is about 130 ft. per floor, a total of 175 square feet of useful living space is consumed by wall construction. This is roughly equal to a 12 ft. by 15 ft. room. If the home owner does not wish to reduce the sizes of each of the exterior rooms, then the total size of the house must be increased by an amount equal to the difference in wall thickness. With an average cost for residential construction between $40 and $50 per square foot, the total cost of the house will be increased by $7000 to $8750.

The conclusions that can be drawn from the Saskatchewan example and those that will help determine the overall cost effectiveness of any superinsulated home should include the fact that labor costs will always be hard to figure, but may go up as much as double those of a typical 2 x 4 stud wall. Also, the cost of space lost to double wall construction and the payback in climates with fewer degree days (Regina is approximately 11,000 DD fahrenheit) must be remembered when figuring overall cost effectiveness.

## 3. WALL DESIGNS

Following our initial review of existing superinsulated buildings, we chose several superinsulated wall designs for further analysis. These walls were compared to a typical 2 x 4 stud wall for their general cost effectiveness, in climates like those found in the United States. With the assistance of local contractors, we identified many of the construction problems in superinsulated walls that are often overlooked when figuring overall costs. A simplified procedure to determine the energy savings for these walls was also developed and

will be discussed later.

The four basic approaches to increasing wall insulation that were studied are shown in Figure 2 through 5. The strategies for adding insulation include increasing the width of the walls studs; adding rigid insulation on the outside; double wall construction with batt insulation; double wall construction with rigid insulation. From a construction standpoint, each of these walls has its advantages and disadvantages.

Wall #1 (Figure 2) is superinsulated by increasing the width of the wall studs and adding insulation. While it is easy enough to find pre-cut 2 x 4 or 2 x 6 studs, when the dimensions increase to 2 x 8 or 2 x 10, they have to be cut on site and are more difficult to handle. This obviously increases labor costs. The added width of the studs will decrease the floor area of the residence as well.

It is often thought the studs will significantly reduce the effectiveness of this wall since there is a complete break in the insulation at this point in the wall. Softwood lumber, however, has a resistance of 1.25 per inch. In a 2 x 8 wall, for example, the total R-value through the stud is 9.37 or two-thirds of the R-value of the insulated portion of a 2 x 4 wall.

Wall #2 (Figure 3) doesn't decrease floor area since the rigid insulation is added on the outside and can be cantilevered past the wall line. Also, rigid insulation typically has a higher R-value (R 4-6 per inch) in comparison to batt insulation (R 3-4 per inch). Since typical wall framing is used, labor is simpler. The problems associated with rigid insulation are related to how many inches are being added to the wall studs. Longer and thicker nails are often required to join the insulation and siding to the studs. This can result in cracks in the siding, particularly at the thin top edge of bevel siding. Also, with the thicker rigid insulation (1-1/2" or greater), a brace must be used at the corners so the house will withstand the wind load. These braces consist of diagonal steel straps.

Moisture is a major issue when rigid insulation is placed on the outside of the wall. The closed cell rigid insulation boards have a low water permeability and in effect act as a second vapor barrier. Just as heat flows from the inside to the outside of the wall when it is cold outside, water vapor in the air tends to migrate from the high pressure warm interior space to the low pressure cold outside air. This movement of microscopic amounts of moisture is stopped by the rigid insulation and condenses at this point in the wall. The result is long term deterioration of the 2 x 4 studs and of the 2 x 4 bottom plate to the wall. Although the use of a vapor barrier on the inside of the wall significantly reduces the deterioration process, it does not eliminate it.

A more subtle problem associated with moisture in this wall type has to do with moisture build up between the outside of the rigid insulation and the wood siding. Standard asphalt sheathing is porous and allows water vapor to pass through it in both directions. At times when humidity is high outside, or during a heavy rain, the siding will take on some moisture and will in turn transmit small amounts of moisture to the sheathing where it is absorbed. As the humidity level outside decreases, the process is slowly reversed. The sheathing gives up its moisture to the siding where it is given off through surface evaporation to the air. A potential problem results on a day when a heavy rain is followed by bright sunshine on the wall. In the typical wall, the sheathing acts as a wick to slow the drying process for the siding and in doing so, protects it from warping. In the case of the rigid insulation wall, the siding will reach a higher moisture level during the period of rain and will tend to dry out faster. Under these conditions, differences in drying rates can cause cracking.

Redwood siding suppliers suggest a framing method that allows ventilation between the siding and insulation. An air space is left at the top, bottom, and behind the rigid board insulation to allow for an air flow to remove any moisture (see Figure 4).

In Wall #3, a double wall insulation method is used as in the Saskatchewan House. Greater R-values can be achieved with this method of construction simply by increasing the space and batt insulation between the two walls. It also does not have the moisture and construction problems noted in wall #2. Yet more floor area is taken up by this construction method, and by

constructing two frame walls, labor and material costs will rise.

Wall #4 (Figure 5) is the same as wall #3 in most respects, except that is has less floor area taken up by the wall framing, and will have higher R-values since rigid board insulation is being used. The moisture problems associated with wall #2 are not as common here either, since the rigid insulation is closer to the inside wall. The labor and material costs will be high since two frame walls are still being constructed.

## 4. WALL REPORT PROCEDURE

The procedure devised for "The Wall Report" is based on several superinsulated walls like those described above. The construction section for each wall is laid out graphically on a separate page of the report with a chart listing the labor factor and the U-values for a particular wall. These U-values take into account all the building materials in the section and vary only with the amount of insulation being used. The wall cost factor is related to a base case wall construction (2 x 4 insulated stud wall) and can be applied to the actual base wall costs in any given region.

To compare the cost effectiveness of two walls, the insulation thickness is first selected for each wall. The desired thickness is indicated by the X dimension, which is actually the thickness of the portion of the insulation that will vary. Wall #1 is the only wall shown in which the X dimension also represents the total insulation thickness.
If rigid insulation is being varied, the next step is to choose the R-value of the insulation that is being specified. By knowing the X dimension and the R-value (for rigid insulation) the total U-value can be found in the corresponding right hand columns of each wall chart. In wall #2, for example, 2" of rigid insulation at R-4 per inch will result in a total U-value for the total wall of .049. A worksheet is supplied in the wall report that uses pre-multiplied fuel-climate cost factors[5] to simplify the calculation of annual heating costs.

## 5. CONCLUSIONS

Overall, we have tried to devise a simplified approach for looking at superinsulation costs so that homeowners, builders, and architects can more easily define the areas where costs can be controlled during construction and if the superinsulated house is actually feasible for their particular environment.

## 6. ACKNOWLEDGEMENTS

Best Panel Homes, Ross, Ohio.

## 7. REFERENCES

[1] Meyer, Jane, and Craig Sieben, "Super Saskatoon", Solar Age, (January 1982), p. 26-32.

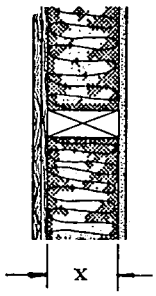
[2] Robert W. Besant, Robert S. Dumont, and Greg Schoenau, "100 Percent Solar in a Severe Climate," Solar Age, (May 1979), p. 18.

[3] Ibid., p. 18.

[4] Ibid., p. 21.

[5] "The Overselling of Insulation," Consumer Reports, (February 1978), p. 72.

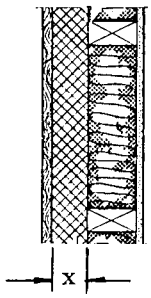
Plan
Section




| x Dim. | R-value of Insulat. | U-value of Wall |
|---|---|---|
| 3-1/2" | 3.14 | 0.072 |
| 5-1/2" | 3.14 | 0.051 |
| 7-1/2" | 3.14 | 0.039 |
| 9-1/2" | 3.14 | 0.032 |

Fig. 2. Wall #1.

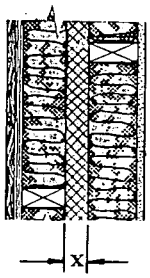
Plan
Section




| x Dim. | R-value of Insulat. | U-value of Wall |
|---|---|---|
| 1" | 2 | 0.069 |
| | 4 | 0.061 |
| | 6 | 0.054 |
| 2" | 2 | 0.061 |
| | 4 | 0.049 |
| | 6 | 0.041 |
| 3" | 2 | 0.054 |
| | 4 | 0.041 |
| | 6 | 0.033 |

Fig. 3. Wall #2.

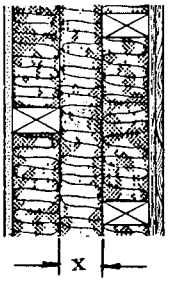
Plan
Section




| x Dim. | R-value of Insulat. | U-value of Wall |
|---|---|---|
| 2" | 2 | 0.035 |
| | 4 | 0.031 |
| | 6 | 0.028 |
| 4" | 2 | 0.031 |
| | 4 | 0.025 |
| | 6 | 0.021 |

Fig. 4. Wall #3.

Plan
Section




| x Dim. | R-value of Insulat. | U-value of Wall |
|---|---|---|
| 2.75" | 3.14 | 0.032 |
| 3.50" | 3.14 | 0.028 |
| 6.50" | 3.14 | 0.023 |
| 7.00" | 3.14 | 0.022 |

Fig. 5. Wall #4.

Notes: (1) For batt insulation, an R-value of 3.14 per in. was used.
(2) For rigid insulation, R-values vary.

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# AN INTEGRATED PHASE CHANGE HEATING AND COOLING SYSTEM FOR RETROFIT AND NEW CONSTRUCTION

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## ABSTRACT

This paper discusses the performance characteristics and retrofit potential of a promising new method of utilizing phase change material (PCM) for heating and cooling of structures. A commercially available phase change salt compound with a phase change temperature of 22.8°C (73°F) is used. The PCM is located within the building structure itself (floors and ceilings) and can be either actively or passively charged. Discharge can also be either passive through radiation and natural convection or active by using fan forced airflow. The system is capable of providing summer cooling operation as well as winter heating operation. General performance characteristics are discussed with respect to various methods of integrating the system into building design. Methods of integrating this system into retrofit and new construction is developed along with a discussion of active/passive charging options and passive distribution methods. Design variations and construction details are also presented.

## 1. INTRODUCTION

Due to their high thermal storage capabilities in lightweight, compact packages, PCMs offer the potential to store heat or "coolth" in buildings in many innovative ways. A well known application of the very same phase change material discussed here has been used successfully in the M.I.T. Solar 5 buildings ceiling tiles in conjunction with reflecting louvers that direct the sunlight to the ceiling surface.[1] The particular method discussed here addresses the issue of using floor and/or ceiling joist space placement of multi-ply flexible PCM filled pouches. The advantage of this technique is that the material is well integrated with the structure in what is otherwise a little used space. Also this space between floor or ceiling joists allows passive distribution of heat or "coolth" upward at floors, downward at ceilings, or both. The PCM may be placed in the floor for optimum heating potential or in the ceiling for optimum cooling potential, the choice being a function of the annual heating and cooling loads. Flow of air in the joist spaces across the PCM pouches is sometimes needed to charge (or discharge) the material. To date, this technique has been utilized in three prototype installations in California. The first and third such installation are outfitted with temperature sensors in all critical areas to aid in the evaluation of the system. At the time of this writing however, the control systems and digital temperature readouts are not yet completed. In all of the existing installations, a fan is used for charging the PCM. There are, however, thermosiphon collector arrangements that may be used to passively charge the PCM (see Figures 1-3), whereas discharge is typically passive. Because so many existing homes today have accessible crawl spaces and/or attic spaces which could be retrofitted with PCM to provide thermal storage, this system is well suited to retrofit as well as new construction installations.

## 2. PERFORMANCE CHARACTERISTICS

Table 1 lists the thermal characteristics of the PCM material used. Note the difference between the heat transfer "out" and heat transfer "in" coefficient for this material. In addition, the phase change temperature may be varied from 18.3 to 31.7°C (65 to 89°F),

in which case the storage capacity also varies.

TABLE 1.
THERMAL CHARACTERISTICS OF THE PHASE CHANGE MATERIAL USED[3]

| | |
|---|---|
| Dimensions | 1.9 cm X 0.3 cm X 0.3 cm (3/4 in. X 12 in. X 24 in.) |
| Area | 0.186 $m^2$ (2 $ft^2$) |
| Weight | 4.54 kg (10 lbs) |
| Phase Change Temperature | 22.8 °C (73°F) |
| Latent storage capacity | 369.3 Joules (350 Btu) |
| Heat transfer Coeff. (out) | 9.08 Watt($°C\ m^2$)$^{-1}$ (1.6 Btu(hr $°F\ ft^2$)$^{-1}$) |
| Heat transfer Coeff. (in) | 27.25 Watt($°C\ m^2$)$^{-1}$ (4.8 Btu(hr $°F\ ft^2$)$^{-1}$) |
| Materials of Construction | 3 ply aluminum foil laminate |

Many of the advantages of using this type of heat storage material are due to the properties of the material itself. The heat transfer coefficients for heat transfer "in" and heat transfer "out", which are influenced by the phase change process itself, is one example. If the material starts out in the solid phase and is heated, a film of liquid begins to form on the outside surface of the salt. Because the pouches are 1.9 cm to 2.5 cm (3/4 in. to 1 in.) in thickness, the distance the heat must flow into the material is minimized. As a result, the heat transfer rate is rapid in the liquid state, meaning that melting (or charging) of the material is not difficult. Table 2 lists approximate charging times for the PCM system. The charging times are based on 9.4 liters/sec (20 $ft^3$/min) airflow moving through a net (after PCM placement) joist cross sectional dimension of 20.3 cm by 35.6 cm (8 in. by 14 in.), with the PCM starting at the phase change temperature of 22.8°C (73°F) in the solid phase.

When discharging, the PCM forms a solid crystalline layer on the outside surface of the salt compound, slowing the release of heat and extending the discharge period. Table III lists approximate discharge times for the PCM system. The discharge times are based on passive discharge through 1.9 cm (3/4 in.) plywood, with the PCM starting out in the liquid phase, completely melted.

TABLE 2.
CHARGING TIME REQUIRED FOR PHASE CHANGE STORAGE SYSTEM

| Charging Temperature Celcius | (Fahrenheit) | Charge Time Req. (Hrs) |
|---|---|---|
| 28.3 | (83) | 13.4 |
| 31.1 | (88) | 9.0 |
| 33.9 | (93) | 6.7 |
| 36.7 | (98) | 5.4 |
| 39.4 | (103) | 4.5 |
| 42.2 | (108) | 3.8 |

TABLE 3.
DISCHARGING TIME REQUIRED FOR PHASE CHANGE STORAGE SYSTEM

| Room temperature Celcius | (Fahrenheit) | Discharge Time Req. (hrs) |
|---|---|---|
| 21.1 | (70) | 27.9 |
| 18.3 | (65) | 10.5 |
| 15.6 | (60) | 6.4 |
| 12.8 | (55) | 4.7 |
| 10.0 | (50) | 3.6 |

From these tables, it can be seen that the integration of the PCM into a given structure can be engineered in such a way so as to provide the desired area of PCM to suit the heat loss characteristics, temperature requirements, and other design restrictions of a given building. To this end, a forward differencing thermal network computer program was developed to engineer the first prototype design and to test the sensitivity of the design to changes in system parameters.

By using remote collection, the heat loss rate of the building is not compromised by collector area as is true in most passive systems. As a result, the floor storage area can be sized to provide the heat needed to satisfy the particular design heat loss rate. Once the floor storage size is fixed, the collector may be sized without the concern of collection area heat loss as in other passive systems. Long term heat storage is possible by stacking two or more pouches on top of one another or by using a building with a superinsulated exterior. This system lends itself well to superinsulation, which further increases the effectiveness of this type of storage technique by decreasing the storage required to overcome design heat loss.

As can be seen from Table 2, many heat source temperatures are useable. If a greenhouse is used, the charging time is considerable, and it is suggested that interior stratified heat (solar, woodstove, cooking, lights, etc.) be used to "backup" the greenhouse heat source. Temperatures in excess of 28.3°C (83°F) are typically

available for 13 to 14 hrs per day at the high point of either of these locations. Wall collectors or roof collectors positioned for optimum winter sun offer higher temperatures and less charging time, although they do not provide added living space and may actually cost more. The combination of a DHW preheat plenum and a solar "attic" has the advantage of "killing two birds with one stone". Under some conditions, when optimally charged, heat from the water tanks may even be reclaimed and directed to the PCM area. For a totally passive system, a photovoltaic powered fan may be used for charging.

Because of the 22.8°C (73°F) phase change temperature the pouches may be used to remove heat from a building during the day in the summer, providing relatively cool air in return. Cool night air is blown across the PCM to absorb the previous days heat gain. If located in the ceiling, heat removal is passive, whereas if the PCM is located in the floor a fan must be used to effectively flush heat to and from storage.

With the phase change process taking place at a relatively constant temperature, the temperature difference is maintained aiding heat transfer by keeping a constant delta-T between the storage and heat source (assuming the heat source temperature remains constant). With sensible heat storage, the delta-T diminishes as the storage is charged, thus reducing the heat transfer rate.

## 3. RETROFIT APPLICATIONS

Floor or ceiling installation of phase change pouches offers unique potential for adding thermal storage mass in retrofit applications. The joist spaces are used to pass the flow of low temperature charging air to the PCM. Temperatures in excess of 93.3°C (200°F) are not recommended due to the long term effects of high temperatures on the wood within the joist spaces. Installation in existing buildings with adequate crawlspace or attic access is relatively straightforward. Installation under a floor with limited crawlspace access however, may necessitate removal of the flooring in order to access the joist space. If insulation is present, it must be removed and replaced with rigid insulation below the floor joists in order to form a plenum. Installation in a ceiling may also require similar preparation. Existing solid blocking must be drilled or removed, and if removed, replaced with metal bridging. The warm supply air to the joist spaces is achieved by a feeder duct (header or soffited plenum) which allows air flow to enter and leave each joist space containing PCM pouches.

Passive charging of the joist spaces can be achieved if the elevation plane of the joists is higher than the heat collection area. The solar collection area might be a ground level greenhouse, domestic hot water pre-heat chamber, or thermosiphon air collector. Figures 1-3 offer diagramatic examples some of these different charging options.

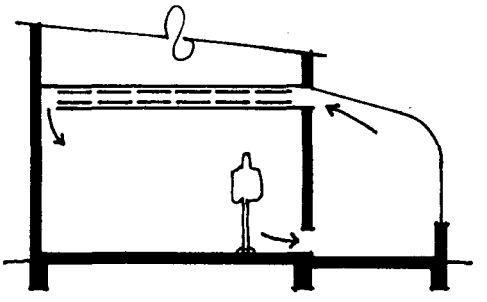


Fig. 1. Greenhouse source.

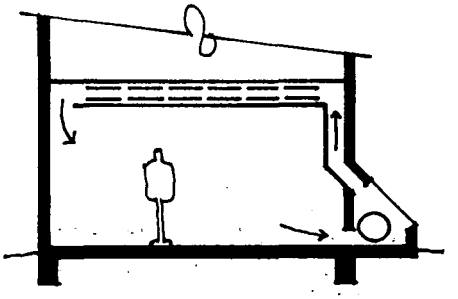


Fig. 2. Preheat chamber source.

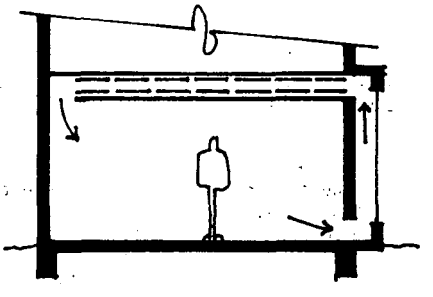


Fig. 3. Wall collector source.

Return air to the collection area can be through return ducting from a return header or by free flow from an interior valence (see Fig. 4), through the interior space, and out a backdraft damper to the collection area. A furred ceiling below an existing ceiling might be feasible in retrofitting older homes with high ceilings. This approach may be used to provide the desired flow direction and minimize demolition. Attic spaces are an excellent opportunity to add PCM above existing ceilings, lending themselves well to applications where cooling is a priority. The PCM is placed above the ceiling material, leaving the joist bay above free for air flow. Rigid insulation is placed over the top of the ceiling joists to establish an airway and thermally isolate the airway from the attic. Floor joists on the other hand, work best in applications where heating is required more often than cooling (see section of this report titled "Installation" for detail).

## 4. NEW CONSTRUCTION APPLICATIONS

New construction applications of PCM pouches in joist spaces offer a wide number of passive, active and/or cooling options. The three new-construction prototype examples built to date have performed well with regard to energy costs and thermal comfort. Probably one of the most important lessons learned in the process of designing and building these systems is to keep them simple. These systems can usually be designed for the same or less cost than comparable performing passive systems. Because owners of such "futuristic" systems often desire lots of "bells and whistles" to complement the space age technology, caution must be used in dealing with this impulse. Many variations on this concept are possible and potentially well suited to both the residential and commercial mass building market. The following is a description of three prototype designs utilizing the joist space PCM system;

### 4.1 (Lake Wildwood Residence, California) Active Air Collector

Charging of the PCM storage in the joist space is done by a double pass air collector or the auxiliary heating and cooling system (a heat pump). The system is designed to allow transfer of heat to storage, directly into the interior, or to domestic hot water via a heat exchanger. Cathedral type ceilings prevented roof installation, so the PCM is installed in the ceiling of the first level and floor of the second level. The entire system requires a central control system (yet to be completed) to automatically monitor temperatures and control air flow via fans and automatic dampers.

### 4.2 (Super House, Nevada City, California) - Vertical South Window Collection

Warm air from high in the three story interior space is fan forced through a 4-inch vertical window collector space into a duct leading to a joist "supply" header along the north perimeter. The window collector is made up of a double glazed exterior window, an interior single glazing, and a small metal venetion type blind in between acting as an absorber plate. The joists are insulated from below with rigid insulation and the PCM is placed against the underside of the flooring. After releasing heat to the PCM, the air returns back to the interior through standard floor registers along the south perimeter. The crawlspace perimeter foundation is insulated, and a diverting damper allows cool night air to be drawn through the crawlspace and into the PCM storage area. During the day in the summer, the collector area is totally shaded by surrounding oak trees. Warm air from high in the space is pulled down through the PCM area to be cooled. At night, cool air is circulated through the storage area to remove the days heat gain.

### 4.3 (Wright Residence, Nevada City, California) - Direct Gain Interior Stratified Air/D.H.W. Preheat Chamber

A simple control system consisting of cooling thermostats operates a fan which pulls air from either a stratified air inlet high in the interior space or through a large, double glazed roof top D.H.W. preheat tank enclosure. The 1.2 m X 1.2 m X 6.1 m (4 ft X 4 ft X 20 ft) preheat tank enclosure contains only three forty-gallon preheat tanks, allowing the majority of the collection area to be used to charge the PCM. The PCM storage is located in both high and low in the second floor joist space. A manual switch allows the owner to choose to have stratified heat or preheat tank heat directed to either the storage system or to floor registers located at the lowest portion of the living space. When directed through the storage system, the air exits through a valence (see Figure 4). Air returns to the preheat enclosure through a backdraft damper located on the floor of the preheat tank area. This system makes good use of "extra" heat within a building (direct solar, wood stove, preheat chamber) by placing it into PCM storage for floor ceiling radiant

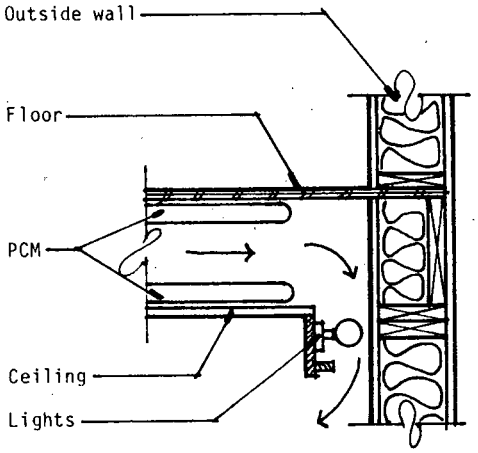



Fig. 4. Lighting valence return detail.

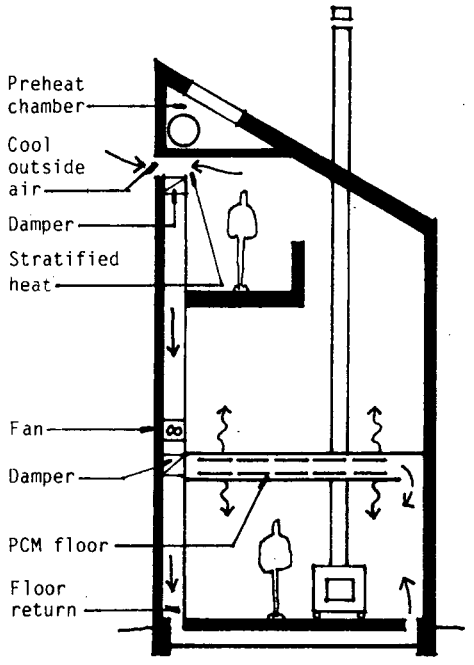



Fig. 5. Wright Residence system schematic.

distribution (see Figure 5). Summer cooling is planned by forcing cool night air through the PCM storage using the same fan and an outside air intake at the loft.

## 5. INSTALLATION

The placement and handling of the PCM pouch is critical. Rigid containers designed for this type of installation will greatly reduce the risk of puncture or abrasion to the PCM containment. Our technique has been to place the 36.8 cm X 61.0 cm X 2.5 cm (14-1/2 in X 24 in X 1 in) multi-laminate pouches into joist spaces after placement of subflooring prior to the installation of insulation or sheet rock. The pouches are heated (in the sun) prior to placement until they melt to assure the bags do not leak and are flat before installation. Ideally the pouches should be in the solid phase when actually installed, due to the fact that the PCM expands to a greater volume because of its crystalline structure in the solid phase. Otherwise, a small gap to allow for expansion and contraction of the material is left between the PCM and the floor unless the support itself allows for the necessary flexing. Care should be taken to assure no splinters, nails or other protrusions exist near the pouches, as during the expansion/contraction process they may work their way through the pouch. We have used two methods of holding the pouches in place.

### 5.1 Sheet Metal Support

Sheet metal pans (24 gauge) are made up by local sheet metal contractors to hold the PCM either against the subfloor at the top of the joist space or at the bottom of the joist space against the ceiling (which is installed after pouch placement) (see Figure 6).

### 5.2 Hardware Cloth Support

Hardware cloth can be cut to suit and is easily nailed through the joists. Roofing nails or staples hold the hardware cloth in place. The advantage of the open hardware cloth is that the air stream has more direct contact with the surface of the pouches, heat transfer is increased due to the increased airstream turbulence caused by the hardware cloth; and the material is less costly than sheet metal. The disadvantage is that hardware cloth has many sharp wires when cut and must be handled and placed carefully to prevent puncture.

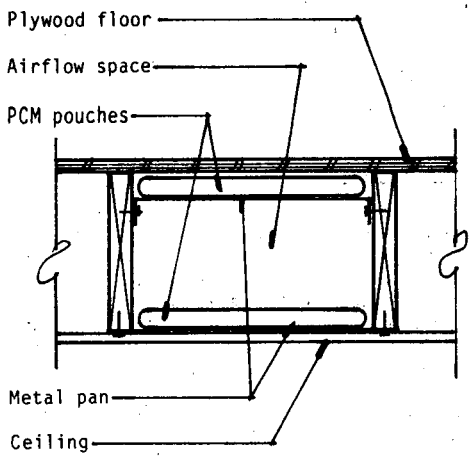



Fig. 6. PCM floor/ceiling detail.

In either case we use a polyethylene "diaper" as an added safety measure should a pouch ever leak. The PCM can be highly corrosive since it is salt substance and will easily corrode any metal support as well as leak through and ruin a ceiling. Care must be exercised to prevent damage by leaking pouches.

## 6. CONCLUSIONS

The flexibility of this application of PCMs to both new and retrofit construction offers another thermal storage opportunity to the building designers ever growing "bag of tricks". It is not meant to be the answer to all problems, however it certainly answers many of them. Because of the high latent heat storage capacities of this type of material, it is possible to store or remove large quantities of heat from within a building. Because of the location possibilities of this method of utilizing PCM, many different charging/discharging options are available as well. The Architectural limitations are reduced in comparison with other passive systems as the storage area is concealed in an otherwise unused space and the heat source location is highly flexible. With so many new companies gearing up to manufacture PCMs[2], we should expect to see many new, innovative, cost-effective phase change storage systems evolve. We are evidencing a growing new technology.

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3) The phase change pouches used are sold by Colloidal Materials Inc., P.O. Box 696, Andover MA 01810.

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# A STATE OF THE ART THERMOSIPHON SYSTEM

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## ABSTRACT

The Mark Jones Corporation's work in developing air thermosiphon systems in Santa Fe has been previously reported in the Fifth and Sixth Passive conferences. The previous papers traced the development of two generations of thermosiphons, the first using rock storage, the second rock plus block storage.

This paper will examine the development and construction of a third generation thermosiphon system built into a relatively expensive custom home. It will focus on the simplified construction techniques of a block bed storage system in which no rocks at all are used for heat storage. An innovative damper door will also be presented.

## 1. INTRODUCTION

Since 1977 this company has been designing and building domestic space heating employing passive thermosiphon collectors and mass storage. Ten systems have been completed as of Spring 1983, each system a modification and simplification of the previous one. Our goal has been to reduce the in place cost of the systems in order to make them a competitive amenity in the speculative housing market. At the same time we have endeavored to keep the systems flexible enough to fit into the complex architectural programs we work with by choice.

These systems employ two major components: Hot air collector and mass storage. The hot air collector is assembled like a stick built home by framing carpenters at a reasonable cost. We have found little reason to modify its basic design. The major cost of our thermosiphon heating systems is the underfloor mass storage.

Placing heavy mass storage materials amidst carefully sized ducts and the structural bearing points and foundations of the house above has required up to 12 man weeks of the hardest kind of labor. We have had the most success at cost cutting by focusing on reducing the labor required to place the mass storage.

Achieving an airtight fit on the damper doors that prevent reverse siphoning in the system has been a sporadic problem with the thermosiphon system. The damper system has been changed on each installation to increase reliability and reduce air leaks.

## 2. HISTORY

Early systems used rock beds remote from living spaces, with heat distribution from the beds by fan forced duct systems. The next step was to design systems where heat transfer to living spaces was by radiation directly from the storage mass to the living space. These later systems are the focus of this paper.

The first generation direct radiation mass system consisted of 6 in. diameter washed river rock contained in underfloor reinforcing mesh cages through which hot air from the collector passed (see Figure 1 and Reference 1). The cages and the river rock were

placed by hand within the perimeter of the house, requiring the aforementioned 12 man weeks labor.

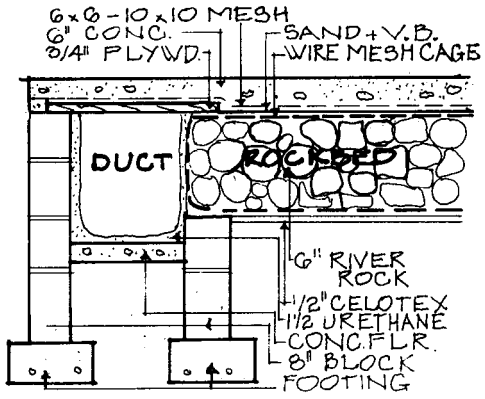



Fig.1. Section through first generation duct and mass storage.

The second generation system (see Fig.2 and Reference #2) replaced half the rock storage with 8 in. concrete blocks. The blocks could be placed two at a time by laborers and rocks were dumped into the beds by a backhoe. The second generation system was considerably less costly to construct than the first and was used in two successful speculative houses in Santa Fe.

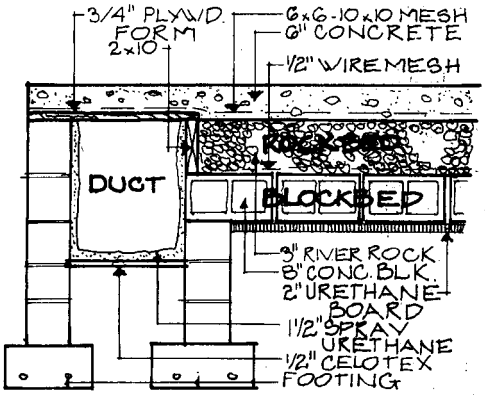



Fig.2. Section through second generation duct and mass storage.

## 3. THE STATE OF THE ART SYSTEM

The third generation system has been used in three houses to date. Two are 2,300 $ft^2$ production homes (see "Medium Density Passive Solar Production Housing" in this publication) and the third, described here, is a 3,000 $ft^2$ custom home.

The 3rd generation system's major innovation is the use of only 12 in. concrete block for mass storage (Fig.3&4), eliminating rock storage altogether. Previous system designs had assumed heated air from the ducts needed to bathe a large surface area of mass (small rocks) in order to transfer heat effectively. Observation of the

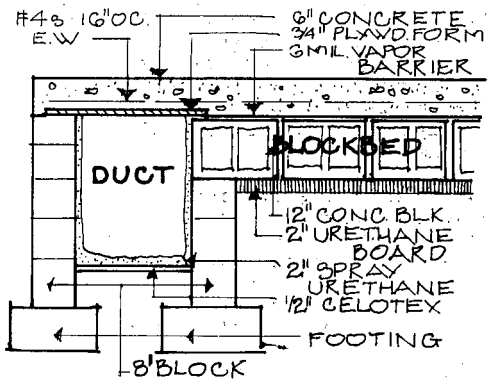



Fig.3. Section through third generation duct and mass storage.

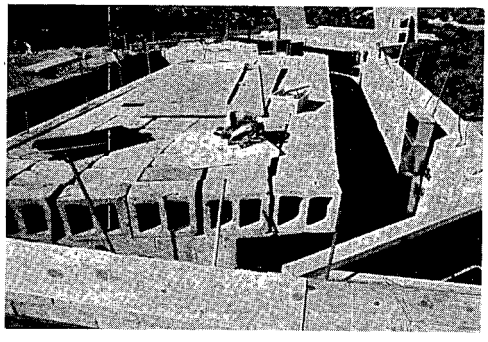


Fig. 4. View of third generation ducts and mass storage.

second generation rock plus block system (See"Performance Evaluation of a Thermosiphon/Blockbed System", by W. Scott Morris in this volume) showed that little air was moving from the block passages into the rock. Instead, effective heat transfer was taking place by conduction from warm air-to-block-to-rock-to-concrete floor. By eliminating rock altogether, installation labor was greatly reduced, block beds could be positioned by the demands of the house shape without great expense, and the lack of clutter in the detailing of the system kept static pressure to a minimum.

The slab on block system (Fig.3) retains the flexibility of the previous systems, allowing for considerable freedom in the architectural design of the house (Fig. 5 & 6).

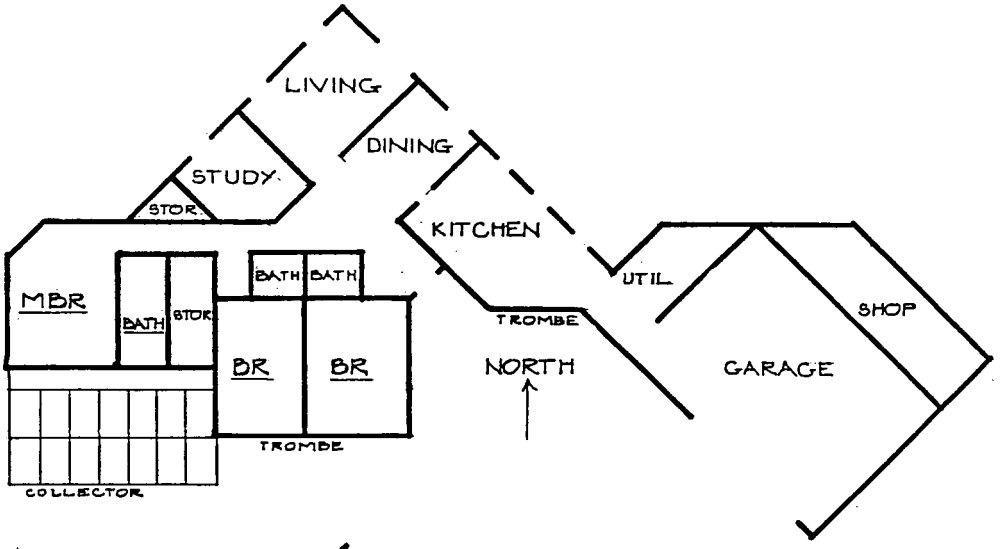



Fig.5. Schematic Floor Plan.

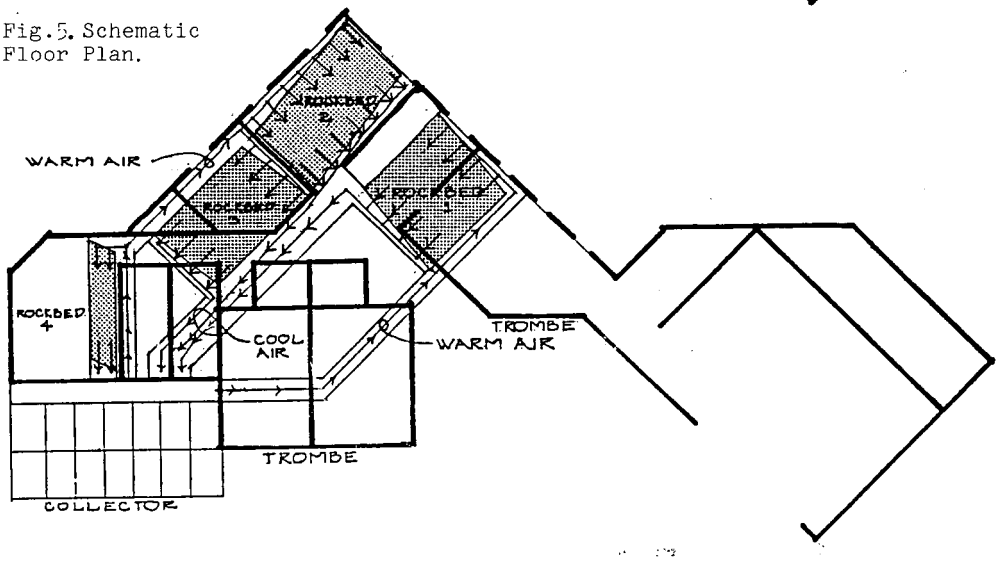



Fig.6. Indication of mass storage under floor slab.

## 4. AIR FLOW CONTROL

Each of the several thermosiphon system designs built during the past four to five years has had in common large dimension hot air supply ducts. Where these ducts orginate at the hot air plenum they can be as large as 4X5 feet. An air tight damper for such a large opening presents special problems. Previous designs have run the full range from plastic back-draft dampers to elaborate designs utilizing cables, pulleys and reversing motors with automatic controllers. Several years ago we rejected commercially available louver-type dampers in favor of a custom made damper that was air tight, insulated, and automatic.

Earlier damper configurations have been reported at past Passive Conferences (see Refs. 1 and 2). Each successive damper design sought to improve reliability, airtightness, and in particular, the current design is intended to reduce field labor costs.

This current damper design consists of a "pre-hung" hinged damper door, made of 1 in. urethane sandwiched in sheet metal. A reversing 15 RPM gear motor and limit switches are mounted on the frame. This unit is made up in the shop at a cost of about $300. The controller for one or two doors consists of a remote bulb thermostat coupled with reversing circuitry and remote pilots for monitoring the system.

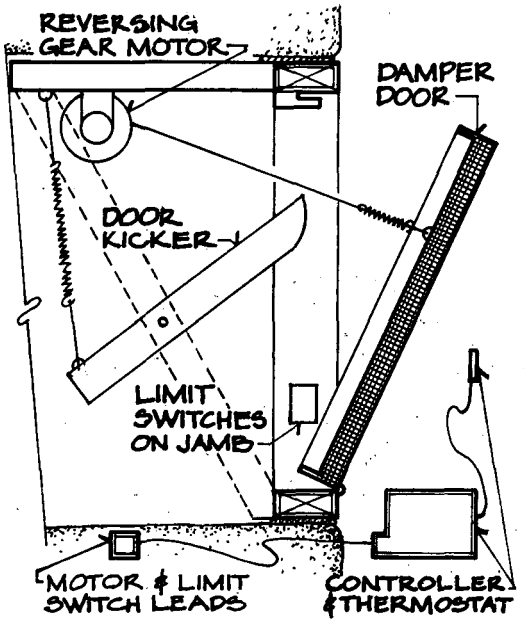



Fig.7. Schematic section of current damper design.

The controller cost $150-$200 depending on the quality of the thermostat. The added cost of this equipment has been more than offset by reduced installation time. The modular damper-door units can be plugged into the controller via 20-25 foot leads and tested in the shop, greatly simplifying installation. The last system was installed and operating in four hours as opposed to two days of rigging and trouble shooting for the earlier model.

## 5. CONCLUSION

With the current blockbed design and damper system the authors believe this system has been optimized for continuing production in its current form. The system provides high solar fractions and extremely even interior temperatures at a reasonable cost.

## 6. ACKNOWLEDGEMENT

W. Scott Morris of Morris Research and Design in Santa Fe was engineer and design consultant on these blockbed systems.

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# TOTAL SOLAR:

# HYBRID PHOTOVOLTAIC, PASSIVE-HOT-WATER AND ILLUMINATION FLUORESCENT-CONCENTRATOR SOLAR-ENERGY SYSTEM

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## ABSTRACT

An inexpensive modular solar-energy system is proposed. The unique feature of this system is that direct as well as diffuse sunlight is collected by non-tracking fluorescent concentrator panels. Light trapped within these panels is reflected out through their edges and into a light-transmitting structure, then "piped" through this structure into buildings or vehicles where it is used for illumination and to generate electricity and heat. Optical joints retain light collimation through the structure, connecting together individual light-guide sections at corners and intersections. Light-extraction units can be located anywhere along the structure; at night they are supplied with light by a single electric light source integral to the structure. In this paper the system's component mechanisms are examined, and theoretical system applications and performances are discussed.

## 1. INTRODUCTION

A combination of several recent developments in the fields of plastics, optics and photovoltaics yields a solar-energy system, here called "Total Solar," that appears capable of satisfying several energy requirements for most buildings.

The proposed system (Fig. 1) uses fluorescent concentrators to collect sunlight which is transmitted to photovoltaic cells for conversion into electricity. Because these high-efficiency photocells require cooling, heat energy (presumably in the form of hot water) is available along with the electricity. Other hybrid energy systems coupling fluorescent concentrators with

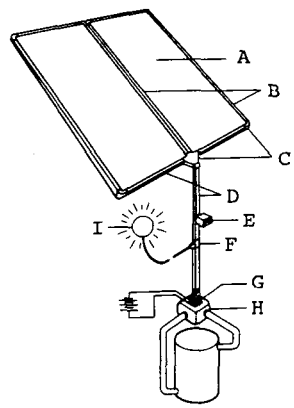



Fig.1. Total Solar system schematic. A:fluorescent concentrator, B:light manifolds, C:fiber-optic joints, D:light-transmitting structure, E:night light, F:diverter, G:photocell, H:heat transfer unit, I:light.

actively-cooled photocells have been disclosed or patented (1,2,3). Total Solar differs from these in that concentrated light is transmitted into an enclosed space for illumination purposes in addition to converting it into electricity and heat, as after Wheeler (4) and Coburn (5).

## 2. TOTAL SOLAR

Total Solar has four major interactive groups of components: solar collectors, a light-transmitting structure, illumination controls and energy-conversion units.

### 2.1 Sunlight Collection: Fluorescent Concentrators

Fluorescent concentrators are relatively new means for collecting and concentrating solar energy. In principle, when light rays fall on a fluorescent material they are

absorbed and then re-emitted, radiating isotropically in a narrow band of longer wavelengths of known energy content; the material fluoresces. When fluorescent dye is dispersed in a smooth-surfaced panel of highly transparent material, such as polymethylmethacrylate (PMMA, or "Plexiglas"), a large fraction of the re-emitted photons are trapped by internal reflection within the panel. The amount of light initially retained in PMMA is about 74.5 percent (1). Trapped light not re-absorbed by the dye or collector material or lost through scattering by imperfect surfaces radiates out through the collector's edges. Since in a panel the ratio of surface area to edge area is very large, a high degree of photon concentration is realized at the perimeter.

The major benefit of these solar collectors is their lower cost per unit of light output, compared to other light-collecting systems. Solar fluorescent concentrators use no delicate tracking mechanisms or expensive lenses; they are constructed entirely from inexpensive sheets of plastic and small amounts of fluorescent dyes. And, focusing devices are unable to capture indirect light (which in some parts of the world accounts for a majority of annual insolation) whereas fluorescent concentrators collect diffuse sunlight as readily as direct sun. It is practical in some system configurations to mirror certain collector edges, reflecting the light that would have emanated from them back into the panel for exit elsewhere. The number of light-transmitting devices needed to gather the collected light is thus reduced.

One chief difficulty associated with fluorescent concentrators concerns the photostability of fluorescent dye molecules; suitable dyes typically have half-lives of less than one year, and even with further refinement are expected to last only 4-5 times longer than that (1,6). Because this period of time is still much less than the useful lifetimes of the collectors' plastic components, which should remain serviceable for at least 20 years, satisfactory methods for periodically replenishing the dye must necessarily be devised. To date, the most promising method involves applying thin acetate-type films containing high concentrations of fluorescent dye to one surface of a clear panel, preferrably on the side facing the sun. This concentrator design permits the old, partially bleached dyes to be "peeled-off" and replaced by sheets of fresh dyes. Efficiencies of such thin-film dye applications are actually greater than those in which dye is dispersed homogeneously throughout the collector material (6).

Another concern is with keeping the panels clean. Water, tree sap and other substances lower the index of refraction of a panel's surface at the points of contamination, letting light escape where it would have otherwise been trapped inside by internal reflection (7).

## 2.2 Light Transmission: Prism Light Guides

The light-transmitting structure used in Total Solar is composed of many individual light-guide segments having one of two different shapes. Both are simply transparent tubes of rectangular cross section, but one has a tapered outer profile (Fig.2-a) while the other is straight-sided for its entire length. Short fiber-optic manifolds direct light from the unmirrored solar-collector edges into pieces of the first type. The inlet ends of these manifolds attach to the panel edges, and their outlet ends are positioned in the tapered section so they stack when viewed from its opening (Fig.2-b). Light-guide pieces of the second shape comprise the remainder of the transmitting structure, in which all pieces are interconnected at corners and intersections by joints enclosing bundles of optical fibers. These joints retain light collimation within the guide structure and hold it together.

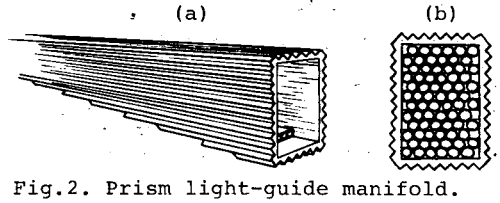



Fig.2. Prism light-guide manifold.

Whitehead (8) showed that the planar surfaces of efficient dielectric light guides must be in octature--all inner and outer surface planes being perpendicular or parallel to themselves, but angled at 45° with respect to each other. Such guides are molded from clear acrylic plastics, and have polished inner walls and prism-type exteriors. If these

light guides are straight, concentrated light collimated to within about 28° of their longitudinal axes can be transmitted through them with very little attenuation. Nearly all of the contained light rays are reflected off the interior walls and remain in the enclosed air space. Those rays that do refract into the plastic of the guides undergo total internal reflection at the outer walls, returning back into the air space after losing negligable energy to the dielectric. Prototypes exhibiting light losses of approximately 50 percent for 18 feet of guide have been claimed (9).

## 2.3 Illumination: Light Outlets, Controls and Night Light

Interior lighting systems must provide diffused ambient illumination and also direct concentrated light onto work areas. Windows and skylights function well in supplying low-intensity background light. Typical 100W incandescent light bulbs produce, on the average, 1750 lumens, usually more than adequate for most residential and commercial task-lighting requirements.

In comparison, the power contained in sunlight is equivalent to about 100 lumens $Watt^{-1}$ (10). Since under clear skies solar radiation falls on the Earth's surface at a rate of over 1000 $Watts\ m^{-2}$, bright sunshine illuminates areas of one square meter with approximately 100,000 lumens, equal to the light of about fifty-seven 100W bulbs. The previously described light-guide structure can safely transmit light at an intensity of about 10 $Watts\ cm^{-2}$, or 100 suns (8). Sunlight collection/distribution systems using such structures--even if only partially efficient--could conceivably provide satisfactory daytime illumination for many interior environments.

Total Solar supplies both task and ambient light by employing apparatus to divert light from within the light-transmitting structure to various types of luminaries. Remote-controlled light diverters can be located anywhere along the structure to intercept variable amounts of the concentrated light. Such units would extend optical fibers or small reflectors into the guide to "tap" its light. Fiber-optic cords, substituting in a sense for electrical wiring, would connect the diverters with non-electric "cold" luminaries, including lamp-type fixtures, furniture, wall sections and exposed (possibly textured) lengths of the light guide itself. Light-actuated appliances, also plugged into the structure via the diverters, could utilize the available light for information displays, image projections or for power by converting it to electricity with built-in photocells.

Interior lighting at night or during heavily overcast days is accomplished by activating a single electric light source integral to the structure. When necessary, one or more high-efficiency incandescent or fluorescent light bulbs would be activated by sensors detecting changes in demand for light (from light switches), determining the intensity level of the light within the guide, then controlling the bulbs' outputs accordingly. Electricity would be supplied to this substitute sun from batteries charged during the day by photovoltaic modules.

## 2.4 Power Conversion: Photovoltaic Heat Exchangers

The portion of collected sunlight not diverted out of Total Solar's light-guide structure is focused onto photovoltaic concentrator cells mounted to heat-exchanging units. The cells' conversion efficiencies determine what percentage of received light energy is actually converted into electricity. Because the photocells are placed inside buildings, etc., they are not subjected to weather extremes, vandalism or dirt contamination, all of which can adversely affect their performances. A centralized interior location also decreases electric line losses, since battery storage could be placed right next to the cells.

Several types of photocells are suitable for use. Gallium arsenide cells achieve conversion efficiencies of over 30 percent under concentrated light. In fact, their efficiencies increase with increasing light intensities, but they are very expensive and may produce toxic arsenic trioxide if burned in a fire. Silicon semiconductor cells are much cheaper and are easily fabricated (even home-made! (11)), and can convert concentrated light into electricity with efficiencies of up to 24 percent. Using photocells especially sensitive to that part of the spectrum emitted by the fluor-

escent dyes in the collector panels increases the electrical conversion efficiency of the system. Very inexpensive amorphous silicon cells have converted fluorescent light at 6-8 percent efficiency (12).

For light densities in the transmitting structure of 10 Watts $cm^{-2}$ (100 suns), a 25 percent-efficient cell would generate about 2.5 watts $cm^{-2}$ of electricity. With 5-10 percent of the incident light reflected back into the guide by the cells' metal contacts, about 60 percent converts to heat within the cell. Under the assumed light intensity this corresponds to approximately 20 Btu $hr^{-1}$ $cm^{-2}$ of energy available to heat water.

## 3. CONCLUSIONS

The versatility of Total Solar is enticing. Large structures, portable and stationary appliances, mobile vehicles and other energy-consuming objects could utilize versions of this system. Used as an architectural solar-energy system, Total Solar satisfies both new and retrofit construction criteria with its low-profile components that are inexpensive, lightweight, durable and expandable in modular increments. Plumbing and electrical wiring connections are centralized and minimized, easing installation while conserving materials.

Increased research efforts are needed to develop longer-lived fluorescent dyes, devise techniques for initiating and retaining light collimation within the transmitting structure, and to eventually establish sizing equations for architectural installations. Total Solar is a step towards powering civilization entirely by the sun.

## 4. ACKNOWLEDGEMENTS

I wish to thank R. Goodman in whose class this system was initially conceived, M. Rubin for introducing me to the concept of solar fluorescent concentrators, and R. Freeburg, C. Benton and C. Gallagher for their valuable suggestions.

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# RESULTS OF TESTING AND MODELING PASSIVE SOLAR DHW SYSTEMS

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## ABSTRACT AND SUMMARY

Comparisons of test results and simulations for batch and thermosiphon passive solar DHW systems. The simulation model is a thermal network model using simplified heat up and cool down tests to establish the efficiency parameters. Simulated results are compared with the SRCC-200 test results and field data. A comparison shows that the simplified tests give equivalent results to the SRCC rating method and, in addition, are capable of predicting performance under a wide range of climatic and usage conditions. Corraboration of the model demonstrates that it can predict individual draws, daily energy outputs and annual solar performance to a high degree of accuracy. Results are also compared to the California PUC method of calculating performance estimates.

## 1. DISCUSSION OF PROCEDURE

The authors have previously described the development of a simulation model and associated test procedure.[1] The method asserts that a modified form of the Hottel-Whillier-Bliss efficiency equation can be applied to those systems for which instantaneous efficiency tests are not possible. The test procedure has been revised to specify that the average tank temperature be determined by circulating the storage volume until a uniform temperature is achieved. We believe this change in the procedure will give more accurate results than our previous method of draining the tank to record temperature. A test procedure has been drafted for use by laboratories using our procedure.[2] The test procedure has been performed under the solar simulator at DSET Laboratories.[3] A diagram of the resulting heating efficiency equation is presented in Figure 1. Analysis of the data shows that the efficiency can be represented closely by a linear expression of the intercept and slope. Testing under controlled laboratory conditions provides better resolution of the data compared to our previous outdoor tests. The laboratory test shows a small difference in efficiency in morning and afternoon testing. During afternoon periods, the greatest solar flux occurs at the start of the period, while the tank is still relatively cool. Thus, efficiency is somewhat greater during afternoon periods. For purposes of our simulation model, a linear regression was performed on the combined results of both morning and afternoon testing. Additional modeling was carried out using separate efficiency equations from morning and afternoon periods without demonstrating any significant difference in results.

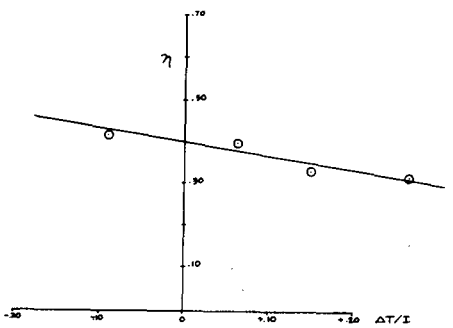



Fig. 1. System B. Heating Efficiency vs. Inlet Parameter.

The simulation model has been revised by the inclusion of a simplified expression for thermal stratification. Examination of the temperature gradients established by draining stratified systems indicated that approximately 67 percent of the absorbed heat is present in the upper half of the storage tank. The model was revised to include two zones for each storage tank. Heating efficiency is calculated on the basis of the inlet parameter derived from the average of the two zones. However, the collected energy is assumed to reside 67 percent in the upper zone and 33 percent in the lower zone. Separate temperatures in the zones are maintained during subsequent draw and cooling simulations without further attempts to model thermal

stratification. Although this model is simplistic, it does improve the correlation between the predicted and actual draw energy (Table 2). Thermal stratification effects tend to be self-correcting. If, for example, more energy is withdrawn than predicted during the first draw, the remaining storage is at a cooler temperature. Subsequent draws will contain less energy and the total draw energy over a period of time will conform to the prediction.

Table 2
Comparison of draw energy -- System A[6]

| Time | Tested Draw Btu | Predicted Draw Btu |
|---|---|---|
| 0800 | 4,082 | 4,233 |
| 1200 | 6,531 | 5,504 |
| 1700 | 9,350 | 10,345 |
| total | 19,913 | 20,083 |

## 2. COMPARISON WITH SRCC-200 TESTS

The SRCC test[4] specifies a procedure by which the system is exposed to specific irradiation, ambient temperature, and draw conditions. After a period of approximately three days, the system reaches an equilibrium where the withdrawn energy attains a constant value. At this point, the system is said to have reached convergence. The converged values of energy output are reported as the SRCC rating numbers for that particular system. The simulated results and the SRCC test results under the same conditions are compared in Table 3. For simplicity, results are reported in terms of the Solar Heating Fraction (SHF). This value is equivalent to the Qnet divided by the total load as reported from the SRCC test. It is comparable to the results from other calculation methods, such as Fchart 3.0, which characterize the solar system as preheating water supplied to an auxiliary tank. It needs to be distinguished from calculations which include heat losses from the auxiliary tank and report the Solar Savings Fraction (SSF) for the entire system. The results demonstrate that the model provides the same quality of information as the SRCC system test. The model has advantages in that the simplified test procedure is less expensive to perform and that the resulting simulation can predict energy output under varied draw conditions. These predictions are discussed in Section 6. System C was tested independently and relies on test data reported to the Oregon Department of Energy by a solar dealer who used the earlier procedure. The model tested was similar but larger in collector area than the model tested in the laboratory. Thus, the comparison is subject to some ambiguity.

Table 3

Comparison with SRCC-200[5,6,7]

| Description | I Btu/ft2 | Tin oF | Tested SHF | Predicted SHF |
|---|---|---|---|---|
| System A | | | | |
| "Breadbox" | | | | |
| batch heater | 1,500 | 71.6 | .497 | .500 |
| | 1,250 | 71.6 | .415 | .427 |
| | 1,750 | 71.6 | .571 | .568 |
| | 2,000 | 71.6 | .649 | .609 |
| | 1,500 | 52.9 | .541 | .554 |
| System B | | | | |
| Absorber design | | | | |
| batch heater | 1,500 | 71.6 | .661 | .626 |
| System C | | | | |
| Open loop | | | | |
| thermosiphon | 1,500 | 71.6 | .499 | .525 |

## 3. COMPARISON WITH FIELD DATA

There was little field data suitable for cross-checking our simulation model. A sequence of 10 days of outdoor monitoring was conducted on System B. A sequence of eight days under the solar simulator was conducted at DSET Laboratories on System A.[5]

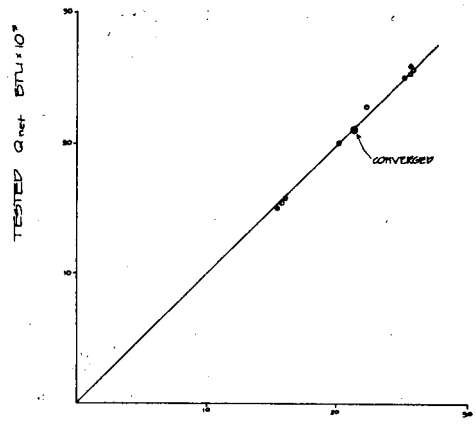



Fig. 4A. System A.

Comparisons of the simulation model to the actual performance are shown in Figures 4a, 4b, 5a, 5b. In general, deviations from the simulation are minimized when a number of data pairs are considered over a long time interval. This relates to an assumption in the annual estimating procedure. It assumes that average performance over a time interval can be determined by the results of a test to convergence based on the average radiation, temperature and draw conditions during that interval. This assumption appears validated during the two monitoring intervals as shown in Figures 4a and 4b.

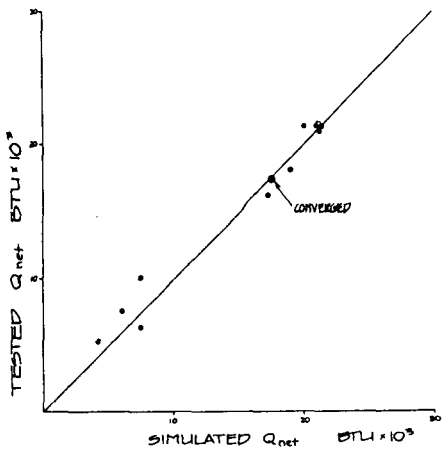


Fig. 4B. System B.

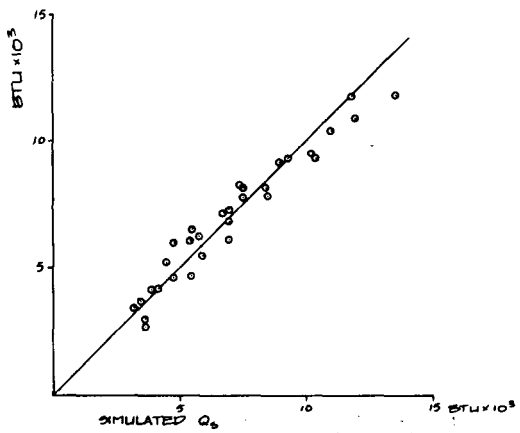


Fig. 5A. System A Individual Draws.

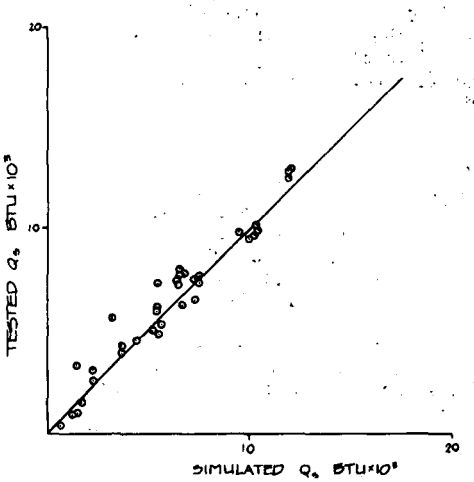


Fig. 5B. System B.

Further field data on System A was available from long-term monitoring at Arizona State[8] and Florida Solar Energy Center.[9] This monitoring was conducted on a different experimental basis. In these cases, the solar units were used as preheaters for a conventional water heater. Output energy was measured across the entire system and included heat loss effects due to the auxiliary tank. Although the additional standby loss is included in our model, the model was not successful at predicting the system output. We suspect that heat losses were more severe than accounted for in our model. In some cases, the monitoring utilized a small draw volume in relation to the collector size suggesting that the collectors would then be close to stagnation. The elevated temperatures would contribute to increased heat losses. We believe that the discrepancy in our predictions is due to limitations in the experimental procedure rather than limitations in the simulation model.

## 4. ANNUAL PERFORMANCE ESTIMATE

The simulation model can be used to develop an annual performance estimate. It is assumed that solar performance during each month can be characterized by the performance during a convergence test based on the average radiation and temperature during that month. This assumption was tested by comparing results modeling the entire year using aggregated hourly data to the results obtained from monthly convergent simulations. Results are shown in Table 8. The column labeled hourly data is based on aggregating hourly data into morning, afternoon, and night blocks. This aggregation retains the difference in irradiation between morning and afternoon periods. The column labeled daily data uses the same ambient temperature values, but assumes that the daily irradiation is distributed equally between morning and afternoon. This assumption makes no difference in the simulated results. The column labeled monthly data assumes average monthly climate data is applied to the system for a three-day period. The converged performance from the third day is assumed to represent the average performance during that month. Hourly climatic data was obtained from monitoring at Oregon State University under the SMERTS program.[10] This data was used because it directly measured irradiation on a surface tilted at latitude. Occasional gaps were present in the data due to equipment malfunction. Reasonable estimates were used where gaps occurred. Monthly averages ignored missing data. It does not appear that the estimates affected the results.

We conclude that reasonably accurate simulations can be made from average monthly climate data. This greatly simplifies the computer model allowing a version for the hand-held programmable calculator.

Table 8

| Hourly Data SHF | Daily Data SHF | Average Monthly Data SHF |
|---|---|---|
| .543 | .543 | .531 |

## 5. COMPARISONS WITH OTHER MODELS

Only one other method is used to predict performance of passive DHW systems. This is the California PUC method (CAPUC) developed by Brian Schumacher[11] and modified by Church/Davis Architects[12] for use in the Bonneville Power Administration program. Simulation results are compared to those from an earlier version of the BPA-modified CAPUC procedure (Table 9).

Table 9
Comparison With CAPUC Estimates

| System | | ODOE | BPA | Fchart 3.0 |
|---|---|---|---|---|
| System A. | Eastern OR | .633 | .500 | -- |
| | Western OR | .646 | .500 | -- |
| System B | Eastern OR | .610 | .500 | -- |
| | Western OR | .594 | .500 | -- |
| System C | Eastern OR | .561 | .500 | -- |
| | Western OR | .551 | .500 | -- |
| System D | Eastern OR | -- | .500 | .562 |
| | Western OR | -- | .500 | .568 |
| (Active solar system) | | | | |

The BPA method appears to be conservative. It underpredicts performance for Oregon sites by 10-20 percent relative to the model and to Fchart 3.0. We did not have the capability to compare units with a large over-night heat loss. It is possible that these units would display more serious divergence in cold climates.

The model was used to analyze the assumptions inherent in the CAPUC method. BPA suggest that solar output energy can be ratioed to irradiation. The model confirms this assumption as does laboratory testing[13] (Table 10). The table also displays simulated values of the total absorbed energy -- Qtotal equals the sum of Qnet and night losses. Since Qreserve was not actually measured during the test sequence, no measured values of Qtotal were available for comparison.

Table 10
Simulation Results -- System A

| I Btu/ft2 | Tested Qnet Btu | Simulated Qtotal Btu |
|---|---|---|
| 1,250 | 16,659 | 17,798 |
| 1,500 | 19,913 | 21,322 |
| 1,750 | 22,932 | 24,948 |
| 2,000 | 26,061 | 28,432 |
| y intercept | 1,095 | 31.8 |
| slope | 12.5 | 14.2 |
| correlation coefficient | .9999 | 1.0000 |

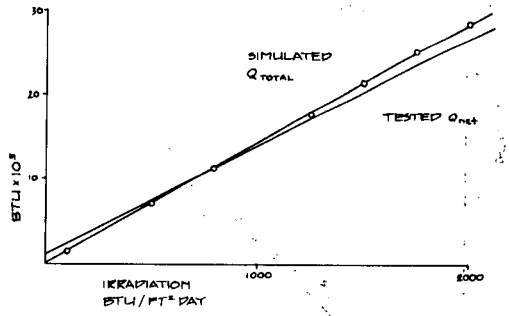



Fig. 11.

The model explains a puzzling fact observed during that testing. The plot of Qnet is quite linear, but displays a positive Y-intercept. This would imply that the system could deliver energy at zero irradiance -- a clear impossibility. However, the plot of the total absorbed energy (Qtotal) displays an intercept very close to zero. Figure 11 shows the plot of Qnet and simulated values of Qtotal.

CAPUC assumes that Qreserve will not change significantly under different ambient temperatures. Qtotal values can be calculated based on expected cooling losses at night (Qcool). Table 12 shows calculations based on CAPUC assumptions applied to the simulated base case. The CAPUC method diverges slightly on calculating cooling losses. The first three columns show values as calculated during the simulation. The last two columns show values calculated from the simulation results using CAPUC methods. The first and last columns show reasonable agreement. It appears that a form of CAPUC can be developed which will provide "ball park" site-specific performance estimates.

Table 12

System A Simulation -- SRCC Conditions

| Night Temperature | Model Qnet Btu | Model Qres Btu | Model Qcool Btu | CAPUC Qcool Btu | CAPUC Qnet Btu |
|---|---|---|---|---|---|
| 40 °F | 16,282 | 5,478 | -5,025 | -5,683 | 15,791 |
| 71.6°F | 20,083 | 5,478 | -1,240 | -1,391 | 20,083 |
| 100 °F | 23,499 | 5,491 | +2,159 | -2,441 | 23,915 |

## 6. DISCUSSION OF PASSIVE PERFORMANCE

As is apparent from the SRCC systems test, passive systems can perform quite well in comparison to active systems. The simulation model predicts a surprisingly uniform system performance over a wide range of climatic conditions. The systems generally perform with 35-40 percent collection efficiency. This makes those systems relatively forgiving in that an unsophisticated model can approximate their behavior. Predictable behavior should make these systems attractive to utility investments where a predictable rate of return is important.

There are several reasons for the good performance of these systems:

1. Most of these systems are under-sized relative to the load. They are providing preheat with high efficiency rather than trying to "top off" the storage. Thus, the systems are functioning at the most efficient end of their curve of diminishing returns.

2. The systems have a low critical threshold and no controller dead band. They can collect energy under diffuse conditions where active systems would not be able to operate.

3. The systems exhibit positive entropy effects. Thermally stratified systems are preferable to mixed systems in that the delivered water is always the hotest and the collector tends to operate from the coldest water. This effect tends to compensate for the reduced heat transfer at low flow rates.[14] It is also more appropriate to store heat at or below the temperature of use rather than at or above. We suggest an entropy function could be developed to describe these systems. This function would demonstrate a higher value for thermally stratified systems than active ones.

The model can provide interesting information on the performance of passive systems. Table 13 details performance predictions under different conditions. Marginal productivity diminishes rapidly by adding units in series. This is especially apparent for large units. On the other hand, little difference is apparent between series and parallel configurations. The previous model showed a slight improvement for series configurations due to enhanced thermal stratification. Including stratification effects in the model produces estimates which do not show that same improvement. The stratification model also changes expectations regarding the effects of changing the thermostat set point on the auxiliary heater. It does not appear that the set point is a serious limitation on solar performance. Changes in draw pattern are still an important variable. Draw pattern can affect daily performance by about 10 percent.

## 7. ACKNOWLEDGMENTS

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Bob Claridge, Florida Solar Energy Center, Church/Davis Architects, Doug Nelson, DSET Laboratories

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Table 13
Marginal Productivity of Last Unit -- SRCC Test Condition

| System A | Marginal Qsolar Btu | Marginal Efficiency | System B | Marginal Qsolar Btu | Marginal Efficiency |
|---|---|---|---|---|---|
| 1 unit 16.5 sq.ft. | 10,528 | .42 | 1 unit 24.4 $ft^2$ | 14,254 | .36 |
| 2 units | 8,322 | .33 | | 10,467 | .28 |
| 3 units | 8,128 | .32 | | 8,328 | .23 |
| 4 units | 6,910 | .28 | | 6,348 | .17 |

Series Compared to Parallel Installations

| System A | SHF | System B | SHF |
|---|---|---|---|
| 2 series | .376 | 2 series | .626 |
| 2 parallel | .383 | 2 parallel | .620 |

Effect of Increasing Load

| | System A SHF | System B SHF |
|---|---|---|
| Base case, SRCC conditions | .472 | .626 |
| Increase load by raising set point to 140°F | .340 | .444 |
| Increase load by increasing draw | .330 | .555 |

Changes in Draw Pattern

| | System A SHF | System B SHF |
|---|---|---|
| Large morning draw | .459 | .550 |
| SRCC test conditions | .508 | .626 |
| Large evening draw | .527 | .673 |

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# LARGE PASSIVE "BREADBOX" WATER HEATER

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## ABSTRACT

Dorena Lake, south of the City of Eugene, is one of several reservoir projects constructed and operated by the Corps of Engineers in western Oregon. Schwarz Park is located along the Row River downstream of Dorena Dam. The park receives substantial recreation use--an average 170 users per day were recorded in June 1979. Improvements to Schwarz Park constructed in late 1982 and early 1983 included a bathhouse with showers and passive solar water heater.

The solar water heating system consists of an array of 16 uninsulated tanks located in a south-facing "greenhouse" type enclosure with 18 square meters (200 square feet) of glazing. The tanks provide 4,860 liters (1,280 gallons) of storage and are arranged in four rows of four tanks each. Cold water is manifolded into the lower portion of each row. Each row is piped in serpentine fashion, high point to low point and end to end to minimize short circuiting. Hot water is drawn off at the uppermost part of each row and manifolded together for distribution through a tempering valve to the bathhouse. No backup water heating has been provided. The bathhouse contains four wash basins and four shower stalls equipped with low flow heads and timed push-button valves.

The park and bathhouse are open to the public from late May to early September. The system is drained during winter months for freeze protection.

System performance is monitored using a totalizing pyranometer, flow meter, Btu totalizer, and multichannel temperature recorder. The equipment has worked well, and available data indicate a system efficiency of about 20 percent. Some changes to increase performance are indicated.

## 1. INTRODUCTION

Schwarz Park, owned and operated by the U.S. Army Corps of Engineers, is located on the Row River downstream of Dorena Dam in Lane County, Oregon. Dorena Lake, 20 miles south of Eugene, Oregon, is one of several reservoir projects constructed and operated by the Corps in western Oregon. Schwarz park is an 80 acre recreation area for picnicking, fishing and camping. It has been open to the public for several years in an undeveloped state except for access roads and some picnic tables, Bar-B-Q stands, running water, and vault toilets. The park receives substantial use during the period when it is open--from Memorial Day weekend through Labor Day weekend. An average 170 users per day were recorded in June 1979.

In late 1982 and early 1983, several improvements were constructed, including a bathhouse to serve a family camping area in the park. That bathhouse is equipped with a large, breadbox type, passive solar water heater as its only source of hot water for showers and wash basins.

## 2. DESIGN AND CONSTRUCTION

Three different water heating systems were considered and analyzed for cost effectiveness in compliance with regulations. The first system was a conventional electric, 450 liter (120 gallon), 54 kW tank-type water heater. It would supply hot water at all times independent of weather and have a relatively low installation and maintenance cost. It would, however have a high operating cost in the form of electric bills. An active solar water heating system was also considerd. The system was sized to have 18 square meters (200 square feet) of collector panels, 4,860 liters (1,280 gallons) of hot water storage and the necessary piping and controls. It would have a low operating cost, but was expected to have a relatively high maintenance cost (vandalism

is sometimes a problem) and reduced performance during cloudy weather.

A passive type solar water heating system was the third type considered. It consisted of an array of uninsulated tanks located in a south-facing "greenhouse" type solar collector. The same collector area and storage volume were used for comparing the passive and active systems. It was believed that the increased collection efficiency of the passive system would largely offset the greater nighttime losses from the uninsulated tanks. Under worst case conditions, losses were predicted as high as 22 kWh (75,000 Btu) per night. The life cycle cost analysis showed the passive system to be the most cost effective. A 16 year estimated payback warranted construction in lieu of the conventional system.

The final design was based on the following assumptions.

a. Peak weekend demand of 3,800 liters (1,000 gallons) per day.

b. Peak weekday demand of 760 liters (200 gallon) per day.

c. Incoming water temperature of 13°C (55°F).

d. Average ambient temperature of 24°C (75°F).

It was decided to use a simplified sizing approach to get the system "into the ballpark" of providing adequate hot water approximately 75 percent of the time. It was assumed that cloudy weather would reduce park usage as well as system production. Our simplified daily heat balance calculations indicated sufficient water available during a normal week except for late Sunday and most of Monday. A three day weekend would severely drain the system.

As constructed, the system consists of sixteen 300 liter (80 gallon) water tanks (standard water heater liners) in a "greenhouse-type" solar collector attached to the south wall of the bathhouse. Figure 1 shows the completed facility. The south-facing collector has wood frame walls with R-19 fiberglass insulation and siding to match the bathhouse. The collector roof is double-walled acrylic glazing (Exolite) and is sloped to match the angle of the bathhouse roof with a pitch of 5 on 12 (22.6°), which is appropriate for summer collection. The concrete floor contains Styrofoam™ board insulation. The south wall was made about 1.5 meters (5 feet) high to discourage people from climbing on the roof. It has "solar hot water" painted on it in large letters. A viewing port is located in the "O" of "hot" where people can look into the collector and see the tanks plus an informative display board (See Figure 2).

The water tanks, painted flat black to increase their heat absorption, are supported on a metal frame (See Figure 3). The tanks are arranged in four rows of four tanks each. Cold water is manifolded into the bottom-most point of each of four rows. The tanks are piped in serpentine fashion, high point to low point and end to end to minimize short circuiting. Hot water is drawn off at the uppermost part of each row of tanks and manifolded together for distribution. Each tank is provided with a manual drain valve and an air release valve. Backup water heating was not provided. A tempering valve, timed push button shower controls and low flow shower heads and wash basins are conservation features included in the bathroom.

## 3. INSTRUMENTATION

Maintenance personnel at the park requested "some way of monitoring the solar system performance more sophisticated than user comments." District office staff also wanted performance information to confirm expections and refine the system design for possible construction of additional units at other Corps facilities. To that end, the Corps purchased a Hersey Model 7002 flow and Btu measurement system and a LI-COR Model LI-1776 Solar Monitor. The Hersey system uses a Niagara Model 442 liquid meter with a register pulser for flow data and a pair of temperature sensors in thermal wells installed in the cold water inlet and hot water outlet for temperature data. Output readings are in total gallons and total Btu. The LI-COR system uses a pyranometer sensor, LI-200SB, to

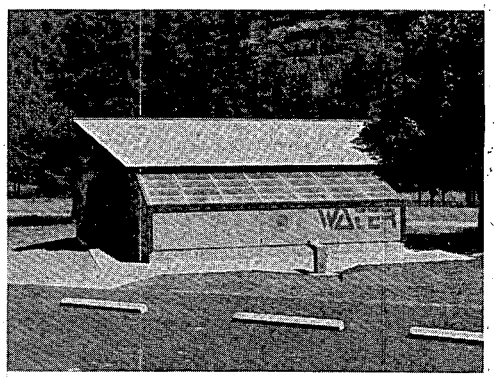
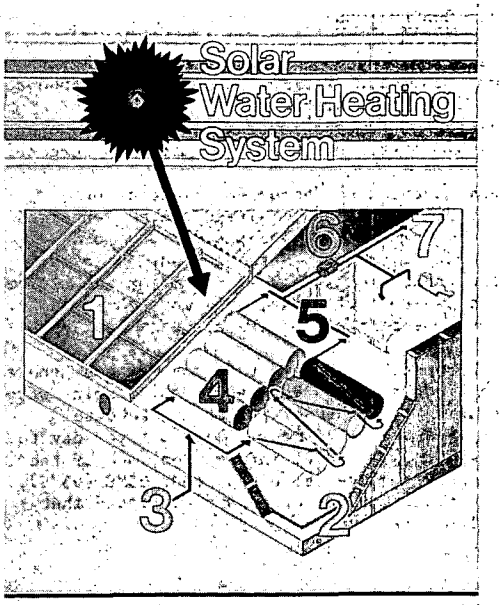


Fig. 1. The Completed Facility.




1 **PLASTIC GLAZING** transmits solar radiation and traps heat by reflecting heat energy back to tanks.

2 **INSULATED WALLS and FLOORS** conserve heat overnight and during overcast periods.

3 **COLD WATER** into storage tanks. (55° F±)

4 **STORAGE TANKS** painted black to absorb radiation and transfer heat to water.

5 **HOT WATER** from storage tanks. (100–130° F)

6 **MIXING VALVE** controls water temperature.

7 **WARM WATER** to showers and wash basins. (95–100° F)

Fig. 2. Interpretive Display seen by the Public Through the Viewing Window.

measure direct and diffuse radiation. The solar monitor provides output data of instantaneous solar energy in watts per square meter and daily totals in watt-hours per square meter. A memory stores up to 117 days of integrated data.

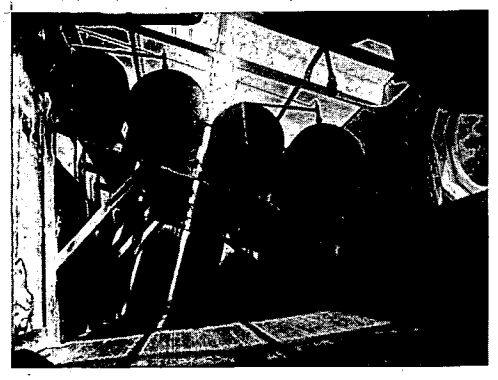


Fig. 3. Interior of Sunspace showing tanks and viewing window.

In addition to that equipment, a surplus 20 channel temperature chart recorder was obtained from the powerhouse at Bonneville Dam and reconditioned for use. The temperature recorder uses precision 10 ohm copper thermohms for temperature sensors.

Since commercially available thermohms are expensive and would take weeks for delivery, the principal author made thermohms for this project. Sensors were located to obtain temperatures of: cold water in; hot water out; output from tempering valve; eight tank locations; and air temperatures below the tanks and at the top of the sunspace. Water temperature sensors were placed in contact with the container and covered with insulation.

It was planned to have the monitoring equipment installed by the Memorial Day weekend, but circumstances prevented that from happening. The Btu and Solar monitors were first operated in early June and the temperature recorder in mid-June. All equipment has operated since installation without any problems.

## 4. OPERATION

Even without monitoring equipment, some qualitative performance information was obtained over the Memorial Day weekend. Maintenance personnel reported clear weather and hot tanks the preceeding Thursday evening. The tempering valve was set to deliver 35°C (95°F) water. The system supplied showers all day and evening Friday and Saturday, and delivered 35°C temperature water until mid-morning Sunday when it finaly dipped

to about 30°C (86°F). The following week, the temperature valve was reset to 32°C (90°F) to conserve hot water during the remainder of the season.

The brief temperature record acquired during a sunny day shows a cold water temperature of 20°C (68°F), hot water outlet temperature varying between 31 and 52°C (88 and 125°F), and a tempered water temperature of 32°C. Those temperatures were found to drift when water was not drawn for an extended period of time. Air temperature below the tanks ranged from 29 to 33°C (84 to 91°F) and at the top of the sunspace ranged from 32 to 42°C (90 to 108°F). Tank temperatures show stratification ranging from a low during the early morning of 1°C in the lowest tanks and 3°C in the third row of tanks to about 12°C (22°F) during a hot sunny afternoon. Temperature difference from the lowest row of tanks to the next row ranged from 5 to 8°C (9 to 14°F). Temperature difference between the other rows averaged 2 to 3°C.

Night cooling of the top surface of the tanks is much greater (10°C) than the back surface of the tanks (4°C) or the bottom surface of the tanks (2°C).

The bottom surface of the top two rows of tanks is consistently warmer than the ambient temperature below the tanks, and the bottom surface of the lowest row of tanks is consistently cooler.

Over an eight day period, the Btu meter indicated an average 70 thousand Btu per day delivered to the showers. That is a saving of about 20 kWh per day compared to conventional electric water heating. Those numbers are probably too low because the cold water sensor was mistakenly located within the sunspace and a significant warming of the sensor occurs when flows are low. During the same time period, the solar monitor provided data that indicated a daily average 5,533 watt-hours per square meter of horizontal surface radiation, which is close to normal for that time of year. Neglecting the small correction for collector angle, the input energy of 100 kWhr per day compared to the output of 20 kWhr per day indicates an average system efficiency of 20 percent.

Brief interviews with a number of campers using the facility revealed a mystified but curious public supportive of solar energy. Even with the explanatory graphics, some did not understand the concept of passive solar water heating. Once explained, the responses ranged from mild appreciation to excitement caused by the enlightenment and realization that they could do something similar for themselves. Comments received indicated the water temperature (32°C, 90°F) was not quite warm enough.

## 5. CONCLUSIONS

Using passive solar water heating for a low maintenance and operation summer use bathhouse facility is appropriate. The system as designed and constructed is minimally adequate with a system efficiency of about 20 percent.

Some changes to increase efficiency or capability that have already been identified are: insulate all hot water pipes; add selective surface to the top surface of all the tanks; insulate the bottom surface of the top two rows of tanks; and move the cold water sensors out of the sunspace.

Other conclusions are that most of the general public does not understand passive solar water heating, the Schwarz Park bathhouse exposes about 170 metric visitors per day to basic passive solar information, and if the tempering valve is set to about 35°C (95°F), the public is impressed and convinced that solar works.

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# A STUDY OF THERMOSIPHON AND RADIANT PANEL PASSIVE HEATING SYSTEMS FOR METAL BUILDINGS

by

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## ABSTRACT

A study of passive heating systems appropriate for use on metal buildings is being conducted at Los Alamos National Laboratory for the Naval Civil Engineering Laboratory, Port Hueneme, California. The systems selected for study were chosen on the basis of their appropriateness for retrofit applications, although they are also suitable for new construction: simple radiant panels that communicate directly with the building interior and a backflow thermosiphon that provides heat indirectly.

## 1. INTRODUCTION

Many US Navy buildings, as well as buildings in the commercial sector, are constructed of corrugated metal. Several passive solar retrofits are appropriate for such structures, the simplest approach being to glaze a portion of the outer surfaces of the metal panels on the south side of the building. If the panels are uninsulated (or if any interior insulation is removed) the inner surface radiates heat to the interior of the building as solar gains raise the temperature of the absorbing surface. Solar absorption should be promoted by employing a dark color on the glazed panels. This simple system will provide significant solar gains.

A second, more elaborate, scheme is to place an insulated surface a few inches behind the radiant panel discussed above. If circulation vents are then cut at the top and bottom of the insulated wall, a convective loop will be established during periods of solar exposure. The advantage of the thermosiphon system over the simple radiant panel is that, provided reverse flow is prevented by backdraft or manually operated dampers, nighttime heat losses are much smaller because of the presence of the insulated panel.

The purpose of our study is to evaluate the merits of the passive systems selected for consideration. Experimental and analytical studies are in progress. The experimental work is being conducted in two test cells at the Los Alamos Solar Laboratory, and the results will be used to validate thermal network computer models that are being developed to represent the systems under study. Once the computer models are validated we will be in a position to evaluate performance potential throughout the continental United States.

## 2. DESCRIPTION OF THE TEST CELLS

We conducted experiments in two adjacent test cells at the Los Alamos Solar Laboratory (see Fig. 1.). The test cells are the same ones previously used to investigate the performance of retrofit systems on concrete block buildings for the US Navy (1). Both cells are approximately 5-ft wide, 10-ft high, and 8-ft deep. Construction is 2 x 4 frame (except for the south wall) with R9 fiber glass batts in the cavities and 1-in. polystyrene foam insulation on the inside surface. Solid concrete blocks 5 3/8-in. thick were placed on the floor and 2-in.-thick slabs of concrete were suspended from the ceiling on a metal rack to provide thermal storage mass. A fixed infiltration rate of two air changes per hour was maintained by a blower to increase the heat load of the cell and to eliminate the need to predict the rate theoretically. Electric light bulbs with a total power of 1 kW were used as a source of auxiliary heat. The light bulbs were thermostatically controlled by a Hewlett-Packard 9845 data acquisition system that limited the air temperature of the cells to a minimum of 75°F.

The south wall of one of the test cells (cell 10) was constructed to represent a metal wall typical of a Navy building. The wall was covered by a corrugated metal panel (uninsulated) manufactured by the Butler Corp. and carefully sealed. The cell was maintained in that configuration as a reference structure throughout the test period.

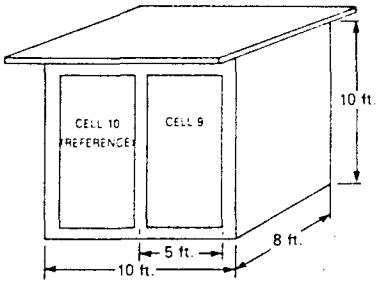



Fig. 1. Passive solar test cells.

The original color of the panel was beige, which yields a solar absorptance of about 0.6.

The variable test cell (cell 9) was initially constructed identical to the reference cell to verify that the two cells were thermally equivalent. (The reference configuration of cell 9 is hereinafter referred to as 9A.)

The building loss coefficient (BLC), defined as the amount of heat required to maintain a 1°F temperature difference between inside and outside ambient temperatures if no heat transfer through the south wall is allowed, has been measured for both cells (2). We found values of 622 and 598 Btu/DD for cells 9 and 10, respectively.

The following list provides a description of all test-cell configurations investigated during the 1982-83 heating season.

Cell 9A (Jan. 12 - Jan. 23)--Reference configuration.

Cell 9B (Jan. 24 - Feb. 8)--The south-facing metal panels on both cells 9 and 10 were painted dark brown to enhance solar absorption. The solar absorptance was 0.9.

Cell 9C (Feb. 9 - Mar. 3)--Double-walled Exolite glazing was placed about an inch in front of the radiant panel, forming a stagnant air gap between panel and glazing.

Cell 9D (Mar. 4 - Apr. 12)--A 4-in.-thick Styrofoam panel with an R-value of 20 was placed over the Exolite glazing from 5 p.m. to 8 a.m. each day to reduce nighttime heat loss through the aperture.

Cell 9E (Mar. 28 - Apr. 30)--A 4-in.-thick Styrofoam panel was placed inside the test cell approximately 3 in. behind the radiant panel. Four-inch-high vents were cut through the panel at the top and bottom to form a flow channel for thermocirculation.

In addition to testing the above configurations at a constant thermostat setpoint of 75°F, we also investigated performance in a nighttime shutdown mode. For the shutdown mode of operation, the auxiliary heating system was turned off during the hours from 5 p.m. to 8 a.m. each day.

## 3. EXPERIMENTAL RESULTS

The primary use for data taken in the passive solar test cells is to provide a basis for validating computer models for the systems under investigation. The computer models then provide the basis for investigating performance in other climates. A secondary use for test-cell data is to provide a side-by-side comparison of the performance of the reference structure and the various retrofit configurations. Such a comparison is of limited utility because each retrofit is exposed to different weather conditions. Nevertheless, direct comparison of test-cell data does provide a rough idea of the performance potential of the systems tested.

The relative solar savings fraction (RSSF) of some of the retrofit configurations is presented in Table 1. The RSSF is defined as the amount of auxiliary heat saved by the retrofit system (relative to that of the reference test cell) divided by the auxiliary heat of the reference test-cell. The following general observations are based on the results presented in Table 1.

- In the absence of night insulation and a shutdown control mode, the thermosiphon system performs better than the simple radiant panel, although both systems significantly improve the performance of the reference design. The superior performance of the thermosiphon is caused by the R20 insulated panel that drastically reduces nighttime losses.
- The use of R20 night insulation and nighttime shutdown, either singly or in combination, improves the performance of the radiant panel and the thermosiphon and tends to reduce the performance differential between the two systems.

For a truly fair estimate of the benefits of using a metal south wall as a passive solar heater, the performance of the various options should be compared to that of an insulated south wall. We have not done this experimentally, but we did calculate the energy that would be used by a test cell without night shutdown during the experimental period, if it were equipped with fixed R20 insulation on the south wall. Such insulation would provide a relative savings fraction of 0.42. We note from Table 1 that the RSSF of any of the proposed retrofit

options is much greater than 0.42, indicating that all of the solar options offer energy savings greater than that of simple insulation.

The development of computer models for the passive solar heating system considered in this investigation is discussed in the next section.

## 4. ANALYSIS

We performed modeling of the retrofit systems for metal buildings with the SUNSPOT (3,4) thermal network code for combined direct gain/thermal storage wall systems. Addition of a thermosiphon analysis and several other modifications were required. SUNSPOT is a derivative of PASOLE (5), an earlier thermal network code developed by R. D. McFarland.

TABLE 1

RELATIVE SOLAR SAVINGS FRACTION OF RETROFIT CONFIGURATIONS

| Configuration | Night Insulation | Nighttime Shutdown | RSSF |
|---|---|---|---|
| Radiant Panel 9C | No | No | 0.68 |
| Radiant Panel 9D | Yes | No | 0.84 |
| Radiant Panel 9D | Yes | Yes | 0.86 |
| Thermosiphon 9E | No | No | 0.77 |
| Thermosiphon 9E | No | Yes | 0.88 |
| Thermosiphon 9E | Yes | Yes | 0.88 |

The radiant panel system was easily modeled as a thin metal, unvented, thermal storage wall. For the thermosiphon system, we investigated two methods of calculating the flow velocity through the channel. The first method uses the numerical results of Akbari and Borgers (6,7); the second method is basically an application of Bernoulli's equation.

Akbari and Borgers carried out a detailed numerical analysis of the flow and heat transfer within the channel. They solved the detailed momentum and energy equations in finite difference form and calculated the mass flow rate and convective heat transfer to the air. Their results were correlated in terms of dimensionless parameters.

Use of the Bernoulli equation follows the method of Varcolic and Versteegen (8) who account for pressure drops by using friction factors for flow through the channel and loss coefficients for flow through the vents. After the velocity has been computed, the heat transfer is calculated using a standard empirical correlation for forced convection in a channel.

Although the Bernoulli method is not so accurate for analyzing flow within the channel, it was found to give more accurate flow rates because it accounts for the pressure drops through the vents, whereas Akbari and Borgers' method does not. Simulations performed for the test cell of Felix Trombe (9), for example, gave mass flow rates using the Bernoulli method within about 20% of the experimental data; the predictions obtained using the Akbari and Borgers method were high by more than a factor of two.

The primary addition to the SUNSPOT code was subroutine THSPH, in which the mass flow rate, average velocity, and film coefficient are computed as functions of the wall temperature, inlet air temperature, and the geometry of the channel and vents. An additional change was made in the iterative procedure used to calculate node temperatures. Although we used forward differencing with respect to time and calculated all nodal temperatures at the end of a time step simultaneously, the method is not fully implicit because the conductances associated with the thermosiphon convection and the radiative conductances are temperature dependent. Iteration is therefore required at each time step. The iterative procedure was initially unstable, and damping was required to insure convergence. An optimal damping factor gives convergence in about five iterations.

The first simulation we attempted was for test cell 9C. Comparisons of analytical predictions and experimental results are shown in Fig. 2 for the collector-surface temperature and Fig. 3 for auxiliary-heat requirements.

The difference between the predicted and measured integrated auxiliary-heat requirements is 4.0%. A simulation for test cell 9B gave similar agreement between theory and experiment.

Preliminary simulations have also been performed for test cell 9D. The results show good agreement between predicted and measured collector-surface temperatures. The predicted air temperature in the cell is significantly higher than the measured values, however, indicating that the predicted fluid velocity and mass flow rate are too high. This is probably caused by a vertical temperature gradient in the cell; the gradient was assumed to be zero in the analysis. We will be installing additional instrumentation

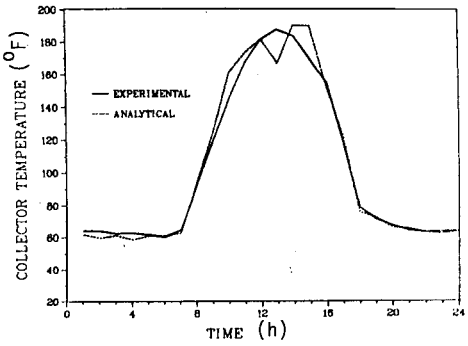



Fig. 2. Collector-surface temperature in test cell 9C.

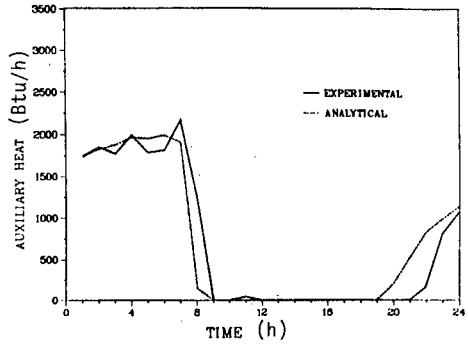



Fig. 3. Auxiliary-heat consumption in test cell 9C.

for the 1983-84 heating season to measure fluid velocities as well as air temperatures at various heights. The results of future experiments should provide a great deal of information concerning the operation of a thermosiphon heating system. The analysis will be altered to account for the effects of thermal gradients.

## 5. CONCLUSION

On the basis of experimental test-cell data, it appears that radiant panel and thermosiphon systems are viable retrofits for metal buildings. The performance of radiant panels can be significantly improved by using movable night insulation. Employing a nighttime setback or shutdown control strategy will save energy with either system.

Determination of the performance potential of metal-building retrofits in other climates awaits completion of our thermal network modeling.

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# COMPARISON OF SINGLE-ZONE GAS AND MULTI-ZONE ELECTRIC HEATING SYSTEMS FOR PASSIVE SOLAR HOMES IN THE NORTHERN UNITED STATES

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## ABSTRACT

Single zone (gas) and multi-zone (electric) heating systems are compared for five cities in Northern United States. The source energies for heating systems have been compared. The difference between source energies of two heating systems has been found to be proportional to the heating degree days. The comparison of central cooling system and multi-zoned cooling system is also made.

## 1. INTRODUCTION

In recent years considerable interest has been expressed in the use of electric heating systems for houses, with individual room temperature controllers. While such heating systems have been available for a long time, it was not until recently that renewed interest in them was expressed. This interest is primarily due to the availability of inexpensive microprocessor-based room temperature controllers. These controllers are programmable and can adjust the room heating or cooling setpoint automatically, according to a given schedule.

The main reason for the comparison of a single zone gas heating system to a multi-zone electric heating system is to determine the expected increase in energy consumption resulting from a single zone gas heating system where the entire house is assumed to be at the same temperature. Some parts of the house may not need heating at certain times; however, the zone with the thermostat does, and therefore, the entire house gets heated. In multi-zone heating systems using electric heaters, it is possible to provide heat to different zones, when needed. In addition, the heating setpoint temperature can be set back in different zones according to the occupancy. The zoned electric heating system gives the ability to control closely the temperature of various zones in the house.

On a source energy basis, a unit of electricity requires about three units of heat. Therefore, in making a comparison of gas and electricity requirements, either the price of gas and electricity or the source energy of electricity can be used. The latter approach was chosen for this study.

Computer simulations were run for a house, both as a single zone gas heated and as a multi-zone electric resistance heated. The simulations were run for a number of cities in the northern United States.

The manner in which the study was done is fairly general, so that it was possible to make a number of comparisons between single and multi-zone heating and cooling systems. For this study, only the comparison between single zone (gas) and multi-zone electric heating is being reported.

## 2. BUILDING DESCRIPTION

The building used for the study was a small three-bedroom tract house with slab-on-grade construction. The total house area was 102m$^2$ (1100 ft$^2$). The walls and ceiling were highly insulated. The total window area on the south was 8.175m$^2$ (88 ft$^2$).

The house was divided into five zones. Figure 1 shows the plan of the house along with the various zones. The largest zone is the living room which includes the hallway.

## 3. WEATHER DATA AND LOCATIONS STUDIED

The weather data used for the study were the hourly weather from National Oceanic and Atmospheric Administration (NOAA). Five cities in the northern United States were studied. These cities are:

- Burlington, Vermont
- Denver, Colorado
- Seattle Washington
- Washington, D.C.
- Pittsburgh, Pennsylvania

Each of these cities has certain peculiar climatic characteristics. For example, Burlington has high heating requirements; Denver has high heating requirements with clear weather; Seattle has moderate heating requirements with little sun in winter; Washington, D.C., has reasonable heating and cooling requirements; and Pittsburgh has high heating requirements with little sun in winter.

## 4. ASSUMPTIONS FOR COMPUTER SIMULATIONS

The computer program used for the simulations was TRNSYS [1] Version 10.2, from the University of Wisconsin. The following assumptions were made in the study.

4.1 The internal gains profile used is shown in Figure 1. The internal gains in various zones were proportioned on the basis of the floor area of the zone.

4.2 The heating setpoint temperature was assumed to follow various profiles. The profile for Zone 1 for multi-zoned house is shown in Figure 2. It is seen that the room temperature is set back at certain times when the area is not occupied. Night setback was also used in the single zone heating system simulations.

4.3 The heat transfer through walls was calculated by the ASHRAE Transfer Function method.

4.4 The doors between various zones were assumed to remain open at all times. The heat transfer through the open doors was calculated by the method given by Weber and Kearney [2, 3, 4].

4.5 The heating setpoint temperature was 21.1°C (70°F) during occupied hours and 15.5°C (60°F) during unoccupied hours.

4.6 The cooling setpoint temperature was 25.5°C (78°F). No cooling setpoint set up was used.

4.7 The cooling system for the single zone house was a central type, and for the multi-zone house, individual room air conditioners were assumed.

4.8 The orientation of the house was such that zones 2, 3 and 4 faced south.

4.9 During the summer months, all of the glass areas were assumed to have external shades on them such that the composite solar transmission through the windows was 36%.

4.10 The efficiency for the gas furnace was assumed as 71% on a yearly basis.

4.11 The rate of air infiltration was 0.5 ACH.

The time step used for the calculations was 0.25 hours. In a yearly simulation 35,040 time steps were used. The error tolerance of calculation was 0.005.

## 5. RESULTS

The results of the simulations for heating system performance are shown in Table 1 The energy required for the single zoned gas heated system is given as gas supplied. This number has considered the efficiency of the gas furnace (71%). Table 1 also gives the source energy requirements for gas and electricity. One unit of electricity was assumed as being equal to 3 units of gas. In order to reduce gas and electricity requirements to the level reference, the gas supplied (in Table 1) has been divided by 3. This gives the source energy gas as equivalent to electricity.

From Table 1 it is seen that on a source energy basis the multi-zone electric heating system uses about twice as much energy for heating as the single zone gas heating system. It is interesting to see that the difference between the source energy for gas and electric system is approximately proportional to the heating degree days.

The cooling requirements for the single zone and multi-zone cooling systems are shown in Table 2. It is seen that when no cooling setpoint set up is used, the multi-zone cooling systems are marginally better than the central cooling system. The savings for using multi-zone cooling system ranges from about 1% to 7% based on the energy requirements for single zone cooling systems.

The frequency of occurrence of the room temperature in various temperature ranges for various zones is shown in Figures 1 through 4. Figure 1 shows the frequency of occurrence of room temperature for various ranges of temperature for Burlington, multi-zone electric heating system. Room temperatures TR1 for zone 1 and TR4 for zone 4 are shown for the month of January. It is seen that the room temperature TR1 was between 16°C and 17°C for 123.75 hours. Similarly the room temperature for zone 4 was between 16°C and 17°C for 141.75 hours. Comparing the similar quantities from Figure 2 for single zone gas heating system, the hours for TR1 are 98 and for TR4 are 114. This shows that in a multi-zone heating system the room temperature for various zones had greater opportunity to approach the night setback temperature. It should be noted that in case of the gas heating system, TR1 was the control temperature (living room) indicating when to provide

heating. The temperatures in other zones for gas heating system will be any value, since they are not directly controlled. This is typical of real situations.

An examination of Figure 3 and Figure 4 shows that the room temperatures in Washington, D.C.,did not approach the night setback temperature as closely as it did in Burlington. In Washington, D.C., the single zone gas heating system rarely approached night setback temperature.

The results reported in Table 1 and Table 2 show the differences in the annual operating costs only. If the single zone (gas) and multi-zone (electric) heating and cooling systems are to be compared on a life cycle basis, then the cost of the air distribution ducts (which are necessary in central heating and cooling systems and not necessary in multi-zone heating and cooling systems) must be considered. Moreover, based on capital cost the multi-zone heating and cooling systems are slightly less expensive than the central heating and cooling systems. For multi-zone heating and cooling systems the cost of programmable thermostats needs to be considered.

The purpose of this study was to show the differences between central (gas) and multi-zone (electric) heating systems under the set of assumptions as given in Section 4 above. A complete life cycle based economic comparison was not performed.

The heat transfer through the doors between various zones was also examined. The heat exchange through the open doors between various zones is not very large; however, the transfer is enough to indicate studying the single zone (gas) and multi-zone (electric) system further with doors between zones closing and opening yielding additional insight into reality.

The heat transfer through the interior partition walls between various zones was also investigated. The transfer of heat between zones through interior partition walls is small and, therefore, not worth further investigation with insulation in the interior walls.

## 6. RECOMMENDATIONS FOR FURTHER STUDIES

It is recommended that further studies on the subject be done. Some of the parameters to study are:

6.1 Distribute the internal gains among the zones as they would be in a realistic house. For example, during the evening hours virutally all the occupants and their activities occur in the living room and the dining room only.

6.2 Investigate the effects of closing the doors between the zones at certain times.

6.3 Evaluate the single-zone (gas) and multi-zone (electric) heating and central and zoned cooling systems on a life cycle cost basis after considering the initial costs of various heating and cooling systems, the annual maintenance, etc.

6.4 A similar study should be done for the southern part of the country, which has predominant cooling requirements.

6.5 The effect of passive solar features on the differences in the energy requirements for single and multi-zone systems should be investigated.

## 7. ACKNOLWEDGMENTS

The authors wish to thank Mr. S. J. Cunningham of Southern California Gas Company, for initially sponsoring this study. Thanks are due Mr. P. Richard Rittelmann and Mr. Kenneth Argall of Burt Hill Kosar Rittelmann Associates for their valuable suggestions. Final thanks are due Ms. Tammy McGaughey for typing this manuscript.

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TABLE 1. HEATING REQUIREMENTS FOR SINGLE ZONE (GAS) AND MULTI-ZONE (ELECTRIC) SYSTEMS

| City | Single-Zone Gas (Supplied)* | Multi-Zone Electric | Source** Energy Required | | Difference Source Energy = Elect.-Gas | Heating Degree Days 65°F |
|---|---|---|---|---|---|---|
| | | | Gas | Elect. | | |
| Burlington | 59.512 | 39.192 | 19.837 | 39.192 | 19.354 | 7875 |
| Denver | 36.236 | 23.938 | 12.078 | 23.938 | 11.859 | 6016 |
| Seattle | 32.642 | 21.652 | 10.880 | 21.652 | 10.771 | 5184 |
| Washington, D.C. | 28.871 | 18.894 | 9.623 | 18.894 | 9.270 | 5009 |
| Pittsburgh | 43.253 | 28.314 | 14.417 | 28.314 | 13.896 | 5929 |

* After considering furnace efficiency of 71%
** One unit of electricity assumed equal to 3 units of gas. To make source energy comparisons, the gas (supplied) is divided by 3.

TABLE 2. COOLING* REQUIREMENTS FOR SINGLE ZONE AND MULTI-ZONE SYSTEMS

| City | Single Zone Cooling | Multi-Zone Cooling | Difference = Single Zone - Multi Zone | Difference with Respect to Single Zone % | Cooling Degree Days 65°F |
|---|---|---|---|---|---|
| Burlington | 9.422 | 9.163 | 0.259 | 2.74% | 396 |
| Denver | 14.059 | 13.894 | 0.165 | 1.17% | 625 |
| Seattle | 5.099 | 4.769 | 0.330 | 6.47% | 128 |
| Washington, D.C. | 18.048 | 17.806 | 0.241 | 1.34% | 940 |
| Pittsburgh | 12.003 | 11.849 | 0.154 | 1.28% | 646 |

* This is the energy to be removed from the space, and is <u>not</u> the electricity used to provide cooling.

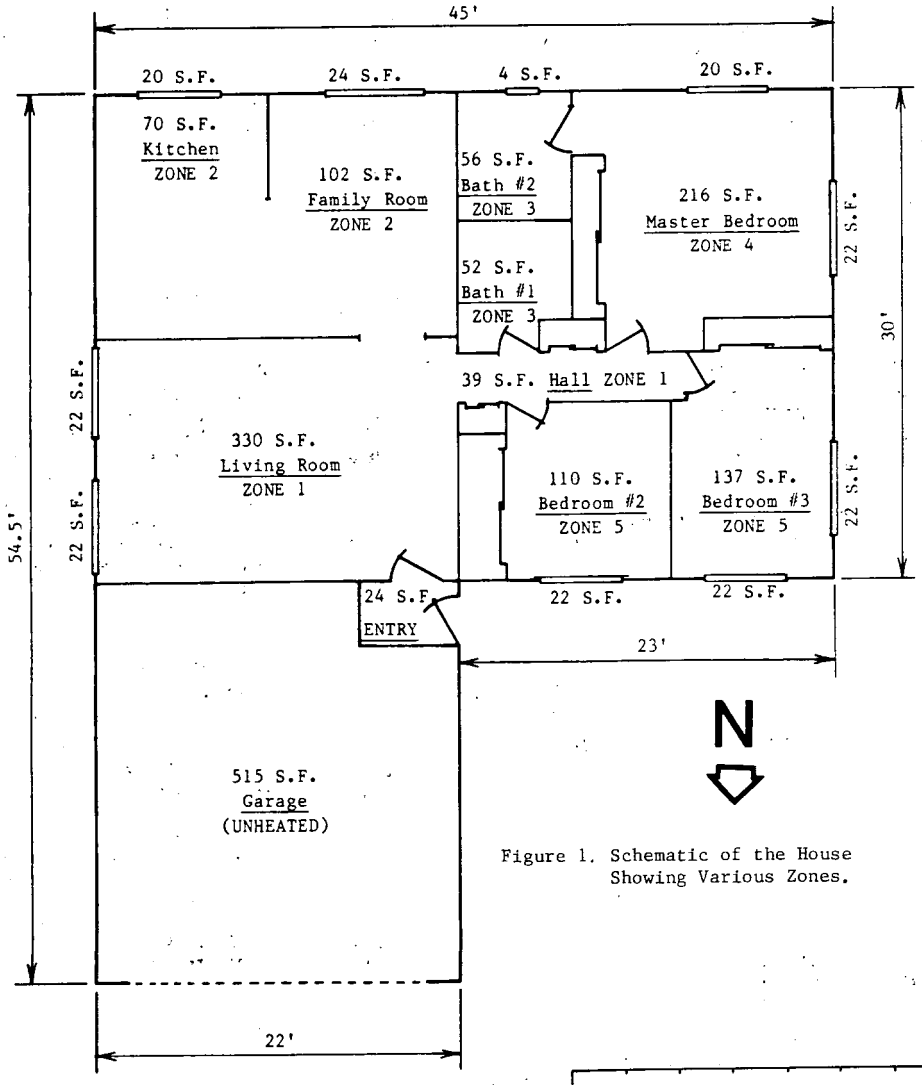



Figure 1. Schematic of the House Showing Various Zones.

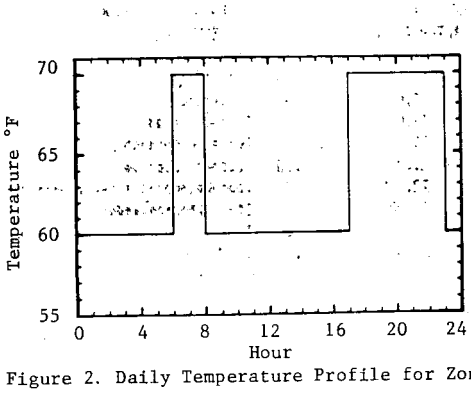



Figure 2. Daily Temperature Profile for Zone 1.

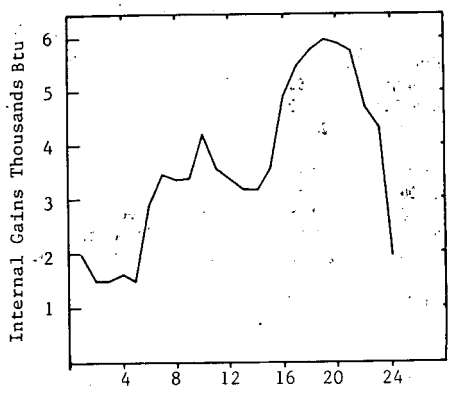



Figure 3. Internal Gains Profile.

HISTOGRAM PLOT, MODE 1 TIME= 744.000 JAN

TR1 : MIN= 15.00 MAX= 39.00

| INTERVAL ENDING | HOURS IN INTERVAL | |
|---|---|---|
| 16.00 | 238.25 | I********** |
| 17.00 | 123.25 | I***** |
| 18.00 | 133.75 | I***** |
| 19.00 | 139.25 | I***** |
| 20.00 | 70.00 | I*** |
| 21.00 | 24.50 | I* |
| 22.00 | 9.00 | I |
| 23.00 | 0.00 | I |
| 24.00 | 0.00 | I |
| 25.00 | 0.00 | I |

TR4 : MIN= 15.00 MAX= 39.00

| INTERVAL ENDING | HOURS IN INTERVAL | |
|---|---|---|
| 16.00 | 346.00 | I********** |
| 17.00 | 141.75 | I***** |
| 18.00 | 89.75 | I*** |
| 19.00 | 58.50 | I** |
| 20.00 | 46.00 | I** |
| 21.00 | 32.50 | I* |
| 22.00 | 20.25 | I |
| 23.00 | 4.25 | I |
| 24.00 | 0.00 | I |
| 25.00 | 0.00 | I |

Figure 4. Frequency of Room Temperature for Zone 1 (TR1) and Zone 4 (TR4) for Multi-Zone Electrical System, Burlington, January.

HISTOGRAM PLOT, MODE 1 TIME= 744.000 JAN

TR1 : MIN= 15.00 MAX= 39.00

| INTERVAL ENDING | HOURS IN INTERVAL | |
|---|---|---|
| 16.00 | 126.25 | I********** |
| 17.00 | 98.00 | I******** |
| 18.00 | 108.75 | I********* |
| 19.00 | 109.75 | I********* |
| 20.00 | 92.75 | I******** |
| 21.00 | 101.25 | I********* |
| 22.00 | 101.25 | I********* |
| 23.00 | 0.00 | I |
| 24.00 | 0.00 | I |
| 25.00 | 0.00 | I |

TR4 : MIN= 15.00 MAX= 39.00

| INTERVAL ENDING | HOURS IN INTERVAL | |
|---|---|---|
| 16.00 | 80.75 | I******* |
| 17.00 | 114.00 | I********** |
| 18.00 | 101.00 | I********* |
| 19.00 | 88.00 | I******** |
| 20.00 | 80.00 | I******* |
| 21.00 | 73.25 | I******* |
| 22.00 | 95.25 | I******** |
| 23.00 | 78.00 | I******* |
| 24.00 | 3.50 | I* |
| 25.00 | 0.00 | I |

Figure 5. Frequency of Room Temperatures for Zone 1 (TR1) and Zone 4(TR4) for Single-Zone Gas System, Burlington, January.

HISTOGRAM PLOT, MODE 1 TIME= 744.000 JAN

TR1 : MIN= 15.00 MAX= 39.00

| INTERVAL ENDING | HOURS IN INTERVAL | |
|---|---|---|
| 16.00 | 62.25 | I***** |
| 17.00 | 64.00 | I***** |
| 18.00 | 93.00 | I******** |
| 19.00 | 121.50 | I********** |
| 20.00 | 130.00 | I********** |
| 21.00 | 146.50 | I********** |
| 22.00 | 117.25 | I********** |
| 23.00 | 1.50 | I |
| 24.00 | 0.00 | I |
| 25.00 | 0.00 | I |

TR4 : MIN= 15.00 MAX= 39.00

| INTERVAL ENDING | HOURS IN INTERVAL | |
|---|---|---|
| 16.00 | 85.50 | I******** |
| 17.00 | 70.50 | I******* |
| 18.00 | 86.75 | I******** |
| 19.00 | 118.50 | I********** |
| 20.00 | 109.25 | I********** |
| 21.00 | 134.25 | I********** |
| 22.00 | 92.00 | I******** |
| 23.00 | 36.25 | I***** |
| 24.00 | 4.00 | I* |
| 25.00 | 0.00 | I |

Figure 6. Frequency of Room Temperature for Zone 1 (TR1) and Zone 4 (TR4) for Multi-Zone Electrical System, Washington, D.C., January.

HISTOGRAM PLOT, MODE 1 TIME= 744.000 JAN

TR1 : MIN= 15.00 MAX= 39.00

| INTERVAL ENDING | HOURS IN INTERVAL | |
|---|---|---|
| 16.00 | 23.00 | I** |
| 17.00 | 33.75 | I*** |
| 18.00 | 78.75 | I******* |
| 19.00 | 95.50 | I******** |
| 20.00 | 113.25 | I********** |
| 21.00 | 183.50 | I********** |
| 22.00 | 200.75 | I********** |
| 23.00 | 7.50 | I* |
| 24.00 | 0.00 | I |
| 25.00 | 0.00 | I |

TR4 : MIN= 15.00 MAX= 39.00

| INTERVAL ENDING | HOURS IN INTERVAL | |
|---|---|---|
| 16.00 | 21.50 | I** |
| 17.00 | 43.00 | I*** |
| 18.00 | 59.25 | I***** |
| 19.00 | 78.25 | I******* |
| 20.00 | 101.50 | I********** |
| 21.00 | 98.75 | I********** |
| 22.00 | 200.50 | I********** |
| 23.00 | 116.00 | I********** |
| 24.00 | 13.50 | I* |
| 25.00 | 0.00 | I |

Figure 7. Frequency of Room Temperature for Zone 1 (TR1) and Zone 4 (TR4) for Single-Zone Gas System, Washington, D.C., January.

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# PERFORMANCE OF INTEGRATED PASSIVE SOLAR WATER HEATERS IN U.S. CLIMATES

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## ABSTRACT

Results presented are based on partially validated, hourly simulations of passive solar domestic water heating systems for selected typical years in 10 cities. The simulated system is an integrated (or "breadbox") collector/storage unit plumbed as a preheater for a conventional gas or electric heater. The base case unit was latitude tilted and contained 4 cylindrical tanks plumbed in series within an R16 box. The aperture and projected absorber area were 1.62 $m^2$, and total tank volume was 145 liters. Water draw was 151 liters/day at 50°C. A variety of design performance sensitivity results are presented. The single-glazed, selective absorber design is recommended. For this design the passive heater delivered 42% to 51% of the annual solar irradiance to the load. Corresponding solar savings fractions ranged from 0.27 (Seattle) to 0.64 (Phoenix). System efficiency decreases significantly as area and solar savings fraction increase beyond the base case. Night insulation (R9) increases base case delivered energy by about 20% in cold and warm climates. Freezing is unlikely except in the coldest climates. If the installed cost of the single-glazed, selective unit is $420 after tax credits, the simple payback period when displacing electricity is about 5 years in all cities except Seattle.

## 1. INTRODUCTION AND OBJECTIVES

Integrated collector/storage passive solar hot water heaters are among the simplest of solar technologies. The "breadbox" version (a cylindrical tank or tanks inside an insulated box with a transparent top) has been a popular owner-built solar device. The insulated box design and the glazed cylinder design have been commercially available for several years. The nearly universal need for domestic water heating and the simplicity and potential low cost of the integrated collector/storage passive water heater make this an important solar technology.

It is widely believed that integration of the storage with the collector results in excessive heat losses through the glazing(s) during nights and cloudy weather. As a result, many people believe that the integrated passive water heater is inefficient and prone to freezing in all but the warmest climates. This report presents the results of a partially validated simulation of the performance of integrated passive water heaters in U.S. climates.

Although, the performance impacts of a variety of design options are included, this analysis is restricted to one design concept. The simulated design is a rectangular insulated box containing one or more series plumbed cylindrical tanks. The solar absorbing surface formed by the top(s) of the tank(s) is assumed to "fill" the glazing aperture. The passive heater is plumbed as a preheater in the main water line to a conventional gas or electric heater. This type of integrated passive heater is designated IPH in this report. The performance effects of most design options are simulated in warm and cold climates. These include:

- R9 night insulation
- multiple glazings
- selective surface absorber
- multiple tank temperature stratification
- time of water draw
- storage volume per area
- installed area (solar savings fraction)

## 2. ADVANTAGES OF THE IPH CONCEPT

In comparison to active solar domestic hot water systems, the IPH offers the advantage of simplicity and the resulting potential of lower installed cost. No pumps, controls, heat exchangers or antifreeze are required. Maintenance is minimized, and no parasitic power is required.

The IPH shares some of these advantages with thermosyphon passive heaters, but the IPH concept also has advantages over the thermosyphon system. The conventional

thermosyphon collector operates at a temperature 10°C to 20°C above the storage temperature. As a result, during clear periods the thermosyphon collection efficiency is slightly lower than the IPH efficiency. The higher peak temperatures and tube-in-sheet absorber plate design also makes the thermosyphon collector more susceptible to carbonate scale deposits than the IPH.

In the conventional thermosyphon water heater, nocturnal thermosyphon flow is deliberately suppressed in order to prevent nocturnal heat losses. As a result of this deliberate nocturnal decoupling of the collector from the thermal mass of storage, and the tube-in-sheet design, the thermosyphon collector is more susceptible to freezing than the integrated passive water heater. The thermosyphon type solar water heater is then considered applicable only in climates which do not have extended periods of sub-freezing temperatures and where the makeup water does not produce scale.

The coupling of significant thermal mass to the collector surface stabilizes the nocturnal temperature of the IPH and makes it freeze resistant. If constructed as a large volume cylinder which can tolerate city mains water pressure, the IPH is tolerant of partial freezing. If the IPH is constructed as a series of separate tanks, the IPH can provide the temperature stratification benefits of the thermosyphon system.

## 3. SIMULATION AND DESIGN ASSUMPTIONS

The hourly simulation attempts to account as rigorously and accurately as practical for all of the heat transfers which are significant for an IPH. The environmental assumptions, data and methods utilized are:

- Hourly typical meteorological year data selected from SOLMET data tapes.
- Separation of insolation into direct and diffuse components by the method of Erbs, Klein and Duffie (1).
- ground solar reflectance = 0.2 (except 0.5 if snow).
- Effective sky temperature was calculated using the Berdahl and Fromberg dewpoint relation (2) and a new cloud correction by Clark and Blanpied (3). Ground emittance was 0.9 and ground temperature was calculated from dry-bulb, insolation and sky temperature (4).
- Inlet water temperature was varied monthly based on local water temperature data.

The "base case" system design assumptions are:

- Installation at latitude tilt.
- Net glazing aperture = 1.62 $m^2$.
- Net water storage volume = 145 liters (38.2 gal) in 4 series tanks.
- The enclosure insulation resistance was 2.8 $m^2$°C/W (R16).
- Non selective absorber emittance (E) is 0.95 and selective absorber has E = 0.10.
- Glazing(s) have n = 1.53, thickness = .0032m and absorption coefficient = 6 $m^{-1}$. They have gap spacing of 2.5 cm.
- Effects due to enclosure shading of the absorber and a 2% dust factor are included.
- Convective losses from the non-planar absorber surface are calculated using the method reported in (5). These convective losses are as much as 20% greater than the typical flat plate convective losses for the single-glazed selective case.
- A heat transfer factor of 4.5 kJ/hr°C was used between tanks inside the IPH.
- Turbulent mixing during draw results in 5% of the water entering each IPH tank exiting that tank during the draw. (This effect decreases the benefits of multitank stratification.)
- The backup heater set point was 50°C (122°F) and it had a storage volume of 151 liters (40 gal) and a standing loss coefficient of 4 W/°C to a conditioned space temperature.
- Water draw was 151 liter/day at 50°C. (This is a typical volume for 2 people or a very conserving family of 4.) If the standing water is preheated above 50°C , a mixing valve reduces the effective draw temperature to 50°C.
- The gas backup burner efficiency was 0.75 and the electric heater efficiency was 1.0.

Additional details of the simulation and other aspects of this report are provided in (4).

## 4. PARTIAL VALIDATION OF SIMULATION

The simulation algorithms used were partially validated by comparison of simulated IPH outlet temperatures with outlet temperatures

measured for a Gulf Thermal model PT40 by Florida Solar Energy Center. Data included two consecutive test days (October 12 and 13) with known initial and final internal temperature conditions in the IPH. On these two days the insolation on the horizontal exceeded 1500 Btu/ft$^2$ day and water draws of 0.50 of the IPH storage volume were made at 0700, 1200 and 1700 hours. The Gulf Thermal design was very similar to the base case design defined in Section 3. (Same area and storage volume, but triple glazed.)

After modification of the simulation to account for the 2 plastic internal glazings and a glass external glazing and assuming a turbulent mixing ratio of 0.20 (20% of the water drawn from each tank is water entering the tank) and inter-tank heat transfer of 20 kJ/hr$^\circ$C, agreement between simulation and data was satisfactory. The average difference between the measured and simulated draw temperature was less than 1$^\circ$C for the six test draws. The maximum difference was 2.5$^\circ$C, and no obvious diurnal pattern remained in the differences. Of course, with the variety of adjustable parameters which can lead to cancelling errors, we do not claim a complete validation. Extrapolation is also necessary when the model is applied in climates more extreme than the mild conditions which occurred during the test. A more complete and definitive validation of the simulation algorithm is now in progress at Trinity.

## 5. REGIONAL PERFORMANCE DESIGN SENSITIVITY

Table 1 lists the simulated solar energy delivered to the load for the base design. The ten cities listed are chosen to represent U.S. solar-meteorological climate regions. Table 1 illustrates the benefits of a selective emitter and multiple glazings in these widely varied climates. On the basis of annual collected energy, the single-glazed selective design is preferred.

The additional energy collected due to the (single-glazed) selective surface would provide a cost effective payback in all climates. However, due to decreased net transmittance, a double glazing on a selective IPH produces either negigible benefit or a slight decrease in collected energy.

Table 2 provides further performance (and climate) information for the single glazed selective case. For the base case load and base case IPH area, the solar savings fraction (SSF) was low in cool, cloudy climates; the SSF ranged from 0.27 in Seattle to 0.64 in Phoenix. The average solar collection efficiency (defined as annual solar heat delivered to the load divided by annual insulation on the net aperture plane) was relatively high in all climates; efficiency ranged from 0.42 in Santa Maria to 0.51 in Seattle. In mild cloudy climates the collection efficiency is high, but the solar savings fraction is low.

TABLE 1. ANNUAL DELIVERED ENERGY (GJ) FOR VARIOUS GLAZING AND SELECTIVE ABSORBER OPTIONS
(Standard 1.62 m$^2$ Integrated Passive Water Heater)

| CITY | 1GN | 1GS | 2GN | 2GS | 3GN | 3GS |
|---|---|---|---|---|---|---|
| ATLANTA, GA | 2.78 | 4.01 | N.A. | 4.14 | N.A. | N.A. |
| BISMARK, ND | 3.63 | 4.60 | N.A. | 4.52 | N.A. | 4.28 |
| COLUMBIA, MO | 3.53 | 4.51 | 3.98 | 4.49 | 3.94 | 4.23 |
| DENVER, CO | 4.19 | 5.43 | N.A. | 5.48 | N.A. | 5.19 |
| MIAMI, FL | 3.83 | 4.86 | 4.25 | 4.79 | N.A. | N.A. |
| PHOENIX, AZ | 4.67 | 5.99 | 5.31 | 6.04 | N.A. | N.A. |
| SANTA MARIA, CA | 3.69 | 4.92 | N.A. | 5.00 | N.A. | N.A. |
| SAN ANTONIO, TX | 3.54 | 4.64 | 4.07 | 4.65 | N.A. | 4.40 |
| SEATTLE, WA | 2.89 | 3.64 | 3.12 | 3.50 | N.A. | N.A. |
| WASHINGTON, DC | 2.71 | 3.69 | N.A. | 3.71 | N.A. | N.A. |

TABLE 2. SOLAR SAVINGS FRACTION, DELIVERED ENERGY (GJ), COLLECTOR EFFICIENCY, AVERAGE CLEARNESS INDEX (KT)

151 LITERS/DAY DRAW FOR THE STANDARD 1.62 $m^2$ SINGLE GLAZED SELECTIVE COLLECTOR (1GS)

| CITY | SSF | ANNUAL ENERGY DELIVERED(GJ) | AVERAGE COLLECTION EFFIC. | ANNUAL AV. TEMP. (°C) | AVERAGE OF MONTHLY KT |
|---|---|---|---|---|---|
| ATLANTA | .40 | 4.01 | .43 | 15.9 | .50 |
| BISMARK | .32 | 4.60 | .48 | 5.0 | .54 |
| COLUMBIA | .37 | 4.51 | .47 | 12.3 | .52 |
| DENVER | .43 | 5.43 | .44 | 10.1 | .68 |
| MIAMI | .54 | 4.86 | .47 | 23.6 | .52 |
| PHOENIX | .64 | 5.99 | .44 | 20.8 | .69 |
| SANTA MARIA | .48 | 4.92 | .42 | 13.3 | .60 |
| SAN ANTONIO | .50 | 4.64 | .44 | 20.0 | .54 |
| SEATTLE | .27 | 3.64 | .51 | 11.3 | .46 |
| WASHINGTON | .32 | 3.69 | .43 | 13.6 | .47 |

Increasing the installed area of the IPH increases the SSF but significantly decreases the efficiency. Table 3 lists the effects of increased IPH area in Denver. For the single-glazed selective IPH, the efficiency declined from 0.56 to 0.30 as the SSF increased from 0.27 to 0.57.

TABLE 3.

SOLAR SAVINGS FRACTION AND COLLECTOR EFFICIENCY AS A FUNCTION OF APERTURE AREA FOR SINGLE AND DOUBLE GLAZED SELECTIVE SURFACE COLLECTORS IN DENVER

| | ----1GS----- | | ----2GS----- | |
|---|---|---|---|---|
| AREA ($m^2$) | SSF | EFFIC. | SSF | EFFIC. |
| .809 | .27 | .56 | .26 | .54 |
| 1.617 | .43 | .44 | .43 | .45 |
| 2.426 | .52 | .36 | .55 | .38 |
| 3.234 | .57 | .30 | .62 | .33 |

The effects of R9 night insulation on annual energy delivered is listed in Table 4. For the selective single-glazed IPH, night insulation increases annual delivered energy by 17 to 20% in warm and in cold climates. This result also provides an estimate of nocturnal losses for this design. Although the additional energy is significant, the benefit is not enough to justify the additional cost and complexity of night insulation. The benefit of night insulation for the non selective IPH is about the same as the change to a selective surface.

TABLE 4.

EFFECT OF R9 NIGHT INSULATION (NI) ON ANNUAL DELIVERED ENERGY (GJ) FOR SELECTIVE AND NON-SELECTIVE SINGLE GLAZED INTEGRATED WATER HEATERS

| CITY | 1GN | 1GNNI | 1GS | 1GSNI |
|---|---|---|---|---|
| BISMARK | 3.63 | 4.64 | 4.60 | 5.41 |
| COLUMBIA | 3.53 | 4.51 | 4.51 | 5.29 |
| DENVER | 4.19 | 5.52 | 5.43 | 6.50 |
| PHOENIX | 4.67 | 6.09 | 5.99 | 7.11 |

Table 5 lists the effect of the number of tanks on energy delivered per month in selected cities. As expected the temperature stratification benefits of multiple tanks in series was significant. The primary benefit (about 20% in the warmer examples) occurs as a result of the increase to two tanks. The two tank benefit is also available if two single-tank enclosures are installed in series.

TABLE 5.

DELIVERED ENERGY (MJ) AS A FUNCTION OF THE NUMBER OF TANKS WITHIN THE COLLECTOR

| NUMBER OF TANKS | ----DELIVERED ENERGY (MJ)----- DENVER JANUARY | COLUMBIA APRIL | PHOENIX AUGUST |
|---|---|---|---|
| 1 | 129 | 156 | 484 |
| 2 | 137 | 200 | 604 |
| 3 | 143 | 208 | 628 |
| 4 | 146 | 212 | 642 |
| 6 | 149 | 217 | 655 |

The sensitivity of net collected energy to a variation in storage volume per area was simulated for the single glazed selective IPH in Miami and Phoenix and the double glazed selective IPH in Columbia. For the base case area (1.62 $m^2$) and other base case assumptions, the storage volume per area had a negligible effect on net collected energy for the range of values considered here (40 l/m2 - 160 l/$m^2$). However, boiling and freezing became more likely for the smaller storage volume option.

The effects of changing the time of draw were found to be significant for an IPH. The base case draw had a strong morning peak with 38% of the daily draw provided before 10 AM and 50% before 2 PM. In San Antonio, the single-glazed selective IPH delivered 11% less annual energy than the base case when 50% of the water draw occured before 10 AM.

The simulation used here is unusual in attempting to include the thermal effects of the sky temperature depression and resulting radiant heat losses. Radiant heat loss to the environment was evaluated by resimulating the IPH with the effective environmental temperature equal to the ambient dry bulb temperature (the conventional approximation). We found that omission of infrared losses from the outer glazing to the environment produces approximately a 5% overestimate of annual energy collected in warm climates. The percent error is much larger in all climates in winter months because of the larger sky temperature depression which occurs during low dewpoint winter weather. Omission of sky temperature depression effects leads to overestimates of about 15% in monthly collected energy for a single glazed selective IPH in a cold winter climate (e.g., Denver or Columbia in January).

## 6. FREEZING

The IPH relies on the large thermal mass of the storage volume and the heat in entering make up water to prevent freezing. Table 6 lists the low temperatures experienced by the single and double glazed selective IPH during a typical year. Strong cylindrical tanks can tolerate some freezing without bursting (e.g., Sunwizard Inc. claims tolerance of up to 8% of water frozen). Freezing of the 1GS occured only in Bismark and Denver. The 1GS IPH was 20% frozen in Bismark and 5% frozen in Denver. The 2GS IPH became 10% frozen in Bismark.

TABLE 6.

LOW TEMPERATURES (°C) EXPERIENCED BY THE BASE CASE IPH DURING A TYPICAL WINTER

For those cases in which the IPH reaches freezing temperatures, the maximum percent of water frozen is listed in parentheses.

| CITY | 1GN | 1GS | 2GS | 3GS |
|---|---|---|---|---|
| ATLANTA | 3 | 7 | 10 | - |
| BISMARK | (35%) | (20%) | (10%) | (5%) |
| COLUMBIA | (10%) | 0.5 | 4 | 6 |
| DENVER | (11%) | (5%) | 2 | 4 |
| MIAMI | 13 | 17 | 19 | - |
| PHOENIX | 8 | 13 | 16 | - |
| SANTA MARIA | 8 | 11 | 13 | - |
| SAN ANTONIO | 9 | 13 | 17 | 18 |
| SEATTLE | (1%) | 3 | 5 | - |
| WASHINGTON, D.C. | (6%) | 0.5 | 4 | - |

Two other conditions can increase the probability of freeze damage beyond that suggested by Table 6. Extended periods of no draw (e.g., family winter vacation) can increase freeze probability during extremely cold and cloudy periods. Extended periods of aberrantly cold weather would also increase freezing of storage water and associated probability of damage.

In order to evaluate these two effects, the previous typical year (TMY) base case simulations were repeated with two changes. The hourly ambient dry bulb, dewpoint and environmental infrared temperatures for the TMY were reduced sufficiently to create record cold temperatures in the five coldest

cities. The dewpoint and dry bulb temperatures were decreased 4°C in Bismark (where TMY ambient temperatures reach -38°C), 11°C in Columbia and 8°C in Denver and in Seattle. No change was necessary in Washington, D.C.

Table 7 lists the results of these simulations for a selected IPH type in each cold city. Results are shown for two draw patterns, the base-case water draw and no-water draw during January and February. Freezing occured during record cold in all cities except Washington. Because the 1GS IPH provided sufficient protection to prevent freezing even under extreme circumstances in Washington, we can assume this option prevents freezing under these circumstances in the warmer cities.

TABLE 7.

EFFECTS OF WATER DRAW AND RECORD COLD ON MINIMUM TEMPERATURES (°C) AND PERCENT STORAGE MASS FROZEN (January and February only) (Percent of mass frozen is listed in parentheses.)

| CITY | IPH TYPE | BASE WATER DRAW TMY | BASE WATER DRAW COLD | NO WATER DRAW TMY | NO WATER DRAW COLD |
|---|---|---|---|---|---|
| BISMARK | 3GS | (.5%) | (2%) | (5%) | (10%) |
| COLUMBIA | 2GS | 4 | (2%) | 5 | (10%) |
| DENVER | 2GS | 2 | (2%) | 1 | (10%) |
| SEATTLE | 1GS | 3 | 0.5 | 2 | (6%) |
| WASHINGTON | 1GS | 1 | 1 | .5 | .5 |

Two other freeze protection strategies are effective. The cheapest is drainage and bypass of the IPH during unusual circumstances. The second possibility is night insulation. If applied only during extraordinarily cold or no-draw periods, the inconvenience of low cost night insulation may be acceptable. Simulated night insulation provided excellent freeze protection with normal water draw during TMY periods. In Bismark the R-9 night insulated 1GS IPH minimum temperature was 6.4°C.

## 7. ECONOMIC BENEFITS

The annual values of natural gas and electricity displaced by the base case IPH are listed in Table 8. These annual values are based on city specific utility rates as of May, 1982. It is noteworthy that city to city variations in utility rates are more important than solar savings fraction when estimating fuel cost saved by one IPH.

Current wholesale distributor costs of an IPH similar to our base case design vary from $400 to $800 depending on quantity and manufacturer. Retail installed prices for this type of IPH are typically $1,800, but may be as high as $2,400 in California. If we assume that competition and efficient mass production decrease the retail installed cost of the base case unit to $700, the after Federal tax credit cost will be $420. The 10 city average annual gas savings of the 1GS IPH was about $30 in May, 1982, and the simple payback, including Federal tax credits, is 14 years. Simple payback against electric resistance heat averages about five years (excluding Seattle) and is 3.5 years in Miami.

TABLE 8.

FIRST YEAR VALUE OF FUEL SAVINGS FOR BASE CASE INTEGRATED PASSIVE HEATER.

(Based on aperture area 1.62 $m^2$, fuel prices as of May, 1982, fuel burning efficiency = 0.75 for natural gas and 1.0 for electricity.)

| | 1GN | | 1GS | | 2GS | |
|---|---|---|---|---|---|---|
| | GAS ($) | ELEC ($) | GAS ($) | ELEC ($) | GAS ($) | ELEC ($) |
| ATLAN | 19 | 59 | 25 | 79 | 26 | 82 |
| BISM | 31 | 55 | 39 | 70 | 39 | 69 |
| COLUM | 17 | 61 | 21 | 79 | 21 | 78 |
| DENV | 23 | 86 | 30 | 112 | 30 | 113 |
| MIAMI | 24 | 91 | 31 | 115 | 30 | 113 |
| PHNX | 35 | 82 | 45 | 105 | 45 | 106 |
| SM,CA | 23 | 72 | 30 | 96 | 31 | 97 |
| SA,TX | 19 | 58 | 25 | 76 | 25 | 76 |
| SEATT | 24 | 33 | 31 | 42 | 30 | 40 |
| WASH | 21 | 51 | 29 | 70 | 29 | 70 |

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# SUNSPACE PERFORMANCE AND DESIGN FLEXIBILITY IN THREE CLIMATES

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## ABSTRACT

In the struggle to achieve a livable, affordable, and appealing solar architecture, the sunspace stands out as a much maligned and often misunderstood entity. Subjects of costs, materials, size, use, structural integration, and even appropriateness are controversial among practitioners. But most solar designers will agree that sunspace configurations with glazing restricted to the south face, with roof and endwalls insulated, produce the greatest energy benefits for the home to which it is attached. This notion is supported by analytical studies and the common-sense physics of solar collection and abundantly reinforced by the popular solar literature.

In fact, this so-called "optimum" design geometry may offer minimal or no net energy benefits to homeowners over more highly glazed configurations, while considerably constraining the design. The conclusion for designers and contractors of sunspace projects is to recommend and implement projects that satisfy their clients' functional and aesthetic needs and desires. Energy savings, at least over a broad range of climates and designs, will not be compromised.

## 1. INTRODUCTION

This paper does not report on any new design methodology or analytical techniques. The data presented here could be generated by anyone familiar with the SLR method of passive solar design performance prediction. The paper is a plea for freedom in design.

Passive solar design is inherently forgiving and flexible. The paper demonstrates this by comparing auxiliary energy usage for several different sunspace geometry and glazing configurations on a typical (hypothetical) residence in three climates: Anchorage, Alaska; Seattle, Washington; and Denver, Colorado.

## 2. METHODOLOGY

A typical, reasonably well insulated home was modeled to provide the heating requirement for the different sunspaces. Floor area was set at 1,500 square feet; the home was insulated to R-30 in ceiling and floor and to R-19 in the walls. 225 square feet of double glazing with ½" air space and wood or thermally broken frames (U=.53) were assumed to be randomly distributed on all four walls of the house. No glazing was assumed in the R-20 insulated wall common with the sunspace.

The performance of the home alone, and with each of five different sunspace configurations, was calculated using the SLR method and the correlations published in Volume 3 of the Passive Solar Design Handbook (1). The configurations are described in Table 1; they correspond to the configurations built into the SLR correlations in Volume 3 except Case 3A as noted. The LCR s of the options have been adjusted so that all sunspaces are the same size; they are 30 feet long, 5½ feet deep, and 9 feet tall at the common wall. The Volume 3 reference sunspace characteristics have been used for all other sunspace parameters. Among these is that the sunspace is maintained at 45$^0$ F by auxiliary heating.

Weather data for Seattle and Denver were obtained from Volume 3; Anchorage solar data were based on horizontal solar data from "Insolation on South-facing Tilted Surfaces for Pacific Northwest Locations"(2) modified for tilt by the Duffy-Beckman model. Anchorage temperature data were obtained from Climates of the United States(3).

The SLR calculations were made with the SUNPAS program by SolarSoft of Snowmass, Colorado, on an Apple microcomputer.

## 3. RESULTS

Tables 2 through 4 show auxiliary energy usage for the base case house and each of the sunspace alternatives for the three climates

studied: Anchorage, Seattle, and Denver.

TABLE 1.

| OPTION | VOLUME 3 SUNSPACE CONFIGURATION | SUNSPACE CHARACTERISTICS |
|---|---|---|
| Base Case | No sunspace | |
| 1 | B7 | All glass; attached to house |
| 2 | B5 | Glass roof and south wall; attached |
| 3 | C3 | Glass south wall; recessed into house |
| 3A | C3 with insulated endwall losses added | Glass south wall; attached |
| 4 | E3 | Glass roof and south wall; recessed |

TABLE 2. AUXILIARY HEATING IN MILLIONS OF BTU

| ANCHORAGE | CASE | | | | | |
|---|---|---|---|---|---|---|
| MONTH | BASE | 1 | 2 | 3 | 3A | 4 |
| Jan | 13.2 | 12.9 | 12.8 | 12.7 | 12.8 | 12.9 |
| Feb | 10.2 | 9.6 | 9.5 | 9.6 | 9.6 | 9.5 |
| Mar | 8.7 | 6.8 | 6.8 | 7.0 | 7.0 | 6.5 |
| Apr | 5.6 | 3.8 | 3.9 | 4.3 | 4.3 | 3.6 |
| May | 2.8 | 1.4 | 1.4 | 1.8 | 1.8 | 1.2 |
| June | .6 | .1 | .1 | .2 | .2 | .1 |
| July | .1 | ---- | ---- | ---- | ---- | ---- |
| Aug | .6 | .1 | .1 | .2 | .2 | .1 |
| Sept | 3.3 | 2.1 | 2.1 | 2.3 | 2.4 | 1.9 |
| Oct | 6.7 | 5.7 | 5.7 | 5.7 | 5.8 | 5.5 |
| Nov | 10.3 | 10.0 | 9.9 | 9.9 | 10.0 | 10.0 |
| Dec | 14.0 | 14.2 | 14.2 | 14.2 | 14.3 | 14.5 |
| Total | 76.2 | 66.6 | 66.5 | 67.9 | 68.3 | 65.8 |

TABLE 3. AUXILIARY HEATING IN MILLIONS OF BTU

| DENVER | CASE | | | | | |
|---|---|---|---|---|---|---|
| MONTH | BASE | 1 | 2 | 3 | 3A | 4 |
| Jan | 6.7 | 4.6 | 4.6 | 4.7 | 4.7 | 4.3 |
| Feb | 5.3 | 3.4 | 3.4 | 3.6 | 3.6 | 3.1 |
| Mar | 4.6 | 2.6 | 2.6 | 3.0 | 3.1 | 2.4 |
| Apr | 2.0 | .7 | .8 | 1.1 | 1.1 | .6 |
| May | .4 | ---- | ---- | .1 | .1 | ---- |
| June | ---- | ---- | ---- | ---- | ---- | ---- |
| July | ---- | ---- | ---- | ---- | ---- | ---- |
| Aug | ---- | ---- | ---- | ---- | ---- | ---- |
| Sept | ---- | ---- | ---- | ---- | ---- | ---- |
| Oct | 1.2 | .3 | .3 | .3 | .3 | .2 |
| Nov | 4.2 | 2.4 | 2.4 | 2.5 | 2.5 | 2.2 |
| Dec | 6.2 | 4.3 | 4.3 | 4.3 | 4.4 | 4.0 |
| Total | 30.7 | 18.4 | 18.3 | 19.7 | 19.8 | 16.8 |

TABLE 4. AUXILIARY HEATING IN MILLIONS OF BTU

| SEATTLE | CASE | | | | | |
|---|---|---|---|---|---|---|
| MONTH | BASE | 1 | 2 | 3 | 3A | 4 |
| Jan | 6.3 | 5.9 | 5.9 | 6.1 | 6.1 | 5.9 |
| Feb | 4.4 | 3.5 | 3.5 | 3.7 | 3.7 | 3.4 |
| Mar | 4.0 | 2.7 | 2.7 | 3.0 | 3.0 | 2.5 |
| Apr | 2.4 | 1.2 | 1.2 | 1.6 | 1.6 | 1.1 |
| May | .9 | .2 | .2 | .4 | .4 | .2 |
| June | .2 | ---- | ---- | ---- | ---- | ---- |
| July | ---- | ---- | ---- | ---- | ---- | ---- |
| Aug | ---- | ---- | ---- | ---- | ---- | ---- |
| Sept | .2 | ---- | ---- | ---- | ---- | ---- |
| Oct | 2.0 | 1.0 | 1.0 | 1.1 | 1.1 | .9 |
| Nov | 4.2 | 3.5 | 3.5 | 3.6 | 3.6 | 3.4 |
| Dec | 5.7 | 5.5 | 5.5 | 5.6 | 5.6 | 5.5 |
| Total | 30.3 | 23.6 | 23.6 | 25.1 | 25.2 | 22.9 |

A separate run of different sunspace configurations for the same house with windows eliminated shows comparable results, with a reduction in overall load, but the differences between the sunspace configurations are not significant.

## 4. DISCUSSION

A fundamental feature of passive solar designs is "load-coupled collection"; that is, the same glazing that admits solar heat is also a significant source of building heat loss. This explains the incredible power of night insulation in improving passive system performance.

Sunspaces are much less subject to this load coupling effect, particularly when they are separated from the house by an insulated wall. To a large extent, the energy savings of a sunspace could be explained by the extent to which it buffers the building from weather extremes.

But wouldn't one expect an efficient design configuration to be more critical in more severe northerly climates? An argument can be made that this is definitely not the case. During the mid-winter months, when low sun angles and narrow azimuth variation argue for steeply pitched, south-facing glazing, solar contribution is minimal at best. This is a consequence of short day length, low solar intensity, and severe cold which reduces collection efficiency.

During the spring and fall months, higher solar altitudes and wider azimuth variation argue for more widely distributed glazing (i.e., roof and endwalls). Significant degree-day accumulation, even through the summer in many northern climates, assures that the increased solar collection will not be wasted.

The more conservative sunspace design, with its insulated roof and endwalls, will be a more efficient solar collector and likely a better buffer against outside weather extremes. More highly glazed designs, on the other hand, will be better "gross collectors" of solar energy, particularly in the spring and fall months.

The apparent indifference of sunspace performance to design configuration should not come as any surprise to students of SLR performance prediction and LCR climate correlations. The design sensitivity curves for sunspace systems are fairly flat for a wide variety of system parameters(1). And even differences that appear to be significant on the basis of predicted solar savings fractions (SSF) can often be negligible when translated into auxiliary energy usage.

This article does not endorse the "three mutually exclusive uses" theory of solariums, widely discussed in the popular literature(4). Those three uses - efficient solar collector; fair-weather, high-style living space; and plant growing environment - can be quite compatible. As we've already demonstrated, the most efficiently designed collection geometries don't always lead to the lowest heating bills. As for using a solarium as a living space extension, triple glazing or one of the new clear, low emission glazings might be considered. In any event, supplemental heat should be provided by efficient "task" heaters, perhaps radiant panels on timers, so comfort can be provided temporally at minimal expense.

The third usage, greenhouse gardening, is slightly more problematic. Of course, important determinants here will be climate and horticultural subjects selected. Photosensitivities and wintertime lighting requirements argue for highly glazed designs, which we've already demonstrated are not in conflict with solar performance.

Evapotranspiration can be a significant energy flow in greenhouses. But soil, pot, bench and walkway evaporation may be even more significant. Plastic pots, runoff collection systems, and other greenhouse management practices will minimize evaporation losses. Tight solarium design with an air-to-air heat exchanger can maintain appropriate humidity levels and provide a source of latent heat recovery. Even moisture condensing on the glass is a source of latent heat generation. Conservative greenhouse practices, such as letting the greenhouse run cool and dry in the winter, will assure minimal interference with solar collection functions. This may also be a good horticulture practice, corresponding to the seasonal resting period which benefits many plant subjects.

Little mention has been made of summertime conditions. Of course, more highly glazed designs will be more prone to overheating. But this can be easily overcome by shading and ventilation, accompanied by evaporative cooling in hotter dry climates. Adequate overheating controls must be included in any solarium project, especially where west-facing or overhead surfaces are glazed.

## 5. CONCLUSION

Sunspace performance is not as sensitive to design geometry and glazing configuration as is perhaps widely believed. This is evidenced by the fairly flat sensitivity curves that define solar heating system performance by the LCR method(1) and as demonstrated here by auxiliary energy usage predictions for different sunspace designs in three climates.

Low-energy shelter can be created alternatively by emphasizing conservation and insulation or solar collection and storage. Similarly, sunspaces can contribute to home heating through efficient collection and thermal buffering or by being better "gross collectors" of solar heat with more episodic and seasonal heating benefits.

The message for designers and contractors is to not get too hung up on so-called "rules of thumb" for solar design. Sunspace projects should be thermally isolated from the house, provided with thermal mass appropriate for their size and anticipated use, and supplied with properly sized mechanisms for transferring useful solar heat into the house. Shading and ventilation should be provided as needed for summertime comfort. But the actual design configuration and distribution of glazing should be directed to the client's functional and aesthetic desires and the project's architectural values. Solar heating performance, over a wide range of climates and design configurations, will not be compromised.

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# RESULTS OF MONITORING FLAT-PLATE, BATCH, AND SOLAR/WOOD DOMESTIC WATER HEATERS

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## ABSTRACT

During the first year of the project, three flat-plate solar water-heating systems, an active site-built, a passive site-built, and an active commercially built system, were monitored. Data controls were the solar systems operated in a nonsolar, electric-only mode, a standard electric water-heating system, and the average single family residence with electrically heated water in the Puget Power service area, predominantly western Washington. During the second year of the project, a batch solar system and a solar/wood/photovoltaic system were monitored. To help isolate the effects of solar energy from other parameters influencing the amount of electricity used to heat water, measurements were also made on the effects of lifestyle and water-heating system insulation levels.

## 1. INTRODUCTION

In September 1981, instrumentation was installed in the first of the three solar water-heating systems originally in the monitoring project. The solar systems were an active site-built system, a passive site-built system, and an active commercially built system. All the systems used single glazed, flat-plate collectors with metal absorbers, parallel flow passages, and remote storage. All the systems had draindown freeze protection.

In late 1982, instrumentation was installed on a (passive) batch site-built system and an active solar/wood/photovoltaic commercially built system. Like the systems monitored the first year, these systems were single glazed and had draindown freeze protection. Other solar water-heating systems of particular interest (flat-plate collector with drainback freeze protection, combination batch-solar/wood, and flat-plate collector with adjoining storage tank) were not monitored because of budget limitations.

To help answer questions arising during the first year's study, the electric consumption of the standard electric reference system was recorded before and after a "conservation package" was applied. In addition, the electric consumption of the active commercially built solar system with a new family in the house was compared to the electric records of the earlier family; the two households had very different lifestyles with respect to energy conservation.

## 2. METHODS

In this monitoring project, the solar water-heating system and the electric auxiliary water-heating system were considered as one composite system. Instrumentation installed consisted of a kilowatt-hour ("kWh") meter to record electricity used by the electric auxiliary tank, a second kWh meter to record electricity used by the controller and pump in active solar systems, and a water meter to indicate the amount of hot water used by the household. In addition, the outside air temperature and the temperature near the storage tank were recorded using maximum-minimum thermometers. Finally, a straight glass thermometer was provided, with which each homeowner or tenant periodically measured the temperature of the incoming cold water supply and the temperature of the hot water exiting from the electric auxiliary tank. House residents generally recorded data on Tuesday evenings and the first of the month. The maximum-minimum and the straight glass thermometers were calibrated in water between approximately 7°C and 49°C (44°F and 120°F). Water meters and kWh meters were also calibrated.

The solar systems were operated on occasion in a nonsolar mode to provide baseline data. In addition, a standard electric water-heating system was instrumented to serve as a reference. A further data control was an average household in the Puget Power service area. An estimate of the electricity used by this latter household ("the average Puget Power control") was obtained by subtracting the average monthly electric usage of households having electric lights and appliances from that of households having electric lights, appliances, and water heating. To estimate

the amount of electricity used for water heating per person, the household total was divided by 2.9, the average number of persons in a single family residence in the utility's service area in 1980.

## 3. DESCRIPTION OF SOLAR SYSTEMS

A brief description of the monitored solar water-heating systems follows; the Appendix contains further details.

Active Site-Built System, "AS" in the Figures. Automatic draindown; retrofit system; single storage tank located in attached insulated shed on north side of residence; total flat-plate collector area 6.3 $m^2$ (68 $ft^2$) until July 1982, 6.1 $m^2$ (66 $ft^2$) thereafter.

Passive Site-Built Thermosiphon System, "PS" in the Figures. Manual draindown; new construction; two storage tanks, solar tank in attic, auxiliary electric tank in utility room; total flat-plate collector area 3.6 $m^2$ (39 $ft^2$).

Active, Commercially Built System, "AC1" (first year) and "AC2" (second year) in the Figures. Automatic draindown; new construction; single storage tank located in bathroom closet near center of residence; total flat-plate collector area 5.6 $m^2$ (60 $ft^2$).

Passive Site-Built Batch System (now available commercially). Manual draindown; retrofit system; two 114 liter (30 gal) cylindrical integral collector/storage tanks; auxiliary electric tank in utility rooom; total collector (glazing) area 3.4 $m^2$ (37 $ft^2$).

Active, Commercially Built Solar/Wood/Photovoltaic System. Manual draindown; retrofit system; solar tank and auxiliary electric tank in attached garage; water-heating coil in fireplace insert; photovoltaic array powers solar system pump; total flat-plate collector area 4.7 $m^2$ (51 $ft^2$); photovoltaic array area 0.22 $m^2$ (2.3 $ft^2$).

## 4. DISCUSSION AND RESULTS

### 4.1 First Year of Project (1982)

Results presented below from the study give the total amount of electricity, both that used by the auxiliary electric water-heating system and that used by the active solar systems' controller and pump. From an electric utility planning perspective, total electric usage is of primary interest. However, to account at least approximately for variations in family size, in Figure 1 the total amount was divided by the number of persons in the household. Shown in this Figure are results both for the solar systems monitored during the first year of the project, and for the standard electric reference system and the average Puget Power control. For the last-named, monthly data were converted into average weekly data. The standard electric system and the average Puget Power control used approximately the same amount of electricity per person to heat domestic water. The solar systems used one third or less of this amount. The savings are due not only to solar energy, but also to insulation, efficient system design, and care in hot water use.

In Figure 1, data points corresponding to weeks when the solar systems were turned off to obtain baseline nonsolar data were omitted from the graph in order to clarify the seasonal variation. For the same reason, three-point moving average values were plotted. Because of budget cuts, some of the data for December 1982 could not be obtained; where available, data for December 1981 are shown instead. As shown in the Figure, a marked seasonal dependence for both solar and control systems was evident.

On an annual basis, excluding weeks when the solar system was turned off, electricity for the controller and pump of the active, site-built system, "AS," was 7.5 percent of the total electricity to heat water. Based on data for the 6-month period, January through June 1982, and excluding weeks when the solar system was turned off, electricity for the controller and pump of the active, commercially built system, AC1, was 18 percent of the total electricity to heat water. (In August 1982, the homeowners moved.) Hot water usage in this household was below average; the solar system early-model controller was malfunctioning. For comparison, during January through May 1983, the value for the same solar system was 3 percent with a new controller and a household with above-average hot water use. During sunny summer weeks of 1982, the 2 to 3 kWh per week of electricity for controller and pump of system AC1 exceeded the 0 to 2 kWh per week electricity for directly heating water.

Figure 2 shows the seasonal variation in the amount of electricity per unit volume of hot water used by the solar and control systems during the first year of the study. The top curve in Figure 2 corresponds to the standard electric water-heating system, which showed a relatively small seasonal variation, approximately 14 percent. The seasonal change is likely due primarily to the change in municipal water supply temperature and to a lesser extent to the change in ambient temperature of the water tank, located in a semiheated basement. As the lower curves of Figure 2 show, the solar systems required considerably less electricity than the standard electric reference system to heat a unit volume of water. The solar systems showed a definite seasonal variation.

In Table 1, approximate solar savings fractions, based on measured values, are given for the three solar water-heating systems. Calculations were based on interpolation between the nonsolar data points; the effect of solar-heated water carried over from previous solar weeks was excluded. The seasonal variation in electricity per unit volume to heat water in the standard electric reference system and in one of the solar systems, for which considerable 1981 nonsolar data were available, served as the basis of the interpolation.

Table 2 lists the three solar systems' predicted annual solar savings fractions. These can be compared with the measured values in Table 1. Sizing of system AS was originally based upon an analysis performed by a national computer service, as modified by the homeowner. Sizing of systems PS and AC1 was based on rules of thumb. System AC1 was sized for a family of three rather than the existing two because of possible eventual sale of the house. Also listed in Table 2 is the savings each of the solar households achieved relative to the average Puget Power domestic water-heating electric usage for approximately the same size household. The appreciable savings are due to a combination of solar heating, insulation, efficient solar system design, and the care the households took in hot water use. Table 2 also shows the initial rates of return on the homeowners' investments in their solar water-heating systems. The initial rate of return on investment was calculated as the first year savings divided by the system initial cost. Values corresponding both to solar savings alone and to the full savings (savings due to solar plus insulation, efficient system design, etc.) are listed, as are values both including and excluding the 40 percent federal tax credit.

4.2 Second Year of Project (1983)

Figure 3 gives the same information for the solar systems monitored in the second year as Figure 2 did for the earlier systems. In Figure 3, 1982 data for the standard electric system are repeated for reference. Seasonal variations for the batch and flat-plate solar systems are similar to results shown in Figure 2. In contrast, the solar/wood/photovoltaic system required little utility-supplied electricity during either summer or winter. Since a full year of monitoring on these systems has not yet been completed to give solar savings fractions, winter baseline data with the systems in the nonsolar mode are indicated in Figure 3 for reference; summer nonsolar baseline data are currently (June 1983) being taken.

While the results of the first year of the project were being obtained, questions arose as to how much of the superior performance of the solar systems relative to standard electric systems was due to the use of solar

TABLE 1
Approximate Solar Savings Fractions

| Solar System | Annual | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AS | .44 | .13 | .28 | .40 | .55 | .69 | .67 | .53 | .51 | .54 | .55 | .41 | .20 |
| PS | .29 | .02 | .12 | .26 | .38 | .43 | .51 | .54 | .47 | .44 | .29 | .13 | .02 |
| AC1 | .55 | .14 | .22 | .43 | .64 | .79 | .75 | .82 | (.82)* | (.80)* | (.64)* | (.44)* | (.21)* |

*Estimated from extrapolated data.

TABLE 2
Solar System Savings

| Solar System | Predicted Annual Solar Savings Fraction (a) | Annual Relative Savings (b) | Initial Rate of Return on Investment (d) Based on Savings in Table 1 | Initial Rate of Return on Investment Based on Savings (b) (c) | Initial Rate of Return on Investment Based on Savings (b) (d) |
|---|---|---|---|---|---|
| AS | .69 | .71 | 3.4% | 6.1% | 10% |
| PS | .50 | .64 | 5.1% | 13% | 22% |
| AC1 | .50 | .86 | 1.5% | 5.7% | 9.5% |

(a) Savings relative to the same system in the nonsolar mode. These values give the contribution of solar energy only. Table 1 gives the measured annual solar savings fraction.
(b) Savings relative to the average Puget Power domestic water-heating electric usage for approximately the same size household as the solar household. These values include the contributions of solar energy, insulation, efficient solar system design, and care in hot water use.
(c) Excluding the 40 percent federal energy credit.
(d) Including the 40 percent energy credit. (The homeowners of these systems all used the credit.)

energy, and how much was due to insulation, efficient system design and care taken in hot water usage. To help isolate the effect of lifestyle, the active commercially built solar system ("AC1" in the Figures) was monitored a second year ("AC2" in Figure 4) when a different family lived in the house. Considering that, on the average, the second family used almost three times as much hot water per person as the first family, that a faulty solar system controller was replaced when the first family moved out, and that the first 5 months of 1983 were up to 3°C warmer than 1982, the two curves shown in Figure 4 are surprisingly similar. During the two January-May time periods, the total insolation was the same within 1/2 percent.

As one example of the effect of a "conservation package" upon a standard electric water-heating system, in late 1982 an RSI-1.8 (R-10) insulated jacket was added to the standard electric reference system in the project, and the water tank was placed on rigid insulation board of RSI-1.8 (R-10), with 12 mm plywood distributing the load on the insulation. Heat traps were added to hot and cold water pipes where they joined the water tank, and RSI-0.4 (R-2.13) pipe insulation was added to hot water pipes. Approximately 1.3 m of cold water pipe near the water tank also was insulated. These measures reduced the electric consumption per unit volume of hot water an average of 13 percent from January through May of 1983 relative to the same period in 1982. Referring to Figures 2 and 3, the electric consumption per unit volume of hot water for the standard electric reference system was reduced after application of the conservation package to 0.23 $MJ\ell^{-1}$ in January 1983, a value in the upper part of the range for the solar systems.

## 5. CONCLUSIONS

Even during winter months, the solar domestic water-heating systems monitored saved electricity for the residents relative to the average electric usage for heating water in the Puget Power service area. In addition to benefitting from solar energy, the monitored systems were better insulated than standard electric systems and had short piping runs when possible. The households that had installed the solar systems were "energy-aware" in that on the average, they used less than the common design quantity of 76 $\ell$ (20 gal) daily hot water per person.

A family that "inherited" a solar water-heating system when they moved into the house and the household that had the standard electric reference water-heating system both used more than the 76$\ell$ design quantity. A comparison of this solar system when used by the two different families who lived successively in the house (and who had very different lifestyles regarding energy conservation) showed a relatively small change in electricity required to heat a unit volume of water. Application of a "conservation package" to the standard electric reference water-heating system was effective in reducing the electricity used to heat a unit volume of water to the upper range of values for the solar systems in winter.

During the summer six months of the year, solar energy provided between roughly 1/2 and 3/4 of the energy needed to heat the domestic hot water supply of the three systems in the first year of the study. Although the two passive systems monitored were less efficient than the active systems, the former's considerably lower cost made them more cost-effective than the latter. From the perspective of both a winter-peaking electric utility and a customer who pays higher rates in winter than in summer, the combination solar/wood water-heating system was the most effective at reducing electric costs.

## 6. ACKNOWLEDGEMENT

Great appreciation is expressed to the residents in these homes who faithfully recorded data so that knowledge might be gained on the quantitative benefits of using solar energy.

## 7. APPENDIX

### 7.1 Details of Water-Heating Systems

From the costs listed below, the homeowners subtracted the 40 percent federal tax credit. Unless otherwise noted, the domestic hot water temperature was approximately 49°C (120°F). The tilt of the solar collectors was between 30° and 45°. The first 3 systems listed below were flat-plate and had timers on the electric heating elements.

Active Site-Built System, "AS," located in Kenmore. Two adults, one teenager; second teenager visited on weekends; average of 3.45 "person-days" per week; storage tank 310$\ell$ (82 gal); daily hot water use, 64$\ell$ (17 gal) per person; solar system material cost $2,455 summer 1981.

Passive Site-Built System, "PS," Redmond. Two adults, one child; solar storage tank 150$\ell$ (40 gal); auxiliary electric tank 190$\ell$ (50 gal); daily hot water use, 61$\ell$ (16 gal) per person; solar system installed cost $1,005 summer 1981.

Active Commercially Built System, "AC1" and "AC2," Olympia. Two adults (AC1), two adults and one child (AC2); storage tank 310$\ell$ (82 gal); AC1 daily hot water use, 34$\ell$ (9 gal) per person; AC2 daily hot water use, 93$\ell$ (24

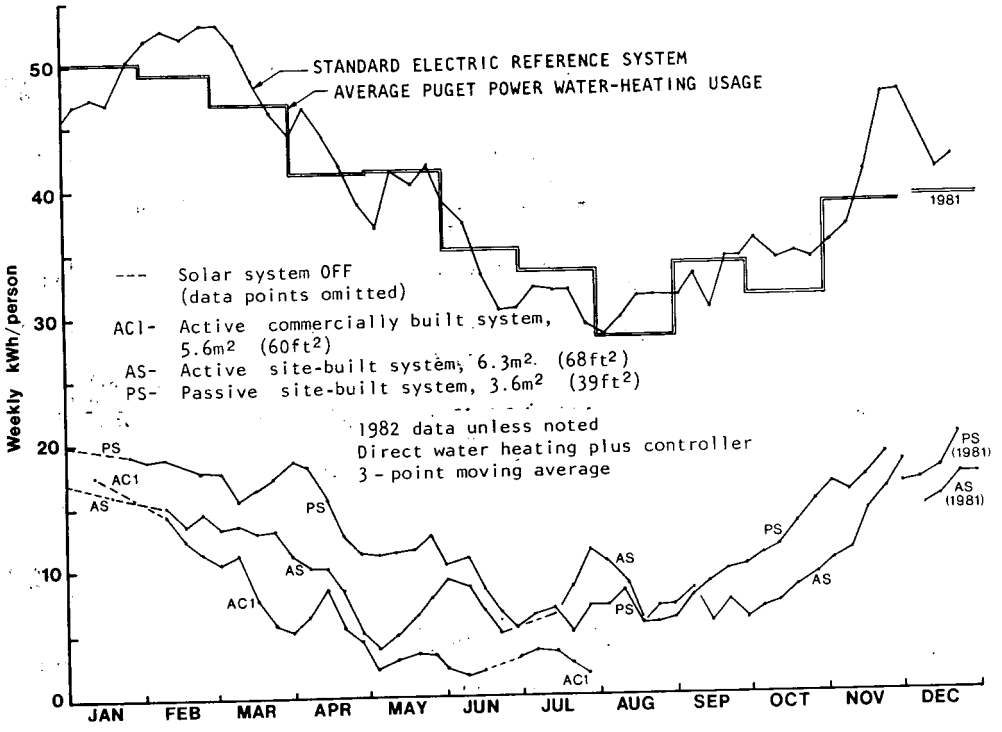



Fig. 1. Electricity per Person for Heating Domestic Hot Water.

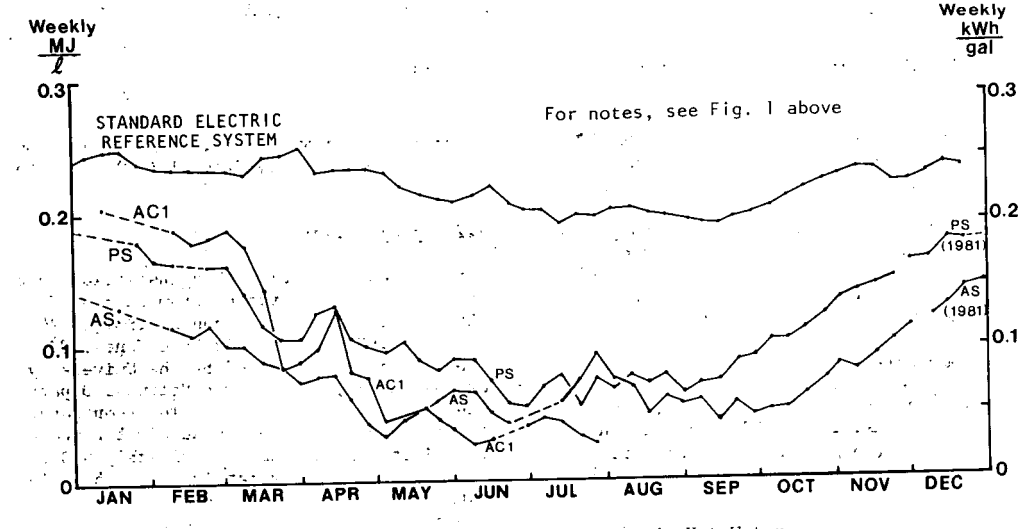



Fig. 2. Electricity per Unit Volume for Heating Domestic Hot Water.

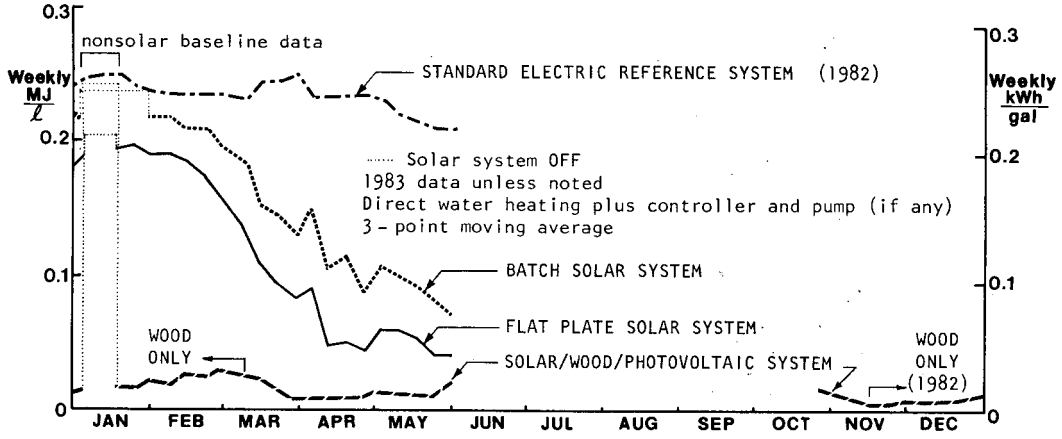



Fig. 3. Utility Supplied Electricity per Unit Volume for Heating Domestic Hot Water.

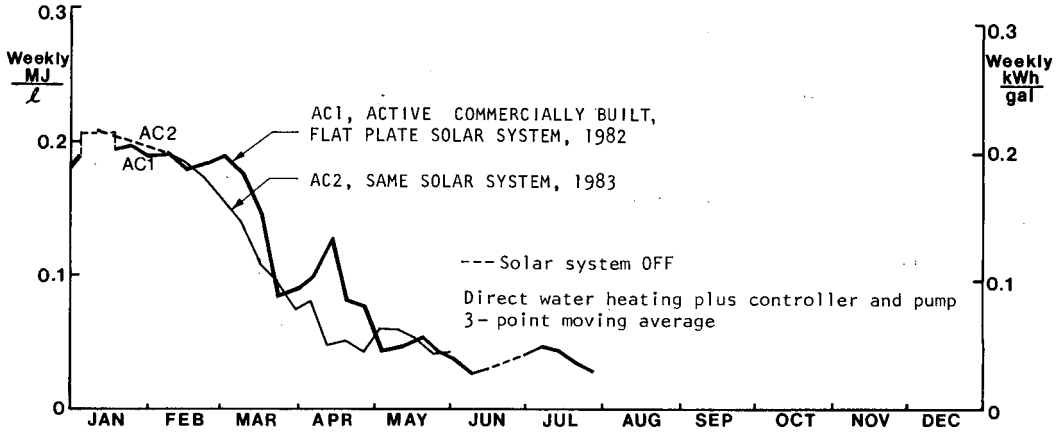



Fig. 4. Electricity per Unit Volume for Heating Domestic Hot Water.

gal) per person; system installed cost $3,175 December 1980. For AC2, 57°C (135°F) hot water until 3/8/83, 49°C (120°F) thereafter.

Passive Site-Built Batch System, Clinton. Two adults, two children; auxiliary electric tank 200 ℓ (52 gal); daily hot water use, 45 ℓ (13 gal) per person; 46°C (114°F) hot water; solar system material cost $650 summer 1982.

Active, Commercially Built Solar/Wood/ Photovoltatic System, Olympia. Two adults, one teenager; solar tank, 310 ℓ (82 gal); auxiliary electric tank, 200 ℓ (52 gal); daily hot water use, 87 ℓ (23 gal) per person; water supply approximately 11C° (51°F) from well; system installed cost $3,000 summer 1982.

Standard Electric Water-Heating System, Seattle. Two adults; storage tank 250 ℓ (66 gal); daily hot water use, 91 ℓ (25 gal) per person; approximately 52°C (126°F) hot water.

## 7.2 Local Climate

For reference, total weekly insolation on a horizontal surface varied from 12.6 $MJm^{-2}$ (201 Langley) in early January 1982 to 203 $MJm^{-2}$ (17,900 Langley) in late June 1982. These data were obtained by the University of Washington, Atmospheric Sciences Department, Seattle, Washington. The temperature of the incoming water supply at all but two of the sites varied from approximately 6°C (43°F) in January to approximately 18°C (65°F) in late August. Weekly average outside air temperatures at the sites varied from approximately freezing in January 1982 to 21°C (70°F) in late June 1982.

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# SUPERINSULATED BATCH HEATERS FOR FREEZING CLIMATES

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## ABSTRACT

An innovative batch-type passive solar water heater has been developed in Denver, Colorado, over the past two years by the Passive Solar Co-op. It is designed for year-round use in Denver's 3300 °C -day (6000 °F -day) climate, and prototypes have performed very well even in sub-freezing winter conditions. The innovations are very simple, consisting of a manufacturing technique incorporating high levels of insulation and a multi-glazed window of thin high transmission solar films to reduce heat losses from the unit without appreciable losses of solar gains.

## 1. INTRODUCTION

The Passive Solar Co-op batch heater is an attempt to fill the need for a convenient source of year-round solar hot water without the high capital costs and reliability problems associated with active solar heating systems. It combines two very simple intuitive energy-saving technologies - superinsulation and passive solar - into a cost-effective whole. It also greatly simplifies the installation job, making it more attractive for the "do-it-yourselfer."

Batch-type passive solar water heaters are enjoying a resurgance of popularity as the design community seeks out a more elegant solution to the problem of solar water heating. The pure simplicity of the design is its greatest asset. By eliminating the need for pumps and controllers, or any external power source at all, the system gains a great measure of reliability, as well as a significant reduction in cost.

With all these benefits why aren't there more batch heaters visible in the field now? The Zomeworks "Breadbox" heater has been available for over a decade, and the Climax passive solar water heater was quite common in the Sunbelt at the turn of the last century, but recently, almost all solar water heaters installed in the United States have been active systems. The problem is, basically, that most people believe tanks of water left outside in the winter will freeze and break.

Recent experience has shown otherwise. New Shelter magazine has recently revised their rule-of-thumb to allow their triple-glazed batch heater to be used outside year-round in areas with less than 670 °C -days (1200 °F -days) per month (most of the United States). We operated a single-glazed batch heater with about 50% solar shading outside all last winter in Denver with no freeze ups. (Except for the pipes - a problem addressed later in this paper.)

## 2. DESIGN

Our design is an outgrowth of Rodale's batch heater, publicized in New Shelter magazine as the winner of their solar water heater head-to-head competition in 1981. Our design uses the involute curve (popularly referred to as the "cusp") to maximize solar radiation reflections onto the tank, two (or three) 170 liter (42 gallon) glass lined steel tanks for collection and storage, a collector box insulated to R-7 RSI (R-40 U.S.) and a selective surface on the tanks and six layers of glazing to reduce heat loss through the window.

The design heat capacity of our unit is .37 kWh/°C (700 Btu/°F ) and heat loss coefficient 3.7 W/°C (7 Btu/hr°F) This is a massive, well insulated unit.

## 3. INSULATION DETAILS

The optimization of the design for an integral storage solar collector is very different than for a conventional collector where heated fluid is stored in a remote location. The extra heat retention during the hours when solar heat is not being collected given by our multiple glazing technique outweighs the slight loss of transmission of solar radiation into the collector. Optimizing the system to maximize the year-round collector efficiency would likely lead to fewer than six glazings. But optimizing for insulation on the storage tank... Six layers of glazings may not be enough.

Consider - a conventionally insulated batch system of this capacity has a heat loss coefficient of about 10.5 W/°C (20 Btu/hr.°F ). If we assume the average year-round operating temperature to be 38°C (100°F), and the Denver climate of 3300°C -days (6000°F -days)(referenced to a 18°C (65°F )base), we have an additional 20x365 degree days referenced to a 38°C base (100°F )(less about 400 for days with an average temperature of above 18°C ), for an approximate number of degree days below 38°C as 10,000 (18,000 °F -days). A heat loss coefficient of 10.5 W/°C multiplied by these 10,000 °C days gives a yearly heat loss of about 2500 kWh (8.6 MMBtu). With our design heat loss coefficient of 3.7 W/°C (7 Btu per hr °F ) this same calculation yields a yearly heat loss of about 880 kWh (3.0 MMBtu), a significant saving. Add to this a greatly reduced chance of freeze damage, and the value of superinsulation becomes clear.

Our first attempts to solve the heat loss problem involved using a shape memory metal actuator to open and close a counterweighted shutter over the batch heater glazing. SME metals (Nitinol is the best known) are a family of alloys which exhibit a reversible change in shape on raising or lowering past a transition temperature. We used springs which expand to double their original length when heated between 21° and 32°C (70° to 90°F ). Upon cooling to below 21°C they regain their original compressed form. The great advantage of SME actuators is that they give a step function change in position on heating (as opposed to the continuous expansion shown by the wax type heat motor) ideal for positioning a reflector.

We have since dropped the shutter idea, partly because of a problem with self-shading of the actuator, but moreso because of worrys about damage from the high winds which we regularly experience in the Front Range of Colorado. However, we believe we can get the same performance from our glazing insulation by using the multiple layers of thin, high solar transmissivity, polyester film.

Our original designs used Teflon for the two inner glazings (all have used low-iron glass for the outer layer), and we had hoped that merely adding more layers would reduce the heat loss through the glazing to an acceptable level. However, the high infrared transmissivity of Teflon would let too much radiant heat out.

Fortunately 3M is introducing a product called Sungain - a 0.1 mm (4 mil) polyester film with an anti-reflective coating. This material has a solar transmissivity of 96% - equal to Teflon - but with much lower infrared transmissivity (15% for Sungain, compared to about 60% for Teflon, and 4% for glass). The Sungain film also has the added benefit of a much lower thermal expansion rate than Teflon and apparently more resistance to static electric charge. The only disadvantages of Sungain we've found so far are its fragility in handling (it's anti-reflective coating smears when touched - like Black Chrome) and its cost, about twice that of Teflon, but still less than glass.

A window made up of one layer of low-iron glass and five layers of Sungain has a solar transmissivity of over 70% and R-value of over 1 RSI (R-5).

## 4. PERFORMANCE

Unfortunately, as an undercapitalized company, we could not afford Btu meters to measure the output of our units. However, we did measure temperatures during the winter, so we have some idea how well our heaters worked.

It should be noted that we include aggressive hot water conservation measures as part of our solar installations. We install water conserving shower heads, insulate exposed pipes to RSI 4.5 (R-25) (exterior) and RSI 1.2 (R-7) (interior) wherever they're accessible, insulate the hot water tank as well as is possible

(at least 10 cm (4") additional fiberglass) and try to educate the homeowner to the costs of washing laundry in hot water.

Under these conditions, a two-tank system with a 1.2m.x2.4m (4'x8') glazing returned water at 50°C (120°F) regularly under constant load by a family of four in January. Tank temperatures reached 55°C (130°F) in March and have stayed at that level since then. (These are afternoon temperatures - by morning the system was returning water at an average of 30°C (85°F).

The single-glazed single-tank system with 50% solar shading returned water at up to 32°C (90°F) on sunny winter days. On cloudy days negligible solar gain was noted, but again this system was designed to test for freezing. The feed and return pipes (60 cm long by 13 mm diameter (24" by 1/2" dia.) soft copper) froze once during the Christmas blizzard, but did not break. The pipe insulation was way too weak at this point, consisting only of 19mm (3/4") wall Armaflex with gaps. When it was covered with a double layer of 25mm. (1") vinyl backed fiberglass (leftover from a tank insulating jacket) there were no more problems with it.

## 5. PROBLEMS

The possibility of freezing of exposed water pipes is more of a problem than freezing of the tanks. The water pipes have much less heat capacity than do the tanks, so they are much more prone to freezing. We have used electric heat tapes in the past, but are avoiding them at present, both because we question their reliability and lifetime and because we question the reliability of electric power supplies, especially on worst-case freezing nights. The solution we've adopted is twofold. One, we insulate the exterior pipe runs to RSI 4.5 (R-25) at present. Two, we use polybutylene pipes for the exterior pipe runs. Polybutylene has the ability to stretch as water inside expands to ice, and thus can be frozen (the manufacturer says down to -50°F). without breaking. Given the fail-safe nature of polybutylene to prevent freeze damage, we may down-size our pipe insulation, for aesthetic and cost reasons.

Two other techniques for protecting exposed pipes filled with water should be noted. A larger diameter pipe contains more water than a small one and thus has a higher heat capacity and freeze protection. Also, as water rises when it freezes, if there is a rise built into the exposed pipes leading to a high spot inside a conditioned space, a thermosiphoning loop will be established inside the pipe, giving additional freeze protection. In our case, we're satisfied with the polybutylene, for the time being.

Another problem, which we have identified but not encountered, is dry stagnation of these units. If the heaters were exposed to the sun without water in their tanks to store the heat, temperatures could breakdown several materials used in the system. This can be avoided by covering the heater glazings until they are plumbed in and if they are ever drained. Of course with water in the system, temperatures will not exceed boiling, as this will trigger the P/T relief valve to open and bring cold water in.

## 6. DEVELOPMENT

We are now developing a new fabrication technique which we believe will simplify production of these heaters: reduce labor, reduce materials, and yield a higher performing unit. Two of the difficulties we have experienced are in forming the involute shape for the reflector, and finding a convenient way to support the tanks structurally while still achieving an acceptable R-value in the shell.

These difficulties can be surmounted by our molding system which will cast a polyurethane foam shell containing steel supports for the tanks, forming the involute curve directly as the inside surface of the shell, and serving both as the exterior structural shape and insulation for the heater. This molded shape will be covered on the inside with a specular aluminum foil, on the outside with a stucco (or optional custom finish), and will contain the glazing supports and mounting brackets as integral parts of the casting. We are also considering extruding the heater bottom, with involute curves and tank supports, but can't afford the tooling at present levels of production.

## 7. CONCLUSIONS

Batch passive water heaters hold great promise as simple, effective solar water heaters,but a major lim-

itation up till now has been night-time heat loss, with the concommitant worry of freeze damage. Superinsulation technology, including thin-film glazings, offers a neat solution to these problems, and will likely lead to wider use of these heaters, even in freezing climates.

## 8 ACKNOWLEDGEMENTS

Thanks to my co-operators, Angela Treinen and Judson Guerard, who contributed equally to the development of this system.

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# THE PERFORMANCE OF A ROOF-POND SOLAR HOUSE: THE NEW MEXICO STATE UNIVERSITY EXPERIENCE

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## ABSTRACT

Presented in this paper are some of the results of tests performed with the New Mexico State University Passive Solar House during the summers of 1981 and 1982. The house is a roof-pond solar house in which movable insulating panels are used to control both the collection and rejection of energy for both the heating and cooling of the conditioned space. Of particular importance to the present study is the effect of several parameters on the cooling performance of the system. The results indicate that insulating air cells (even though deflated) have both positive and negative effects on the performance of the system; that an increase in the water pond depth from 7.5 to 15 cm results in a decrease in the temperature swing of the water which is approximately proportional to the the increase in the thermal mass of the house; that the difference between the daily average ambient temperature and daily average water bag temperatures for water bags cooled by evaporation (in addition to convection and radiation) is twice that of the bags cooled by radiation and convection alone; and that the cooling of the house is not sensitive to the opening and closing times for the insulating panels as long as they are open during the early morning hours and closed prior to sunrise. In addition to the performance of the house in the cooling mode of operation, some of the maintenance and operational characteristics of the system are discussed.

## 1. INTRODUCTION

The roof pond system for heating and cooling has been discussed by a number of investigators including its inventor Mr. Harold Hay (1,2,3,4,5,6, and 7); therefore, only a brief discussion will be presented here. Figure 1 is a schematic diagram depicting the operation of the Skytherm™ system. When the system is in the summer cooling mode of operation, the movable insulating panels are removed at night and

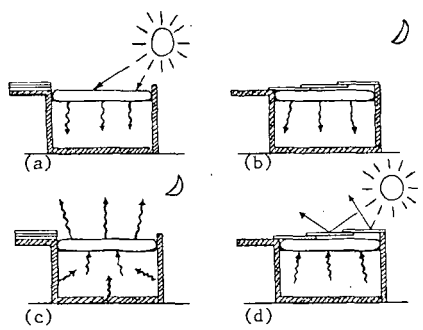



Fig. 1. Schematic Diagram of the Operation of a Roof-Pond System; a and b represent the winter operation, and c and d the summer.

closed over the water bags during the daylight hours. In this way the energy absorbed by the water is rejected through the heat transfer mechanisms of convection and radiation to the the clear night sky. One of the attractive features of this particular cooling system is that it can also be used for heating the house during the winter by simply reversing the operation of the panels. That is, the panels are opened during the day and closed at night. The dual usage of the system, for both heating and cooling, is an important cosideration from a cost/benefit point of view and in terms of its potential commercialization.

## 2. BACKGROUND

The climate of New Mexico varies across the State with the terrain ranging from high mountain valleys to arid desert. The NMSU Passive Solar House is located in Las Cruces in the upper Chihuahuan Desert. The climate is classified as arid with an average annual rainfall of 21.1 cm, temperature of 15.6°C, 80% possible sunshine, and low relative

humidity (8,9). June, July and August are the hottest months of the year with average high temperatures of 34.4°C, 33.9°C, and 33.3 °C, respectively. Daily high temperatures of 43 C are not uncommon during late June and early July. More than half of the annual rainfall occurs during the months of July, August and September.

The house was designed using a computer code developed at New Mexico State University (10,11,12,13). The results of the simulations indicated that the system would operate very well in the arid Southwest. Of paricular interest to us was the predicted performance of the roof-pond system in the cooling mode of operation. The analysis suggested that the most sensitive parameters are the internal loads, panel control, infiltration rate, and water pond depth. Using the results of the simulations and funds provided by the State of New Mexico Energy Resources Board (now the New Mexico Energy Research and Development Institute), we designed and built the house in 1977 and 1978. Figure 2 is a floor plan for the house. Energy efficient design and construction were utilized throughout the house. In addition all of the exterior walls and the three, load bearing interior walls are constructed from precast concrete 15 cm thick. The panels were fabricated at the plant and then trucked to the site for assembly. In all the house contains 130,000 kg of concrete. Once the walls were installed they were insulated externally with 5 cm of air-sprayed urethane foam, U = 2.1 W $M^{-2}$ $K^{-1}$. Metal lath was then attached to the building and a stucco exterior applied.

The roof-pond and movable insulation systems for the house were designed to use off-the-shelf components wherever possible. Therefore, conventional garage door tracks and wheels were selected for use on the movable panels. Two types of panels have been used on the house. The panels on the roof during the tests presented in this paper are made of urethane foam with an aluminum skin on the bottom side. The roof ponds were designed to match the floor plan of the house with five bays running in a north-south direction. The location of these bays is shown in Figure 3. The two outermost bays are longer than the three inner ones and a total of 121 $m^2$ of the roof is covered with water ponds. The bags are constructed from Monsanto 602 which is 8 mils thick. Some of the water bags have inflatable air cells and others are of single wall construction. These are the subject of some of the tests which will be described later.

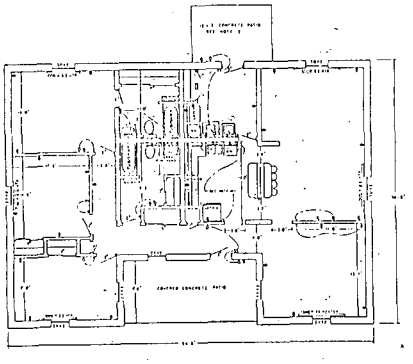


Fig. 2. Floor Plan of the NMSU Passive Solar House.

The data acquisition system for the house is an Acurex Autodata 10. Ninety-one channels of data are collected and dumped onto magnetic tape each hour of the day. A variable which can change rapidly, such as solar radiation, is sampled every 15 seconds and the hourly average value recorded. Other variables are sampled at rates of once each minute or each hour depending on how much they might vary over an hour's time. The measurements made are temperatures, solar radiation, infrared radiation, relative humidity, wind speed and direction, and heat fluxes through the walls ceiling and floor. These data were then analyzed and used to evaluate the performance of the system under various operating conditions and several configurations.

The four objectives of the tests performed during the 1981 and 1982 summer cooling seasons are:

1. To evaluate the effect of the deflated air cells on the ability of the system to reject heat;
2. To evaluate the effect of water pond depth on the system performance in the cooling mode of operation;
3. To evaluate the effect of evaporative enhancement on the heat rejection from the system;
4. To evaluate the effect of panel

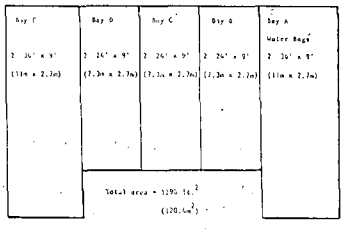



Fig. 3. The Five Bays on the Roof of the NMSU Passive Solar House.

opening time on the cooling performance of the system.

The results of tests designed to evaluate these four objectives are presented in the following section.

## 3. RESULTS AND DISCUSSION

The effect of the deflated, polyethylene air cell on the cooling performance of the system is shown in Figure 4. Presented in Figure 4 are water bag temperatures over a four day period during September 1981 for a bag with an air cell (B) and a bag without an air cell (D). The bag which has the deflated air cell, and therefore an additional 8 mils of polyethylene, does not experience either the high or the low temperatures which the bag without the extra layer does. This is because the additional layer of Monsanto 602™ not only reduces the energy which the water bag can reject through radiation and convection but it also reduces the heat gain during the day when the panels are closed. The bags without air cells have an additional 7% ability to reject energy over the water bags with the deflated air cells and a 5 to 10% greater ability to gain energy. From the point of view of only the cooling performance of the system, the two effects add to zero. Considering the heating mode performance of the system, however, one finds that the addition of the air cell greatly reduces thermal losses from the system both when the panels are open and when they are closed.

The effect of increasing the water depth from 7.5 to 15 cm is shown in Figure 5. In Figure 5 the daily average maximum (triangles), daily average (asterisks), and daily average minimum (plus signs) water temperatures in Bay E over the course of the summer of 1981 are presented. The data on the horizontal axis correspond to days when the data were unusable for one reason or another. The

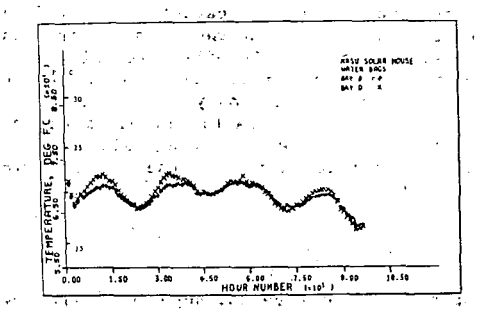



Fig. 4. Water bag temperatures for bags with an air cell (B) and without air cell (D).

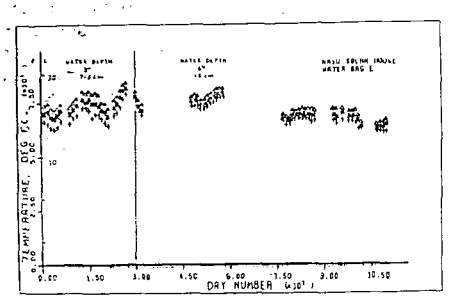



Fig. 5. The daily maximum, average and minimum water temperatures in Bay E.

temperature swing of the water is reduced by about 40% in both the bags which have the air cell and those which do not. The house air temperature swing is reduced by about 20%.

The enhancement of the cooling of the water bags through the addition of evaporation was evaluated during the summer of 1982. Some of the data for these tests are presented in Figure 6 (day 1 is June 1, 1982). Shown in this figure are the daily average values for the ambient temperature, the temperature of a water bag which is sprayed with water to enhance cooling through evaporation (B), the temperature of a dry water bag with and without insulating air cells (C and D), and the house inside temperature. The average daily temperature of the water in the bags which are cooled by convection and radiation alone ranges from 2.8 to 6.7 °C below the average daily ambient temperatures. The

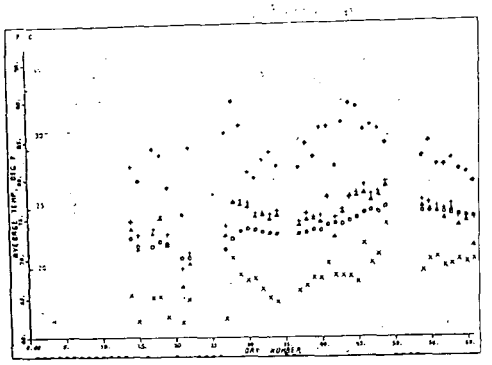


Fig. 6. Daily average temperatures for the wet (exes), dry (plus signs), and uninsulated (triangles) water bags, the ambient (diamonds) and inside house (circles) temperatures.

average daily temperature of the water in Bay B which is cooled by evaporation in addition to radiation and convection is from 6.1 to 13.3 °C below the average ambient temperature. Only on isolated occasions do the average water temperatures fall below the daily average house inside temperatures except for the wet Bay B which is always cooler than the average house inside temprature by from 2 to 5°C.

Figure 7 is a daily temperature profile in which is shown the hourly variation of the ambient temperature, wet water bag temperature, dry water bag temperature with and without air cell, and the inside temperature. These data show that the temperature of the wet Bay B remains almost constant during the early morning hours while most of the heat is being rejected and never reaches a temperature above the house inside air temperature. The other water bags are always warmer than the interior space and, therefore, a source of heat to the house during this period.

Evaluation of the data for the panel control strategy indicates that the heat rejection from the water bags is not affected by varying the opening time of the insulating panels from 9:00 to 11:00 P. M. MST. This is due to the fact that convection is serving as a net heat gain to the bags during the late evening hours. Referring to Figure 7 one can see that a similar two hour change in the closing time of the panels will result in a decrease in the energy rejected from the bags. The conclusions which can be reached are that the performance of the system is not particularly sensitive to the time at which the panels are opened as long as they are opened prior to 12:00 P. M.; and the panels should remain open as long as possible (until sunrise) in the morning.

There are two primary areas of concern with regard to the operation and maintenance of the system; leaks of air and water from the bags and the movement of the panels. We experienced leaks of both air and water from the bags; it was particularly difficult for us to keep the air cells inflated. Water leaks were not nearly as bad as the air leaks but there always is standing water on the roof of the house either from the bags or from rain water. We had no leakage of water into the house because of the roof design which is a metal deck with concrete poured over the top and coated with a rubberized sealant. The leaks occurred mainly at the seams of the bags although there were some leaks at what appeared to be pin holes in the polyethylene. The water bags are custom made of a special mill run of 8 mil polyethylene. Under a mass production scenario the quality of the bag manufacturing process could presumably be held at a higher level than can be accomplished in a one-time operation. Also a special mill run of 10 or 12 mil polyethylene could be made. These two factors could eliminate the problems associated with air and water leakage from the bags.

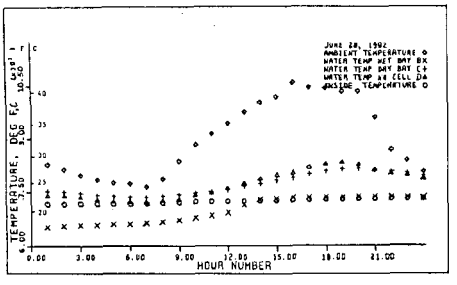



Fig. 7. Daily Profile for a wet and a dry water bag, ambient and inside house temperatures.

The question of having a movable insulating panel which is tight with regard to air infiltration is really determined by just how tight one wants the roof system to be. In previous studies (14,15,16) we have shown that the overall panel loss coefficient for our roof lies between 3.3 and 5.4 $W\,M^{-2}\,C^{-1}$. Our roof was not particularly tight in that it had about a one centimeter gap around each of the panels. We had problems with the panels sagging due to snow loads and absorption of water and interfering with one another. The proper materials to make a good, solid panel are available and the question of how to solve this problem is linked with the mass production and the cost of production of the system.

## 4. CONCLUSIONS

The roof-pond system is capable of providing the cooling for a house located in Las Cruces, New Mexico. It will marginally meet the cooling requirements if convection and radiation are the only heat transfer mechanisms. If evaporation is added to the system, it will easily meet all of the cooling requirements in the hot, arid Southwest.

## 5. ACKNOWLEDGMENTS

I want to acknowledge the support of the New Mexico Energy and Minerals Department for the construction of the house and the United States Department of Energy under contracts EG-77-C-03-1606 and DE-AC03-80CS30228 for the support to perform the experiments and analyze the data.

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# EVALUATION OF A SOLAR THERMAL AND DAYLIGHTING SYSTEM

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## ABSTRACT

A solar energy system that incorporates solar space and domestic hot water heating with dayighting advantages was constructed by California Solar Technology (CST).

The advantages of reduced space and domestic hot water heating loads, coupled with lower interior lighting loads, resulted in culmulative energy savings of more than 45 percent for a single-family residence in the San Fernando Valley, according to tests conducted over a two-year peroid.

More rigorous and detailed photometric analyses are currently being completed on the CST-designed Litetnerm System to verify initial results. Information from the photometic tests is dictating parameters for computer simulation programs that are being completed in the following three areas: optical simulation of the Litetherm System, thermal simulation of the system and optical simulation of the CST 1001 Litetnerm Collector.

This paper outlines the procedures and calculations used to obtain testing thermal performance data under actual operating conditions for the residential Litetherm System.

Also described here is the luminance method of photometry developed for deriving field data. Brief descriptions of the computer simulations described above are given at the end of the report.

It is hoped that results from the more refined testing currently underway will be the subject of a future paper presented to this society.

## 1. LITETHERM SYSTEM DESCRIPTION

In brief, the Litetherm System provides supplementary space heating, domestic hot water heating and natural lighting, through roof and wall fenestrations.

Figure 1 depicts the system's piping network. A schematic of the simplified flow is shown in Figure 2. Hot water from the solar panel array is stored in the hot water tank.

Air originating from the lower solar array is circulated throughout the room, heating the living area. This temperature increase is not only achieved from the solar array during the day but also at night from the hot water storage tank.

Only when solar power is absent and the solar storage tank is below 75°F is the forced air furnace turned on. Table 1 outlines the results of the Litetherm System.

## 2. DATA ACQUISITION FOR INITIAL TESTS

Temperature readings from various points throughout the prototype test solar system were taken on an incremental basis for several hours on two days. These data were then used to determine the thermal efficiency of the installed Litetherm System (with CST Litetherm Model 1001 collector) in two modes of operation - operative and inoperative.

With integral collector space heating fans inoperative, the analysis revealed the collector thermal efficiency ranges from 60 to 65 percent. With the fans operative there is an increase in thermal efficiency in the range of 70 to 72 percent.

The collector data were taken in August. This was done to determine the effect, if any, of simultaneous fan operation on the overall performance of the system.

## 3. THERMAL EFFICIENCY DETERMINATION

The thermal efficiency of the collector is given by:

$$\eta_{TH} = \frac{\text{Total Collected Power}}{\text{Total Incident Power}} = \frac{\dot{Q}}{IA}$$

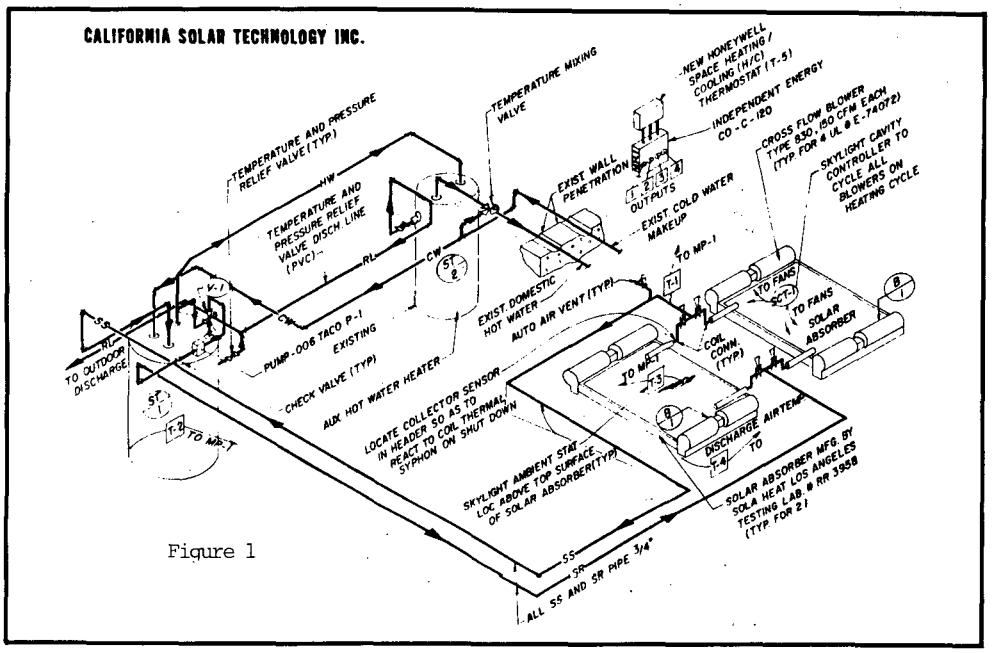



Figure 1

where:

$\dot{Q}$ = rate of useful energy extracted from the solar collector (Btu/hr)

I = Total solar insolation incident upon the plane of the collector ($Btu/ft^2$ hr)

A = Gross collector area ($ft^2$)

When collector efficiency is determined based on domestic hot water only (i.e., fan inoperative), the rate of useful energy extracted from the solar collector, $\dot{Q}$, may be expressed as:

$$\dot{Q} = \dot{m} cf (T_{out} - T_{in})$$

where:

$\dot{m}$ = Mass flow rate of the working fluid through the collector (lb/hr)

Cf = Specific heat of working fluid (Btu/lb $^{\circ}F$)

$T_{out}$ = Temperature of the working fluid as it leaves the collector ($^{\circ}F$)

$T_{in}$ = Temperature of the working fluid as it enters the collector ($^{\circ}F$)

However, when the collector efficiency is based on both DHW and space heating (i.e., fans operative) the rate of useful energy collected is the sum of rate energy collected by working fluid and rate of energy collected by space.

To calculate the rate of energy collected by space (ARR) the following method was used:

$$\dot{Q}_{space} = \dot{Q}_{total} - \dot{Q}_{water} - \dot{Q}_{lost}$$

where:

$\dot{Q}_{space}$ = Rate of energy collected by air

$\dot{Q}_{total}$ = Rate of total energy incident on the collector

$\dot{Q}_{water}$ = Rate of energy collected by working fluid.

$\dot{Q}_{lost}$ = Rate of energy being lost.

For this analysis, solar position data and insulation values for 32 degrees north latitude were obtained from ASHRAE Standard 93-77, Table A-2. The CST Litetherm Model 1001 collector is mounted on a south facing roof surface with a 19° angle from the horizontal.

Data available from the 1977 ASHRAE Handbook of Fundamentals for a 22° angle from the horizontal were used, however, in all subsequent computations. This was done because the difference in total solar insulation between a 19° and 22° tilt angle was found to be negligable and well within the accuracy of the test runs.

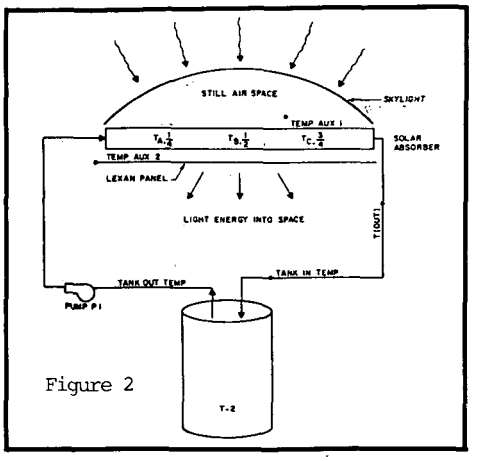



Figure 2

A mass flow rate of water through the panel of 0.35 gallons per minute (gpm) was used in subsequent data analysis. This rate was determined from energy balances around the collector and available corroborating data on Taco pump system head characteristics.

## 4. F-CHART ANALYSIS

The California Public Utilities Commission presently requires 60 percent of a dwelling's estimated usage of conventional fuel for domestic hot water to be displaced by solar domestic hot water systems to obtain agency approval.

Employing the commission's analysis, the flat plate collector area required to provide 60 percent of the dwelling's assumed load is 90 $ft^2$. This size is compatible with conventional flat plate collectors.

However, it must be noted that actual monthly Southern California Gas Company billings for comparable earlier year periods show an average decrease during the summer months of 55 percent for the two collectors, which together occupy a roof area of approximately 28 $ft^2$ and a projected finned surface area of approximately 88 $ft^2$.

This 55 percent gas fuel savings represents a decrease in natural gas consumption associated solely with the domestic hot water load (since there are no space heating demands during this seasonal period) and is accomplished with the two nominal 14 $ft^2$ (each) finned solar absorbers.

Comparing the results to those predicted from a conventional F-chart analysis, one would expect a comparable collection with 70 $ft^2$ flat plate for the collectors to supply 51 percent of the estimated residence domestic hot water load.

For the combined load (DHW and space heating) 72 percent of the total load can be provided by 500 $ft^2$ of the collector area.

It appears that the prototype CST Litetherm installation significantly out performs standard flat plate collectors of the same nominal area. Furthermore, F-chart analysis procedures are not believed appropriate for predicting system performance with finned absorbers for the type tested.

## 5. CONCLUSION OF INITIAL TESTS

Based on efficiency curves, the thermal efficiency performance of the CST Litetherm 1001 collector is believed SUPERIOR IN PERFORMANCE to existing flat plate solar collectors now on the market.

## 6. LIMINANCE METHOD OF PHOTOMETRY

The methodology used for developing the photometric analysis currently underway is described here. Luminance distribution diagrams were found for luminaire materials and applied in the design of the collector system.

Manufacturers usually find the reflection and transmission factors of luminaire materials from diffuse integrating sphere measurements *[1]. Light from luminaires is given in intensity diagrams as though they were point sources, whereas luminaires used here were extended. Thus, the available data and application are inappropriate for the collector design.

Table I

ANALYSIS OF COMPARATIVE TOTAL GAS CONSUMPTION
YEARS 1980 VS. 1981

| BILLING PERIOD | 1980 / 1981 THERMS (4) | | 1979 / 1980 THERMS (4) | | ENERGY SAVINGS EACH MONTH | |
|---|---|---|---|---|---|---|
| | MONTHLY | CUMULATIVE | MONTHLY | CUMULATIVE | MONTHLY | CUMULATIVE |
| 1. DEC. / JAN. | 97 | 97 | 257 | 257 | 62.3% | 62.3% |
| 2. JAN. / FEB. | 161 | 258 | 178 | 436 | 10.1%(2) | 40.8% |
| 3. FEB. / MAR. | 158 | 416 | 191 | 627 | 17.3%(2) | 33.7% |
| 4. MAR. / APR. | 52 | 468 | 129 | 756 | 59.7%(5) | 38.1% |
| 5. APR. / MAY | 29 | 497 | 81 | 837 | 64.2% | 40.6% |
| 6. MAY / JUNE | 22 | 519 | 77 | 914 | 71.4% | 43.2% |
| 7. JUNE / JULY | 9 | 528 | 33 | 947 | 72.7% | 44.2% |
| 8. JULY / AUG. | 13 | 541 | 25 | 972 | 48.0%(5) | 44.3% |
| 9. AUG. / SEPT. | 15 | 556 | 21 | 993 | 28.1%(3) | 44.2% |
| 10. SEPT./ OCT. | 9 | 565 | 51 | 1044 | 84.2% | 46.1% |
| 11. OCT. / NOV. | 47 | 610 | 88(6) | 1132 | 53.4% | 46.1% |
| 12. NOV. / DEC. | 108 | 718 | 182(6) | 1314 | 40.7% | 45.4% |

NOTES:

(1) SEE ATTACHED BILLING. (SKYTHERM SYSTEM COMMENCED OPERATIONS ON 12/12/1980.

(2) DURING THIS PERIOD, MODIFICATIONS WERE MADE TO BLOWER SYSTEMS TO PERMIT VARIABLE TEMPERATURE/FLOW DISCHARGE FROM CONSTANT VOLUME OPERATION.

(3) LEXAN PANEL ADDED BELOW ABSORBER.

(4) 1 THERM = 100,000 BTU

(5) NUMEROUS HOUSE GUESTS AND TEENAGE DAUGHTERS WERE NOT HOME LAST SUMMER.

(6) FOR PERIOD OCT. THROUGH DEC., IT WAS NECESSARY TO ELECT 1979 AS BASE YEAR SINCE ALTHOUGH SKYTHERM BECAME FULLY OPERATIONAL ON 12/12/80 SYSTEM WAS IMPARTIAL OPERATION FROM OCT. 1980 (i.e CONSTRUCTION COMMENCED IN AUG. 1980).

Luminance, $L_\theta$, the intensity density of light from a surface, with units of $cd/m^2$, nit or foot Lambert, fL, is the key to field measurement. A telephotometer can be used at any distance from the surface and does not require shielding from stray light.

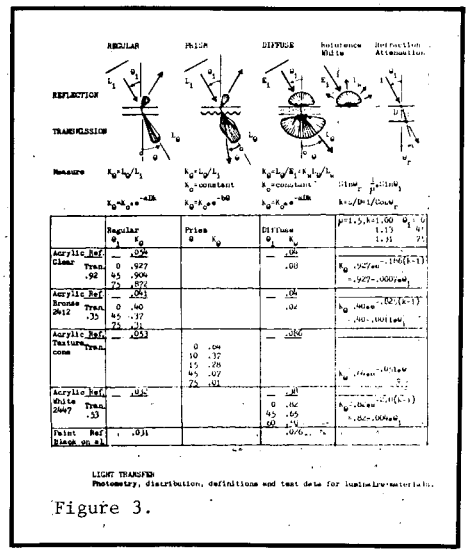
It is important for the measured surface to subtend a greater angle than the acceptance angle for the sensor head. Lens telephotometers are about $1^0$ and operate about $10^0$.

Reflection and transmission factors $K_\theta$ are found from the ratio of the luminances at the various angles as defined in the diagram for regular, prism and diffuse surfaces. Clear materials are compared with the source luminance, and diffuse with the illuminance E, on the surface.

Illuminance E(fc) is found by substituting a mat white ($K_w$ =1) plaster surface and measuring its luminance $L_w$ (fL). Diffuse surfaces have a constant luminance and appear the same brightness from any direction.

Five materials were tested in an unlighted room using a 1 $ft^2$ luminous panel as a source, a white plaster reference and an aperture telephotometer. Data were analyzed to determine the regular (specular), prism and diffuse components of the transmission and reflection.

It was found that the regular and diffuse transmissions were exponentially attenuated according to the absorption in the refracted paths in the material (See Figure 3). As a check, the manufacturer's light transmission factors correspond to the hemispherically integrated test values.




| | Regular $\theta_1$ | $K_\theta$ | Prism $\theta_1$ | $K_\theta$ | Diffuse $\theta_1$ | $K_\theta$ |
|---|---|---|---|---|---|---|
| Acrylic Ref | — | .924 | | | — | .08 |
| Clear Trns. | 0 | .927 | | | | .08 |
| .92 | 45 | .904 | | | | |
| | 75 | .807 | | | | |
| Acrylic Ref | | .843 | | | — | .08 |
| Bronze Trns. | 0 | .40 | | | | .08 |
| 2612 .35 | 45 | .37 | | | | |
| | 75 | .21 | | | | |
| Acrylic Ref | — | .893 | | | — | .086 |
| Texture Trns. | | | | | | |
| cons | | | 0 | .04 | | |
| | | | 10 | .32 | | |
| | | | 15 | .26 | | |
| | | | 45 | .07 | | |
| | | | 75 | .01 | | |
| Acrylic Ref | — | .845 | | | — | .81 |
| White Trns. | | | | | 0 | .82 |
| 2447 .53 | | | | | 45 | .65 |
| | | | | | 60 | .47 |
| Paint Ref | | .831 | | | | |

LIGHT TRANSFER
Photometry, distribution, definitions and test data for luminaire materials.

Figure 3.

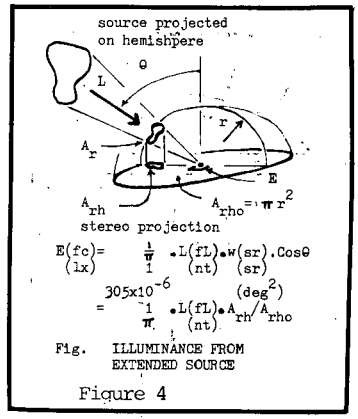



Fig. ILLUMINANCE FROM EXTENDED SOURCE

Figure 4

Application of the field data gives the luminances of the luminaire and space in the visual assessment of brightness dependent responses in terms of discomfort, veiling and disability glare criteria and visibility. Illuminances E(fc) from extended sources are found from the luminance L(fL), the solid angle W (sr) and angle of incidence as explained in the diagram (See Figure 4). Now reflection and transmission factors $K_\theta$ are applied $L_\theta$ (fL) = $K_\theta$. E(fc) as appropriate from Figure 3.

## 7. LUMINAIRE DESIGN

The black fins of the collector both direct and shade so that the daylight penetration is an attenuation of the sky luminance perpendicular to the fins. A fin shading factor $K_f$ is set by the fin aperture $A_f$ for a collector $A_c$.

$$K_f = A_f/A_c$$

Generally, direct sun does not pass through the fins since it is angled to be primarily a solar collector. A diffuse outside dome would significantly increase the luminance by redirecting the sunlight, but it also reduces the thermal transmission. A clear dome is appropriate.

The inside panel separates the hot collector air from the space. An essentially clear material would provide a "sky beam" that forms a light patch on surfaces. The fin would be seen. A diffuse material would redirect the light as a glow in the ceiling. Some spreading of the beam and obscuring of the fins is needed, which suggests a prismatic or partially diffusing material.

Daylighting calculations were based on an equivalent sky luminance $*^a_\theta$ which depends on the attitude of the sun — alt and cloud condition. As a guide, the noon sun in month M rises to . . .

$\theta_{Alt\ Noon} = 90 - \theta_{Latitude} + 23.5 \cdot Sin.\ 360 \cdot (m-3)/12$

$L(fL)_{Sky\ overcast} \simeq 35 \cdot \theta'_{Alt.}$

$L(fL)_{Sky\ clear} \simeq 1600 \cdot Sin.\ 1.63 \cdot \theta'_{Alt}$

$E(fc)_{Sun.\ Horiz.} \simeq 9000 \cdot Sin.\ (\theta'_{Alt} - 9)$

For example, for latitude 32° N in winter, the noon sun altitude is 54.5°, giving an overcast sky 1,200 fL, clear sky 1,300 fL and horizontal illuminance 5,900 fc. With a clear dome .927 transmission, fin shading factor .4 and cone textured panel .64 transmission, the downward sky beam luminance would be about 285 fL on an overcast day.

A 2' X 8' panel 6 feet from a table subtends 18° x 68°, producing a light patch of about 11.5 fc illuminance allowing for its angular fall off in distribution. Alternatively, a white diffusing panel would be illuminated through a 4° x 110° fin subtense giving 48 fc 32 transmission for the same sky, which would then illuminate the table with 4.7 fc without a patch shape. In summer, the clear sky is about the same and an overcast sky more than twice the value.

The luminaire is a complementary lighting system providing an interesting varying downlight. Applications may be in the general lighting of computer spaces, task lit areas, lobbies, lounges, storage and bedrooms.

## 8. COMPUTER SIMULATIONS

The Litetherm System computer simulation will use the optical model of the CST 1001 Lightherm solar collector and incorporate that into a hypothetical office. This office will be illuminated by CST 1001 Litetherm Solar collectors and fluorescent tubes will be controlled by light intensity on the desk level. These tubes will be turned off whenever the solar collectors provide the desired level of lighting.

## 9. OPTICAL SIMULATION OF LITETHERM SYSTEM

Following is a list of inputs this computer simulation will employ:
Room length, room width, number of collector rows along the length, number of collectors in each row, number of fluorescent light fixture rows between collector rows (half this many assumed by the walls), number of fluorescent fixtures in each row, length of each fixture (assumed to be narrow strips), wattage of each fixture, wall reflectance factor (reflectances of floor and ceiling are assumed to be 0, the light reflected from one wall to another is ignored), collector orientation, hourly solar radiation data (intensity as a function of direction as expressed by polar coordinates), hours that the office is open, day of the year and desired lighting level.

Outputs from this simulation incude, hourly light intensities on desk level, hourly wattage consumption and a summary to establish savings.

## 10. THERMAL SIMULATION OF LITETHERM SYSTEM

The model that is used to described the performance of an ordinary flat plate collector cannot be utilized here because of the following:

- CST Lightherm 1001 collectors use two fluids, air and water.
- There are two ambient temperatures, indoor and outdoor.
- CST Lighthem 1001 collectors also act as heat exchangers, giving one more parameter.

A model was devised using the following parameters:

- Y-intercept using water (and air)
- curve slope using water assuming no thermal transfer to indoors (and outdoors) assuming ambient temperature to be outdoor temperature
- curve slope using air assuming no thermal tranfer to outdoors and assuming ambient temperature to be indoor temperature.
- heat transfer factor when used as a heat exchanger (units of heat transferred for each unit of temperature difference between incoming water and incoming air at the used air and water flow rates.)

To fit the panel with the above parameters into an actual working situation, the following parameters are needed: orientation, tilt, incident angle modifier and total area.

Because of the Litetherm System's special features, the storage tank cannot be modeled as a well-mixed tank, but must be divided into multiple layers, each having its own temperature. Since the top layer loses more heat through the increased surface at the top of the tank, and thus causes mixing, tank dimensions and R-values are needed.

The tank is assumed to be cylindrical sitting on one end. Required parameters follow: top R-value, bottom R-value (as installed), side R-value, radius of the cylinder, height of the cylinder, discharge/intake level of each pipe and location indoor/outdoor.

The following information is required for piperuns: length, heat loss per (unit length x unit time x unit temperature difference), volume per unit length for the following piperuns:

- tank to collector
- tank to hot water heater
- collector to tank
- hot water heater to tempering valve

These piperuns are assumed to be outside.

The water heater is assumed to be well mixed. The following parameters are required:

Power in (Btu/hr), power out (100°F rise time), volume, heat loss (Btu/hr x °F difference) and location indoor/outdoor.

The settings of the temperature valve and the flow rate are needed from the circulator.

From the control the following are needed: indoor stage 1 thermostat setting, indoor stage II thermostat setting, collector core temperature for fans (on and off), tank to collector core differential for circulation (on and off), heating threshold for collector core (on and off temperature), heating threshold for tank (on and off temperature), collector and tank sensor location.

The role moisture plays in heating is ignored. A dynamic value is used for thermal mass. This can be determined from the building heat loss factor by looking at the indoor rate of temperature change when the heat is turned off and there are no solar heat gains when outdoor temperature is known. The following parameters are needed: daily hot water use, hourly distribution of above, building heat load (Btu/hr x °F) and building dynamic thermal mass (Btu/°F).

Other required information includes latitude, hourly ambient temperature data, hourly radiation data and street water temperature.

Outputs from the thermal simulation of the Litetherm System include hourly indoor and tank temperatures displays as well as heat gains by the collector to storage and/or the indoor air. Totals for collector heat gains and furnace and water heater gas usage will be displayed. Gas use totals can be employed to compare to situation without given system in order to get an estimate of savings. Temperatures and heat flows anywhere in the system can be displayed.

## 11. OPTICAL SIMULATION OF CST 1001 LITETHERM COLLECTOR

The computer model of the CST 1001 Litetherm collectors looks at light intensity as a function of the two polar coordinates. A transformation to this function is done three times: first through the outside bubble, then the core and finally the Lexan. The final light intensity function along with the shape and location of the final stage will enable the lighting intensities on any plane in the room to be calculated. Light from multiple CST 1001 Litetherm collectors also will be combined.

In this model, light is seen as having intensity and direction only. Possible changes in the spectral distribution of the intensity are ignored.

The test sequence of outside light at different hours, versus inside light at the same time at different angles, are run with and without Lexan to improve accuracy.

Input for the optical simulation of the CST 1001 Litetherm Collector follow: collector area, tilt, orientation and hourly solar radiation data, intensity as a function of direction as expressed by polar coordinates.

Output will include data that coincide with the input about light intensities shining down from the collector at different directions.

## 12. REFERENCES

a*
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ACKNOWLEDGEMENTS

Dr. John Halldane developed the photometric methods and test data. Skyline Plastics of Colorado Springs provided the samples for testing. Davenport Hydronics Inc. of Inglewood, California, is currently the distributor of the Litetherm System. Wilhelm Sarasalo, Conservation Engineering, Manhattan Beach, California, comptuer-modeled the thermal and lighting systems. California Solar Technology (CST) designed and is manufacturing the Litetherm System.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# RESULTS OF VALIDATED SIMULATIONS OF ROOF POND COOLED RESIDENCES

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## ABSTRACT

Results based on new validated simulations of roof pond cooled residences (RPR) in 14 hot U.S. cities are reported. Radiant heat transfer dominates heat removal from the RPR interior and from the pond exterior. The RPR is a water-conserving cooling technology even in arid climates. In all but arid climates the ventilated RPR requires dehumidification to prevent mold and mildew. Ceiling condensation is frequent in humid climates. Total heat removal from the interior is only about 100-140 Btu/ft$^2$ day. The RPR must be very well insulated in order to maintain interior comfort conditions below PMV=0.5 in the hottest climates. Ceiling fans are essential for comfort in most climates. PMV=0.5 conditions are found to be comfortable by other recent comfort criteria.

## 1. INTRODUCTION

The Trinity University Passive Cooling Research Group previously conducted a simulation of comfort conditions in "Skytherm" type roof pond cooled residences (RPR) and concluded that comfort can be achieved during all hours of a typical summer in all U.S. climates (1). Ceiling fans were found to be essential for comfort in most climates. In all but arid climates, dehumidification was required for mold, mildew and condensation control, but not for comfort (2). Supplemental sensible cooling was not required (1).

These conclusions elicited doubts and questions which focused on two issues:

a) The comfort estimates are the result of computer simulation. Does the simulation produce accurate estimates of interior temperatures in a realistic RPR?

b) Simulated comfort conditions are based on the Fanger PMV methodology (3). Is PMV an accurate description of the frequently warm and humid conditions which occur in the simulated RPR? In particular, is comfort perception as sensitive to air speed over the body and as insensitive to humidity as the PMV methodology implies?

This report addresses these issues in brief summary form. The previous simulations were based on theory and on heat transfer data from a variety of sources including one RPR and small-scale experiments in only a few climates.

The building simulated in the older assessment was defined to be similar to the original Skytherm residence constructed at Atascadero, California. The results of the older simulation were compared with several days of data taken at the Atascadero residence, and agreement was satisfactory (4). However, because the Atascadero data were not detailed and did not extend over a wide range of meteorological conditions, unverified assumptions and extrapolations were necessary. Because the Atascadero roof pond was sealed rather than an open (wet) surface, the evaporative heat exchange algorithm was derived from theory.

In the older simulations, total heat dissipation from the roof pond was dominated by radiative heat loss to the night sky. Because wet ponds operated relatively close to the wet bulb temperature, radiative loss was important even for open surface ponds in dry climates. However, the radiative heat exchange algorithm utilized in the old simulation was derived from data taken only in San Antonio. The accuracy of this radiative exchange algorithm when applied in other climates was unknown.

Since the development of the original Trinity RPR simulation, the state-of-the-art has advanced. A highly instrumented thermal test facility including two residential scale RPR buildings was completed on the Trinity campus. The design, construction, instrumentation and operation of these buildings have been documented in an earlier report (5).

During the period May, 1981, through November, 1981, these two buildings were operated as unoccupied RPR in the cooling mode. One building had an open roof pond and the other a sealed or "dry" roof pond. Detailed heat transfer data and meteorological data were acquired during this period and used to develop the new verified computer simulation of these buildings. The development, validation and content of this new simulation is documented in detail in another report (6).

In addition to data from the Trinity Test Facility, the new Trinity RPR simulation incorporates a new algorithm for the infrared radiance of the nocturnal sky. The new sky radiance formula is based on new infrared irradiance measurements made by Trinity University, Georgia Institute of Technology, and Lawrence Berkeley Laboratory (6,7).

## 2. OBJECTIVES, SCOPE AND RELATED REPORTS

This report is based on new simulations (using the validated algorithms) of wet and dry RPR in 14 U.S. cities. Among these are the U.S. cities with the greatest residential air conditioning loads. The simulated residences are assisted only by ceiling fans and ventilation. Simulated comfort perception is still based on Fanger's PMV. The PMV comfort assessment methodology is compared with other recent comfort perception analyses. The thermal characteristics of the new simulated RPR are defined. Selected heat transfer and PMV results are presented to support general conclusions drawn from the complete 14 city simulation results. Sensitivities of comfort and thermal load components to design assumptions are evaluated. Interior humidity and ceiling condensation problems are described. The primary result presented is a list of general conclusions. Several of the conclusions will apply to many other passive cooling systems, not just to RPR.

Other recent reports present related details and complementary information. A national map of the geographic limits of comfort provided by an RPR at 6pm on a July 2½% ASHRAE design day is presented in another report in these Proceedings (8). The map evaluates the benefits of ceiling fans and the benefits of the additional cooling provided by evaporation from a wet surface roof pond. Another report evaluates the energy displacement potential of an RPR assisted by innovative high efficiency dehumidifiers (9).

## 3. FANGER PMV AND OTHER COMFORT ANALYSES

The comfort conditions in the simulated RPR are evaluated as hourly distributions of Predicted Mean Vote (PMV). The PMV comfort scale evaluates the results of all relevant personal and environmental thermal effects in a single comfort perception parameter.

The range of PMV is -3 (cold) to +3 (hot). The percent of a sample of people dissatisfied with their thermal environment is listed in Table 1 (3). At PMV=0 thermal dissatisfaction is minimized with 2½% warm and 2½% cool (3). The 7 point ASHRAE comfort perception scale translates PMV=+1.0 as "slightly warm".

TABLE 1.

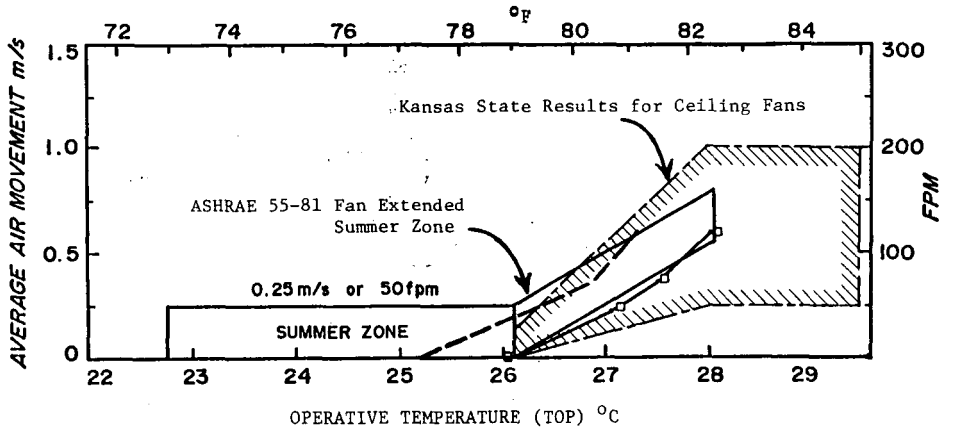
PERCENT DISSATISFIED AT GIVEN PMV
(From reference (3).)

| PMV | % Dissatisfied Warm | Cool |
|---|---|---|
| 0 | 2.5 | 2.5 |
| +0.2 | 4.5 | 1.3 |
| +0.4 | 7.7 | 0.6 |
| +0.5 | 9.8 | 0.4 |
| +0.8 | 18.5 | 0.1 |
| +1.0 | 26.4 | 0.0 |

In this report we assume residents are dressed with clothing of thermal resistance clo=0.5 (informal, summer office wear) and activity level of met=1.2 (sedentary, standing). Figure 1 compares the operative temperature required by ASHRAE Comfort Standard 55-81 with the operative temperature required to meet several PMV levels with these clo and met assumptions. Operative temperature is the weighted average of the mean radiant temperature (MRT) and the dry bulb air temperature (DB). The weighting is proportional to the relative importance of infrared transfer and convective transfer at the body surface. Operative temperature is equally dependent on MRT and DB at low air speeds and is dominated by DB at air speeds over 100 fpm. Figure 1 assumes that the interior dewpoint is 62°F, the upper dewpoint limit allowed by ASHRAE 55-81. Table 2 presents information similar to that in Figure 1, but assumes that the interior relative humidity is 68%.

Figure 1 illustrates that for the assumptions made here, PMV=0.5 defines thermal conditions in good agreement with ASHRAE 55-81. Figure 1 also shows the results of new comfort chamber tests of ceiling fans (10). These Kansas State results are based on relative humidity of 50%, and at that condition the air speed comfort benefits estimated by ASHRAE 55-81 and PMV appear conservative.

The PMV methodology implies that dewpoint or relative humidity has only a small effect on preferred temperature, if the temperature is low enough to provide comfort and if there is air motion. For clo=0.5, met=1.2, speed=0 and MRT=DB, the DB defined by constant PMV in the range from 0 to 0.5 decreases only 2°F as dewpoint is increased from 62°F to 76°F.




PMV calculations assume met=1.2, clo=0.5 and Dewpoint=62°F

- — — TOP if PMV=.20, mean rad. temp.(MRT)=Dry bulb(DB)
- ——— TOP if PMV=.45, DB=MRT
- ——□ TOP if PMV=.5, DB=MRT-4°F

Fig. 1. Comparison of PMV, ASHRAE and Kansas State Comfort Requirements.

The insensitivity of comfort to an increase in dewpoint from 50°F to 68°F has been confirmed independently (11).

Nishi and Gagge (12) have pointed out that excessive skin wettedness (SKW) can result in perceived discomfort even if the body is thermally comfortable (i.e., by PMV criteria). At met=1.2, the allowed upper limit on skin wettedness is 0.233 (12,13). Table 2 and other results (13) show that skin wettedness does not produce discomfort under the conditions simulated in ceiling fan assisted RPR.

TABLE 2.

EFFECT OF VARYING VELOCITY ON TEMPERATURE AT CONSTANT PREDICTED MEAN VOTES

clo=.5, met=1.2, Relative Humidity=68%

| PMV | TOP F | MRT F | DB F | VEL FT/MIN | SKW |
|---|---|---|---|---|---|
| 0.00 | 75.6 | 73.7 | 77.7 | 20 | .135 |
| 0.20 | 76.8 | 74.9 | 78.9 | 20 | .157 |
| 0.40 | 78.0 | 76.1 | 80.1 | 20 | .181 |
| 0.50 | 78.6 | 76.7 | 80.7 | 20 | .193 |
| 0.00 | 79.1 | 76.4 | 80.4 | 100 | .065 |
| 0.20 | 80.1 | 77.4 | 81.4 | 100 | .079 |
| 0.40 | 81.0 | 78.3 | 82.3 | 100 | .091 |
| 0.50 | 81.4 | 78.8 | 82.8 | 100 | .099 |
| 0.00 | 80.0 | 77.1 | 81.1 | 160 | .054 |
| 0.20 | 80.9 | 78.0 | 82.0 | 160 | .065 |
| 0.40 | 81.8 | 78.9 | 82.9 | 160 | .077 |
| 0.50 | 82.2 | 79.3 | 83.3 | 160 | .082 |

## 4. THERMAL CHARACTERISTICS OF SIMULATED RESIDENCES

The simulated building has the following characteristics:

- Conventional slab-on-grade construction with perimeter insulation. The slab is covered by an R2 carpet.
- Floor 34x36ft (1224ft$^2$) and corrugated metal ceiling covered by a 1224ft$^2$ pond of 6" depth.
- There are 90ft$^2$ of south facing and 60ft$^2$ of north facing double glazed windows. The windows are shaded by 3 ft overhangs and by interior shades with shade factor= 0.4.
- The infiltration rate is 0.5 ACH with 8am and 6pm peaks of 1.0 ACH.
- The residence is occupied by four persons. Total internal load is 50,000 Btu per day sensible and 16 lb of water per day latent load.
- The residence is ventilated at 10 ACH whenever the ambient air is cooler and/or drier than the interior air and sensible cooling and dehumidification are desirable. If the wind speed is less than 5 mph, ventilation is provided by a .33kW fan.
- Interior air motion is provided throughout the residence by three ceiling fans. For purposes of computing PMV, the 3 speed ceiling fans create air speed over the

person of 20fpm (fan off), 60fpm (speed 1), 100fpm (speed 2) and 160fpm (speed 3). The interior surface convection coefficients are adjusted for ceiling fan-induced air motion. The three ceiling fans together require .28kW on speed 3.

- The base case wind speed across the roof pond (just above the boundary layer) is assumed to be only 0.1 of the meteorological wind speed (6,13).

Thermal characteristics of the base case (and improved) walls and pond insulating panels are listed in Table 3.

TABLE 3.

THERMAL CHARACTERISTICS OF WALLS AND ROOF PANELS FOR COMFORT SENSITIVITY ANALYSIS

Base Case Walls

Total effective U=.096 R=10.42
0.5" Gypsum Board
3" Insulation and Studs (with mass)
3/4" Plywood

(Note: Base case wall used unless specified otherwise.)

Medium R Walls with Low Mass Exterior (W)

Total effective U=.052 R=19.23
0.5" Gypsum Board
5 5/8" Insulation and Studs (with mass)
3/4" Plywood

High R Walls with High Mass Exterior (MW)

Total effective U=.047 R=21.3
0.5" Gypsum Board
R19 Massless Insulation
0.12" Cellulose
0.372" Pine Siding
R.48 Massless Air Space
1 7/8" Brick

Base Case Movable Roof Pond Panels

U value of panel = .086
Air changes per hour under panel = 12.1

(Note: Base case panels used unless specified as (P))

High R, Low Infiltration Panels (P)

U value of panel = .043
Air changes per hour under panel = 6.1

## 5. RESULTS

Table 4 lists the results of the new simulation in Miami, San Antonio and Phoenix, three of the most difficult climates for a RPR (8). Ceiling fans are required most of the time in these cities. The thermally improved walls and roof insulating panels are required to provide comfort in Phoenix. In fact, to reduce PMV below 0.5 during all hours would require air speed of 200fpm during 15 hours.

Table 5 lists the total hours during July when relative humidity exceeds 68% in Tallahassee, San Antonio and Phoenix. Hours of ceiling condensation are also listed. Even with the aid of ventilation, excessive relative humidity will cause mold and mildew problems in all but arid climates (9,13). Ceiling condensation is frequent in humid climates.

TABLE 5.

TOTAL HOURS OF CEILING CONDENSATION AND INTERIOR RELATIVE HUMIDITY ABOVE 68%

(Wet RPR, Typical July, Roof Wind=0.1 Met. Wind)

Day R.H. is average interior relative humidity between 9am and 7pm inclusive. Night R.H. is average interior relative humidity between 7pm and 9am inclusive.

| CITY | R.H.>68% (Hrs.) | DAY R.H. (%) | NIGHT R.H. (%) | CEILING COND. (Hrs.) |
|---|---|---|---|---|
| TAL., FLA. | 743 | 85 | 89 | 59 |
| S.A., TX. | 666 | 75 | 85 | 6 |
| PHOENIX | 52 | 46 | 55 | 0 |

The simulated heat removal from the interior air and the pond are both dominated by infrared radiant transfer. The interior infrared heat removal proceeds in two stages; first the carpeted slab and interior wall surfaces radiate to the ceiling and cool below the air temperature. The interior air is then convectively cooled by these extended cool surfaces. Only at fan speed 3 does convective heat removal at the ceiling approach radiative heat transfer rates.

Only in desert climates (Phoenix) does the base case wet roof pond lose as much heat by evaporation as radiation. In Miami only 85 gal are evaporated from the pond during July. In San Antonio 161 gal are evaporated and in Phoenix 516 gal are evaporated. If the roof wind speed is assumed to increase to 0.33 of the meteorological wind speed, the rate of evaporation doubles. However, radiative loss decreases and convective gain increases. The net effect of increased wind speed on the total pond heat loss rate is minor. Even in Phoenix in July the increased roof wind speed increased the total heat lost by less than 10%. In comparison to mechanical evaporative coolers (which cool a large volume of hot ambient air) the RPR is a water conserving cooling technology in arid climates.

## 6. ACKNOWLEDGEMENT

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TABLE 4.

SENSITIVITY TO IMPROVED WALLS AND ROOF PANELS

Unassisted Wet Roof Pond Residence, Typical July
Roof Wind Speed = 0.1 x Met. Wind Speed

NOTE: See Table 3 for definition of column headings.

| Hours at Listed PMV | SAN ANTONIO | | | | | | MIAMI | | | | | | PHOENIX | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base | MW | W | P | W&P | MW&P | Base | MW | W | P | W&P | MW&P | Base | MW | W | P | W&P | MW&P |
| PMV ≤ 0.2 | | | | | | | | | | | | | | | | | | |
| Fan = 0 | 116 | 132 | 119 | 143 | 150 | 166 | 16 | 19 | 16 | 22 | 23 | 30 | 96 | 125 | 110 | 159 | 228 | 237 |
| Fan = 1 | 324 | 351 | 374 | 379 | 476 | 450 | 212 | 256 | 250 | 272 | 310 | 311 | 200 | 234 | 240 | 244 | 261 | 261 |
| Fan = 2 | 139 | 162 | 167 | 158 | 104 | 112 | 189 | 190 | 207 | 188 | 219 | 202 | 97 | 103 | 100 | 116 | 99 | 99 |
| Fan = 3 | 118 | 79 | 66 | 57 | 14 | 16 | 163 | 181 | 171 | 180 | 154 | 163 | 107 | 107 | 110 | 89 | 68 | 62 |
| 0.2<PMV<0.5 | 41 | 20 | 18 | 7 | 0 | 0 | 155 | 96 | 99 | 81 | 37 | 37 | 119 | 92 | 98 | 78 | 73 | 70 |
| 0.5<PMV<1.0 | 6 | 0 | 0 | 0 | 0 | 0 | 9 | 2 | 1 | 1 | 1 | 1 | 116 | 83 | 86 | 58 | 15 | 15 |
| PMV > 1.0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9 | 0 | 0 | 0 | 0 | 0 |
| Hours/Month of Ventilation | 234 | 225 | 228 | 228 | 215 | 211 | 211 | 217 | 217 | 226 | 236 | 233 | 18 | 14 | 16 | 11 | 12 | 10 |
| Ceiling Condensation | 7 | 9 | 9 | 10 | 14 | 14 | 22 | 31 | 30 | 38 | 45 | 47 | 0 | 0 | 0 | 0 | 0 | 0 |
| Heat Transfer ($10^4$ Btu/day) | | | | | | | | | | | | | | | | | | |
| Pond Loss | 17.3 | 16.7 | 16.7 | 15.6 | 14.8 | 14.7 | 16.9 | 16.4 | 16.4 | 15.7 | 15.2 | 15.2 | 24.4 | 23.3 | 23.4 | 21.3 | 19.8 | 19.6 |
| Panel Gain | 5.7 | 5.8 | 5.8 | 3.0 | 3.1 | 3.1 | 4.2 | 4.3 | 4.3 | 2.2 | 2.3 | 2.3 | 9.2 | 9.4 | 9.4 | 5.0 | 5.2 | 5.3 |
| Wall Gain | 2.5 | 1.3 | 1.4 | 2.7 | 1.4 | 1.5 | 2.1 | 1.1 | 1.2 | 4.4 | 1.2 | 1.1 | 4.4 | 2.3 | 2.5 | 4.6 | 2.7 | 2.5 |
| kWh/Month (Fans) | 142 | 132 | 133 | 125 | 113 | 111 | 203 | 198 | 198 | 196 | 189 | 187 | 152 | 138 | 142 | 126 | 106 | 103 |

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# ENERGY SAVINGS POTENTIAL OF DEHUMIDIFIED ROOF POND RESIDENCES

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## ABSTRACT

The energy displacement potential of roof pond cooling in humid climates is sensitive to the type of dehumidification equipment employed and the humidity levels allowed. This paper reports the simulated energy requirements of roof pond residences assisted by two high efficiency dehumidifier options. One dehumidifier is a vapor compression air conditioner with sensible cooling recovery by an air-to-air heat exchanger (referred to as an "improved mechanical dehumidifier (IMD)"). The second option is a solar regenerated desiccant dehumidifier (SRDD).

Results for 15 cities were compared to simulation results for a very energy conserving conventional house. The simulation was performed using typical April through October meteorological data. Comfort was controlled to a predicted mean vote (PMV) of ±0.2 and relative humidity was controlled to 68% or less to prevent mold and mildew growth.

An IMD assisted roof pond house had energy savings of 30 to 65% in humid climates and 90% in dry climates compared to the conventional house. An SRDD assisted roof pond house had energy savings of 70 to 75% in humid climates. Conventional house peak power demand was displaced by 10 to 60% in an IMD assisted roof pond house and 50 to 75% in an SRDD assisted roof pond house. A method is given relating the energy savings to July dew point average and annual cooling degree days.

Cooler temperatures forced about twice as much dehumidification to be done in the roof pond house than in the conventional house in humid climates. Recommendations are made for more optimal pond temperature and interior humidity control strategies to prevent overly cool interior temperatures.

## 1. INTRODUCTION

Validated simulations of ceiling fan assisted roof pond ("Skytherm") cooled residences imply that this system can provide sufficient sensible cooling for comfort in all U.S. climates (1, 2, 3). However, without the dehumidification normally provided by air conditioning, mold, mildew and ceiling condensation are problems in all but the driest climates. Conventional air conditioners are not efficient dehumidifiers for such residences because the sensible cooling which they provide displaces the sensible cooling which would have been provided by the roof pond. As a result of this displacement of the passive cooling system, the energy savings potential of passive cooled buildings dehumidified by air conditioners would be quite limited in humid climates. A roof pond cooled building assisted by a conventional air conditioner which is enthalpy controlled to produce ASHRAE conditions (dewpoint less than 16.7°C) was previously simulated. In humid Gulf coast cities, the simulated air conditioner dehumidified building required 70% of the energy of a simulated conventional residence (3). Conventional vapor compression dehumidifiers require even more energy and also add sensible heat to the conditioned space (3).

This report presents the results of validated simulations of roof pond residences assisted by two innovative types of dehumidifiers. Each of these dehumidifiers is well adapted to use with a passive cooling system because these dehumidifiers invest a minimum of energy in sensible cooling. The two dehumidifiers simulated are:

1) A vapor compression air conditioner with sensible cooling recovery by an air-to-air heat exchanger (designated here as an "improved mechanical dehumidifier" or "IMD").

2) A solar regenerated desiccant dehumidifier (SRDD) which absorbs moisture from the air using a silica gel packed bed. The silica gel is dried using heat from a solar hot air collector. The SRDD system is assumed to employ a pair of switched beds so that a dry bed is always available.

Both dehumidification methods have been described in previous reports (4, 5). Prototype models of each were constructed and tested at Trinity University and the performance data were used to develop simple validated computer models (4, 5, 6).

The primary objective of this report is to evaluate the potential for energy displacement of a system combining passive cooling and innovative dehumidification systems compared to an energy conserving conventional (non-roof pond) residence. The results are based on detailed hourly simulations for selected typical April through October months in 15 U.S. cities.

## 2. THE SIMULATION

The simulation described in (1) for an unassisted roof pond house was modified for the energy displacement analysis. Variations from the unassisted roof pond house building and simulation are:

- The building has the same construction characteristics, except the walls are always insulated with R-19. The pond panels are well insulated {6.1 air changes per hour and 2.44 $W/m^2{}^oC$ (0.43 Btu/hr $ft^2{}^oF$)} for the Southern Coastal and Southwestern Regions (defined below); and the pond panels have standard insulation {12.1 air changes per hour and 4.88 $W/m^2{}^oC$ (0.86 Btu/hr $ft^2{}^oF$)} for the milder climates.

- The interior sensible load profile was increased to a total of 55,000 KJ/day (52 MBtu/day), including some occupant load each hour. The total interior latent load is 20,000 KJ/day (19 MBtu/day or 17.9 lb of $H_2O$/day).

- The roof pond insulating panel control was run in one of two modes each month. During a "cooling season" month the roof panel closed if the pond gained heat or if the pond temperature decreased to $20^oC$ ($68^oF$). During a month termed a transition season month, the panels were controlled so that the pond target temperature was between $23^oC$ and $23.6^oC$ ($73.5$ and $74.5^oF$). This control was added as an attempt to prevent overcooling and to permit a longer season (April through October) of analysis. Although more nearly optimal than a single control mode, even more efficient control schemes can be devised.

- Comfort is controlled to a predicted mean vote (PMV) between -0.2 and +0.2. A backup furnace and a backup air conditioner (1 ton size) assure the criteria are met at all times. This air conditioner has the performance characteristics of the Lennox AC described below but scaled to 1 ton capacity. It is assumed that clothing and ceiling fans are adjusted as defined in (1).

- Relative humidity is controlled to a level of 68% or less. This upper limit is based on reports (7, 8) that mold and mildew growth are encouraged by relative humidities of 70% or greater. A relative humidity control permits higher interior dew points at higher interior temperatures and forces more dehumidification at lower interior temperatures (a penalty for "overcooling").

- The IMD is simulated using a constant dehumidification COP of 3.2. Dehumidification COP is defined here as the ratio of latent heat removed per time divided by the total power input to the dehumidifier/air distribution system. This system efficiency is based on measured performance of a prototype IMD (4) and the assumption that high efficiency compressor, low pressure drop distribution ducts and fans will be used. The sensible cooling recovery heat exchanger effectiveness is assumed to be 0.80 so the IMD sensible to total cooling ratio is 0.20.

- The SRDD is simulated assuming a constant electric dehumidification COP = 9.9. "Electric dehumidification COP" is defined as latent cooling provided divided by electric parasitic energy required during a complete desiccation/regeneration cycle. Performance of a prototype (5) implies that the listed COP is realistic if the collectors, desiccant bed, duct work and fans are designed for low pressure drop and high efficiency. Half of the parasitic power is used during the hours dehumidification is needed, and half during the period 8:30 to 15:30 (local solar time) when solar regeneration is possible. The heat of absorption, 2790 kj/kg (1200 Btu/lb) released to the air stream exiting the desiccant bed is absorbed by the roof pond before the air returns to the room. (A ceiling plenum heat exchanger with 80% effectiveness could provide such a result because the pond is colder than the room air (5).) The collector area and desiccant bed(s) are assumed to be sized such that they can meet any latent load.

- Except for uncontrolled infiltration, no ventilation takes place in the roof pond house. This is a simplifying assumption.

The thermal characteristics of the energy conserving conventional house were the same as the roof pond house with the following exceptions:

- The horizontal roof was insulated with R30 insulation and had a solar absorptance of .3 and an infrared emissivity of .85.
- A ventilation rate of 10 air changes per hour was simulated in the conventional house when it would not increase the interior dew point and when the exterior dry bulb temperature is below 25.6°C (78°F) and also below the interior dry bulb. Ventilation was simulated as forced (with a fan consuming 328 watts) if the wind speed was less than 2.2 m/s (5 m.p.h.) and natural (no electrical consumption) if the wind speed was higher.
- The primary source for sensible and latent cooling was a Lennox Landmark IV Series H514-411V-413V (with CB15-900/41 Evaporative Unit), 14.0 SEER (Seasonal Energy Efficiency Ratio) unit. The unit was simulated using an algorithm validated against the manufacturer's data (9). The 3 ton simulated values were linearly scaled to 2 ton values. The air conditioner was required to be on for 10 minute intervals if the fan assisted PMV > 0.20. The unit was permitted to operate in three modes.

  1) A high compressor speed, high air volume mode to produce maximum cooling (used when PMV > 0.25 or when the ambient dry bulb was > 40.6°C (105°F).
  2) A low compressor speed, high air volume mode for the most energy efficient sensible cooling (used at all times other than specified by modes 1 and 3).
  3) A low compressor speed, low air volume mode for the most energy efficient latent cooling (used when the relative humidity was > 68%).

  Thus, the air conditioner was simulated in mode 3 for 10 minutes at a time if needed for dehumidification purposes. The distribution fan was assumed to use 125 watts at high speed and 45 watts at low speed.

More details of the simulation are given in (9).

## 3. REGIONAL ENERGY DISPLACEMENT

The conventional house used 30 to 50% less energy in July than the conventional house previously simulated in (3). The major differences in the conventional residence as now simulated are the use of ceiling fans, greater insulation (R19 walls vs. R12.5 and R30 ceiling vs. R23). A relative humidity latent control strategy (vs. a dewpoint upper limit of 16.7°C (62°F) and a dry bulb upper limit defined by PMV < 0.2 (vs. a dry bulb upper limit of 26.7°C (80°F). The currently simulated air conditioner is now more efficient and can operate in three modes (vs. a one mode of operation air conditioner).

Energy use patterns for the 39 runs (made in 15 cities) are shown by region in Tables 1 through 4. The total cooling

TABLE 1.

ENERGY USE PATTERNS IN SOUTHERN COAST CITIES

| CITY | HOUSTON | | | MIAMI | | | | NEW ORLEANS | | | TALLAHASSEE | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RUN | WET IMD | CONV | WET SRDD | WET IMD | DRY IMD | CONV | WET SRDD | WET IMD | DRY IMD | CONV | WET IMD | CONV |
| SEASONAL | | | | | | | | | | | | |
| kWh USED | 1066 | 2252 | 584 | 1377 | 1584 | 2924 | 891 | 1115 | 1134 | 2072 | 958 | 2143 |
| % SAVED | 53 | -- | 74 | 53 | 46 | -- | 70 | 46 | 45 | -- | 55 | -- |
| MONTH OF | AUG | AUG | AUG | AUG | AUG | AUG | AUG | AUG | AUG | AUG | JUL | JUL |
| HIGH kWh | 240 | 551 | 165 | 255 | 327 | 561 | 197 | 274 | 295 | 521 | 216 | 496 |
| MONTH HIGH | JUN, | | | JUL, | | | | | | | JUL, | |
| LB H2O | AUG | JUN | JUN | SEP | SEP | SEP | SEP | AUG | AUG | AUG | AUG | JUL |
| DEH/DAY | 65 | 31 | 59 | 64 | 57 | 26 | 57 | 77 | 73 | 31 | 63 | 27 |
| MNTH, HR OF | JUN | JUN | JUL | JUL | JUL | AUG | JUN | JUL | AUG | AUG | SEP | SEP |
| PEAK kW | 6-7 | 16-17 | 15-17 | 16-17 | 16-17 | 16-17 | 16-17 | 6-7 | 16-17 | 16-17 | 16-17 | 16-17 |
| USED | .73 | 1.54 | .66 | .73 | 1.04 | 1.47 | .77 | .91 | 1.13 | 1.55 | .68 | 1.51 |

TABLE 2.
ENERGY USE PATTERNS IN SOUTHWESTERN CITIES

| CITY | EL PASO | | FT. WORTH | | PHOENIX | | SAN ANTONIO | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| RUN | DRY IMD | CONV | WET IMD | CONV | WET IMD | CONV | WET IMD | DRY IMD | CONV | WET SRDD |
| SEASONAL kWh USED | 173 | 1439 | 714 | 2078 | 372 | 2786 | 852 | 1121 | 2379 | 540 |
| % SAVED | 88 | -- | 66 | -- | 77 | -- | 64 | 53 | -- | 77 |
| MONTH OF HIGH kWh | JUL 74 | JUL 389 | JUL 149 | JUL 552 | AUG 154 | JUL 696 | JUL 188 | JUL 271 | JUL 552 | JUL 136 |
| MONTH HIGH LBs H2O | JUL,AUG, SEP | JUL | JUN | JUN | AUG | AUG | JUL | JUL | JUL | JUL |
| DEH/DAY | 2 | 6 | 45 | 24 | 12 | 13 | 47 | 36 | 24 | 41 |
| MNTH, HR OF PEAK kW USED | JUL 17-18 .68 | JUL 15-19 1.09 | SEP 6-7 .57 | AUG 16-17 1.52 | AUG 16-17 1.12 | JUL 17-18 1.56 | AUG 16-17 .65 | JUL 16-17 1.12 | JUL 16-17 1.54 | JUL 17-18 .38 |

TABLE 3.
ENERGY USE PATTERNS IN EASTERN CITIES

| CITY | ATLANTA | | BALTIMORE | | | CHARLESTON | | |
|---|---|---|---|---|---|---|---|---|
| RUN | DRY IMD | CONV | DRY IMD | CONV | DRY SRDD | WET IMD | DRY IMD | CONV |
| SEASONAL kWh USED | 587 | 1114 | 456 | 675 | 206 | 965 | 978 | 1635 |
| % SAVED | 47 | -- | 32 | -- | 69 | 41 | 40 | -- |
| MONTH OF HIGH kWh | JUL 138 | JUL 342 | JUL 129 | JUL 203 | JUL 58 | AUG 245 | AUG 250 | JUL 420 |
| MONTH HIGH LB H2O | JUL | JUL AUG | JUL | JUL | JUL | AUG | AUG | JUL AUG |
| DEH/DAY | 46 | 28 | 42 | 27 | 38 | 70 | 67 | 32 |
| MNTH, HR OF PEAK kW USED | AUG 16-17 .61 | JUL 16-17 1.50 | SEP 6-7 .56 | JUL 16-17 1.09 | SEP 15-16 .36 | AUG 16-17 .84 | AUG 16-17 1.01 | JUL,AUG 16-17 1.51 |

TABLE 4. ENERGY USE PATTERNS IN MIDWESTERN CITIES

| CITY | DODGE CITY | | LITTLE ROCK | | | NASHVILLE | | ST. LOUIS | |
|---|---|---|---|---|---|---|---|---|---|
| RUN | DRY IMD | CONV | WET IMD | DRY IMD | CONV | DRY IMD | CONV | DRY IMD | CONV |
| SEASONAL kWh USED | 347 | 918 | 746 | 787 | 1510 | 608 | 1237 | 380 | 754 |
| % SAVED | 62 | -- | 51 | 48 | -- | 51 | -- | 50 | -- |
| MONTH OF HIGH kWh | JUL 159 | JUL 403 | JUL 202 | JUL 226 | JUL 425 | AUG 149 | AUG 337 | JUL 108 | JUL 237 |
| MONTH HIGH LB H2O | AUG | AUG | JUL | JUL | JUL | JUL | JUL | JUL | JUN |
| DEH/DAY | 19 | 14 | 57 | 51 | 30 | 43 | 27 | 34 | 21 |
| MNTH, HR OF PEAK kW USED | JUL 17-18 1.00 | JUL 16-17 1.09 | JUL 16-17 .82 | JUL 16-17 .94 | JUL 16-17 1.55 | AUG 16-17 .65 | AUG 16-17 1.53 | JUN 16-17 .61 | AUG 13-15 1.10 |

energy savings of the dehumidified roof pond residence relative to the efficient conventional residence range from 30% in the humid regions to 90% in the energy intensive hot dry regions. The small percent energy displacement in the humid regions can be improved by other design and control assumptions as described in the conclusions.

## 4. ENERGY SAVINGS BASED ON AVERAGE METEOROLOGICAL CONDITIONS

Attempts were made to define climate categories using averages of meteorological parameters so that simulated energy savings for all cities in one climate category were nearly equal. The most useful climate categories identified for this purpose were defined by total annual cooling degree days (base 18.3°C (65°F) and July average dewpoint as provided in (10,11). The percent total energy and peak power savings (comparing the IMD assisted roof pond residence with the efficient conventional residence) so defined are shown in Tables 5 and 6. These tables also recommend a dry or wet pond surface. A wet surface is recommended if it prevents significant air conditioner assistance or produces significant total energy savings due to decreased ceiling fan requirements. Total kWh savings ranged from 300 in warm, moderately humid climates, to 2400 in very hot, moist climates. Peak power savings were very sensitive to backup air conditioning.

## 5. DISCUSSION AND CONCLUSIONS

Total energy and peak demand required for cooling of conventional residences can be dramatically reduced by use of efficient mechanical systems, proper envelope design, interior load management, ceiling fans, and a PMV/relative humidity controller. The assumption made here that comfort and humidity control are provided for 24 hours every day will decrease peak demand and increase

TABLE 5.

PROJECTED % ENERGY SAVINGS OF RECOMMENDED IMD ASSISTED ROOF POND TYPE RESIDENCES

| | | SENSIBLE CLIMATE TYPE | | | |
|---|---|---|---|---|---|
| | | VERY HOT | HOT | MOD. HOT | WARM |
| TOTAL COOLING DEGREE DAYS | Base 18.3°C (Base 65°F) | >2000 (>3600) | 1500-2000 (2700-3600) | 1000-1500 (1800-2700) | 500-1000 (900-1800) |
| RECOMMENDED | POND TYPE | WET | BOTH | DRY | DRY |
| LATENT CLIMATE TYPE (JULY AVG. DEW PT.) | Very Humid (22.2-22.8°C)(72-73°F) | 55 | 50(Dry) | 40 | X |
| | Mod. Humid (18.3-21.1°C)(65-70°F) | X | 65(Wet) | 50 | 40 |
| | Moist (14.4-16.1°C)(58-71°F) | 75 | X | X | 60 |
| | Dry (12.8°C)(55°F) | X | X | 90 | X |

TABLE 6.

PROJECTED % PEAK DEMAND SAVINGS OF RECOMMENDED IMD ASSISTED ROOF POND TYPE RESIDENCES PROVIDING COMFORT OF PMV=0.2 AT ALL TIMES (WITH AC BACKUP)

| | | SENSIBLE CLIMATE TYPE | | | |
|---|---|---|---|---|---|
| | | VERY HOT | HOT | MOD. HOT | WARM |
| TOTAL COOLING DEGREE DAYS | Base 18.3°C (Base 65°F) | >2000 (>3600) | 1500-2000 (2700-3600) | 1000-1500 (1800-2700) | 500-1000 (900-1800) |
| RECOMMENDED | POND TYPE | WET | BOTH | DRY | DRY |
| LATENT CLIMATE TYPE (JULY AVG. DEW PT.) | Very Humid (22.2-22.8°C)(72-73°F) | 50 | 45(Wet) 33(Dry) | 33 | X |
| | Mod. Humid (18.3-21.1°C)(65-70°F) | X | 60(Wet) | 50 | 45 |
| | Moist (14.4-16.1°C)(58-71°F) | 30 | X | X | 10 |
| | Dry (12.8°C)(55°F) | X | X | 38 | X |

total energy use relative to a real residence of similar design. However, this assumption provides a conservative basis for comparisons with a roof pond residence with the same comfort/humidity control requirements.

Annual total electricity required by the simulated 113 $m^2$ (1200 $ft^2$) efficient conventional residence (ECR) peaked in Miami and Phoenix at about 3000 kWh. (Peak demand was only 1.6 kW.)

Innovative dehumidification devices enhance the ability of a roof pond residence (RPR) to displace cooling energy required by the efficient conventional residence. An IMD dehumidified (and an air conditioner assisted) RPR can save 30% to 90% of the cooling energy required by the ECR. The savings in peak electric demand provided by the IMD dehumidified RPR ranged from 10% to 60% (0.1 to 0.9 kw). These peak power savings could be increased to at least 50% in all cities if the residents briefly moved closer to the ceiling fans during the warmest few hours rather than turning on the air conditioner.

Relatively small percent energy was displaced by the IMD assisted RPR in warm (not hot) humid cities (e.g., Baltimore and Charleston). The control/design assumptions made in this simulation handicap the RPR in this climate type because the residence overcools during the night. As a result, the relative humidity controller causes the IMD to remove about twice as much water from the RPR than is removed from the ECR. The nocturnal overcooling/high latent load problems can be decreased by changing the roof panel control strategy, increasing the pond depth and raising the allowed nocturnal relative humidity above 68%. It is common practice in humid climate residences during the cool early spring to ventilate at night. This produces nocturnal relative humidities which are above 80% during several hours each morning and mold/mildew growth is not always a problem. The total period of high relative humidity which can be allowed each day is not yet well defined; some authorities assert that as much as 12 hours is tolerable (8).

The SRDD is technically well suited for dehumidification of a RPR. In humid climates the roof pond is able to dissipate the nocturnally peaked heat of absorption and still provide acceptable comfort. In the 4 relatively humid cities simulated with SRDD assistance, the SRDD displaced about 75% of the total cooling energy required by the ECR. However, the total additional energy displaced by an SRDD relative to an IMD is only about 500 kWh per year.

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# GEOGRAPHIC LIMITS FOR COMFORT IN UNASSISTED ROOF POND COOLED RESIDENCES

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## ABSTRACT

Heat load calculations for a 1224 square foot roof pond building have been made for 35 locations across the United States. Except for the roof pond feature, the building is of standard low-mass construction on a concrete slab foundation. Interior air temperature was calculated using a simple empirical method. The comfort benefits of "wet" and "dry" ponds and of ceiling fans were evaluated. The resulting interior temperatures were plotted on a map of the U.S. The plotted contours are lines to the north of which roof pond houses will provide comfortable temperatures without additional air conditioning at 6pm on a July 2½% ASHRAE design day. Comfort can be achieved on such a day in a ceiling fan assisted dry roof pond residence in most of the geographic area of the U.S. Comfort is most difficult to provide with this passive system in the desert of Southwest Arizona and Southeast California.

## 1. INTRODUCTION

"Dry" roof ponds are those in which the water is sealed in transparent polymer bags. They reject heat at night by convective exchange with the night air and radiation into the night sky. "Wet" roof ponds are either open surface water ponds or the same polymer bags flooded or sprayed with water on the outside. They offer additional cooling capacity through evaporation. During the day the cooled water mass is covered with insulating panels and absorbs heat from the building below through a conductive ceiling by convective and radiative heat exchange. Ceiling fans increase the convection coefficient between the ceiling and the interior air and decrease the temperature of the interior air. Ceiling fans also make occupants feel comfortable at a higher interior air temperature (1).

This report presents the results of application of a simple, empirical thermal design method for estimation of interior air temperature in roof pond buildings. The empirical method is derived from measurements made at the Trinity University Passive Test Facility and from resulting validated simulations applied in other climates (2,3,4,5,6). The simple design method is based primarily on the rule of thumb that the minimum sealed roof pond temperature is equal to the minimum dry bulb ambient temperature for roof ponds of depth near 6 inches. Corrections are made for pond depth. The minimum temperature of the wet roof pond is estimated from the minimum dry bulb temperature and the corresponding wet bulb depression.

The resulting contour plots apply only to the residence described below. Of course, comfort conditions can be extended with auxiliary air conditioning. However, the contour map can serve as an initial feasibility assessment for anyone contemplating the design or construction of roof pond houses.

It should be noted that mold, mildew and condensation control will require dehumidification equipment in all but arid climates (7).

## 2. THE BUILDING

The following building parameters are used in computing the geographic limits:

a. 34x36ft building (1224 $ft^2$).

b. 8 ft high walls.

c. concrete slab foundation.

d. roof pond covers entire building.

e. 90 $ft^2$ of south facing and 60 $ft^2$ of north facing windows, fully shaded by external overhangs or awnings, double glazed, tinted heat absorbing glass.

f. 50 $ft^2$ of solid wood exterior doors.

g. exterior walls wood frame with R-13 insulation and ½" gypsum board.

h. deep folded steel deck ceiling (2).

i. ½ air change per hour (ACH) average with 1 ACH peaks at 8am and 6pm.

j. residence occupied by family of four; total daytime (7am to 6pm) internal heat load of 22,900 Btu with 6pm peak of 3,700 Btu/h.

k. insulating panel closes whenever the pond cannot dissipate heat to the environment.

l. roof pond covering panels similar to those used at Trinity University Passive Test Facility (PTF) (2). These panels have R-16 isocyanurate insulation and edge infiltration seals. However, due to sol-air heating, thermal bridging and exterior air infiltration past the closed panels, the effective resistance of the closed panels is only R-5 (here heat gain is referenced to the difference between average daytime ambient temperature and pond temperature).

## 3. METEOROLOGICAL DATA

Performance of the roof pond house was calculated for a hot July day. The following meteorological data were used for each location:

a. $T_{a,max}$, the ambient air dry bulb temperature peak, is the ASHRAE 2.5% summer design dry bulb temperature (8).

b. $T_{a,min}$ is the overnight low ambient dry bulb preceding a design day (3,4).

c. $T_{wb,min}$ is the overnight low wet bulb temperature. It can be determined from $T_{a,min}$ and the Mean Highest Relative Humidity, which typically occurs at the same time as $T_{a,min}$ (3,4,5).

d. $T_{annual}$ is the mean annual temperature.

## 4. HEAT LOAD CALCULATIONS

In order to evaluate the performance potential of the roof pond during extreme summer heat, the ASHRAE 2.5% summer design temperature was used for roof pond temperature and load computations. This means that for 2.5% of the time the house temperature may be higher than estimated here. The "comfortable" condition is derived from a Fanger PMV analysis and is defined here as an operative temperature of 79°F without ceiling fans or 81.2°F with an air motion of 115 fpm created by ceiling fans (4). Under typical 6 PM conditions these operative temperatures can be obtained with an interior air temperature of 80°F without fans or 81.5 with fans. (Operative temperature is defined as the weighted average of the interior dry bulb temperature and the mean radiant temperature.)

The peak heat load on the building is calculated using the Manual J Load Calculation procedure by the Air Conditioning Contractors of America (10). It is used for sizing air conditioners for residences and provides the peak heat load for a defined building construction and temperature differential between inside and ambient air. It can also provide, with some modifications, an estimation of the total daytime heat load on the building.

This daily heat load, together with the heat that enters through the closed panels during the day, is absorbed by the pond and causes a rise in its water temperature that is inversely proportional to the water mass, and therefore its depth.

## 5. THE POND DEPTH

The simple thermal design method employed here allows estimation of the roof pond depth required to provide comfort under given climate and load conditions. The pond depth selected will be an important thermal design input. Increased pond depth will suppress the afternoon temperature. Increased pond depth also increases structural expense. However, increased pond depth can substitute thermally for the expense of load suppression (e.g., increased wall insulation, better roof panel insulation).

Since deeper ponds cool slower than shallower ponds (4), iteration is usually required to arrive at the final pond depth. As the heat load rises, more water mass is needed to absorb it. However, as the mass increases in the pond the nocturnal temperature swing is reduced because the pond does not cool off as much at night. For depths greater than 10 inches, the nocturnal and daytime effects nearly cancel and thermal benefits are minimal. The simple thermal design method also becomes unstable for pond depths greater than 10 inches. For this reason a 10 inch depth of water was selected as a maximum for roof ponds in the cooling mode in this report.

## 6. THE MAP OF GEOGRAPHIC LIMITS

Tha analysis described above was carried out for 35 locations across the US; the limiting comfort contour was drawn to the south of any location that resulted in less than 10 inches of water depth, and to the north of any location where the simple design method predicted excessive pond depth. Because of interpolation errors, microclimate effects and inherent uncertainty in the simple design method (6), comfort contour positions can't be assumed to

be accurate to better than 200 miles.

The resulting contour map is presented as Figure 1. The four lines represent geographic limits for the following roof pond options:

a. "dry" pond with no ceiling fans.

b. "wet" pond with no ceiling fans.

c. "dry" pond and ceiling fans creating 115 fpm average air motion.

d. "wet" pond and ceiling fans creating 115 fpm average air motion.

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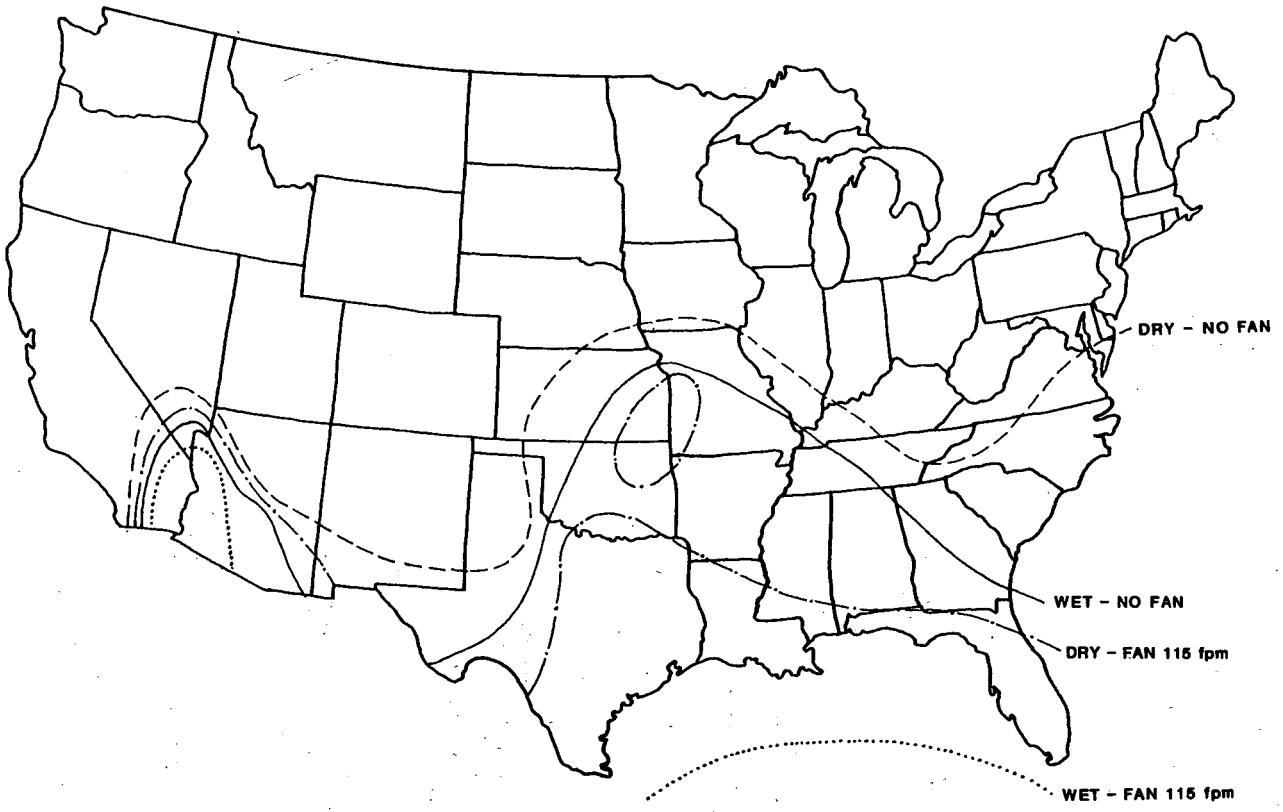



FIGURE 1. COMFORT CONTOURS ACHIEVED BY WET AND DRY ROOF POND RESIDENCES
(SOUTHERN LIMITING BOUNDARY FOR COMFORT AT 6PM ON A JULY 2½% ASHRAE DESIGN DAY)

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# RAISING THE "OPEN U" VALUE BY PASSIVE MEANS

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ABSTRACT

In hot climates where it is cool at night, buildings can be kept comfortable during hot days by storing cool in the building structure. This is a common technique used throughout the world. This paper describes how to analyze this method.

## 1. INTRODUCTION

The building must be well insulated with low internal gains and be constructed so that inside there is exposed a great deal of surface area of masonry or other thermal mass, two or three square feet per square foot of floor area. Such buildings can be kept cool by using very high nighttime ventilation rates, flow rates such as 3 to 6 cfm/ft $^2$.

The analysis proceeds by introducing, in addition to the normal U value, a second U value for the building, the open U value. The usual U value (closed U value) does not normally differentiate between the inside air temperature and the temperature of the walls and floor. The open U value does; it is the rate of heat transmission between such massive building components and ambient air, not between inside air and ambient.

In hot climates, ceiling fans are favored to make warm air more comfortable to inhabitants. The present study points out the value of leaving such fans on at night to increase heat transfer between cool night air and the inner thermal mass; a simple ratio is given that indicates which is more beneficial, to increase the rate of ventilation or to stir the present flow of air as it passes through the house.

This is a crude study with many simplifications, the thermal mass is assumed to be all at the same termperature, the h value between the inner air and the thermal mass is assumed to be uniform; in a real building neither would be true.

The building with air blowing through it is a huge heat exchanger. The resistance to heat transfer between the inner thermal mass and the ambient air is divided into two parts, the normal h value and another resistance inversely proportional to the supply of ambient air. Three temperatures, ambient, thermal mass and exhaust air, tell a great deal about building ventilation by indicating the ratio between the two resistances.

Cool night air is at least as difficult to use in cooling buildings as the sun is for heating, and it demands that building design reach for a large open U value just as they reach for a small closed U value for winter comfort. Winter designs can solve all problems by means of insulation. Cooling design cannot completely substitute insulation for thermal mass.

## 2. NOMENCLATURE

| | | Units |
|---|---|---|
| $U_c$ | Heat transfer coefficient normalized per unit area of floor between building and ambient with building in closed winter condition. | Btu/ ft$^2$ °F hr |
| $U_o$ | Heat transfer coefficient normalized per unit area of floor between building and ambient with building in open (summer night) condition. | Btu/ ft$^2$ °F hr |
| $U_{om}$ | Heat transfer coefficient between thermal mass and ambient. | Btu/ ft$^2$ °F hr |
| M | Thermal mass of building normalized per unit area of floor. | Btu/°F ft$^2$ |
| h | Heat transfer coefficient between inside air and building. | Btu/°F ft$^2$ hr |
| $h_v$ | Heat transfer coefficient of ventilation | Btu/°F ft$^2$ hr |

| | | Units |
|---|---|---|
| | air between thermal mass and ambient. | |
| J | Ratio of area of exposed thermal mass to floor area. | |
| $V_f$ | Ventilation rate normalized per unit area floor. | Cfm/ $ft^2$ |
| $V_m$ | Ventilation rate per unit area of thermal mass. | Cfm/ $ft^2$ |
| q | Internal gains of building normalized per unit area of floor. To simplify we assume that q emanates from the thermal mass. | Btu/ $ft^2$ hr |
| v | Inside air speed. | ft /min |
| $t_m$ | Temperature thermal mass. | °F |
| $t_a$ | Temperature ambient. | °F |
| $t_x$ | Temperature exhaust air. | °F |

## 2.1 Calculating $U_{om}$

We wish for the inner thermal mass to transfer its heat to the cooler ambient air. It is prevented from doing so by two resistances. The film factor, h (h≐.8+.004v) and the supply of ambient air, $h_v$.

$h_v = (.077 \text{ lb}/ft^3)(.24 \text{ Btu/lb °F})(60 \text{ min/hr}) V_m$

$h_v = 1.1\ V_m$

$$U_{om} = \frac{1}{\frac{1}{h} + \frac{1}{1.1\ V_m}}$$

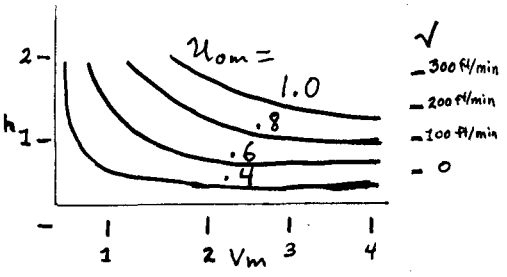



Fig. 1.

Fig. 1 illustrates what we must provide to these exposed surfaces within the building in the way of fresh air and also air velocity to transfer the heat to the night air. At this point in our attempt to cool buildings, we may jealously look at a section of similar thermal mass that is completely outside the building. Its $V_m$ is essentially infinite and according to wind speed its h and thus its $U_{om}$ is normally between 5 and 10. The ratio between the temperature drop we accomplish if it were outside (but shielded from radiating to the night sky) we can call the ventilation effectiveness: $\frac{\Delta t_m}{\Delta t_{mo}}$

Another simple relationship should prove useful: $\frac{t_x - t_a}{t_m - t_x} = \frac{h}{h_v}$

## 2.2 Calculating $U_o$

$U_{om}$ is the coefficient of heat transfer from an element of exposed thermal mass to the ambient air. We wish to discuss buildings in terms normalized to their floor area. J is the ratio of exposed thermal mass to floor area. Then for each square foot of floor we are transferring J Uom ($t_a - t_m$) to the ambient air. Heat transfer continues through the shell of the building so that $U_o = J\ U_{om} + U_c$, but $U_c$ is relatively small and for our crude study we assume: $U_o = J\ U_{om}$.

## 3. PREDICTING THE TEMPERATURE OF THE BUILDING

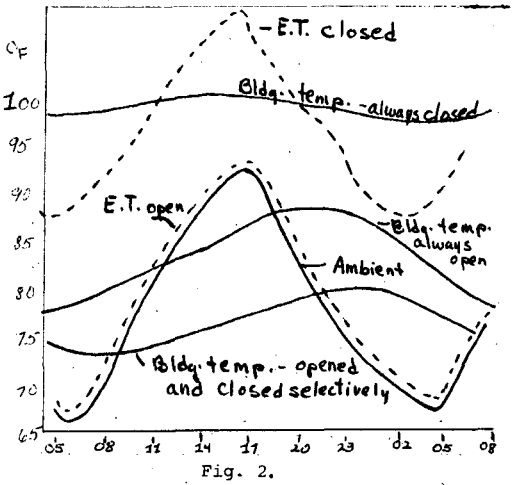



Fig. 2.

Figure 2 shows three building temperatures resulting from three ventilation schemes: always closed, always opened, opened when $t_a$ falls below $t_m$.

The building has the following characteristics.

| | | |
|---|---|---|
| $U_c$ | = .25 Btu/ | °F hr |
| $U_o$ | = 2.5 Btu/ | °F hr |
| M | = 25 Btu/ | °F |
| q | = 5 Btu/ | hr |

### 3.1 Equilibrium Temperature

The dashed lines indicate the equilibrium temperature, E.T.

$$E.T. = t_a + \frac{q}{U_o} \quad \text{or} \quad E.T. = t_a + \frac{q}{U_c}$$

depending on whether the building is opened or closed. The E.T. is plotted to facilitate graphing the building temperature.

### 3.2 Time Constant

The Time constant is $\frac{M}{U_o}$ or $\frac{M}{U_c}$ depending on whether the building is open or closed.

The temperature $t_m$ approaches the E.T. at a rate that promises to reach that moment's E.T. in exactly one time constant. This greatly facilitates graphing temperatures by pencil on a sheet of graph paper without a computer. The curves in Fig. 2 were plotted by trial and error until they showed equilibrium, that is, the same temperature 24 hours later. The ambient temperature on Fig. 2 is the average temperature during July in Albuquerque, New Mexico.

### 3.3 Different Building Designs with the Same Temperatures

We may build an entirely different kind of structure that has these exact same temperature curves. We only require that;

$\frac{U_o}{U_c} = 10$, $\frac{q}{U_c} = 20°F$, $\frac{M}{U_c} = 100$ hrs.

For instance, our first building is well insulated but does not contain a huge thermal mass. A second, entirely different structure, a partially translucent tent with openable side flaps for night ventilation over a storage yard filled with drums could behave the same way;
$U_c = 2.5$ Btu/ft$^2$ hr °F, $U_o = 25$, $M = 250$, $q = 50$ Btu/ft$^2$ hr

## 4. EXPERIMENTS

### 4.1 Ventilation Effectiveness

$t_i$ = temperature of 5 gal pail $H_2O$ inside.

$t_o$ = temperature of 5 gal pail $H_2O$ outside under tree.

| 16 July 1979 19:15 | 17 July 1979 06:50 |
|---|---|
| $t_i$ 79.7°F | $t_i$ 76.5°F |
| $t_o$ 76.0°F | $t_o$ 65.0°F |

$$\text{Effectiveness} = \frac{79.7° - 76.5°}{76.0° - 65.0° + 2°} = 25\%$$

2°F added as adjustment.

| 10 July 1979 21:20 | 11 July 1979 06:50 |
|---|---|
| $t_i$ 76.5°F | $t_i$ 75.5°F |
| $t_o$ 78.7°F | $t_o$ 68.5°F |

$$\text{Effectiveness} = \frac{76.5° - 75.5°}{78.7° - 68.5° - 1.5°} = 12\%$$

1.5° subtracted as adjustment.

. . . . . .

$$\text{Ratio of Resistances } \frac{h}{hv} = \frac{t_x - t_a}{t_m - t_x}$$

$t_m$ drum wall temperature 6' above floor.

$t_x$ vent air temperature from 3'x3' vent at top (13' above floor) of same room.

### 4.2 Venting by Convection

14 July 1979
06:35

$t_m$ 78, $t_x$ 76.3, $t_a$ 72

$$\frac{h}{hv} = \frac{76.3 - 72}{78 - 75.3} = \frac{4.3}{1.7} = 2.5$$

17 July 1979
21:00

$t_m$ 78.5, $t_x$ 77, $t_a$ 68

$$\frac{h}{hv} = \frac{77 - 68}{78.5 - 77} = \frac{9}{1.5} = 6$$

### 4.3 Forced Ventilation 6000 cfm fan

30 June 1980 05:30

$t_m$ 78.5°F, $t_x$ 74°F, $t_a$ 72°F

$$\frac{h}{hv} = \frac{74 - 72}{78.5 - 74} = .44$$

05:45 fan off

$t_m$ 78.5°, $t_x$ 75.8°, $t_a$ 72°

$$\frac{h}{h_v} = \frac{75.8° - 72°}{78.5° - 75.8°} = \frac{3.8}{2.7} = 1.4$$

1 July 1980 06:25 fan on

$t_m$ 79°, $t_x$ 73.2°, $t_a$ 69°

$$\frac{h}{h_v} = \frac{73.2° - 69°}{79° - 73.2°} = \frac{4.2}{5.8} = .72$$

### 4.4 Influence of Ceiling Fan on h

First gallon jug, surface = 1.4 ft$^2$, filled

with 98°F water placed 15' beneath Emerson 42" heat fan on high blowing 82°F room air past jug.

Second gallon jug, placed in still air in adjoining room, h values plotted by temperature decay.

h = 1.9 natural convection

h = 3.2 with fan

## 5. VENT SIZE

How big must our vents be to provide sufficient ventilation? Call X the fraction of floor area that the vents, both exhaust and intake, must equal. Using the natural ventilation equation from the ASHRAE handbook,

$$V = 9.4 \sqrt{(t_i - t_a)H}$$

v exhaust velocity (ft/min)
$t_i$ average inside air temperature
$t_a$ ambient temperature
H elevation difference between exhaust and intake vents
$V_f$ ventilation rate normalized, $ft^2$ floor (cfm)

$$VX = V_f = X\ 9.4 \sqrt{(t_i - t_a)H}$$

$$X = \frac{V_f}{9.4 \sqrt{(t_i - t_a)H}}$$

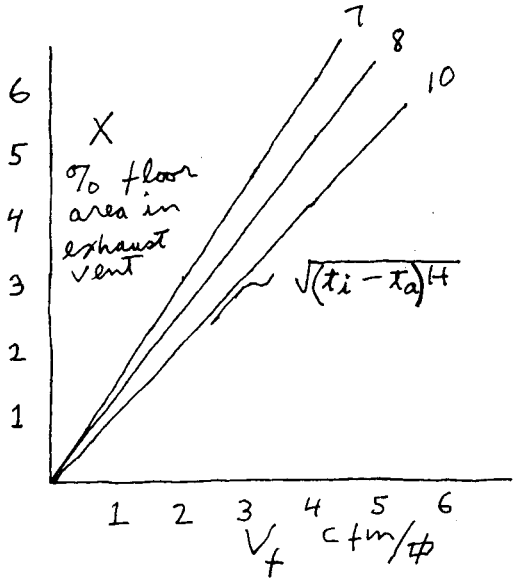



Fig. 3.

Fig. 3 shows X as a function of $V_f$ and the stack effect $(t_i - t_a)H$.

to provide adequate ventilation on a still night you need very large openings or a very tall stack. Insect screens cut down the flow of air through vents and windows. Crude experiments show that a screen will cut air flow by 50%. This must be taken into account when sizing vents. There are usually enough windows to allow air to enter a house. The bottleneck is the exhaust venting. A few turbine vents will do next to nothing. We have found that openable skylights are the most convenient exhaust vents. In Albuquerque, the size skylight you pick for winter heating will be close to the same size you pick for summer night ventilation, provided you have a way to shade the skylight from summer heat gain.

## 6. CONCLUSION

My own house, on which most of these experiments were performed, did not have large enough vent openings for convective ventilation. During Albuquerque's hottest weather the 6000 cfm exhaust fan which did provide adequate ventilation was much too noisy.

In order to move enough air through the house passively, the top exhaust vents should have an aperture equal to 2% to 4% of the floor area or even more.

Experiments should be done to determine the COP of forced ventilation systems and ceiling fans.

## 7. BIBLIOGRAPHY

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# THE COURTYARD: PASSIVE COOLING PERFORMANCE AND SHADING VARIABLES

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## ABSTRACT

This study was begun in winter 1981-1982, in which season Colima's temperature and relative humidity daily range matches the hottest summer conditions of the United States Pacific Northwest.

Colima's street grid is oriented about 40° west of south. "East" and "South" faces are heavily sun-stressed in winter; "West" and "North" get the strongest summer sun. From an initial casual observation of about 450 courtyards, a matrix was prepared for categorizing. About 80 were selected for a closer look, of which 31 were photographed and measured for plan. A range of residential-commercial-institutional buildings, economic status of occupants, and courtyard usages was included.

Six of the courtyards were then monitored for two days in December. Daylight, air temperature, surface temperature, relative humidity (RH) and mean radiant temperature (MRT) were recorded both in the courtyards and the street outside. Then the building containing the most cool of these six courtyards was monitored on a hot January day, to compare upper floor-lower floor and interior room-courtyard-street conditions.

Part One Conclusions: While the deeper courtyards stayed cool as expected, the more common shallow courtyards seemed much cooler than the measurements indicated, compared to the street. These courtyards combined many slight improvements in a much more pleasant psychological setting. They successfully became markedly cool retreats from the hot dry streets.

Part two concerns the testing of courtyards for midday shading; square plan courtyards at 32°NL were tested at solstices and equinox for both 0° and 45° azimuth orientations, and for wall: floor ratios of 2:1 and 1:1. Varying arcade widths were also tested. Arcade width was found to be quite influential on % wall shading in the shallow courtyards. Deeper courtyards experienced greatest % wall shading both in summer and winter, therefore seemed particularly appropriate for year-round overheated climates.

## 1. INTRODUCTION

This study of courtyards in residential and commercial buildings of Colima, Mexico was conducted from late October 1981 until late January 1982. Colima was selected because its winter daily range of temperature and RH corresponds closely to that of the hottest summer days of the U.S. Pacific Northwest (Washington and Oregon).

7:00: 17.1 DB, 15.0 WB (°C)
14:00: 29.7 DB, 19.3 WB
21:00: 21.8 DB, 19.1 WB

Sky cover statistics are also similar. The mid-day sun position at Colima's 20°NL in November is similar to the mid-day sun position of Eugene's 44°NL in September. The opportunity thus exists for a transplant of passive cooling techniques, given proper sun controls and the fact that the U.S. Pacific Northwest is only seasonally overheated, while Colima is hot the entire year.

Colima is a densely settled city of over 100,000 people. The approximately 650,000 sq. meters of the central city are dominated by one-story colonial style buildings, about one-fourth of which are residences. Most blocks are smaller than typical U.S. city blocks, and the streets are much narrower. The sidewalks are minimal; front and side yards are very rare. Backyards are less rare, but very small. Although roof terraces are numerous, courtyards are the only private, outdoor space for the typical building.

The central city has a roughly square grid street pattern, with an orientation of about 40° west of south. This seems strange to the U.S. observer accustomed to due-south city grids which favor solar heating collecting walls. Further, the prevailing wind directions cross the grid on a diagonal, daily from the south, nightly from the north. Thus, minimal wind velocities occur in the streets, since none are parallel to the

breezes.

A closer look at the wind, weather and seasonal sun paths reveals that a kind of "democracy" in street comfort results from this orientation and that the worst conditions (at least in winter) occur during siesta. Obviously, breezes tend to move about equally rapidly down all streets, since they cross at a diagonal. The sun overheats east and south facades in winter, but north and west facades in summer.

## 2. COURTYARD OBSERVATIONS AND CATEGORIES

I found that Colima's winter cooling methods consist of some sun shading, windows that stay open (with some exceptions during siesta), lots of thermal mass, and courtyards everywhere. I decided to look more closely at the courtyard, particularly after reading the variety of their attributes in papers at the 1981 Miami cooling conference. Initially I walked around some 50 blocks in central Colima, trying not to annoy as I peered through open doorways and noted the more interesting courtyards. The resulting 450 noted courtyards needed categorizing, which produced the matrix of Fig. 1.

There seemed to be two main variables among the many that enrich Colima's courtyards. First, the primarily psychological aspect of plants, fountains and often birds in cages, the creation of a little paradise outdoors in contrast to the stark street a few meters away. Second, the depth of the courtyard relative to it's north-south width, which determines hottest-hour shading in fall, winter, and spring. April through August, the sun is higher than 70° for several hours, and no Colima courtyard can escape by depth alone.

For the category matrix, I chose increasing size of plants as one variable, from bare courtyards to full-grown trees. The other variable was more arbitrary. After measuring a few courtyards that I thought were quite deep relative to their width, I found that an impression of more-than-normal depth begins when north-south width is less than 1.4 times the wall height, for a minimum profile angle of 35°. Going further, a courtyard can seem really deep with the north-south width about 1.1 times the wall height, profile angle 42° or more.

Using the twelve categories in the matrix, I selected 80 of my initial observations for a

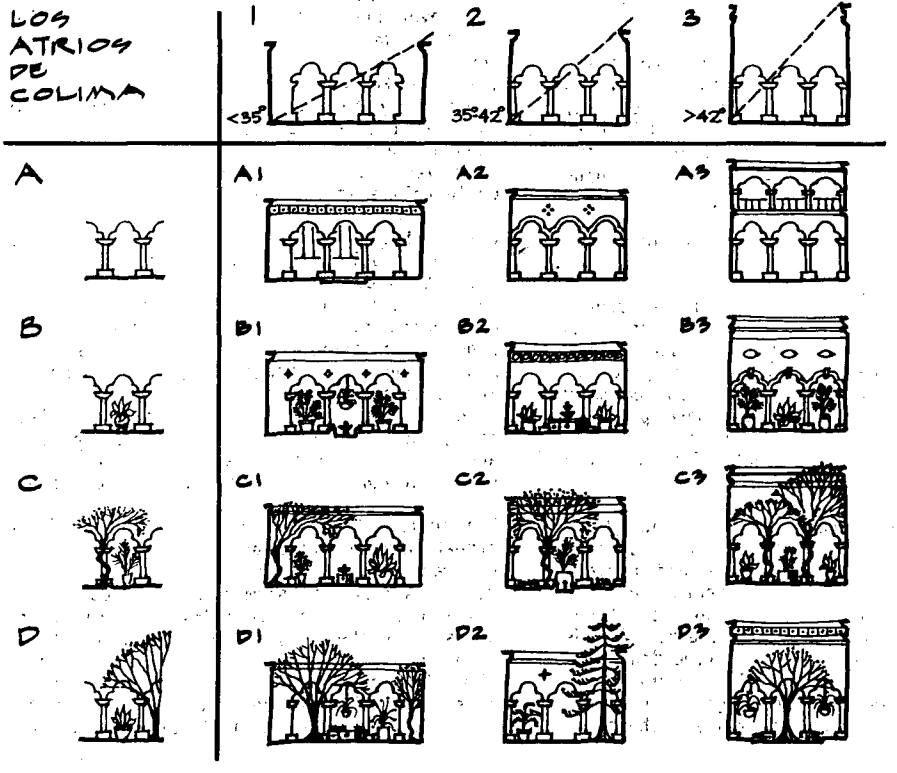



Fig. 1. Matrix of courtyard types. The main variables here are depth and vegetation. Types A1 through A3 were relatively rare. Type D3 was very rare. Types B1, C1 and D1 were most common.

closer look. Lingering at doorways, I aroused a few suspicions while narrowing these to 31 courtyards for photographing. By this time my Spanish permitted me to introduce myself, camera, notebook and tapemeasure in hand, explaining my interest in natural cooling, and asking permission to measure the courtyard. The matrix helped explain why their particular courtyard was of interest. I was ultimately admitted to every courtyard, which, considering the privacy of such places, is a tribute to Colima's hospitality.

In addition to covering the twelve types of the matrix, these courtyards ranged in usage from residential to commercial/institutional; their owners ranged from quite poor to very wealthy. They vary in area from 20 to 324 $m^2$ and range in plan proportions from square to 4:1. Some are isolated, jewel-like gardens to be seen rather than walked through. Others are like another room with furniture, but without a roof; one courtyard even contained the kitchen stove.

There was little variation in sun control devices, other than trees and vines. Arcades were usually used to separate the courtyard and its sun from the bedrooms, dining rooms, etc. Several relied on venetian blinds hung in the arches around the courtyard. Awnings were used in rare cases, as were louvres. It's possible that more devices are used in summer, and portable ones are probably moved to opposite sides of courtyards.

Slightly more than half had fountains or other potential water sources, a few of which were dry. There was a profusion of potted plants (only four of these courtyards lacked them), which add a pleasing variety and a commitment to daily watering in a climate that can go for months without rain.

There was also a variety of placement of courtyards relative to the rest of the building. It was usually near the middle, but could also be on one edge. A wide variety of room depths existed beyond the courtyard, but I was not comfortable in asking to measure these more private spaces. Approximate building-courtyard relationships were drawn with the help of a detailed map of central Colima. In one office building, a few such spaces were later monitored.

## 3. MONITORING

Six courtyards were selected for measurements of daylight, temperatures and RH. They were chosen to cover a variety of proportions and degrees of vegetation, as well as of sizes, building functions and income levels. Some are gardens; some are just another room. The primary requirement was accessibility, as I had to carry my shopping bag of instruments from site to site. Each site was visited three times a day for two days at the winter solstice. Colima's weather is remarkably constant, with little change from one day to the next. Conditions in the courtyard and both sides of the street were recorded.

The instruments included a surface temperature bi-metal thermometer, a sling psychrometer, a light meter (Gossen Panlux), and a globe thermometer that I constructed from a copper toilet float about 11 cm diameter, painted flat black. This was mounted precariously on my camera tripod, not quite 1 meter above the floor. It raised a number of Mexican eyebrows and resulted in many conversations. A few suspected that it was an *intelligence-gathering device; gringos are* apparently capable of almost anything. Once established that it was indeed a toilet float with a thermometer inserted, I was accepted.

When results from the six courtyards were compared (Fig. 2), one of them (in the A2 office building) performed particularly well. This courtyard and several offices on the upper and lower floors were then monitored on a hot day (Jan. 21). The building is over 150 years old, has walls almost a meter in thickness, and rather high ceilings (Fig. 3).

## 4. RESULTS

MEAN RADIANT TEMPERATURE at the hottest times of the day, in the shaded arcades around the courtyards, was of course dramatically lower than that of the sunny side of the street. However, for the common more shallow (type 1) courtyards, this arcade MRT was about equal to the shaded street. The deeper (types 2, 3) courtyards maintained lower MRTs than either side of the street (Fig. 2). Dry bulb temperatures were not as dramatically different.

This seems to mean that the more shallow courtyards are more psychologically than physically effective, with their oasis-like atmosphere but not-so-different temperatures. However, the achievement of MRT equal to shaded winter streets is also physically advantageous, since at midday they lie in the lower half of the comfort zone. At the same time, air temperatures have passed the upper edge.

The A2 office courtyard's lower arcade maintained MRTs from 2.2° to 4.4°C below the shaded side of the street, while its upper arcade MRT stayed from 0.5°C to 3.3°C below. The offices between the courtyard and the street maintained MRTs ranging from equal to 2.2°C below the shaded street. The greatest differences in all these cases were at the hottest hour, just as siesta was beginning. The offices' MRTs were raised by workers and fluorescent lights of 75 watts per desk.

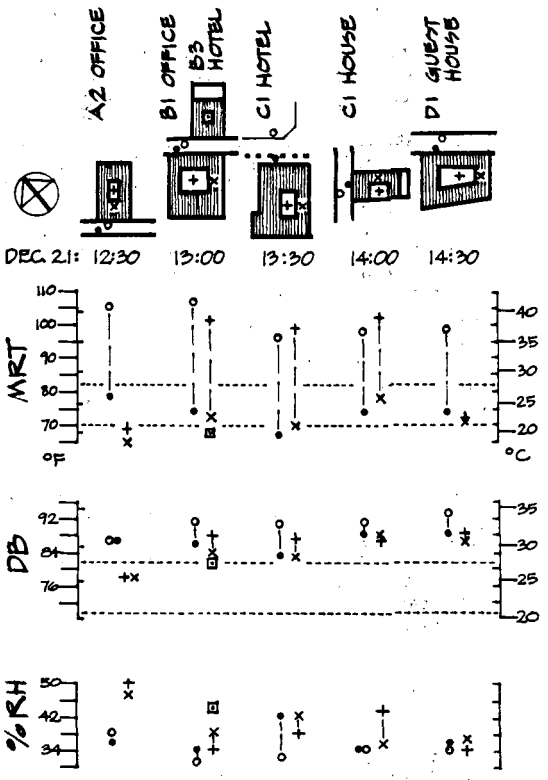



Fig. 2. Comparisons at midday. The six monitored courtyards and their streets are compared for MRT, DB and RH during the hottest hours on Monday December 21. Olgyay's "comfort zone" of 70°F to 82°F is shown on both the MRT and DB charts, for reference.

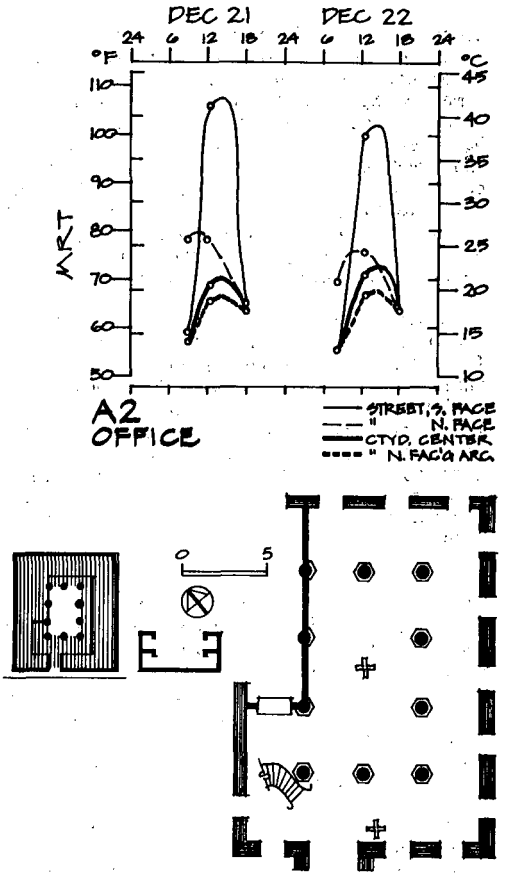



Fig. 3. Office, type A2. A two story bare and paved courtyard maintained far cooler conditions than the street. Some fluorescent lights and ceiling fans were in use in the offices around the courtyard; the upper east facing windows had awnings. Function: government offices of public health. Courtyard scale is in meters. The approximate building plan and north-south courtyard section are also shown. Crosses mark location of MRT monitoring.

DAYLIGHTING near noon on the shaded side of the street varied from 7% to 14% that in direct sun, opposite. In the arcades around the courtyards, daylighting varied widely due to changing sun position, reflected light from walls and floor, courtyard depth, and varieties of trees and vines. This variation illustrates the difficulty of predicting daylighting levels under clear sky conditions. It was clear that the courtyard provided enough daylight to adjoining rooms that electric light was rarely used. Psychologically, the darker the room the cooler it seems, and minimal daylighting seemed welcome.

The two story courtyard, as expected, had more daylight in the upper arcades than the lower ones; in the rear of the upper arcades, the daylight factor (DF) was about 1.7 times the lower arcades near noon, and about four times higher near sunset. This large increase in daylight was accompanied by a very small MRT increase; at most, the upper arcade was 1.6°C MRT higher than the lower arcade.

RELATIVE HUMIDITY at midday was nearly always somewhat higher in the courtyards than in the street, but especially in the one that had no plants or water bodies (Fig. 2). Thus, the RH is more related to cooler air than to purposeful evaporation. The small fountains typical in courtyards were rarely activated (never during monitoring) so surface evaporation is the primary physical contribution

they make, along with thermal mass and a sparkling light when in sun. Evaporative cooling could be used in Colima's winter, but I found no evidence of it except in the public plaza fountains after siesta.

PLANTS add softness and shade; also, lightweight branches such as on potted palms, ornamental figs and vines sway in the slightest breeze, adding an impression of air motion when there is actually almost none. Plants are also magnificently handsome when the sun shines through their leaves, which seem to glow in contrast to the dark arcade surfaces around them.

The most successfully cool courtyard (from measurements) had no plants whatever, so their role in winter seems clearly more psychological than physical. With the overhead sun of summer, larger plants become more important for their shade.

THE STREET ENVIRONMENT can be markedly improved by shade trees and especially by arcades such as those around Colima's main plaza. In Figure 2 compare the street conditions of the C1 Hotel to the other streets. This hotel faces the partly shady main plaza, its own sidewalk covered by an arcade. However, neither arcades or street trees are practical in a town with such narrow streets and small blocks. Sidewalks are scarcely wide enough to walk two abreast; trees would make them nearly impassable. Perhaps more important is the question of whether the courtyards would seem so successful if the streets themselves were more pleasant?

## 5. SOME UNANSWERED QUESTIONS

A. How well do these courtyards perform at the opposite extreme of the year, with higher temperatures and sun, and relentlessly hot streets? This is an especially important question for the A2 office building, which has no shading, little ventilation and plentiful thermal mass.

B. Is a tree cover (type D) truly advantageous? Without it, the courtyard floor could radiate freely to the cold, clear night sky. But also, the sun could flood the courtyard by day, bringing more daylight but much more heat.

C. How does air move in the courtyard, with Colima's weak and diagonal breezes? In the summer, do more Colimense adopt a closed-building strategy in the hottest hours, then open buildings to cooler night ventilation?

D. What is the tradeoff between daylight and cooling? Shallow courtyards maintained higher temperatures but offered much more daylight to adjoining rooms. The courtyards with lush vines and trees had far less daylight in the surrounding arcades than similar, more barren ones, but MRT levels were about the same.

E. Under what conditions can the courtyard successfully transfer to the U.S. Pacific Northwest, which is a seasonally overheated climate in contrast to Colima and which endures frequent light rain for nine months?

## 6. PART ONE CONCLUSION

This study has reinforced my impression that comfort is a state of mind first and only secondarily a measurable set of factors. These courtyards invariably seemed much cooler at midday than either side of the street, more so than the measurements suggest. I believe that this approach to passive cooling succeeds largely because it visibly integrates so many things that are indicators of coolness. Taken separately, the more common shallow courtyard's measurements often seem but slight improvements upon those of the street. When all such courtyards' impressions are taken together, however, they provide an environment that is distinctly more comfortable than the street beyond.

## 7. PART TWO: SHADING VARIATIONS

In order to understand the courtyards' adaptability to a variety of climates and settings, in vernacular or high style forms, this part of the study focuses on generic configurations for sun penetration and shading. The variables affecting sun penetration are latitude, geometry and azimuth orientation. For the testing we chose 32° N Latitude which crosses a range of climate zones representative of areas where courtyard buildings are most common. Geometric variations were: (a) plan shape, where we tested square courts only; (b) relative depth: ratio of wall height to floor width of 1:1 (deep) and 1:2(shallow); and (c) relative arcade width: ratio of arcade width to floor width of 30% (wide) and 15% (narrow). Azimuth orientation was tested for two cases: true south, and at 45° from south.

Four models were built with the size of courtyard opening kept constant, and then tested in direct sun, using a sun peg chart for 32° N Latitude. Each model was tested at the two orientations, for three seasons (winter solstice, equinox, summer solstice), and at two times of day: noon and 3 hours from noon. We measured the percent of floor area shaded and of the four walls shaded, averaged for 2 hours from noon.

## 8. SHADING RESULTS

A. The percentage of shaded floor seldom

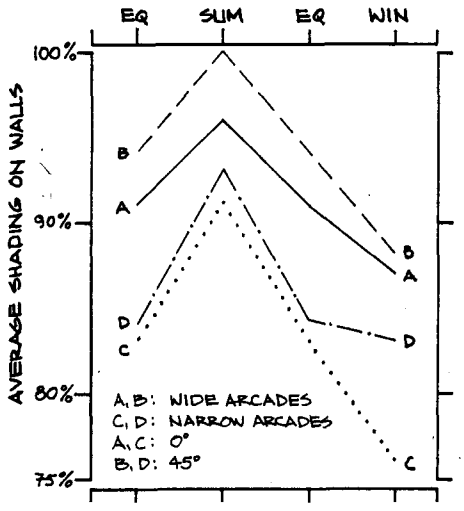



Fig. 4. Shading in shallow courtyards. Shallow courtyards are predominantly shaded by their arcades, and arcade width is thus of particular importance to these courtyards.

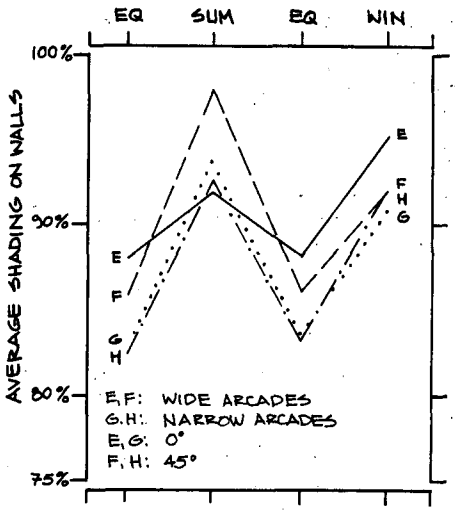



Fig. 5. Shading in deep courtyards. Deep courtyards are shaded by their own opposite walls as well as arcades. Azimuth orientation has a small impact on both shallow and deep courtyards.

falls below 40%, and deep courtyards have much more shaded floors than shallow ones, as expected. Further, each wall is at least 50% shaded during this time period.

B. The time of day is more influential than the season of the year upon shading for each wall. Thus, in permanently overheated climates, an individual fixed shading strategy may be adopted for each wall. However, in climates with more distinct seasonal change, a variable shading strategy seems appropriate for the walls.

C. Wall shading in shallow courtyards (Fig. 4) is distinctly different than in deep courtyards (Fig. 5). The arcades do most of the wall shading in shallow courtyards, as demonstrated in the contrast between wide arcades (curves A,B) and narrow ones (C,D) in Fig. 4. Also, these shallow courtyards' walks are shaded most in summer, least in winter, as would be expected from the overhanging roof of the arcade. By contrast, the deeper courtyard's high walls block out the lower winter sun, so that high % shading occurs in winter. The arcades also provide high % shading in summer, but less difference is evident between wide (E,F) and narrow (G,H) arcades in Fig. 5.

D. The azimuth orientation of the courtyard does not greatly influence the overall % wall shading in these square courtyards. However, the daily distribution of wall shading is more evenly distributed among the walls when the azimuth is $45^{0}$ from south.

## 9. CONCLUSION

Courtyards can be tuned to a particular climate (and its seasons) by varying the extent of shading of its walls and floor. These shading variations are dependent primarily upon courtyard depth and arcade width and less so upon azimuth. Several additional directions for further study:

- rectangular courts other than square in plan
- walls without arcades
- Latitudes other than $32^{0}$ N
- testing for a wider daily range of hours, beyond 3 hours from noon
- subtleties of thermal exchange between sun, courtyard surfaces, sky and atmosphere.

## 10. ACKNOWLEDGEMENT

Part one's study was made possible by a sabbatical leave granted by the University of Oregon. Most of part one also appeared in Passive and Low Energy Alternatives I, 1982, Pergamon Press.

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# TOTAL ENERGY CONSIDERATIONS FOR PASSIVE SOLAR STRATEGIES IN DESERT CLIMATES

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## ABSTRACT

The use of passive solar features for family housing at an Army Base in the Mojave Desert, California, has been studied. The passive solar features studied are such which reduce the overall energy requirements for the house both in heating and cooling. Design curves are provided which could be used to estimate the energy savings for heating and cooling for various passive solar strategies and for different size of houses in the area.

## 1. INTRODUCTION

This study was sponsored by the United States Army Corps of Engineers, which had a requirement for constructing 114 family housing units of three sizes. The housing units were to be located at Ft. Irwin, California, in the Mojave Desert. The housing units were required to use passive solar features to reduce the overall energy consumption for both heating and cooling.

The base case houses to be considered were energy efficient houses as detailed in the U. S. Army Corps of Engineers Engineering Technical Letter 1110-3-296. Only well proven passive solar strategies were to be considered.

A large number of strategies to reduce heating and cooling energy requirements were considered, including the use of single glass, triple glass, earth cooling, attic ventilation, concrete construction, with and without high ventilation with cool outside air, and shades, etc. Evaporative cooling was not considered because of the water requirements. Earth contact cooling and other such strategies were not to be considered.

The literature search revealed that very little has been reported on the use of passive solar for the reduction of total energy use of the buildings. It was therefore decided to perform a number of computer simulations for a few strategies to determine the energy savings associated with each strategy.

## 2. BUILDING DESCRIPTION

Three different building sizes were considered--small, medium and large. The small building had two bedrooms, the medium had three and the large building had four bedrooms. The total glass area on the three buildings was 80 ft $^2$, 130 ft $^2$ and 180 ft $^2$, with 50% of the glass on south and 50% on the north side.

According to the U. S. Army Corps of Engineers requirements, the south, east, and west glass was to be shaded 80% of the time from April to October. The glass used was double glass. The base case buildings were of wood frame construction.

The energy source for heating and cooling was to be an air to air heat pump.

## 3. WEATHER DATA

Ft. Irwin is situated in the Mojave Desert at an elevation of 2,500 ft. The heating degree days are 2,547 and the cooling degree days are 2,272. The clearness factor for solar radiation (KT) varies from 0.58 in winter to 0.78 in summer. The nearest station for which typical meteoro-

logical year (TMY) data are available was Daggett, California. These weather data were used for the simulations.

## 4. ASSUMPTIONS FOR SIMULATIONS

The computer program used for the simulations for various strategies was TRNSYS Version 10.2 from the University of Wiconsin. The major assumptions made for the simulation are given below.

4.1 The heating set point was 21.11°C (70°F).

4.2 The cooling set point was 23.88°C (75°F).

4.3 Dead band for the thermostat was 0.833°C (1.5° F).

4.4 Infiltration rate of 0.5 air changes per hour was considered.

4.5 The internal gains profile used was the same as used by Los Alamos Scientific Laboratory. The total internal gains per day were 71,258 KJ (67,585 Btu).

4.6 The ASHRAE transfer function method was used to calculate the heat transfer from opaque areas of walls and roof.

4.7 During the cooling with ventilation with outside air, the air conditioning unit was not allowed to come on.

4.8 The internal gains were assumed to be the same for small, medium and large houses.

The simulations were performed with a time step of 1 hour and error tolerance of 0.005 for the whole year.

## 5. PASSIVE SOLAR STRATEGIES EVALUATED

The energy saving strategies used were to be the ones which were well proven and practical and did not require extensive maintenance and excessive user participation. Several strategies, such as the use of single glass, triple glass, attic ventilation, etc. were considered but were not found to be feasible. The following strategies were the only ones which could be considered under the given criteria.

5.1 Shading of all windows with external sunshades, with a solar transmittance of the composite assembly (shade and double glass) of 0.2 from April to October.

5.2 Shading as in above with solar transmittance of 0.5 from April to October.

5.3 Building using cement block construction and ventilation with cool outdoor air at the rate of 7 ACH.

5.4 Building using cement block construction and ventilation with cool outdoor air at the rate of 14 ACH.

5.5 Building using wood frame construction and ventilation with cool outdoor air at the rate of 7 ACH.

5.6 Building using concrete block construction and no ventilation with outdoor air.

## 6. RESULTS

After performing a number of simulations, it quickly became apparent that in Ft. Irwin, California, the major energy use was the cooling energy and that heating requirements were minimal. Therefore, any passive solar strategies would have to address the problem of cooling. Any attempt to reduce the heating requirements could have increased the cooling requirements. With these considerations, the strategies listed in Section 5 above were evaluated in detail.

The results of the evaluations for all the strategies considered are presented in Table I through Table III for small, medium and large buildings, respectively. It can be seen from the tables that some strategies have reduced cooling requirements considerably while leaving the heating requirements unchanged, and others have reduced the energy requirements for both heating and cooling.

The results given in Table I through Table III are presented in Figure 1 through Figure 4 in the form of energy saving with respect to the base case buildings (small, medium and large). The energy savings shown is electrical energy savings, associated with the heat pump. The Coefficient of Performance (COP) of the heat pump has been considered both in heating and cooling.

Figure 1 shows the energy requirements for the base case buildings, plotted against energy savings, with respect to the base cases, for external shading devices.

Figure 2 shows the base case building energy requirements and the savings for the building with concrete block construction

and the use of cool outdoor air, using 7 ACH ventilation rate. The energy savings for cooling does not increase at a uniform rate with the increase in building size, because with the similar internal gains, the cooling requirement may be less for a large building. The energy required to run the ventilation fan has been considered in the cooling energy savings. The same information is shown in Figure 3 for 14 ACH ventilation rate. It can be seen that the savings in case of 14 ACH ventilation rate are only slightly more than with 7 ACH.

Figure 4 shows the savings for total energy for the houses with wood frame construction and 7 ACH ventilation and the houses with concrete construction and no ventilation. Comparing Figure 2 and Figure 4, it is seen that the saving in total energy for concrete construction with 7 ACH ventilation is much greater than the buildings with wood frame construction and 7 ACH ventilation. The addition of mass only (concrete construction) with no ventilation is a marginal strategy.

The potential for cooling by ventilation for small and the large building is shown in Table IV. It is seen that during the month of July, almost no cooling can be obtained by ventilation.

The manner in which the ventilation cooling and the air conditioning interact with each other is shown in Figure 5 and Figure 6. This information is for the small building with concrete construction and 7 ACH of ventilation. These figures show the total hourly energy for all hours in the month of June. From Figure 5, it is seen that in hour 12 for the month of June, 172935 KJ of heat was removed by the cooling unit. It does not, however, mean that cooling was required in hour 12 for each and every day. From Figure 6, it is seen that cooling potential by ventilation was good in early morning and late evening. Figure 7 and Figure 8 show the cooling provided by air conditioning unit and by ventilation, for the month of July. It is seen that negligible amount of cooling is provided by ventilation.

## 7. CONCLUSIONS

This study has indicated that in desert areas and the areas where cooling is as important as heating, only those passive solar strategies should be used which result in minimization of the annual energy requirement for heating and cooling. This might mean that only the cooling requirements be reduced without increasing the heating requirements or decrease both heating and cooling.

The careful use of glass area along with external sunscreens and massive construction seem to be a viable strategy when used with high rate of ventilation.

The savings curves given in Figure 1 through Figure 4 can be used as design curves for the preliminary design of passive solar energy systems using various design strategies mentioned. However, these curves are specific for the site and the type of building. As long as the building is between the small and the large building and is generally similar to the base case defined, the curves can be used. If more than one strategy is used, then the saving may be read from each figure and added together. It has been seen that the error in doing so is small in most cases.

This study has shown the need to exercise extreme caution in using passive solar strategies when cooling is an important consideration.

The reduction of cooling energy requirements may be very important in some areas; the simplified methods to estimate the cooling requirements for various strategies are non-existent. At the present time the designer has to resort to either a large computer simulation or a yearly simulation on a microcomputer.

It is recommended that studies similar to this be done for other areas of the country so that the information can be used for design purposes.

## 8. ACKNOWLEDGMENTS

The authors gratefully acknowledge the useful suggestions and comments provided by Mr. Lou Layton and Mr. Ed Zulkofske of the U.S. Army Corps of Engineers during the study. Thanks are also due Mr. P. Richard Rittelmann, Mr. Harry Gordon and Mr. Kenneth Argall of Burt Hill Kosar Rittelmann Associates for their valuable suggestions throughout the study. The authors thank Ms. Tammy McGaughey for typing this manuscript.

## 9. REFERENCES

Please consult the authors for the list of references.

TABLE I. BUILDING ENERGY REQUIREMENTS FOR VARIOUS STRATEGIES STUDIED--SMALL BUILDING 100 $m^2$ (1,080 $ft^2$)

| | Electrical Energy Requirements kWhRS (Btu x $10^{-6}$) with Air to Air Heat Pump | | |
|---|---|---|---|
| | Energy for Heating | Energy for Cooling | Total Energy for Heating and Cooling |
| Base Case Building (Small) | 132 (0.450) | 5,287 (18.039) | 5,419 (18.489) |
| Shading on all windows solar transmittance 20% | 132 (0.450) | 4,465 (15.234) | 4,597 (15.684) |
| Shading on all windows solar transmittance 50% | 132 (0.450) | 5,140 (17.537) | 5,272 (17.988) |
| Ventilation 7 ACH*; building with concrete construction | 50 (0.170) | 4,175 (14.245) | 4,225 (14.415) |
| Ventilation 14 ACH; building with concrete construction | 44 (0.150) | 4,255 (14.518) | 4,299 (14.668) |
| Ventilation 7 ACH; building with wood frame construction | 125 (0.426) | 4,495 (15.336) | 4,620 (15.763) |
| Building with concrete construction and no ventilation | 41 (0.139) | 5,272 (17.988) | 5,313 (18.127) |

* Air changes per hour

TABLE II. BUILDING ENERGY REQUIREMENTS FOR VARIOUS STRATEGIES STUDIED--MEDIUM BUILDING 163 $m^2$ (1,750 $ft^2$)

| | Electrical Energy Requirements kWhRS (Btu x $10^{-6}$) with Air to Air Heat Pump | | |
|---|---|---|---|
| | Energy for Heating | Energy for Cooling | Total Energy for Heating and Cooling |
| Base Case Building (Medium) | 480 (1.637) | 6,893 (23.518) | 7,373 (25.156) |
| Shading on all windows solar transmittance 20% | 486 (1.658) | 5,434 (18.540) | 5,920 (20.199) |
| Shading on all windows solar transmittance 50% | 477 (1.627) | 6,682 (22.798) | 7,159 (24.426) |
| Ventilation 7 ACH; building with concrete construction | 288 (0.982) | 5,587 (19.062) | 5,875 (20.045) |
| Ventilation 14 ACH; building with concrete construction | 285 (0.972) | 5,571 (19.008) | 5,856 (19.980) |
| Ventilation 7 ACH; building with wood frame construction | 484 (1.651) | 5,993 (20.448) | 6,477 (22.099) |
| Building with concrete construction and no ventilation | 283 (0.965) | 6,871 (23.443) | 7,154 (24.409) |

TABLE III. BUILDING ENERGY REQUIREMENTS FOR VARIOUS STRATEGIES STUDIED--LARGE BUILDING 232 $m^2$ (2,500 $ft^2$)

| | Electrical Energy Requirements kWhRS (Btu x $10^{-6}$) with Air to Air Heat Pump | | |
|---|---|---|---|
| | Energy for Heating | Energy for Cooling | Total Energy for Heating and Cooling |
| Base Case Building (Large) | 826 (2.818) | 8,190 (27.944) | 9,016 (30.762) |
| Shading on all windows solar transmittance 20% | 810 (2.763) | 6,782 (23.140) | 7,593 (25.907) |
| Shading on all windows solar transmittance 50% | 786 (2.681) | 7,945 (27.108) | 8,731 (29.790) |
| Ventilation 7 ACH; building with concrete construction | 557 (1.900) | 6,860 (23.406) | 7,417 (25.306) |
| Ventilation 14 ACH; building with concrete construction | 551 (1.880) | 6,702 (22.867) | 7,253 (24.747) |
| Ventilation 7 ACH; building with wood frame construction | 815 (2.780) | 7,373 (25.156) | 8,188 (27.937) |
| Building with concrete construction and no ventilation | 543 (1.852) | 8,176 (27.896) | 8,719 (29.749) |

TABLE IV. ENERGY REMOVED BY 7 ACH VENTILATION DURING SUMMER MONTHS FOR SMALL AND LARGE BUILDINGS, CONCRETE CONSTRUCTION

| | Energy Removed by Ventilation GJ (Btu x $10^{-6}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | APR | MAY | JUN | JUL | AUG | SEP | OCT |
| Small Building | 1.89 (1.79) | 1.81 (1.72) | 1.16 (1.10) | 0.03 (0.02) | 0.34 (0.32) | 1.27 (1.20) | 2.15 (2.04) |
| Large Building | 2.88 (2.73) | 2.99 (2.83) | 1.72 (1.63) | 0.04 (0.03) | 0.51 (0.49) | 2.09 (1.98) | 3.79 (3.59) |

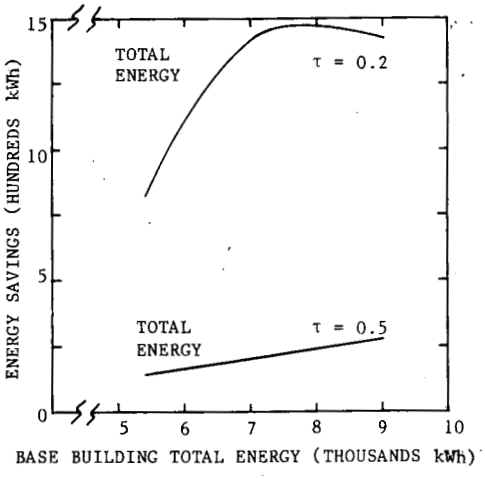



Figure 1. Energy Savings for Shading Devices of Different Solve Transmittances

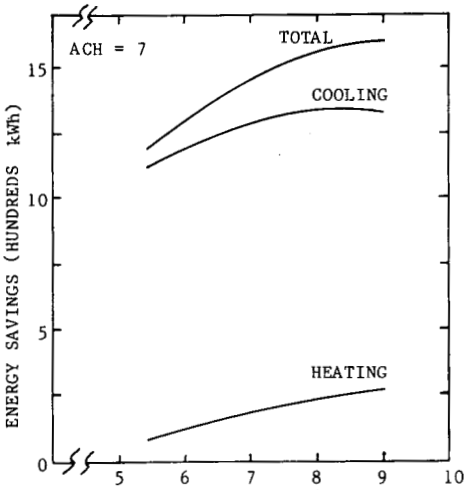



Figure 2. Energy Savings for Concrete Construction and 7 ACH Ventilation

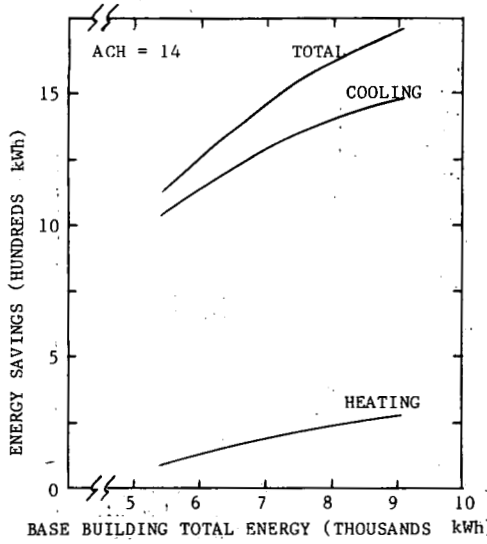



Figure 3. Energy Savings for Concrete Construction and 14 ACH Ventilation

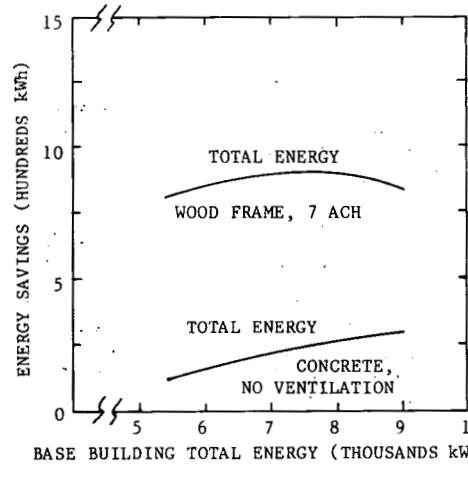



Figure 4. Energy Savings for Wood Frame Building and 7 ACH Ventilation and Concrete Building with No Ventilation

HISTOGRAM PLOT, MODE 2 TIME= 4344.000 JUN

| QAC TIME INT ENDING | : MIN= 0.00 SUM OF INTEGRALS OVER TIME INTERVAL | MAX= 24.00 |
|---|---|---|
| 1.00 | 32328.10 | I*** |
| 2.00 | 25422.32 | I** |
| 3.00 | 21982.50 | I** |
| 4.00 | 10991.25 | I* |
| 5.00 | 3663.75 | I |
| 6.00 | 43965.00 | I**** |
| 7.00 | 113367.64 | I********** |
| 8.00 | 156247.19 | I*************** |
| 9.00 | 161885.47 | I*************** |
| 10.00 | 192043.53 | I****************** |
| 11.00 | 186151.91 | I****************** |
| 12.00 | 172935.59 | I***************** |
| 13.00 | 206323.63 | I******************* |
| 14.00 | 252040.56 | I************************ |
| 15.00 | 273630.13 | I************************** |
| 16.00 | 317434.06 | I****************************** |
| 17.00 | 317573.81 | I****************************** |
| 18.00 | 293427.31 | I**************************** |
| 19.00 | 190997.22 | I****************** |
| 20.00 | 115373.97 | I*********** |
| 21.00 | 104831.25 | I********** |
| 22.00 | 174996.22 | I***************** |
| 23.00 | 200638.84 | I******************* |
| 24.00 | 101594.91 | I********** |

Figure 5. Cumulative Daily Profile of Cooling Provided by Air Conditioner, Small House, Concrete Construction, 7 ACH, Ventilation for the Month of June

| QVENT TIME INT ENDING | : MIN= 0.00 SUM OF INTEGRALS OVER TIME INTERVAL | MAX= 24.00 |
|---|---|---|
| 1.00 | -123811.47 | ############################I |
| 2.00 | -115290.33 | ##########################I |
| 3.00 | -126218.50 | ############################I |
| 4.00 | -133897.16 | ##############################I |
| 5.00 | -120020.31 | ##########################I |
| 6.00 | -56775.38 | ############I |
| 7.00 | -9904.88 | **I |
| 8.00 | 0.00 | I |
| 9.00 | -8160.52 | **I |
| 10.00 | -8702.76 | **I |
| 11.00 | -7509.53 | **I |
| 12.00 | -5067.00 | *I |
| 13.00 | 0.00 | I |
| 14.00 | 0.00 | I |
| 15.00 | 0.00 | I |
| 16.00 | -1544.76 | I |
| 17.00 | -7991.81 | **I |
| 18.00 | -17288.17 | ****I |
| 19.00 | -30248.87 | *******I |
| 20.00 | -46767.76 | **********I |
| 21.00 | -71621.23 | ***************I |
| 22.00 | -78743.45 | ****************I |
| 23.00 | -91098.63 | ******************I |
| 24.00 | -108068.63 | ########################I |

Figure 6. Cumulative Daily Profile of Cooling Provided by Ventilation Small House, Concrete Construction, 7 ACH Ventilation, for the Month of June

HISTOGRAM PLOT, MODE 2 TIME= 5088.000 JUL

| QAC TIME INT ENDING | : MIN= 0.00 SUM OF INTEGRALS OVER TIME INTERVAL | MAX= 24.00 |
|---|---|---|
| 1.00 | 175472.91 | I************ |
| 2.00 | 142777.66 | I********** |
| 3.00 | 73264.77 | I***** |
| 4.00 | 76904.06 | I****** |
| 5.00 | 76938.75 | I****** |
| 6.00 | 106212.36 | I******** |
| 7.00 | 267263.31 | I******************** |
| 8.00 | 405556.19 | I****************************** |
| 9.00 | 395891.38 | I***************************** |
| 10.00 | 391158.06 | I***************************** |
| 11.00 | 327141.00 | I************************ |
| 12.00 | 266063.06 | I******************** |
| 13.00 | 291181.75 | I********************** |
| 14.00 | 330448.63 | I************************* |
| 15.00 | 322736.19 | I************************ |
| 16.00 | 351344.69 | I************************** |
| 17.00 | 402596.13 | I****************************** |
| 18.00 | 403910.44 | I****************************** |
| 19.00 | 363246.69 | I*************************** |
| 20.00 | 283210.06 | I******************** |
| 21.00 | 200614.16 | I*************** |
| 22.00 | 185280.97 | I************** |
| 23.00 | 223561.75 | I***************** |
| 24.00 | 214680.00 | I**************** |

Figure 7. Cumulative Daily Profile of Cooling Provided by Air Conditioner, Small House, Concrete Construction, 7 ACH, Ventilation for the Month of July

| QVENT TIME INT ENDING | : MIN= 0.00 SUM OF INTEGRALS OVER TIME INTERVAL | MAX= 24.00 |
|---|---|---|
| 1.00 | 0.00 | I |
| 2.00 | 0.00 | I |
| 3.00 | -5187.69 | ############I |
| 4.00 | -8194.73 | ###################I |
| 5.00 | -12243.95 | ##############################I |
| 6.00 | -2962.75 | #######I |
| 7.00 | 0.00 | I |
| 8.00 | 0.00 | I |
| 9.00 | 0.00 | I |
| 10.00 | 0.00 | I |
| 11.00 | 0.00 | I |
| 12.00 | 0.00 | I |
| 13.00 | 0.00 | I |
| 14.00 | 0.00 | I |
| 15.00 | 0.00 | I |
| 16.00 | 0.00 | I |
| 17.00 | 0.00 | I |
| 18.00 | 0.00 | I |
| 19.00 | 0.00 | I |
| 20.00 | 0.00 | I |
| 21.00 | 0.00 | I |
| 22.00 | 0.00 | I |
| 23.00 | 0.00 | I |
| 24.00 | 0.00 | I |

Figure 8. Cumulative Daily Profile of Cooling Provided by Ventilation Small House, Concrete Construction, 7 ACH Ventilation, for the Month of July

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# WINGWALLS TO IMPROVE NATURAL VENTILATION: FULL-SCALE RESULTS AND DESIGN STRATEGIES

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## ABSTRACT

Natural ventilation can be used to cool buildings during many months of the overheated season. A significant design problem arises in ventilating rooms which have only one external wall and, therefore, cannot be normally cross ventilated. Architectural projections called "wingwalls" can be used effectively to ventilate these rooms. This paper confirms the benefit of wingwalls from airflow measurements in a full-scale room with and without wingwalls. Alternative design strategies for incorporating wingwall features in residences are also described.

## 1. INTRODUCTION

In designing naturally ventilated buildings one frequently faces the problem of ventilating rooms which cannot be normally cross ventilated (i.e. rooms without opposing external walls). If this occurs on the leeward side of a building, then it is quite difficult to improve ventilation. However, if the wall is located on the windward side, ventilation can be enhanced by wingwalls. Wingwalls are ground-to-eave vertical projection walls located at the inner edges of the windows (Figures 1 and 2). For many wind directions these wingwalls create a positive pressure inlet and a negative pressure (suction) outlet—in effect, cross ventilating the room (see section 4.)

Wingwalls were first suggested by Givoni [1]. He tested scale-model buildings in a wind tunnel and found wingwalls to be quite effective. The primary objective of this study is to confirm Givoni's findings by conducting full-scale experiments in the natural wind. This paper will also present interesting findings about the influence of the natural wind turbulence on ventilation. Lastly, alternative design strategies incorporating wingwall - type features in residences are explored.

## 2. EXPERIMENTS

Full-scale experiments were performed in the FSEC Passive Cooling Laboratory (PCL)—a residential scale test facility used to research various passive cooling and dehumidification alternatives [2]. Tests were conducted in the southeast room of the PCL (Figure 1). Figure 2 is a photo illustrating the south and east facades of the PCL. The wingwalls are shown in Figures 1 and 2 adjacent to the 1.18m (3ft 11in.) wide by 0.91m (3ft) high window apertures. The room internal dimensions are 5.36m (17ft 7in.) x 3.57m (11ft 8in.) x 2.45m (8ft 1in.) making the total window area equal to 5.6% of the floor area and 8.2% of the east wall containing the two windows. Note that these "windows" are really holes in the wall with no glazing. Wooden doors, the size of the openings, are used to open and close the apertures. The upward sloping window overhangs were in place for all experiments. Experiments reported in this paper consist of room airflow measurements under varying external wind conditions for two cases: 1) without wingwalls and 2) with the wingwalls in place.

Room airflows were measured using the $SF_6$ tracer gas decay technique. The room was closed, a small amount of $SF_6$ was injected and was mixed well by a ceiling fan. After taking initial samples, the fan was turned off; the windows were opened for two minutes and then closed again. The room air was mixed again for five minutes and then final samples were taken. Gas samples were analyzed by a gas chromatograph and air change rate per hour (ACPH) computed as

$$ACPH = \ln (C_i/C_f)/\Delta t \qquad (1)$$

where $\Delta t$ is the time (hr ) windows are opened and $C_i$, $C_f$ are initial and final $SF_6$ concentrations, respectively. The infiltration rate in the room with the windows closed is very small—about 0.15 air change/hour at a 4m/sec external wind speed, and thus it does not significantly affect the $C_f$ sample. The room airflow is the product of room volume and ACPH, assuming perfect mixing. The outside wind speed (WS) and direction (WD) were

measured at a height of 10 meters and sampled every 10 seconds. The overall accuracy of the measurement procedure is estimated to be within 15%.

## 3. RESULTS AND DISCUSSIONS

Experiments were conducted over a period of four months during December 1982 - April 1983 during warm weather (Ambient Temperature >20°C) conditions. Table 1 presents a summary of the external conditions and measured air change rates.

Table 1. Summary of Data Collected

| CONDITION | WITH WING-WALLS | NO WING-WALLS |
|---|---|---|
| No. of Expts. | 54 | 33 |
| Average and (std. dev.) of 2 min avg. wind speeds during expts. in m/sec. | 3.23 (1.65) | 3.48 (1.20) |
| avg. ACPH and (std. dev.) during expts. | 73.9 (35.9) | 40.4 (14.7) |

It is clear from Table 1 that wingwalls can improve airflow substantially. To investigate the directional effects, the ACPH can be plotted against the wind direction (WD). However, it would be more appropriate to plot the ratio of air velocity through the aperture to exterior wind speed against the exterior wind direction. To obtain this ratio the ACPH was multiplied by the room volume to obtain airflow through the room. This was then divided by one of the aperture areas. The result is an effective average inlet velocity (u), equal to that at the outlet, since the inlet and outlet areas are equal, given by

$$u = \text{ACPH} \times \text{ROOM VOL/INLET AREA}$$

or,

$$u \text{ (in m/s)} = 0.012 \times \text{ACPH} \qquad (2)$$

This u can then be divided by WS to obtain a dimensionless parameter indicative of the total airflow and the average airspeed at the apertures. A further benefit of airflow data represented as u/WS is that this quantity is likely to be independent of reasonable variations in aperture size so long as the inlet to outlet area ratio is not changed.

Figure 3 plots u/WS against WD for all the experiments. The WD is clarified by the small drawing of the experiment shown in Figure 3. WD = 0,90, 135 indicate northerly, easterly and southeasterly winds respectively. WD = 90 is thus perpendicular to the wall containing the window. As can be seen, there is significant scatter in the data. The trend is indicated by the hand-drawn solid and dashed lines through the data points.

Considering the data for the room with the wingwalls, we can see that the airflow has a broad double peak. It peaks first at about WD = 55 and then decreases to a low at about WD = 100; it increases to another peak about WD = 145 and then decreases again. The valley in the curve around WD = 100 is expected since there are no large pressure differences acting across the apertures for normal (90° to wall) winds. However, the reduction in airflow around WD = 100 is not severe. The reason for the substantial airflows, and the high, narrow peak without wingwalls, is the fluctuation in the natural wind direction.

The WD fluctuates quite extensively. Measured standard deviations of WD over the 2 min experiments based on 10 second scans of the WD have ranged from 10 to 35 degrees. This means the actual WD may fluctuate ± 40 degrees or more about the mean value. For a mean easterly WD, the WD really alternates between ENE and ESE. This results in the two windows alternating as inlets and outlets as the WD shifts. This phenomenon of the south window alternating as inlet and outlet has been visually confirmed by smoke tests. This was also seen for northerly winds. We believe this WD fluctuation is the prime reason the windows with wingwall behave like those without wingwalls for normal winds. This also is the reason the curve tends to rise at WD >330; for those WDs there are times when the WD becomes greater than 360 (i.e. 0) and the wingwalls become effective. The reason why the curve dips around WD = 100, rather than at 90, is not clear. It may be due to the asymmetry of the ventilated room (corner) in relation to the building, with the southeast corner of the building shifting the effective wind at the building by 10°.

For the room without wingwalls, the airflow rate peaks around WD = 100. This high narrow peak in airflow is believed to be due to WD fluctuations. This creates pulsating pressure fluctuation across the apertures causing them to alternate as inlets and outlets. If you compare the two curves you will see that wingwalls can significantly improve airflow through the room. If the windows are located on a windward wall (i.e. for $0 \leq$ WD $\leq 180$), the average improvement in airflow is around 100%.

### 3.1 Other Implications of Results

WD fluctuations that arise in nature are difficult to model in a wind tunnel. Consequently, wind tunnel tests may not reveal all the details. This was indeed the case when a 1:25 scale model of the PCL containing this room was tested in the atmospheric boundary layer wind tunnel at Colorado State

Universty. The wind tunnel tests [3] failed to reveal the dip or the peak in airflow for easterly winds seen in Figure 3.

The uncertainty or scatter in the data is disturbing. To ascertain whether the scatter in the data was due to experimental error or to turbulence properties in the wind, we tried to correlate the data better using information on standard deviation of WS and WD during the 2 minute experimental periods.

After many attempts, a quantity called the Alp number (after its discoverer) seemed to correlate the data for the room with the wingwalls quite well. The dimensionless Alp no. is defined as

$$Alp = 100u\sigma_{WS}/WS^2/\sigma_{WD} \quad (3)$$

where, $\sigma$ refers to the standard deviation of the windspeed or the wind direction during the 2 minutes the windows were opened for airflow measurements. u is the average inlet velocity defined in eq. 2 and WS is the 2 min average windspeed at 10m.

Figure 4 shows a plot of Alp no. vs. WD for the room with wingwalls. It also replots the u/WS data of Figure 3.

The reduction in the data scatter is substantial. This indicates that the scatter in the data is due to wind turbulence and not experimental error.

However, the Alp number actually increased the scatter in the data when applied to the airflow data from the room without any wingwalls. Thus, it does not seem to be a universally fundamental dimensionless parameter. It may well be that the Alp number can collapse airflow data only when it is predominantly mean pressure driven. When the room airflow pulsates due to the lack of a steady unidirectional pressure differential, the Alp number cannot reduce the data scatter. If this is true it would increase our understanding of airflow in rooms.

In any event, correlations involving turbulence properties will be of little use to building designers since wind turbulence properties are seldom available from weather bureau data tapes.

In the next section we discuss design implications of wingwalls. Also see Givoni [1].

## 4. DESIGN STRATEGIES

When ventilating rooms using wingwall strategies it is important to remember that their effectiveness is limited to wind directions which cause one window to be in a positive pressure zone and the other to be in a negative zone. Thus, a single window will not work.

Winds perpendicular (i.e. at a zero degree incidence angle) to the building face tend to separate at the leading edge of the projecting wingwalls, creating alternating and roughly equal amounts of suction and pressure on each window. When the wind is perpendicular to the window, the wingwall configuration behaves in a similar fashion to the normal aperture (Figure 3). This presents no actual problem because true perpendicular wind is a rare phenomenon in the real world as has been shown in section 3.

Wingwalls should ideally be ground-to-eave high. Alternatively, casement windows can also be used to "catch" the wind if only one sash is opened per window. However, tight-sealing awning windows appear to be the best window type for natural ventilation. They provide the best combination of maximum airflow through a given window area as well as maximum rain protection.

Figure 5 shows the expected ventilation results for a number of wingwall configurations or patterns. In some cases the best strategy is very difficult to define, and windows and their wingwalls must be specifically placed to take advantage of a given site condition. As an example, pattern #7a in Figure 5 would prove to be an excellent, if not the best, design decision in a situation where alternating breeze patterns occur (e.g. the land breeze by night and the sea breeze by day). On the other hand, if this pattern is adopted for a predominant direction like that shown in Figure 5, it will prove to be a design failure. Pattern #7b is considered to be poor in all wind directions, because of the extensive short circuiting caused by the close proximity of the windows. Airflow will occur only through that very small corner of the room.

These patterns also illustrate the benefit in overall room airflow which can be gained through the separation of the windows (#5 and #6, a versus b). However, pattern #2 is helpful in situations where rows of rooms allow only single-sided ventilation. This is often the case for double-loaded corridors. The wingwalls can become a significant element of design and unity in such a building.

Pattern #3 is shown as a weak pattern. In this situation it is; however, Aynsley [4] has shown that extended eaves and wingwalls placed at opposite ends of both sides of a truly cross-ventilated building can, as a rule, significantly enhance cross ventilation of the building. It has also been pointed out by Givoni [1] that the wingwall edge offers an excellent surface for the attachment of flyscreens thereby increasing the effective opening area of the unscreened windows and improving overall room airflow rates.

The requirement that wingwalls be placed only at certain edges of windows can be a constraint to the architect. Many potential architectural solutions exist which will enhance the use of wingwalls. One solution is shown in the 1,334 $ft^2$ house plan of Figure 6. It is a plan for ventilating homes on a south-facing lot designed for prevailing wind directions of either SE or NE as shown at the bottom inset. The east wall of the garage acts as a wingwall deflecting SE winds into the house. The solid west wall of the screened porch serves a similar purpose for NE winds. The BR1 and BR2 closets are designed to act as wingwalls in a similar fashion to the patterns shown in Figure 5. The wingwall in BR1 creates a negative pressure on window 1 (W1) and makes it an exhaust. The wingwall next to W2 creates a positive pressure and makes it an inlet for BR2. The only room which cannot be directly cross ventilated is BR3. The door to this room must be left open in order to provide cross ventilation. If the door is closed, ventilation through the kitchen is improved. The arrows in windows indicate the natural airflow patterns likely for SE winds with all the internal doors closed (except for BR3 door). Opening other doors and having a screen door at the entrance will further improve cross ventilation. Outdoor small-scale model tests of this design conducted at FSEC show that it ventilates quite well for all wind directions. This is due to the many protrusions which, as wingwalls do, help induce positive and negative pressure zones at the windows as the natural wind direction fluctuates randomly.

Another small (1,369 $ft^2$ ) home design for west-facing lots is shown in Figure 7. Both this plan and the previous plan have few or no windows in the west wall to minimize solar gains from the hot afternoon sun, a principal source of discomfort in hot, humid regions. In this plan the master bedroom is ventilated by a French door or large casement window (W1) augmented by the dressing room wall and the leeward window W9. Wingwalls are integrated into closets in bedroom #2 and bedroom #3. The second bedroom is ventilated by windows on both external walls with a wingwall on W4 to make it an outlet. A wingwall is not provided on W3 as it would block ventilation for northeast winds.

The arrows in Figure 7 illustrate airflow patterns for SE winds with the doors closed. During the non-sleeping hours the bedroom doors and the entry screen door can be kept open; windows W4 and W7 can be closed to maximize ventilation through the living, kitchen and dining areas.

Note that only the ventilation aspects of the designs have been discussed. These houses should, of course, be well insulated so that they are easy to heat or cool mechanically when natural ventilation cannot provide comfort. These designs were developed with the constraint of small lot sizes where the traditional ventilation design of a one-room deep long house with extended balconies are generally impractical due to lot size.

## 5. CONCLUSIONS

Outdoor full-scale tests have confirmed the benefit of wingwalls in improving natural ventilation in rooms with only one exterior wall by about 100%. The importance of wind turbulence properties in influencing natural ventilation was identified and discussed. Design patterns incorporating wingwalls were presented and architectural solutions to improve ventilation in compact floor plans for typical suburban North American homes have been demonstrated.

## 6. ACKNOWLEDGEMENTS

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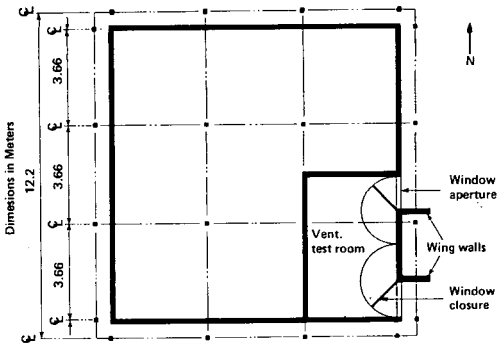



Fig. 1. Plan view of FSEC Passive Cooling Laboratory (PCL) showing location of test room and wing walls.

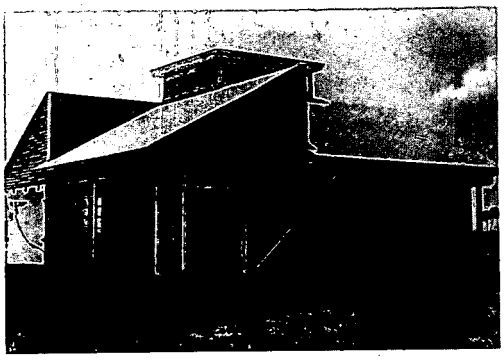


Fig. 2. Southeast view of PCL showing wing walls and overhangs over the two windows in the east wall.

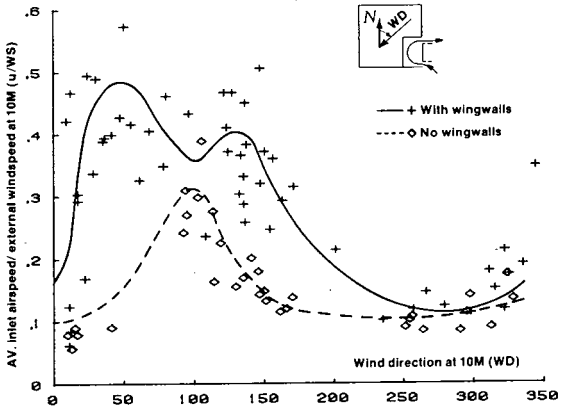



Fig. 3. Airflow data sets with and without wing walls obtained in fullscale PCL experiments. Solid and dashed lines indicate authors' opinion of data trends.

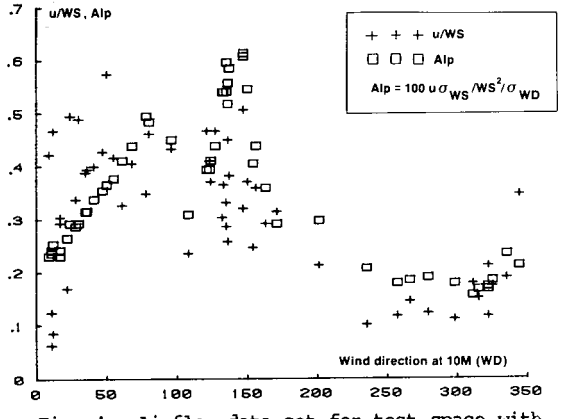



Fig. 4. Airflow data set for test space with wing walls showing effectiveness of Alp number in reducing data scatter.

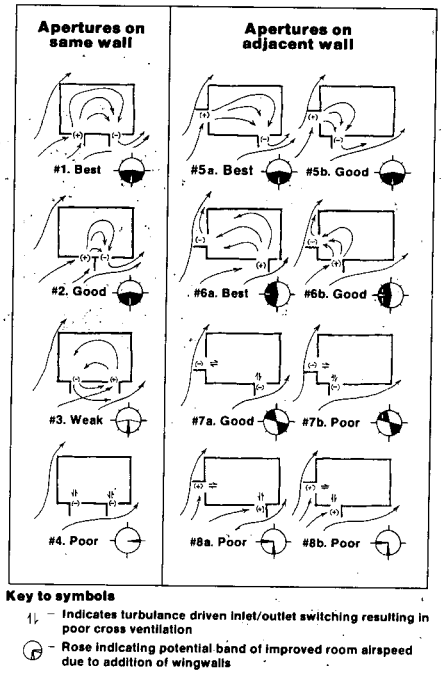



Fig. 5. Wing wall design patterns for two windows on the same or adjacent walls showing probable airflow patterns and wind directions for improved ventilation performance due to wing walls.

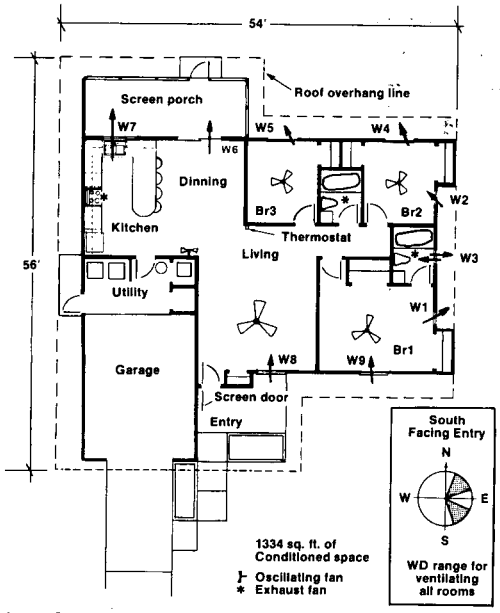



Fig. 6. A compact house plan employing wing walls for south facing lots and SE or NE winds.

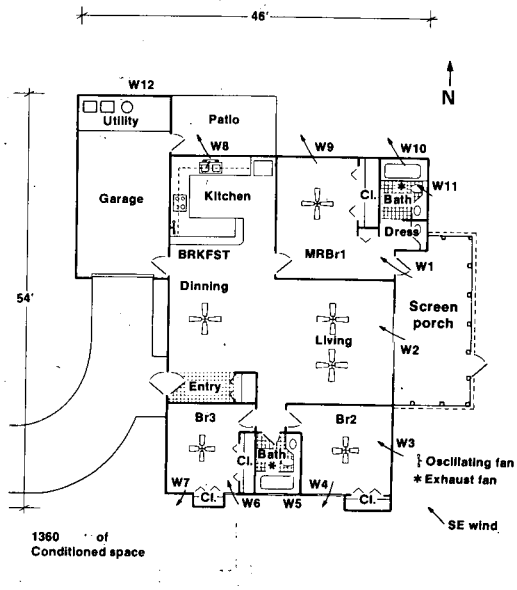



Fig. 7. A compact house plan for SE winds and west facing lots. Note all three bedrooms are cross ventilated.

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# MOISTURE CONTROL IN PASSIVE BUILDINGS IN WARM, HUMID CLIMATES

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## ABSTRACT

Moisture Control in passive residential buildings in warm, humid climates has been a persistent problem. Tighter construction and use of a vapor barrier in building envelopes have led to the accumulation of internally generated moisture in winter as well as in summer. In winter, infiltration and ventilation are effective in reducing indoor humidity levels. Figures are presented to show how these processes can effectively remove internally generated moisture as a function of outside and desired inside conditions. Mechanical cooling and dehumidification are essential in the design of passive buildings in warm, humid climates. While passive cooling strategies can reduce cooling requirements, they do not reduce the need for dehumidification. Air conditioners, which are commonly used in passive buildings, do not remove enough moisture from the air because they operate for limited periods of time due to the reduced cooling load in passive structures. This results in a high humidity level in these homes. The humidity problem is aggravated when high efficiency air conditioners are combined with passively cooled buildings. Since these air conditioners can cool more efficiently, they operate for an even shorter period of time, thus removing even less moisture from the air. The following analysis presents the average inside conditions in a "typical" and a "passive" Florida home using both a conventional and a high efficiency air conditioner.

## 1. INTRODUCTION

Excess moisture is a nuisance to both building materials and human comfort. Due to tight construction practices and the use of vapor barriers in building envelopes, internally generated moisture is trapped inside. This moisture is generated by the normal, every day activities of the occupants such as cooking, bathing, showering, dishwashing, etc. Since these activities are highly dependent upon individual behavior, it is often difficult to estimate the extent of them. Guidelines are provided in the ASHRAE 1979 Equipment Handbook and by other researchers (1,2). It is estimated that an average family of three will produce about 10.8 kg/day. (Human activity @ 50% occupancy 6.9 kg, bathing/shower 1.4 kg, cooking, dishwashing, houseplants, etc: 2.5 kg).

In winter, inside accumulated moisture will condense on cold surfaces such as the inside of exterior walls and on glass. Mold growth is almost inevitable if the relative humidity exceeds 70% for a continuous 12 hours or more (3). A vapor barrier in the walls is recommended in cold climates to avoid the condensation of moisture that can migrate through the wall to the outside. In less cold areas like central and south Florida, where moisture can migrate from the outside to the inside during long summer periods and condense in the wall just before the inside vapor barrier, the use of tight vapor barriers should be avoided.

In any event, moisture transfer through the walls is very small. Infiltration and ventilation can be used effectively in venting excess moisture. Since outside air is not very dry in mild climates, higher infiltration or ventilation rates are required. A major disadvantage is additional thermal energy is required to heat incoming air. The heating requirement could be reduced by controlled ventilation through air — to — air heat exchangers. This problem is similar to that faced in cold climates; ample solutions are available. A word of caution, however. Although heating requirements are small, heating is usually provided through inefficient electric strip heating. Therefore, the overall heating bill could be expensive. Problems due to high indoor humidity in winter are discussed in detail in references 1, 2 and 3.

In summer, unless outside humidity falls below inside humidity (e.g., during cool nights) ventilation and infiltration only bring in more moisture. During four to six months of summer in warm, humid climates, the outside

humidity level rarely falls below the inside level. These hot, humid conditions are ideal for the growth of mold, fungus and bacteria associated with Legionnaire's disease. A climatic analysis of Florida (Miami, Orlando, Jacksonville) weather data reveals that for four to six months in summer, at least 12 consecutive hours with an outdoor average temperature above 75°F and relative humidity above 70% occur. These conditions aid mold growth (3); consequently, ventilating with outside air during summer should be limited. Mechanical dehumidification must then be considered.

Cooling also is required during summer. Considering high average daily ambient temperatures with a low diurnal swing, coupled with solar heat gain through transparent windows and internal heat generation from occupants and appliances, the inside temperature can rise well above the thermal comfort range. Due to a long summer period, buildings are primarily designed to reduce cooling requirements. Passive cooling techniques can be grouped into the following:

- Load reduction - Strategies include shading the building skin from the sun with overhangs, external and internal shading devices on transparent windows, external shading of walls, e.g., vent skin wall (4), double envelope buildings, reduction of heat gain from the ceiling using radiant barriers in the roof (4), ventilation of attics and providing higher insulation in walls and ceilings. Generally known conservation strategies can be included in this category.

- Load levelling - Using the thermal mass of a building structure to store cool air or delay a rise in temperature. An example would be cooling the building structure at night. Due to a small diurnal temperature swing, load levelling may not be very effective in warm, humid climates.

- Heat Rejection - Effectiveness in heat rejection is the key to passive cooling strategies. Unfortunately, there are no very efficient options available. Natural or forced ventilation can be used to dump heat outside. However, it can bring in undesirable moisture. Heat rejection to night sky via long wave radiation has been considered. Since the presence of ambient moisture reduces heat loss through long wave radiation, these strategies have not been extensively used. Roof pond (5) and ground coupling (6) can be classified as heat rejection strategies.

An air conditioner can provide cooling as well as dehumidification. However, an air conditioner controlled by a thermostat provides dehumidification only as a by product. The amount of dehumidification that an air conditioner can provide depends upon its design and operating parameters. A conventional air conditioner (CAC) with a Seasonal Energy Efficiency Ratio (SEER) of about 7.5 to 8.0 uses about 75% of its capacity to cool air and only 25% to remove the moisture or latent load at ARI test conditions (80°F dry bulb and 67°F wet bulb conditions). However, when inlet air conditions are more humid, the CAC removes a greater percent of latent heat as shown in Figure 7. A sensible heat factor (SHF) of an air conditioner shows what fraction of total cooling provided is for cooling; the rest is for dehumidification. A high efficiency air conditioner (HEAC) provides efficient cooling, but it generally does not remove as much moisture. At ARI test conditions, a HEAC with SEER of about 10.0 may use only 21 percent of its capacity in removing moisture. Of course, its moisture removal capacity also rises with the increased coil inlet wet bulb temperature as shown in Figure 7.

A sensible heat factor (SHF) of cooling load, defined as the ratio of sensible load to total load, can be used to indicate the fraction of dehumidification or latent load (1-SHF). A low SHF is indicative of a high dehumidification load and vice versa. For proper cooling and dehumidification, the SHF of cooling load and SHF of the air conditioners should match. Should there be any mismatch between the two, the desired indoor conditions can not be maintained. Since temperatures are controlled by thermostat, it is the humidity or the dew point which shall not be maintained as desired. An analysis of a typical 120 sq m home in Florida shows that the SHF of cooling load is lower than the SHF of the air conditioner, forcing a higher inside humidity than desired. With a HEAC which has a high SHF, the problem is worse.

All passive cooling strategies are primarily aimed at reducing the sensible cooling load, and, consequently, the SHF also is reduced. This further increases internal humidity that can be maintained by a CAC. The problem is aggravated when a HEAC is used with a passive home, because a HEAC has a high SHF, whereas a passive home has a low SHF. The problem is further aggravated when the room thermostat is raised by an occupant who uses a ceiling or table fan for comfort. This further reduces sensible heat gain, and internal humidity levels may rise. The use of a vapor compression dehumidifier is not recommended because it adds about 2500 Btu per pound of moisture removed, negating the effects of passive cooling.

The following analysis gives average inside conditions maintained by conventional and high efficiency air conditioners in typical and

passive Florida homes. It suggests that a high efficiency dehumidifier air conditioner will go a long way in providing desired indoor conditions in typical and passive homes in warm, humid climates and promote passive cooling and conservation strategies.

## 2. METHODOLOGY AND ANALYSIS

A typical 120 $m^2$ home as shown in Figure 1 was analyzed. Thermal characteristics of the building envelope are provided in Appendix A. The proposed ASHRAE TC 4.7 simplified energy analysis methodology (7) was extended to each temperature bin in calculating seasonal cooling requirements. The seasonal sensible loads from modified methodology were validated with hour-by-hour BLAST mainframe computer programs within 8 percent. Internal sensible heat gains were estimated at 15.6 kWh/day and latent gains of 10.8 kg/day. The infiltration rate was varied from 0.5 air change per hour (ACPH) for a tight construction to 2.0 ACPH for loose construction. Although 0.5 ACPH is not very hard to obtain in the field, the typical Florida home may have a higher infiltration rate. This is due to the fact that homes have large, operable windows used for natural ventilation during fall and spring; however, they may not close tightly in summer.

The passive home analayzed is similar to the typical home, but load reduction techniques were used to reduce by half the solar gain through windows and transmission heat gain through the building envelope. This could easily be achieved by reducing the glass area, repositioning the glass on walls of different orientation, external or internal shading, and increasing the insulation of envelopes. Clark (5) and Akridge (6) suggest that a significant proportion of sensible load can be reduced by passive cooling techniques.

Inside dry bulb temperatures were assumed to be 21.1°C (70°F) for winter. The potential for moisture removal by infiltration/ventilation at an outside temperature of 1.7°C (35°F) and 70% rh, and a desired inside humidity varying from 30% to 70% rh is shown in Figure 2. Figure 3 shows the average infiltration/ventilation rate required to remove internally generated moisture in Orlando and Jacksonville, Florida, in January when inside conditions are maintained at 21.1°C (70°F) and 55% rh. It is interesting to note that in Miami (south Florida), a very high infiltration/ventilation rate is required to maintain desired conditions. Mechanical dehumidification may be necessary even in winter, or the inside humidity level may rise. Dedicated water heat pumps, which heat domestic hot water and provide dehumidification as a by product, may be a good choice in such climates.

The seasonal cooling loads for typical and passive homes with one air change are shown in Figure 4 and 5 for Orlando (central Florida). The sensible and latent heat factors for inside design conditions of 25.6°C (78°F) and 55% rh are shown in Figure 6. It is interesting to note the SHF did not vary for the Orlando or Miami climate or if the inside desired conditions were changed to 26.7°C (80°F) and 55% rh.

The performance of a conventional air conditioner (CAC) and a high efficiency air conditioner (HEAC) as a function of coil inlet wet bulb temperature as shown in Figure 7 were used to estimate the average inside dew point temperature and relative humidities. The average inside dew point temperatures maintained by the CAC and HEAC as a function of air infiltration rate are shown in Figure 8 and 9. A line at dew point of 16.7°C (62°F) was also drawn to show the upper level of ASHRAE 55-81 thermal comfort chart. Figure 8 is for a designed inside temperature of 25.6°C (78°F). Figure 9 is for an inside temperature of 26.7°C (80°F). The average inside relative humidities maintained by the CAC and HEAC are shown in Figures 10 and 11. Figure 10 and 11 correspond to an inside temperature of 25.6°C (78°F) and 26.7°C (80°F), respectively.

## 3. RESULTS AND DISCUSSIONS

It is evident from Figure 8 and 9 that, in the passive home, the average inside dew point temperature is around 64°F to 69°F, depending upon the inside set point temperature and an air change rate of .75 to 1 ACPH. According to the ASHRAE thermal comfort chart, 62°F is the maximum dew point temperature for thermal comfort, therefore the CAC and HEAC will not maintain the required comfort conditions. The dew point is about 1.5°F higher when HEAC is used compared to CAC; therefore an air conditioner with a high SHF should be avoided for passively cooled buildings. A relative humidity below 80% is considered acceptable for human comfort; however, for the sake of building materials, which can be adversely affected, a relative humidity above 70% is not recommended. Some researchers do not consider relative humidity an appropriate thermal comfort criterion and use instead the absolute humidity or dew point. ASHRAE 55-1981 standards also recommend a maximum absolute humidity of 12g/kg or a dew point temperature of 16.7°C (62°F). The average inside relative humidities are 62% to 68%. It is interesting to note that the relative humidities at 26.7°C (80°F) are slightly lower than at 25.6°C (78°F); however, absolute humidities are higher, as illustrated by the dew point temperatures. This is due to the fact that at a higher temperature the saturation humidity level is higher and therefore reduces the inside relative humidities at higher temperature. This is one

reason why some researchers do not consider relative humidity a good indicator of thermal comfort.

At this point, it is appropriate to mention that the above analysis gives average inside conditions. However, variations from hour to hour may occur depending upon sensible loads. In the daytime, inside humidity may be lower, while at night, in the absence of sensible loads, the inside humidity level will be higher. This is the reason why people complain about "muggy" or "clammy" inside conditions at night and then lower their thermostat to remove moisture. They then have to cope with an undesired cold temperature.

## 4. CONCLUSION AND ACKNOWLEDGEMENTS

Conventional air conditioners maintain average inside dew point temperatures of 1°F to 3°F above the ASHRAE maximum recommended dew point of 62°F in typical homes at one ACPH. When high efficiency air conditioners are used, inside dew points are 3°F to 5°F above the ASHRAE maximum value. In passive homes CAC maintain 2°F to 4°F above the ASHRAE limit and HEAC maintain about 4°F to 6°F above the ASHRAE limit.

An efficient air conditioner which can remove a larger fraction of the latent load would be helpful in many typical and passive homes in warm, humid climates. Doderer (8) and Akridge (6) have been developing such air conditioners under separate Department of Energy funded projects. FSEC is currently developing a high-efficiency dehumidifier/air conditioner aimed at two-to-three times the dehumidification efficiency of a conventional air conditioner. This project is funded by a grant from National Aeronautics and Space Adminstration's Kennedy Space Center. The research detailed in this paper was partially funded by NASA-KSC, Mr. Reed Barnett, program manager.

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## 6. APPENDIX A

Thermal characteristics of a "typical" home. The plan shows dimensions, window and wall area in each orientation. A 2 ft overhang is considered in all directions. Single-pane glass with a shading coefficient of 0.55 is taken in all windows. The walls are concrete block structure with interior finish of gypsum and no insulation (U = .325). R-19 insulation is considered in the ceiling. R-11 wall insulation is considered between house and garage. The house is slab on grade and no heat gain through the floor is considered. Internal heat gains are discussed in the text. The infiltration rate is varied from 0.5 to 2.0 air change per hour.

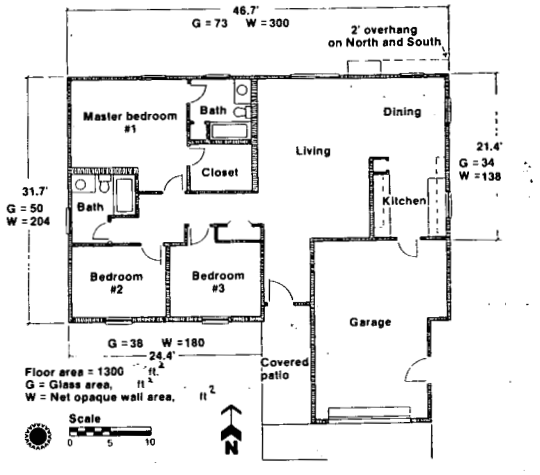



Fig. 1. Plan of "typical" home.

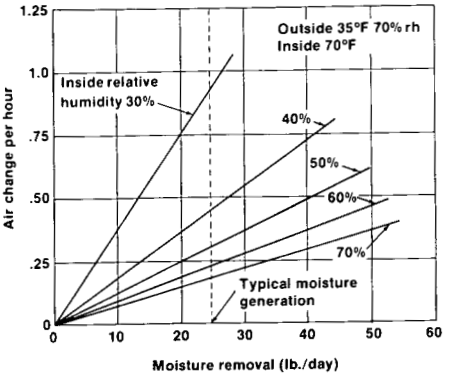



Fig. 2. Ventilation and infiltration potential in moisture control of a 120 $m^2$ "typical" and "passive" home.

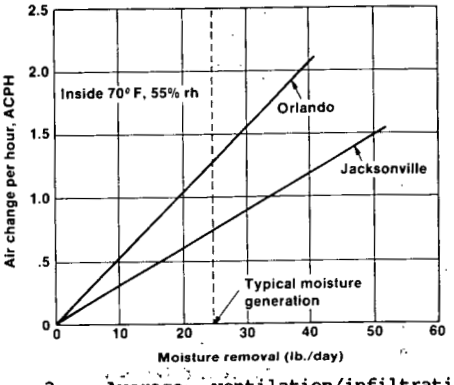



Fig. 3. Average ventilation/infiltration requirement during January "typical" or "passive" 120 $m^2$ home.

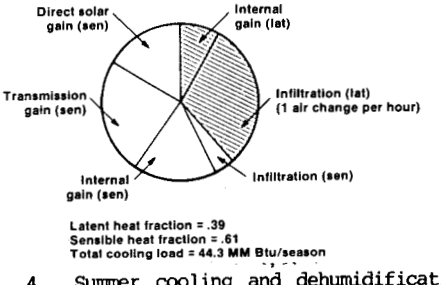



Fig. 4. Summer cooling and dehumidification loads in a 120 $m^2$ "typical" Florida home.

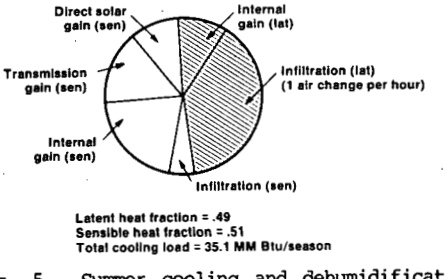



Fig. 5. Summer cooling and dehumidification loads in a 120 $m^2$ "passive" Florida home.

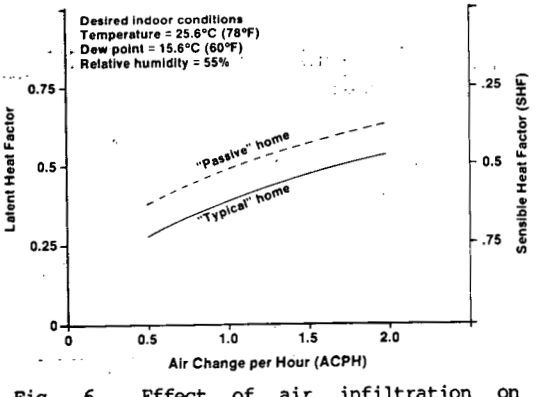



Fig. 6. Effect of air infiltration on dehumidificaton (latent) and sensible load factors in a 120 $m^2$ "typical" and "passive" Florida home.

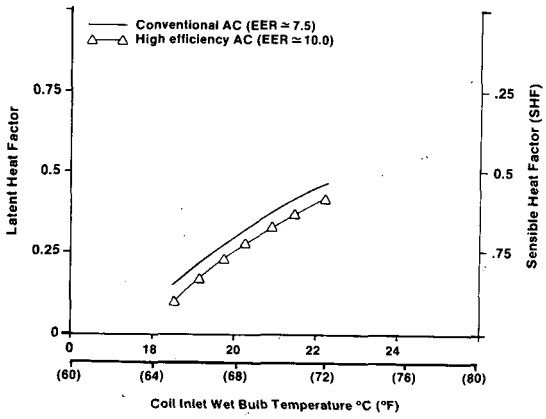



Fig. 7. Dehumidification (latent) and sensible heat removal fractions of a conventional AC (CAC) and a high efficiency AC (HEAC) as a function of inlet air wet bulb temperature.

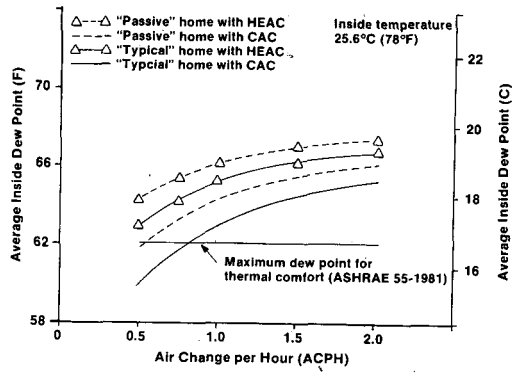



Fig. 8. Average inside dew point maintained by a conventional AC (CAC) and a high efficiency AC (HEAC) in "typical" and "passive" Florida homes as a function of infiltration rate. Inside temperature = 78°F.

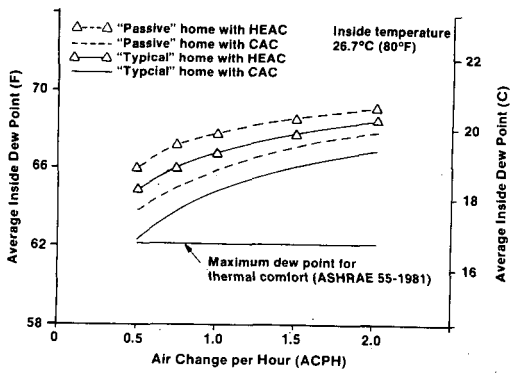



Fig. 9. Average inside dew point maintained by CAC and HEAC in "typical" and "passive" Florida homes for an inside temperature = 80°F.

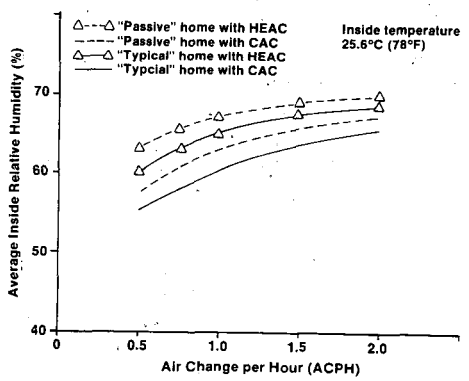



Fig. 10. Average inside relative humidity maintained by CAC and HEAC in a "typical" and "passive" Florida homes for inside temperature = 78°F.

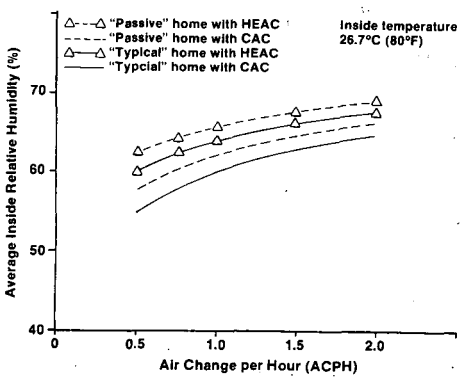



Fig. 11. Average inside relative humidity maintained CAC and HEAC in "typical" and "passive" homes for inside temperature = 80°F.

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# THE DESIGN AND TESTING OF A HIGH PERFORMANCE VENTILATOR COWL: AN ELEMENT IN PASSIVE VENTILATION

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## ABSTRACT

This paper describes recent efforts in an ongoing search begun by one of the authors in 1979 to find and demonstrate a high performance rooftop ventilator. In this third phase of the investigation a speculative form was modeled to incorporate: (1) criteria established after preliminary tests, (2) design guidelines uncovered through a literature search, and (3) three untried concepts. Eight cowls were molded in fiber-reinforced plastic and altered in various ways in an attempt to optimize performance. For testing, the one-third scale models were centered in a 3 foot (91 cm) diameter open throat wind tunnel on a 4 inch (10 cm) diameter stack. Induced air flow through the stack was manually monitored with a pitot tube and micromanometer. Results are presented as percentages of enhancement over an open stack and are also compared with results from previously tested types which were reproduced and retested at this same scale.

## 1. INTRODUCTION

Prior to the almost universal adoption of mechanical ventilation the rooftop ventilator (monitor, cowl, cap) was a primary element in the ventilation system of most public buildings, factories, barns, and some dwellings. The variety and ingenuity exhibited in patent cowls was astonishing. Designs and design features patented in the U.S. between 1850 and 1940 number no fewer than 300. Comparative testing of ventilators has probably been a design tool since it was first learned that certain caps when presented to the wind actually enhanced air movement through the stack or chimney. The oldest published test results found by the authors were done in 1842, while the most comprehensive were done in the 1920 s.

Today the use of ventilators to promote natural ventilation is being reestablished as a viable alternative to power ventilation. Designers of passive solar heating/cooling systems, for instance, often use turbine ventilators in various ways as important components of their systems. However, manufacturer's performance data are usually of little help to designers. In some instances the published rating figures apply only when the ventilator is mounted on a 40 foot (12.2 m) stack having a 20°F (11°C) temperature differential. On such a stand, stack effect (air movement as a product of temperature and height) may contribute more to ventilation than the ventilator being rated. The question of actual performance and a desire to find and demonstrate an optimized roof top ventilator prompted this investigation.

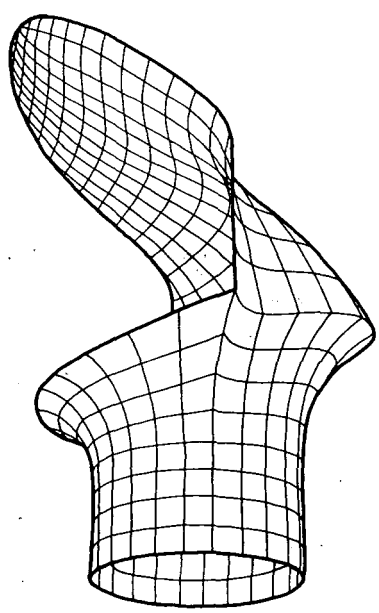


Fig. 1. The Fiberglass Cowl

## 1.1 Background

Initially a series of commercial and experimental cap types were modeled at 1/5 scale (2 1/2 inch (6.4 cm) diameter stack) and comparatively tested in a 3 foot (91 cm) diameter open throat wind tunnel. Three experimental types and a commercial wind driven turbine were then tested at full scale (on a 12 inch (30.5 cm) diameter stack) in a 6 foot square (1.8 m) stability wind tunnel. In addition to comparison with the open stack, as in the initial tests, performance was plotted as a function of tunnel velocity. These tests demonstrated the potential for improvement over the ubiquitous turbine and consequently generated considerable interest.

However, of the three experimental cap types evaluated (delta wing, inverted air foil, and spade shield) none were suitable for use in their tested form. The delta wing and spade shield were not storm proof and the airfoil, whose maximum dimension was more than four times stack diameter, became questionable due to size. Size may also have influenced the airfoil's tunnel performance by increasing tunnel back pressure. Therefore, design criteria for new forms included weatherability and a subjective size/weight limit.

The third phase of this investigation was broadened in scope to include numerous alterations, hybrids, untried elementary forms and the experimental form described in this paper. The large number of tests envisioned in this phase necessitated a return to the readily available 3 foot (91 cm) wind tunnel. This reduction to 1/3 scale (4 inch (10 cm) diameter stack) did not, as will be shown, compromise the significance of the results.

## 2. DESIGN

In the first phase of this work, development of "wake" (the turbulent low pressure region in the lee of objects) was seen as the most promising strategy for stack flow enhancement. This effect is perhaps more correctly described as entrainment or aspiration, phenomena defined by Bernoulli. Indeed, the investigators who conducted ventilator tests at the National Bureau of Standards in 1920 concluded that ... "The most effective way of obtaining a large volume of air exhaust is by making use of the region of low pressure produced at the back of a properly designed obstacle." This premise was accepted as a sound enough principle on which to base a contemporary design. Therefore, maximum wake from minimum frontal area became the objective. Three criteria established to further guide the design were: (1) size - no dimension greater than twice stack diameter; (2) weatherability - strength to resist environmental forces, no rain penetration; (3) configuration - directional, to permit aerodynamic optimization. In addition to these criteria the evolving design was guided by a basic understanding of fluid flow over surfaces, comparative data from the past, and judicious intuition.

Many clay and plaster models were made to visually study proportional relationships, molding feasibility, and adherence to criteria. The final design, Fig. 1, was sculpted as a plaster positive and used to make a two piece mold from which eight models were pulled. Essentially, the cowl is a modified elbow. Its uniqueness is due to the use of molded fiber-reinforced plastic, a material which allowed three important concepts to be incorporated: (1) smooth compoundly curved surfaces for predictable fluid flow; (2) a smoothly flared terminous for reduced flow resistance; (3) the integration of an air intake as a second function. Numerous alterations were made to determine their effectson performance. A selection of these are described.

## 3. TESTING

The tests were performed in the three foot (91 cm) diameter test section of an open throat, closed circuit, single return wind tunnel. For testing the models were centered in the test section on a 30 inch (76 cm) long, 4 inch (10 cm) diameter stack. This stack was equipped with a flared entrance, straightening vanes and a pitot tube as shown in Fig. 2. Tunnel and stack dynamic pressures were manually monitored using micromanometers. Flow visualization techniques used included attached yarn tufts and tracer smoke. All of the test results presented in Table 1 were taken at a sea level tunnel velocity of 31.9 mph (51 kmph). Results of this velocity were more consistent than those at lower more "natural" velocities.

The rating system devised during previous tests was used to evaluate performance. The velocity induced in the stack by each tested form was compared with the stack velocity induced in an open stack at an identical tunnel velocity. A percent enhancement figure was then derived from the two velocity figures by the following standard formula:

$$100(V_s - V_{os}/V_{os}) = \text{percent enhancement (\%E)}$$

where:

$V_s$ = velocity in the stack

$V_{os}$ = velocity in the open stack

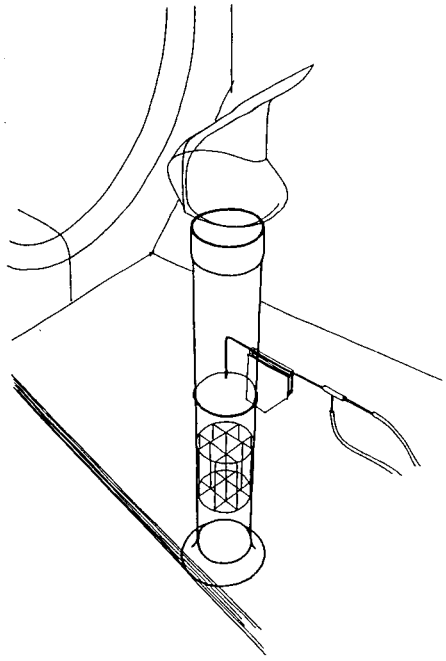


Fig. 2. Test Stand

To check the validity of the percent enhancement rating method and to establish correlation between tests at different scales, a preliminary series of tests were done. Three of the experimental ventilators tested by Schubert and Kennedy, a spade shield, a delta wing, and the inverted airfoil (see Table 1), were precisely duplicated at 1/3 scale and tested on the previously described stand. Figures 3 and 4 show the positive correlation across scales for the inverted airfoil. In Fig. 3 enhancement percentages are plotted against tunnel velocity, while in Fig. 4 the percentages are charted with respect to Reynold's Number, a dimensionless parameter used to equate the properties of fluid flow through scale and medium changes. In this case aerodynamic equivalence was achieved by tripling tunnel velocity for the 1/3 scale tests.

## 4. PERFORMANCE

Table 1 graphically displays enhancement value against a performance baseline for the open stack. Because turbines are in such common use their enhancement value as indicated by the full scale tests is extended as a secondary baseline. Although this project is concerned primarily with comparative analysis, Table 1 also has scales indicating actual stack velocity and volumetric flow. These are accurate only for the 1/3 scale (4 inch stack) models. It is assumed that exhaust capacities for full scale versions of these ventilators may be

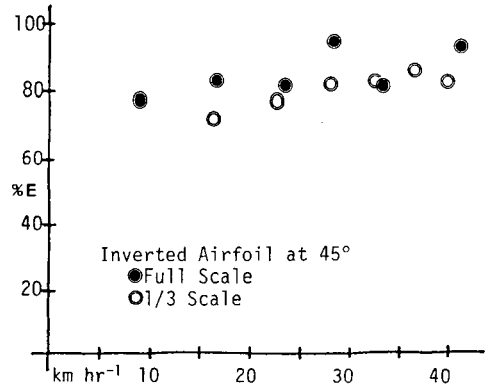



Fig. 3. Comparison of Tests at Two Scales With Respect to Velocity

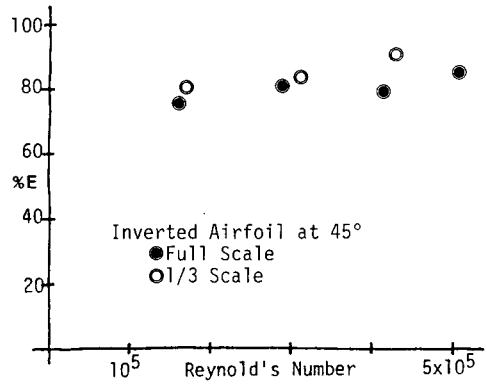



Fig. 4. Comparison of Tests at Two Scales With Respect to Reynold's Number

extrapolated to the degree of accuracy indicated by Fig. 3. When extrapolating bear in mind the high tunnel velocity used in these tests. As stack velocity is roughly proportional to impinging (tunnel or ambient) velocity, an 8 mph (13 kmph) wind, for example, would induce only one-fourth the flow of a 32 mph (51 kmph) wind. The alterations on the fiberglass cowl were made to qualify and/or quantify their relevance for future design. While few of the beneficial alterations were individually of great significance, the assumption is that through combination they will result in a truly optimized ventilator.

Test #1 in Table 1 shows results for a full scale (12 inch stack) turbine as tested in an earlier phase of this work. Tests #2 and #3 show results for the experimental delta wing and airfoil as tested at one-third scale. At 94% and 85% they show significant improvements over the turbine at 30%. Full-scale results were very similar.

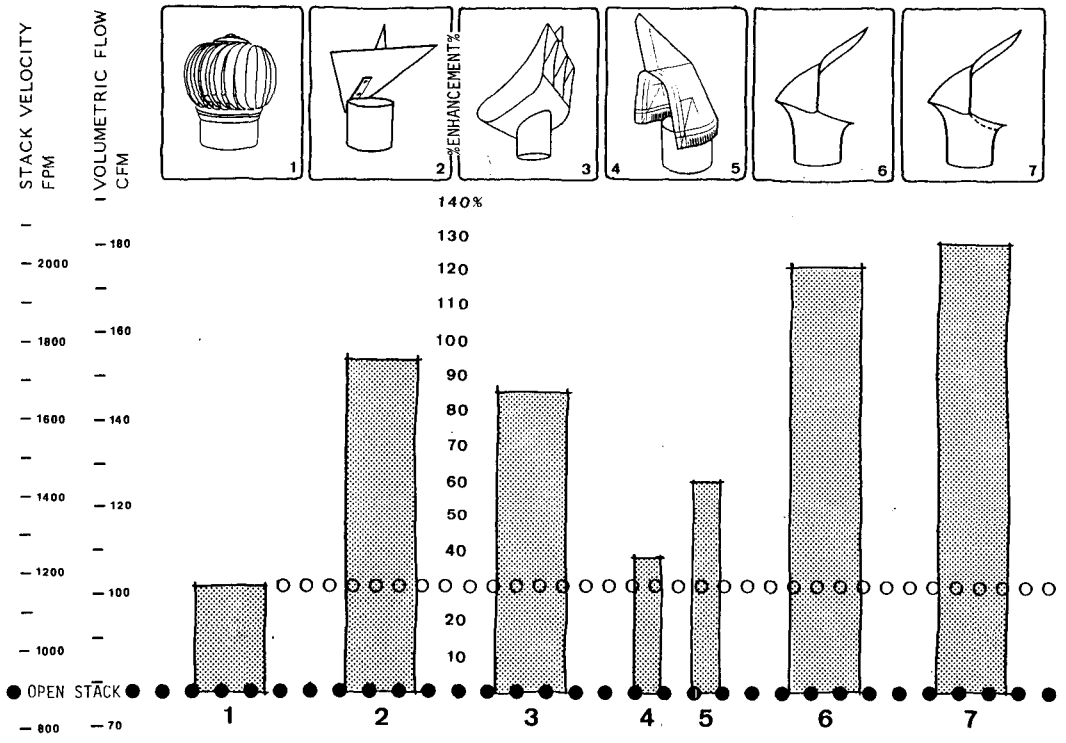



Table 1A

In test #4 another commercial ventilator type, not unlike the fiberglass cowl in concept, enhanced the open stack velocity by 38%. In test #5 it was altered by spreading its "sides" till the rear opening was twice the stack diameter of six inches. This increased its performance rating to 60%.
The remainder of the tests are on the fiberglass cowl. In test #6 the unaltered cowl improved upon the open stack velocity by 121%.

In the first alteration, tests #7 and #8, the flared edges were incrementally extended and reduced. Optimizing the rear flare (removal of 1/2 the arc) upped performance slightly to 128%. The greatest single improvement, at 138%, was achieved by adding a one inch (2.5 cm) extension to the flared rim on the windward face. An extension such as this, however, would compromise the size criteria.

For tests #9, #10, and #11 a model was separated into two parts. In tests #9 and #10 the upper piece or "face" was pivoted forward and back on its flared base. At 15° forward, test #9, performance remained at 121° but with the angle of attack reduced by 20%, test #10, enhancement dropped to 85%. In #11 the "face was fastened with clay to a truncated non-flared base, effectively eliminating the influence of a flared terminous.

For #12 and #13 clay was used to alter an otherwise "straight" model. In #12 the outer concave portion of the face was leveled, essentially eliminating that part of the wake generating flare and depressing performance slightly to 113%. In #13 the "nose" was filled to make a smooth continuous internal curve, thus simulating a "noseless" version. Perhaps it was the reduced turbulence inside the cowl that resulted in a slight increase to 124%.

Many directional patent cowls attempted to promote further aspiration by admitting wind into the cowl through various passages. For test #14 openings were made under the nose and fitted with an interior baffle. The performance value of 118% is actually an average of several runs with varied baffles.

Tests #15 thru #19 show how performance changes with yaw angle, 0° being a normal presentation.

For use on a concentric tube air to air heat exchanger a cowl was modified as shown in Fig. 5. This configuration permits a single cowl to perform both exhaust and intake functions. Relevant figures for this two-

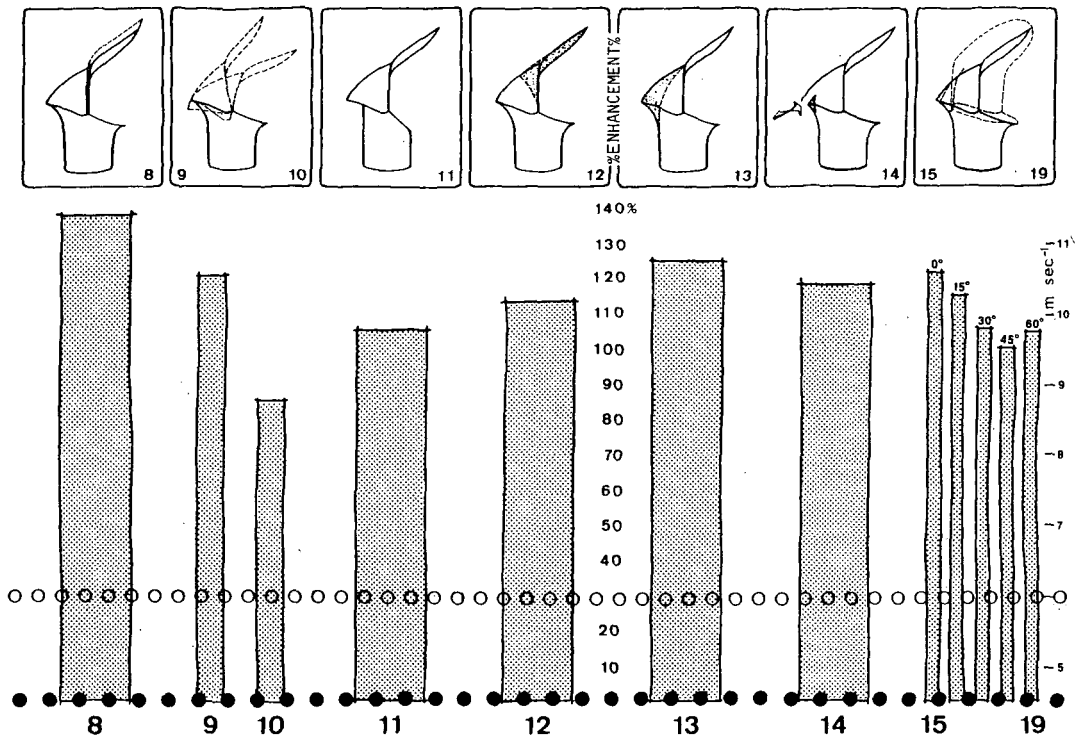



Table 1B

way cowl are given in Table 2. The choice of a two inch (5.1 cm) diameter intake tube was more or less arbitrary, as in a final version tube diameter would be chosen for balanced flow. The flow rates shown in Table 2 were calculated assuming uniform velocity across the sections. This of course is never the case, but these figures do suggest a relationship between cross section and volumetric flow for this modified cowl. Figure 6 illustrates an inverse valve that governs air change with wind speed. As wind speed increases side vanes activate the butterfly valves, preventing excessive air change and inefficient heat exchange. Figure 7 illustrates one envisioned configuration for the two-way cowl and a concentric tube heat exchanger. In Fig. 8 an additional heat exchange element is incorporated into the system to improve the efficiency of short concentric tubes.

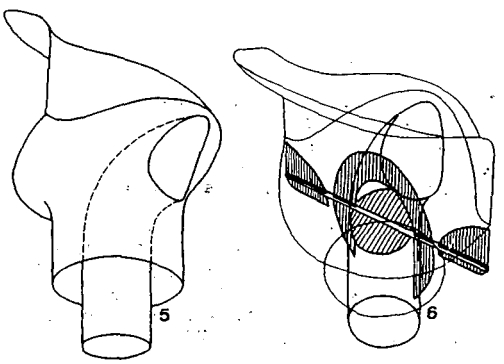



Fig. 5. Two-Way Cowl With Concentric Intake

Fig. 6. Schematic for an Inverse Valve

Table 2

| | Intake (Center) | Exhaust (Perimeter) |
|---|---|---|
| Tunnel Velocity MPH (km $hr^{-1}$) | 21.6 (34.8) | 21.6 (34.8) |
| Stack Velocity FPM (m $min^{-1}$) | 1440 (439) | 900 (275) |
| Cross Sectional Area $in^2$ ($cm^2$) | 3.14 (20.26) | 9.42 (60.77) |
| Volumetric Flow CFM ($m^3$ $min^{-1}$) | 31.4 (.89) | 58.9 (1.67) |

## 5. CONCLUSION

The authors feel that the testing of this prototype has conclusively demonstrated the performance potential of an optimized ventilator. Be reminded that, as with any model, complications with details usually accompany a scale up. Performance improvements realized in a final version would likely be offset somewhat by losses from grills, ducting, screening, and the mounting system. The cowl as illustrated is self-orienting except when caught squarely in the "mouth." To prevent it being locked in this down draft mode a small vane would need to be incorporated. Simple rain tests on the "normal" cowl did not indicate a problem with rain penetration. The splash-in from heavy or gusty rains could be easily drained away with drip edges. The two-way cowl, on the other hand, would probably require a redesigned intake and an internal drain.

Also, the method of evaluation used in this study can be misleading. A cowl that enhances open stack flow by 120% does not even double the flow of one that performs at 30%. Furthermore, if at equivalent velocities flow increases proportionally with cross sectional area, merely upsizing a 12 inch (30.5 cm) system to a 16 inch (40.6 cm) system produces a 77% increase in flow. It is for this reason that a scale for volumetric flow is included in Table 1.

For some applications, however, a high performance ventilator cowl would be more appropriate than previously available types. Pulling air into a space through long underground earth tubes, for instance, would no doubt require an optimal solution. A high performance directional cowl would excel in the venting of a building's skin, such as the summer venting of a Trombe wall. A ventilator of this type could maintain a positive flow through the cavity regardless of the normal wind-generated pressure pockets around a building that might otherwise impede the desired air change.

A two-way cowl as described in this paper would be especially appropriate for year around supplementary ventilation in underground or other hard to ventilate spaces. An instance where increased stack diameter offers no advantage is in a dual functioning system where the two-way cowl is directly coupled to a concentric tube heat exchanger. Unfortunately, calculations done by others do not show high efficiencies for concentric tube air-to-air heat exchangers except when they are very long with low uniform flow rates. However, the potential of such a system does warrant investigation.

## 6. ACKNOWLEDGMENTS

Special thanks are extended to the Department of Aerospace and Ocean Engineering at VPI & SU for use of the wind tunnel, and to William R. Sevebeck, College of Architecture's Environmental Systems Lab, whose guidance and skill were crucial in the production of the molded cowls.

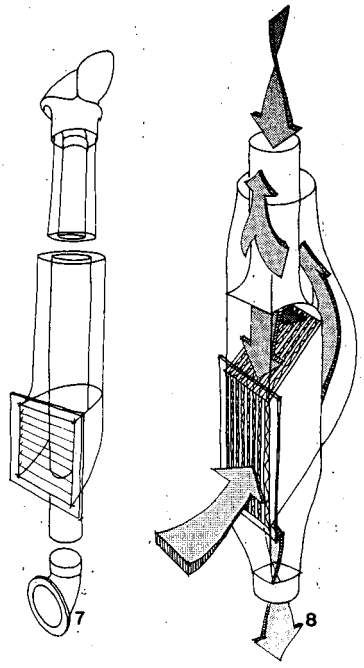



Fig. 7. A Possible Configuration of the Dual Cowl and a Concentric Tube Air to Air Heat Exchanger

Fig. 8. The Incorporation of a Sandwich Type Heat Exchange Element to Improve Efficiency

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# AN ENVIRONMENTALLY RESPONSIVE RESIDENCE FOR SOUTH LOUISIANA

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## ABSTRACT

With a grant from the Louisiana Department of Natural Resources, Assistant Professor Hector Lasala and I researched how to build in south Louisiana to provide maximum comfort with minimum energy use for people with low to middle income FHA type housing. The product of the study was the design of a four foot modular proto-type house built with the help of architecture students from the University of Southwestern Louisiana.

## 1. INTRODUCTION

The residence has 1320 square feet of conditioned space with 3 bedrooms, bath, kitchen, dining and living area. There is a 120 square feet utility room that is insulated but not conditioned and a one car carport (see Figure 1). A family of four have been living in the house for a little over a year now.

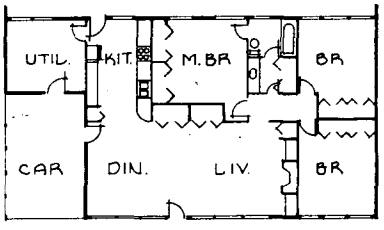



Fig. 1. Floor Plan.

One of the major objectives was to solve the harsh comfort requirements imposed by the hot and humid south Louisiana summers. While passive heating and cooling are relatively easy tasks in dryer and cooler climates, the problem becomes more formidable in the hot, humid, sub-tropical climate associate with the Gulf of Mexico. Whereas heating is the more important conditioning problem in most of this country, it is very secondary to cooling in south Louisiana.

## 2. LOCATION AND CLIMATE

The house is located in Cade, Louisiana, approximately 16 miles from the Gulf of Mexico. The house sits on the edge of the Coteau Ridge or the westward most escarpment made by the Mississippi River millenniums ago. South of the house, as seen in Figure 2, is

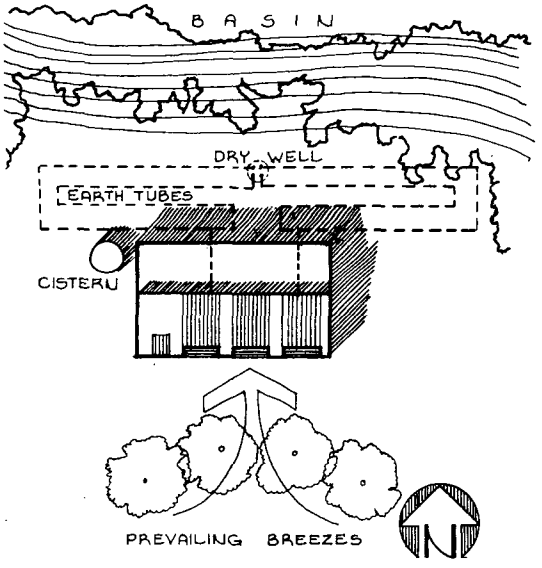



Fig. 2. Site Plan.

considered the prairie and behind the house is an eighteen foot drop into the Mississippi Delta Basin. The house is rectangle in shape and elongated in the east-west axis. There are trees on the east and north, and it is open to the south where the prevailing breezes come from the Gulf. This area has 2632 cooling degree days as opposed to only 1551 heating degree days. Compounding the problem is

the unusually high relative humidity (R.H.) during the majority of the year. Daytime humidity ranges from 50% to 60% R.H. during summer days while reaching dew point (100% R.H.) at night is normal. Summer temperatures range from daytime highs of 90°F to 100°F while night time lows are in the mid 70° F. It is the combination of high humidity levels, lack of cool nights and clear skys for night deep sky radiation that makes cooling such a considerable problem for passive design. Winters in the area are much milder with temperatures varying greatly with the passing of frequent cool fronts. Coolest temperatures, 25°F to 30°F, occur immediately after the frontal passage. Very low R.H. and clear skys also accompany this period which makes solar collection by direct gain a simple task. Spring and fall are seasons of ideal dayround temperatures and relatively dry conditions. No heating or cooling is generally necessary the majority of the time during these seasons when ventilation is itelligently used.

## 3. CONSTRUCTION

While providing an energy efficient home for this area was the primary goal of this project, it was of equal importance to produce it at an affordable cost since those who will benefit most are that segment of the public who can least afford the rising cost of conventional energy. The cost of construction for 1656 square feet under roof was $52,000 or $31.50 per square foot. This cost includes about $3,000 of instrumentation which reduces the actual construction cost to $29.50 per square foot.

### 3.1 Foundation, Floor and Air Distribution

A grade beam was poured around the exterior and two, in the east-west direction, through the center separated by 20 inches as seen in Figures 3 and 4.

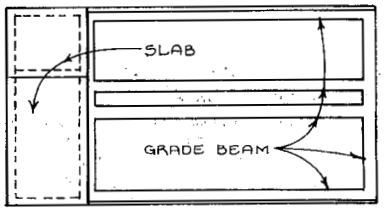



Fig. 3. Foundation Plan.

On top of this was placed hollow core concrete planks which act as the air distribution

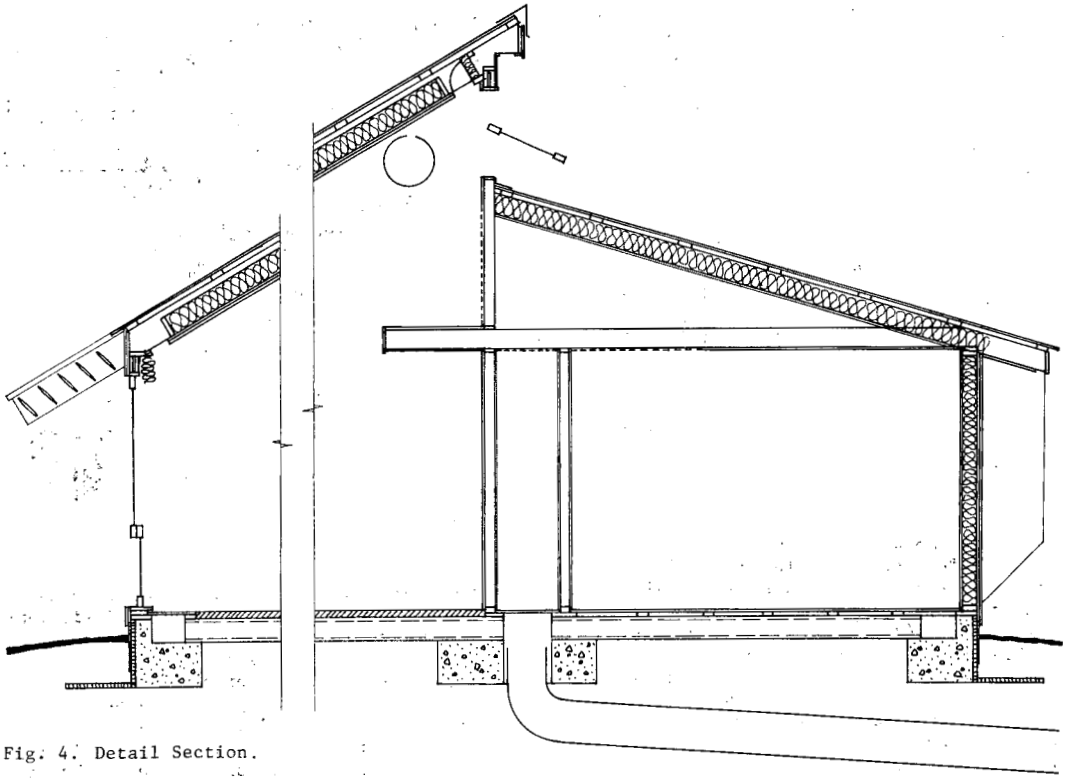


Fig. 4. Detail Section.

system. A 20 inch by 24 inch plenum was created in the center and runs the full length of the conditioned space. One inch rigid insulation was placed two feet vertically along the outside of the exterior grade beam, and then two feet out horizontally. The concrete planks were covered with dark full pavers on the south side. No mortar was used below or between the bricks. They were butted tight against one another, a fine masonry sand swept between, and sealed. As thermal storage, this is 14,657 lb of brick and 66,614 lb of concrete planks. No insulation was placed under the planks so that the floor could be thermally grounded to the earth.

### 3.2 Earth Tubes

In trying to take advantage of the 68°F undisturbed (open field) deep soil temperature in this area, 530 feet of 8 inch diameter PVC pipe was put on the north, shaded side of the house as shown in Figure 2. Two 15 inch PVC pipes are run from the central plenum to just outside the north wall where each T-off to two 8" diameter pipes. These pipes serpentine the north yard dropping from 4.5 feet below ground (top of pipe) to 9 feet at the end. At this point a 3 foot cube drywell drains the condensation.

### 3.3 Walls

All exterior walls are constructed of 2 X 6 studs 24 inch on center with full batts. The outside is sheathed with one inch rigid insulation and cedar faced plywood stained. The interior is finished with 5/8" drywall. No vapor barrier was provided because of the controversy over which is the warm side in south Louisiana. All other cavities in the wall were foamed. Part of the east wall is finished with both a white and dark brick veneer to study their heat transfer (brick veneer is a popular exterior finish in this area because it is maintenance free). The air cavity behind the brick is also being tested as a ventilated wall system. There are no openings on the east and west wall, and the west wall is shaded by the carport and utility room. Wall fins, extending 2 feet out from the north wall, shade the north wall glass early in the morning and late in the evening during the summer. All windows are located on the north and south walls for ventilation, daylighting and heat gain. All glass is provided with movable insulation.

### 3.4 Roof

The south roof is constructed of 2 X 10 rafters at 24" on center with 6.5" batts between and 3/4" rigid insulation below the rafters finished with 1 X 6 tongue and groved fir. The exterior is a contiguous corrugated roof of galvanized steel or Tedlar coated reinforced fiberglass where collectors are located. The north roof is 2 X 8 rafters at 24" on center with 6.5" batts between and 3/4" rigid insulation below the rafters. The exterior is finished with a white metal roof.

The 3'-6" overhang on the south roof is made to be operable for maximum flexibility of shading or heat gain. This is accomplished by using 5 aluminum extruded louvers which span 12 feet. Three sets of these are used above glass on the south wall.

### 3.5 Collectors

Three site-built air collectors 12 feet wide by 15 feet long were constructed in the south roof over the conditioned space. This was accomplished by nailing the 1.5" flange of a sheet metal pan, with selective coating, into the top side of the rafters (see Figure 5).

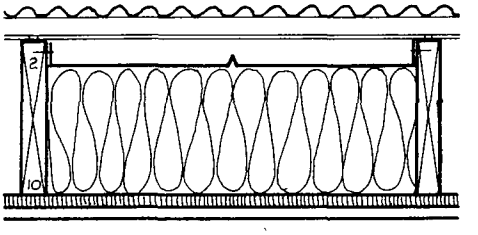



Fig. 5. Collector Detail.

The top of the rafters were glazed with Kalwall's Sun-Lite allowing for expansion and contraction. On top of that are 2 X 4 purlins on the horizontal to support the corrugated roofing.

There is a simple insulated flap at the top of the collector which can direct the heat to the outside or back to the interior. The inlet vent at the bottom of the collector has a backsyphon flap to prevent cold air in the winter from spilling back into the interior at night.

The thermosyphon water collector was built in the carport roof in a like manner. Three Olin absorber plates (2' X 8') were used in place of the sheet metal. The largest storage tank that could fit into the allocated space was a 65 gallon electric water heater with a heat exchanger. A propylene glycol-based heat transfer fluid is used in the collector.

## 4. SEASONAL MODES

The house is designed to have considerable flexibility allowing the occupant to adjust the house according to the existing ambient

conditions. A mini-computer used to take temperature readings at 130 locations in, around, and under the house for research documentation also works to help the occupant understand what is happening around the house so adjustments can be made for maximum comfort.

With 322 square feet of glass on the north and south walls, daylighting works very efficiently all year round. All wall surfaces are light in color to help distribute the daylight in the room. During the daylight hours, no lights are required in the house for most activities.

### 4.1 Spring - Fall Mode

Spring and fall are the most pleasant times of the year in south Louisiana, and it is this time that must be capitalized upon to cut down on the need for air-conditioning or heating. The two major elements to take advantage of at this time are shading and ventilation.

The house was designed for self shading (as discussed under wall and roof construction) and also takes advantage of shading from trees on the north-east and north-west sides of the site.

Close attention was paid to cross ventilation so that no heat is trapped inside the house. Some interior partitions (walls and ceilings) were designed to allow air movement even though doors are closed. This was accomplished by providing wood lattice on the clerestory wall and the south side of the ceilings of the north rooms (see Figure 4). At this time the air collectors induce ventilation by the solar chimney effect. During these times of the year the prevailing breezes are predominantly from the south. Therefore, a clerestory with operable windows are located high on the north (leeward) side. The negative pressure created at the clerestory, when a wind is blowing, works well to ventilate the house (see Figure 6). Window

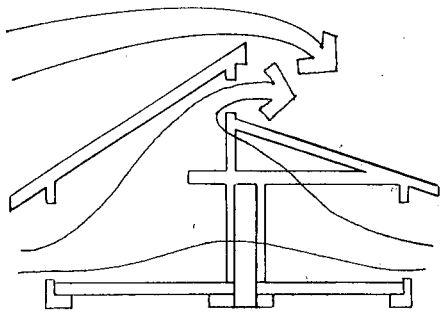


Fig. 6. Section - Spring/Fall Mode.

openings at floor level are low on the north and south walls. The house is designed to allow any heat in the house to rise up to a high point where the clerestory is located. Even on a calm day warm air will rise up through the house and exit through the clerestory windows pulling in cooler air through the lower windows on the north and south (see Figure 7). A whole-house fan is also pro-

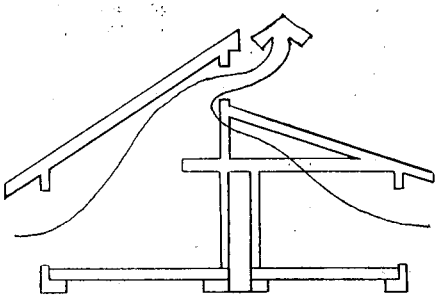


Fig. 7. Section - Spring/Fall Mode.

vided for mechanically ventilating the house. The whole-house fan works best on calm nights after the outside temperature has dropped. Ceiling fans are provided throughout the house to help with the air movement. The mass floor being thermally grounded to the earth provides a cool heat sink for the body to relate to.

### 4.2 Summer Mode

The greatest challenge presented by this project is trying to stay comfortable in south Louisiana summers with its hot temperatures and unusually high relative humidity levels. The earth tubes are designed to try and cool and dehumidify the air that is brough into the house. The earth tubes are the major research of the house while most of the other energy efficient features are more demonstration. The earth tubes are designed for testing in three situations: open loop passive, open loop active, and closed loop active.

For the use of the earth tubes in a passive situation, the house is closed up. The only openings are from the top of the air collectors to the outside, and the exterior entrance to the earth tubes in the shade of the trees on the north side of the house. The heat rising in the collector (solar chimney) creates a negative pressure on the interior thereby pulling air into the tubes from the outside (see Figure 8). Computer calculations showed a complete air change every 14-15 minutes at noon on June 21. The amount of dehumidification could not be determined, but visual inspection showed condensation flowing out of the tubes.

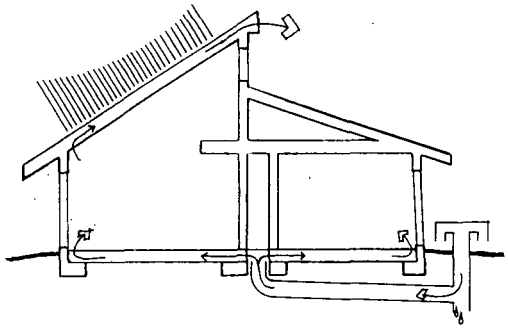


Fig. 8. Section - Summer Mode.

The earth tubes were used in two different active open loop situations. The first was to use the whole house fan. This also created negative pressure in the house while the roof collector was by-passed (see Figure 9).

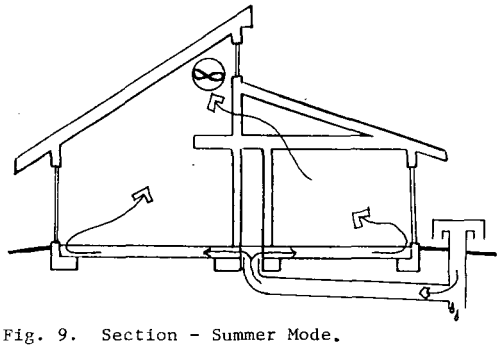


Fig. 9. Section - Summer Mode.

This provided a complete air change every 4-5 minutes. The other situation was to provide fans in the tubes. This created a negative pressure in the tubes and a positive pressure in the house (see Figure 10). This proved to be more beneficial in two ways. First it allowed the clerestory windows to be opened slightly letting stratified heat in the top of the house escape, and second it forced more air through the collectors keeping them cooler. Again the air exchange in this situation was a complete air change every 4-5 minutes.

The fans noticeably increased the efficiency of using the earth tubes. This summer the tubes will be tested in a active closed loop situation. It seems that the amount of moisture we have in the soil, and moving through the soil (54 inches of rain per year), aids significantly in taking heat away from the earth tubes. My major concern in using the

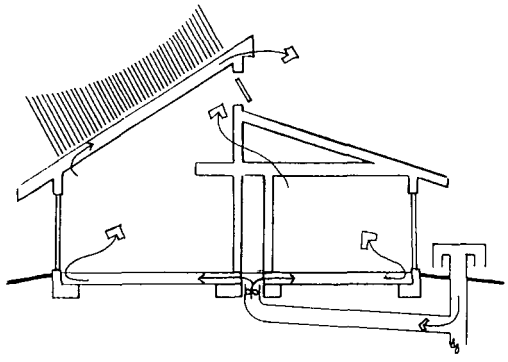


Fig. 10. Section - Summer Mode.

earth tubes is biological growth in the tubes (i.e., Legionnaire's Disease Bacteria). The entrance to the tubes are screened and filtered. At the end of the summer mode hot air from the collector is pushed through the tubes to dry them and, it is hoped, burn out any biological growth. The tubes are then flushed with a solution of one cup of Clorox per gallon of water and capped off. The air coming out of the tubes was 71°F at the beginning of the summer 1982 and warmed up to 77°F by the end of that summer. This air is distributed to the house, through the hollow core concrete planks, moving from the central plenum through the floor to out-lets along the north and south wall.

### 4.3 Winter Mode

The winters in south Louisiana are relatively mild, but some heat gain is required to stay in the comfort zone. The house is designed to receive direct gain through 175 square feet (261 MBtu/day) of south glass. This direct gain shines on dark full pavers on the south floor. There is 540 square feet (2.07 MMBtu/day) of air collector working in a passive convection loop. Heat is allowed to naturally rise to the highest point in the house where a 1/5 horsepower fan returns it to the central plenum to distribute it through the north side floor by keeping the floor vents on the south side closed (see Figure 11). The first backup system is an efficient fireplace, and the second is a small electric heater.

## 5. ENERGY AND THERMAL PERFORMANCE

The house is equipped with 130 temperature probes throughout the interior, exterior, under the floor, in the ground, and in the earth tubes. A computer is just now being installed to take readings every hour. It will be at least one year (fall 1984) before a complete analysis can be made for all four

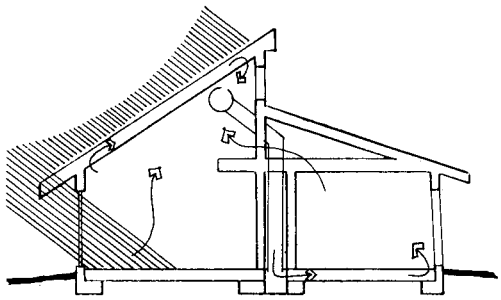


Fig. 11. Section - Winter Mode.

seasons. The house is all electric, and 5 sub-meters were installed to separate energy use. The kitchen and utility room are on one meter, all fans on another, the conventional heater on a third meter, the water heater on another, and all lights and receptacles on the other meter. There are also two hygrometers to take relative humidity readings inside and outside. Some thermometers have been placed around the house temporarily to understand interior temperatures.

The greatest energy use is in the kitchen/utility room. The occupants were allowed to equip these spaces, and they have more than taken advantage of the free utilities and rent the university allows them. In fact the occupants have no incentive to be energy conscious in the way they live and have not paid utility bills for the last 7 years that they have stayed on school property. In the first 9 months of living in the house without any heating required, they averaged 1292 kWh/mo. However, 720 kWh (56%) of that was for the kitchen/utility room which supports other than house uses. The remaining energy use was 211 kWh/mo for lights and receptacles, 198 kWh/mo for hot water, and 163 kWh for fans.

The occupants, who had never lived in south Louisiana without air-conditioning, only felt uncomfortable towards the end of the summer mode. At this time the air coming from the earth tubes had warmed up from 71°F to 77°F. The mass floor temperature at this time was 78°F, the inside air was 83°F, and the outside temperature was 95°F. I did not find the interior space uncomfortable at this time with the ceiling fans moving air. The human body relates more to the lower mass floor temperatures than to air temperatures.

Relative humidity readings vary only slightly between interior and exterior when the house is open to ventilate (spring/fall mode). The interior R.H. was only 5% lower than the exterior. However, when the house was closed in the winter mode the interior R.H. was fairly stable between 35% and 65% R.H. while exterior readings were between 30% and 100% R.H. This year will be the first opportunity to get humidity readings for the summer mode.

There are times during the south Louisiana winters that are similar to spring or summer days. At these times the house will over heat if closed up. To prevent over heating some windows are opened and the operable overhang closed. However, hot air at the top of the house is still returned and passed through the floor during these times because the nights are cold and the warmth is needed.

## 6. CONCLUSION

It is very possible to live in south Louisiana without a conventional heater and air-conditioner and remain in the comfort zone for the majority of the time. If a conventional mechanical system is used in a structure that is passively designed its use can be kept to a minimum. The mechancial system would also be much smaller. A builder's house of this size would require 2.5 tons of A/C while this house requires only 1 ton.

Malcolm Wells once said "the only head that will save water is the one that sits on your shoulders." A passively designed structure can only go so far in saving you energy. The occupants of the structure need to be energy conscious to take maximum advantage of the design.

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# FROM VERNACULAR TO DAYLIGHTING ARCHITECTURE

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## ABSTRACT

Our work started in 1976 with the rehabilitation of an ancient building in mediterranean climate. At that time, the main concern was to integrate the passive solar architecture in the socio-cultural context, e.g., Les Perdrigals. Another aspect of our work is designing greenhouses for new buildings or retrofits. In a mountain climate, a two story greenhouse will be presented. The use of sun as natural lighting and energy source is demonstrated in a partly underground single family dwelling. First example of a low cost housing program is described. Our project for the new Prefecture in Montpellier focused on extensive utilization of daylighting systems. The approach of this project will be presented.

## 1. INTRODUCTION

New technology has freed man from the constraints of his environment. He has been able to take advantage of the technological advances to improve not only his living conditions but also to escape the restrictions imposed by the environment. The result has been modern architecture which totally neglects problems of energy. Its aim has been mainly to develop standardized industrial techniques which can be applied anywhere to create an international type of architecture. Rising costs of energy may lead us to a salutary reexamination of this trend. Faced by such problems, we took a look at vernacular architecture. In the beginning, when the function of shelter was to serve only the very basic needs of life, environment was the overuling factor of the morphology of a dwelling. Physical, geographical, climatic and geological parameters were the determining factors in the choice of the type of shelter with the materials available for its construction. These various factors associated with the socio-economic and cultural characteristics of an area produced what is recognized now as regional architecture. Our first work was strongly influenced by the vernacular architecture of our region (Languedoc), and we will show then how it evolved.

## 2. LES PERDRIGALS.

Our approach for the first house, Les Perdrigals, was to take into consideration environmental and socio-economical factors. To these, we added our concern for energy conservation by looking in depth at geographic and climatic factors, (insolation, wind, temperature), including a priority for solar energy collection in our design. Analysis of the regional architecture demonstrated the following main characteristics : a- protection against the prevailing wind by the choice of orientation and morphology of the building, b- organization of outside protected areas, c- use of natural cool air systems by cross ventilations, d- seasonal internal migrations. These components were applied together with devices to optimize solar gains and minimize heat losses. The architectural result is actually very close to the regional architecture (Fig. 1).

## 3. THE SOLAR GREENHOUSE.

Another aspect of our work is designing greenhouses for new buildings or retrofits. We shall attempt to show constraints and needs to be taken into consideration when constructing a solar greenhouse by describing the steps followed in the planning and

the construction of retrofits greenhouses. Our approach is based on 3 main aspects : function, architecture and thermal control. Of these the most important is the first.

The conditions required by plants are different from those of man. Temperature and hygrometry will vary as a function of wether the greenhouse will be semi-habitable or strictly for horticulture. Therefore the first step is to define clearly the function of the greenhouse since this will greatly influence its conceptualization. Architectural design is the next important factor, because the greenhouse must be adapted to the existing building while still facing south. The morphology and aspect of the building will influence those of the greenhouse. Moreover, the choice of materials will be based on its design.

Thermal control within the greenhouse the third parameter to be studied, is not only related to the use, but also to such factors as climate. Ensuing problems are essentially overheating and cooling, ventilation, stratification and energy storage.

The "Maison du Lac" greenhouse was built as a part of the renovation of an old house. It was essentially designed for habitation. The 2 level area connects externally with the old building between the family room on the ground-floor and the living room on the first floor. The old walls, insulated from the outside (except for those directly adjacent to the greenhouse), form the storage element. The greenhouse is built from redwood with single glazing and the solid portions are insulated pressed board panels. The greenhouse does not have nocturnal insulation; fluid insulation has been considered but not implemented. Caloric input of the greenhouse is manually controlled by the inhabitants (doors, windows on both levels) (Fig. 2).

## 4. THE ANHOUR-EOLE HOUSE.

This house is a reflection of the evolution of our present research. We designed a compact plan for energy efficiency. The sun entering the house is used as a source of heating, (direct gain), and as a mean of lighting (indirect gain). The dwelling is located in a pine grove, on a south-facing slope. We took advantage of a natural clearing in which to build the house. The desire to integrate the building into its environment led to a house completely buried on the north side and partially buried on the East and West. This results in efficient protection against temperature losses due to prevailing north-west wind. The building steps down to the South which despite its compact plan allows sunlight and energy into every level of the building (Fig. 3). The house is built in cast-in-place concrete with exterior insulation. Special care has been given to the finish carpentry work, especially windows and skylights These are equipped with insulated movable shutters which reflect sun outside in the summer and inside in winter.

## 5. LOW COST HOUSING.

So far, we described individual dwellings, where motivated people, concerned about energy saving, had the necessary funds to realize their ideas. If this situation was a chance for designers to improve their skills, it nevertheless became clear rapidly that energy conscious design should cover a much larger housing market.

Well-integrated buildings using solar energy had also to be designed for low income housing. The idea was promoted by the deciders, the politics and the administration. The Office Public d'HLM de l'Aude (Public Office of Low Income Housing) has made pioneering work in that direction. They launched a program for bioclimatic low-cost housing with 3 objectives :

a- to promote the development of small clusters of low cost housing using bioclimatic design criteria, integrated to villages and towns of the administrative region.

b- to revitalize the local building trades by this new market well adapted to their structures.

c- to improve architectural and thermal quality of low cost housing. The first project we designed was for a small community and fullfilled these objectives : the rather compact building takes advantage of the south-west slope of the site. The small programm could be handled by qualified local enterprises. And the thermal characteristic of the heat losses coefficient G) is of 0.9 and that of energetic needs (coefficient B) is of 0.4, when the maximal required legal values are respectively 1 and 0.7. Direct gain systems were used, partly

as clerestory with inside automated insulated shutters. The garages are part of the building and protect entrance airlock and hall. The domestic hot water systems work on thermosyphon separately for each appartment, yet are grouped together on the south elevation (Fig. 4).

## 6. THE USE OF NATURAL DAYLIGHTING IN ADMINISTRATIVE BUILDINGS.

Studies undertaken during the last ten years for administrative buildings in Europe and the United-States have revealed that energy consumption for daylighting represents 50 to 60 % of energy costs. Artificial lighting in public buildings during the summer has the added drawback of increasing the need for air conditioning. Such findings have recently spurred the search for new systems for improving natural lighting in these buildings.

Within the context of a national contest for the design of the new Préfecture of Montpellier, our team (1) wished to apply this new concept of daylighting. We applied our research to the project keeping in mind the following goals : a- integration of urban development and environment requirements, b- keeping with the demands imposed by the overall construction project while maximizing functional potential, c- demonstration that the preferential use of bioclimatic architecture in Languedoc-Roussillon region, where solar energetic ressources are frequently overlooked, would contribute to reducing the region demands on imported energy supplies.

Architectural responses :

1 - Site integration : in the design, incorporation of variations in site configuration as the existing wooden areas (and some to be planted) protects the building from the predominant north-west and north-east winds. In addition, the design of a low and compact building recessed into the ground will help reduce heat losses.

2 - Orientation : in spite of the land configuration and orientation, building lay-out resulted in a significant portion of south elevations. This enables good winter exposure and easy protection from the sun during the summer. The east and south-east elevations presented problems for direct sun exposure and natural lighting which were solved by placing horizontal sunshadings.

3 - Light-shelves : They are architectural elements designed for capturing sunlight and controlling its way into the buildings as a function of season changes. They are designed to avoid direct lighting in working areas. In winter, the curved portion of the light-shelf reflects slightly inclined sun-ray towards the center of the building. The rays hitting the horizontal part are immediately reflected into the slanted ceiling. In spring and autumn, sunlight penetrating the center of the building remains constant but that which falls on the horizontal portion is reflected several times to decrease its intensity. During summer, heat and light are in excess and the light shelf is designated to deflect most of the incident light towards the outside, (Fig. 5).

4 - Light-passageways : they are created by a centrally located passageway in each building and covered by a transparent vault. They provide the main communicating passage which links the ground-floor of the various buildings to the vertical axes of circulation (i.e., staircases, elevators). Reflectors from the light-passageways provide natural light for the central areas of the building. In winter, warm air statified in the upper part of the light-passageway is recovered and blown into the slab between the ground-floor and the first floor, thereby conserving excess calories. During summer, large openings in the transparent vault produce rapid evacuation of heat from the building by natural convection. Efficiency was enhanced by thermo regulation offered by the massive concrete structure of the light-passageway which also can be ventilated at night to discharge excess heat from the building (Fig. 5)

Design tools :

The design of the windows on south, east and west elevations and their solar protection was based on graphic studies using the angle of iso-transmission and the tracings of the obstructions on the sun's course at the given latitude. This resulted in hourly and monthly recordings of direct energy transmitted during a theoretical day (clear sky conditions). The light shelves were designed after a complete review of the state of art in natural lighting (2).

This was followed by a trial study using a 1/50 model of building. This model was useful in determining the

configuration of the building, i.e., the central patio, its covering and the office space. This was analyzed to ensure the compatibility with the available height beneath the floors, the slope of the ceiling and the exterior projection of the south wall light-shelf. Test trials were performed under natural sky conditions.

For accurate determination of heating and air conditionning needs and a precise prediction of energy consumption, we used the american CALECO-DOE 2 program presently available in France. This program seemed the most suited for simulating large buildings and public buildings. It responds to changes in the internal load (people, lighting equipment) and intermittent use of such buildings. The simulation has shown that approximately 50 % of the building needs are supplied by solar energy in form of direct gain and daylighting for the winter season. No air conditionning equipment is needed for the office space except those with special equipment.

## 7. REFERENCES.

(1) The SOLERGIE team, architects : Blanc, Dauvergne, Rigaill, Rey, Caremoli, Miramond, Gerber, Pous, Wursteisen, Knyszewski.

(2) Proc. of the 6th National Passive Solar Conference, (1981), Vol 6, Eds. Hayes J. and Kolar W., ASES, U.S.A.

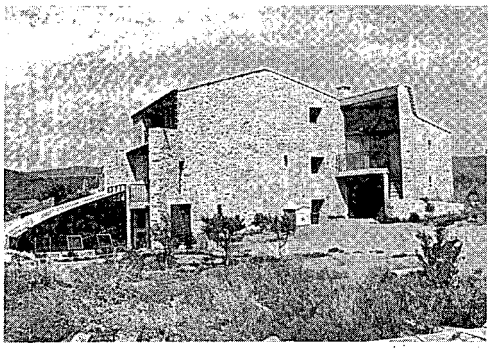


Fig. 1. Les Perdrigals, View from East

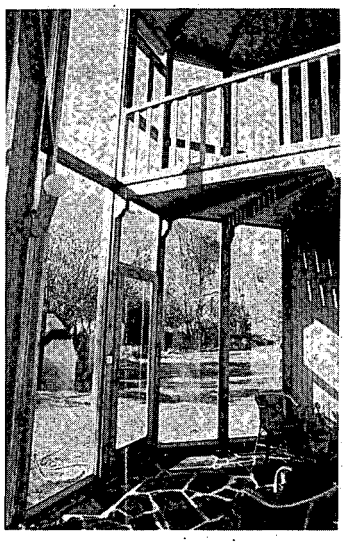


Fig. 2. Maison Du Lac, Interior

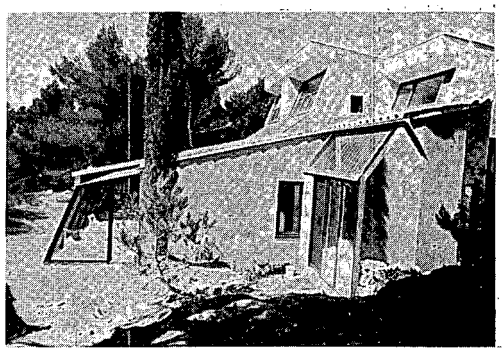


Fig. 3. The Auhour Eole House

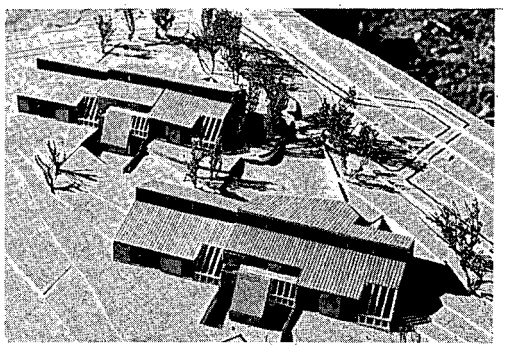


Fig. 4. Low Cost Housing Project

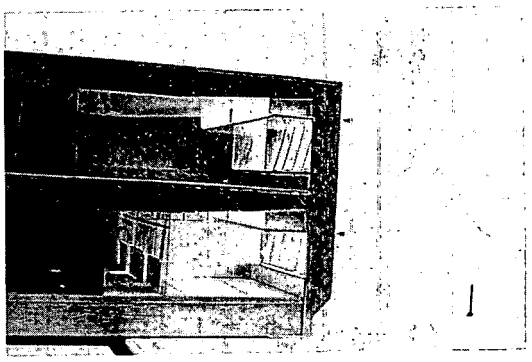


Fig. 5. View of Simulation - Model

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# VALIDATION OF ENERGY SIMULATION MODELS FOR BUILDINGS WITHIN THE IEA SOLAR HEATING AND COOLING PROGRAMME, TASK VIII PASSIVE AND HYBRID SOLAR LOW ENERGY BUILDINGS

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## ABSTRACT

Within Task VIII, "Passive and Hybrid Solar Low Energy Buildings" of the IEA Solar Heating and Cooling Programme, one of the subtasks focuses on Energy Simulation Models for Buildings. Up to now a survey of these models has been completed and a validation programme undertaken. The survey provided detailed information on 29 simulation models. The validation programme encompasses model-to-test cell validation and model-to-model comparisons of the three basic passive designs (Direct Gain, Trombe-wall and Attached Sunspace) on three different climates.

## 1. INTRODUCTION

Subtask B, Modelling and Simulation, is one of five subtasks that constitutes the international cooperative project: Passive and Hybrid Solar Low Energy Buildings within the Solar Heating and Cooling Programme of the International Energy Agency (IEA), (1). The objectives of the subtask are to increase the capability of the participants to accurately predict and analyse the performance of Passive and Hybrid Solar Low Energy Buildings.

A number of activities has been defined to accomplish these objectives:

1. Survey of existing simulation models.
2. Validation of a selected number of models
3. Support to the evaluation of design tools
4. Analysis of innovative designs.

The work commenced in mid-1982. Since then activity no. 1 has been completed and for activity no. 2 a strategy has been worked out and partly completed.

## 2. ANALYSIS MODEL SURVEY

In almost all of the member countries of the IEA Programme one or more computer programs for a thermal analysis of Passive and/or Hybrid Solar Low Energy Buildings have been developed.

The purpose of surveying these models is to establish an overview of the analysis capabilities, validation experiences, availability, intended use, input data, calculation procedures and output results.

A survey form was developed and a total number of 29 completed forms have been compiled and analysed. A report will be published in November 1983.

## 3. MODEL VALIDATION

The creation and use of large computer programs imply many possibilities for errors: Physical and mathematical errors, logical errors, programming errors and user errors. To the last category can be added the use of the program outside its range of applicability. Recognizing this, the validation programme of this task does not aim at reaching a Utopian goal of claiming the selected programs to be "validated", but merely to establish confidence in the use of these programs. Many of the programs are either new programs or programs under development, and especially for these programs the adopted strategy allows for an early check to eliminate major errors.

### 3.1 Validation Strategy

Actual validation studies in the sense of comparing the results of the computer analysis models to measured data from test cells, test buildings or standard houses were surveyed at a working group meeting in July 1982.

The validation experiences with the programs were surprisingly limited. Even for Direct Gain test cells only four studies were reported. The primary reason for this was claimed to be lack of adequate performance data.

On the basis of this survey a validation strategy was formulated and agreed to by the participants.

The strategy is a three-step approach on the three basic passive designs (Direct Gain, Trombe-wall and Attached Sunspace). First step is validation on test cell data. Second step is model-to-model comparisons on the same test cells simulated over one year in three different climates. Third step is model-to-model comparisons on the same three designs incorporated in real buildings and simulated under the same three weather conditions.

### 3.2 Test Cell Validation

Three different test cells were selected to provide data for the validation of the models. For Direct Gain a test building monitored by the National Research Council of Canada was chosen. The test building is a 3 by 9.5 m massive building with two rooms and a door and a fan between the rooms. The aperture area of the south window is 2.6 $m^2$.

The Trombe-wall test cell is located in the southern part of Switzerland. It is a 2.9 by 2.5 $m^2$ cell with an aperture area of 5 $m^2$.

The Attached Sunspace test cell chosen is one of the test cells of the U.S. Los Alamos National Laboratory. This cell has a 5 $m^2$, 60° sloping glazing pane in front of two small rooms, each of 3.5 $m^2$. There is a door for natural convection between the sunspace and one of the rooms and another door is connecting the two rooms.

Preliminary results from the Direct Gain validation work have been presented by five task experts. The agreement between the model results and the measured data was rather good. Auxiliary energy for heating was calculated to within 10% of the measured value and the dynamic behaviour of the building was tracked quite well by the models. Results on the Attached Sunspace have been presented by four modellers. The fact that this is a more complicated structure shows up in a less good agreement. Auxiliary heating was predicted to within 20% of the measured value for the considered fourteen-day period.

### 3.3 Model-to-Model Comparisons

After having finished the validations of the model against the test cell data, the models are run on a one-year weather data file using exactly the same input data file as for the validation work. Thus the results of the models can be mutually compared for a longer time period. Results are not yet available.

The last step in this model evaluation procedure is the modelling of the three basic passive concepts incorporated in single-family houses. The simulations are performed under the same weather conditions as before and with the same models.

In short, this can be considered as an extrapolation in time followed by an extrapolation in systems.

## 4. FUTURE WORK

After the completion of the validation work, the participants will be modelling the performance of typical buildings to evaluate various design alternatives. A series of focused parametric studies will be performed, the results of which will be presented in the form of curves and tables in a handbook produced by subtask C.

In each country a passive and hybrid solar building will be developed. These designs will be evaluated by using the simulation models before entering into the construction phase.

## 5. ACKNOWLEDGEMENT

The task is an international cooperative effort and as such has to cope with the inherent difficulties which long distances create. However, because of the interest and engagement shown and the amount of work already carried out by the participants of this subtask, I have all reasons to believe that the entire work plan of this subtask will be successfully completed.

## 6. REFERENCES

(1) Holtz, M. (1982). IEA Task VIII: Passive and Hybrid Solar Low Energy Buildings. International Solar Architecture Conference, Cannes.

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0731-8626/83$3.00

# INTERNATIONAL ENERGY AGENCY TASK VIII: DESCRIPTION AND SELECTED RESULTS

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## ABSTRACT

This paper discusses the background and results achieved to date of an International Energy Agency Solar Heating and Cooling Program Task on Passive and Hybrid Solar Low Energy Buildings. Task objective, approach and participants are presented as well as results from two international surveys on simulation models and design tools. Conventional reference buildings are described representative of typical design and construction practice in each participating country. Climate similarities are compared through a simple graphic technique. Work in progress is briefly discussed.

## 1. INTRODUCTION

The International Energy Agency Solar Heating and Cooling Program undertakes cooperative research, development, demonstration and exchanges of information in order to advance the activities of member countries in the field of solar heating and cooling.(1,2) Ten research tasks have been approved by the Executive Committee since December 1976 with seven tasks currently active. In October 1981 the Executive Committee approved Task VIII entitled Passive and Hybrid Solar Low Energy Buildings. Table 1 lists the participating countries.

TABLE 1: Task VIII PARTICIPATING COUNTRIES

| | |
|---|---|
| Austria | New Zealand* |
| Belgium | Norway |
| Canada | Spain |
| Denmark | Sweden |
| F.R. Germany* | Switzerland |
| Italy | United Kingdom* |
| Netherland | United States |

*Participation not confirmed as of 1 June, 1983.

## 2. TASK OBJECTIVE

The overall objective of Task VIII is to accelerate the development and use of passive and hybrid heated and cooled low energy buildings in the participants' countries. This will be done, in general terms, by:

(1) Increasing the understanding of the design and performance of buildings using active and passive solar and conservation technologies, the interactions of these technologies, and their effective combination in various climatic regions; and

(2) Verifying that passive and hybrid solar low energy buildings can substantially reduce the building load and consumption of non-renewable energy over that of conventional buildings while maintaining acceptable levels of year-round comfort.

The present Task scope includes only new residential single family and multi-family buildings. The participants may, at a later date, choose to expand the scope to include commercial buildings. The current schedule calls for the work to be completed over four years.

A unique aspect of Task VIII is its emphasis on integrated active and passive solar systems, so called hybrid systems, combined with energy conservation techniques and advanced mechanical and electrical systems into optimized energy efficient dwellings. The underlying intent of Task VIII is to gather, organize, evaluate, apply and share the current body of knowledge on passive and hybrid solar low energy building design and construction. As the Task is structured, it combines applied research in performance testing and modeling with design tool development and building design, construction and evaluation.

New research on integrated systems analysis and design will also be conducted during the course of Task VIII activities. The research results are designed to provide the home-building industry in each participants' country with the understanding, experience and tools to apply current knowledge of passive and hybrid techniques to current design and construction problems.

## 3. APPROACH

Task VIII is organized into five major Subtasks, each coordinated by a lead country (Lead Country):

| | |
|---|---|
| Subtask O: | Technology Baseline Definition (U.S.A.) |
| Subtask A: | Performance Measurement and Analysis (Switzerland) |
| Subtask B: | Modeling and Simulation (Denmark) |
| Subtask C: | Design Methods (U.S.A.) |
| Subtask D: | Building Design, Construction and Evaluation (Holland) |

Subtask "O" establishes a technology baseline in terms of cost and performance of a conventional reference building from which to compare the results (improvements) obtained from designs developed during Task VIII research. Also, candidate passive and hybrid solar and energy conservation techniques and cost/performance goals are identified in Subtask "O." Subtask "A" collects, analyzes and reports performance data on passive and hybrid solar techniques for comparison against simulation results (validation studies of Subtask "B") and for characterizing system performance parameters. Common measurement procedures for monitoring passive and hybrid solar low energy buildings are to be developed within this Subtask.

Subtask "B" will evaluate the capabilities, accuracy, and limitations of current building energy analysis simulations and conduct parameter studies to understand the design and integration issues of passive and hybrid systems. The results of this Subtask are used in preparation of the design handbook. Subtask "C" will survey and evaluate available passive/hybrid design tools, develop new or improve existing design tools and prepare a Passive and Hybrid Solar Low Energy Building Design Handbook. Subtask "D" will design, construct and evaluate a state-of-the-art passive and hybrid solar low energy building(s) based upon the research results and information obtained from Subtasks "O," "A," "B," and "C."

The primary results of the Task are to be:

(1) IEA design and construction handbooks for passive and hybrid solar low energy buildings;
(2) Exemplary passive and hybrid solar low energy buildings designed, construction and evaluated; and
(3) Technical reports on performance measurement, design tools, simulation models, validation tests, parameter sensitivity studies, etc...

## 4. RESULTS ACHIEVED TO DATE

The Task was formally initiated in February 1982 when the first experts meeting was held. Since this time two other working group meetings have been held. Results are presented in the following areas: reference building documentation, climate comparison documentation, simulation model survey, and design tool survey.

### 4.1 Reference Building Documentation

Each participant was to document in a standard reporting format a conventional "reference" building that would be the basis of comparison for passive and hybrid solar low energy building designs developed during the Task. In this manner, improvements in energy efficiency and energy consumption of the passive and hybrid building could be evaluated against the conventional reference building. The reference building was to be "typical" of standard design and construction practice and represent the largest housing type of this country.

Table II shows location and climate information for each country's reference building. Table III shows selected characteristics of the reference building.

### 4.2 Climate Comparison Documentation

The climates of representative cities within each participating country have been compared through the use of a graphic technique that plots key climatic variables. Of primary concern was a reasonable correlation between climatic variables and residential energy consumption. Research at the Los Alamos National Laboratory (3) and the Solar Energy Research Institute (4) has shown good correlation between residential energy consumption and the ratio of solar radiation incident on a south facing vertical surface to the degree day heating load during the heating season.

Figure 1 shows a plot of the ratio of the solar radiation on a south facing vertical surface to the heating degree days for the month of January. A constant 18.0°C Base has been used to determine the number of heating degree days. The diversity of climate is readily apparent. Figure 2 plots the ratio of solar radiation on a

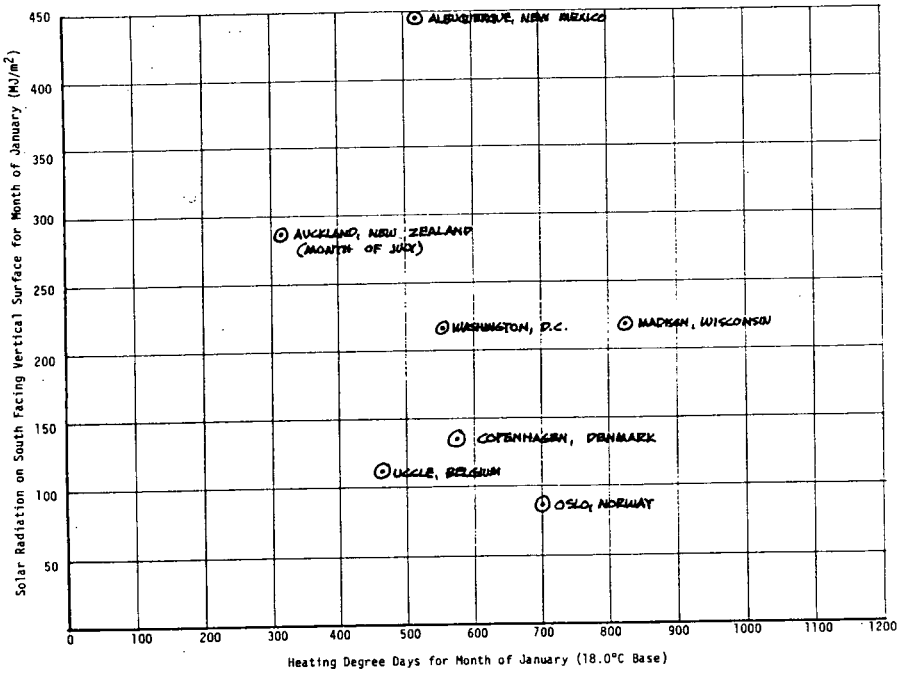



Fig. 1. Ratio of Solar Radiation on Vertical Surface to Heating Degree Days for the Month of January

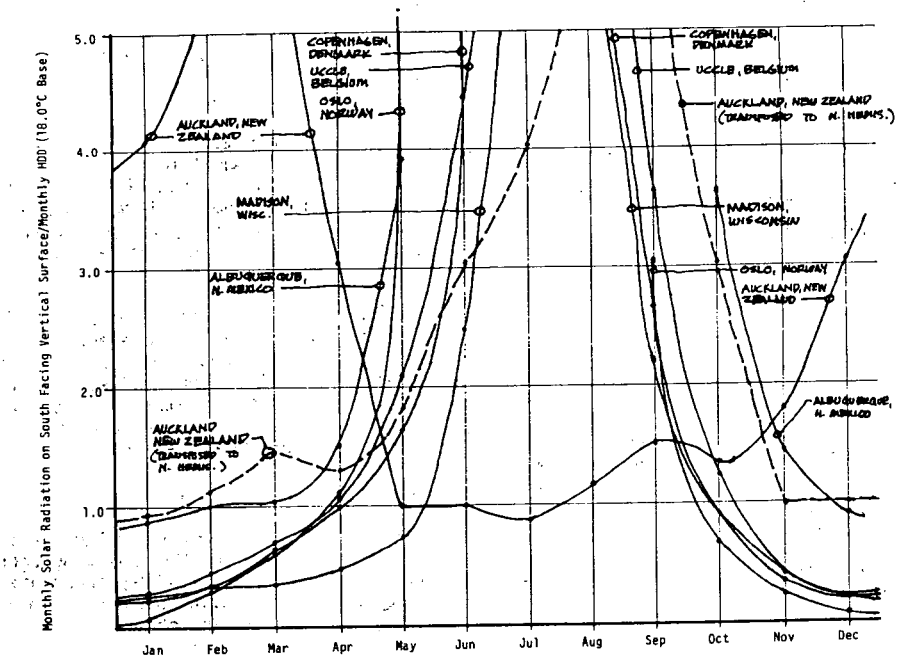



Fig. 2. Ratio of Solar Radiation on Vertical Surface to Heating Degree Days by Month

TABLE 2. REFERENCE BUILDING LOCATION/CLIMATE SUMMARY

| COUNTRY | LOCATION | LATITUDE | HDD (BASE-C°) | CDD (BASE-C°) | GLOBAL RADIATION ON HORZ. SURFACE (MJ/M²) |
|---|---|---|---|---|---|
| AUSTRIA | | | | | |
| BELGIUM | | | | | |
| CANADA | OTTAWA | 45° N | 4673 (18) | 242 (18) | 4806 |
| DENMARK | COPENHAGEN | 55° N | 3091 (17) | - | 3676 |
| F.R. GERMANY | | | | | |
| HOLLAND | DEBILT | 52° N | 2903 (18) | - | 3318 |
| ITALY | | | | | |
| NEW ZEALAND | AUCKLAND | 41.28°S | | | |
| NORWAY | TRONDHEIM | 63.25°N | 4003 (17) | - | 2990 |
| SPAIN | | | | | |
| SWEDEN | STOCKHOLM | 59.15°N | 4232 (17) | - | 3538 |
| SWITZERLAND | ZURICH | 47° N | 3230 (18.3) | - | 4313 |
| U.S.A. | | | | | |
| 1. | ALBUQUERQUE | 35° N | 2500 (18.3) | 600 (18.3) | 8030 |
| 2. | MADISON | 43° N | 4000 (18.3) | 400 (18.3) | 5037 |
| 3. | WASHINGTON | 38.5°N | 2600 (18.3) | 600 (18.3) | 5110 |
| U.K. | | | | | |

TABLE 3. REFERENCE BUILDING SUMMARY

| COUNTRY | BUILDING TYPE | FLOOR AREA (M²) | VOLUME (M³) | HEATING DESIGN LOAD (MJ) | OVERALL HEAT TRANS. COEFF. (W/M² °C) | INFILT. RATE (ACH) | INTERNAL GAINS (MJ/DAY) | TOTAL COSTS (U.S. $) |
|---|---|---|---|---|---|---|---|---|
| AUSTRIA | | | | | | | | |
| BELGIUM | | | | | | | | |
| CANADA | S.F.D. | 310* | 860* | 83,000 | 0.25 | 0.25 | 100 | 105,000 |
| DENMARK | S.F.D. | 140 | 320 | 43,000 | 0.60 | 0.63 | 64 | - |
| F.R. GERMANY | | | | | | | | |
| HOLLAND | S.F.D. | 110 | 330 | 40,000 | 0.90 | 1.0 | 54 | 93,000 |
| ITALY | | | | | | | | |
| NEW ZEALAND | S.F.D. | 104 | 252 | - | - | - | - | 34,000 |
| NORWAY | S.F.D. | 109 | 260 | 55,000 | 0.22 | 0.50 | 42.5 | 63,500 |
| SPAIN | | | | | | | | |
| SWEDEN | S.F.D. | 137 | 314 | 68,400 | 0.78 | 0.10 | 68 | 82,000 |
| SWITZERLAND | | | | | | | | |
| 1. | M.F. | 96 | 257 | 23,000 | 0.72 | 0.3 | 63 | 110,000/Un |
| 2. | S.F.A. | 154 | 416 | 47,000 | 0.50 | 0.3 | 72 | - |
| 3. | S.F.D. | 144 | 414 | 60,000 | 0.16 | 0.3 | 72 | - |
| U.K. | | | | | | | | |
| U.S.A. | | | | | | | | |
| 1. | S.F.D. | 222 | 541 | 33,000 | 0.39 | 0.35 | 56 | 90,000 |
| 2. | S.F.D. | 222 | 541 | 33,000 | 0.39 | 0.35 | 56 | 90,000 |
| 3. | S.F.D. | 222 | 541 | 33,000 | 0.39 | 0.35 | 56 | 90,000 |

S.F.D. = Single Family Dettached
S.F.A. = Single Family Attached
M.F. = Multi-Family

*Includes area and volume of basement

vertical surface to heating degree days for each month of the year. The general shape of the curves are similar with variations occurring during swing seasons of fall and winter. The Auckland, New Zealand data has been plotted for both actual southern hemisphere conditions and transposition to northern hemisphere conditions. The shape of both curves are substantially different from the others. The fall and spring seasons occur a month or more later than in northern hemisphere climates, typical of a coastal climate.

## 4.3 Simulation Model Survey

A survey was conducted as part of Subtask "B" to identify existing computer models for passive and hybrid techniques. The survey questionaire was designed to obtain an overview of existing analysis programs; their capabilities, limitations, equipment requirements and intended users. The results of the survey will be used to select representative models that will undergo evaluation/validation by the participants.

Fourteen models from six countries have been documented.(5) All of the models but one have been developed for mainframe computers. Eight of the programs have been developed primarily for research purposes while six are designated as all purpose programs. Adequate documentation is available for only eight of the programs. The reported set-up time varies between half a man day and two man days.

The capability of each program to model passive and hybrid techniques is not clear from the survey results. Five of the programs - Encore/Canada, BA4, HAUSER, Byvok and Encore - appear to be able to model only a direct gain house. The remainder of the programs claim the ability to model direct gain, Trombe walls and sunspaces. Three of the programs can handle a single-zone building, four of the models 2-10 zones, two models from 10-25 zones and five models more than 25 zones. Only BLAST and DOE 2.1 have subroutines built in for economic calculations. Lighting and DHW systems are modeled by only five of the programs.

All of the programs can calculate heating loads and space temperatures. HVAC equipment is handled by seven of the programs, active solar systems by three, shading by ten, underground loads by nine and thermal mass by twelve. Four programs cannot calculate cooling loads.

Five programs use the response factor method, one uses a finite element method and the rest are based on finite differences. Five of the models use a simple Euler integration and three an implicit method. One model is capable of using any integration technique desired.

## 4.4 Design Tool Survey

A survey was conducted as part of Subtask "C" to identify available building energy design tools.(6) The survey questionaire was designed to obtain an overview of each design tool, including phase of design for which the tool is suitable, initial investment, operating cost, ease of use, range of applications, calculation method used, and type/number of inputs required.

The results of the survey provide a glimpse of the state-of-the-art as well as a useful guide to building designers in better understanding available design tools.

Table IV summarizes the design tools by country and the major equipment. One hundred and fifty-six (156) design tool survey questionaires were returned from seven countries. 30% of the design tools were developed for mainframe computers, 30% for microcomputers and only 18% for programmable calculators. The remainder are manual methods. This illustrates a dramatic rise since 1980 in the use of microcomputers.

TABLE 4. DESIGN TOOLS BY COUNTRIES AND THE MAJOR EQUIPMENT

| Participating Countries | No. of Tools | % of Total Main-frame Computers | No. of Tools | % of Total Micro-computers | No. of Tools | % of Total Programmable Calculators | No. of Tools | % of Total Manual-Methods |
|---|---|---|---|---|---|---|---|---|
| CANADA | 2 | 4% | 3 | 6% | 0 | 0% | 3 | 9% |
| DENMARK | 0 | 0% | 1 | 2% | 1 | 3% | 0 | 0% |
| ITALY | 1 | 2% | 1 | 2% | 0 | 0% | 4 | 12% |
| NETHERLANDS | 2 | 4% | 1 | 2% | 0 | 0% | 1 | 3% |
| NORWAY | 1 | 2% | 1 | 2% | 1 | 3% | 1 | 3% |
| SWITZERLAND | 7 | 15% | 4 | 8% | 5 | 18% | 5 | 15% |
| U.S.A. | 34 | 73% | 36 | 76% | 22 | 76% | 19 | 57% |
| TOTAL | 47 | 100% | 47 | 100% | 29 | 100% | 33 | 100% |

Total Number of Design Tools = 156

The majority of design tools in all equipment categories were developed for architects and engineers. The greatest percentage of design tools were developed for heating calculations (84%); followed by cooling (45%); service hot water (42%); lighting (37%); and miscellaneous equipment (16%). Also, the majority of the design tools have been developed for "skin-dominated" residential and small commercial buildings.

Of the 156 design tools surveyed, 70% are for the Schematic Design Phase, 52% for the Design Development Phase, 47% for Pre-Design, 20% for Post Design Services and only 14% for Research. However, only 7% of the mainframe tools are suitable for Pre-Design, while 21% of mainframe tools are appropriate for the Design Development Phase. Microcomputer-based design tools appear to be suited to all phases of building design. Again, the majority of design tools for all building design phases were applicable to residential and small commercial buildings.

Design tools for passive systems relied primarily on the Solar Load Ratio correlation or thermal network/finite difference approach to the solution technique. A smaller percentage of passive design tools used the response factor solution technique.

Several other conclusions which emerged from the survey results are:

- a general lack of validation against measured performance data for all design tools surveyed;
- very few simplified tools for cooling calculation;
- very few design tools exist for large commercial buildings in all phases of building design;
- the microcomputer is growing rapidly as the most common design tool; and
- run cost and input set-up time varies considerably with complexity of design and skill of tool user.

## 5. WORK IN PROGRESS

The work completed to date and reported in this paper was done in support of research now in progress. Considerable work is still to be done including the primary research and design tasks. The most significant work in progress is documentation of performance results, simulation model validation, design tool evaluation and integrated system design research.

### 5.1 Performance Data Reporting

Performance data from monitored passive and hybrid solar low energy buildings and test facilities are being documented at three levels of detail. The first documents sources of passive/hybrid system performance data and includes a description of the building, its energy systems, and performance monitoring equipment. It is designed to enable the reader to determine if the data are appropriate for his/her use. The second level of reporting is concerned with passive/hybrid system characterization. It will provide sufficient thermal performance data on a particular building or test facility to describe the typical thermal characteristics/response of its passive or hybrid design features.

The third level of reporting is highly detailed for purposes of simulation model validation. Only data from highly controlled, highly instrumented buildings or test facilities are reported. The quality of the data must be very good so that comparison to model predictions is possible and credible.

### 5.2 Simulation Model Validation

To establish confidence in selected simulation models surveyed and proposed for use by the participants, three validation exercises have been developed. The first two exercises rely on the use of empirical

data (from Subtask "A" level three reporting) for comparison to model predictions. The third exercise relies on model to model comparisons by varying parameters away from the test buildings. Each participant has selected one or more models to validate. Two test facilities have been chosen for the first validation test. The first is a sunspace test room located at Los Alamos National Laboratory, New Mexico. The second is a direct gain house located in Ottawa Canada. Both facilities are unoccupied test structures designed and instrumented specifically for validation of simulation models.

Each participant has been given a detailed building description and a limited data set. A standard set of parameters and a standard reporting format have been developed for documenting the predicted performance of the test buildings. Based upon the agreement between measured and predicted performance, the simulation models will be modified and subjected to further empirical and analytical tests. The ultimate purpose is to establish a "reasonable" level of confidence in the simulation models to accurately predicted changes in performance based on changes in building design. Models that achieve this level of accuracy/confidence will be used to perform parametric sensitivity runs on key passive/hybrid design features. These results will be incorporated into the Design Handbook prepared in Subtask "C."

### 5.3 Design Tool Evaluation

An activity similar to the model validation exercise will be performed for a limited number of design tools selected from those surveyed. However, in addition to concerns of technical accuracy of energy predictions, will be a careful evaluation of ease of use, appropriateness to building design phase, cost of use and other design tools use attributes. A test home will be documented at two levels of specificity - schematic design and design development. Design tools appropriate to each level will be selected by the participants and used to analyze the test home. Complete documentation will be kept of the experience in using the design tool as well as the resultant energy consumption prediction.

This procedure should lead to the first rigorous evaluation of the major passive/hybrid design tools.

### 5.4 Integrated System Design Research

Each participant is presently preparing a topical report describing the status, problems and opportunities of integrated residential energy systems within their country. The report will describe existing projects, their energy performance, and any problems of integrating the passive, active or hybrid solar techniques with the energy conservation and mechanical system features. The purpose of this effort is to identify the research that needs to be addressed by other parts of the Task VIII research effort.

## 6. CONCLUSION

IEA Task VIII represents a bold, innovative experiment to link, both nationally and internationally, solar researchers with design practitioners for the purpose of developing and accelerating the use of an important energy technology. To date, the program has been very successful and this researcher-designer partnership has proved of benefit to both parties. It is vital to the long term energy savings of all participating countries that this partnership remain after the completion of this Task.

## 7. ACKNOWLEDGEMENTS

The author is indebted to Dr. Fred Morse and Mr. Robert Holliday of the U.S. Department of Energy for their support of this program. Also, the author would like to thank Mr. Ove Jorgensen of Denmark and Mr. Richard Rittelmann of the U.S.A. for use of results from their reports on the model and design tool surveys.

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# COMPARISON OF DESIGN TOOLS: CARRIED OUT BY MEMBER COUNTRIES OF THE EEC

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## ABSTRACT

Of the main frame and mini computer models examined, ESP and SUNCODE were found most appropriate for the design of passive solar dwellings in Europe. ESP will be developed further within the EEC Passive Solar Programme and SUNCODE within the UK National Programme. Of the small models, SPIEL, LANL III, CASAMO and Methode 5000 were recommended.

## 1. INTRODUCTION

In 1981 the Commission of the European Communities set up a group with members from eight countries to make recommendations concerning numerical design methods for passive dwellings to be used in Europe. The complete Report (1) will be published in late 1983, and this paper represents only the views of the UK member. Criteria described below were used in a survey of about 50 design tools, to select short lists in each of three categories: mini or main-frame methods, methods running on micros and manual methods. Short listed programs were then independantly used by at least two members of the group in order to make a final selection.

## 2. MINI AND MAIN-FRAME MODELS

The eight members of the group polled the research communities in their own countries and listed 25 large programs. It was quickly apparent that most could be immediately rejected for European-wide use, for these practical reasons:

-lack of complete documentation (eliminated 12 programs);
-strong machine dependancy or non-standard language (e.g. CDC specificity, and packed Fortran, eliminated 2 programs);
-ease of commissioning (eliminated 6 programs);
-ready availability (eliminated all programs running only on bureau service).

When the facility to address most of the common passive solar designs was added to the list of constraints, only five programs survived: SUNCODE (identical to SERIRES)(2); DEROB(3); ESP(4); MORE(5); and LPB-1(6). Table 2 lists some of the qualities of these models. A major obstacle to the widespread use of such models, even in research environments or highly motivated design offices, arises because many programs deal with few of the six or so types of passive technique (e.g., LPB-1, which was excluded on those grounds); or deal with them only after extensive juggling by the user (e.g.,ESP). Thus ESP, which is a highly complex finite difference model comparable in its detailed handling of visible and thermal radiation with DEROB, can be made to simulate all the passive systems of Table 1; but unlike for example SUNCODE, it does not yet prompt the user to enter details relevant to a mass wall, sunspace etc. Users have found DEROB very expensive to run, and MORE only has Italian documentation and thus both models were excluded. ESP and SUNCODE were further compared using these five tests:

1. Response to a step change in ambient temp.
2. Annual auxiliary heat load of a glazed 1 m cube.
3. Annual auxiliary heat load of a LANL direct gain test cell.
4. Hourly temperature predictions in June and January for the 1 m cube.
5. Hourly temperature predictions in June and January for the LANL test cell.

Comparisons were not made with measured data. Figure 1 illustrates the monthly auxiliary heating predicted for a heavily glazed, heavy weight, LANL cell, driven with hourly Danish weather. ESP was used totally independantly by its author (Clarke) and at PCL (Littler). SUNCODE was used independantly at PCL (Littler and Lebens). Table 1 summarises the annual auxiliary for tests 2 and 3.

TABLE 1. PREDICTED ANNUAL HEATING LOAD IN kWh

| | LANL cell | 1 m cube |
|---|---|---|
| ESP | 1100 | 240 |
| ESP | 1160 | 225 |
| SUNCODE | 920 | 325 |
| SUNCODE | 870 | 380 |

TABLE 2. MAINFRAME AND MINICOMPUTER MODELS

| NAME OF PROGRAM | LPB-1 | MORE | ESP | DEROB | SUNCODE |
|---|---|---|---|---|---|
| INPUTS | | | | | |
| Building description (N=numeric, G=graphic) | N | N & G | N & G | N | N |
| Building data alteration (I=interactive, N=completely new input) | I | I | I | I | I |
| Climatic data | | all use | files | from disc | |
| Support of climatic data | | all use | tapes | | |
| Human data: occupancy patterns | yes | yes | yes | yes | yes |
| Data to assess comfort | yes | yes | yes | yes | yes |
| PASSIVE SOLAR DESIGNS | | | | | |
| Solar : separate diffuse and direct ? | yes | yes | yes | yes | yes |
| ground reflected ? | yes | yes | yes | yes | yes |
| Systems: E=explicitly modelled | | | | | |
| I=user must create passive design | | | | | |
| Direct gain | E | E | E | E | E |
| Sunspace | E | E | E | E | E |
| Trombe wall | yes | yes | I | E | E |
| Mass wall | yes | yes | I | E | E |
| Roof pond | no | no | I | - | no |
| Water wall | no | no | I | - | E |
| Thermosiphon | no | no | I | - | no |
| CALCULATION DETAILS | | | | | |
| Building: Number of zones | 20 | 20 | 10 | 9 | 10 |
| Auxiliary heating system: | | | | | |
| inertia included ? | no | yes | yes | no | no |
| efficiency ? | no | yes | yes | no | no |
| Climate : Shading (m=monthly, h=each time step) | h | h | m | m | m |
| Movable insulation (dn=twice/24 hours) | | | | | |
| inside | no | no | h | dn | dn |
| outside | no | no | h | dn | no |
| Time step (h=hourly, a=annually) | h,a | h,a | h,a | h,a | h,a |
| Comfort : Mean radiant temperature calculated? | yes | yes | yes | yes | no |
| Stratification of air | no | no | no | no | no |
| Air movement between zones | no | no | yes | yes | yes |
| OUTPUT | | | | | |
| Type : Room air temperature | yes | yes | yes | yes | yes |
| Heating and cooling loads | yes | yes | yes | yes | yes |
| Energy consumption | yes | yes | yes | yes | yes |
| a=annual, m=monthly, d=daily | all | all | all | all | all |
| Format : Numeric tables | yes | yes | yes | yes | yes |
| Graphs | no | no | yes | yes | no |
| COMPUTER DEMANDS | | | | | |
| Hardware: Mainframe=l, mini=m | l | l | l | l | l/m |
| K words to run | 600 | 360 | 200 | 77 | 59 |
| Language (F=Fortran) | F | F | F | F | F |
| SOFTWARE PURCHASE COST | 0 | 0 | £5000 (1) | $500 (2) | $1500 (3) |

(1) ESP has graphic input via BIBLE which must be purchased separately
(2) DEROB has output graphics which must be purchased separately
(3) SUNCODE costs $1500, SERIRES is public domain

The small discrepancies between runs on the same model arise from user assumptions made during input. Models always need some judgements on the part of the user (for example SUNCODE requires an estimate of the amount of solar radiation reflected out of zones). In other words, although the details of the test buildings were described exhaustively, the building description files used by the two models varied widely depending on the whim of the code-author. The discrepancies between ESP and SUNCODE are much more serious. They probably stem from variations in parameters such as wall heat transfer coefficients, which are input variables in SUNCODE and calculated in ESP. Clarke for example (1) finds for January that the ESP prediction of annual auxiliary energy in the LANL cell rises from 163 to 180 kWh if combined radiative and convective coefficients are hard-wired at values of 7.2, 10 and 8.7 $W/m^2K$ for walls, floor and roof. Unfortunately of course, the values calculated rely on literature relationships between h and air-speed etc. which may well not be reliable. Similarly if wall areas are calculated using external rather than internal dimensions, the January load rises from 163 to 231 kWh. (Like most models ESP assumes one dimensional heat flow). Hourly temperature predictions by SUNCODE and ESP were uniformly in agreement in January (mean deviation 1 K); but rather poor in June (mean deviation 4 K with peak differences of 11 K).
The conclusion must be that reached previously by Judkoff et al (7), namely that inter-model comparisons without good experimental data are not very helpful in validation. However they are helpful in terms of assessing usability. Operators found little difficulty in implementing SUNCODE on a DEC-10 or VAX. They also reported on the convenience of the edit-mode for constructing a building description. The main criticism concerned the lack of graphics output (however this is a feature which will be added during the UK Department of Energy Passive Solar Programme). Users had little difficulty in implementing ESP on a DEC-10, but more on a VAX and a great deal more on a Burroughs.Running ESP produces very large output files on disc but this problem is offset by the comprehensive output routines which exist to plot almost any combination of variables.
The costs of running a job with various programs has been assessed (8) as follows: SUNCODE 1: BLAST 7: ESP 25: DEROB 30.

## 3. MICROCOMPUTER AND MANUAL METHODS

Table 3 summarises the variability in annual auxiliary energy found using various models on the LANL cell driven with monthly weather data derived from the hourly data used in Table 2.

TABLE 3. PREDICTED ANNUAL HEATING LOAD IN KWH

| | |
|---|---|
| Methode 5000 (9) | 810, 800, 1020, 840, 830 |
| LANL III (10) | 1110, 1210, 1500 |
| CASAMO (11) | 1070, 1010 |
| SPIEL (12) | 1130, 1150 |

A major advantage of the manual Methode 5000 is that it teaches designers as they use it to become aware of the interplay between internal gains, solar gains and auxiliary energy; but in the opinion of the author it is tedious to use by comparison with the tabular form of LANL III, and virtually impossible to exploit unless programmed for a micro, in which case it loses transparency. SPIEL has an interactive graphics package up-front and runs on several micros including Apples. It requires mean monthly temperatures and swings plus monthly values of daily hours of bright sunlight.
All the methods shown here cope with most of the common passive designs, having been shortlisted from a compilation of about 40 design tools.

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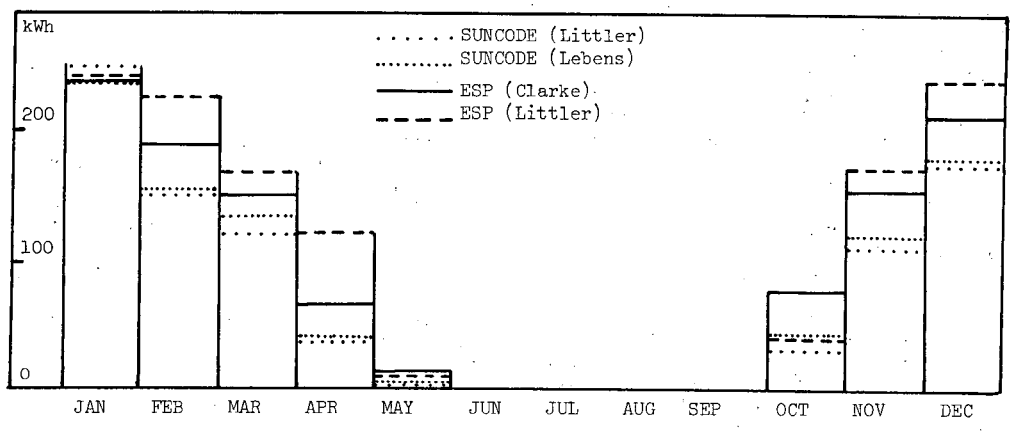



Fig. 1. Monthly Predicted Auxiliary Energy Consumption of a Direct Gain LANL Test Cell, Set Point 18.3 C, Driven with Danish TRY Hourly Data.

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# THE 'MABATHOANA HOUSE IN QOALING: A TRANSITIONAL MODERN DESIGN IN LESOTHO

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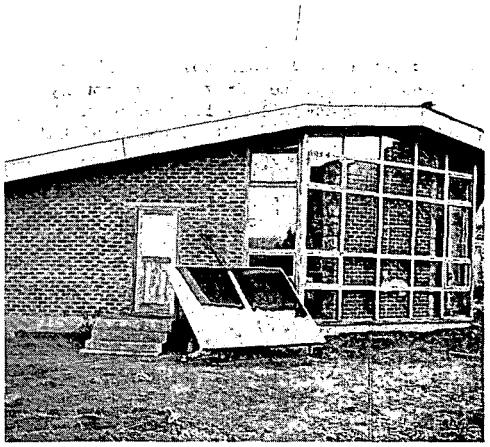


Fig. 1. Northeast View.

ABSTRACT

This paper concerns the design, construction and performance of a thermal storage wall and direct gain house in the lowlands of Lesotho. Infrastructural self-reliance was integral to the design in that the demand for water has been minimized, and the need for grid-supplied electricity eliminated. Alternative, on-site systems provide for very comfortable living at low personal and societal costs. Coupled with the use of locally available, "modern" building materials, this house represents another step in the transition from existing practice to environmentally wise architecture.

## 1. INTRODUCTION

Many modern homes built in Lesotho use electricity for space and water heating and cooking. Few of them, however, are oriented to take advantage of solar energy, and even fewer are insulated above the ceiling. Standard building materials consist of concrete blocks or fired clay bricks and single-glazed, metal-frame windows. Roofs of corrugated metal are common.

Given these facts, plus a need for heat in winter and an excellent solar regime, the author decided to build a house to demonstrate the effectiveness of energy conservation and passive solar design. Heat, hot water and electricity for this house would be supplied by the sun, cooking fuel from bottled gas, and water demand minimized by use of a low-volume toilet. No backup systems would be included during construction and, in fact, should never be needed.

Designed to be a modern house, it draws on traditional Basotho architecture. Its most distinctive feature is the grouping of one-room units around a courtyard. However, instead of separate units around an open courtyard, four rooms surround the living room, and the entire space is under one roof. The floor plan is shown below in Figure 2.

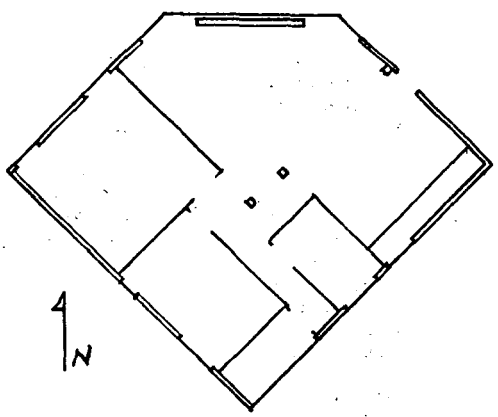



Fig. 2. Floor Plan.

## BUILDING AND DESIGN FEATURES

### 2.1 Building Components

Locally available materials were used

throughout the building. The bricks were fired by the subcontractor for the project. Sandstone used on the inside of the thermal storage wall was quarried about 300 meters from the house. The blocks used in the foundation were made in Maseru. Store-bought items, for the most part, were off-the-shelf. These included cement, wood for roof framing, ceiling boards, glass and corrugated iron roof sheets. The biggest problem was getting insulation. While one supplier in Maseru stocked one size of fiber-glass rolls, these were not of very good quality. Eventually, I decided to order directly from the manufacturer and have them shipped by train to Maseru. I have since learned that given enough lead time, the major building suppliers will provide insulation for special requirements. As can be seen, its widespread use is far from common at this time.

## 2.2 Energy Conservation

First consideration was given to conserving energy. This meant that, unlike most dwellings, this house would have insulation in the ceiling, walls and foundations. Windows would be double-glazed, and frames made of wood instead of steel. Doors and windows would be properly weatherstripped to help control infiltration losses.

The insulation used for the foundation is 50mm of polystyrene board. This has been replaced on the inside of the foundation wall and extends 1.2m below floor level. The brick walls are insulated with 150mm of fiberglass batt insulation, installed between the inner and outer walls. This total is comprised of two batts with staggered joints to minimize thermal breaks. Brick reinforcing is used every third course. The ceiling is insulated with 225mm of fiberglass batts, installed above 10mm tongue-and-groove pine and a continuous vapor barrier. As in the walls, the joints are staggered, and the lower chord of the roof trusses are covered with insulation over all rooms except the living room, where the cathedral ceiling made this impossible. Ventilation above the insulation has been provided with vent blocks in the walls and continuous venting between the ridgecap and corrugated roof sheeting.

Very few windows face anywhere other than northeast, north and northwest. Window frames, made in Maseru, were designed to have two layers of glazing over both fixed and opening portions. To date, only fixed portions have been double-glazed. Pre-made, hermetically sealed, double-glazed windows are very expensive and, generally, unavailable, so they were not used in this design. Moisture buildup between panes appears to be a problem only during rain and dries up after a day or so of sunny weather. This potential problem will be monitored closely.

Infiltration is controlled primarily by careful weatherstripping of windows and doors, and by sealing around frames. The main entry is in an alcove, protected from wind. The other door is on the northeast, a side of the building usually in the lee of the wind. It is expected that the infiltration rate is less than one air-change per hour.

## 2.3 Solar Design

The sandstone and brick thermal storage wall is the primary heating and aesthetic design component. It is 3m wide, approximately 3.6m tall and .4m thick. Dark color brick faces north and is separated from the window by 125mm. This space allows for use of night insulation when needed. The inside of the wall is white sandstone, which helps make the transition from a dark interior to bright outdoors easier on the eyes, and does not require a plaster finish that must be painted.

On either side of the thermal storage wall, large windows allow sunlight to penetrate deep into the house. These windows wrap around the corner, facing northeast and northwest as well as north. Energy is absorbed by interior walls and floors. Additional direct gain is provided by windows in the bedroom and kitchen that face northwest and northeast, respectively.

The floors are made from either a 125mm-thick concrete slab (as in the living room, hall and bathroom) or a 150mm-thick slab made of a tamped mixture of sand and clay (as in the bedrooms and kitchen). Coloring was provided by a red soil, locally called Khubetsoana. The earthen floors have been sealed with a urethane floor sealer. Thermally, floors are comfortable, but the coating and sealer are less durable than I had hoped.

The overhang shades north-facing glass from noontime summer sun and provides cooling. The large northeast and northwest sections let in more energy through their lower half than is desirable, but the internal thermal mass controls excessive temperatures, unless the ambient temperature exceeds 30°C, which is rare. Annual plantings planned for the future will help control the influx of undesired energy. Cross ventilation through the bedrooms and out through the living room provides the rest of the cooling needed.

## 2.4 Other Design Features

Hot water is provided by two $2m^2$ flat-plate collectors, connected to a 200 liter tank. The collectors are made from stainless steel sheets, spot-welded together to form a

virtually continuous surface for absorbing the sun's energy. The glass-lined tank is mounted vertically on an indoor wall and connected to the city water supply by a thermo-syphon system. At this stage, no backup exists for long periods of cloudy weather.

Electricity comes from photovoltaic panels mounted on the roof. Since the demand is only for lights, just one panel and battery have been hooked up. By September, 1983, we plan to install additional lights and a 12-v DC refrigerator. This will mean increasing the number of panels to a total of four. A 300-watt generator provides power for the occasional use of electric hand tools. We plan to run completely on direct current, as resources and equipment availability permit.

The water-conserving toilet was manufactured in South Africa and requires only 1.5 to 2.5 liters per flush. Operated by a foot pedal, the water pan drops, releasing waste into a septic system next to the house, just outside the bathroom. The water seal is broken for about 10 seconds during this operation. Initial problems with the ventilation system have been remedied, and it now functions well.

The septic tank accommodates toilet waste only. Gray water goes through a grease and silt trap, then directly into a leach field. Papyrus and bamboo plants help absorb any excess water.

Landscaping will become the priority for the coming year, with a mixture of annual and perennials planned for climate control as well as a sustainable food supply. Small livestock, such as chickens and rabbits, are also part of future plans.

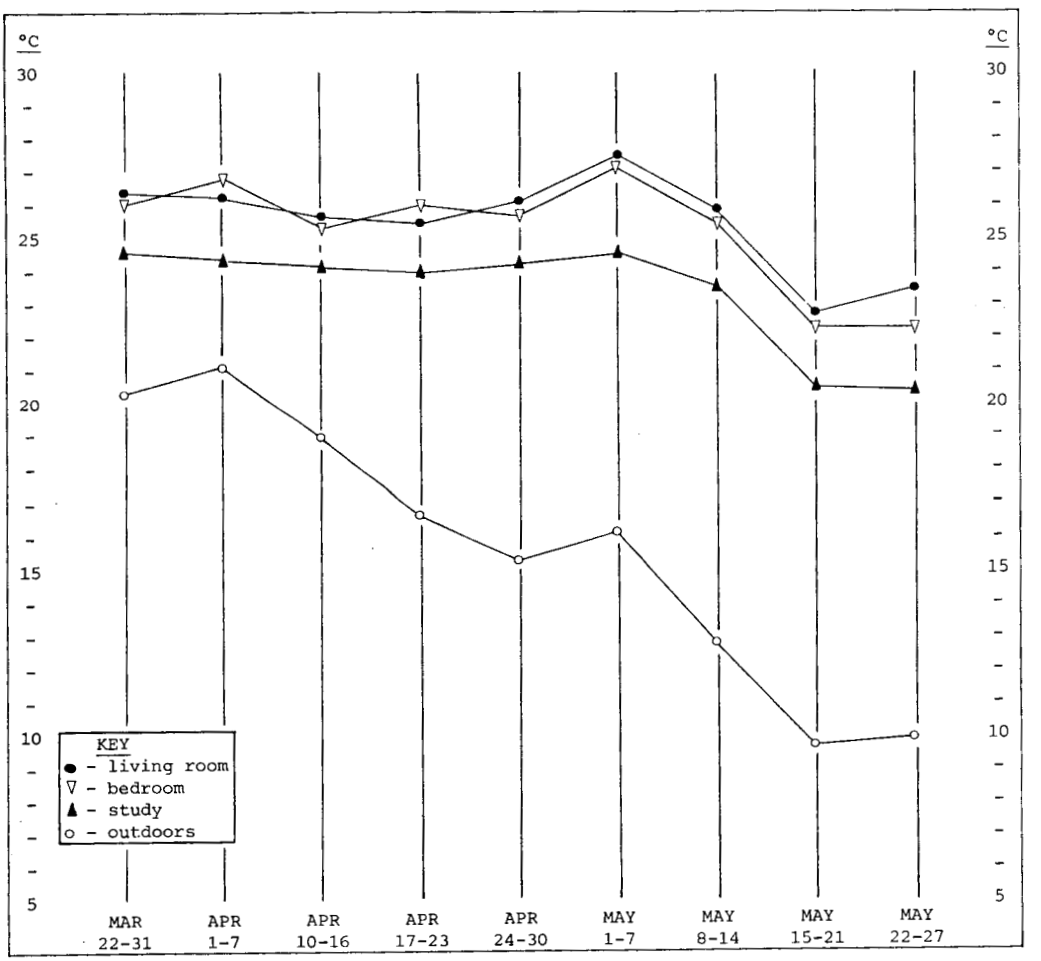



Fig. 3. Information from Maximum-Minimum Thermometers.

## 3. PERFORMANCE

The house is monitored by two systems: the first, maximum-minimum thermometers, installed in March, 1983; the second, an Aeolian Kinetics data logger, installed at the end of May, 1983. This unit will monitor air, surface and radiant temperatures, solar radiation and wind speed for about one month. Data from this system is not yet available.

Information from the maximum-minimum thermometers, for a period of about two and a half months, is presented in Figure 3. As expected, the colder the weather, the greater the differences between indoor and outdoor temperatures. Apart from the last two weeks in May, indoor temperature fluctuations were within 4°C. Bedroom and living room temperatures tend to be the same, and a southwest-facing study is the coolest room in the house.

The last two weeks in May were cloudy, windy, rainy and comparatively cold. During this period, the house temperature dropped, but the average never went below 20°C. The hot water ran out after the second day, and electricity was low after three days. This pointed to the need for further efforts to conserve water--specifically, taking showers instead of shared baths, and increasing the electrical system capacity, which is scheduled for later this winter.

## 4. CONCLUSION

Most construction details used in building this house worked well. Much was learned about installing insulation in a brick cavity wall, a process unfamiliar to local builders. Earthen floors were also a new idea and still present a few problems to sort out, as mentioned.

The building's thermal performance met my expectations. The house may be warmer than most Americans consider desirable, but that feature is greatly appreciated by Basotho visitors. All visitors, in fact, are surprised at how comfortable it feels, even on cloudy days. The solar hot water and photovoltaic electrical system have also been performing well. These features generate the most curiosity among our guests, indicating the local desire for hot water and small amounts of electricity.

We are looking forward to winter and putting the house to its sternest test. All indications, however, are that no auxiliary heat will be needed--unless we have a week of cold, cloudy weather. If that is the case, we'll just have to wait and see.

## 5. ACKNOWLEDGEMENTS

Special thanks must be given to the builder Karabo Leotlela for his patient attention to detail throughout construction of the house; to Jens Saxtorf for being there whenever we ran into seemingly insurmountable problems; and to David Norris, who helped create the final design. Finally, I must thank my wife Manuna, who was skeptical at first, but now very pleased with our warm, new home.

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# THREE PASSIVE SOLAR ARCHITECTURES IN TOKYO

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## ABSTRACT

Japanese traditional architectures have had passive methods for natural energy, and so it is not difficult for the client to agree about passive design in spite of most of the people thinking that the technology will advance in the future. But it may take time to broaden it because the society has seen high energy equipment. Consulting with each client to agree, it is important to find a common advantage.

## 1. INTRODUCTION

Tokyo is located at a latitude of north 36° 40'. The altitude of summer solsice is 77.5° and one of winter solstice is 30.6°. The climate is mild; it is cold and dry, -4°C to 10°C, in winter, and hot and damp, 24°C to 31°C and 75% to 80%, in summer. Passive solar heating is easily designed because a room will be warm enough if it has insulation and direct gain. For example Japanese traditional houses have had the methods like double shells which are constituted of thick sliding doors, sliding paper doors of SHOJI and the veranda between them; they are opened in day, and the sun radiates on the thick straw floor of TATAMI in a house which will store the heat and control the moisture to be comfortable. They are closed at night. As an auxiliary heater, there is a fire box or hole in the floor of a TATAMI room. Thus passive solar heating has been shown to be suitable for Japanese houses. There have been many methods of passive cooling, but the moisture is a problem.

In 1982 to 1983, I have designed three passive solar architectures which have had a common way and different design methods. The common way has meant to use an air flow duct which will distribute heat by bringing it down from the top space. Another important design method is how to insulate external walls: the first has insulation on the inside of the walls; the second has cast insulation panels in the outside of the walls; and the third is a combination of a massive structure wall and just insulated wall. The costs of them are different. One of the other design methods is that all of them are passive and hybrid solar houses because they have had different active solar collectors.

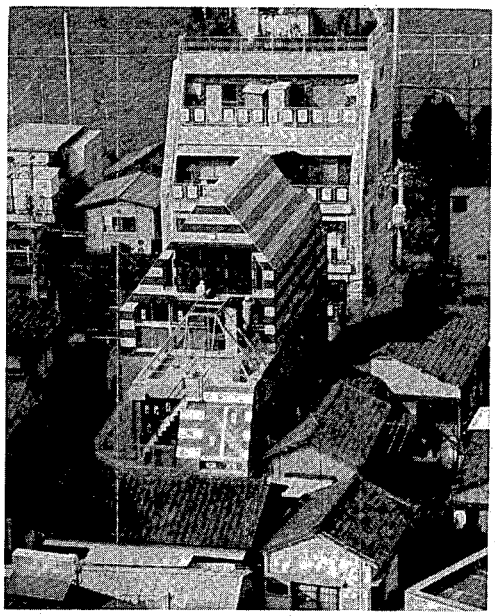
## 2. A DANCE SCHOOL WITH AIR FLOW DUCT

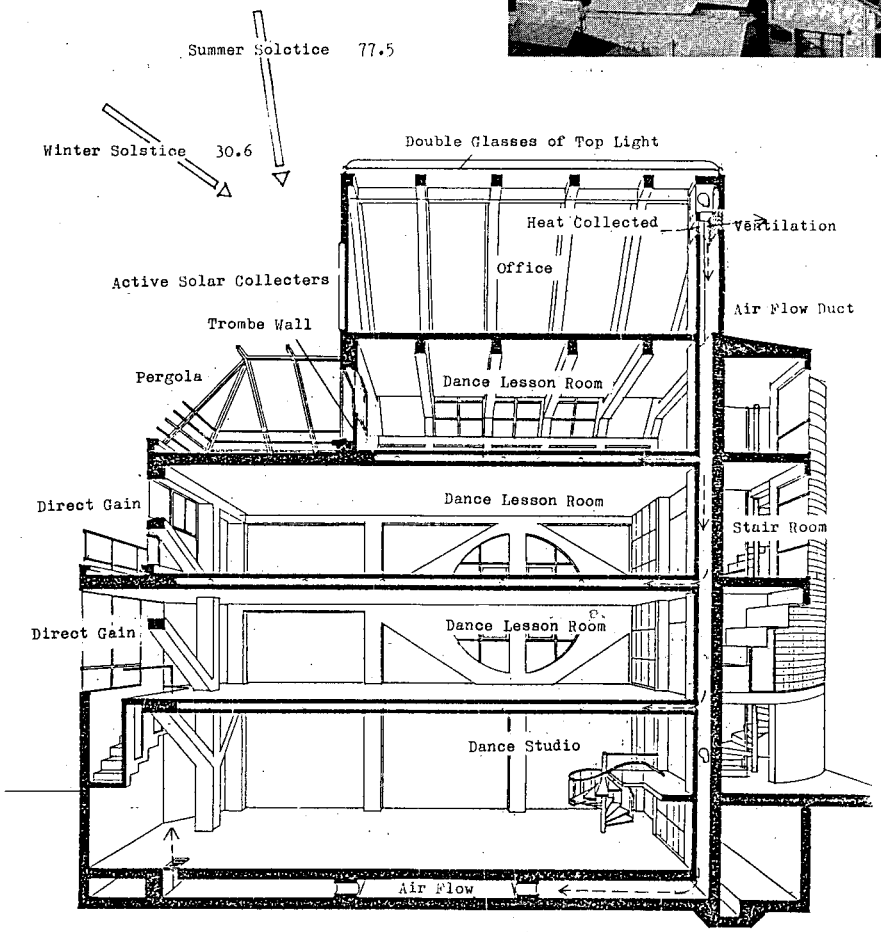
A vertical air flow duct, the second, third and fourth floor hollow slabs, and the underground hollow space of the basement by which the air connects from the top to the underground will balance the heat inside this building. The insulation (50 mm wood chip cement boards) was cast in the inside of the concrete wall. Direct gain through the top light and south windows, indirect gain by a Trombe wall, and the heat produced by human bodies will assist the air flow system.

This dance school has five floors, which are a studio at the first floor which is underground, three lesson rooms on the second, third and fourth floors, and an office on the top floor. It is located in Shinjuku which is the most popular and crowded town in Tokyo and in the commercial district by law. The upper floors have enough sun bathing but the lower ones do not. The top light is flat, 80 cm wide and 9 m long from south to north. Three active solar collectors on the south wall provide a shower room and toilets with hot water. The auxiliary hot water tank is an electric 480 liter one. The Trombe wall area is 8.2 $m^2$ with an 8 $m^2$ glass window above the Trombe wall.

The heat of human bodies is expected for passive heating because 17-20 dancers will take lessons at each floor of four levels and there will be 68-80 dancers moving hard. As a human body produces 1350 to 1450 Btu/h when it is taking hard exercise, a lot of heat will be expected.

The hollow slabs are the structural floor of reinforced concrete and metallic spiral with parallel tubes. In this case the tubes were designed as a place to move the heat.






DANCE SCHOOL, 1982-1983

## 3. TAKASAKI RESIDENCE WITH A MEDICAL CENTER

Superinsulated construction, 75 mm polyurethane panels with 6 mm glassfiber reinforced concrete boards over the structural concrete, 11 active solar collectors for hot water, 19 $m^2$ passive solar collectors on the roof, 3 $m^3$ rock bed, an air flow duct assisted by fans, and attached sun space.

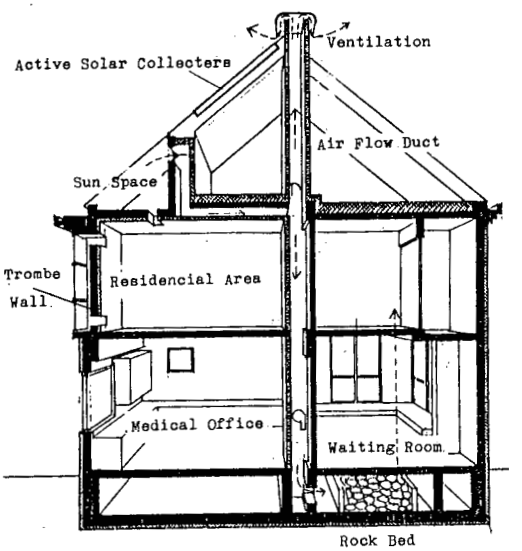
This is a house with medical office of otorhinolaryngology. The site is in the residential area. As the surroundings are crowded, it is difficult for the south windows to have enough sun bathing. The basic designs are superinsulation and air flow duct. The vertical angle of the roof is $40^{o}$. The angle of the collectors is the same. 20 $m^2$ active solar collectors will provide two families in the residence and the medical area with hot water. The auxiliary tanks are two electric 480 liter hot water tanks.

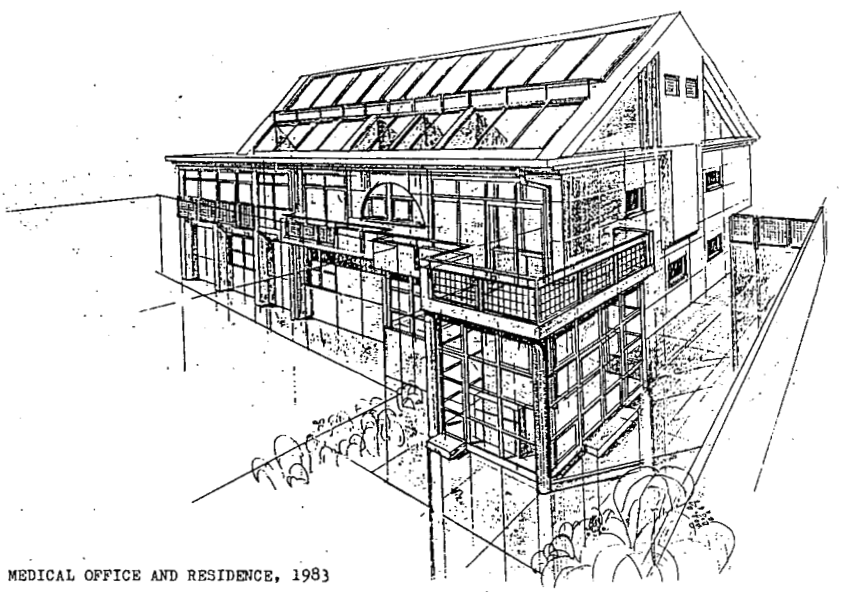
The residential floor is on the second floor with the medical office on the first floor. The wall insulation is 75 mm polyurethane, and there are 200 mm of polyurethane over the ceiling of the second floor.

A return air tube after the rock bed opens to the second floor. The air will move up to the passive solar collectors through movable insulated valves. It is the air circulation from the passive solar collectors to the passive solar collectors. The height and volume are strictly restricted by law. There are 200 to 300 persons with whom the client consults in a day.

Total solar design system was assisted and led by Professor of Waseda University Kenichi Kimura.

The facade design is assured to follow a classic style and Japanese godown to find new regional form.



TAKASAKI MEDICAL OFFICE AND RESIDENCE, 1983

4. MIKI RESIDENCE

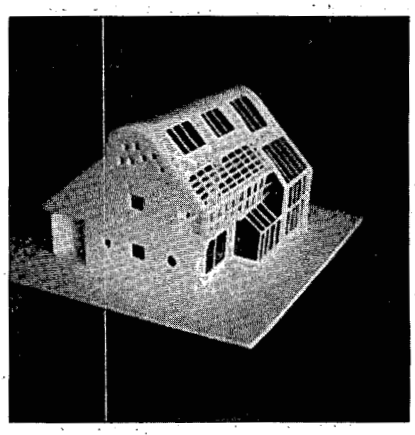
Attached sunspace, direct gain, rock tower, fans assist circulation of air to rock bed under first floor slab, chimney for heat outlet and inlet, internal massive concrete wall and slab, external insulated wall, a fire box at the foot of rock tower, active solar collectors.

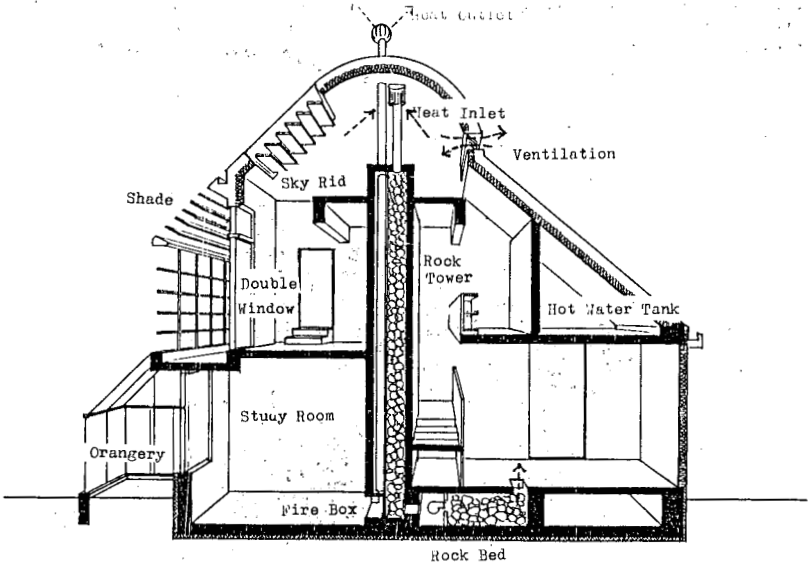
The owner is a law scholar who requested low energy cost and a lot of library space. The site is surrounded with many greens and has enough sun bathing. So passive solar heating is expected to completely succeed. There are book shelves everywhere in this house. Insulation and books on the external wall will become superinsulation. The concrete and metallic chimney in the midst of this house circulates and stores heat to take its balance. In order to move and circulate it smoothly and gently, the top ceiling was designed in a semi-circle to show the round roof shape as the approach elevation.

There are some north openings to take prevailing winds for passive cooling. The winds will run from north to south, and ventilation fans assist it.

15 $m^2$ active solar collectors provide the owner with hot water and auxiliary floor heating to the library.

Total solar design system was assisted and led by Professor of Waseda University Kenichi Kimura.






MIKI RESIDENCE, 1983

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# SOLAR PASSIVE HEATING IN GREECE

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## ABSTRACT

This paper reviews the state of the art of the solar passive heating field in Greece. Some generally applicable climatological data are first presented and hence the need and suitability of solar passive heating is explained. Examples of climatologically adapted dwellings from the antiquity and from modern vernacular Aegean architecture are discussed. Some modern solar passive applications are presented together with computer calculated estimates of the performance of direct gain and Trombe wall examples. The paper concludes that solar passive heating in Greece is desirable both on economic and architectural grounds.

## 1. CLIMATE

Greece is divided into three basic climatological zones with regard to solar radiation distribution, ambient air temperature, air humidity and cloud cover (1). Table 1 presents some climatological data for three representative sites, one from each climatological zone. These sites correspond to the cities of Salonica, latitude 40°33′; Athens, the capital of Greece, roughly located in the middle of the country, (lat. 37°58′), and Chania, in the south, on the island of Crete, latitude 35°30′. The information in Table 1 is drawn from a recent study by Pelecanos (2). It can be generally stated that Greece is a country with abundant solar radiation, even during the winter months, with relatively mild winters where temperatures rarely fall below 0°C for the greatest part of the country, and from this respect ideal for solar energy applications. Solar energy radiation, on the horizontal plane, varies from an average low of 6.1 $MJ/m^2$ in winter, to a high of 25.1 $MJ/m^2$ in summer. This seasonable variation is typical of the temperate climate of southern Europe and is mainly due to the general moderate degree of cloudiness. According to a study by Katsoulis (3) periods of five consecutive days in winter with less than 17 $MJ/m^2$ day occur only 7.4 % of the time. This observation is indicative of the fact that there are rarely any sunny periods with low solar radiation to be of concern to solar energy applications.

## 2. HISTORIC SOLAR PASSIVE APPLICATIONS

Greece has a long tradition in the building of human settlements. The question of human comfort and how this can be achieved by means of proper construction is exemplified by a statement attributed to Socrates who said that the ideal house should be cool in summer and warm in winter. As quoted by Xenophon (4), Socrates explained this approach: "In houses that look toward the south, the sun penetrates the portico in winter, while in summer the path of the sun is right over our heads and above the roof so that there is shade." (6)

In a recent paper Lavas (5) has reviewed the energy planning parameters that affected the design and construction of ancient Greek houses and settlements. Examples of energy determined planning are given from archaic period houses in Crete and Aegina. Classical period examples include houses in Athens, Delos, Olynthos and Priene. In most cases the structure of these houses is organized in successive levels from north to south and is open to the south or south-east thus trying to achieve better conditions for cold wind protection and excessive heat gain. The town of Priene situated on a slope is a well known example of planning which shows a very compact building construction. In Olynthos alike, which is situated on plane landscape, a similar principle is also applied: all living, sleeping and working spaces are situated in the northern zone of the house, open to the south. The town plan of Olynthos is an often quoted example of how houses were organized in rows, so that each dwelling had a good and equal south solar exposure. Perhaps the first known enforcment of solar access law!

From the amount of considerable archeological evidence available and from various written sources it appears that ancient Greeks possessed an advanced level of knowledge and experience, in the planning of settlements and the construction of individual dwellings, which was largely based on energy saving and comfort and achievement considerations.

TABLE 1. SOME GENERAL CLIMATIC DATA CORRESPONDING TO THE THREE CLIMATIC ZONES OF GREECE

(Abstracted from ref. 2)

| Towns and latitudes | | J | F | M | A | M | J | J | A | S | O | N | D | total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CHANIA | Ambient Air temperature (Daily Average C°) | 11.9 | 12.2 | 13.5 | 16.4 | 20.4 | 24.7 | 26.9 | 26.7 | 23.6 | 20.0 | 16.9 | 13.6 | - |
| (35°30′) | Degree Days (18°C) (for Heraklion) | 188 | 156 | 143 | 104 | 9 | - | - | - | - | 9 | 50 | 123 | 782 |
| | Global Irradiance kwh/m² mo (horizontal) | 59 | 75 | 112 | 149 | 196 | 215 | 229 | 210 | 154 | 101 | 74 | 56 | 1,630 |
| | Global Irradiance kwh/m² mo (vertical) | 79 | 81 | 88 | 80 | 75 | 69 | 76 | 94 | 106 | 102 | 101 | 82 | 1,033 |
| ATHENS | Ambient Air temperature (Daily Average C°) | 9.4 | 10.3 | 11.7 | 15.8 | 20.6 | 25.2 | 27.9 | 27.8 | 23.9 | 18.7 | 15.0 | 11.4 | - |
| (37°58′) | Degree Days | 264 | 224 | 196 | 85 | 10 | - | - | - | - | 29 | 96 | 206 | 1,100 |
| | Global Irradiance kwh/m² mo (horizontal) | 58 | 74 | 110 | 147 | 190 | 204 | 219 | 202 | 149 | 104 | 70 | 54 | 1,581 |
| | Global Irradiance kwh/m² mo (vertical) | 87 | 86 | 91 | 83 | 78 | 72 | 80 | 97 | 109 | 114 | 104 | 89 | 1,090 |
| SALONICA | Ambient Air temperature (Daily Average C°) | 5.5 | 7.0 | 9.9 | 14.6 | 19.7 | 24.1 | 26.7 | 16.3 | 22.2 | 16.7 | 11.9 | 7.4 | - |
| (40°33′) | Degree Days | 396 | 313 | 268 | 130 | 23 | - | - | - | - | 70 | 187 | 338 | 1,725 |
| | Global Irradiance kwh/m² mo (horizontal) | 49 | 64 | 96 | 135 | 174 | 186 | 205 | 178 | 131 | 87 | 55 | 44 | 1,403 |
| | Global Irradiance kwh/m² mo (vertical) | 77 | 78 | 83 | 81 | 78 | 72 | 82 | 92 | 101 | 98 | 83 | 75 | 1,000 |

## 3. ENERGY CONSERVING VERNACULAR BUILDINGS

The different types and forms of vernacular buildings to be found in the Aegean islands of Greece are the result of an organic growth of human activities which includes the evolution of settlements, over the last few centuries. The good understanding of local climatological conditions played an important role in the development of energy conserving structures. Small window openings, thich structural walls and well insulated roofs were the key elements which combined to achieve comfort conditions throughout the year. In an introductory paper by the author (6) the climatic factor in the development of Aegean vernacular architecture has been discussed. In this paper the observation is made, (for the first time and supported with field data), that some of these traditional buildings maintain a steady internal temperature, ranging from 20°C - 30°C in summer and 11°C - 18°C in winter, depending on the type and location of each particular dwelling. On this island there are some earth submerged and earth surrounded dwellings which of course have been observed to maintain the most comfortable interior environment. In a subsequent paper Andreaki-Chronaki(7) has confirmed the author's initial observation with considerable more field data, obtained from independent measures in other houses on the same island. Further work is now in progress by several researchers in order to determine the function of different building and climatic parameters in the maintenance of comfort conditions in vernacular houses.

TABLE 2. MONTHLY AND YEARLY TROMBE WALL CONTRIBUTIONS, FOR TWO DIFFERENT TYPES OF HOUSES IN ATHENS, HAVING DIFFERENT OVERALL HEAT TRANSFER COEFFICIENTS

| | OVERALL HEAT TRANSFER COEFFICIENT ($W/M^2.C^o$) | SOLAR AND AUXILIARY CONTRIBUTIONS (MJ/DAY) | J | F | M | O | N | D | TROMBE YEARLY CONTRIBUTION (%) |
|---|---|---|---|---|---|---|---|---|---|
| Case A 2 floors Volume: 570 $m^3$ Floor area: 180 $m^2$ Trombe wall Area: 70 $m^2$ | 0.5 | Trombe | 74.16 | 75.36 | 76.82 | 85.30 | 80.72 | 76.36 | 89.0 |
| | | Auxil. | 22.00 | 15.10 | 8.60 | 00.00 | 0.48 | 10.31 | |
| | 1.0 | Trombe | 74.25 | 74.45 | 76.94 | 84.95 | 80.86 | 76.46 | 87.3 |
| | | Auxil. | 27.53 | 17.84 | 9.91 | 0.00 | 0.52 | 12.02 | |
| | 1.5 | Trombe | 74.29 | 75.52 | 77.00 | 85.46 | 80.92 | 76.52 | 84.5 |
| | | Auxil. | 37.00 | 22.15 | 11.73 | 0.00 | 0.61 | 14.39 | |
| | 2.0 | Trombe | 74.35 | 75.58 | 77.05 | 85.34 | 80.98 | 76.58 | 74.3 |
| | | Auxil. | 97.33 | 31.34 | 14.52 | 0.00 | 00.75 | 18.24 | |
| | 2.5 | Trombe | 74.40 | 75.63 | 77.10 | 85.33 | 81.02 | 76.63 | 60.0 |
| | | Auxil. | 169.71 | 92.07 | 20.07 | 0.00 | 0.89 | 29.90 | |
| Case B 2 floors Volume: 380 $m^3$ Floor area: 120 $m^2$ Trombe wall Area: 50 $m^2$ | 0.5 | Trombe | 63.52 | 64.56 | 65.82 | 73.12 | 69.17 | 65.43 | 90.0 |
| | | Auxil. | 16.94 | 11.34 | 6.44 | 0.00 | 0.36 | 7.74 | |
| | 1.0 | Trombe | 63.64 | 64.69 | 65.95 | 72.76 | 69.30 | 65.53 | 88.8 |
| | | Auxil. | 20.57 | 13.36 | 7.42 | 0.00 | 0.39 | 8.97 | |
| | 1.5 | Trombe | 63.66 | 64.71 | 65.97 | 73.30 | 69.34 | 65.58 | 86.3 |
| | | Auxil. | 27.33 | 16.48 | 8.76 | 0.00 | 0.44 | 10.71 | |
| | 2.0 | Trombe | 63.73 | 64.78 | 66.04 | 73.15 | 69.40 | 65.64 | 77.3 |
| | | Auxil. | 70.22 | 22.90 | 10.80 | 0.00 | 0.55 | 13.50 | |
| | 2.5 | Trombe | 63.77 | 64.82 | 66.09 | 73.17 | 69.45 | 65.69 | 63.7 |
| | | Auxil. | 126.44 | 66.65 | 14.66 | 0.00 | 0.66 | 20.60 | |

## 4. FEASIBILITY OF MODERN SOLAR PASSIVE HEATING APPLICATIONS

If we carefully examine the climatic data presented in section 1 of this paper and other relevant climatic information for Greece it becomes evident that the heating requirements for the largest part of the country are moderate. The great majority of dwellings require to be heated from late October to early April and for a relatively small number of degree days (700-1500). Given the good solar radiation regime of the country it is obvious that modern solar passive heating techniques can be applied in order to cover the greatest part of the heating load. In order to assess the possible contribution of solar passive heating a number of other studies have been undertaken by the author and others. (8) (9).

In a recent study by the University of Patras's Working Group on the country's five year development plan (10) results are reported on estimated direct gain systems for twenty different towns in Greece. The potential contribution of solar energy has been calculated for different area openings and for different insulation practices. The results show that considerable heat gains may be achieved with relatively small south facing openings of up to 10 $m^2$. The results from computer based performance simulations for a Trombe wall system are shown in Table 2.

The results are drawn from a series of simulations carried out for different size dwellings, having different insulation properties and for a number of different locations in Greece (8). These results show that 60-70% of heating needs can be covered for well insulated buildings for the greater part of Greece.

Direct gain and Trombe wall systems can also be cost effective since construction cost estimates show that for most cases, aiming for a substantial solar coverage, overall passive component costs correspond to 5-8% of the total building construction cost. Detailed estimates and cost comparisons are presented in the same paper (8).

## 5. EXAMPLES

A recent survey (11) has shown that there are very few solar passive heated buildings in Greece today. (Their number is estimated to be less than five.) Architects and engineers alike are not at all informed on the availability and applications of solar passive systems nor any effort is made by the government to promote such techniques. It is therefore not surprising why so few applications have been realized so far.

Kalligeris (12) has reported on a passively heated house which he designed and which has now been constructed outside the town of Chania in Crete. The house uses a 15 $m^2$ Trombe wall system to heat a total floor of 145 $m^2$. It is estimated that 87% of its annual heating load will be covered through the passive system. Kalligeris has also reported work on a new solar passive residential project at Drapanias, Crete (13). Another interesting project has been reported by Kontoroupis and this concerns a passive retrofit of an old building at Poulithra, Arkadia, in Peloponese (14). Tombazis has reported on two major projects. The first concerns the Solar Village 3, solar settlement to be constructed outside Athens, (15) and which will use several passive systems. The second project is a passively heated, cooled and daylit nursery school which is now under construction in Athens (16). The author has already reported on the design of a solar passive-hybrid 2,200 $m^2$ office building in Khalkis, north of Athens. This system makes use of Trombe wall and sunspace components combined with active solar air collectors and a massive rock store (17). The design and construction of a solar passive heated residence in Salonica has been reported by Axarli (18) and the design of a solar passive heated school has been announced by Papadopoulos and co-workers (19). Finally, Tsigas has completed the retrofitting of an unheated workshop situated within a Public Power Corporation plant in Salonica (20). An attached greenhouse runs along the west side of the workshop while a passively operated wall air-collector covers the south facade. The performance of this retrofitted workshop is being monitored within the framework of an EEC funded project and results so far show that all the heating needs of the workshop, which operates only during daytime, are covered from solar energy. A report on the building's thermal performance is expected to be published later this year. No projects involving roof-ponds, for solar heating and cooling, have been reported so far, apart from a small test-room in Heraclion, Crete which operated briefly in 1979 and which was designed and constructed by the author and Kalliyanni. Performance results of this test-room have been reported by Kalliyanni (21).

## 6. CONCLUSIONS

Solar passive applications in Greece have been slow to come and most difficult to introduce. There appears to be little interest from practicing architects and engineers and clients alike to attempt any serious energy conservation exercises. As a result it is not foreseen that solar passive will be introduced in any significant scale, at least comparable with USA or France, over the next two or three years. Education, both for the professionals and through a government backed energy conservation campaign, is seen as essential for the promotion of solar passive schemes.

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Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

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# THE TIMBERLOFT: A SUPERINSULATED HOUSE FOR COLD CLIMATES

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## ABSTRACT

As a logical extension of research in passive solar space heating technology, "superinsulation," (or, as William Shurcliff once suggested, "micro-load passive solar") is emerging as a simple, cost-effective building technology for cold-climate residential design. The transfer of superinsulation technology to the mainstream of new home construction requires detailed construction drawings for those building this type of housing for the first time. This paper presents and discusses the design rationale, significant architectural detailing, integration of an air-to-air heat exchanger system, and estimated construction costs of an architecturally attractive superinsulated house, the plans for which the authors are marketing by mail order. Computer simulations indicate that this house, if located in Great Falls, Montana, (7652 degree days) can be heated for $118. per year using electric heat at $.0295 per kWh.

## 1. INTRODUCTION

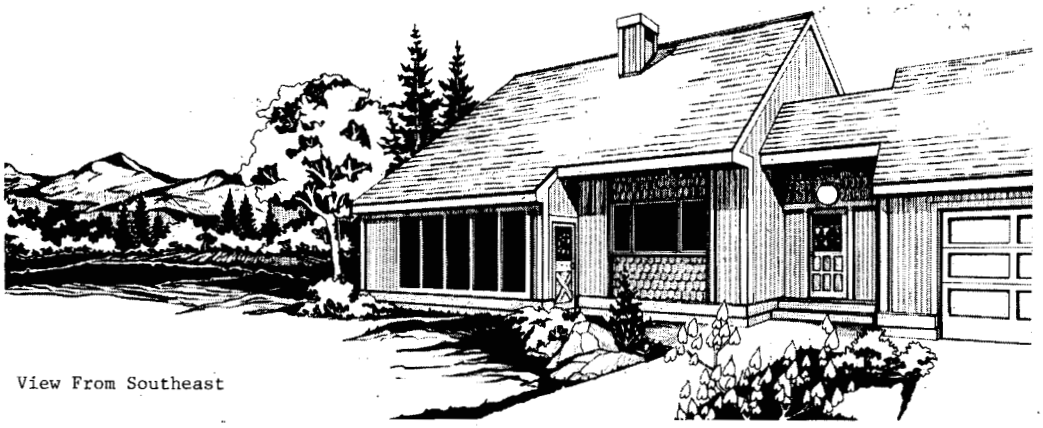
While superinsulation has received a fair amount of attention in the popular press in the last couple of years, it has yet to reach its full potential in the mainstream of the housing industry. In response to this challenge, the authors formed "Superinsulation Designs - Corbett/Hansen & Associates," an architectural design firm dedicated to the technology transfer of superinsulation as an energy-efficient housing concept. The authors' combined eight years of research experience at the National Center for Appropriate Technology (NCAT) has shown that superinsulation is the most cost-effective, simple and fool-proof method for achieving ultra-low space heating bills in new home construction.

To respond to the growing interest in superinsulation, and to expedite its acceptance within the housing industry, the authors have produced and are marketing very detailed sets of working drawings for several houses. While the details and notes in each plan set apply to a specific house design, the plans are drawn to serve as an educational tool to aid architects, contractors, and owner-builders alike to understand the underlying basic principles of superinsulation. In lieu of a book on the subject, the authors have endeavored to produce a useful document illustrating how to build this new type of high-performance housing more effectively. The drawings go far beyond what is conventionally offered in "stock" house plans, affirming the precept that the more detailed and complete the drawings are, the better the chances are that the houses will get built tight...and right, and the better they will perform.

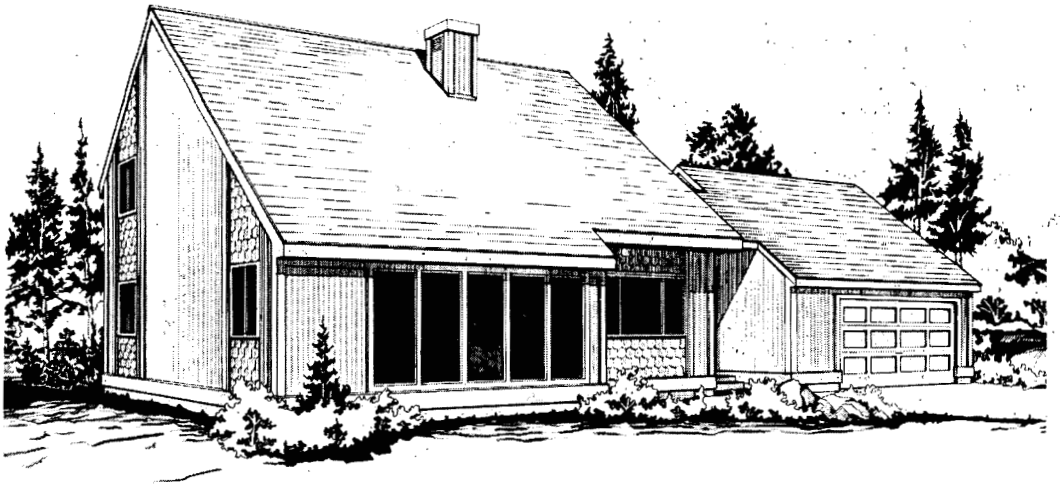
In an effort to reach beyond the local market, mail order has been utilized as the major means to facilitate this technology transfer. The challenge was to develop a plan that would assure the co-existence of design quality and marketability in meeting the criteria of a mail-order medium.

## 2. DESIGN DESCRIPTION

The "Timberloft" was designed to meet this challenge, proving that a superinsulated house can be architecturally interesting, be built within a moderate price range, and not sacrifice energy conserving performance. The house is two stories on a crawl-space foundation, with one bedroom and a bath on the main floor, and two bedrooms and another bath on the loft-like second floor. A sunspace is located off the family room, with space allocated for an optional solar hot tub. The living room and kitchen-dining area are arranged to flow into one another. The plan has been arranged to take advantage of solar geometry, with south facing windows for passive solar gain. The house is designed for a flat site, as found in typical residential settings, and it's orientation can vary 30 degrees east or west of true south without significantly affecting the solar contribution (see Figure 1).



View From Southeast





View From Southwest

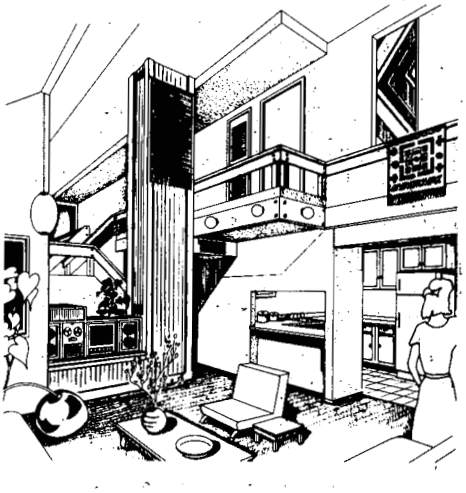
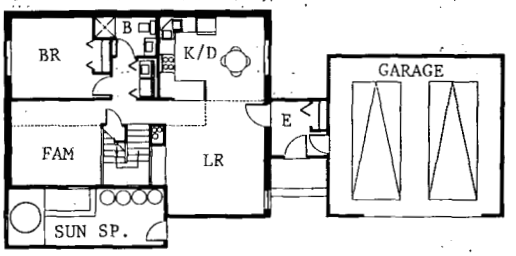


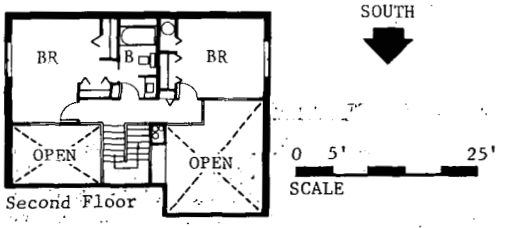
Fig. 1. Exterior Views and Interior Perspective.

## 2.1 Discussion of Plan Versatility

The "Timberloft's" flexible nature and versatility of arrangement allow the plan to be easily adapted to a variety of family needs, desires, and site conditions. The addition of bedrooms and several different kitchen-dining area layouts is possible. The potential exists for the plan to be expanded along the east-west (longitudinal) axis, without requiring any major structural change. The openness of the plan is accentuated by the cathedral ceilings and open loft area, creating a dramatic feeling of spaciousness, while the overall plan remains quite compact and efficient (see Figure 2). While the thermal significance of the air-lock entry may be questionable, it does allow adaptability to several site access arrangements (see Figure 3). As a transition vestibule between the house and garage, it, along with reversed plan potential, (see Figure 4) allows entry from all directions with no major modifications.




First Floor Plan




Second Floor

Fig. 2. Timberloft Floor Plans

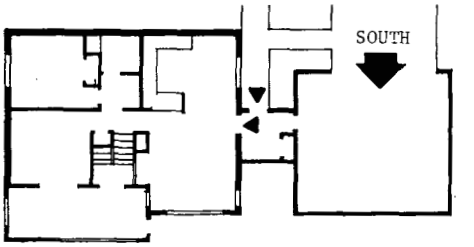



Fig. 3. Access From North

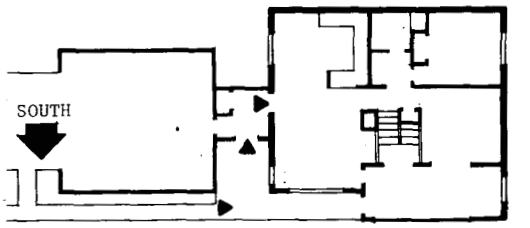



Fig. 4. Reversed Plan - Access From West

The "Timberloft" can also be built as a one bedroom starter unit, and with a reversed plan, can form any number of attached multi-family combinations for clustered high density housing (see Figure 5).

## 2.2 Description of Construction

The design features an 11", R-38 double 2x4 stud wall, filled with two 5 1/2" fiberglass batts (see Figure 7). While there exists many double wall techniques to accomodate high levels of insulation, the method we have chosen most closely follows standard conventional building practice. The exterior walls remain the structural load bearing walls, and are erected in the same manner and sequence as in conventional construction. The inner non-structural stud walls of the double wall system are tilted

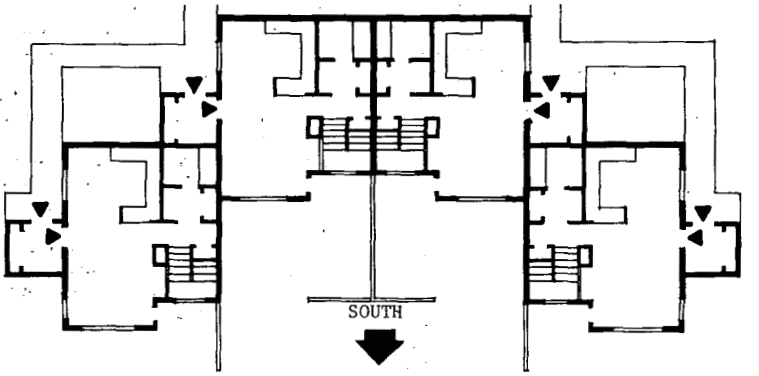



Fig. 5. Combined Studio Units

up later in the construction sequence. All windows are triple glazed casement to permit adequate summer ventilation, and roof overhangs are included, which shade south facing windows in summer while allowing direct solar gain in the winter.

The roof is framed with 2x12 rafters to allow the installation of 9 1/4" R-30 fiberglass batts. In the vaulted portion of the ceiling, a 2x4 false rafter is furred down 5 1/2" under the 2x12's to accomodate an extra R-19 batt. The 2x12 rafter system with a 9 1/4" batt allows for a 2" free vent path from the continuous soffit vents to the continuous attic ridge vent. Insulation baffles are installed between the rafters to prevent blocking the vent path with the R-50 loose fill insulation in the attic.

The first floor and the foundation wall perimeter is insulated within the crawl space with R-22 fiberglass batts. The rim joist is let in 1" to allow the installation of 1" of rigid insulation board. A unique crawl space vent detail is integrated into the band board at the rim joist on spring loaded hinges, allowing summer ventilation, and the ability to be latched tightly shut for winter conditions.

## 2.3 Infiltration/vapor barrier Installation

A 6-mil polyethylene infiltration/vapor barrier is used throughout the house to minimize infiltration and exfiltration, and to keep unwanted moisture out of the insulation. Care is taken that all seams of the barrier are overlapped and sealed with a non-hardening caulk or mastic. Since the vapor barrier is conventionally located on the warm side of the inner stud wall, special precautions are indicated to seal around wiring and electrical boxes. Electrical outlets are minimized on exterior walls for this reason. Wall mounted lighting fixtures are used instead of recessed ceiling fixtures to eliminate the precautions necessary to prevent heat build-up around the fixtures, and to eliminate piercing the ceiling vapor barrier. A 1" low permeability rigid insulation board is carefully sealed between the 2nd floor joists to insure the integrity of the infiltration/vapor barrier between the first and second floor levels.

In the interest of technology transfer, and because of the importance of having the house constructed as tightly as possible, a full sheet of the plans has been devoted to illustrating the proper construction sequence regarding the points mentioned above. The construction sequence sheet presents one way of achieving a proper infiltration vapor barrier installation, as an effort to remove any mystery for the first time builder. The sequencing presented allows the house to be closed in rapidly, and also permits the work of various trades to be accomodated with minimum conflict. The plans also include a resource list to give the builder more information regarding superinsulation technology.

## 2.4 Air-To-Air Heat Exchanger System

Because of the air-tight nature of the house, an air-to-air heat exchanger is integrated into the building to keep indoor air quality fresh and comfortable. It power ventilates the stale air from the house and replaces it with fresh air from the outside, using the stale warm moist house air to pre-heat the fresh incoming cool air, thus allowing a controlled rate of air exchange and a constant indoor relative humidity. This pre-warmed fresh air is then distributed to all rooms in the house through a dropped ceiling plenum, eliminating the need for a costly duct system. Bedroom doors are undercut 1" to allow return air circulation back to the exchanger. Primary control is by a dehumidistat which automatically activates the heat exchanger fans. Secondary control is by manual "on-off" switches equipped with timers, located in the bathrooms. The "on" mode overrides the dehumidistat to provide ventilation of the bathrooms. The unit is also equipped with automatic defrost capability and a condensate drain line. A detailed isometric cutaway drawing and full explanation of the air-to-air heat exchanger system is presented to fully explain it's operation, distribution, and installation for the first time builder unfamiliar with the technology (see Figure 6).

## 3. CONSTRUCTION COSTS

A builder who is well versed in double wall superinsulated building techniques has estimated it would cost $58,027 for building the "Timberloft" in Butte, Montana in the summer of 1982. This price is for the basic house without the garage, and does not include land costs, contractor's overhead and profit, a rerigerator, and floor coverings, but does include everything else. The additional cost for the garage was estimated at $6,123. Owner-builders should note that the estimate for materials only for the basic house was $36,267, and materials only for the garage was $4,082. For the preparation of these estimates it was assumed that water, power, and sewer were all within a distance from the site that is usually found in a residential setting, and that no unusual excavating problems would be encountered. In addition, it was assumed that the fixtures, appliances, and cabinetry were all of good but not expensive quality, and typically available at local builders' supply houses.

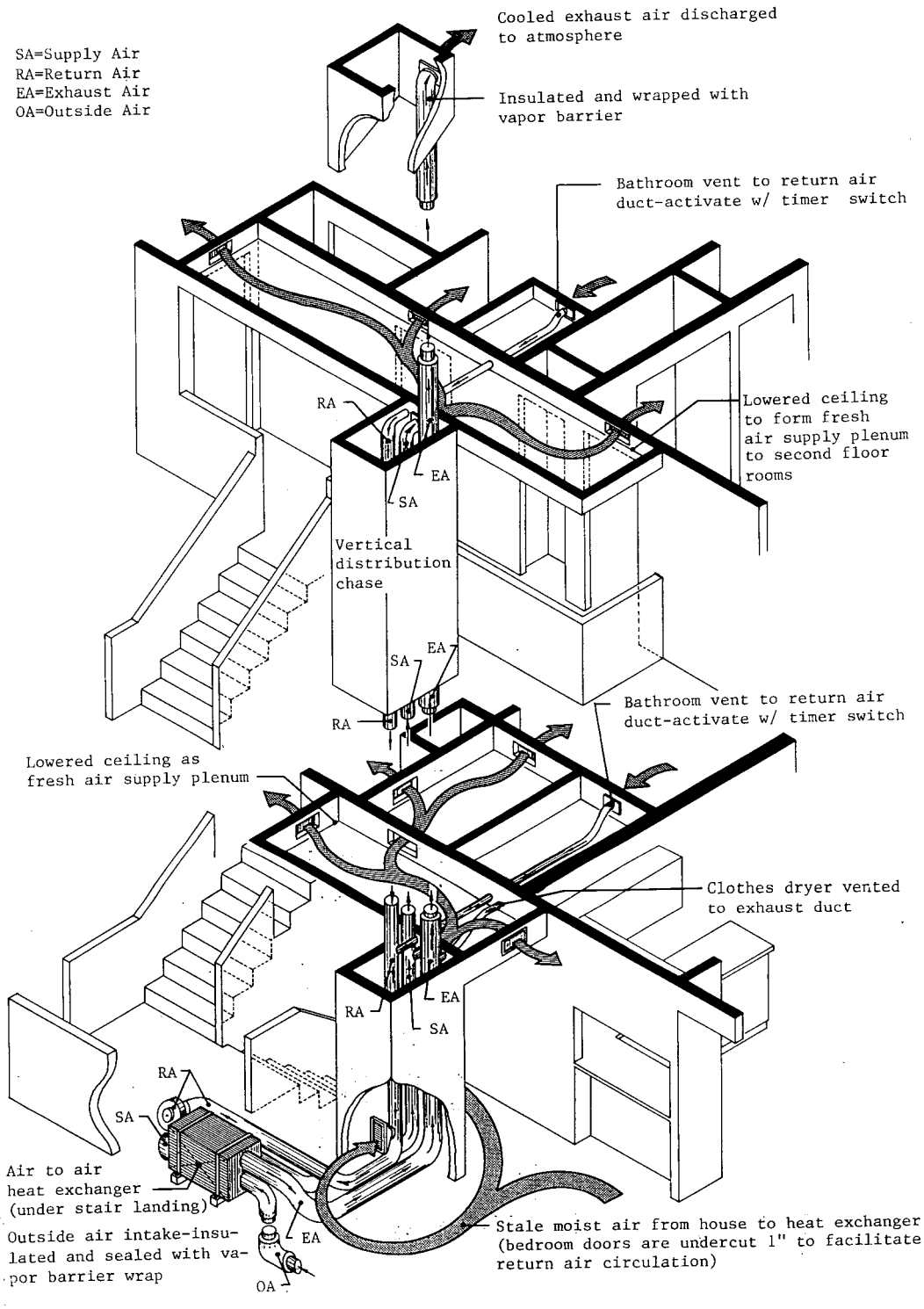



Fig. 6. Isometric Cutaway Of Air To Air Heat Exchanger System.

## 4. CONCLUSION

As of this writing, more than 240 sets of Timberloft plans have been sold to prospective builders in the colder regions of the United States and Canada. The authors are currently surveying the Timberloft planholders to determine how many houses have been built and where. Actual heating performance and construction cost of several houses will be reported in a future paper.

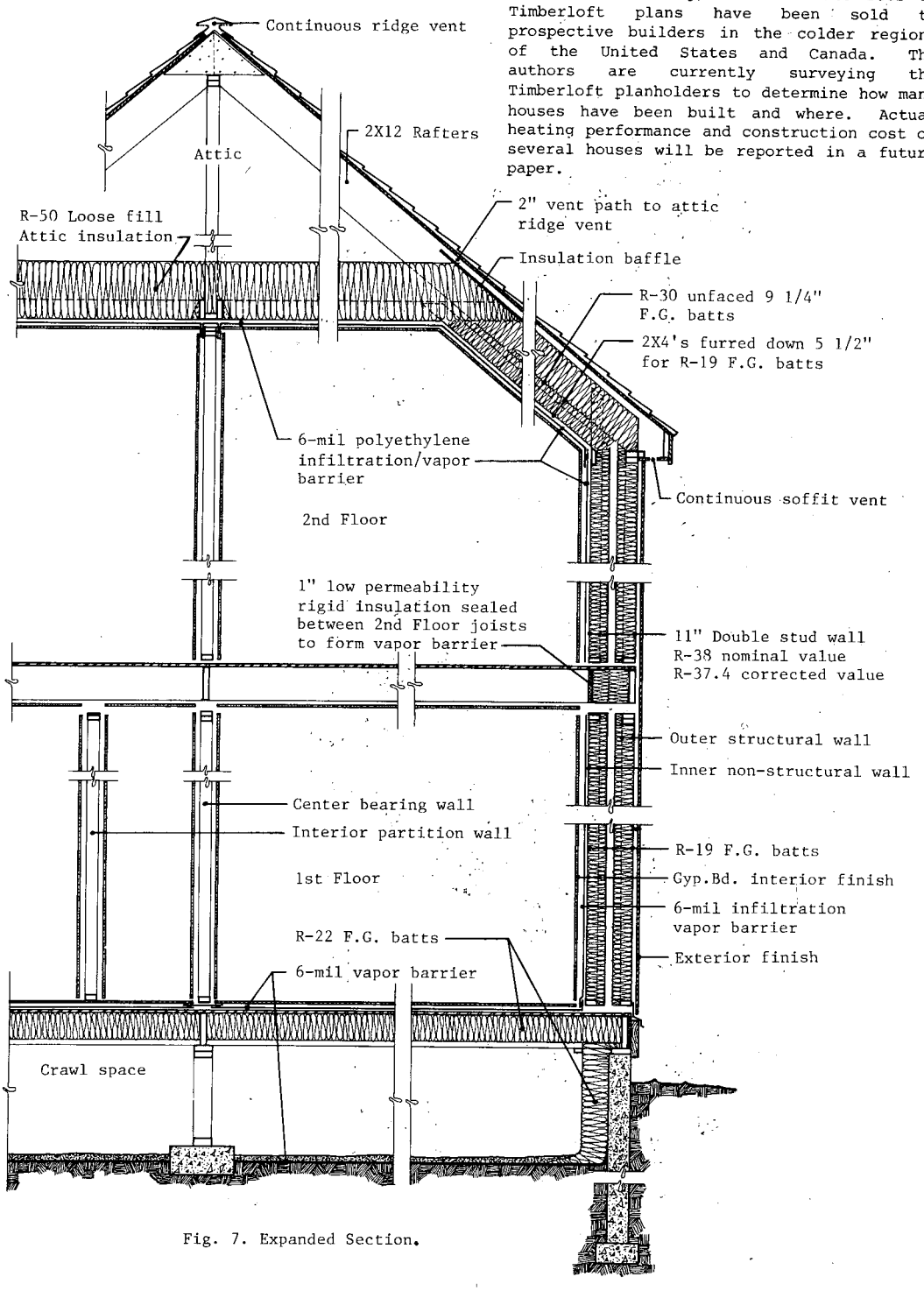



Fig. 7. Expanded Section.

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# BUILDING AS HEARTH
# THE ARTICULATION OF BUILDING MASS IN COLORADO ARCHITECTURE

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## ABSTRACT

Responding to a high altitude environment, Colorado residential architecture is being shaped by intense solar radiation, extreme seasonal temperature swings, potent winter winds and abundant snowfall. The emerging architecture finds form in responding to these forces through the articulation of mass and glass. Out of this expression of architectural mass, a new sense of hearth is evident as building mass is coupled with the sun to provide radiant warmth to the inhabitants.

## 1. HISTORICAL/ENVIRONMENTAL CONTEXT

The Rocky Mountains are a collection of unique geological forms, exposing endless organic expressions of rock, carved over millenia by wind, water and most recently man. This indigenous heritage makes use of masonry as an especially appropriate architectural extension of the natural Colorado environment. Remains dating back to the eleventh and twelfth centuries A.D. find Indian cultures, such as the Anasazi, constructing in and of stone to find security in cliff dwellings. Longhouse Pueblo at Mesa Verde, Colorado is perhaps the most notable example of the use of native stones as the primary building material. Combining stone from the cave, timbers from the mesa above, and clay from the river below, terraced dwellings were constructed within the cliff face. The geometry and material resulted in a relatively stable thermal environment, as the heat storage ability of the stone acted as thermal mass for the living space within. Seasonal sun angles interacted with the upper edge of the cave opening to provide full winter exposure, as well as summer shade to the exposed inhabitants (Figure 1). In this way, the communal form is a very natural response to site and microclimate, resulting in a visually harmonious order spilling out of protected rock face.

Man's use of masonry became especially obvious in the late 1800s as the pursuit of the rare and valuable resources that lie within the mountains brought passionate prospectors into the Rockies. Severe manipulation of the environment took place as the miners tunneled into the mountains in search of their prize. Structures to process the extracted ore climbed up the mountain sides toward the mine shafts above. To support the extensive mechanisms that crushed and separated the ore, substantial masonry foundations were constructed to integrate the mill into the steeply sloping building sites. These monumental walls were the product of stone masons from as far away as Belgium and China. Many of the massive stone retaining walls remain today as a permanent reminder of man's interaction with the mountain.

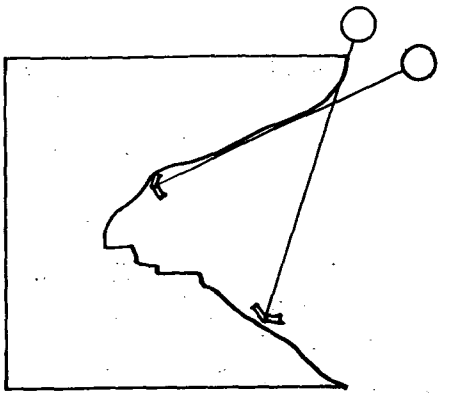


Fig. 1. Cliff Dwellings at Mesa Verde, CO

Through the years, Colorado architects have looked to masonry to marry their structures with the colorful and angular stone environment. This can be seen throughout the state in "Ski Country" stone and timber residential architecture, or in more monumental structures such as the University of Colorado campus in Boulder, or I. M. Pei's National Center for Atmospheric Research, also in Boulder.

Until recently however, masonry has been used more for its aesthetic and indigenous qualities, than its thermal capacity, which is realized when the mass is isolated from exterior temperature swings, and charged with the intense solar radiation available at these elevations. It is the assemblage of mass and glass, oriented with the dynamics of the sun, site and people, that is the essence of Colorado solar architecture. Given the historical attraction of using masonry in mountain architecture, the major shift that contributes to the thermal capability of the building mass, is the internalization of the masonry. With the mass isolated from the exterior thermal environment, the designer has new opportunities to articulate the mass and glass in ways that not only increase the solar contribution to the thermal comfort environment but also exploits the qualitative potential of mass as an architectural device. We will explore a series of architectural patterns that relate to the use of mass in Colorado Architecture.

2. PASSIVE SOLAR ARCHITECTURE IS FIRST A RESPONSE TO SITE AND CLIMATE. BUILDING MASS SHOULD RELATE TO THIS CONTEXT TO PROVIDE EXPOSURE TO SUN, BUFFER FROM THE COLD AND CONNECTION TO THE EARTH.

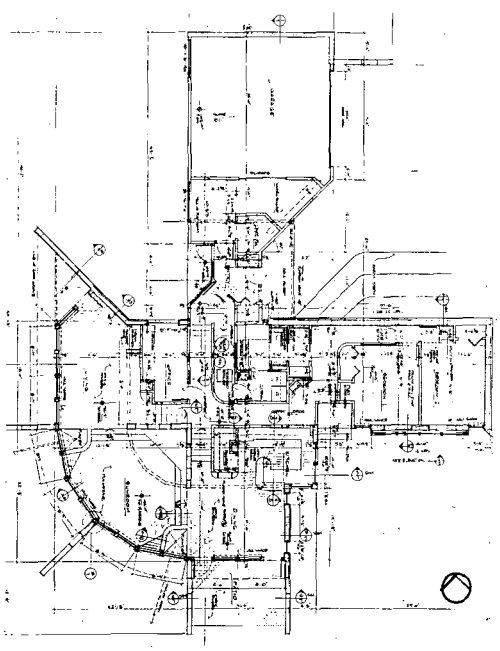


Fig. 2. Foss Residence, Boulder, Colorado

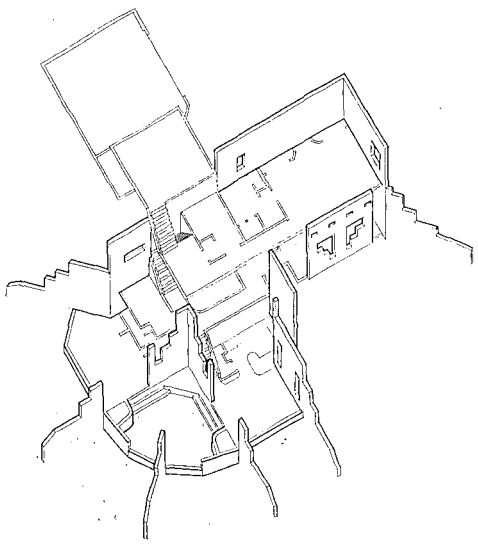


Fig. 3. Foss Residence, Mass isometric

Set in a south/west facing hillside west of Boulder, Colorado, the Foss Residence opens to sun and spectacular alpine views while nestling into a gradual slope (Figure 2). The masonry forms seem to grow out of the bedrock profile which the terraced structure follows and rests on (Figure 3). Bermed retaining walls to the north shelter the intense windward exposure, while exterior buttresses to the south and west act to support roof structure and window walls. The stepped wingwalls, which are thermally isolated from the interior, also act as windbreaks to the immediate sunny exterior pockets. Site placement provides for two basic living zones. The sleeping zone to the southeast is a two story structure with parents' above two children's bedrooms. A 16 ft x 16 ft Trombe wall acts as the nighttime heater. Openings puncture the one foot thick stuccoed concrete wall to provide direct gain into the children's spaces for morning warmth while framing views of the valley below. The stepped openings also provide a sunny place for sitting and contemplation as well as surfaces for potted plants. The second zone is the more communal spaces for living, dining, cooking and office. These direct gain spaces open to the panoramic views of the Continental Divide. Functional definition is provided by interior mass wall elements and changes in floor, light and volumetric levels. Mass is evenly distributed throughout the direct gain zone in the form of exterior (with outside insulation) retaining walls, interior mass dividers and loose laid brick floors on slabs. The heart of the primary living zone is a recessed garden room with integral mass steps/seats and planters. Central to this space and pivotal

to the radiating exposed roof structure is an intersecting vertical mass element that supports the roof, defines stair circulation on the backside, and acts as the focal hearth for the woodburning stove. The stable interior temperatures in such an intense high country environment is the result of cumulative building mass arranged around the functional living patterns in a very site specific architectural response.

3. DUE TO THE PHYSICAL QUALITIES OF MASONRY, i.e., THICKNESS, DENSITY, COLOR, TEXTURE AND THERMAL CAPACITY, MASS CAN BE USED AS AN ARCHITECTURAL DEVICE TO FUNCTIONALLY ZONE, DEFINE SPACE AND SUPPORT STRUCTURE IN WAYS THAT ADD A RICH, COHERENT THREAD TO OUR BUILDINGS.

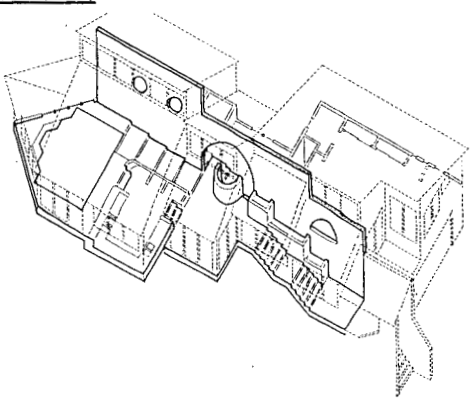


Fig. 4. Smith Residence, Mass Isometric

As we found in the Foss Residence, mass can provide the language that satisfies the functional and thermal needs for structure. In responding to the uniqueness of the site and client, the Smith Residence is an example of expressing mass in the form of earth toned plastered concrete block and local flagstone pavers (Figure 4). In this case zoning is accomplished through the development of an east/west spine wall that follows the gradual east/west slope. The timber frame is hung off the spine wall to enclose a more public living zone to the south, and a private bedroom zone to the north. A recessed sitting room links the two zones through a large arched opening, where the nighttime fire is enjoyed before retiring. Other circular and arched openings puncture the spine to allow the flow of air and light from the southern clerestory windows into the more intimate northern realm. The sunstruck spine wall radiates warmth to the adjoining spaces while acting as the architectural thread that defines circulation and seperation while tying the structure to the site.

4. DUE TO THE WEALTH OF EXISTING MASONRY BUILDING STOCK, FOUND MOSTLY IN OUR CITIES AND NEIGHBORHOODS, RETROFIT CONSTRUCTION OFFERS OPPORTUNITIES TO REUSE EXISTING BUILDING MASS IN WAYS THAT CAN BETTER PROVIDE FOR OUR THERMAL COMFORT WHILE RENEWING THE QUALITY OF OUR LIVING ENVIRONMENTS.

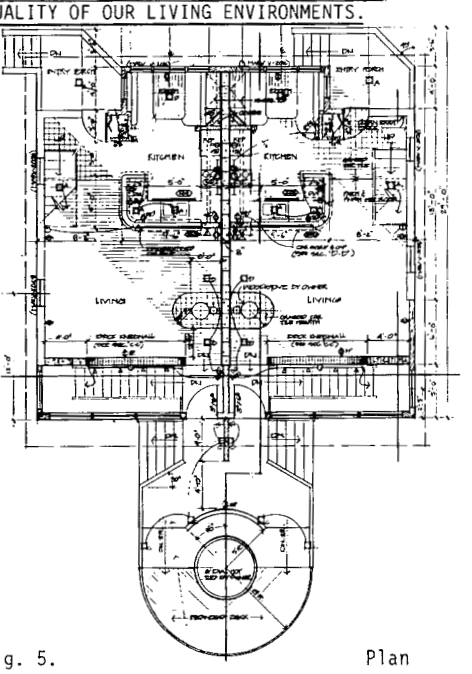


Fig. 5. Plan

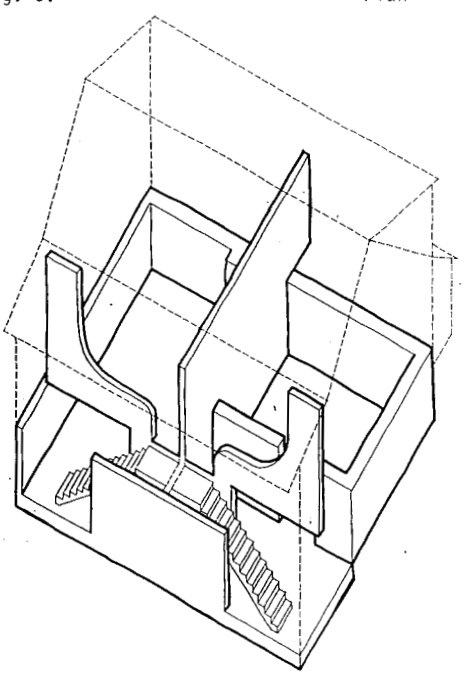


Fig. 6. Lopez-Marshall Duplex Isometric

Existing masonry structures often have distributed their mass in ways that is either ineffective thermally, or even detrimental to the thermal performance. This mass is usually in the form of masonry vaneer exterior skin, uninsulated solid exterior masonry walls, fireplaces and uninsulated foundations. In some cases we are able to locate our solar aperature in a way to strike the mass with the sun. It is then essential to properly size the mass/glass relationship to adequately store and distribute the solar heat. Insulation or isolation of the existing mass is also critical to minimize the thermal bleeding to the outside environment. In the case of the Lopez-Marshall duplex conversion, much of the mass was relocated to satisfy a total reorientation to the longer E-W axis (Figures 5 and 6). The townhouse units in this way share equally in access to the southern exposure for sun, views and access to a private yard. In opening up the southern exposure, sun is brought into the heavily massed foundation, enabling it to serve as a habitable space, rather than a dark cold basement. The existing solid 16 in. thick uninsulated exterior walls were insulated to the exterior to bring them into the stable interior environment. Brick that had been removed from the southern exposure was recycled into new sunstruck mass southwall, articulated in a form to absorb solar radiation as well as frame a Boulder mountain view. The 1200 $ft^2$ units were developed within a budget of $40,000/unit in 1982.

5. MASS MUST BE COUPLED WITH SUN AND GLASS TO FUNCTION AS A PASSIVE SOLAR HEATING SYSTEM. THIS RELATIONSHIP PROVIDES OPPORTUNITIES TO EXPLOIT THE QUALITIES OF DAYLIGHTING. THIS MIGHT BE ACCOMPLISHED BY DIFFUSING SUNLIGHT, WASHING MASS SURFACES WITH LIGHT, PENETRATING MASS FOR SHARING LIGHT TO MORE REMOTE SPACES, AND GENERALLY BALANCING THE LUMINOUS QUALITY WITHIN OUR PASSIVE BUILDINGS.

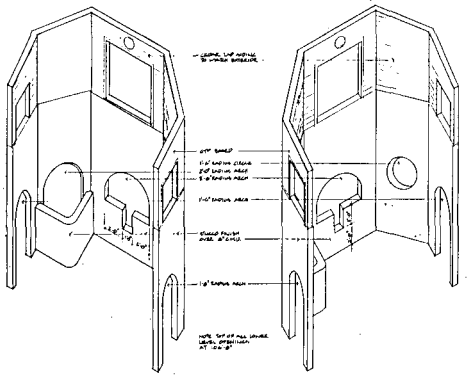


Fig. 7. "Warm Heart" Isometric

Passive solar structures run the risk of glare and uncomfortable light levels when the South wall alone is heavily glazed. An effort should be made to bring daylight into spaces from at least two walls. This can be accomplished through a combination of windows, skylights, or shared light so to provide a more consistent light level within the direct gain space. These methods of balancing interior light levels can often also provide for air flow and ventilation as penetrating mass and integrating operable overhead glazing can encourage air movement. The degree and quality of light should be designed to correspond with the desired function, mood and spacial experience. The play of light and shadow, rhythm with time, are qualities that architecture, which is in tune with the cycles of the sun and earth, can delight in. It connects us with our source.

6. WHEN MASS AND GLASS ARE EXPRESSED AS INTEGRAL ARCHITECTURAL ELEMENTS, ALLIGNING USAGE PATTERNS WITH THE RADIANT SURFACES, THE SPACES DISPLAY A NEW SENSE OF WARMTH AND PLACE, OR WHAT MIGHT BE DEFINED AS A NEW SENSE OF HEARTH.

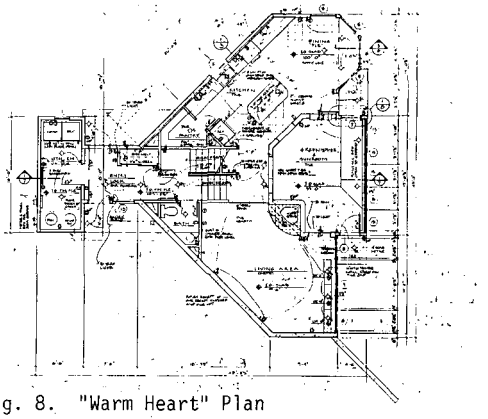


Fig. 8. "Warm Heart" Plan

With the internalization of building mass comes the potential to create people places that associate with the radiant qualities of the surrounding materials. Where the fireplace was once the focus of warmth in the home, the passive solar house offers a new potential for expressing this quality of fire and place. In this instance our fire is 93 million miles away, supplying warmth to the places and objects which we will gather in or around, sleep next to, eat on, or grow in (Figure 8). In claiming a slice of the sun the home not only becomes a vehicle for comfort and survival, but also a place for experiencing our connection with the universe.

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0731-8626/83$3.00

# A THERMAL HISTORY OF THE KELBAUGH HOUSE

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## ABSTRACT

The Kelbaugh House in Princeton, New Jersey, the first to incorporate a Trombe wall in the U.S.A., has been monitored for annual energy consumption since 1975. Auxiliary space heating, as well as DHW, cooking and electricity consumption have been recorded for eight years. Results are shown in tabular and graphic form and discussed in light of improvements made to the house over the years.

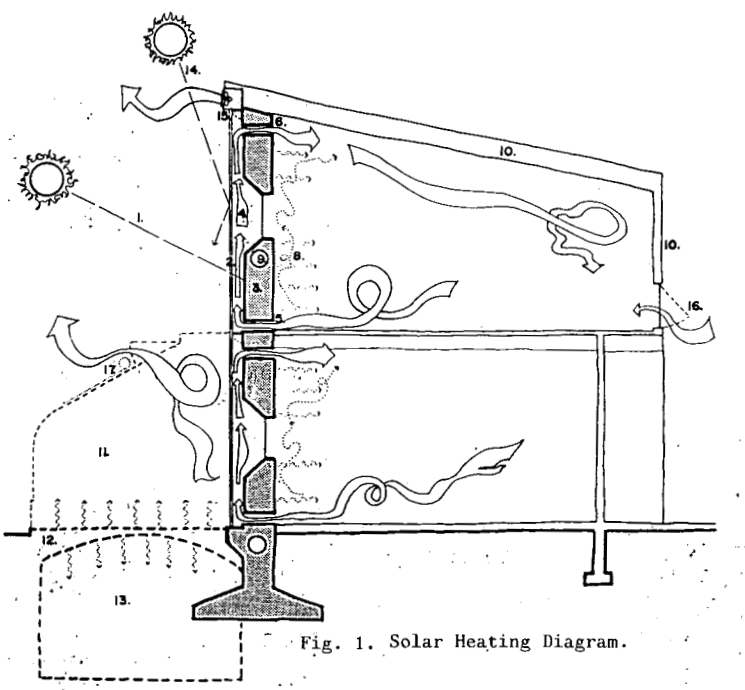



Fig. 1. Solar Heating Diagram.

## 1. CONSUMPTION, 1975-1983

The Kelbaugh House has consumed an average of about 27,000 Btu/ft$^2$ yr. This represents a total of 44 MMBtu per year for all energy uses. For the average year, consumption was divided into rougly 40% space heating, 40% DHW and cooking and 20% lighting and appliances. In recent years, after improvements in the design, total consumption has been as low

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

as 21,000 Btu/ft$^2$ yr or 35 MMBtu per year. At an averaged cost of $9.68/MMBtu, the average energy bill for the house has been $428 per year. Space heating the primary beneficiary of the house's passive solar system, has consumed 19 MMBtu per year or 2 Btu/ft$^2$ DD on the average. Assuming a furnace efficiency of 67%, the average space heating load has been 13 MMBtu per year or 1.4 Btu/ft$^2$ DD.

The space heating cost, at a recorded average natural gas cost of $6/MMBtu, has been $114 per heating season over the history of the building.

## 2. COMFORT

The house has provided reasonable comfort for the past eight winters and summers. The furnace thermostat has typically been set at 62°F during winter days and 55°F at night. The author estimates that the average daytime temperature during winter is 63°F downstairs and 66°F upstairs and that the mean radiant temperature in the house after a sunny day adds two or three degrees Fahrenheit to the apparent air temperature. On winter nights the downstairs typically drops to between 55°F and 58°F on the first floor, but rarely below 60°F on the second floor. During early and late winter, the air temperatures are often in the low or mid-70's on sunny days, sometimes allowing the occupants the thermal luxury of opening a window or two. The furnace typically runs in the morning to warm the house up about 4°F or 5°F, occasionally during the day if it is cloudy, and in the evening after thermosiphoning has stopped but before the inner surface of the Trombe wall has become warmer than the air. During extended periods of cloudiness, the Trombe wall becomes a thermal liability and uncomfortable to live with unless the furnace runs more frequently. The luminous environment in the house is entirely satisfactory. Many visitors remark that there is a surprising amount of natural light admitted through the Trombe wall and that the house is brighter than they expected.

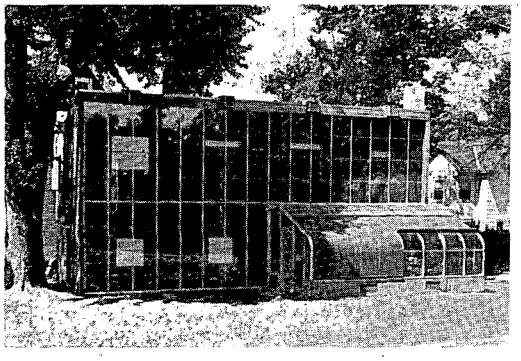


Fig. 2. House from the South.

## 3. IMPROVEMENTS MADE

### 3.1 1976 After the First Winter

Sunspace double-glazing. As a standard lean-to aluminum Lord & Burnham, double glazing was a difficult and time-consuming job. Some custom aluminum pieces and glass had to be cut. It is estimated that the second layer of glass almost halved the heat loss of the sunspace. This improvement played a major role in cutting the space heating consumption from 34.5 MMBtu for the first winter to 25.1 MMBtu for the second, much colder winter.

Trombe wall Check Valve. A simple flap made of very thin plastic film was scotch taped over the dozen upper openings on the inside of the Trombe wall. A hardware cloth ($\frac{1}{2}$" x $\frac{1}{2}$" mesh) screen prevented the flap from opening inward thereby arresting reverse thermosiphoning at night. This improvement also played a major role in the dramatic reduction of gas consumption for the second winter.

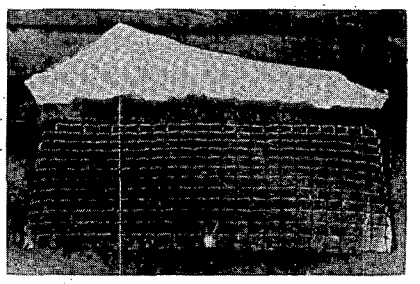


Fig. 3. Check Valve at Trombe Wall.

Moveable Insulation. At two upstairs windows, one inch thick styrofoam slabs wrapped in fabric were installed inside two aluminum tracks attached to the wall. They have since been raised above the window in the morning and lowered each night. They have had a miniscule effect on energy consumption but are a good night shutter for privacy and for locally boosting the mean radiant temperature. A large, miluim-lined curtain over an eight foot wide sliding glass door in the living room provided the same benefits on a larger scale.

Water Drums. To counter excessive temperature fluctuation in the sunspace (80°F on a sunny day, 40°F on a cold night) eight 55 gallon drums of water were added. They have flattened the diurnal temperature swings noticeably, but it still drops to the mid-30s on a very cold night at the outside corners of the greenhouse. Nonetheless, the floor register from the furnace has never had to be opened in the first eight winters. Several of the drums are developing pin-hole leaks after six or seven years (some of which have been patched without emptying the drum).

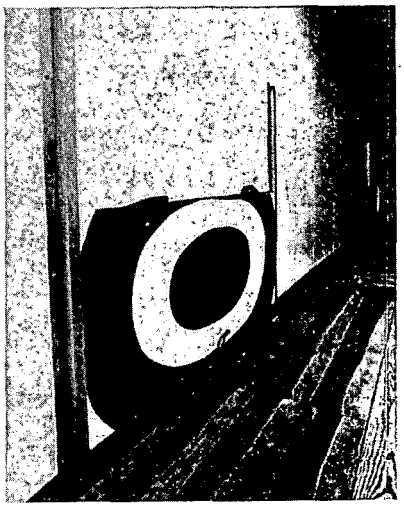


Fig. 4. Moveable Insulation.



Fig. 5. Water Drums in Greenhouse.

3.2 1977, After the Second Winter

Thermal Curtain. A heavy, lined, pull curtain was added at the ten foot wide archway between the sunspace and the living area. It was a belated, but obvious revelation to the author that keeping plants warmer than necessary at night was a waste of energy. The curtain is closed every winter night and opened every morning. It is not airtight so as to let the sunspace rob some heat back from the house at night. On very cold nights, the curtain is left 12-24 in.open to allow the sunspace to siphon enough warm air from the house to protect against frost. The curtain is remarkably effective at maintaining a high temperature delta across it. The author has measured a 7°F difference from one side of the fabric to the other. The curtain was a major reason that space heating consumption dropped from 2.6 Btu/ft$^2$ DD to 2.2 Btu/ft$^2$ DD the next winter.



Fig. 6. Thermal Curtain between Sunspace and Living Area.

Triple Glazing. All operable windows (but not sliding glass doors) on the north, east and west side of the house had storm windows added. The calculated and actual effect that triple-glazing this relatively small window area has had on energy consumption is small.

Stairwell Door. In an attempt to reduce the temperature stratification in the house, a door was added at the top of the open stairwell. It seemed to have little effect on the 4°F or 5°F difference that typically prevailed between the first and second floor. Because it was a nuisance and ineffective, it was demounted the next summer and never rehung. The family has simply learned to live with the difference.

3.3 1978, After the Third Winter

Little was done except the addition of hot air circulating tubes at the fireplace. A fresh air intake, overlooked during construction, was subsequently deemed too messy to retrofit in the concrete floor. The air tubes, which throw some of the room air back, seem quite effective but the fireplace is still estimated to be a net energy loser or break-even at best. The Kelbaughs continue to appreciate the localized comfort and cheer it provides and hope to install glass doors on it rather than convert to a wood stove.

They also continue to burn between half and a full cord of wood per season in the fireplace.

### 3.4 1980, After the Fifth Winter

Roof Vents. The arrival of a second child brought a flurry of changes in the house, after several years of energy complacency and gloating. While converting an office to a third bedroom, two roof vents were added, one in the master bedroom, another to vent the children's rooms. For the first five summers, the bedrooms had been poorly ventilated and stuffy. This problem was anticipated during design but it was too expensive at the time to include operable windows in the Trombe wall glazing. The vents at the eaves and in the Trombe wall did not provide sufficient natural cross-ventilation and the four small fans at the eave vents proved noisy and relatively ineffective. The new roof vents, plastic operable skylights of approximately 5 $ft^2$ area each, have immensely improved summer comfort on the second floor. (Summer comfort has always been good on the first floor).

Big Fins. Ten Big Fins were added to the greenhouse to preheat domestic hot water (see Solar Age, March, 1981). They have proved very effective and cut annual DHW Consumption by an estimated 8 MMBtu. We are able to turn off our gas fired DHW heater for June, July and August and depend entirely on the Big Fin, although there are occasional cloudy spells which produce only tepid DHW.

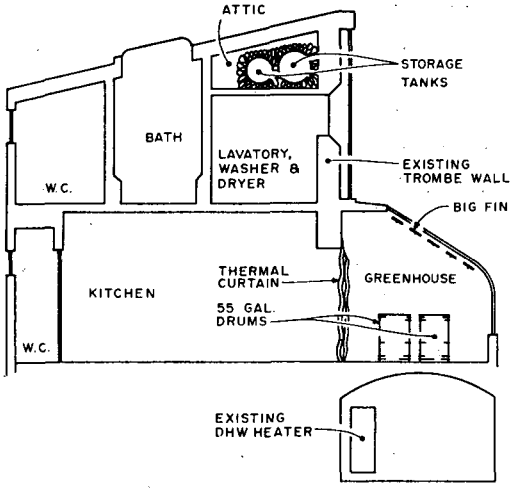



Fig. 7. Big Fin, Water Drums and Thermal Curtain.

### 3.5 1982, After the Seventh Winter

More Triple Glazing. After seven years, the author finally got around to installing a third layer of acrylic to several fixed windows and skylight. Their effect on energy consumption has been immeasurable.

Flue Dampers. Temperature sensitive metallic flue dampers have been added to the 3-4 in. flues of the DHW heater and furnace respectively. It is too early to judge its effect on system performance.

## 4. IMPROVEMENTS NOT MADE

The author has never been able to figure out an inexpensive and simply-installed way to retrofit a fresh air intake to the fireplace, which remains a thermal parasite. As noted above, glass doors are being considered.

Destratification fans or ducts have never been installed. The family has adjusted their life style in this case, retiring early to the second floor on cold winter nights or lighting the fireplace in the first floor living area.

An airlock at the entry has never been added despite its cost effectiveness. There is not enough space either inside or outside the house.

## 5. ACTUAL VS. SIMULATED PERFORMANCE

The author considers the measured space heating consumption figures to be accurate within 10%. Space heating load, however must be estimated because neither the seasonal nor instantaneous efficiency of the furnace is known. Assuming a seasonal efficiency of 67%, the Kelbaugh House has averaged about 13 MMbtu auxiliary heating load per year. If calculated by the annual SSF method (Vol. 3, Passive Solar Design Handbook), the auxiliary heating load should be 16.4 MMBtu/year or 23.2 MMBtu/year, depending on whether a Degree Day Base of 60°F or 65°F is used. The annual SSF method is quite pessimistic. A closer look shows how sensitive this calculation is to the Degree Day base and to furnace efficiency. For instance, if either a DD base of 56°F or a seasonal furnace efficiency of 86% is used, the LCR simulation will agree with the measured performance. The older, SHF simulation method, on the other hand, is overly optimistic. With a DD base of 65°F, this method predicts an auxiliary heating load of 7 MMBtu - almost 50% less than measured.

Pay-back calculations utilizing measured auxillary energy consumption are equally unsatisfactory. Depending on assumptions of Degree Day base and furnace efficiency, the annual savings can vary tremendously - from 31 MMBtu to 52 MMBtu with the SSF method and from 59 MMBtu to 92 MMBtu with the now obsolete SHF method. Using the actual gas utility bill charges of the last seven years ($6/MMBtu), the simple pay-back period for the $10,000 incremental cost of the solar system ranges from 18 to 54 years. Actual pay-back will of course, be considerably quicker because the simple pay-back method does not account for an escalation in the real cost of fuel.

## 6. OTHER WRITINGS

An architectural documentation of the Kelbaugh House, beyond the scope of this paper, can be found in over 50 books and magazines. Other articles by the author about the house are in the Proceedings of the 1st, 2nd, 3rd and 5th National Passive Conference, as well as Solar Age (July 1976, March 1981), Home Remedies (M.A.S.E.A., 1981), Notes from the Energy Underground (ed. M. Wells, 1981), Solar 4 (Amerika Haus, 1981), and A.D. (November, 1976).

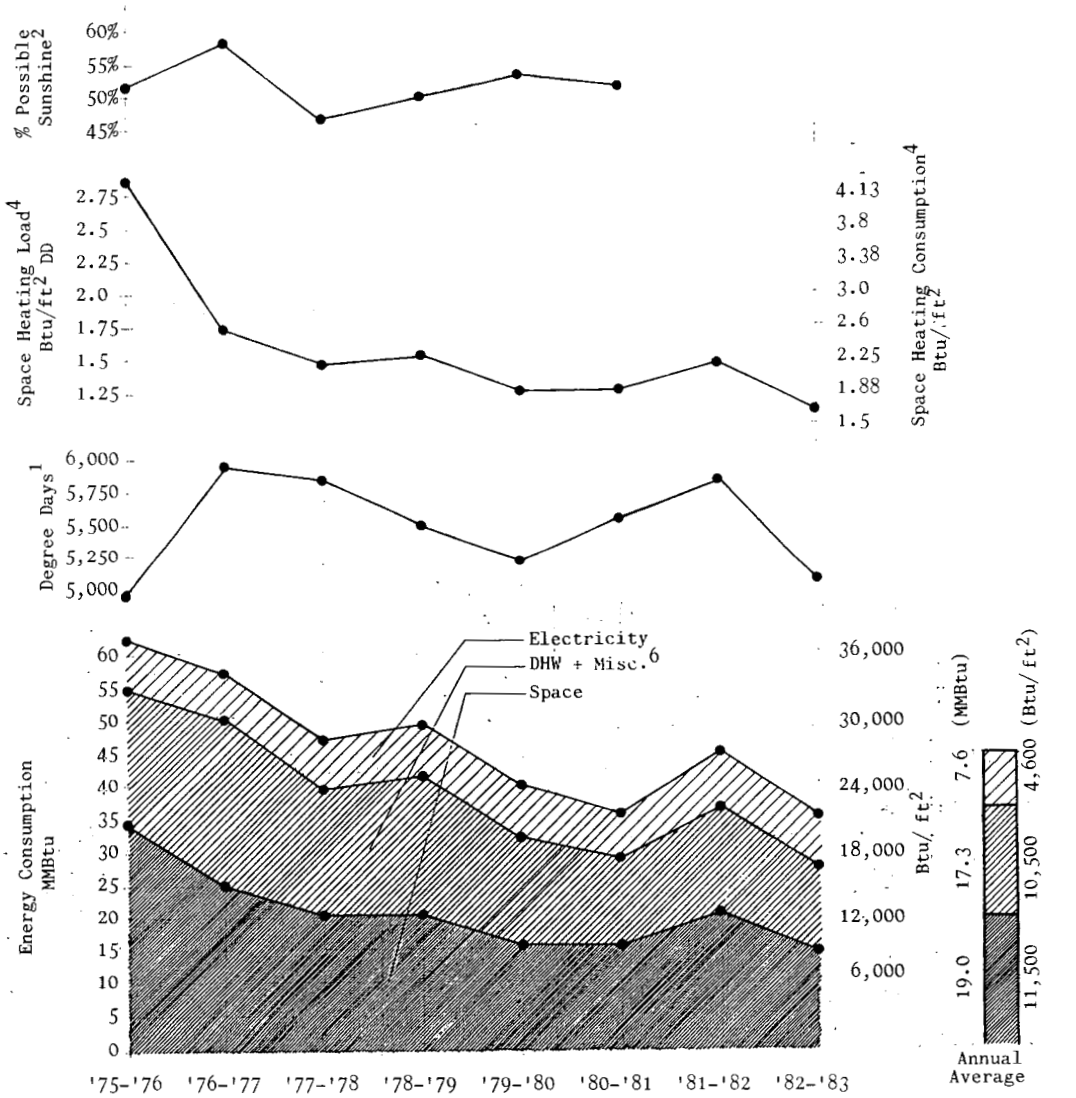



Fig. 9. Performance Graph.

| YEAR | CLIMATE | | SPACE HEATING CONSUMPTION/LOAD[4] | | | | DHW and MISC. CONS.[6] | ELECTRICITY[7] | TOTAL CONSUMPTION | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | DD[1] | PPS[2] | CCF[3] | MMBtu | MMBtu/ft$^2$[5] | BTU/ft$^2$ DD | MMBtu | kWh / $ | MMBtu | Btu/ft$^2$ | $ |
| '75-'76 | 4973 | 52% | 338 | 34.5 / 23.6 | 20,900 / 14,300 | 4.2 / 2.87 | 20.4 | 2194 / $155 | 62.4 | 37,800 | 338 |
| '76-'77 | 5934 | 58% | 246 | 25.1 / 17.2 | 15,200 / 10,400 | 2.56 / 1.75 | 25.1 | 2217 / $166 | 57.8 | 35,000 | 343 |
| '77-'78 | 5827 | 47% | 203 | 20.7 / 14.2 | 12,500 / 8,600 | 2.15 / 1.48 | 18.1 | 2449 / $183 | 47.2 | 28,600 | 356 |
| '78-'79 | 5501 | 50% | 200 | 20.4 / 14.0 | 12,400 / 8,500 | 2.25 / 1.54 | 21.1 | 2270 / $189 | 49.2 | 29,800 | 394 |
| '79-'80 | 5225 | 53% | 157 | 16.0 / 11.0 | 9,700 / 6,600 | 1.86 / 1.27 | 16.8 | 2138 / $195 | 40.1 | 24,300 | 393 |
| '80-'81 | 5546 | 52% | 157 | 16.0 / 11.0 | 9,700 / 6,600 | 1.86 / 1.27 | 12.2 | 2039 / $226 | 35.3 | 21,400 | 438 |
| '81-'82 | 5832 | - | 203 | 20.7 / 14.2 | 12,500 / 8,600 | 2.15 / 1.48 | 15.8 | 2484 / $265 | 45.0 | 27,300 | 543 |
| '82-'83 | 5060 | - | 136 | 13.9 / 9.3 | 8,400 / 5,600 | 1.66 / 1.11 | 11.9 | 2200 / $270 | 35.1 | 21,300 | 526 |
| Average ('76-'77 to '82-'83) | 5560 | | 186 | 19.0 / 13.0 | 11,500 / 7,800 | 2.07 / 1.39 | 17.3 | 2224 / $204 | 43.9 | 26,800 | 428* |

Fig. 8. Performance Chart

* represents average energy cost of $9.68/MMBtu

1. Degree Days in New Brunswick, N.J., 15 miles north of site (July to July).
2. Percentage possible sunshine in Trenton, N.J., 10 miles south of site (discontinued in 1981).
3. Natural Gas, 1 CCF = 102,000 Btu.
4. Upper number is energy consumption; lower number is estimated load, i.e., heat delivered to space assuming furnace efficiency of 67%.
5. 1,650 gross ft$^2$ heated area does not include 200 ft$^2$ greenhouse.
6. Consists of DHW, cooking and clothes drying; author estimates that DHW represents about 2/3 of miscellaneous consumption before installation of Big Fin and about 1/2 after installation.
7. Lights, refrigerator, 1 TV, 1 Stereo, 2 clocks, vacuum cleaner, fans, miscellaneous small appliances; upper number is kWh and lower number is cost.

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# SUNCATCHER MONITORING PROJECT: THREE YEARS OF MONITORING

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## ABSTRACT

The Suncatcher Monitoring Project has accumulated a wide variety of data on the Nittler/Maeda Suncatcher house located in Davis, California. The Suncatcher is an innovative passive solar house designed by Living Systems of Winters, California. Highlights of the data include a 81.5% solar heating fraction during the full monitoring period from March 1, 1978 to July 1, 1981, a 100% natural cooling fraction for the three and one half summers monitored, and an average 40% increase in solar gain through the clerestory glass due to the Suncatcher design relative to ordinary south facing vertical glass. Due to various problems, the hourly data acquisition system functioned intermittently during the monitoring period, but hourly data were gathered about 35-45% of the time and daily data was 99% complete. The daily data was gathered as both a complement and a supplement to the hourly data from September 1, 1977 to July 1, 1981. The total collected data has allowed a reliable estimate of the Suncatcher house's performance for both solar heating and natural cooling.

Special experiments, including the radiant isolation experiment, the special short wave radiation monitoring experiment, and the basal energy use experiment were completed in 1980 and 1981. The basal energy use experiment was used to derive a better estimate of the Suncatcher's heat loss coefficient and hence to recalculate loads and solar contributions. The results of the other special experiments are presented herein.

## 1. INTRODUCTION

### 1.1 Purpose

The purpose of this project was to monitor the thermal performance of an innovative passive solar residential design, Living System's Suncatcher House, and to provide detailed, quantitative data on the performance of the Suncatcher's reflective roofing design and the house's breadbox solar hot water system. An additional purpose was to compare the house's actual performance to the performance predicted by four computer programs. The programs used for comparison were SOLSIM, SOLEST, CALPAS3, and LASL6.

### 1.2 Location & Climate

The monitored Suncatcher is situated in Davis, California, at 38°32' North latitude and 121°46' West longitude, about twenty four kilometers southwest of Sacramento. The elevation of the site is approximately 18 meters (60 feet) above sea level. The climate of the site is very similar to that of Sacramento, a Local Climatological Data station.

Davis has 2819 heating degree days and 1063 cooling degree days with 1052 average annual hours over 26.7°C (80°F). The average daily maximum temperature in January is 12.3°C (54.1°F) an the average daily minimum is 2.50°C (36.5°F); while in July, the temperature typically varies between 35.1°C (95.1°F) and 12.9°C (55.3°F). The winters, while mild compared to other parts of the United States, can be quite uncomfortable due to the clamminess caused by the rain and fog, which tends to increase the need for heating. The three winter months of December, January and February have 420 out of a possible 887 hours of sunshine or about 47% possible sunshine on the average. The hot, dry summer months of June through September have 95% of the possible hours of sunshine and an average of twelve days per year when temperatures will exceed 37.8°C (100°F). Luckily, the hot, dry summer days are most often accompanied by cool evenings. In addition, the cool evenings are often associated with a light maritime breeze penetrating into the California Central Valley through the Carquinez Straits.

### 1.3 Solar and Energy Conserving Design of the House

The Nittler/Maeda Suncatcher was designed by Jim Plumb of Living Systems and is located in

Davis' Village Homes, a subdivision featuring a variety of active and passive solar home designs. The Suncatcher design is characterized by reflective soffits under the clerestory overhang and a reflective north sloping roof surface in front of the clerestory windows. This configuration provides enhanced collector area for reflective solar heat gain through 8.55 square meters (92 square feet) of clerestory windows during the winter months. The roof and overhang surfaces form a cavity that increases winter solar gain, while preventing overheating in the summer (see Figures 1 and 2). Manually operated, insulated shutters (R-6) inside the house reduce winter heat losses, and also decrease cooling loads by reflecting diffuse solar gain away from their exterior-facing reflective surfaces.

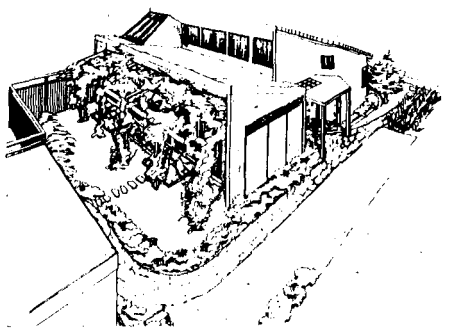
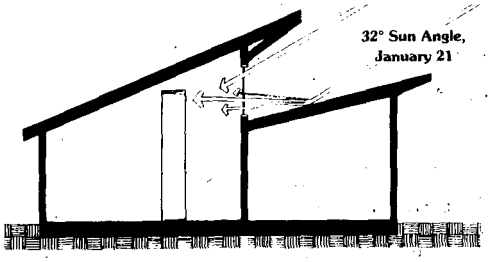


Fig. 1.




SUNCATCHER WINTER RAY TRACING

Fig. 2.

The central water collector thermal mass consists of seven galvanized steel culverts two feet in diameter and ten feet high, located seven feet behind the clerestory windows. The water-filled tubes, centrally located within the living space, remain at temperatures within or slightly above the comfort range (18.3 - 30.6°C or 65 - 87°F in winter; 18.3 - 26.7°C or 65 - 80°F in summer) and moderate temperatures in the residence. Three south-facing bedrooms are heated by direct solar gain through 14.5 square meters (156 square feet) of south facing windows, completely shaded in summer by a grape arbor. Heat storage in the bedrooms is provided by thermal mass in 208 liter (55 gallon), water-filled drums and the parquet-covered slab floor. The location of these drums is indicated in Figure 3 in section 2.1.

To reduce the impact of the Davis climate's severe cooling demands (more than 1000 hours annually above 26.7°C (80°F)) the house uses heavy wall insulation, double glazing and windows that are well-shaded from the exterior. Interior shutters and drapes also help reduce heat gain to a minor degree. Additional cooling needs are met with the storage of daytime and early evening internal heat in the thermal mass elements and later heat rejection by cross ventilation through the south windows above the collector/storage tubes and the north windows. Relatively consistent, cool evening and night breezes from the Carquinez Straits provide the driving force for nighttime ventilation. On calm nights the ten foot height difference between the operable clerestory windows and the operable north windows provides for ventilation via the stack effect.

The breadbox solar water heater has a net collector area of 3.34 square meters (36 square feet) of double glazed, tempered glass. The system heats water through a total of four tanks with a total capacity of 120 gallons. The two middle tanks are plumbed in parallel to each other and they in turn are plumbed in series with an inlet tank and a fourth tank for final solar heating.

Other energy efficient features include natural lighting with a light shelf above a south bedroom closet, an interior clerestory window providing additional light into the living room (on the north side of the house), a ceiling to north wall hot air circulation duct and fan, and a photovoltaic powered Casablanca fan. The house has fewer than normal appliances, the residents using only a stove, washer, refrigerator, and several small electric appliances. There is no dishwasher, clothes dryer (except solar), garbage disposal or trash compactor. The refrigerator is a used manual defrost model that is fairly energy efficient. The residents' demand for hot water and electricity is modest.

## 2. DATA ACQUISITION SYSTEM AND PROCEDURES

### 2.1 Sensors and Equipment

The Nittler/Maeda Suncatcher house was monitored with a variety of equipment. Temperatures were measured both daily and hourly with max-min thermometers and 130 type T iron-constant thermocouples. The

## SUNCATCHER FLOOR PLAN & SENSOR PLACEMENT

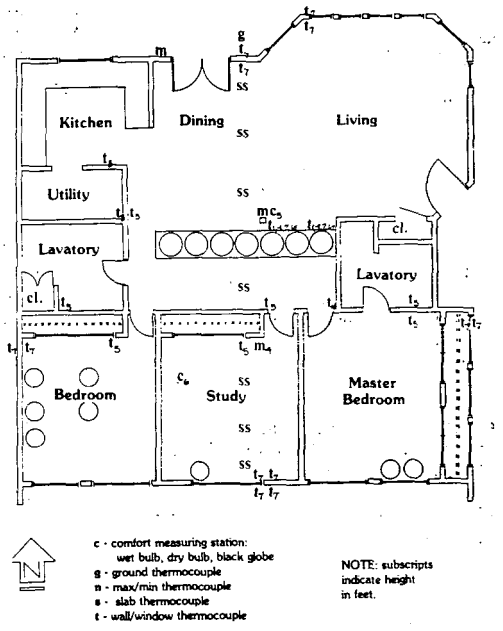



Fig. 3.

thermocouples were polled and recorded under the control of an IMSAI 8048 computer/ controller board. Three gas meters were used to monitor the furnace, the water heater, and overall gas usage, and three electric meters were used to monitor the refrigerator, the lighting circuits, and overall electric usage. A BTU meter was used to measure the output of the "breadbox" solar water heater. Solar radiation was measured by an Eppley PSP pyranometer and a small array of solar cells. Black globes and a heat flow meter shielded with polyethylene were used to measure radiant temperatures. Wind speed was measured by a Weathermeasure W121 recording system. A Thermatrace$^{tm}$ and rapid response thermistors were used for special experiments.

### 2.2 Daily Data Acquisition

Daily monitoring and recording of meter readings and max-min temperatures began on November 2, 1977, and ended July 1, 1981. During the first several months procedures were adjusted and the final meters and monitoring devices installed. Nevertheless, some of the data gathered are valid through the full period of monitoring and the daily procedure did not change significantly after the additional gas meters were installed by the local utility company in February, 1978. Daily recording of the six utility meters and max-min temperatures for the outside, the south study and the living room, and the instantaneous value of the wind speed was taken at approximately 8:00 AM local standard time. In addition, weather data from the Davis benchmark weather station (located approximately one mile south of the house on an open site) at the University of California at Davis, was incorporated into our data. These daily data provided the primary information for our analyses of performance of the Suncatcher house.

### 2.3 Hourly Data Acquisition and DAS

After a variety of complications, the DAS started gathering data in August 1978, but despite several debuggings, system problems continued through May 1979; hourly data were gathered only sporadically, but with increasing reliability during the monitoring period. Overall the DAS functioned approximately 35-45% of the period from May 1979 to June 30, 1981.

A single board microcomputer did all the necessary collecting, storing, and initial processing of the hourly data gathered from temperature sensors within the house. The central processing unit was an IMSAI 8048 computer controller interfaced to multiplexing, analog to digital conversion and amplification circuits for the respective sensor input signals. The 75 to 90 channels were first selected by a CMOS analog multiplexer, then amplified with a high performance modular CMOS chopper, and finally converted from analog to digital form using a monolithic successive approximation A/D converter with 8-bit resolution. The computer controlled the multiplexing, amplification and conversion, and received the 8-bit data words through its I/O port. Data was temporarily stored in random access memory (RAM) and later transferred to a paper tape punch. This microcomputer system was well suited to the relatively simple tasks required of it. Pre-processing of data was kept to a minimum since all programming was in machine language. Since interrupt capabilities of the 8048 had been pre-empted by a PROM monitor, the on-board timer was not available for providing the time during the data logging. Real time was provided by an external crystal controlled clock that was interrogated by the computer.

The paper tape was later transferred to magnetic tape for further reduction and analysis on the Burroughs B6700 or the B7800 computer at University of California at Davis.

### 2.4 Special Experiments

A few special experiments were performed during the course of the monitoring. The first of these was a mapping of the interior distribution of solar radiation coming through the clerestory windows compared to the

insolation through the lower south windows. This was done on six separate days at various times during the year to determine the time variation over the annual solar cycle.

On the days of solar radiant mapping of the Suncatcher cone, hourly temperature data were taken for the water storage tubes from 8am to 6pm or later to determine the extent of thermal stratification of the water in the thermal mass storage culverts. Some of these data are presented in the section on performance results.

During the period from February 4, 1980 to February 9, 1980, a basal energy use experiment was conducted. Operational and occupancy effects were tightly controlled or eliminated to aid in determining the house heat loss coefficient and the impact of different operations. Due to the nature of much of the monitoring, the house could not be totally unoccupied, but it was possible to minimize occupancy effects to a substantial degree. One occupant, Lynne Nittler, slept in the house, kept meter readings, and checked the data acquisition system. The occupant's schedule and energy impacts were severely restricted.

Hourly data from two consecutive nights (February 5-6 and February 6-7) were used to calculate a new estimate of the house heat loss coefficient, HHLC:

$$HHLC = 280.6 \text{ watts-}^{\circ}C^{-1} \quad (532 \text{ Btu-hour}^{-1}\text{-}^{\circ}F^{-1})$$

This value indicated that previous heating loads had been underestimated.

On March 8, 1980, a day was spent on several experiments related to monitoring the infrared environment of the Suncatcher system. A ThermAtrace[tm], a black globe with a thermistor temperature sensor, and an air temperature sensor were used. Foylon[tm] was used to block the radiant temperatures of the windows and the water tubes in sucession and a transect of air and globe temperatures were taken.

The results of the globe temperature/air temperature measurements were inconclusive probably due to nonsimultaneity of measurements and lack of radiation shielding of the air sensor. The ThermAtrace[tm] picture demonstrated the anticipated infrared differences due to surface temperature differences amongst windows, walls, and mass storage tubes.

This experiment involved the direct comparison between insolation at the same height and approximately similar environment as the insolation received behind the Suncatcher windows. For a period of 6 weeks during late February and March, these two were measured under the same environmental conditions to compare south vertical insolation to south

## 3. PERFORMANCE RESULTS

### 3.1 Overall Performance

The overall three year average solar heating performance was 81.5% of the net load. Natural cooling performance was 100% by default since there is no backup cooling system. The gross heating load was determined by using the outside Davis station heating degree days to base 19.7°C (67.5°F) and deducting the inside degree days to the same base to account for days where the interior temperature was lower than average. The net heating load is the gross heating load less the internal heat gains if these gains were less than the gross load. Otherwise the net heating load was zero. New loads were calculated based on the estimate of the house heat loss coefficient derived from the basal energy use experiment. As previously mentioned the new house heat loss coefficient was calculated to be 532 Btuh/°F. The heating degree day base of 19.7°C (67.5°F) was chosen because a base of 18.3°C (65°F) normally includes internal gains and some solar gains to predict auxiliary energy use. In this case internal gains were deducted after the load calculations and solar gains were calculated as a residual from the net load. Moreover the average winter interior temperature was closest to 19.7°C (67.5°F).

Generally, the temperatures inside the house were quite comfortable, although early morning low temperatures were noticeably cool in summer and winter.

On the average the house interior maximums peaked over 26.7°C (80°F) nine days or about 54 hours per year. Only three of these days had maximums of 28.3°C (83°F) or more for an average of 18 hours per year. Only during a four day period in June of 1981 did interior maximums reach or exceed 25.4°C (85°F). Since this was a record minimum temperature spell, one would expect no more than one to two hours per decade to exceed 25.4°C (85°F) inside the house.

The utility bills and usages for the three years were:

TABLE 1. SUNCATCHER UTILITY BILLS AND USAGE

| YEAR | ANNUAL TOTAL | AVERAGE MONTHLY |
|---|---|---|
| Jul.78-Jun.79 | $135.88 | $11.32 |
| Therms | 205 | 17.1 |
| kWh | 2498 | 208 |
| Jul.79-Jun.80 | $162.09 | $13.51 |
| Therms | 237 | 19.8 |
| kWh | 2342 | 195 |
| Jul.80-Jun.81 | $173.82 | $14.49 |
| Therms | 190 | 15.8 |
| kWh | 2212 | 184 |

The average annual bill increased primarily due to rate increases rather than increased usage.

More details and extensive graphic performance information is available in the final report for this project to U.S. D.O.E., entitled THE SUNCATCHER MONITORING PROJECT - FINAL REPORT FOR THE PERIOD MARCH 1, 1978 TO JUNE 30, 1981, designation number, DOE/CS/30169-8, hereinafter referred to as the FINAL REPORT. The FINAL REPORT contains more information on all aspects of the monitoring mentioned in this paper.

### 3.2 Daily and Hourly Performance

Details, both verbal and graphical, of the daily and hourly performance of the Suncatcher house, integral solar water heater, and house components are given in the FINAL REPORT.

### 3.3 The Suncatcher Reflective System

The results of the monitoring and special experiments indicate several conclusions about the Suncatcher system:

-Winter energy increases of 40% over standard vertical south facing double glass. Peak hour doubling of the solation through the clerestory windows compared to the lower south windows.

-Doubling of the diffuse sunlight in summer, i.e., over twice as much energy transmitted in summer when both Suncatcher windows and the south study windows are shaded from direct insolation by overhangs. This indicates a need for operalbe reflectors for the Suncatcher windows in summer to prevent overheating problems.

-Although exact heat balances were not measured, additional heat gains in cloudy winter weather indicate a positive heat balance for these clerestory windows on all but the darkest cloudy days.

The Suncatcher design has many benefits in climates with little or no snow loads on roofs, although special care must be taken to avoid leaks because of the roof configuration.

### 3.5 Integral Solar water Heater Performance

The results of the separate metering of the natural gas used for domestic hot water and the integral solar water heater Btu and gallon usage over a three year period indicated:

| | |
|---|---|
| Solar water heater | 165.67 therms |
| Stand. water heater | 188.25 therms |
| Total Energy Needed | 353.92 therms |

Thus the integral solar water heater provided an average of 46.8% of the total water heating energy demand over a three year period. The total hot water usage during this period was 47,700 gallons or an average of 15,900 gallons per year.

### 3.6 Results of Special Experiments

The overall results of the radiation mapping were presented in section 3.3 above. Mapping also indicated that the primary solation was the ordinary pattern of direct beam through the windows and that this fell on the water columns. Additional solation from the reflective system was mostly diffuse though reflection patterns were visually evident.

Stratification in the water columns was typically 8.3°C (15°F) on a sunny winter day and 3.9°C (7°F) on a hot summer day. The value of mixing is not clear but most likely is quite small.

The primary result of the basal energy use experiment was the determination of the house heat loss coefficient (HHLC) mentioned in section 2.4 above.

Although different radiant temperatures were detectable, especially with the ThermaTrace™, and were measurably blocked by the low emissive Foylon™ fabric, the results of this experiment were inconclusive and the results difficult to quantify.

The shortwave monitoring experiment essentially confirmed the results of the radiant mappings done earlier in the project. The amount of solation transmitted through the double pane clerestory glass was equal to the outside insolation, hence the transmission losses due to the glass were compensated by the Suncatcher reflective system.

## 4. PERFORMANCE VERSUS COMPUTER SIMULATION AND ESTIMATION

### 4.1 SOLSIM

On December 7 and 8, 1978, two cold but clear days in Davis, California, the DAS and D.A.T.A. staff recorded 43 hours of intensive measurements. These measurements were then compared to hour-by-hour simulations of the Suncatcher house using a program called SOLSIM derived from the NBSLD program by the author of this paper. A series of ten simulations was integrated against the full spectrum of temperature data to simulate performance. The final simulations mock the temperature performance of the thermal water mass quite well. The slab mass temperatures appear to be accurate, but the average slab temperatures is difficult to compare to the geometric temperature distribution of the slab. Air temperatures in the simulation cycle with a

maximum of 6°F higher than measured temperature.

### 4.2 SOLEST

Earth Integral's SOLEST estimation program predicted a performance of 83% solar heating and 100% natural cooling for the Suncatcher. The house design analyzed was a thermally tight version with insulated shutters, some drapes, and low infiltration. Predicted gas usage for heating was 86.4 therms. This prediction agrees very well with the average gas usage per year of 86.2 therms. Even though the long term performance estimate was calculated two years ago, the accuracy of the SOLEST prediction is probably coincidental. However, previous predictions for a short period of real data were also quite accurate for this house.

### 4.3 LASL6

The designed version of the Nittler/Maeda house was run using the LASL6 program, which evaluates the house's passive performance using Balcomb's solar-load ratio technique. Using average climatic data, a solar heating performance rating of 84% was achieved. Comparing the house with actual 1978 data, a rating of 68% was found for that year which agrees well with the actual data; however, the house was not entirely finished with regards to its thermal performance for the winter months of early 1978. Hence this methodology appears to underestimate performance in this particular case.

## 5. GENERAL CONCLUSIONS

It is quite evident that the Suncatcher design provides a high percentage of solar heating, around 80%, and a high percentage of natural cooling, about 99.5%, at very low additional construction costs and a reasonable level of comfort. When compared to similar sized houses built in Davis, the Nittler/Maeda Suncatcher had no additional costs, although the owners did help with construction and this may have reduced costs. Despite the relatively poor solar economics of the Davis area - a mild climate having low loads and available, cheap natural gas - the Suncatcher design has proven cost effective.

Due to these results and solar design calculations for over 600 passive solar houses all around the country, including Alaska and California, and from the work of others in passive solar energy, Earth Integral, Inc. feels that all new housing (everywhere in the United States including Alaska) can achieve over 60% solar heating and natural cooling over and above the effects of good insulation alone. Moreover, in virtually all climates of California, except the hottest deserts, 100% natural cooling can be readily achieved. Solar heating can be done cost effectively using any of a variety of passive solar designs. Natural cooling is more difficult to achieve in some areas and will require designs more carefully adapted to the local climate.

## 6. ACKNOWLEDGEMENTS

Many people gave their time and effort to this project. The principal workers were Bruce T. Maeda, Paul W. Grant, Tim Allis, Kathy Treleven, John Stephens, and Ken Nittler.

The work was financially supported by the U.S. Department of Energy, Solar Heating & Cooling Research and Development Branch, Office of Conservation and Solar Application, under grant number DE-FG02-79CS30169. The contract administrator, Eric Simpson, at the Chicago operations office, was helpful and courteous throughout the project. The technical monitor, Dick Oswald, of T.E.A. Inc., was always helpful and available to answer questions. The Earth Integral principals and staff wish to extend their appreciation to the Department of Energy for support of this passive solar research project.

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(3) Maeda, B.T., Dean Anson, and Paul W. Grant, "Suncatcher Monitoring and Performance Evaluation Project", Proceedings of the Third National Passive Solar Conference, American Section of the International Solar Energy Society, Killeen, Texas; 1979.

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0731-8626/83$3.00

# SOLAR LEVITTOWN

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## ABSTRACT

The authors' work at developing passive solar technology for production housing has previously been reported in "Evolution of the Air Thermosiphon: Toward Production Housing" at the Sixth Passive Conference in Portland. That paper described a two home speculate development. This paper examines a 125 home passive solar development presently under construction in Santa Fe, New Mexico. The development consists of single family detached dwellings at a five unit per acre density, with passive solar heat provided by direct gain and trombe walls. Topics reviewed include site planning, with an emphasis on lot orientation, solar access, house design, "add-on" potential, cost savings with owner "do-it-yourself" options and construction cost economics.

## 1. INTRODUCTION

Nationally, there has been much discussion in recent years of the issue of affordable housing as high interest rates and escalating construction costs have forced the price of new housing ever higher relative to average earned incomes. In the City of Santa Fe, with a population of roughly 50,000, the problem of high cost housing is considerably more serious than for the nation as a whole. A Mayor's task force on affordable housing has just released a report showing that the median priced new house today in Santa Fe costs $105,000, affordable by only 8% of the families in the community (based on census income data and normal mortgage qualifying criteria). It is doubtful that any other statistic more starkly defines the problem than this one.

Within the community of designers and builders working in the passive solar field, there has been much discussion and little action on attacking the affordable housing problem. Because of market and financing conditions, most builders have been forced to the upper end of the price scale in the last three years. Only recent changes in market and financing conditions have made it possible to even consider production passive solar housing in an affordable price bracket. This paper describes such a project currently under construction by The Mark Jones Corporation in Santa Fe.

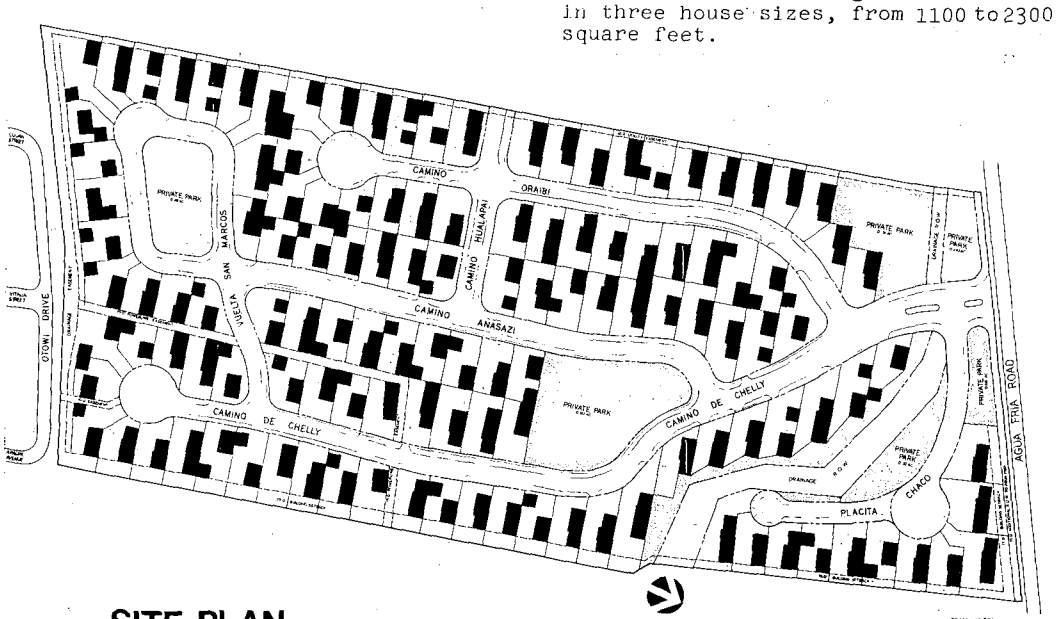
The Pueblo Alegre project is a R-5 density, 126 home, single family development with homes in the $60,000 to $90,000 price range. The project has several key features: 1) an intown, "infill" project location adjacent to a well-established neighborhood of similar lot size and price range; 2) the project is within easy walking distance of schools, churches, shopping and a local college; 3) the project is aimed at families with children and designed to provide maximum usability of private outdoor space; 4) the project utilizes a "sweat equity" concept providing the maximum enclosed square footage per dollar, designed for owner completion; 5) site planning and design maximize energy conservation and incorporate a variety of passive solar design strategies.

## 2. SITE PLANNING

Lots, typically 56 X 100 foot in size, are oriented in an East-West direction to provide solar access to the long side of the buildings. Using a zero lot line concept, the North wall of each house, which has no openings, becomes a garden wall for the next lot. Six foot adobe walls and wood fencing enclose the balance of each lot, creating a walled compound, the use and finishing of which is completely at the owner's option. This walled compound concept is a familiar and favored local tradition and provides for the screening of vehicles, outdoor storage, and a variety of landscapes while preserving a consistent streetscape. The short dimension of each house faces the street; and the varying setbacks of the houses themselves, along with the adobe privacy walls, provide architectural definition within an overall order. All this is achieved while providing full solar access to the South wall of every building in the project.

## 3. THE AFFORDABLE HOUSE

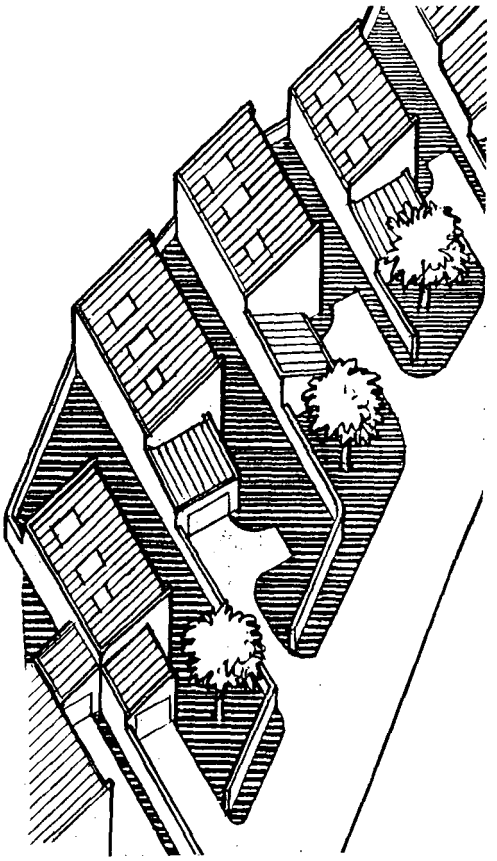
Structural budget limitations and a need to minimize lot coverage while maximizing interior volume led to a two-story, "loft" design concept. The main floor, with its key living spaces of kitchen/dining/living/bath are completely finished to allow owners to move in immediately. The balance of the spaces including the entire loft are unfinished on the inside allowing the owners a variety of floor plan options. Because the exterior of the building is totally finished, owners can complete the interior spaces at their own pace without concern for outdoor working conditions. Backup heating, electrical and plumbing stubouts are already in place and the City has approved the partially finished concept. A one-way sloping roof is inexpensive to install and minimizes shading of the adjacent lot. Finally, the flexibility of the building plan allows a traditional room layout or more contemporary, open plan at the owner's option. The basic building in three different lengths results in three house sizes, from 1100 to 2300 square feet.



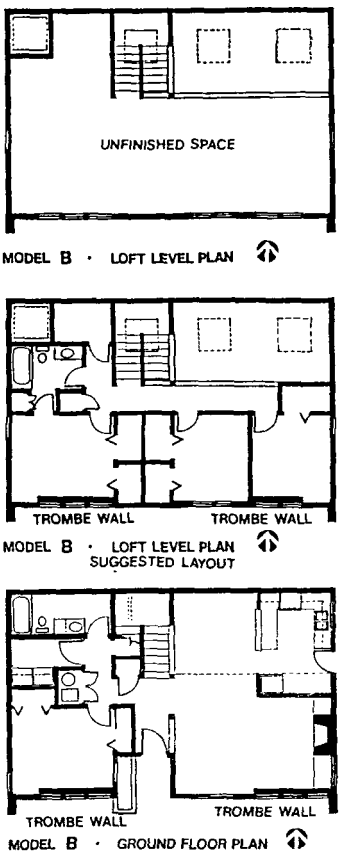

**SITE PLAN**

PUEBLO ALEGRE
PASSIVE SOLAR COMMUNITY

THE MARK JONES CORPORATION
SOLAR PROJECT ARCHITECTURE/DEVELOPMENT
p.o.box 892 santa fe, nm 983-7037
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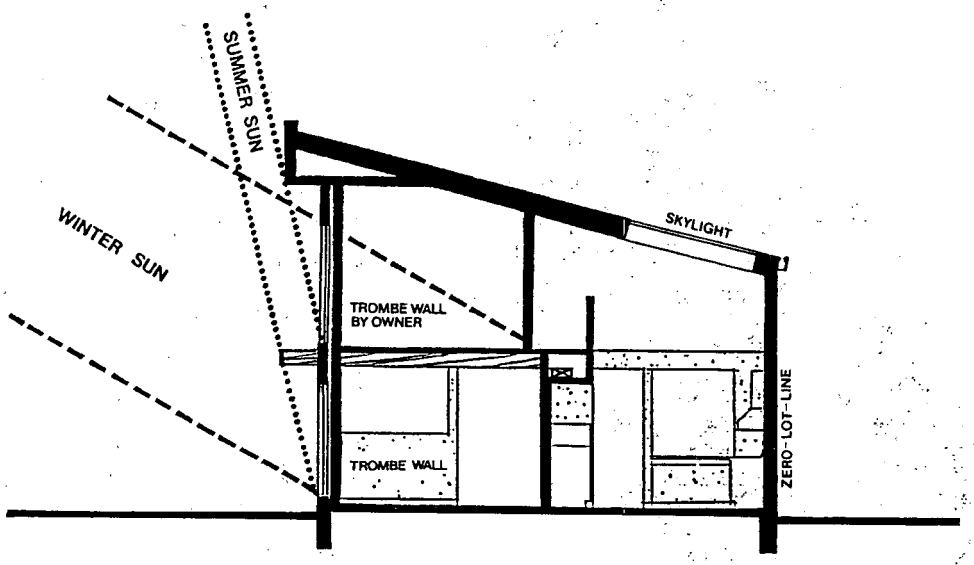
AERIAL AXONOMETRIC



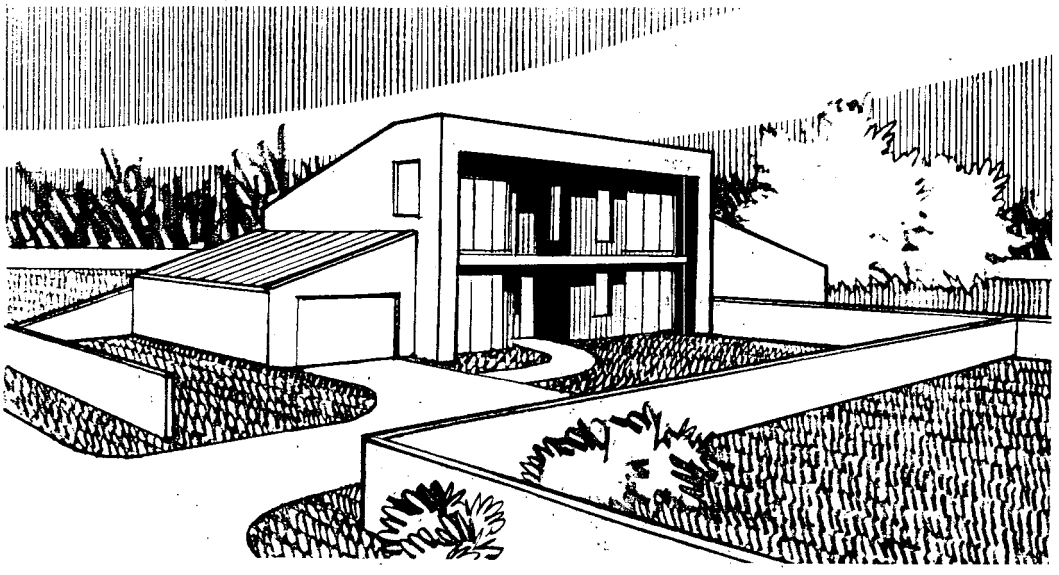

BASIC UNIT

4. PASSIVE SOLAR FEATURES

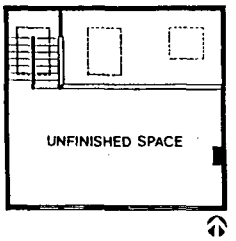
The design objective was to provide a combination of conservation and other passive strategies with the objective of reducing heating costs at least 50% relative to comparable conventional houses, Several familiar conseration strategies have been used: 1) reduction of infiltration to ½ air change per hour by careful use of materials and extra manhours for proper sealing of the house; 2) no openings on the North side of the house and very few on the East and West ends; 3) R-38 roof insulation and R-19 wall insulation; and 4) pilotless backup furnace and appliances. Trombe walls are the principal solar gain-storage device on the main floor, utilizing simple-to-build, relatively cheap 8" concrete block walls. In addition, the unfinished loft level provides the option for owners to either extend the Trombe wall upward through the loft level, or to provide mass storage in a variety of other ways such as water tubes or eutectic salts. A typical 1696 square foot home has about 298 square foot of south facing solar glazing and 23,000 lbs. of Trombe wall mass (with Trombe walls completed on both floors). Of the



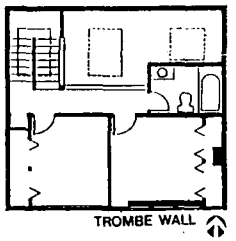

SECTION · SOUTH TO NORTH



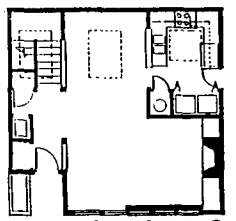
PERSPECTIVE OF BASIC UNIT



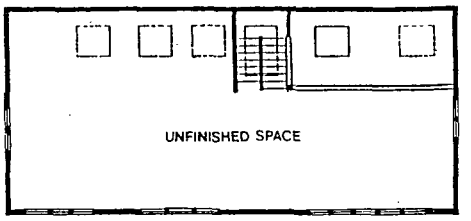

MODEL A · LOFT LEVEL PLAN



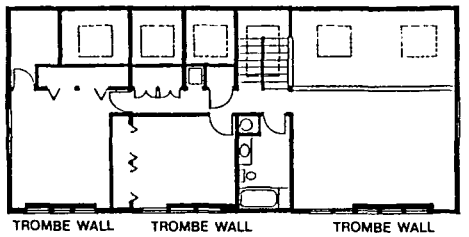

MODEL A · LOFT LEVEL PLAN
SUGGESTED LAYOUT



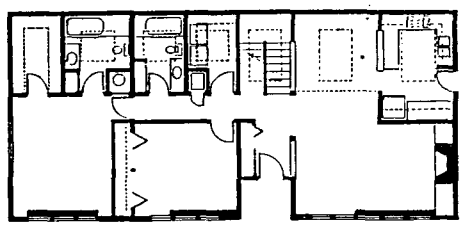

MODEL A · GROUND FLOOR PLAN




MODEL C · LOFT LEVEL PLAN




MODEL C · LOFT LEVEL PLAN
SUGGESTED LAYOUT




MODEL C · GROUND FLOOR PLAN

total glazing, 50 square foot are direct gain with thermal storage in quarry tile on concrete floors. This allows the balance of the building to be a straight-forward, low mass, low cost, frame structure while still providing adequate mass for solar storage and damping of temperature swings.

## 5. CONCLUSION

The Pueblo Alegre project is not an attempt to innovate new site planning or passive solar techniques. What it does do is to combine a variety of siting conservation/passive solar strategies and familiar production building techniques to provide quality, energy efficient housing in a well-planned neighborhood setting at affordable prices.

As a matter of comparison, the average price of conventional tract housing selling in Santa Fe today is $63 per heated square foot. Depending on unit size and level of finish, the Pueblo Alegre project will offer housing ready to live in at prices ranging from the high $30 to mid $50 per square foot range with most units under $45 per square foot total cost. Construction of roads, utilities and the first housing units began during summer, 1983, with the first deliveries to owners prior to the end of the year.

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# MEDIUM DENSITY PASSIVE SOLAR PRODUCTION HOUSING

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## ABSTRACT

The authors' previous work in passive solar production housing was reported in the Sixth Passive Solar Conference with a report on a two unit speculative housing development. This paper describes a completed 31 house passive solar housing development in Santa Fe, New Mexico. It reviews three house types heated by Trombe walls, direct gain or underfloor thermosiphon systems. The paper focuses on site planning, microclimate evaluation, solar access, architectural shading elements and natural cooling strategies.

## 1. INTRODUCTION AND BACKGROUND

The Housing Development is part of a larger, 189 acre, master planned development that the authors' participated in, as part of the development team, to create a combination of clustered and single family housing.

The master planning began in 1980. The process involved political, community and natural environmental considerations since the land is located within one mile of the historic Santa Fe Plaza and was immediately adjacent to several major water run-off channels, called arroyos, from the mountains east of town.

The re-emphasized goals of the master plan are the preservation of existing topography and vegetation, special attention to natural water drainage, solar access, views, and pedestrian walkways within the community. Special care was given to establishing restrictive convenants and architectural guidelines to insure the fulfillment of the goals. While the entire master planned development will take several years to be realized, this first development was designed to act as a prototype, for all future building, by accomplishing all of the goals on one of the most difficult sites.

The final clustered site plan of both attached and detached houses, results in a humanly-scaled streetscape. Each house captures expansive mountain and city views while retaining individual privacy of outdoor living spaces. This was accomplished by placing each street on top of the fingered ridges between the arroyos and "draping" the houses over both slopes of the ridges. The three basic house designs were begun after basic site analysis and housing design analysis continued together. As a result, a number of passive solar heating and cooling design strategies were employed to fit each individual site situation while still retaining the three basic house designs.

All of the houses are either completed or under construction and most are occupied. Many visitors have toured the model home located on the north ridge. The development is shown on the location map inserted below and those interested are welcome to visit.

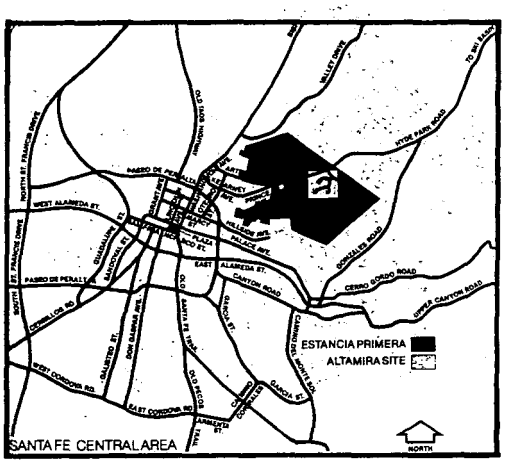



Fig. 1.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

## 2. PROJECT SITE

Figure 2 defines the complexity of the site. Topography, views, solar access, wind direction, traffic and drainage patterns were refined to compass directions. The primary strategy was orientation and site integration. Each house turns its back to the north winds of winter and spring's west winds, while allowing summer's predominant SW to NE breezes to ventilate each house. The primary views were determined to be to the southwest, southeast and northeast. The hot sun of summer was excluded by east and west overhangs and heavy roof insulation, while the south faces were exposed and heavily glazed to welcome winter sun. It was determined that three basic house types would accomplish our marketing, site and topographic strategies. These house types follow, pictorially situated on idealized topography Figure 3, House A.

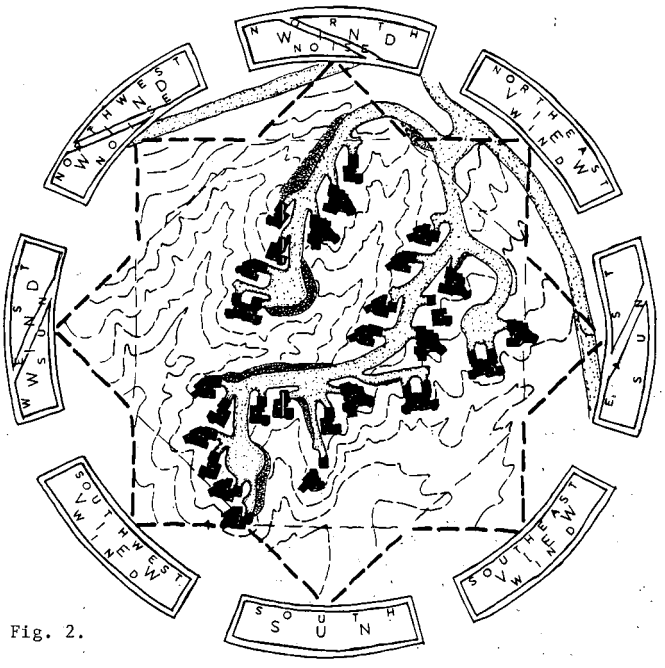



Fig. 2.

### 2.1 House $A_1$

Figure A contains 1575 gross heated square feet on two levels plus 280 square feet of usable basement space. The house combines regional architectural elements with a high l solar heating fraction, acheived by use of a Trombe wall, direct gain and a tall central stair/entry tower for return air circulation. The typical topography, as shown, defines House $A_1$ as a southwest slope house that steps down from the garage level to the lower elevation living area.

### 2.2 House A

House A is identical to House $A_1$, with the exception that it is "flipped" (mirror image) in order to fit a southeast slope, as shown. Note that garage orientaitons and levels have some variability to account for variations in road levels and orientations. The "A" houses fall on slopes similar to "B" and "C" houses, with the exception that the "A" sites drop off more steeply.

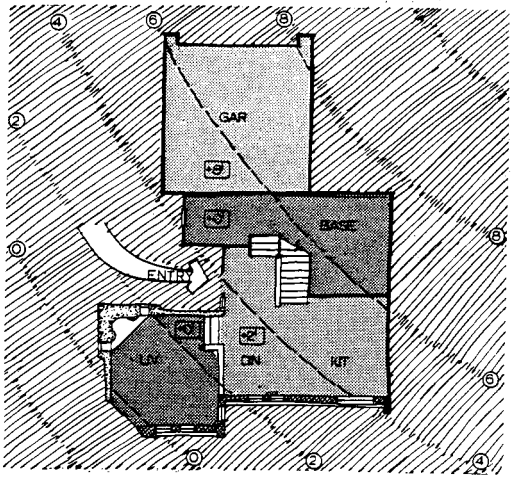



Fig. 3. House $A_1$.

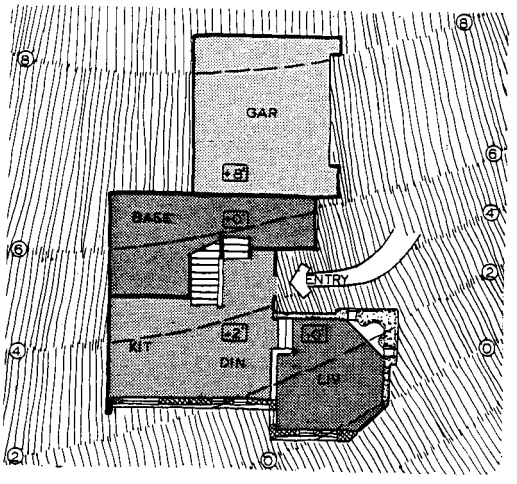



Fig. 4. House A.

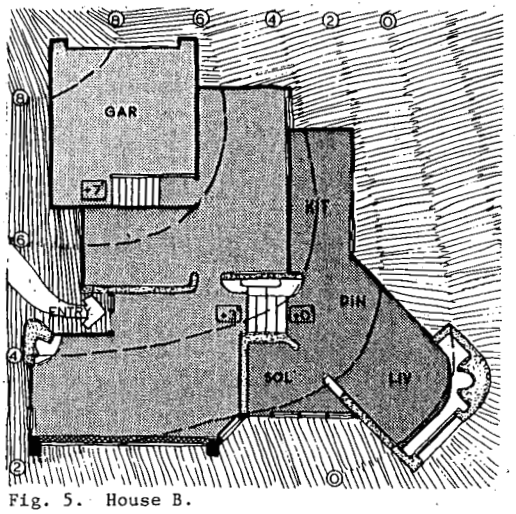


Fig. 5. House B.

2.3 House B - Thermosiphon

The house is the same as House B with the addition of a passive air thermosiphon system with underfloor block-bed storage at the intermediate bedroom level. The trombe wall radiant system is eliminated in order to avoid overheating due to the known and tested efficiency of the thermosiphon system. (Jones & Morris 1980 ISES Conference Vol.5.2). The B-Thermosiphon unit used when the natural topography at the building site has an arroyo or low elevation at ground level in front of the master bedroom suite. The thermosiphon system is described in these proceedings by Agnew and McIntosh, "A State of the Art Thermosiphon System". The primary hot air flow is to the north, and proceeds back to the south so that the most heat is released at the north end.

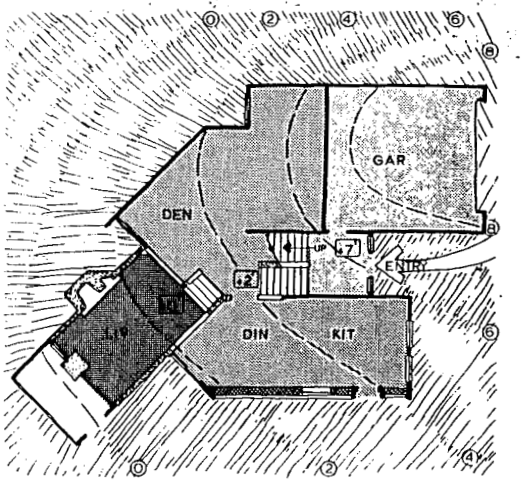


Fig. 7. House C.

2.4 House B

The house contains 2120 gross heated square feet on two levels with an additional 84 square feet loft storage located in the clerestory area. The house employs three solar heating strategies as follows: a trombe wall at the master suite, a solarium for direct gain onto masonry walls and floors, and clerestory glazing for direct gain onto adobe masonry flat wall and sculptured wall located in the interior high space of the house. The idealized topography shows this house located on a south to southeast slope with garage at the higher level (north or northwest location) bedrooms at intermediate level and kitchen/dining/living area at the lower level.

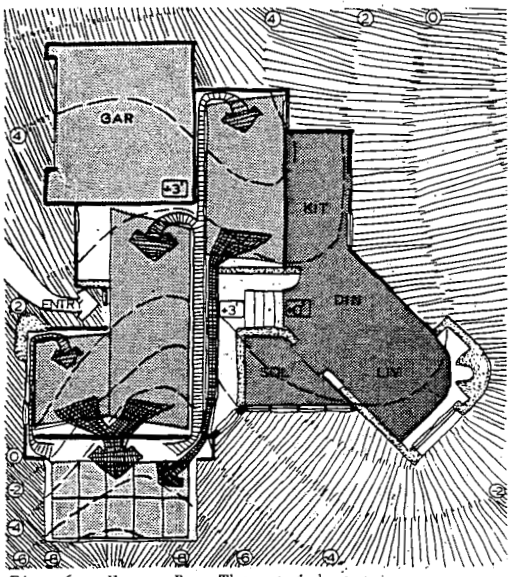


Fig. 6. House B - Thermosiphon.

2.5 House C

This house is the largest at 2614 gross heated square feet. The major passive heating strategy is a two story Trombe wall, horizontally divided to serve each floor separately, and a central clerestory (at the stairs and entry) for daylighting. The topography for this house falls from east to west and is usually located in the steepest slope areas.

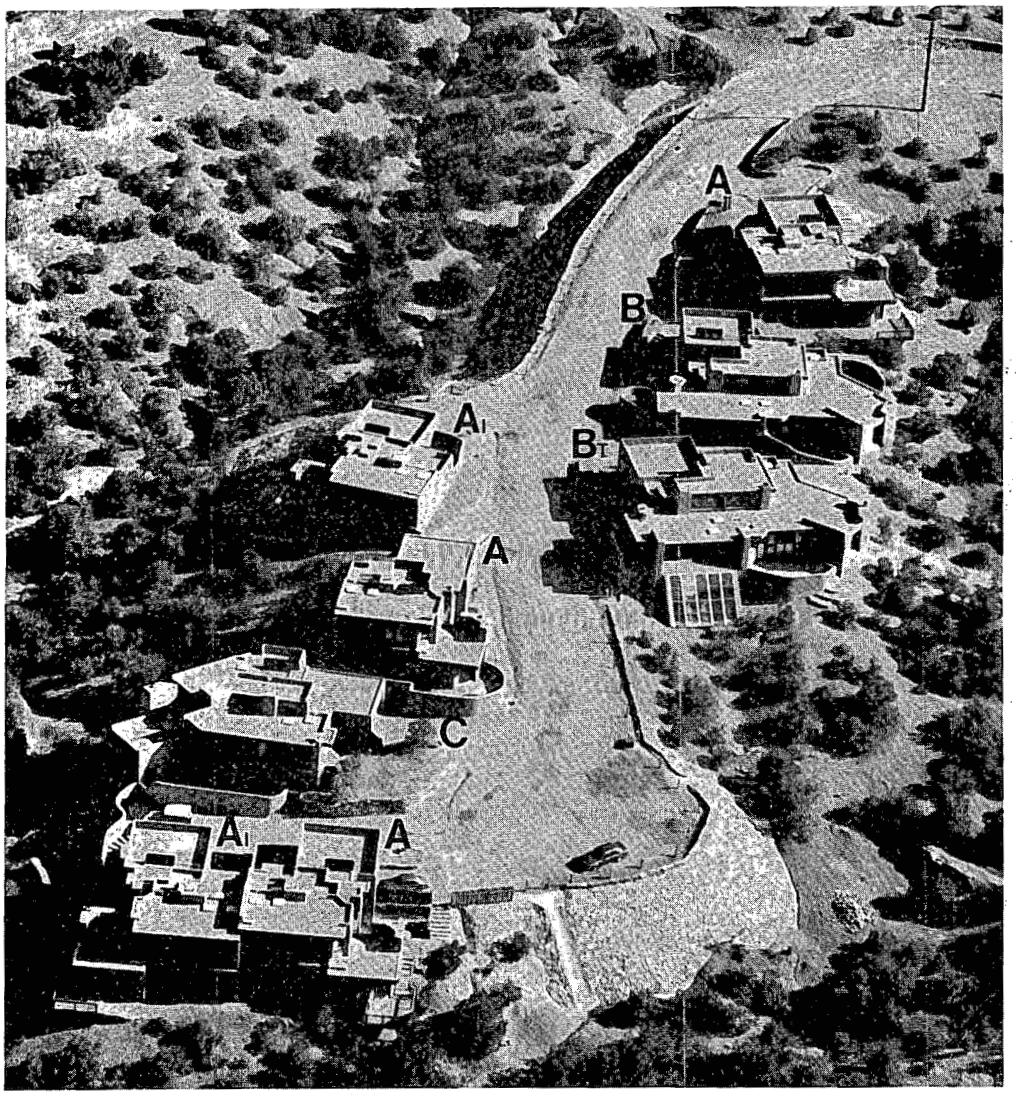



Fig. 8. Aerial Photograph of First Phase of Project.

3. VIEWS, SOLAR STRATEGIES & NATURAL COOLING

Figure 8 is an aerial photograph of the first phase, upper level, of the project. All house types were built in this phase because each topographical situation occurred and as our means of testing and refining construction techniques for the lower level houses.

Note on the aerial photography the attention paid to the preservation of natural vegetation and site conditions. Local stone was used extensively to prevent erosion. Virtually all vegetation was retained downhill from the houses. Entry and patio landscaping paid particular attention to the original, natural contours.

The photograph shows each of the house types, and the following figures relate directly to the photograph. The figures are shown to more clearly show the three dimensional aspects pertaining to views, solar strategies, and natural ventilating and cooling techniques.

Figure 9. House A was able to achieve a very high solar efficiency with a concentration of interior spaces to the south. The views and private outdoor areas are concentrated to the southeast and east. Cooling strategies utilize dominant summer air flows, ponding of cooler air, east overhangs and an insulated west wall.

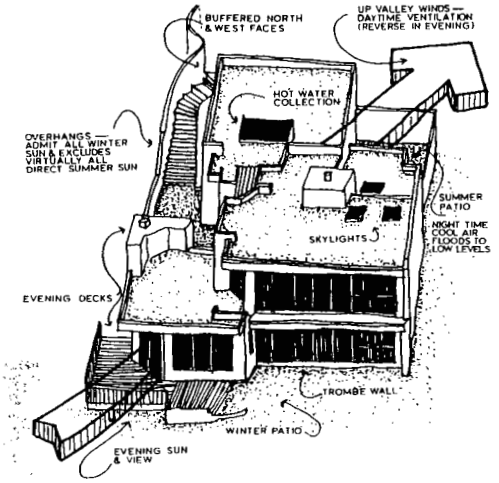



Fig. 10.

Figure 11. House B occupies topography similar to the A House and it also concentrates views and private outdoor areas to the east and southeast. The Trombe wall, clerestory, and solarium attempt to balance solar gain throughout the house.

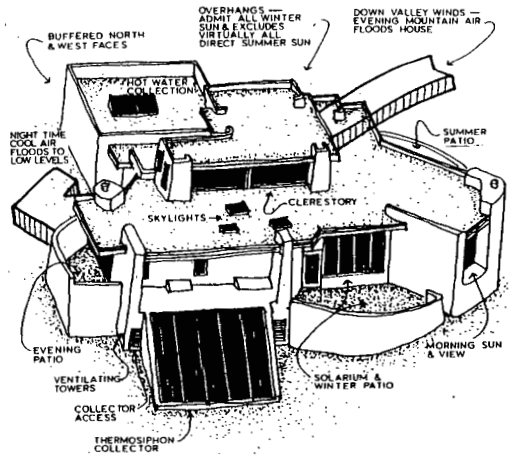



Fig. 12.

Figure 13. House C responds very clearly to the site determinates with it's nearly blank northwest walls shunning noise and wind and affording visual privacy for houses to it's northwest. The heating and cooling strategies are similar to the other house types.

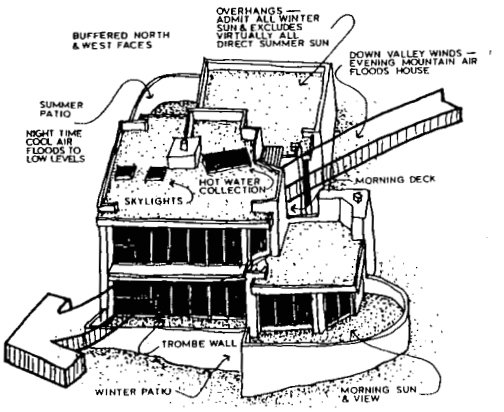



Fig.9.

Figure 10. House $A_1$ is the reverse of A. Views and privacy are to the southwest and west. Cooling strategies are similar, with the stair tower acting as a heat chimney. It's east wall may adjoin an A unit where site conditions permit.

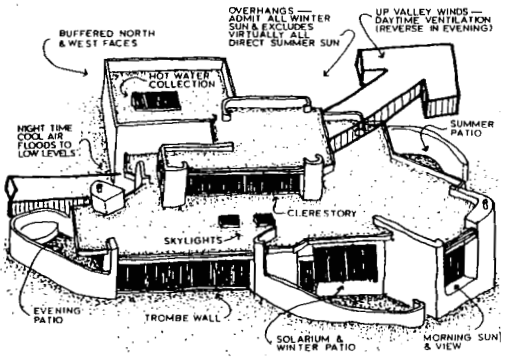



Fig.11.

Figure 12. House $B_t$. The thermosiphon replaces "B's" Trombe wall and can store solar gain further to the north. (See Figure 6 and text). Patio areas were developed to respond to daily and seasonal microclimatic variations.

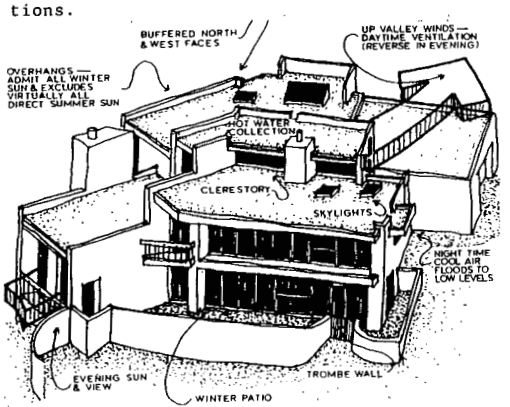



Fig.13.

## 4. CONCLUSION

This 31 unit housing devlopment shows the importance of a strong and clear overall creative and analytical approach, rather than the simplistic attitude of "let's build some passive solar houses". One of the most important aspects of this project is its success. Despite the economic recession, sales have been strong and property values have risen dramatically. The heating and cooling strategies have worked as well. User reports and our observations, show the predicted 60% to 80% solar heating fraction is correct. Also, a 5° to 15°F. indoor to outdoor temperature differential between June and August, show the cooling strategies are working. Individual site location and building design integration have worked very well for views, natural ventilation and privacy. The Mark Jones Corporation is looking forward to its next development to have the opportunity to both repeat and improve on this successful project.

## 5. ACKNOWLEDGEMENTS

There have been many invaluable people involved in this project. Doug Roberts analyzed the solar contribution, Scott Morris helped design and engineer the thermosiphon system. Dick Metzner, Tony Scozzafava, and Joan Daw have been invaluable during the construction and sales phase of the project.

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# THE PROVO OFFICE COMPLEX

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## ABSTRACT

The design concept for the Provo Office Complex in Provo, Utah includes a series of south-facing clerestories for daylighting and passive solar gain in this severe Rocky Mountain climate. An artificial lighting scheme is well-integrated with the strong and successful daylighting scheme. In addition, the design concept includes the integration of the architectural and mechanical components through the use of an AIRFLOOR concrete floor to provide a second return plenum. In conjunction with the return air plenum in the ceiling, a double return system is established where the most thermally beneficial return path can be used, depending on the temperature of the floor, the office space and the outdoor environment. Thus the thermal mass of the floor can be used to improve both the heating and cooling performance of the building.

## 1. INTRODUCTION

The Provo Office Complex is a 55,640 $ft^2$ suburban office building housing Department of the Interior district offices. Berkeley Solar Group (BSG), with Scott Matthews of Van der Ryn, Calthorpe and Partners, developed the energy systems design for architect Niels Valentiner of Salt Lake City.

The project is located in Provo, Utah, 50 miles south of Salt Lake City. The climate of Provo is characterized by cold winters (6766 heating degree days), and short hot summers (mean July maximmum temperature is 94 degrees F). Better than average year-round solar radiation makes combined daylighting and passive solar heating an attractive possibility in building design. The summer months also have a wide diurnal temperature swing and low relative humidity levels. These conditions make Provo an ideal site for the use of high thermal mass and night venting passive design strategies for cooling.

## 2. ENERGY CONCEPTS

The energy design concepts for the Provo Office Building were based on experience with the BSG Office Building retrofit in Berkeley, California[1]. The major question was: could a very successful integrated passive heating, cooling, and daylighting system be translated to a larger building in a more severe climate? The design goal was to provide nearly 100% natural lighting without increasing heating and cooling energy consumption over that of a conventionally designed building. The design was limited economically by a normal office building budget. The lowest contractor bid for the project was $0.5 million below the budget.

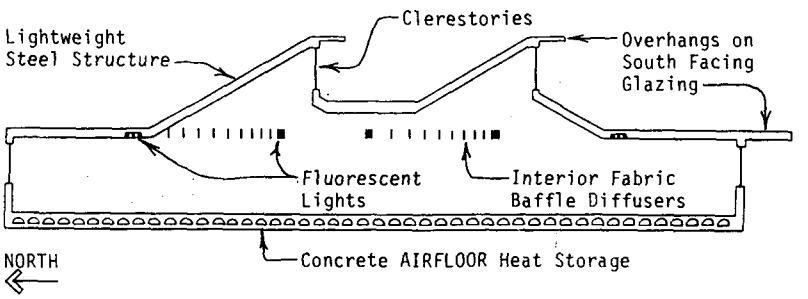



Fig. 1. North-South Schematic Section

Figure 1 shows a schematic section of the concepts which were developed. Daylighting is provided primarily through south windows and clerestories which are shaded to reduce cooling loads while still providing significant winter solar gains. The clerestories are spaced to provide daylight throughout the space. Interior fabric baffles intercept any direct sun and diffuse it for daylighting and to prevent glare. The building skin features high insulation levels and is of conventional light steel construction for low cost. Thermal storage for heating and cooling is provided in an inexpensive return air plenum through the concrete floor slab. The thermal mass is thus integrated with the building mechanical system where its impact can be carefully controlled.

## 3. BUILDING DESCRIPTION

Proper siting of the building was accomplished by elongating it along an east-west axis. This allowed more north and south facing glazing providing direct and diffuse solar gain for daylighting and passive heating. East or west facing glazing was limited to entrances. North and south glazing allowed a more even and controllable solar gain not associated with morning or afternoon peaks in the cooling load or glare problems caused by large expanses of east and west facing glass. Shading was also more easily accomplished on south facing glazing.

Fixed exterior overhangs and interior light diffusers control solar gain and prevent glare and contrast ratio problems. The windows are 4 ft high and the clerestory lights are 5 ft high. The resistance values for the opaque portions of the building skin are R-19 for the walls and R-30 for the roof. The effect of the wall insulation is augmented in many cases by earth berming.

The integration of architectural and mechanical components of the building provide a heat storage system in the floor of the building. Through the use of a product called AIRFLOOR the thermal mass of the concrete floor is used advantageously as a second plenum. In the heating mode, the warm floor will provide a radiant heat source for the space. In the cooling mode, it will function to store heat removed from the space. Night venting can then be used to discharge the mass. Thus the thermal mass of the floor can be used to improve both the heating and cooling performance of the building.

## 4. LIGHTING

The Provo Office Complex is designed as a one story office building. Given the one story configuration, it was assumed and then shown in the analysis, that full daylighting of the structure could be cost effective as well as conductive to a good office environment.

The siting with a long east-west axises provides large amounts of glass area on the north and south. North and south exposures are preferred for daylighting because they provide the most even and diffuse light. South facing windows must be properly shaded on the exterior of the building in order to provide diffuse light and minimize direct light. Diffuse light is best for daylighting because it is glare-free and easily supplemented by a uniform artificial lighting scheme. The redesign of the roof from flat to having two long south facing clerestories provided full daylighting to the interior of the building.

In the preliminary design stage, a 1/2 in. scale model was built to test the daylighting features of the building. At that stage in the design, an 80 ft building section was assumed with two clerestories facing south. A five foot height for the clerestories produced the best results, both in model testing and in computer simulation. The light levels across the building section on different types of days during the year are shown in Figure 2. A winter sunny day produced the best performance, but even under the worst overcast conditions tested, light levels were at least 30 fc everywhere in the building during daylight hours. The other curves shown on the graph are a sunny summer day and an overcast day, either winter or summer[2]. The end result provided relatively even daylighting in the interior under the clerestories and for one-half bay around the perimeter.

The basic specifications for the artificial ambient lighting system were as follows: Columbia Parabalume fixtures with GE Watt Misers II or Sylvania supersaver flourescent bulbs, or equivalent, and Mark III ballasts or equivalent. This efficient lighting system provided 60 fc at 1.25 watts/ft$^2$ everywhere within the open office plan. The ambient office lighting can be dimmed according to available daylight. The dimming process was simulated for the computer analysis as beginning at 5 Btu of solar gain per SF of zone to full dimming (no lights on) at 10-15 Btu/ft$^2$ of zone. The ambient lighting (natural or artificial) will be supplemented by task lighting as needed in specific task areas.

## 5. HVAC

The HVAC system is a system of varying return air paths that is both thermally efficient and well-integrated with the architectural design. Thermal mass was incorporated into the building in the form of floor mass and the HVAC system was tied directly to it as one return in a double return system.

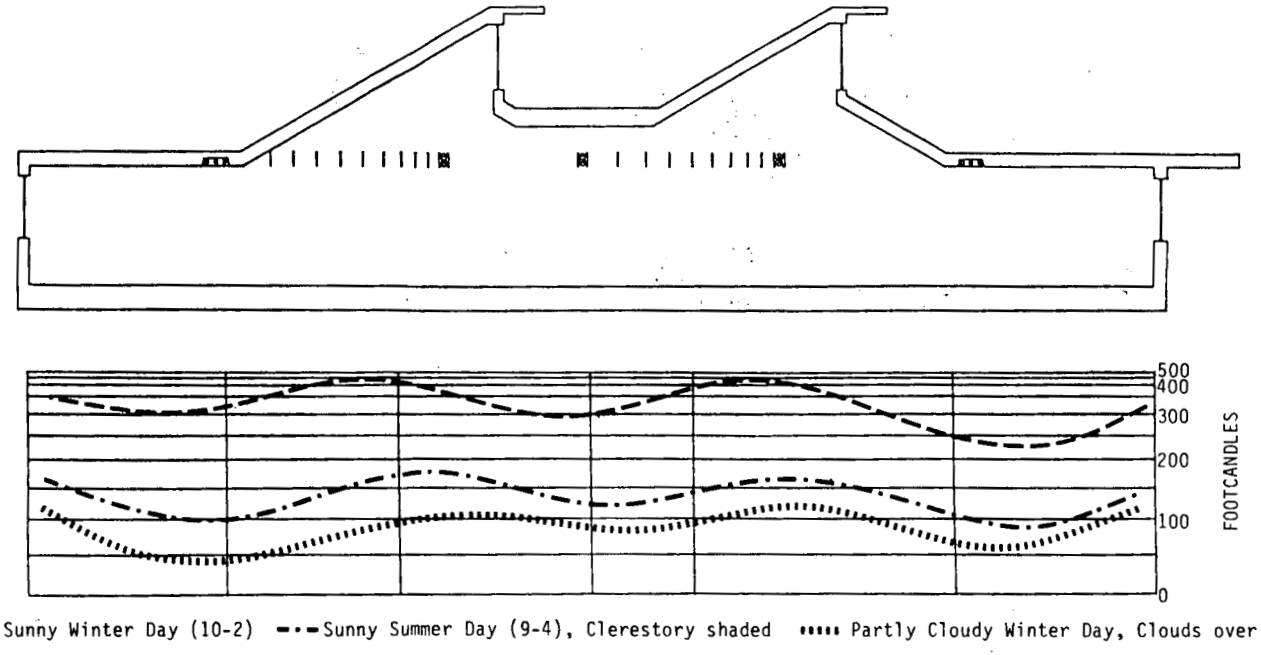



Fig. 2. Light Level Measurements from Daylighting Model

Placing the mass in the return air path worked better, both thermally and architecturally, than placing it in either the supply air path or exposed in the interor space itself. Other strategies investigated included summertime night venting to cool the building and mass down, and evaporative cooling and economizer operation for swing season cooling. The evaporative cooling did not offer significant energy savings and was expensive. Both night ventilation and economizer cycles were integrated into the overall scheme.

The floor mass can be used in all modes: heating, cooling, and swing-season. The rules that govern the double return system are simple in concept and easy to employ in the mechanical operating system. They are designed to take advantage of the thermal mass capacity when it is needed. Several modes can be operated with the system as designed (two are illustrated in Figures 3 and 4). On economizer cycle, when the building is operating on all outside air, the return should be through the ceiling. The floor mass will absorb some heat directly from the space.

The summer modes start with this scenario: If it is morning and the space temperature is floating up to the set-point, return through the ceiling: to prevent heating the mass up before the peak hour. Once the set point is exceeded, return through the floor will dump excess heat into the floor mass. Once the floor has heated up to 78 °F (the set point), the return should be through the ceiling, to prevent the floor from exceeding the set point. This last condition would only occur on peak summer days. During summer night venting, the return should be through the floor to cool the mass as much as possible. A reverse fan could supply air through the floor to make the mass even more effective.

The winter modes begin with this scenario: In the morning, if the space is colder than the heating set point, the return should be through the ceiling. Until the office air warms up, all the heated air should be used to heat the space. Once the office space is at the heating set point (68 °F), the return can be through the floor, keeping both the floor warm and the space warm. The radiant heating from the floor adds to the comfort of the space.

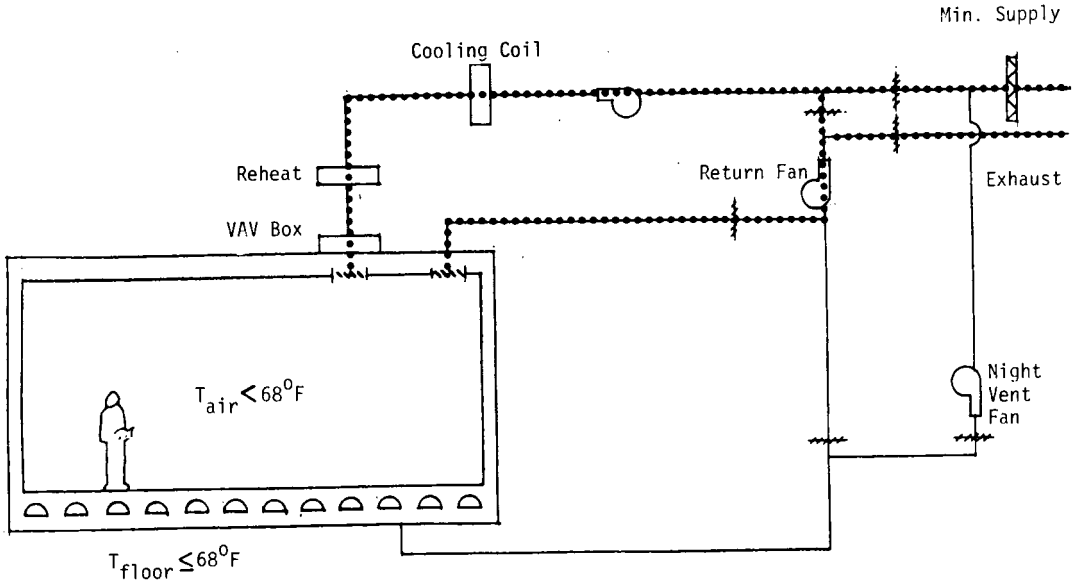
## 6. ENERGY PERFORMANCE RESULTS

The building's annual energy consumption was calculated to be 46,818 Btu/ft$^2$ yr using NBSGLD and NEWSYS computer simulation programs. This budget was based on final design development drawings and included a warehouse space as well as the main open office space. The peak chiller load was 68 tons and the peak boiler load was 15.6 therms/hr. The peak boiler load was a winter start-up load. The peak chiller load occurred when the outside air temperature peaked at 100°F on summer afternoon. The annual operating costs in Provo were estimated to be $13,182, or $0.24/ ft$^2$ yr. The gas charge was $5255, the electrical energy charge was $2349, and the electrical demand charge was $5578. If the building were located in Salt Lake City, or even outside the Provo City Power jurisdiction, these charges would increase considerably.

## 7. REFERENCES

1. Wilcox, B.A., Gumerlock, A., Cunningham, G., Barnaby, C.S.. "Performance of Passive Retrofit Small Office Building." Proceedings, 7th National Passive Solar Conference, American Solar Energy Society, Knoxville, TN, 1982.

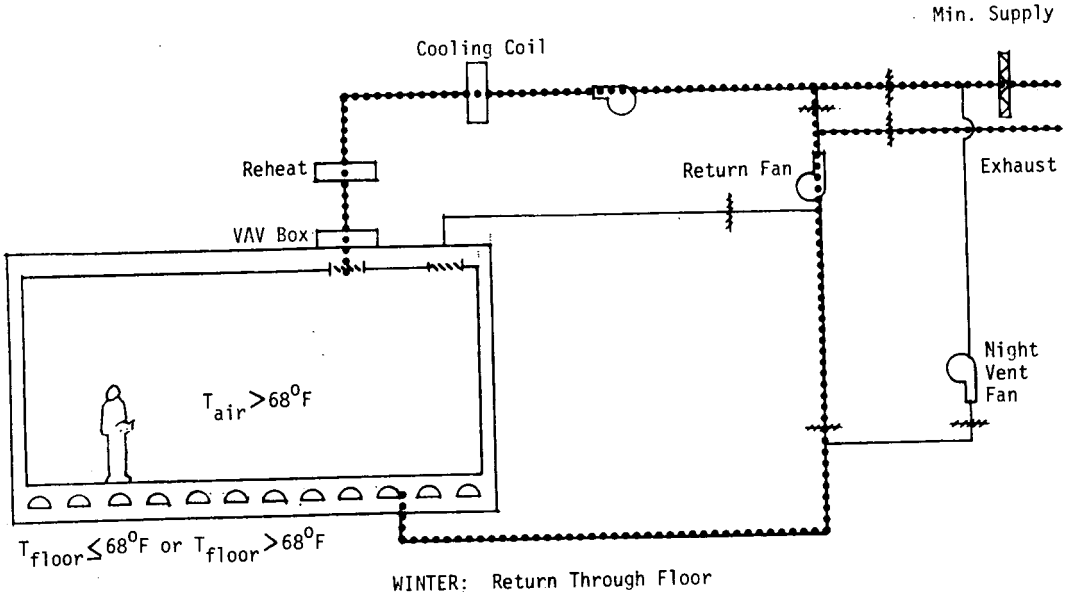
2. Matthews, Scott. "Proving the Benefits of Daylighting," Architectural Record, Mid-August 1981, Vol. 169, No.11., 46-51.




WINTER: Return Through Ceiling

- Temperature in office is less than heating set point.
- Floor is cool.

Fig. 3. Mechanical Schematic - Return Through Ceiling




WINTER: Return Through Floor

- Space is floating above heating set point.
- Floor can be either warm or cool.

Fig. 4. Mechanical Schematic - Return Through Floor

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# A CONTEXTUAL APPROACH TO DAYLIGHTING

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## ABSTRACT

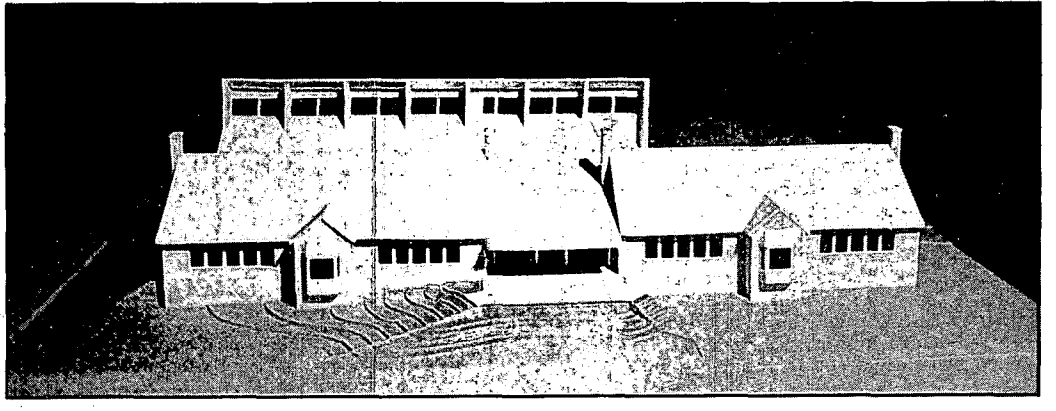
Contextual aspects, that is the effect of surrounding landscape and buildings are more important than sky brightness in determining the quality of daylight in interior spaces. By using traditional design techniques that consider context, daylighting becomes a dependent source of natural light for public buildings used during the daytime.
This paper focuses on daylighting principles determined from the collective experience of traditional building forms, applying them to a recently completed DOE commercial passive solar demonstration project: Essex Dorsey Senior Center in Essex, Md. Daylighting and cooling are integrally related as both require a shallow high ceiling space and emphasize perimeter.

## 1. INTRODUCTION

Traditional forms suggest that, ideally, to eliminate direct sky glare and control the brightness and contrast of the visual field, daylight should enter a space reflected from a nearby surface of even brightness. A random visual field--the unconsidered view out the window--upsets the physiological response of the eye to useful light. Classical ratios describe enclosure in terms of height of surrounding walls to width of space. These ratios exclude the brightness of the sky from the normal cone of vision. Daylighted spaces require a greater ratio of height to depth than modern prototypes. Because the eye accommodates changing levels of brightness, the problem of daylighting is also a problem of perception. Above certain threshholds, quantity of light is an unimportant measure of daylighting effectiveness.

The traditional use of daylighting applies to situations in which most activities occur during daylight hours. As an example of this traditional approach, the early development of school buildings in the United States shows the rational development of a daylight determined building form. The Essex Dorsey Senior Center incorporates two old frame school buildings constructed around 1905, specifically designed for daylighted classrooms. The new "L" shaped addition continues this approach using traditional forms and techniques. Qualitative control is achieved by a courtyard, deep overhangs, planting, placement in relationship to the surrounding environment, movable panels, and clerestories which remove sky brightness from

Below: Architectural model of the center incorporating the two old schoolhouses.



the normal field of vision.

The local climate is characterized by pleasant although often humid springs and falls, hot humid summers and cool winters with occasional snow. This Mid Atlantic weather is somewhat tempered by a maritime location; the building is within a mile of a Chesapeake Bay estuary. Annual rainfall is approximately 40 in. There are 4800 annual heating degree days and 1100 annual cooling degree days.

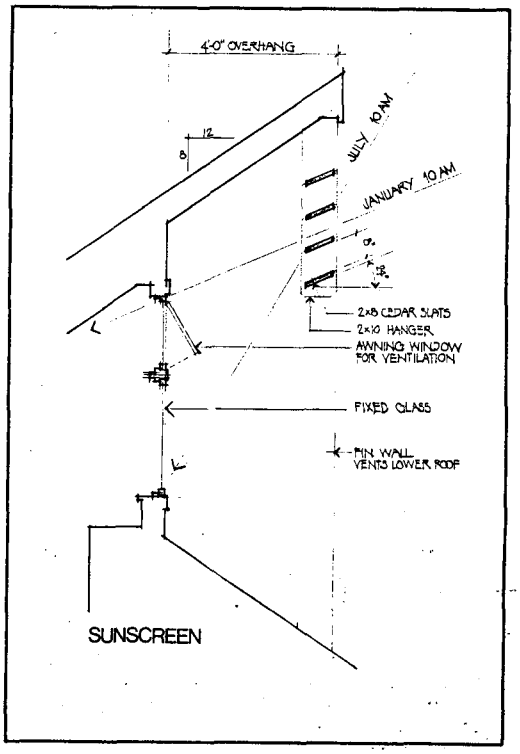
The Center was completed and occupied at the beginning of April, 1983. It is one of 18 Centers planned by the Baltimore County Department of Aging Programs and Services. Activities in the center are built around a noon nutrition program, with both scheduled and unstructured social activities, classes, and crafts programs before and after. The program is designed to keep aging people active in the community in order to reduce physical and mental deterioration and dependence. Since the building does not accommodate "work" structured by the clock, flexible scheduling based on seasonal change is planned.

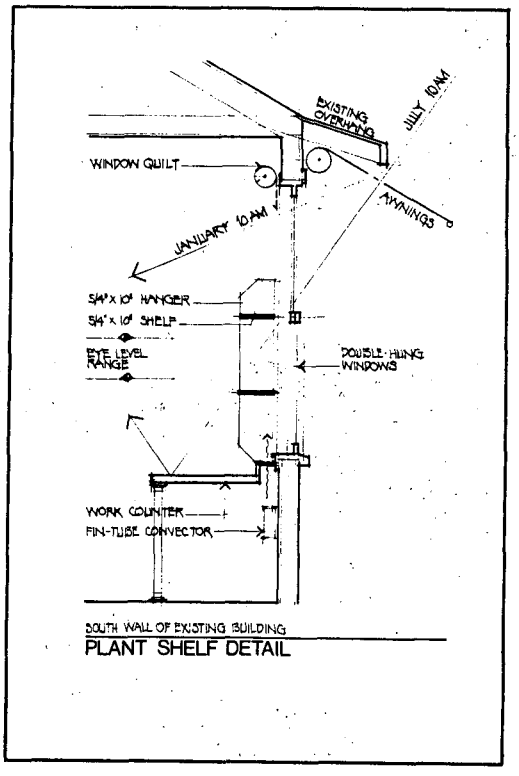
## 2. DAYLIGHT TESTING PROCEDURES

Physical monitoring of building performance began at the spring 1983 equinox as part of a year long evaluation of the building in use. Each type of space under a variety of outside sky conditions is currently being measured. Readings are taken horizontally at 30 in. above the floor and vertically to the window. To establish diurnal variations, each of the readings is repeated four times at intervals between noon and sunset. By plotting useable time before sunset on an annual chart, the anticipated time when adequate daylighting is available for each type of space can be estimated.

Additional readings at each point are taken at noon on days when sky condition varied from the average reading. these readings show the effect of normal cloudy skies and a worst condition for dark rainy skies. With these data reduction of useable daylighting because of cloud conditions is estimated. Measurements will continue through the winter solstice to examine the worst daylighting conditions. In addition, energy consumption for lighting is submetered and behavioral observations will monitor the actual use of ambient and task lights, curtains, and placement of people in the space. Readings were made with a Sylvania EP-20 Cosine Corrected Digital Lightmeter accurate to within 2% for readings between 1 fc and 2000 fc.

A successful new center in the county designed for the same functions is used as a control building. It relies entirely on artificial lighting and mechanical systems in a sealed environment. Light readings in similiar areas of the control building are compared with daylight readings at Essex.



## 3. PRELIMINARY FINDINGS

Data are plotted on semilog graphs on which suitable ranges of light are indicated for the type of activities. Upper ranges of excessive brightness are indicated as well. Unlike artificial light, daylighting becomes unusable in areas of excessive brightness and direct sunlight.

A selection of graphs with accompanying explanatory remarks are illustrated here. These graphs represent only a few of the many daylighting issues which are being explained.

3.1 Figure 9 . Does sky brightness determine distribution when context is controlled?

Figure 9 shows the distribution of light in the Assembly Room at separate times when sky brightness at the courtyard measured the same level (320fc). Distribution through the courtyard windows is much greater (2-3x) under late day bright sky conditions than under a dark rainy midday sky. Performance of the clerestory, however, is nearly the same for both conditions. The clerestory is more predictable because it only admits light reflected from the sky. Light reflected from the wall of the courtyard, however, varies greatly as a result of direction and quality of sunlight, wetness, and other factors.

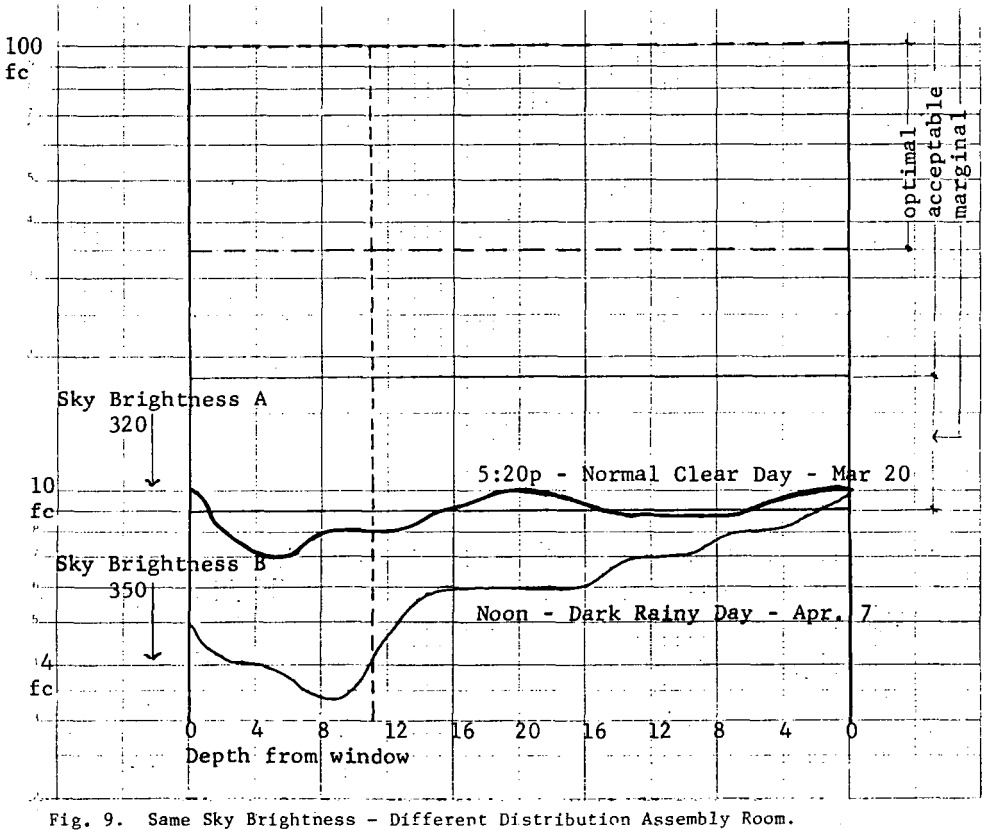



Fig. 9. Same Sky Brightness - Different Distribution Assembly Room.

3.2 Figure 11. What energy savings can be effected by daylighting.

Figure 11 shows average monthly sunrise and sunset for the year on a time scale. By plotting available hours of daylighting useful hours of daylighting under average conditions is indicated. The extremes for this building are the assembly room (most), and the office area (least). A percentage reduction must be made for dark rainy hours.

Perimeter offices have useful daylight for an 8 hour day during a 6 month period, and for 5-6 hours during the shortest month. A reduction of 10-15% is estimated due to adverse sky conditions. The original estimate indicated that 80% of lighting needs could be accomplished with daylighting; this is a reasonable expectation on the basis of preliminary data. Actual use will depend on scheduling demand and whether people actually turn out the lights.

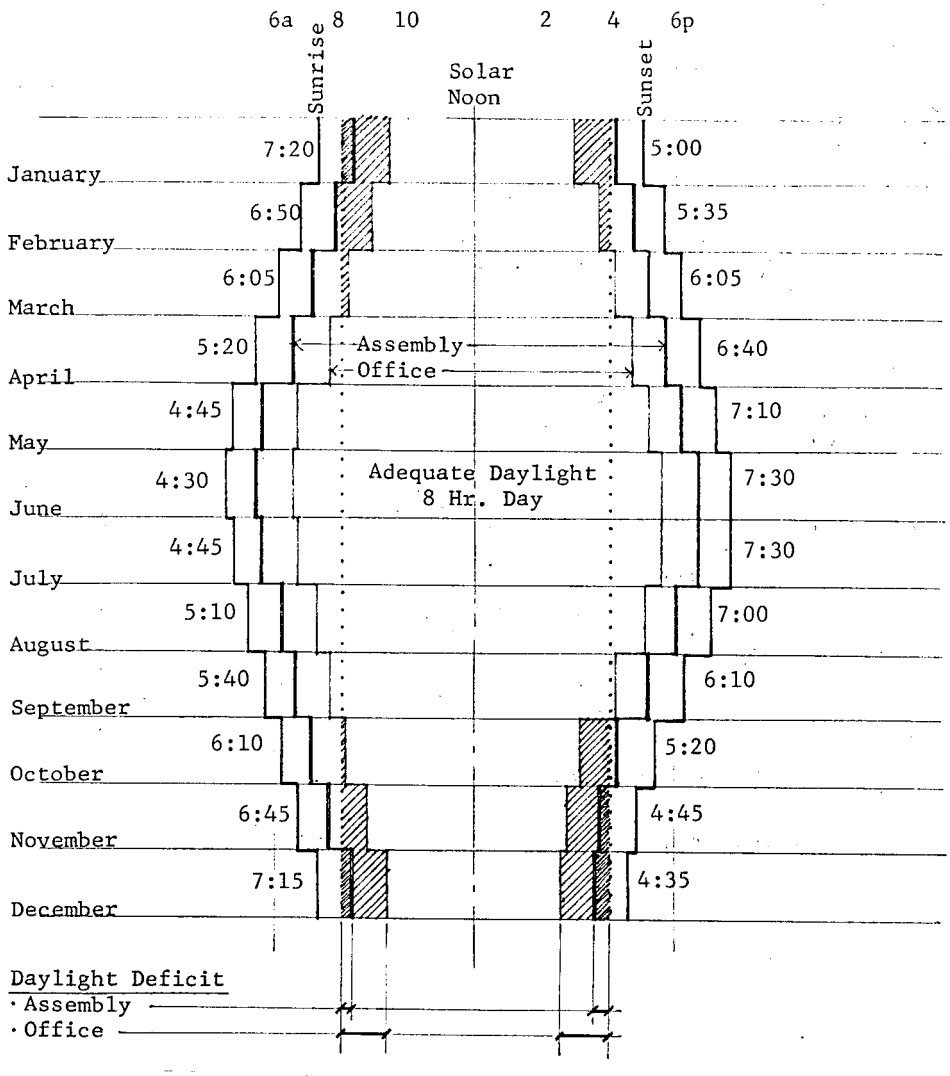



Figure 11. Available and Useable Hours of Daylight.

## 4. CONCLUSIONS

### 4.1 Design Method

The design method was a traditional one in the sense that the designers understood the generally accepted body of principles of daylighting design through experience and systematic study. These principles utilize a body of visual examples that are generally unquantified. The design was refined by discussion with other experienced designers but not fundamentally changed.

No computer models for daylighting introduced during the project effectively altered the design or permitted an engineer or technician to replace the designer. Thus far a set of useful ideal mathematical relationships do not emerge from the testing.

### 4.2 Mathematical Models vs. Context

The tests show that a reasonable correlation between sky brightness and interior daylighting may be established for the clerestory where daylighting is affected only by sky brightness. Direct relationships between outdoor brightness and interior daylighting performance are too general and too undependable for mathematical programming. Simple glass to floor area ratios are actually misleading. From windows at eye level the adjacent environment is too complex to quantify. Light reflected from trees and buildings changes as the sun moves across the sky or when it disappears from view on a cloudy day. Light filtering through trees varies greatly with seasonal change; the distribution, quantity and contrast of filtered daylight differs significantly from daylight unaffected by trees. Since contrast and distribution become critical factors in daylighting, the difference in the visual field between bright sky and dark landscape makes daylighting a contextual problem.

### 4.3 The added perimeter and clerestory costs.

The shape of the Essex building differs significantly from a building of comparable area constructed for a sealed mechanical environment. A 13,000 $ft^2$ building, which was 100 ft wide would have significantly less perimeter, than this building which was constructed of 40 ft wide wings. 335 lf of additional perimeter means an added construction cost of $19,000, or $1.50/$ft^2$ for the overall building. The clerestories added approximately $27,000 over the cost of a comparable building with flat ceilings -- about $4.00/sf applied to the addition alone. Added fenestration, assumed to be the difference between a glass to floor area ratio of 5% and the actual glass area of the building cost approximately $52,000 more.

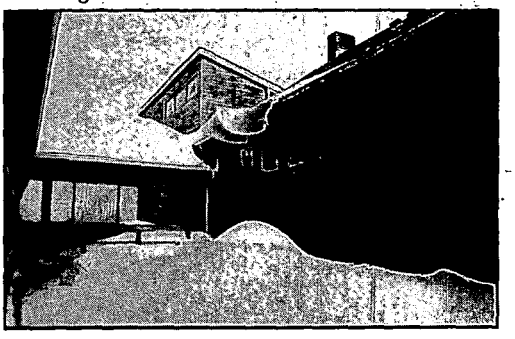
The estimated energy savings for lighting alone are estimated at 40,000 kWh or about 2,000 annually @.05/kWh. The improvements are not cost effective for daylighting alone; for this project, cooling and daylighting benefitted integrally from the added perimeter, fenestration and clerestories, and the additional perimeter costs were offset by elimination of air conditioning in 800 $ft^2$ of the building. Total cost of the Essex building was approximately $65/$ft^2$ which compares with an updated cost of about $60/$ft^2$ for another Senior Center constructed a year before with a sealed mechanical environment and no daylighting contribution.

### 4.4 Dependability

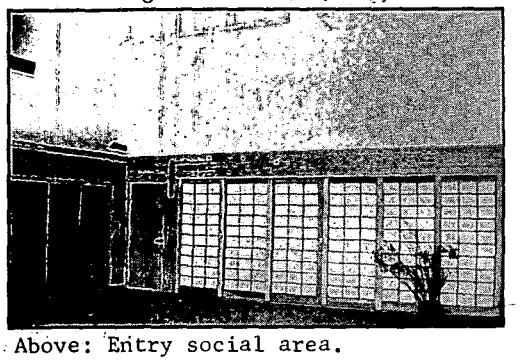
In a suitable environment, daylighting is relatively dependable for many public applications. Because the human eye adjusts to light by changing the area of the iris, it accommodates itself readily to changing qualities of light which occur in a daylighted space. Within acceptable limits this variety is an advantage. Affecting both the rods and cones of the retina in balance daylight provides natural lighting color. It is preferable to artificial lighting; adequate quantities are available for public applications during normal working hours.

If dependability is defined as human control over a artificial environment daylighting is not predictable. The difference between a normally bright day and a dark rainy day is quite significant. The user must be willing to adapt to the variations of nature rather than controlling them.

The problem of daylighting design is a qualitative one of controlling extreme contrast. Spots of too much brightness affect the ability to see as



Above: Courtyard in winter.



Above: Entry social area.

well as visual comfort. Direct sunlight which is very bright provides too much light for most tasks. By comparison design for artificial lighting reduces the problem to one of minimum lighting levels; neither dependability nor contrast needs to be considered. As a daylighting evaluation, this paper describes performance and qualitative advantages of daylighted environment. The empirical results confirm Bill Lam's guidelines for daylighting in 1979 the beginning of the DOE program. He reviewed design principles for daylighting that were often complex and contradictory. He concluded that there were no acceptable mathematical models for predicting daylighting. For those who want the beiefits of daylighting a contextual approach utilizing traditional design methods may still be the best alternative.

## 5. ACKNOWLEDGMENTS

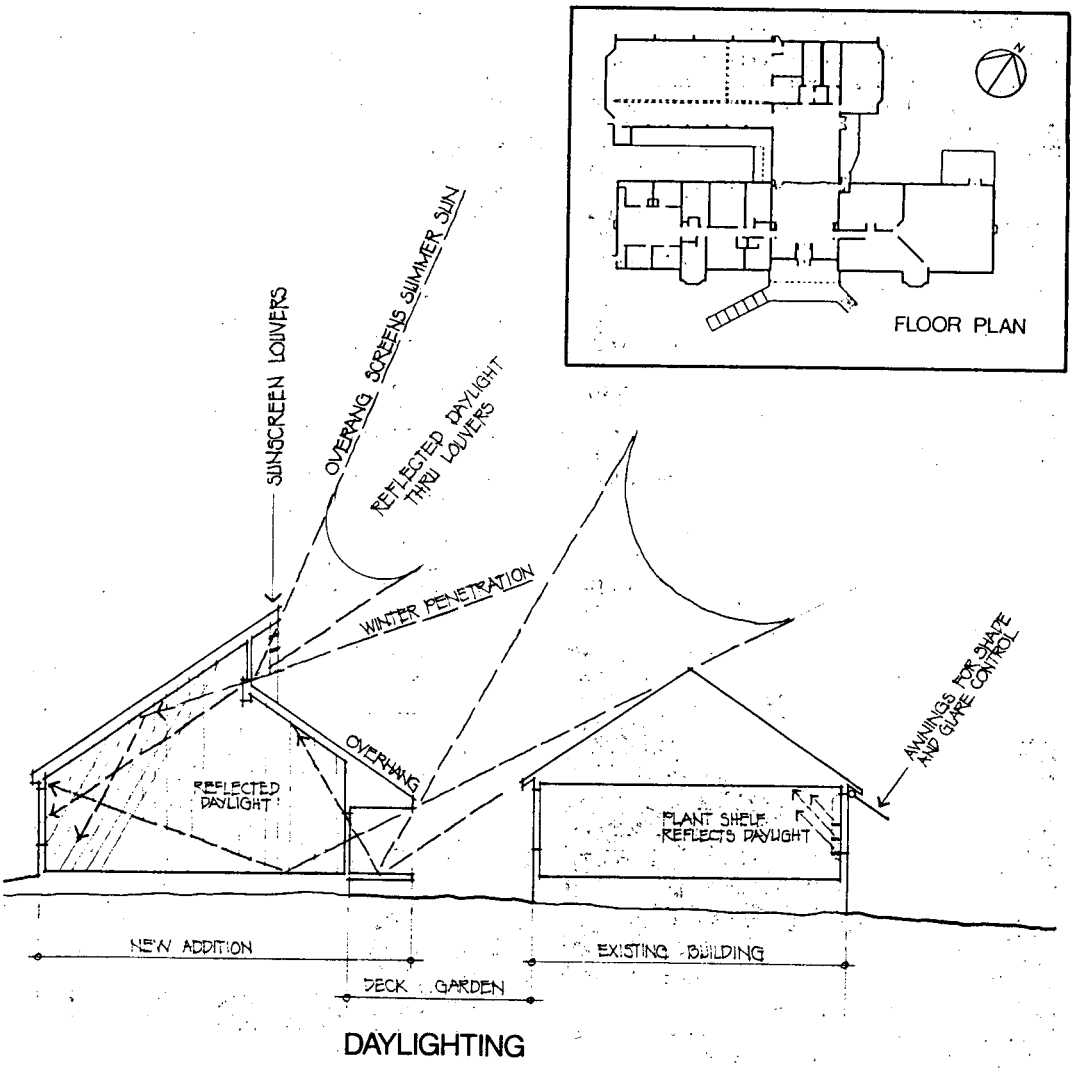
Project Architect: Robert Dolny, The Paul Partnership.

Daylighting Evaluation: Peter D. Paul, The Paul Partnership. Amy Glorioso, University of Maryland.

Project Designer: Daylighting Designer: Barbara Sandrisser, The Paul Partnership.

Owner: Baltimore County Aging Programs and Services, Tim Fagan, Director.

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DAYLIGHTING

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# PASSIVE SOLAR HOUSES WITHOUT FURNACES IN THE HIGH ROCKIES

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## ABSTRACT

Recently completed buildings in the author's architectural practice have shown convincingly that passive solar architecture in the high Rockies can achieve nearly 100% space heating and summer cooling at conventional building cost. It is now possible to own a home in this region that requires no auxiliary fossil fuel or electrical energy for heating or cooling--no back-up fans or motors. Back-up wood stoves may be necessary to achieve comfort for a small percentage of the time--depending on the user's willingness to dress appropriately.

Utilizing a flexible combination of closed-cell Trombe walls, direct-gain fenestration, floor mass, and solarium/solar chimney in a well-insulated open-plan building, we have been able to achieve comfort during all seasons in settings from 6,000 to 10,000 degree-days F.

The two projects that follow, the Champion Residence and the Soft House, also give witness to the author's fondness for the Domus Aurea built in 1st Century Rome.

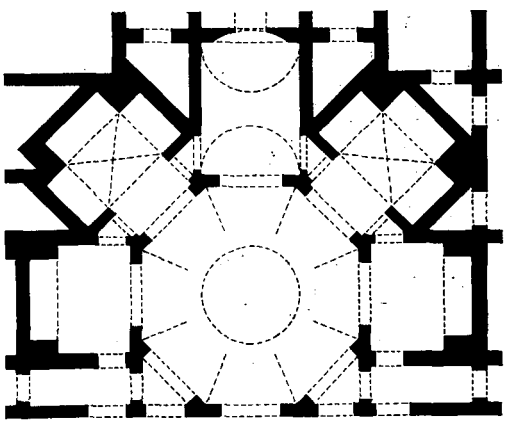


Fig. 1. Plan, Domus Aurea, 1st Century Rome.

## 1. THE CHAMPION RESIDENCE[1]

### Participants

Owners: Matthew and Ellen Champion
Architect: Dennis R. Holloway
Engineering: Nicol & Giltner
Contractor: Erdkamp Construction
Photographer: Youngblut Photographics

### Building Data

Location: near Nederland, Colorado
Completion date: Spring 1981
Square footage: 3060
Building cost: $55 per square foot
Heating degree days: 8900
Design heating load: 4.69 Btu/($^{o}$F-day ft$^{2}$)
Auxiliary heat contribution: one cord of pine for winter of 1981.
Systems: direct gain, mass walls and floors, unvented Trombe wall, Novan DHW system, two woodstoves.
Glazing: double insulating glass on all windows, low-iron on southern elevations and Trombe walls.

### Construction Details

Foundation: 8-inch concrete with 4-inch rigid foam to 4 feet below grade
Walls: 2x6 studs with 1/2-inch plywood sheathing, 3/4-inch lapped cedar interior/exterior, mirrorized vapor barrier, R-19 batts, one-inch rigid foam sheathing
Floor: main floor--quarry tile over 3-inch concrete slab over 2x12's. Lower floor--quarry tile over 4-inch concrete slab
Ceiling: 1/2-inch cedar boards, 2x10 joists, R-30 batts

[1]For another discussion of this house see: Steve Bliss, "A House High in the Rockies", SOLAR AGE, March 1983.

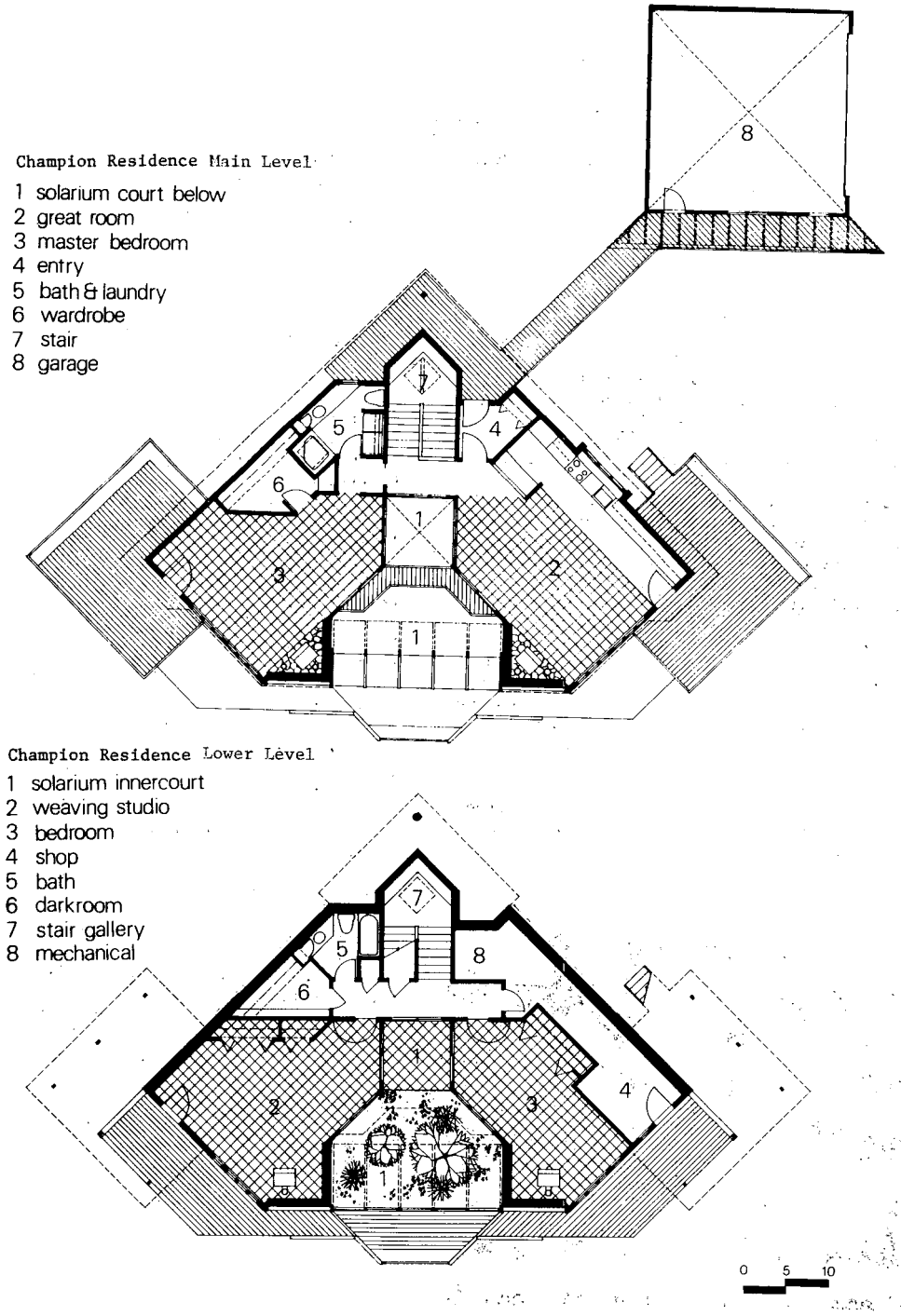

Champion Residence Main Level
1 solarium court below
2 great room
3 master bedroom
4 entry
5 bath & laundry
6 wardrobe
7 stair
8 garage
Champion Residence Lower Level
1 solarium innercourt
2 weaving studio
3 bedroom
4 shop
5 bath
6 darkroom
7 stair gallery
8 mechanical
0 5 10

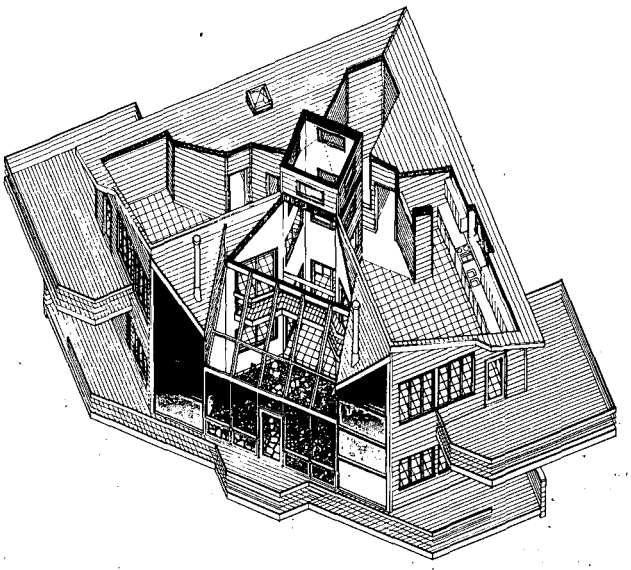
Fig. 2. Plans.



Fig. 3. Exterior of Champion Residence.



Fig. 4. Interior of Champion Residence
Great Room.



Nestled into the rocks of a south-facing slope high above Boulder Canyon in Colorado, the Champion home commands an extraordinary view of the Continental Divide and the glaciers of James Peak to the southwest.

The owners requested the architect to design a house that was to the greatest extent possible heated and cooled by the sun. They also wanted a solarium where table crops (tomatoes, green beans, carrots, lettuce, cabbage and herbs) could be grown year-round.

Major glass areas for viewing and passive solar heat gain are positioned to the southeast, south and southwest sides of both levels of the house. Because the house is built into the hillside (see cross-sections), there are no windows on the cool north sides of the lower level, thereby reducing the heat loss in winter. Windows are also minimized on the north sides of the main level.

The form of the house is symmetrical to absorb the energy from the symmetrical arc of the sun in the southern sky. The plan is L-shaped with a wide exposure to the south and reduced exposure to the north. The architect's design places the two-story solarium at the center of the plan. Inspired by the Austrian/Germanic "Innenhof" (inner court), this central space which utilizes the "greenhouse effect," is a primary source of the house's solar heat gain in the heating season. During the summer months, when the solar heat gain is unwanted, vent windows are opened at the bottom and top of the solarium, thereby allowing the heated air to rise and be drawn off the top. Utilizing the "chimney effect" in this way, the house is never uncomfortable in the summer, because Colorado's dry air is always being drawn through the house by the solarium.

During the heating season the solar heat gain in the solarium can be shared with all of the house rooms by opening windows and rolling doors in the interface wall. When heat is not wanted from the solarium, or when the solarium is cooling on winter nights, these windows and doors are closed to isolate the solarium.

The house has no back-up fossil fuel or electric heating or cooling systems. There are no fans or motors in the house. The secret of this passive solar house is "mass under solar-oriented glass." Two L-shaped concrete walls on either side of the solarium give necessary heat storage capacity to the house. The inner legs of the Ls are heated by solar gain from the solarium, and the south-facing legs are glazed over to form solar-efficient "Trombe" walls. The Ls are also designed as alcoves where wood-burning stoves are located.

Together the solar gain and the wood heat are stored in these walls which in turn stabilize the air temperature swing of the house. Additional building mass in the earth floor of the solarium and ceramic tile-clad concrete slabs of both floor levels help to stabilize the house air temperature.

Two wood-burning stoves, the only backup heating for the house, are located in the L-shaped alcoves of the main level and are used only when the house needs heat. Seamed copper in the alcove ceilings (see Fig. 4) reflects wood heat downward onto the ceramic tile floor to enhance overall house comfort. Last winter (1982) the Champions burned less than a cord of wood; this was usually burned after 9:00 P.M. on cold evenings. The Champions testify that their passive solar house is comfortable in the mid-60°F. range, because the heat is available to the skin as radiation.

Construction costs for the Champion house were consistent with conventional housing costs ($50-$60/ft$^2$ in 1980) because of the simplicity of the design. Domestic hot water is heated by a Novan system located on the roof of the solarium.

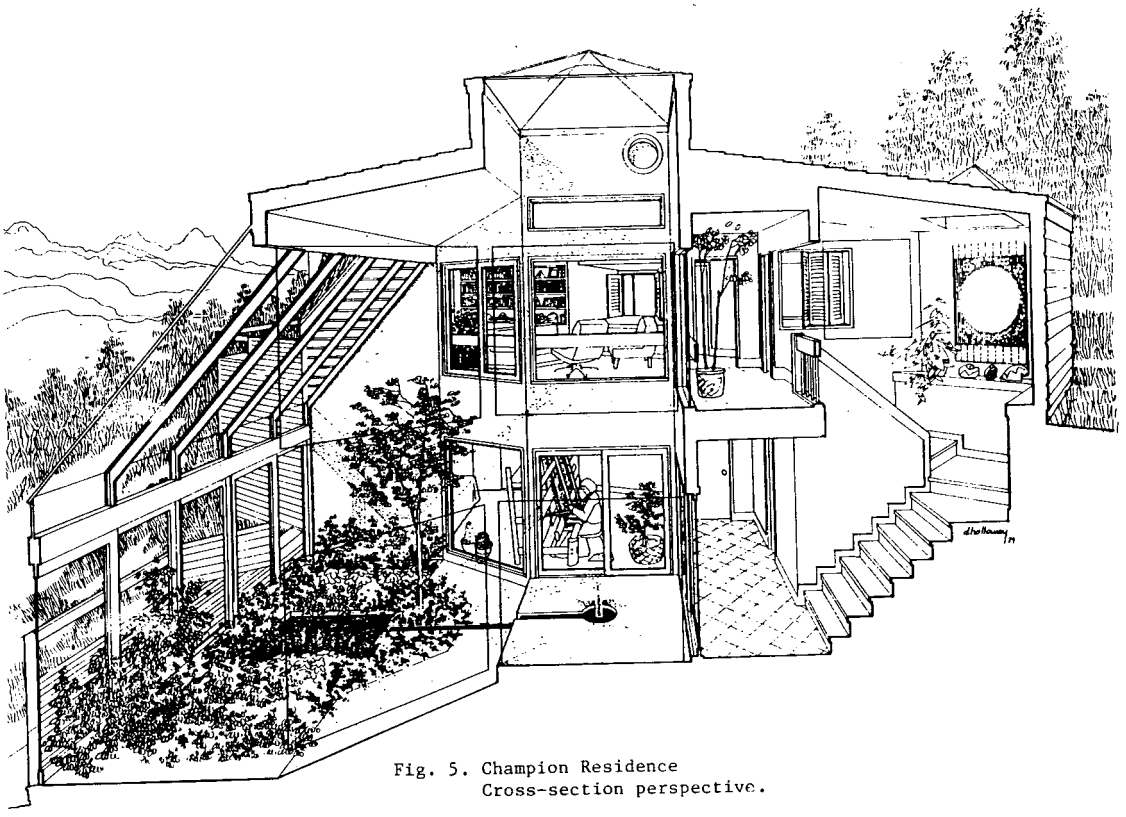


Fig. 5. Champion Residence
Cross-section perspective.

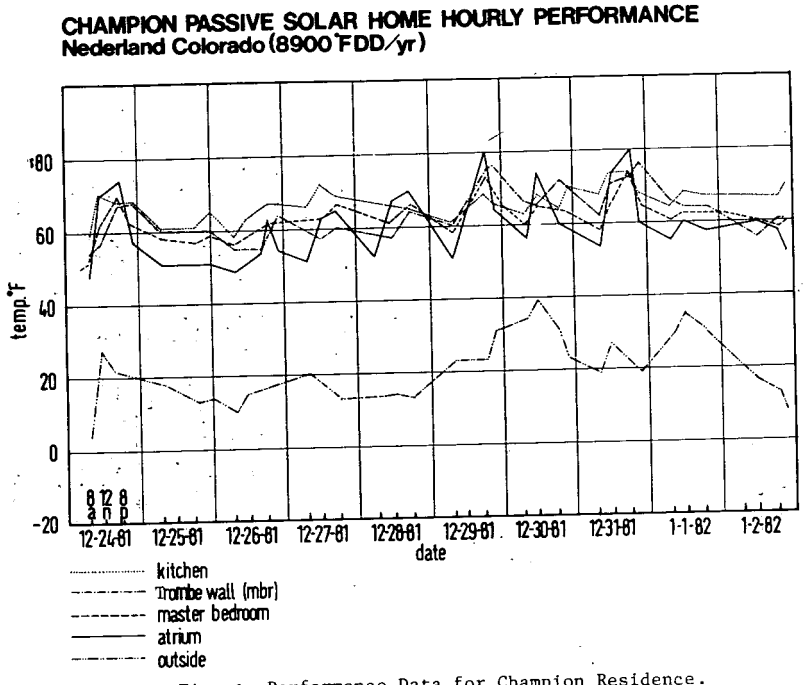



Fig. 6. Performance Data for Champion Residence.

## 2. THE SOFT HOUSE

### Participants

Architect: Dennis R. Holloway
Solar Engineer: Robert Rushnell

### Building Data

Construction status: Project
Square footage: 1000
Building Cost Estimate: $35-$40 per $ft^2$
Heating Degree Days: 10,802°F
(Rocky Mountain ASHRAE)
Systems: direct gain, mass walls and floors, unvented Trombe wall.
Glazing: double insulating glass on all windows, low-iron on southern elevation and Trombe walls.

### Construction Details

Foundation: 12-inch concrete with 4-inch rigid foam to 4 feet below grade
Walls: 12 in. rammed earth, 4-inch rigid foam, stucco
Floor: ceramic tile over 4-inch concrete slab
Ceiling: sheet rock, 2x12 joists, R-30 batts.

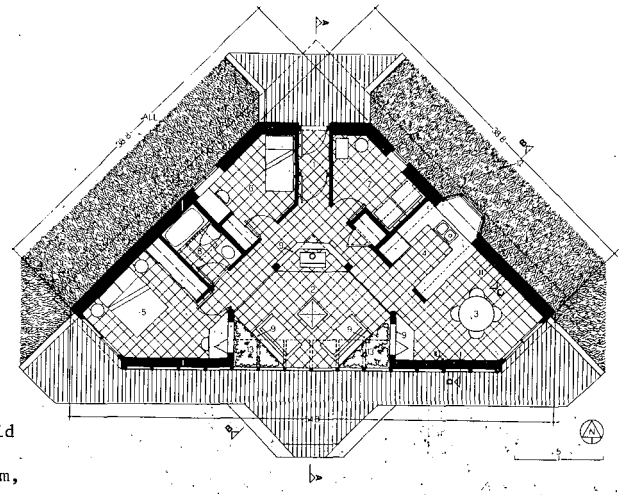


Fig. 7. Soft House Plan.

The Soft House is an integration of several appropriate technologies. Rammed earth wall construction, known for its labor (job creating) intensiveness and low capital/material cost is utilized as the passive solar storage mass. Earth berms against the northeast and northwest rammed earth walls raise the frost line, thereby reducing heat loss through the concrete slab, as well as reducing exposure to the northwest winter winds.

Rammed earth Trombe walls, a living room/solarium, and direct gain through southeast/southwest glass doors are the primary solar gain components of the house. Opened low and high awning vent windows in the living room/solarium exhaust unwanted hot air via the "chimney effect" in the overheating season. This movement of air in Colorado's semi-arid climate provides comfort to the human skin and eliminates the need for air conditioning. Night time insulation on the solarium reduces winter night heat loss.

The roof form is integral to the design concept. North sloping roofs on the L-shaped plan reduce summer solar exposure, while the south sloping living room roof provides a base for the active solar domestic hot water system. Because solar heating in this house prototype may be as high as 100%, depending on the yearly climate, a conventional backup furnace may be unnecessary. Available firewood on this rural site can be burned in the centrally located wood stove.

Although the area of the house is small, the space feels large because of the several long viewing axes. The living room/bedroom/dining room may be opened to create a 54-foot long space.



Fig. 8. Soft House Perspective.

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# THE "FOLDED PLATE ROOF" A UNIQUE PROBLEM SOLVER

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## ABSTRACT

The folded plate roof has been used successfully by designers and builders for three generations. Its unique strength and simplicity of construction are well established. This paper will review two such plans as applied to solar additions and their thermal performance.

The design concept allows for the development of large, pleasant interior spaces while providing ideal angles for solar gain at any latitude. It can be built of inexpensive materials (2 x 4s and plywood) and adjusted for broad spans on widely spaced centers as in these passive solar examples.

Our construction firm has specialized in solar plans and remodeling for the past five years. During this time we have found that the sun is even more reluctant to negotiate the design than the client. Problem southern obstructions have frequently obliged us to resort to roof apertures for our solar gain. The most effective system we have used is a folded plate roof design. This sawtooth configuration can be angled to optimize winter gain without unreasonable nighttime loss or summer overheating.

Here are two examples of our plate application.

## 1. APPLICATIONS

The "U"-shaped home of Don and Ellie Blossom wrapped around a courtyard with the narrow end open to the South. This end was glazed and the courtyard covered with a folded plate roof of four bays. Diffusing glazing was placed on the South slopes. These triangular bays were constructed on the adjacent flat roof and rolled into place beside each other. Connections were made from below. The original 2 x 4 walls are able to support the light weight roof without strain and the 800 square foot interior space is unobstructed.

Heat is stored in the thick stucco wall finish, the floor of brick on sand, and many small plastic water containers. Winter heat is distributed by two ceiling fans to the original house through wide doors. Summer heat is dissipated by two exhaust fans near the roof peaks. Nevertheless, a four year history records winter lows above 50°F and the room temperature is lower in June than in December. The home heating bill has been cut by 30%. This location has 7000 degree days.

Nearby, but in a warmer summertime climate, the Raymond home had a courtyard between the garage to the South and the house to the North. Again, a folded plate gave us access to the overhead sunshine. This plan called for clear glass on the southern slopes of the plates with moveable nighttime insulation. These bays were built on the ground and were levered into place over the new West wall. There are two large West fixed glass windows because of the views.

This solarium has a tendency to overheat in summer and would benefit greatly from exterior shade cloth. Both the clear glass and West windows contribute to this summer overheating. The owner feels that the winter performance is excellent without using any window insulation.

### 1.1 *Theory*

Folded plate construction, as a thin shell form, probably originated in Germany in the 1920s Shortly thereafter a design theory was developed in Europe.[1] The first technical paper in the United States appeared in 1947.[2] The capacity of the folded plate to carry loads directly, offered great advantages to roof design.

The traditional beam design of a roof is a very inefficient system. Only one cross-section of the beam is ever in maximum stress, yet the full dimension of the material is used across the entire span. The thin shell principle transfers stresses throughout the roof structure, allowing thinner, more efficient members. In the last 30 years, examples of huge roof spans without intermediate supports have become common.

The significantly large spans built in

America have been concrete, but many clear spans of around 100 feet have been plywood skins. Their use in the passive solar industry is surprisingly rare. The general theory of folded plates, and the newer "solar folded plate" will be presented here.

The folded plate roof is a series of structural slabs. Reference to the figure helps explain its efficiency. A single plate, acting by itself, would tend to deflect along its long dimension, between the end diaphragms. If the "foldlines" are held rigid the plates cannot act independently. The folds themselves resist the lengthwise deflection. The loading is therefore distributed along the folds. The resistance to bending along the long axis results in support of the plate or slab along the fold lines. Since the fold lines cannot deflect without causing "inplane" deflection (the plate acts as a deep web), the plates resist deflection and spread the loading efficiently. The plates act as slabs supported at the fold lines.

The reason the folded plate works is the capacity of its rigid fold lines to transfer 100% of the deflection action to the adjoining plates. The engineer must ensure the integrity of the slab action in the plate, design the folds to be rigid, and prevent buckling (more about buckling later).

The folded plate is not a truss, but a "thin shell," like the dome, the vault, or the hyperbolic paraboloid. A truss is a frame of tension and compression members whose stresses can be precisely calculated. The folded plate spreads a load throughout the roof in all directions.

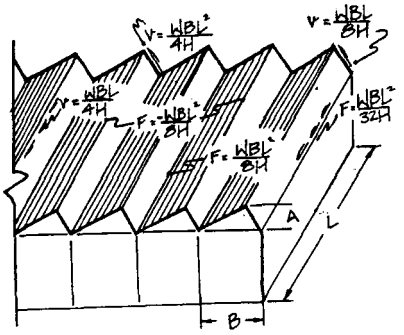



Fig. 1.

Figure 1 shows the popular design stress formulas for the classic folded plate. Many design manuals are available to the engineer. Stress distribution factors and stress carryover factors may become necessary for spans over 30 feet, but for most solar additions, ensuring a rigid connection between plates to satisfy the shear stresses in Figure 1 should be adequate.

Applying the folded plate theory to solar construction is very simple. One method is presented here, but many possibilities may become obvious to the reader. Figure 2 shows the obvious differences between the South-facing plate and the "shaded" plate.

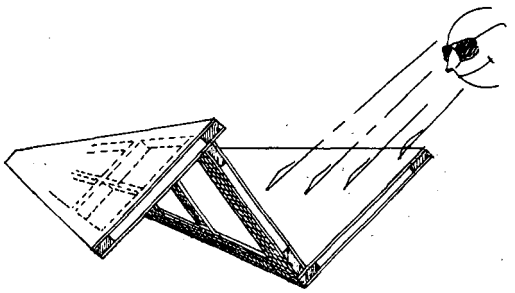


Fig. 2.

An ideal solution for the construction of the shaded plate is a "stress-skin panel," or skins of plywood on each side of alternating 2 x 4s and 4 x 4s, with end panels of 1 x 4s and mid-panels of 2 x 4s. This provides spaces for high performance insulation. The unique twist to the folded plate presented here is the South plate. Structurally, it is a plywood and lumber Vierendeel Girder, a rigid-frame type of girder that is, like the classic folded plate, a rigid, statically indeterminate frame. Care must be taken--usually with a lot of nails, a lot of glue, and perhaps some shear plate connectors--to ensure that corners and splices are all tight and rigid so they will not twist or deflect. Again, rigid, glued connections between the plates fold lines are mandatory. Do not forget the glue on the stress skin panels, either.

To model the phenomenon of folded plates, a piece of bond paper is folded into a symmetrical folded plate "roof." The outside edges are then glued to a wood box, or frame, as in Figure 3.

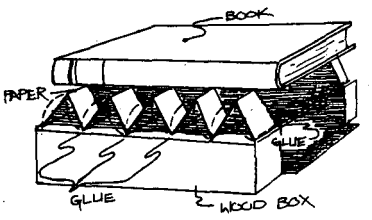



Fig. 3.

A book, representing an extreme loading condition, was placed on the top of our model. The immediate failure was in buckling at the end of all the plates, but only in the ends. Flat toothpicks were then glued at those points where buckling occurred, as in Figure 4, to resist buckling. The system then held a rather heavy book without any sign of failure.

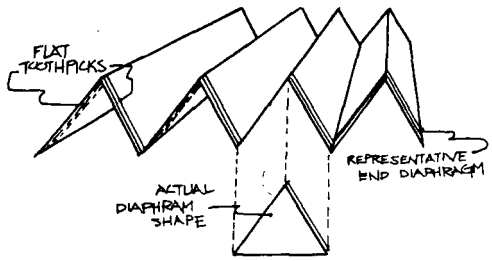



Fig. 4.

The significance of the end diaphragms was quite obvious. In fact, the toothpicks at only one end made the model comparatively strong, even toward the opposite end. With both ends stiffened, the ultimate failure (by adding books) was slab failure, with the "folds" remaining stiff and straight until the whole system was crushed.

Of course, the folded paper model represents ideal shear transfer at the fold lines. The significant points demonstrated by the model were the importance of the end diaphragms and that extremely long spans (over 50 feet) parallel to the fold lines are possible if intermediate diaphragms are constructed. An intermediate support is the more economical solution for handling spans over 30 feet.

## 2. REFERENCES

1. Winter, Urguhart, O'Rourke, Nilson, Design of Concrete Structures, McGraw-Hill Book Company, Inc., New York, (1964).

2. G. Winter and M. Pei, "Hipped Construction," Journal, American Concrete Institute, January 1947.

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# DAYLIGHTING, DIMMING & DESIGN

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## ABSTRACT

Two EQUINOX, Inc. designed institutional classroom buildings have recently been built. In addition to super-insulation, the major energy conservation feature is perimeter and ridge line daylighting with automatic dimming of the lighting systems. The Swartley Music and Arts Center, Dwight-Englewood School, Englewood, NJ, is a 7,500 $ft^2$ renovation of an existing 2-story abandoned gymnasium building with a long quadruple-glazed "Kalwall" skylight providing high qaulity natural light to the second floor studios. A "Lutron" automatic dimming system is provided. The graphical daylighting design method developed at the University of Washington (Millett, M.S.) was used as a design tool. The New England Regional Wastewater Institute building, South Portland, ME, is a new 2-story 9,000 $ft^2$ classroom and laboratory addition. High and low perimeter double-glazed windows with intermittent skylights provide daylighting deep within the various clssrooms. "Lutron" automatic dimming systems are provided for the classrooms and a site-built photoelectric dimming system is used to control the corridors and stairwell lighting. A ½ in. scale model and light meter, as well as the daylighting factor method using the *QUICKLITE* computer program was used in the design process. This paper discusses both buildings, the design process and the daylighting design tools used.

## 1. THE DESIGN

The Dwight-Englewood School is a private, co-ed day school located in Englewood, New Jersey, just across the Hudson from New York City. Architecturally, the campus is a loose collection of pleasant but not architecturally distinguished buildings that step up a hillside along the major road into this suburban town. The campus is without a real center and, until this year, the Arts Department has not had an adequate facility.

The EQUINOX design for the renovation of an old gym into the Swartley Arts Center was in response to a number of planning and architectural goals (see Figs. 1 & 2). First, by reorienting the entry to the Arts Center from its previous location facing the parking lot to a new one facing the Administration Building, and by landscaping the grassy expanse between the two, focus and life were added to the otherwise ill-defined center of the campus. Second, by proposing an amphitheater (as yet unexecuted) along the new connecting axis between the two entries, an outdoor performance area and school-wide events area was created. Third, by exploiting some of the architectural possibilities of the existing heavy timber structure and by adding a building-length skylight, the old gambrel-roofed, shingle-style, barn-like gym was transformed into a dramatic new center for the music and visual arts. Finally, by incorporating many energy conserving features and devices, the design seeks to avoid long-term drain on limited school capital that is created by high energy costs.

The new entry echoes the porte-cochere entry of the Administration Building opposite. The basic organization of the plan is cross-axial, with one axis developing the outdoor spaces (path, amphitheater, pavilion/gateway, and entries to both the Arts Center and the Administration Building), while the other axis organizes the internal spaces (plaza, downstairs studios, gallery, music rooms and photo lab). The two axes cross at a central

"plaza" which also acts as the distribution point for the upstairs studios and faculty room. Downstairs, the ceilings (14 ft) and lengthy free span (40 ft) of the old basketball court permitted an active and varied articulation of the plaza and circulation spine in both plan and section. The high ceilings also permitted the inclusion of interior windows high on the classroom walls in order to bring daylight into the otherwise obscure hallway and plaza. Upstairs, the old low ceiling was removed, the form of the fine old timber trusses creating an 80 ft long skylight to flood the studios with natural light.

The major energy conservation effort focussed on daylighting, projected to save over 50% of the normal lighting energy charges (which include a Lutron Pasar dimming system in the upstairs studios where daylight is plentiful). In fact, daylighting levels are so good on the second floor that artificial lights are rarely used.

Using the graphical daylighting design method, the second floor open space area had a daylight factor from 4% to 10% with the maximum value beneath the quadruple-glazed Kalwall ridge-line skylight. On a "standard" overcast day, this translates to lighting levels from 50 to 100 fc. Although no illumination measurements have been made to date, the fluorescent lighting installed is rarely used during the day, indicating that these footcandle illumination levels are being met by the building. Oddly enough, the Lutron automatic light dimming system is unnecessary. It had been thought that the fluorescent lights would always be turned on from habit and thus without automatic dimming no savings would be achieved. Obviously, however, when the daylighting levels are of sufficient amount and they are uniform throughout the space, people will recognize this fact and choose not to use fluorescent lighting.

At a more ethereal and, as yet, unrealized level, the Arts Center design deals with the architectural perception of time, as it has developed from a fundamentally solar cycle to a mechanical abstraction of that solar cycle. First, the seasonal cycle of the sun is signaled by the circle of sculpture pads which centers on the front-most column of the entry pavilion and which align from there with a cardinal point of equinox or solstice, sunrise or sunset. Second, the entry pavilion's four columns are oriented to the cardinal points and the south-facing slope of the pyramidal roof is an east-west sundial signalling the daily cycle of the sun. Finally, the interior plaza contains at its center a four-faced clock signalling the advent of mechanical time and the passing of the direct link between the sun and the telling of time.

The New England Regional Wastewater Institute (NERWI) is a training facility for sewage treatment plant operators. The NERWI building is an addition on the southwestern face of the existing Chemistry Building on the Southern Maine Votechnical Training Institute campus on Casco Bay in South Portland, Maine (see Figs. 3 & 4).

The existing Chemistry Building is static and self contained, hiding behind the predominantly north-facing black shaded glass. The new building couples up to the old to pull it out across the landscape, to attempt to turn that oblivious 60s inward gesture into a recognition of the landscape around it. The new building reverses the glazing notion of old. It is open on the south, with only high windows for daylighting on the north. High windows riding up high, like a train cruising through a small town station. The blue stripe of the deeply corrugated siding picks up the awning windows of the old grid and pulls them across the new building to the sky.

Highlights of the program are as follows:

* A 20-student workshop with vehicular access and tool storage;*two 40-student classrooms; *conference room for 12; *four faculty offices, director's office and secretary's office; *mobile training facility storage and loading area, access for mobile van unit; *elevator, to provide handicapped access to the adjacent Chemistry Building.

*Steel building for economy; *solar heat; *design compatible with the existing building of red brick and single black glass; *the NERWI facility to be functionally separate operations.

The daylighting analysis involved graphical studies using the design method of the University of Washington (Millett, M.S.) and light meter measurements from scale models of the

design in progress suggested optimum window areas and locations. For the deeper spaces, high continuous windows were best for distributing light most evenly without high contrast. Ceilings of 11 ft were made possible by the 13 ft floor-floor height in the Chemistry Building. Further computer modeling of the usable passive solar heating suggested the appropriate window sizes for each room. Most windows are triple glazed. Reflective shelves and shutters were investigated for distribution of light into the room but were found to be inferior to the more adjustable polished upside-down venetian blinds for this $45^{o}$ off-south application. Fluorescent lighting is to be installed parallel to the exterior walls. Each bank of lights is controlled by a light-sensitive automatic dimming system, allowing intensity to vary relative to the available natural light.

Figures 5, 6 & 7 show the results of the QUICKLITE daylight factor program (actual values here have been reproduced using the microcomputer program MICROLITE 1.0). Unlike the Swartley Arts Center above, footcandle values drop off toward the interior enough so that the artificial lights will usually be on. Thus, each classroom has a Lutron dimming system which controls only the outside and middle bank of fixtures. The inside row of fixtures is not controlled. Illumination levels appear adequate near the perimeter and middle for an "average" overcast day.

It was extremely difficult to get accurate, reliable, and consistent measurements with the $\frac{1}{2}$ in. scale model and light meter (a Simpson meter was used). Problems encountered were variability of sky illumination (greater than 10% over test period), scheduling of people for the tests, and the relatively large cost in time to make and test the model. These data were just not reliable enough to make design decisions (a reflective light shelf was being tested). In the end, it was dropped for cost and maintenance concerns. CAVEAT: Scale model analysis is easier said than done!

An initial energy analysis showed that lighting and ventilation were the two major energy uses. A heat exchanger was used in the air handling system to recover 70% of the heat content in the exhaust airstream. Even in Maine, student body heat would supply much of the heating required for the well-insulated building. Both the lighting and start-up heating energy loads were reduced by architectural means. The southeastern orientation of the building coincided well with the desire to have the building step back from the ocean to maintain the view and provide morning solar exposure for early start-up heat in all classrooms. The real energy contributions are from the building itself. The design will yield annual energy savings of 23,000 kilowatt hours of electricity from daylighting and 3,000 gallons of oil from the passive solar features, as compared to a building meeting the state energy code. Three conventional solar collectors supply hot water in the laboratory and bathrooms.

Why all this? An energy efficient building does not need to scream at you. It can equally take its cues from the coincident requirements of the site, materials and functional and symbolic roles. A simple building, NERWI achieves a unity of purpose between the site, interior plan and energy issues. The horizontal use of deeply corrugated tile red and royal blue siding connect and animate the existing and new building in simple and economic ways. In high contrast to the old building, this new example shows how a school on a limited budget can achieve significant annual operating savings without sacrificing architectural quality.

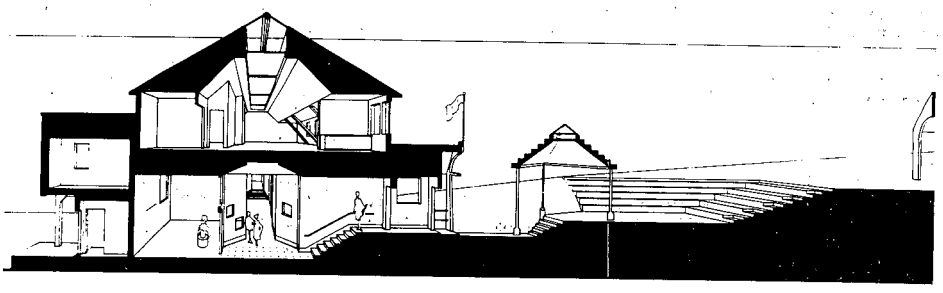


Fig. 1. Swartley Arts Center Perspective.

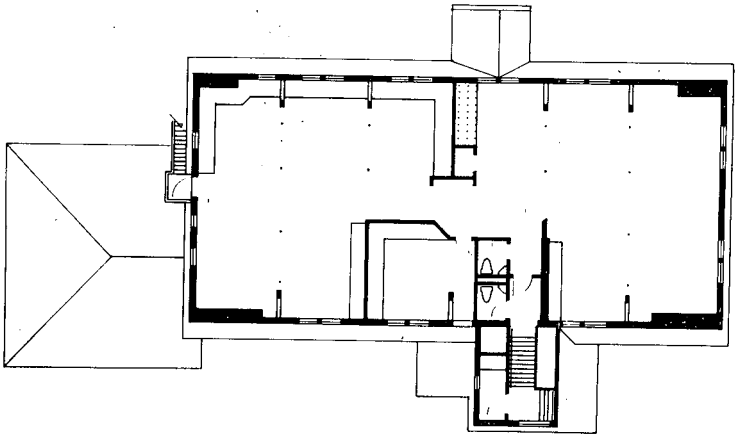


Fig. 2. Swartley Arts Center Second Floor Plan.

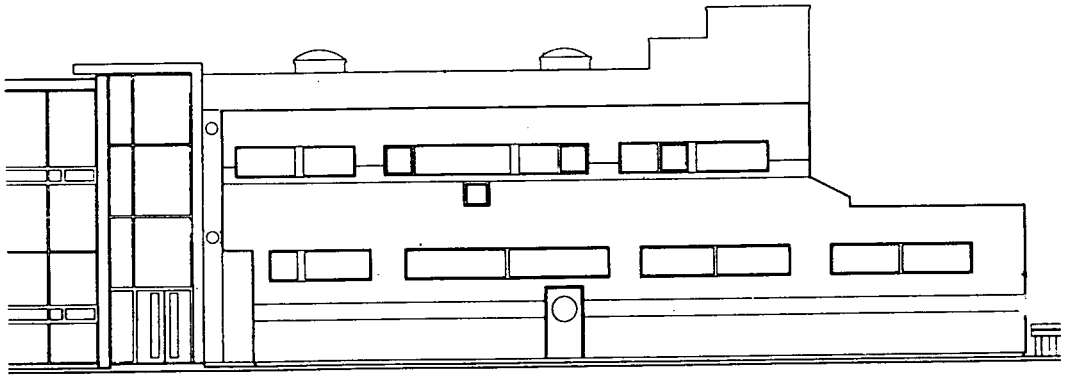


Fig. 3. NERWI Northwest Elevation.

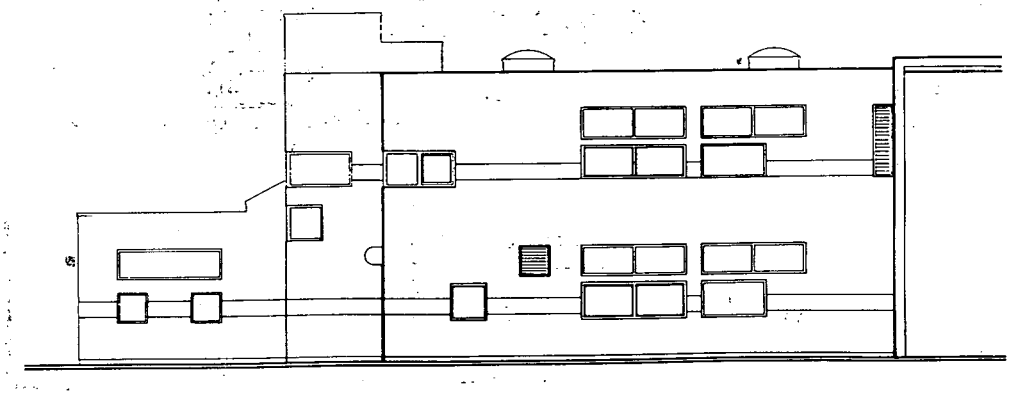


Fig. 4. NERWI Southeast Elevation.

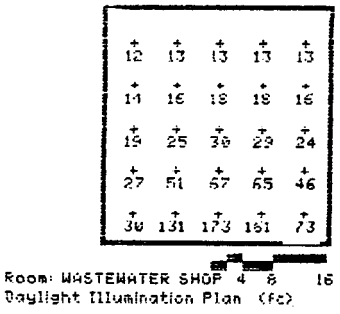



Fig. 5. NERWI fc Levels.

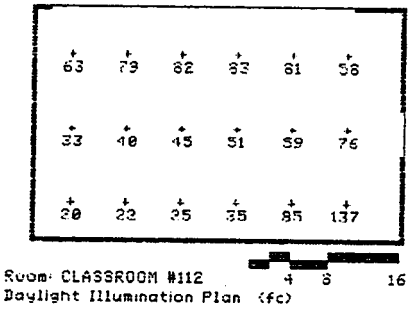



Fig. 6. NERWI fc Levels.

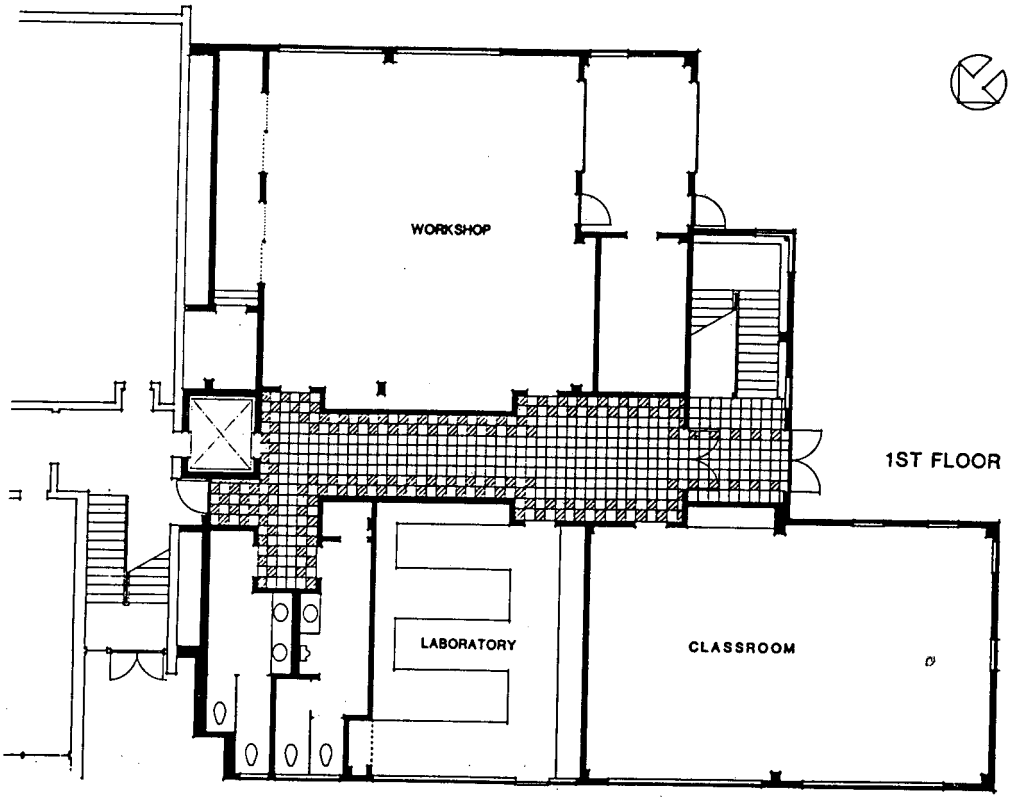



Fig. 7. NERWI First Floor Plan.

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0731-8626/83$3.00

# A FEW EXAMPLES OF PASSIVE SOLAR ARCHITECTURE IN SWITZERLAND

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ABSTRACT

This paper presents a few examples of passive solar architecture in Switzerland as seen through the projects and building experience of the architect and as lived in and felt in the daily life by the "users."

## 1. INTRODUCTION

When I went to buy 100 five gallon black plastic bins to fill them up with water and organize the heat storage in my greenhouse, the store first thought I was planning to set up a business of my own selling these bins. When I explained that it was merely to store solar heat, they asked if I was going to mail them to Africa myself. They would never figure out that there is enough solar radiation in Switzerland to have it stored in plastic cans!

This little story gives an idea on how people react when you talk of solar energy and solar architecture. In spite of this fact, quite a lot is being done, even though only a small minority is involved and interested. A few Swiss architects believe that solar (or bioclimatic) architecture represents the future because it makes sense and is in harmony with nature and human beings.

The following examples have been built between 1976 and 1983.

## 2. CASE 1: BEGNINS - 1976/1977

System: direct gain
Latitude: 46.5° N
Altitude: 600 m (1969 ft)
SSE: 0.6
Auxiliary heating: kitchen stove + fireplace with air heat exchanger.

### 2.1 The Architect's Viewpoint

This is a passive solar system using direct gain. The southern facade is entirely covered with windows to allow the sun to penetrate into the house. To avoid local overheating, properly located internal thermal mass and good air circulation are provided. During winter, the low sun penetrates deep into the house (Figure 2), but in summer the overhangs block the sun out. At night movable insulation is used. No obstacles shade the southern facade. The altitude of the house is above cloud level in spring and fall and frequently so in winter. Snowy conditions prevail in December, January, and February. High insulation in the walls (0.4 $W/m^2$ °K) and roof (0.2 $W/m^2$ °K) reduces the heat losses.

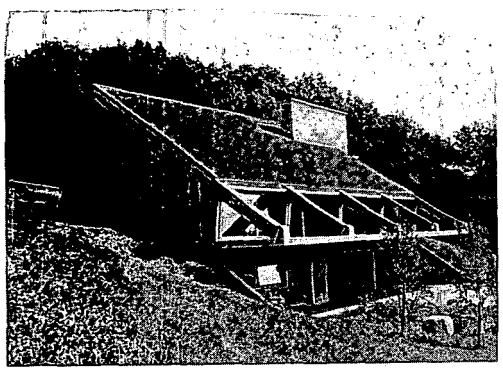


Fig. 1. View from the Southwest.

Auxiliary heating is provided by one open fireplace with an air heat exchanger and a kitchen stove. The ground floor is an earth sheltered non-heated zone.

This is a low energy consuming house, taking advantage of the direct solar gain with no extra building costs.

### 2.2 The Users' Viewpoint: The Architect's Family

They first felt like pioneers...then simply felt good. As for me, as architect and user at the same time, I thought I should have had some kind of heat storage in the kitchen's

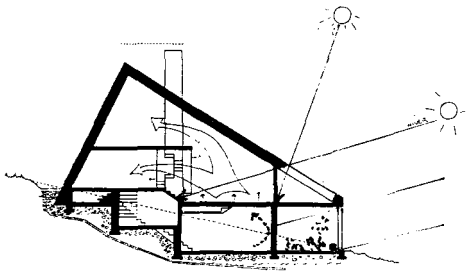


Fig. 2. Cross Section.

floor combined with a greenhouse somewhere on the south. All kinds of improvements are possible. Three years later we decided to build the greenhouse on the ground floor to contribute to the heating of a new office space created in one of the unheated premises.

## 3. CASE 2: BEGNINS - 1980

A greenhouse retrofit to the previous house.
System: direct gain in the sunspace, radiant and convecting heat in the office.
SSF: 0.7
Auxiliary heating in the office: one 500 W electric baseboard heater (Figure 3).

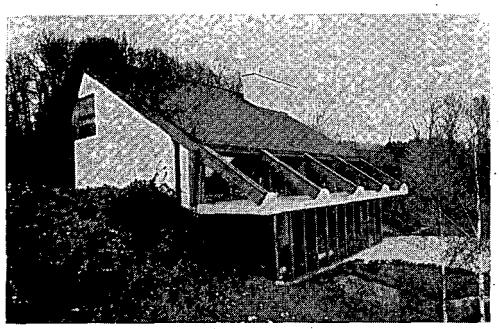


Fig. 3. The Greenhouse Under South Balcony.

### 3.1 The Architect's Cum Users' Viewpoint

The main idea was to demonstrate to the clients entering the office two energy saving devices: earth-sheltering and greenhouse effect. The cost of the retrofit was purposely kept very low. We built it ourselves, used single glazing, no night insulation (because I know people are lazy), and I wanted to make measurements in the worst conditions. In front of the south glazing are three rows of black plastic bins--the ones referred to in the Introduction. After several freezing days at -14°C (6°F), the northern wind blowing, the maximum temperature reached was 6°C (42.8°F) and stayed at that point until the weather improved. Besides all kinds of subtropical plants, we grow citrus fruit and strawberries. The greenhouse is ventilated in summer. This experience has been referred to in the French translation of Yanda/Fisher's "The Food and Heat Producing Solar Greenhouse" (13). Besides being a very valuable tool and a green environment all year long, the greenhouse makes it unnecessary to heat the office during 11 months of the year. The adjoining workshop with no heating at all has a stable temperature of 12°C (54°F) in winter.

## 4. CASE 3: POMPAPLES - 1980/1981

System: direct gain + sunspace (greenhouse/atrium) shared by two dwellings. Partially earth-sheltered.
Latitude: 47°N
Altitude: 500 m (1640 ft)
SSF: 0.75
Auxiliary heating: kitchen stove, fireplace with an air heat exchanger, heat storage for the sunspace in a rockbed.

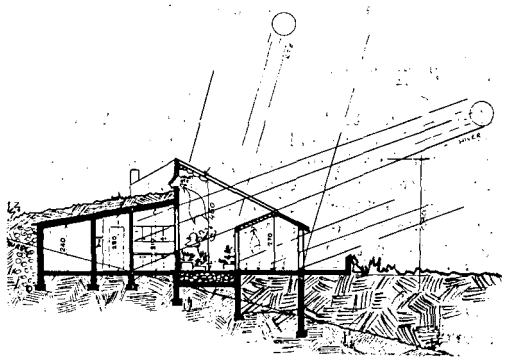


Fig. 4. Cross Section of Living Space and Sunspace.

### 4.1 The Architect's Viewpoint

The key element here is the central location of the sunspace common to both dwellings. Both apartments also have a direct gain system. The orientation is due south with no natural or built obstacles. This house has been built taking into account the principles of "bio-construction:" Hartman's network, suppression of concrete works where possible, when concrete is used all iron-rods are earth-massed. The northern part of the house is earth-sheltered. Very few openings occur on the east and west sides. Heavy 8 in. masonry walls are used and the slab is covered with terracotta. This thermal mass has a 4 in. exterior insulation. The roof is insulated with 7 in. rock-wool mats. 75% of the space heating needs are covered by the solar gain, 20% by wood auxiliary heating, and the remainder corresponds to the internal gains. The inner greenhouse is a "buffer stock" for both habitats in winter and is a ventilating chimney in summer.

4.2 The Users' View: Apartment 1

The apartment is inhabited by a young couple with one child who were convinced beforehand by the features of a passive solar home.

"The main advantage is that we live very close to nature; we are conscious of the change of seasons and weather. Our health improved considerably. Wood handling doesn't bother me; I feel I should pay for our comfort with some physical work (although my wife disagrees on this point!). The greenhouse plays an important energetic and hygrometric part in our comfort. Energywise the house works very well. The drawbacks? Someone has to be home to feed the fires. In our case it works, but I imagine it may cause some problems. We would have preferred to have the shutters on the outside. And, of course, washing windows is not exactly the way we prefer to spend our leisure time. It is not that easy to acceed to the glazed roof of the sunspace.

"Anyway, if we had to make a new choice, we certainly would choose again our present home."



Fig. 5. An Inside View of the Sunspace.

4.3 The Users' View: Apartment 2

Apartment 2 is inhabited by the parents of the couple in apartment 1. They were very suspicious before moving in.

"We were living before in an apartment house in which we never felt really comfortable. In winter, in spite of the central heating system, we were always chilly. The outside walls were not insulated and the windows were single glazed. In this new house, we appreciate the comfort. We like very much this new way of life in spite of two main inconveniences: we have to prepare and carry our wood, just like in former times. We thought we would never "progress back", but on the other hand it will keep my husband busy when he retires. The other inconvenience is to have large expanses of glass to clean periodically.

"Weighing the pros and cons, we are still willing to pay this price for a sunny and healthy home."

5. CASE 4: GENOLIER - 1982

System: direct gain and non-ventilated Trombe wall
Latitude: 46.5° N
Altitude: 550 m (1805 ft)
SSF: 0.9
Auxiliary heating: "Swiss" stove and fireplace with an air heat exchanger



Fig. 6. South Facade (Direct Gain and Trombe Wall).

5.1 The Architect's Viewpoint

Strangely enough, when Mr. and Ms. King entered my office two years ago, they had never heard of passive solar architecture whatsoever. They wanted me to build them a "traditional" house, which I refused to do. They were so puzzled so hear that an architect refused to build that one week later they came back and asked what was so wonderful about solar energy. I explained in a few words my way to see the present and the future and sent them back to school. At that moment the Swiss Solar Energy Society was organizing a three-day conference and exhibit with the main topic of "The Passive Solar House." There is where the Kings got their knowledge, albeit not enthusiasm. In spite of their lack of enthusiasm, they decided to have a try and asked me to build for them such a house.

Typically there are two heating zones corresponding to the day area and the night zone (see Figure 7). The day area is located on the main floor with a direct gain system. The south, southeast, and southwest elevations are entirely glazed. They admit the sunlight during fall, winter, and spring while during summer the overhangs block undesirable solar radiation. Fall and springtime are usually chilly in this part

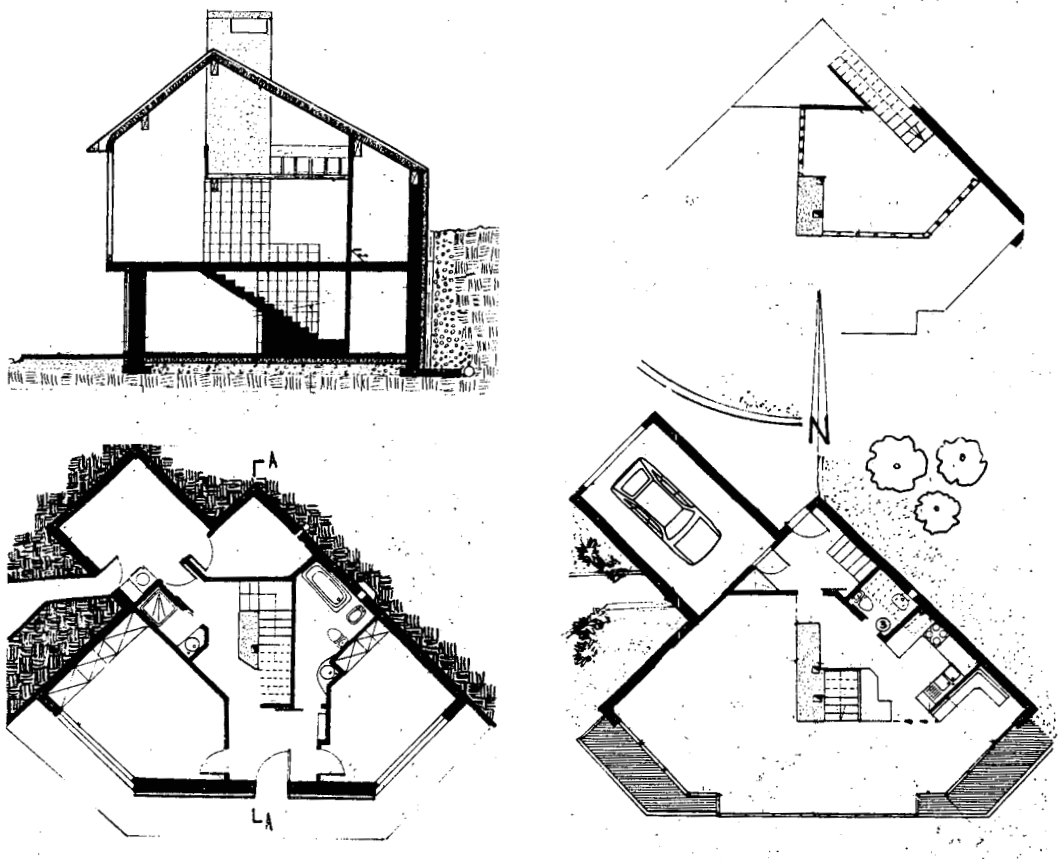



Fig. 7. Cross Section and Plans of the Three Level.

of Switzerland and no overheating is foreseen, although outside movable shades could, if necessary, prevent it. The thermal mass is well dimensioned: thick masonry walls with 4 in. outside insulation and a slab covered with dark unglazed tiles. There are no east, west or north openings, except for the entrance door with the living space being protected by an air lock vestibule. On the ground floor, with a direct access to the courtyard, we find the night zone which is partially earth-sheltered. It has two bedrooms on the southeast and southwest with the adjoining bathrooms. On the north side is a root cellar with a utility room on the northwest. The bedrooms and the "all-purpose" hall are heated by direct gain and by an unventilated Trombe wall. The auxiliary heating for the whole house is a "Swiss" stove made of a special type of thick tiles. This kind of stove had been extensively used in Switzerland and Germany and, in general, in all the central part of Europe as far east as Russia until the 1930s and then progressively replaced by central heating. The hearth of the stove is located in the night zone and the fumes go through a long tiled bench in the living room around the fireplace before escaping up the flue. This stove uses both systems of radiant heat and convection. The annual thermal load is 17,693 kWh; the total solar gains (direct and indirect) are 17,067 kWh. The auxiliary heating needed for the whole heating period is 626 kWh. The degree-days in the night zone are 3100°C and 3700°C for the day area to maintain an inside air temperature of 19°C (66.2°F) and 21°C (70°F) respectively.

5.2 The Owners' Views

"We are amazed at the low wood consumption during last winter, the first we lived in this house. Most of our friends don't like the house because it is too modern and too different from theirs. They don't believe us or don't understand why we are trying to save conventional fuel. It is so easy to set a thermostat on 20°C.

"We finally like the architecture, although it

was difficult in the beginning to get used to the big volumes of the living space. We now realize that we don't have to open the windows all the time to have the impression of having enough air, and we also appreciate not seeing our neighbors from our south-oriented windows. We are a little worried though, by the damage the sun will cause to our furniture and carpets. Instead we partially close down the shutters, if necessary, and consume more wood in the stove, although we know our architect disagrees. Maybe we'll find a solution; we have to get used to the system, and maybe our furniture will adapt itself to it as we do.

"We are especially interested by the Trombe wall; it is very efficient, and we see an advantage for the reasons stated above.

"As a banker, I know this house has a good value on the market, and I will advise my clients on this type of contruction. It is energy and maintenance efficient."

## 6. CASE 5: ST. CERGUE - 1983/1984

System: direct gain and sunspace (atrium in the middle of the house)
Latitude: 46°N
Altitude: 1050 m (3445 ft)
SSF: 0.73
Auxiliary heating: kitchen stove and Swiss stove and fireplace with air heat exchanger.

### 6.1 The Architect's Viewpoint

This house is now being built in a ski resort near Geneva and is going to be the permanent home of a family of five (see Figure 8).

The shape of the house is determined by the need for a maximum protection against winds and snow almost seven months of the year! There are few openings except on the south elevation. The living space is naturally located on the south; the bedrooms are around the atrium. The design is inspired by the vernacular architecture and, indeed, exaggerates some features. The roof, for instance, reaches the ground, protecting the whole house and decreasing the losses through the external walls. It also has a practical purpose: the wood storage is provided for under the outside ventilated roofed space.

The atrium offers a microclimate in the center of the house, and during snowstorms, the living space may be isolated from the outside by closing the rolladen shutters and therefore centered around the well planted and daylighted area. Movable glazed partitions make it possible to separate the atrium from the rest of the habitat when its temperature falls under 18°C, but it is assumed that will occur as an average only one month during the year. Otherwise the atrium adds to the living surface and volume an unconventional environment.

According to the Solar Savings Fraction method used to estimate the thermal characteristics of the house, we have an annual thermal load of 40,012 kWh versus 32,422 kWh of solar gain. The need for auxiliary heating would be 7590 kWh for a heating season from mid-September to mid-June. The site location is above cloud level in fall and winter.

### 6.2 The Future Users' View: Why We Have Chosen Passive Solar Energy

"For several years, we had to live in rented

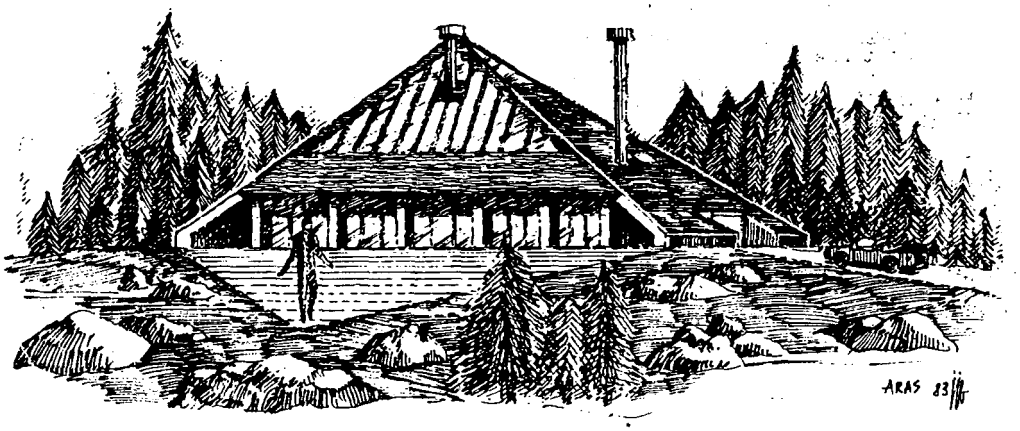



Fig. 8. Perspective from the South/Southeast.

apartments or homes poorly designed to fit the local climates, both in Switzerland and in the States. The rental space had single glazed windows, insufficient insulation and bad integration into the landscape. These were responsible for difficult heating as well as expensive cooling. Thus we slowly discovered that mastering nature is a very costly way to live comfortably. Therefore, getting an opportunity to build our own house brought a decision to follow more ecological principles and to adapt ourselves and our house to the local environment. Since our land is located in a woody mountain area with snow during five to six months as well as sun at the same time, a very well insulated passive solar design with a greenhouse and the help of appropriate woodstove and fireplace appeared to be our best choice to withstand winter conditions. Natural ventilation is adequate during summertime. In addition, an active system with heat exchangers for preheating the sanitary water is still under investigation to determine economical feasibility.

"It is our belief that the implantation of huge energy sources is political nonsense. Our adaptation to a more natural solar way of life will be our contribution to the necessary decentralization and diversification of energy resources."

## 7. CONCLUSIONS

Besides a better energy management and a greater comfort for the occupants, one can see that the architectural response brought up by these buildings (published in references 1 to 14) is a close integration to the environment, and the use of all natural elements contributes to a better quality of life.

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# SOLAR ELEMENTS AS CLASSICAL COUNTERPOINT: PASSIVE SOLAR DESIGN AND THE REVITALIZATION OF HISTORIC BUILDINGS

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## ABSTRACT

This paper presents how passive solar strategies have been used by ARCHETYPE in the design logic for the restoration, renovation, and infill of historic buildings. A design process and two representative projects are described. One project involves a large 84 year old detached Georgian style house. The goal of the project was to restore the original classical historic structure, and renovate and add to the building in such a way as to reinforce its Georgian character and proportion, and, at the same time, exploit the excellent solar orientation and improve the energy efficiency of the house. The second project concerns a 10,000 square foot Beaux Arts townhouse built in 1880 and located in the heart of the historic district of Dupont Circle in Washington, DC. Renovation and restoration of this landmark building for use as professional offices provided an opportunity for the incorporation of passive solar strategies that were by-products in the search for increased efficiency in spatial utilization and architectural enhancement. Both projects have been recognized by local and national preservation groups, proving that passive solar strategies can be successfully compatible with this area of design concern.

## 1. THE DESIGN PROCESS

Successful revitalization of historic buildings involves a careful, selective design process. This is a process that must seek beyond simplistic surface compatibility between that which is original and that which has been added or changed. For a building to be brought back to life, it is necessary to first understand its original essence and nature, that is, those aspects of its design that gave it meaning. These aspects occur at many levels and may be elements of spatial organization, structure, use of materials, and/or the articulation of detail. In a good building, these levels are consistent, with one level reinforcing another. Every historic style in architecture is the result of a design method, of sorts, that evolved in response to the needs, concerns, technologies, and ideas of a time. To revive and extend a product of any style, one must understand the rules of this method, or the style's logic. Armed with this logic and those found elements of the existing building, which represent remnants of the logic's architectural application, the architect has the possibility to use this logic, reapplied now to enhance what he has found. This sets up a framework for design decision-making. It concerns the interplay between that which is to be enhanced, and those elements which will perform the enhancement. As such, this interplay, this interaction between elements, can be a conscious reuse of classical counterpoint - applied in this context according to the logic of the style.

The tool offers several possible directions of design development with regard to the building's restoration, renovation, addition, as well as integration with passive solar and energy conserving strategies. In one direction, the historic logic may be applied to modern materials, recalling classical organization, space, and form. These relationships, as such, are often climate responsive in terms of summer and winter air and heat movement, and winter solar collection, or can be made to be such within the rules of the historic logic. In another direction in which counterpoint can be used, equally strong elements are purposefully juxtaposed to create a tension. Original elements can be isolated, within an anonymous background, in order to emphasize the interaction between them. Likewise, a new element can be paired with an existing one creating a new tension and strengthening the definition of the original elements. The design of this new element can be simultaneously guided by the logic of the historic style as well as the logic of climate response and function. The anonymous background used to contain, or backdrop, that which is emphasized provides opportunity for the use of another level of counterpoint. The homogeneity and transparency of abstracted forms built of modern materials and vocabularies can give support to historic elements by receeding from them, their contrast staging the historic element rather than rivaling it. Here suggests the appropriate use of industrialized products, such as greenhouse and panel systems to create expansive areas of glass or building mass for solar collection or storage, the introduction of metal in louvered patterns for energy distribution or control, or even the geometric articulation of wall and ceiling surfaces for daylighting purposes.

## 2. APPLICATION: THE GEORGIAN DETACHED SUMMER HOUSE

### 2.1 The Problem

This project involved the restoration, renovation, and extension of an 84 year old detached Georgian house located in the suburbs of Washington, DC. The building was intended for use as a summer house by its original owners, a fact evidenced by its numerous north-facing windows, wide porches, and location beyond turn-of-the-century development in Washington, DC. As an historic structure, it qualified for development tax credit according to the Preservation Act.

The stucco on wood frame construction contained no insulation and had severe termite damage at the rear. The property slopes toward the south, exposing nearly a full story of the 20 inch thick stone foundation walls which enclose a crawl space and partial basement. The southeast corner of the lot is emphatically established by an enormous oak tree said to be the oldest in the county and shading virtually the entire rear yard throughout the summer. The new owners wished to restore the classically organized structure. They also wanted to extend the house to provide an enlarged master bedroom, additional living space, children's play areas, improved kitchen, and a working (food-producing) greenhouse. At the same time, they wanted to exploit solar strategies and improve the house's energy efficiency.

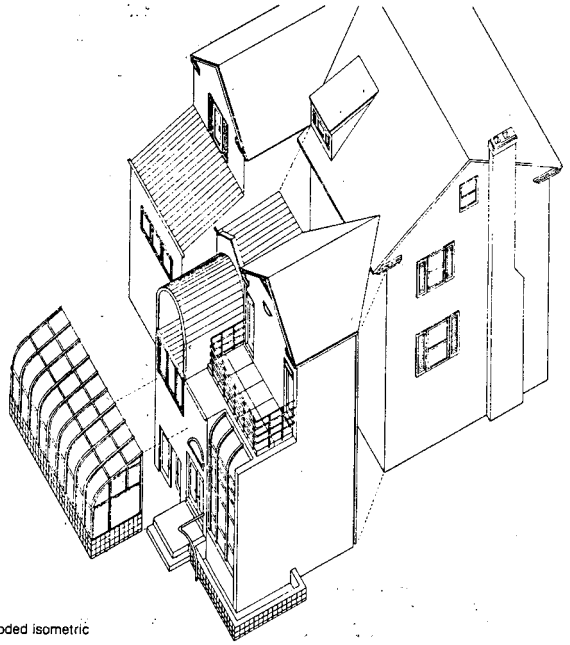
### 2.2 The Solution

The existing house was tightened through careful insulation and other conservation strategies; then, an addition was introduced whose thermal and formal characteristics respect and reinforce the qualities of the original building. The addition is massed to visually 'complete' the original house. The central entry hall has been extended to the rear, terminating in a two story vault about which the other spaces have been arranged. An existing gable-



south elevation

ended projection on the west side has been repeated on the east to provide a 'bed chamber' for the master bedroom suite at the 2nd floor. The first floor provides informal eating and living spaces as extensions of the formal ones. The lower level includes play areas and a windowless 'media' room, enveloped by the convection chamber of a 'sunken' Trombe wall. Other components of the passive solar system include direct gain glazing over the Trombe wall and at a new arched window that ends a new two story vault, and a 22 foot long greenhouse, placed at grade abutting the stone foundations. The solar elements have been located according to functional needs and serve as counterpoints to the rear elevation's new found symmetry. By using a variety of solar strategies, the characteristics of each solar element have been matched to the spatial and functional needs of the areas served.

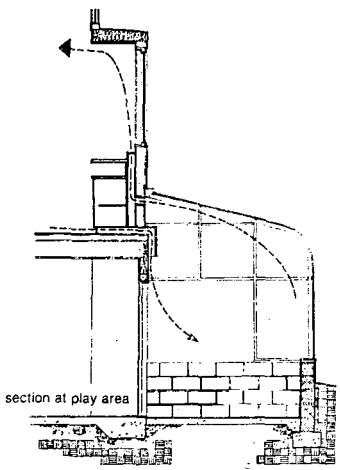


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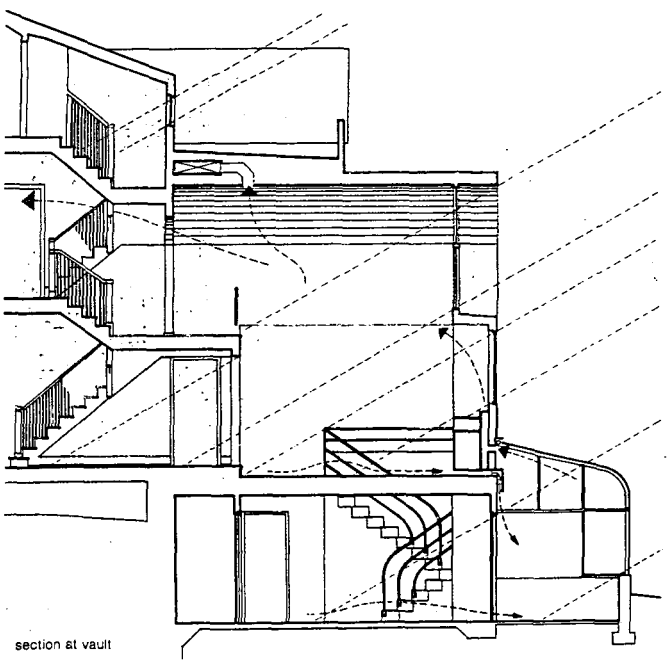
2.3 The Passive System

*Winter*

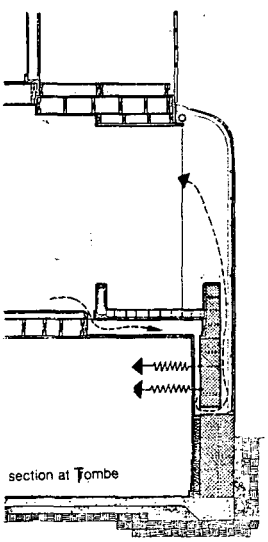
The primary source of heat gain for the living spaces is from south-facing windows. This method allows rapid warming of areas used extensively in the morning. A 3 1/2 inch thick mortar bed for the dark green floor tiles and a solid limestone stair serve to retain heat until evening when the family reoccupies the spaces. A linear floor grill set on axis with the formal living room provides an inlet to a convection loop powered by a trombe wall. This wall is located below the floor line so as not to obstruct views of the renowned oak tree. The loop helps draw off cooler air from the floor and maintains air circulation when fans are not operating. Heat stored in the Trombe's 8 in., thick concrete is distributed by convection to the living spaces and by radiation to the evening-occupied 'media' room. Additional heat is provided from the main greenhouse through operable vents located in the cabinets at the base of the vault's window. Greenhouse temperatures are moderated by the now enclosed granite foundation walls which also radiate to adjacent potting and play rooms. A primitive heating system in the original house has been replaced by two electric heat pumps with gas rather than electric back-up. This feature allows full use of night set backs and still provides economical and rapid morning heat up. The control logic and ducting have been designed to take advantage of heat collected in the sun spaces. Each heat pump has been provided with high return air openings at the vault's peak. As a result they act as both auxiliary heat source and active distribution for solar-heated air. During the day, hot air rising to the top of the vault can be distributed directly to cooler north-facing rooms, or it can be mixed with mechanically heated air when necessary. A separate automatic damper modulates the quanitity of supply air to south-facing spaces. This permits spaces that have been warmed by the sun to be isolated form the area served by the auxiliary systems. Insulation has been added to the crawl space (R-11), walls (R-19), and ceiling (R-30) of the existing house. Storm windows have been installed throughout. All new glazing is insulating glass and has been provided with R-3 night insulation.



section at play area



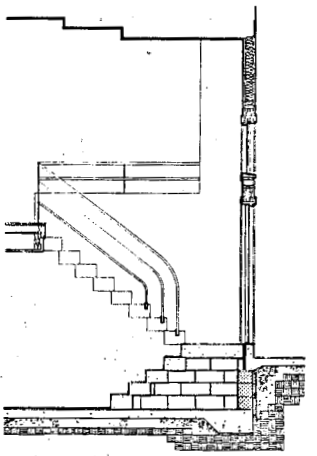
section at vault



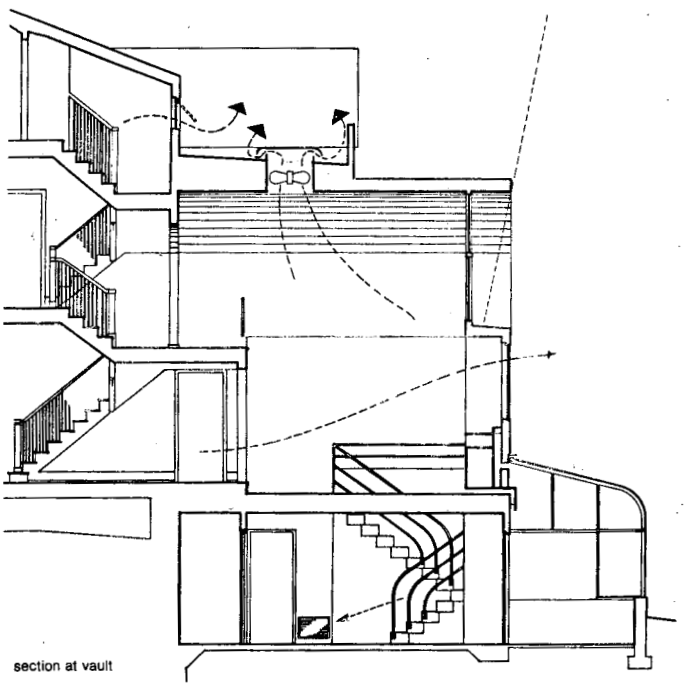
section at Trombe

Summer

In as much as the original house was intended as a summer residence, passive cooling performance was already good. It was found that virtually every space had been arranged with large windows on at least two exterior walls. The central hall containing the main stair was capped at the attic level with small awning windows serving as exhaust vents for warm air rising from below. The addition sought to maintain and expand upon the house's inherent qualities. Existing trees eliminated the need for elaborate overhangs by providing shade for all the south-facing facade except the upper arched window which was recessed into the vault to provide an overhang. The west end of the greenhouse also receives some sunlight in the afternoon. This is modulated by exterior shades which filter out sixty percent of the light or interior reflective blinds which roll down from the ridge. In addition, eleven individual squirrel cage exhaust fans produce a continuous power vent to supplement, when necessary, natural ventilation in the greenhouse. Numerous operable windows in the south facade and generous openings between the existing house and the addition assure continued good cross ventilation for all living and bedroom areas. A thermostatically operated whole house fan draws out air from the top of the vault whenever significant stratification occurs or when natural breezes are inadequate for good air flow. An interlock in the fan's circuitry prevents its operation when mechanical cooling is in use. During this mode, low return air grills at the basement level draw in cooler air which has pooled near the bottom of the addition and mixes it with return air drawn from other locations.

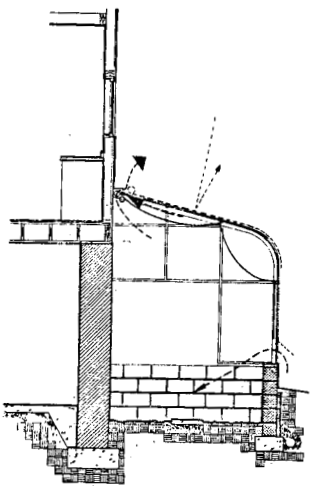


section at stair



section at vault

section at greenhouse



Performance

The building to date has performed better than predicted, with temperatures in the addition not dropping below 60 degrees F at night winter when night insulation was used. No overheating has occurred on mild winter days or in transitional months. Even distribution of heat through the whole house in winter has brought energy consumption of the original house down to 1/3 of its previous load.

## 3. APPLICATION: THE BEAUX ARTS TOWNHOUSE

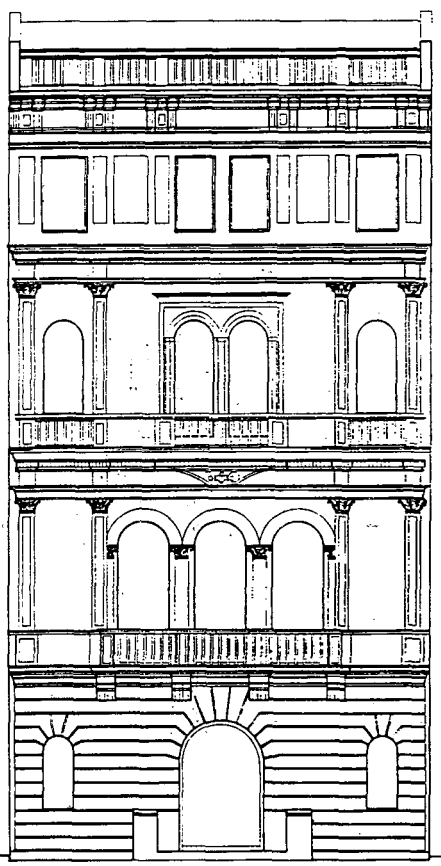
Designed by George Oakley Totten, a renowned Washington architect, and completed in 1880, the Beaux Arts style building at 1706 New Hampshire Avenue with its rusticated limestone facade was one of Washington's grand residences. Since that time the house had suffered through an assortment of other uses. Most recently, and until 1965, it served as the West German Embassy. It then remained unoccupied until restoration work began.

While the exterior of the building was in remarkably good condition, the interior, although structurally sound, graphically displayed the effects of several generations of less than inspired alteration work. Previous remodeling efforts had obliterated the rich detail and labyrinthian subdivisions of once grand spaces had radically altered the character of the design. In addition, 15 years of neglect had extracted its own toll. Leaking water from an upper deck had caused the collapse of over 40% of ornamental plaster ceilings in the second floor dining area. Broken windows and other openings permitted water to stain and warp large sections of the original wood floors.

The new owners sought to reuse the building for their own professional offices on the lower floors while renting the upper two. Although the program called for the usual mix of office, secretarial and other functions necessary for effective work space, the owners wanted the new layout to respect the qualities of the original design and permit as much of the interior as possible to be returned to its original state.

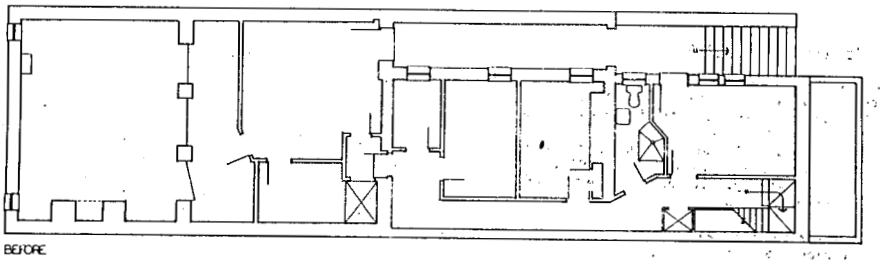
The design initially focused on the need to make optimum use of existing basement space and to organize circulation to allow the placement of smaller offices and ancillary spaces at the rear of the first, third and fourth floors. This strategy sought to reduce space requirements on the front of the first and all of the second floors so their design integrity could be maintained. The key to this approach was infilling a two story areaway on the southwest side of the building, which ran parallel to the building's long exposed southern face.

The new glazed enclosure of the areaway was held back from the face of the brick arcade so as not to alter the visual massing of the original elevation. The infilling permitted a corridor to be extended to the back of both floors. This freed space to accomodate a large number of the required office spaces.

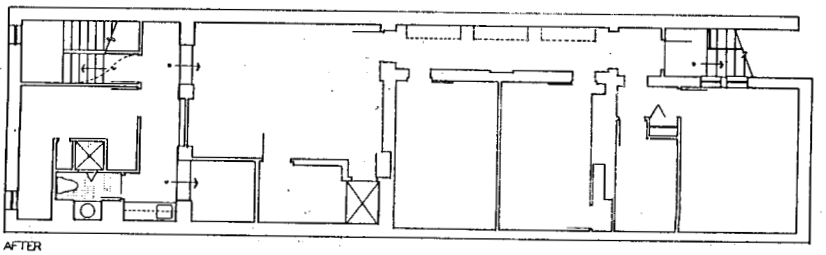


In addition, the infill created a number of conditions which operated to offset heating, cooling, and daylighting requirements for this portion of the building. By holding the floor back from the original arcade, daylighting was provided to basement office spaces. This was also true at the first floor offices which were connected to the corridor by original openings. Former exterior brick walls now serve to separate offices from the corridor space. The greenhouse effect that is created in the corridor tempers this office space, with the original brick walls providing heat for the nighttime utilization of these spaces. In summer, the doors to the offices remain closed during the day when they are not in use, and heat is mechanically exhausted, leaving interior masonry cool for evening comfort.

In designing the new mechanical heating and cooling system for this building, strategies for energy efficiency and historic preservation were developed in close harmony with each other, and were found to reinforce each other. The system consists of several small electric heat pumps installed throughout the building. For the moderate climate of Washington,DC, the heat pump represents a conserving alternative for mechanical heating and cooling. Using several small units throughout the building decentralized the system into separate zones, each served by an individual unit. This concept allowed for greater system control in response to the varying thermal needs of each particular zone. In this building, such zoning is extremely critical to energy usage. Facing east with one long side completely exposed to due south, the building's thermal requirements vary considerably from one space to another. Small individual units allowed for zoning without the burden of costly and sophisticated control equipment necessary in more centralized systems. Also, smaller units could be easily integrated within the building. Units were located above lowered ceilings in closets and bathrooms, and tucked discretely into wall pockets. Smaller units could also be located adjacent to spaces served, eliminating the need for extensive ductwork and dropped ceilings in any of the main spaces. Decorative grilles were located within the geometry of the Beaux Arts wall paneling. Because gas fuel was available as an energy source at the building, it was used as the back-up boost to the electric heat pumps. This increases the efficiency of the heat pump operations still further during those periods of extremely low outside temperatures.

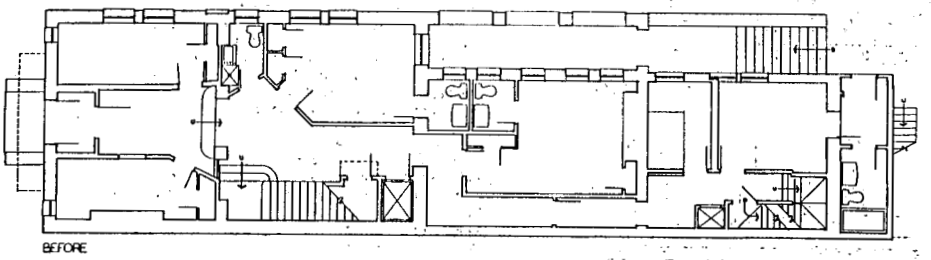


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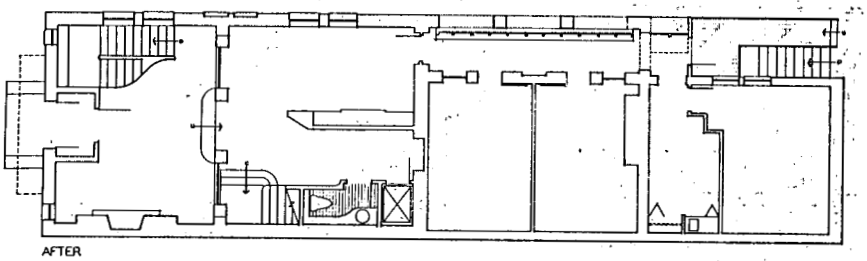


AFTER

BASEMENT LEVEL PLANS



BEFORE



AFTER

FIRST LEVEL PLANS

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0731-8626/83$3.00

# MULTI-SITE LIBRARY DESIGN
# SOUTH BEND BRANCH LIBRARIES

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## ABSTRACT

This report addresses the development of a single energy-frugal branch library design to accommodate four different sites in the city of South Bend, Indiana.

## 1. INTRODUCTION

South Bend, Indiana's branch library system is trying to avoid the "endangered species" syndrome---meaning, as things have been going in recent years, operational budget strain, already resulting in some branch services curtailment, is threatening the continued existence of the branch system---literally literary extinction. At the root of these economic problems are three factors:

1) uncontrollable, rising rental rates for functionally inadequate buildings
2) steadily increasing patron usage and rising staff costs exacerbated by inefficient space utilization
3) increasing utility and maintenance costs on a fixed rate income for operations

Through a coordinated effort by the Library Board, Library Staff, concerned citizens' support groups, and an energy-aware architectural team, a community responsive solution has been reached---replacement of the four existing rented facilities with four new 7,500 $ft^2$ library-owned facilities in the same neighborhoods as are the present ones---at an affordable initial cost and minimal future cost. The design goals that yielded this result were:

1) minimizing construction and design costs by utilizing a single design and documents package for all four branches
2) maximizing staff effectiveness by designing for "1-point" control and computerization of circulation and cataloging
3) minimizing immediate/long term utility and maintenance costs by energy-frugal design and careful materials selection/detailing.

## 2. ENERGY DESIGN PRIORITIES

Focusing on energy issues, the architectural team at LeRoy Troyer and Associates, set the following priorities:

1) establishment of parameters for orientation, circulation, and physical proportions that would fit four different urban sites. (Architect had input to site selection process.)
2) design emphasis on daylighting followed by cooling and heating---based on historical operating schedule for branch libraries and the degree of difficulty/constraint of daylighting design vis-a-vis that of cooling and heating
3) "conservation and controls first"---i.e., reducing building load and demand by the basics before diving into the exotics. (We never did find the waters of exotica.) The goal of cutting the existing facilities average usage by at least 50% set 50 MMBtu/$ft^2$ yr as a minimally satisfactory upper limit

One restraining consideration was the fact that any mistake would be replicated four times, thus making an already conservative project (in terms of regional climate, locally prevailing expectations, and funding) slightly more so. Other tempering factors included design of building systems to be understood and operated on a regular basis by the librarians as no maintenance personnel are permanently assigned to the branch facilities; absolute prohibition against flat roof systems for reasons of maintenance and residential roofline character; and a need to accommodate significant changes in future operations and services.

### 2.1 Building Configuration

South Bend's climate is one of some gloom and doom for solar enthusiasts---about 73 days during an average year are clear according to NOAA, and of those, 49 occur between May 1 and October 31. Heating degree days average

6462 and cooling 695 with an average humidity of about 72% from June through September. Temperatures are moderate with diurnal swings of 15°F in winter months to 20°F during the summer. Winds prevail from the south/southwest with winter storms often coming across Lake Michigan from the west/northwest giving South Bend an average of 72 inches of snow (usually wet type) each winter. Therefore, every ray of sunlight is important during the winter grays while cooling is a significant summer and fall concern.

As the sites available were somewhat restricted in terms of size and location, the architects brainstormed a number of general circulation/orientation program schemes and decided that a compactly E-W elongated plan shape with a sheltered entry from the east would accommodate both the regional climate and a variety of vehicular and pedestrian approaches. Final site selections supported this scheme (see Floor Plan Fig. 1 and Site Plans Fig. 2 below).

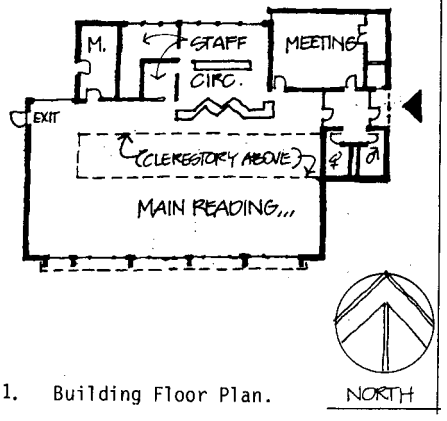



Fig. 1. Building Floor Plan.

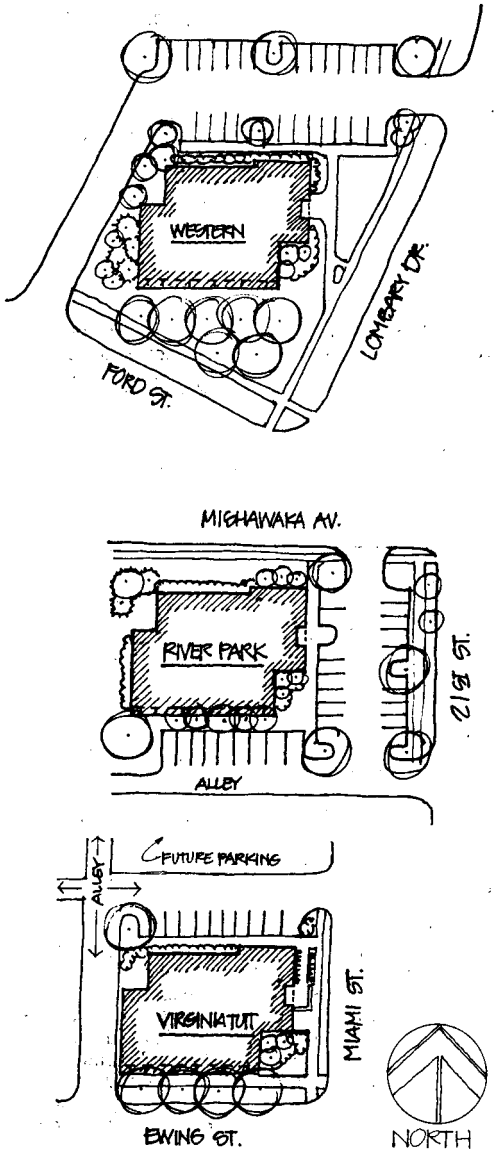



Fig. 2. Building Site Plans Showing Varying Sites with Identical Building Floor Plan/Orientation.

## 2.2 Daylighting

Reasons for our urge to daylight these buildings included a proposed yearly operating schedule of 90% daylit hours; impact of lighting loads on relatively expensive cooling process; the significance of lighting quality to the branch library function (in this case, non-critical reading and materials display); and building proportions, sizes and openness appropriate to simple daylighting methods.

The strategy was to light the main reading space from the south perimeter and from a high south-facing clerestory. Thus light enters the main library space by three glazing areas (see Building Section, Fig. 3). Vision glass along the south wall allows perimeter illumination while a higher glass band above a shading/light-shelf device admits light further into this space. Midway in the building but towards the back of this main area, a nearly full length south clerestory drops light through a splayed well to serve the back third to half of the main space plus the circulation desk and entry area. Size and angle of splay are so designed hopefully to minimize glare on the circulation desk surface throughout the year.

Some additional high north facing windows are situated to help illuminate the staff work area along the building's north perimeter and to compensate for a "dim corner" in the main reading room's northwest corner. There are essentially no east or west facing windows although the glass wall of the entry vestibule faces east. (It is recessed 6 feet.)

To complement the daylighting and to insure its practical effectiveness, the electrical lighting design incorporates an indirect system running parallel to the primary glazing controlled by an automatically dimming, essentially full-range LUTRON PRF system utilizing energy-saving ballasts and lamps. Further, the main reading space is divided into four lighting zones with a maintained level of 50 fc at the work plane height set for general illumination purposes.

Light-colored surfaces and furnishings are used throughout with exception of carpeting (each branch has a "theme" color with the carpet serving as the prime accent color. Exterior building surfaces and vertical fin walls are all light-toned brick and the roof clerestory is surrounded by white metal cladding and a red standing seam metal roof (a somewhat compromising decision made for visual, material and cost reasons).

## 2.3 Cooling and Heating

Given the building configuration and daylighting design strategy, the primary design approach for thermal conditioning was to opt for conservation techniques. Infiltration, air circulation, envelope insulation levels, shading and landscaping, zoning, simple timer controls, and high efficiency equipment comprise the most important design issues.

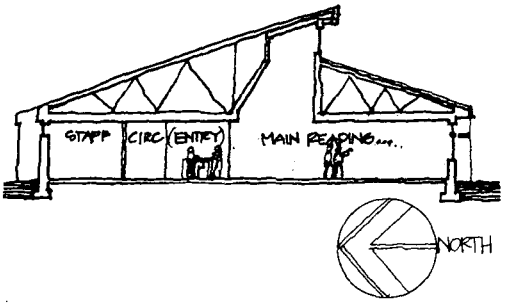



Fig. 3. North/South Building Section.

Since infiltration in this size building usually dominates, a tight building became the number one goal. Minimization of code-required cfm's (quantity and duration) and exterior doors and openings constituted our primary targets. Staff and public entries were combined into one and an ample, protected, and slightly pressurized vestibule was provided. Vapor barriers, double-dampered exhaust and intake louvers, direct feed-combustion air, minimal flue sizes with pulse boilers, and point-of-use water heaters for the public restrooms are additional measures to reduce infiltration.

South and north facing awning and casement windows provide natural cross ventilation during hospitable weather and the clerestory well contains return air grilles and thermostatically controlled exhaust fans. Clerestory windows are fixed, triple-glazed units shaded by an overhang and a series of vertical fin walls. Lower south glass is a combination of fixed and operating double-glazed units also shaded by overhangs and fin walls (see Building Section, Fig. 3). Landscaping designed uniquely for each site strives for south deciduous shading, heavy west wall shading, northwest corner and north perimeter protection, and high foreground reflectivity along south perimeter.

Construction is chiefly of block and brick with a wood truss roof structure and metal roofing. Insulation levels provided are R10, R20, R40 for foundation/slab perimeter walls, and roof/ceilings, respectively and vapor barriers are 6 mil throughout. Manually operated Window Quilts™ in lieu of

draperies or blinds at the lower south window, offer some additional night time insulation and sun control.

HVAC systems include 90+% efficient, staged-gas pulse boilers with separate air handlers and condensors with economizer cycles serving three thermal zones. Night setbacks, meeting room system timer, staff hot water storage tank timer, and point-of-use water heating for public restrooms combine to reduce building demand loads. Location of mechanical equipment room in northwest corner, occasional-use public meeting room in northeast corner, public restrooms as a buffer to east, and primary user spaces occurring along southern exposure demonstrate architectural plan zoning.

2.4 Other Considerations

Several things considered and not done were clerestory insulating systems, super-insulation, micro-computer controlled management system, light-colored roof apron at clerestory, a spike suppression system at main electric panel, and LeRoy Troyer's underground "Terra-Temp" system.

Clerestory insulating systems would have to be automatically or at least mechanically operated to be effective in this design and savings would not justify costs and design problems. Superinsulation for the size and function of this building also seemed to be not as consequential as the costs of unusual wall sections and added materials. The light-colored roof apron just below the clerestory windows seems a good idea that just did not come to fruition, as is the building electrical spike suppression device. Both of these proposals are feasibly retrofit items for future consideration. Due to the simplicity of the building and its systems, the lack of electrical demand/time of day/ratchetting charges, and the rapidly changing nature of microcomputer controllers, it was decided that an EMS was a matter for future implementation.

The last item of consequential consideration was the use of LeRoy Troyer's patented Terra Temp design for providing tempered air via an underground rock-filled concrete tunnel system. While analysis indicated the system to be potentially viable (ecnomically speaking), the complications of tailoring it to four sites (as it is external to the building) added substantial design time and overhead as well as further complicating the site variables.

3. SUMMARY

South Bend's new branch libraries being constructed nearly simulataneously are due to be completed in late fall of 1983 with occupancy staggered into early 1984. Financing was accomplished by a 15 year tax-free municipal bond with construction costs being under $70 per $ft^2$ including furnishings and sitework.

One last item that has not been addressed is the unique potential in this project for comparative monitoring and analysis. Due to tight time and cost budgets, no attempt has been made to obtain funding or equipment for such a study. Nonetheless, the new South Bend Branch libraries offer a wonderful opportunity for observing influences of non-residential user patterns and microclimate variables on building performance over a statistically significant period of time.

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0731-8626/83$3.00

# PASSIVE SOLAR STRATEGIES AS A LOGIC FOR IMPROVED ARCHITECTURAL DESIGN: TWO PROTOTYPES FOR MODULAR HOUSING

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## ABSTRACT

In developing two passive solar modular housing prototypes for mass production, design research was done by ARCHETYPE. This research was directed toward effectively utilizing the strengths of the current modular industry, and developing climatically responsive, economical and beautiful solutions that would expand the market, save energy, and stimulate do-able qualitative change within the modular industry. Herein we present some of the data derived from that research which has been incorporated within our framework for future design.

## 1. PROJECT DESCRIPTION

The goal of the project was to develop a prototype which incorporates passive solar strategies and technologies into modular housing. Two passive solar modular housing prototypes were developed for Usry, Inc., a manufactured housing distributor. Receiving support from the U.S. DoE under its Passive Solar Manufactured Buildings Program, both prototypes were built and are currently being monitored for a year to determine their actual thermal performance. Usry is marketing both designs.

## 2. APPROACH TO DESIGN

The conservative nature of the modular housing industry advocated that designs slated for immediate mass production must be fabricated within the confines of the current industry. The investment in the prototypes, although always planned to be higher than the cost to mass produce the standard, was to be minimized. Major deviations from factory organizational or construction standards were inappropriate. The designs had to be a response to existing methods, geometries, and building components. Change must come from within, providing the greatest impact with the least variation from typical practices.

Viewing the logic of passive solar strategies as a vehicle for improving the quality of architectural design, and becoming aware of the structural qualities of the typically constructed module which is built to be carried virtually intact over long distances, we determined that by increasing design quality, an up-market could be approached. The stigma associated with modular construction was in response to design and specification, not construction method. It was proposed then, to develop two prototypes, one of moderate cost to compete with the traditional market of site built housing, and the other of low cost to appeal to the current modular housing market.

## 3. EXISTING INDUSTRY: AREAS OF CONCERN

Investigation of current factory procedures, construction methods, site operations, current design and products revealed the following:

a. Construction of the envelope of each unit is fast, a fraction of the cost of site built construction, far ahead of traditional construction in terms of structural integrity and tightness of seal, although methods of construction are intrinsically the same.

b. The double wall plane at which the boxes are joined is always an interior visual and spatial barrier. This joinery is structurally sound, but thermally vulnerable.

c. Designs are devoid of variation in interior space. There are low ceilings throughout with a lack of cross ventilation. Windows are equally distributed on all exposures.

d. There is no transition of space from interior to exterior. There is no entrance condition, no vestibule.

e. There is no 'permanent' quality in the building materials and hardware used within the typical units. Door and window framing is thermally vulnerable.

f. Plans currently offered were organized around a core design that was adaptable to a number of alternative options. Material options were also offered.

g. Factory construction procedures logically respond to minimal labor costs.

h. Sitework employed traditional foundation construction, using simple but precise methods of attaching and setting the modules on the foundations.

i. The 1000 square foot double wide modular house, and the 1500 square foot variation are the most popular combinations sold in the southeastern market.

## 4. THE RESEARCH: DESIGN RESPONSE TO CONCERNS

Various series of alternatives were generated. Each series was structured according to the use of three generic passive system types, direct gain, trombe, and solarium, and to a possible low cost 1000 square foot unit and a moderate cost 1500 square foot unit.

### 4.1 Module Groupings

In response to length and width limitations for each module (due to transport regulations), diagrams were derived which organized modules for space and form articulation, and optimal solar exposure.

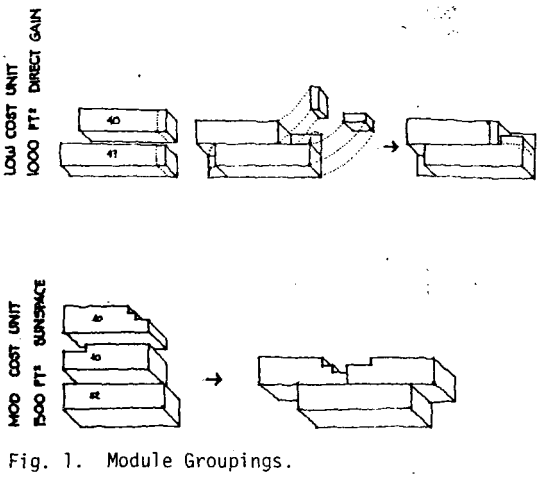



Fig. 1. Module Groupings.

4.2 Thermal mass

The integration of thermal mass into the wood frame units that were fabricated, transported, and then set upon typical foundations suggested two alternatives. These being the incorporation of lightweight materials such as phase change or water storage containers, which were rejected due to cost and concern for container life and durability, and site installed building mass.

Pre-cast concrete panels were found to require special handling equipment with high initial costs. Poured-in-place concrete required factory built formwork that could be integral with the framing construction and building structure. This however suggested interior finishing at the site rather than in the factory and more on site inspections, which could lengthen the construction period and add costs. Site built masonry units offered the possibility to simply extend the masonry normally built for foundations. No new trades, materials, or module setting procedures would be required.

Studies suggested a central mass wall, extended from the central foundation wall required in a double wide configurations, would provide the most even distribution through the house.

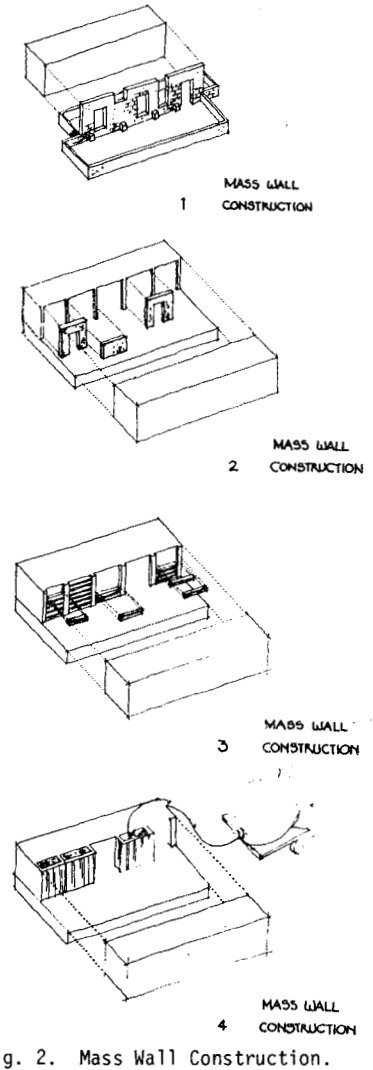



Fig. 2. Mass Wall Construction.

4.3 Articulation of Space

4.3.1 Plan Evolution

Design intensions at this point concerned the creation of spatial hierarchy in ways which would be energy-conserving and responsive to passive solar strategies. Variation of spatial experience was necessary to overcome 'smallness' perceptions, articulate energy flows (both heat and light) and improve functional-spatial relationship to the outside. Plan also sought to retain the qualities of existing modular design by structuring a core design that would have the same optional variation as those currently offered. In addition, the plans intended to offer expanded options such as north or south entries, trombe with later greenhouse expansion. Plans also sought to offer more to the core design with such features as master bedroom suite, (bedroom, bath, dressing, and private outdoor deck), and other decks as expanded outdoor living space.

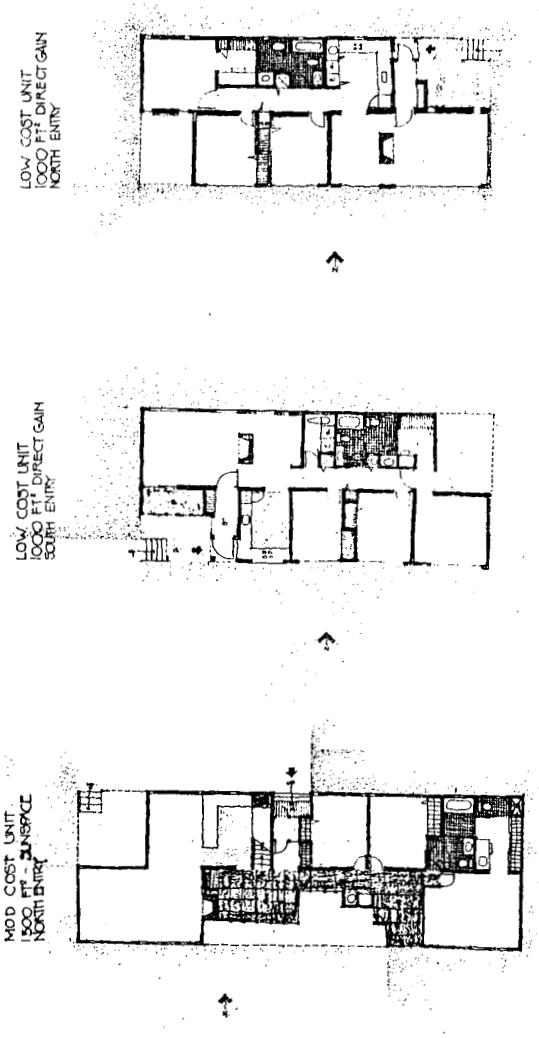
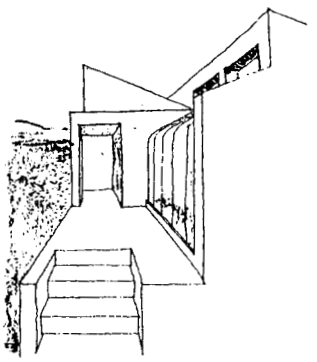
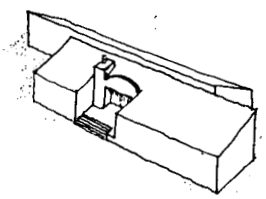



Fig. 3. Plans.

4.3.2 Building Volume

Massing of building volume was studied in terms of plans, relation to site, solar collection, spatial experiences in and around the building (also linked to climate response), and visual organization of form and materials.



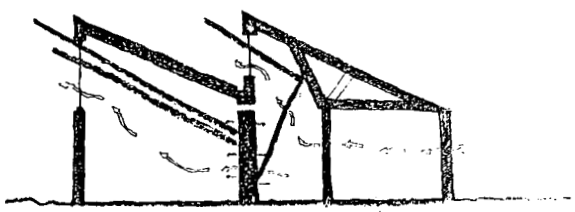




4.4 Passive Solar Components

The constants and variables with regard to passive solar strategies and improved architectural design had been indentified. It was concluded that the passive solar systems for both prototypes could be concepts which effect change within each house's organization. In this way, the systems could influence building form and space achieving project intensions of of energy use and improved design. With form articulation as the major differentiation, a series of simplified components would then serve to control system operations.

In the low cost house, a simple direct gain system was approached.Studies addressed the articulation of the roof section in order to maximize exposure to central mass. Skylights in the conventional roof geometries, make large apertures possible and provide a good relationship to central mass. They are, however, highly reflective of winter sun, minimally reflective of summer sun, suggest vulnerable detailing, and high heat loss at night without moveable insulation. Vertical apertures in saw tooth roof geometries offered good winter collection and summer reflectance, easy detailing, easily controlled daylighting into the corridor, heat gain on both sides of the mass wall, and allowed for good cross ventilation. This geometry however, also suggested troublesome roof drainage. The shift to a saw tooth roof was developed for the final prototype. Model and section studies determined optimal configurations for winter gain, summer shade to both sides of the central mass wall. The resulting form, detailed with a gutter sized for worst day rainfall or snow fall, and an integral cornice-like lightshelf, provides dramatic daylight to the corridor, living, dining, and kitchen spaces, houses a possible hot water preheat, auxiliary lighting, and moveable insulation, and induces cross ventilation through its operable windows. Where the living area intersects the outdoor deck, the mass wall becomes a radiant trombe, which can be later expanded to enclose part of the deck with greenhouse.



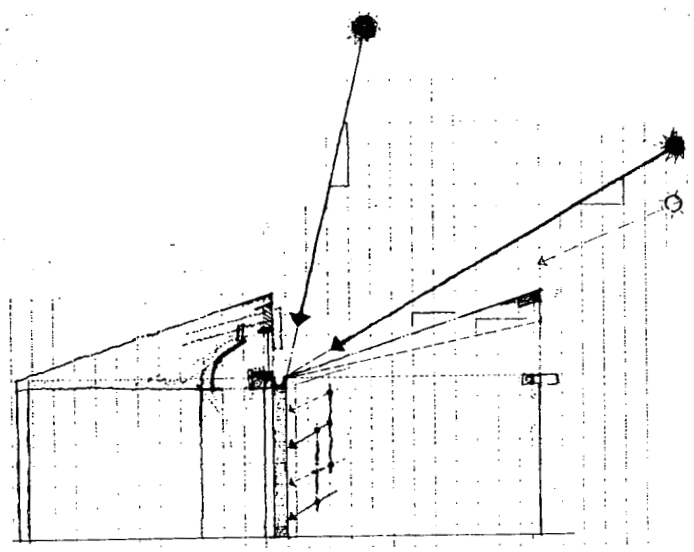


Fig. 4. Building Concepts.

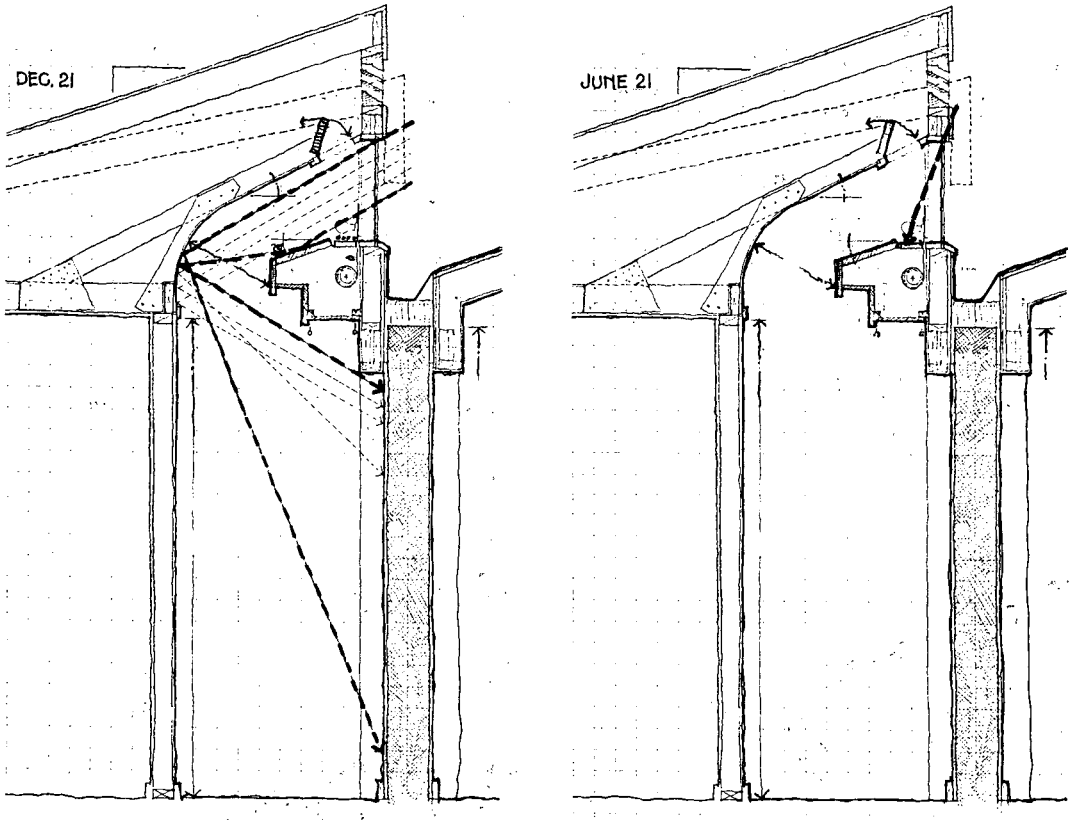



Fig. 5. Clerestory Details/June and December.

In the up-market prototype, extra floor area and maximum system control were desired. The solarium system was chosen because it could be linked to the house using the central mass concept, expand living space, and offer the possibility to be thermally separated from the living spaces. Plans located the solarium in such a way as to form an airlock entrance condition. Section studies derived patterns of energy distribution between the solarium and the rest of the house and determined roof profile.

As the central spatial and thermal element of the house, all rooms can benefit from shared heat and light. Collected heat is absorbed by mass walls, then convected through attic loop to the north facing areas, with excess heat finally ducted to rockbins under master bedroom and living room for direct radiation at night. An insulated curtain separates the solarium from the rest of the house at night and in summer. In summer a canvas canopy shades the mass wall and mechanical exhaust augments ventilation.

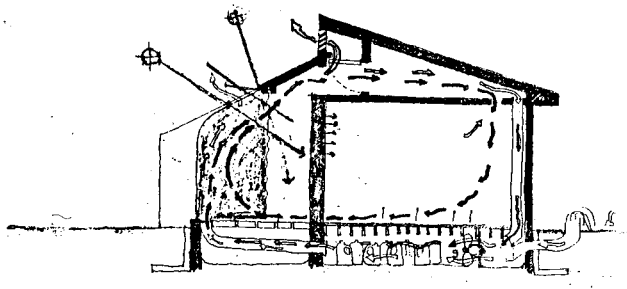
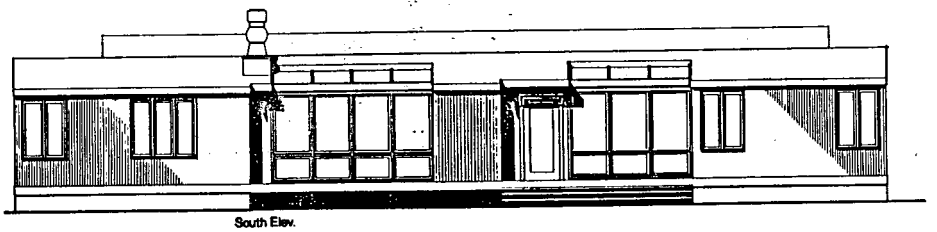
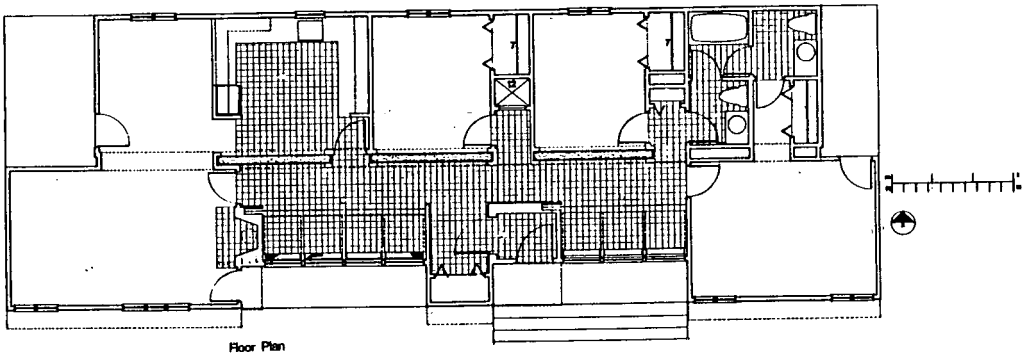
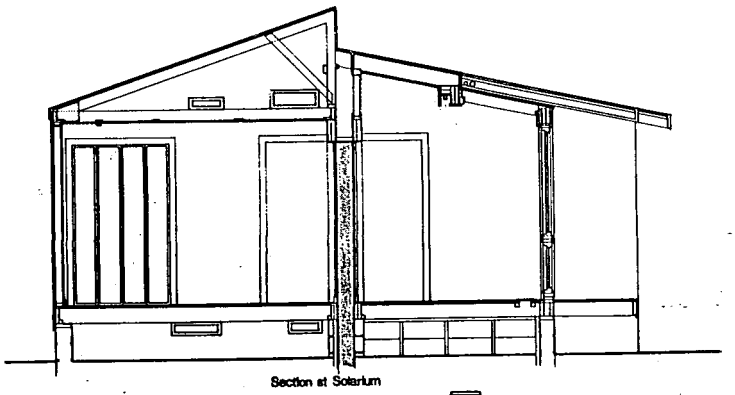
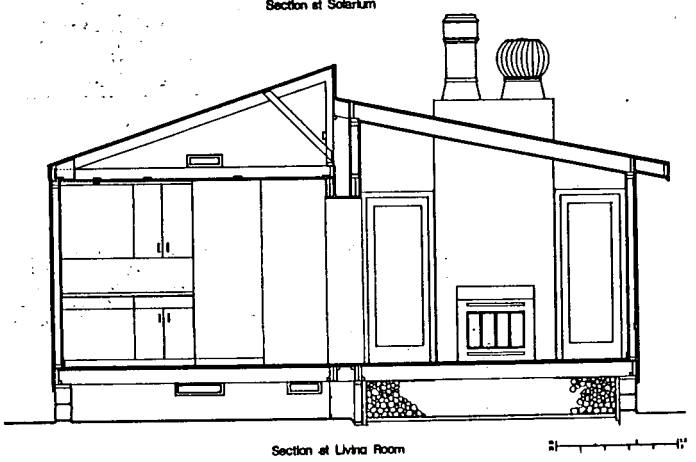


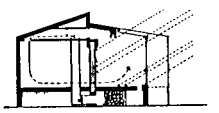
Fig. 6. Cross Section.

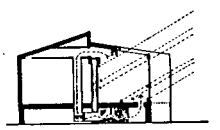


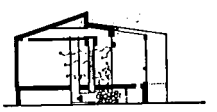





heat to space


heat to storage


heat from storage

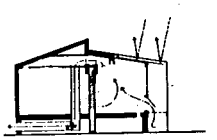
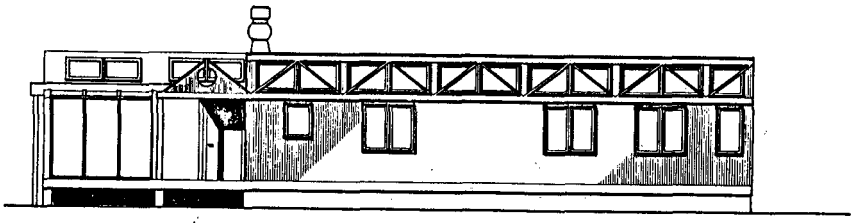
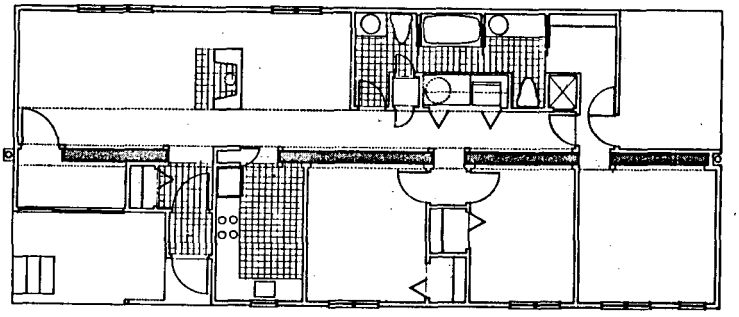

summer ventilation

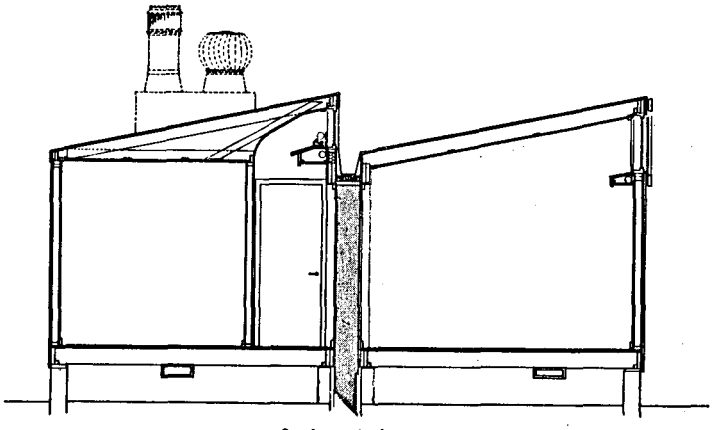
Fig. 7. Solarium House.



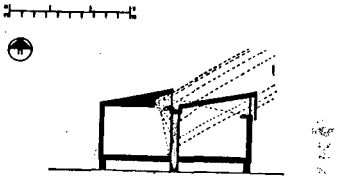
South Elev.



Floor Plan



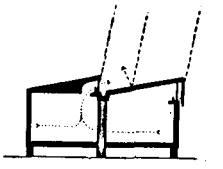
Section at bedroom



winter day



winter night



summer

Fig. 8. Direct Gain House.

6. PERFORMANCE

Although recorded data is as yet unavailable from SERI, frequent inspections of the houses reveal that their general thermal performance thus far has supported initial design assumptions regarding areas of mass to collection areas, and spatial articulation in order to achieve even heat distribution. Neither house has overheated during transitional months or on sunny mild winter days. During February of this year, the solarium space in the Solarium House consistently manitained a 75 degree F temperature until 9 PM. The Direct Gain House has, through this heating season, maintained a temperature range of 60-75 degrees F without the assistance of auxiliary heating.

7. Second Generation

The Solarium models for mass production eliminated the rock bins and lengthened interior masonry walls to be adjacent to living and master bedroom spaces, as a cost and time-saving factor. This greatly simplified the system, eliminating the need for much of the ductwork in both attic and crawl spaces. This served to minimize the vulnerability of thermal leaks in later models. Further options for expanded or contracted living rooms have evolved in response to market demand. The Solarium space has been widened for improved spatial utilization. Prefabricated operable skylights have replaced the sloped glazing in the solarium space. In this way, the solarium space can be fully framed in the factory and skylight components shipped with the units, minimizing cost of sitework that turned out to be a high cost factor within this industry. The development of the north entry option has been completed. In the Direct Gain models, the north entry option has been developed.

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# THE CUSTOM PASSIVE SOLAR SUNSPACE: SOME DESIGN ALTERNATIVES

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## ABSTRACT

During the past few years new housing has become more difficult to afford. Many people are turning to upgrading their existing homes to meet their changing needs. Passive solar additions are a popular way to improve an older home. They provide added living space, bring sunlight into dark interiors, reduce heating costs, and add to the resale value of the house. Passive solar greenhouses also provide growing space for vegetables and house plants and provide a wonderful source of recreation for the home owner.

The design of the custom sunspace addition requires trade-offs between performance, architectural integration and the owner's needs. This leads to some very interesting design solutions that bear no resemblance to the "optimum" sunspace design generated by computer simulations.

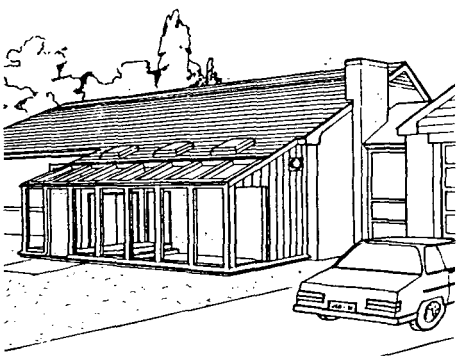
## 1. INTRODUCTION

Three types of projects are presented in this paper. The first project (Linderman addition) is a simple low cost and versatile sunspace addition that can be either contractor built or owner built from a kit or do it yourself plans. The second project (Bates addition) is a major custom sunspace addition. This second project shows how a sunspace can be added to a house with very poor orientation. The third project (Quail Run) is a new house with a very large sunspace integrated into a traditional colonial style.

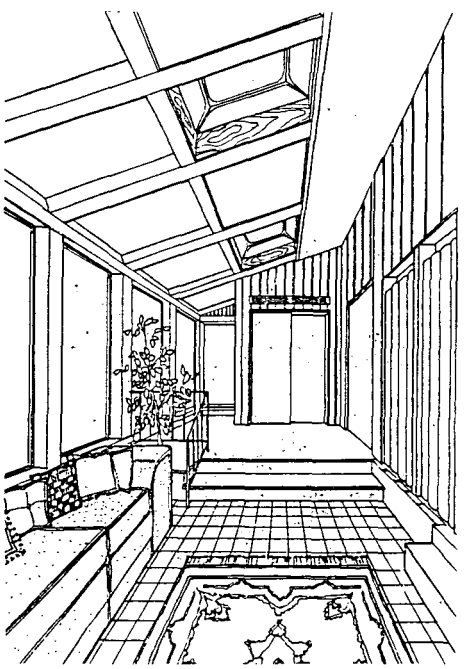
## 2. LINDERMAN ADDITION

The Linderman addition is a good example of a standard sunspace design that can be integrated well with most home styles. It is easy to construct and low cost. The average contractor installed cost of this sunspace is approximately $43.00 per square foot.

The structure is a 4 x 4 post and beam frame on a 4 in. concrete slab. The glazing consists



**LINDERMAN HOUSE** **EXTERIOR**



**INTERIOR**

of 34 in. x 76 in. quad-pane units with two layers of glass and two layers of 3M Sungain film between the glass.

The glazing is mounted on the outside of the 4 x 4 with a 1 x 4 cap. The sunspace can be constructed with various configurations of glass and solid walls. The best performing system on an annual basis consists of south wall glass only and a solid roof (Fig. 1).

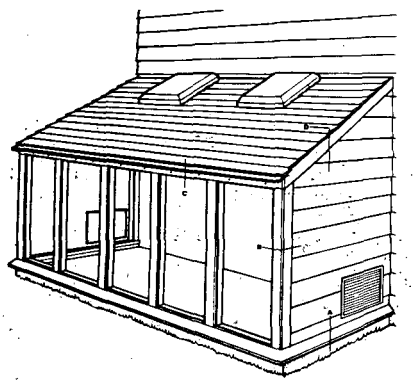


Fig. 1.

The most popular model for combined solar and horticultural purposes consists of one-half glazed room and end walls partially glazed. The roof glass is covered in the summer with a shade cloth to prevent overheating. The glazing caps on the roof are aluminum with EPDM gaskets (Fig. 2.).

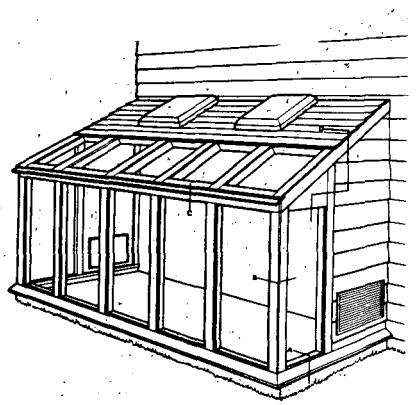


Fig. 2.

Two operable skylights are used in the roof of all models for summer venting. Screened vents in the end walls allow venting in the summer without having doors or windows open which presents a security problem. The vents have an insulated door to close them off in the winter.

This addition is very versatile and can be installed on either the side, rear, or the front of the house. The Linderman addition is on the front of the house and serves as a new entry way and as an addition of the living room.

## 3. BATES ADDITION

Ralph and Gwen Bates were growing out of their house in Annandale, Virginia. They decided to add about 500 $ft^2$ to expand the kitchen, dining room and living room. They also were aware of the fact that their utility bill would increase due to this additional space. They decided to construct a passive solar addition and hopefully reduce their utility bills.

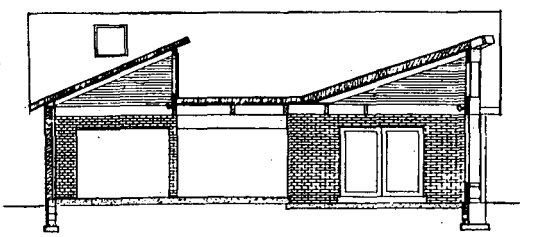


Fig. 3. Section.

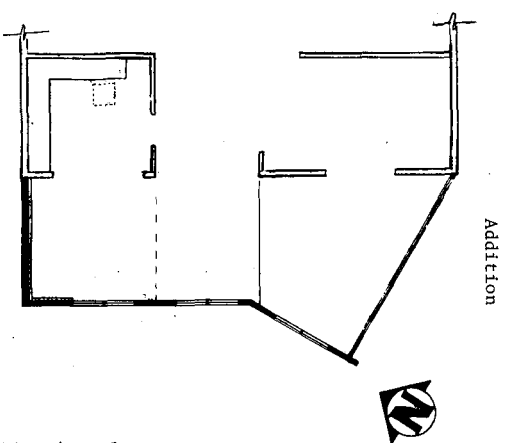



Fig. 4. Plan.

The addition is 42 ft long and expands the kitchen area on the north, the dining room in the middle and the living room to the south. A deck was added to the southwest for an outdoor living area.

The Bates' house presented a real challenge in terms of solar access. The area of the house where the addition was to go faces about 60° west of south. This ruled out a square addition with glass facing the backyard. The solution was to use two clerestories which face south and southeast. The living room has an angled wall of double pane glass facing due south and the kitchen addition has a clerestory which faces 30° east of south. The southeast exposure in the kitchen area does two things. It provides morning sun to the kitchen area for early morning warm-up and it also allowed the north facing roof of the addition to work into the existing roofline of the house. This side of the house is seen from the street and the addition blends very well with the house on that side.

Thermal storage is provided by a 6 in. concrete slab floor with terracotta tile and a new interior brick wall on the north wall of the kitchen addition. The north wall is illuminated by the kitchen clerestory. The existing wall is brick on block and provides additional mass.

The new addition has approximately 500 $ft^2$ of floor area with 200 $ft^2$ of south facing glass. The walls are 2 x 6 studs insulated to R-19. The roof is insulated to R-30. The new addition has reduced the overall heating bills of the house in spite of the fact that the house is 500 $ft^2$ larger. The savings from the sunspace addition was 20-30% in terms of Btu/DD $ft^2$.

The sunspace also reduced the cooling load. The clerestories contain operable windows which allow warm air to vent in the summer drawing in cooler air from outside. Two reversible cycling fans also aid in air-movement and provide cooling. The Bates did not use their air conditioner last summer due to the new addition.

The passive features of the Bates' addition did not add to the cost of the project. The Bates' addition cost $30,000 in 1981 or $60.00 per square foot. Other additions to the same house in the same development cost about $60.00 per square foot.

## 4. QUAIL RUN

In 1980, a local Maryland builder named Jay Walfarth called me to assist him in designing and building a passive solar home in the Quail Run subdivision in Darnestown, Maryland. He has been building homes since 1953 and is well known for his traditional English colonial homes. Walfarth said he was having difficulty integrating the "modern" all glass passive solar features into the traditional colonial style of the Quail Run subdivision.



Fig. 5. Quail Run.

Many people believe passive solar is a "modern" architectural style and could not fit more traditional styles. As we discussed the project more, I explained to him that Thomas Jefferson lived in a passive solar colonial home. George Washington also had a passive solar greenhouse on his estate in nearby Mount Vernon, Virginia. I felt that these examples would serve as good points of reference to begin designing the Quail Run passive solar home. Together we began to design a traditional solar home. The result was a truly elegant and very energy-efficient English manor colonial home.

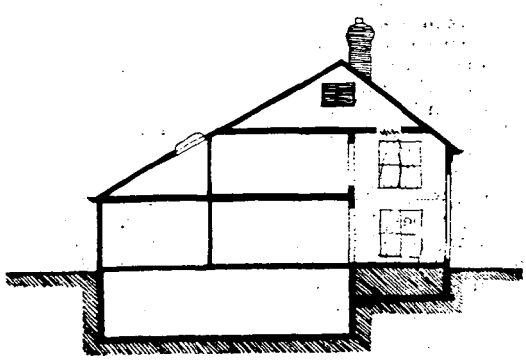


Fig. 6. Section.

The home is designed around a two-story 50 ft wide solarium with five beautiful arched-top two-story divided light wood windows. The center window incorporates a glass entry door

as the main entrance to the home. The solarium contains approximately 410 ft$^2$ of double-glazed windows on the south side. The east and west walls of the solarium consist of double-hung windows for summer ventilation. The interior of the solarium has brick floors and walls. All the rooms of the house, except the dining room, open to the solarium through a pair of french doors. The two upstairs bedrooms each have their own 10 ft x 12 ft balconies overlooking the sunspace.

The first floor also contains a large living room with a marble fireplace, a large formal dining room, and a large gourmet kitchen. The first floor master bedroom suite includes a bath with separate tub and shower and a gigantic 19 foot walk-in closet.

The hand-built Chippendale staircase leads down to a finished game room with wet bar and fireplace. The north staircase is daylighted with a small skylight to avoid high contrast lighting from the bright south wall and the dark north wall. The staircase is brightly lit all day.

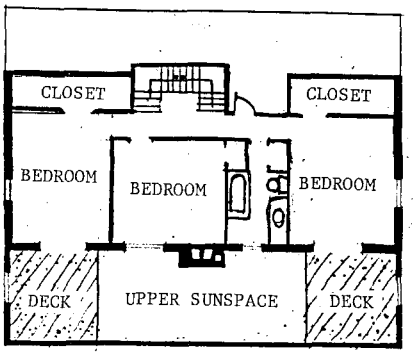
People who visit Quail Run are immediately impressed by the dramatic two-story solarium entryway, but have no idea it is solar. Some people who have seen the house think it is an old colonial home that has been renovated. Many people have told me they don't like the all glass solar homes, but this home they love because it doesn't look solar.

The building is constructed of 2 x 6 studs with R-19 insulation and a brick veneer. The attic is insulated with R-30 fiberglass insulation. The heat collected in the solarium is stored in the brick floors and walls and circulated throughout the house by natural convection and at times can be ducted from a large return air grill in the ceiling of the solarium to the large volume, low velocity heating system. The solarium is cooled by natural ventilation and supplemented by a 36 in. variable-speed attic fan. This fan not only ventilates the solarium but also cools the entire house.

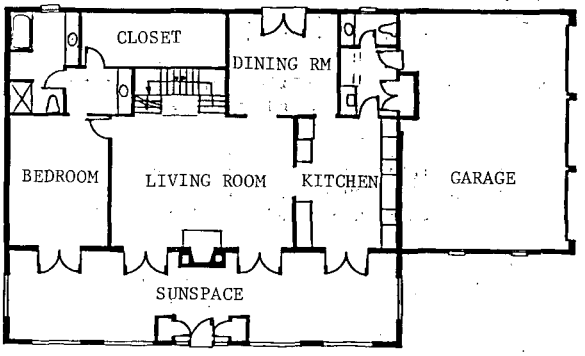
The house is protected on the north and northwest by a heavily wooded ridge of large evergreen trees. The north elevation is one story with only two small windows and a pair of french doors. The minimal east and west windows are shaded by deciduous trees.

The auxiliary heating system is a forced-air, large volume, low velocity gas furnace with its own fresh air supply. The two fireplaces also have outside air and glass doors.

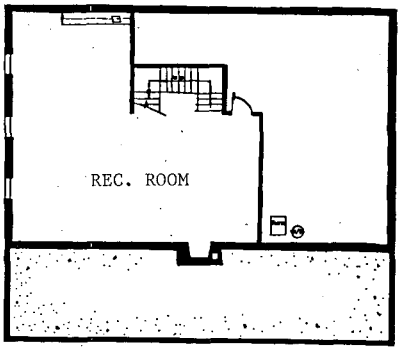
The performance of the house has been excellent not only in terms of energy conservation but also in terms of enriching the quality of life of the occupants. The owners, Dr. Paul Wertlake and his wife Shirley, love the house




Second Floor




First Floor




Basement

Fig. 7. Quail Run Floor Plans.

and spend most of the time in the solarium. Shirley said they never had heard of passive solar before they bought this house, but now they would never live in any other type of home. Shirley said, "It's like living outside. It reminds us of living on our sailboat. We love it."

In terms of energy performance, the building works very well. The home was under construction during the winter of 1981-1982. Due to the passive features, the building maintained comfortable temperatures in the 60s before the heating system was installed. The owners moved into the house in the summer of 1982. The building remained cool and comfortable throughout the hot humid summer without air conditioning, due to the abundant mass and generous ventilation provided by the whole-house fan.

During the heating season, the building consumed a remarkably low 1.5 Btu/DD/$ft^2$ based on a utility bill analysis. This includes auxiliary heat and internal gains. For comparison, the average passive solar home monitored by the National Solar Data Network (NSDN) consumed approximately four Btu/DD/$ft^2$.

The Quail Run home did not cost any more to build than other nonsolar homes in the area. Quail Run sold for $65.00 per square foot on a one acre lot.

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0731-8626/83$3.00

# THE UMBACH RESIDENCE AS A RESPONSIBLE SOLAR DESIGN FOR A COLD, CLOUDY CLIMATE

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## ABSTRACT

In a time of ever-increasing energy and construction costs for housing, we find that the homes which do get built are either relatively inexpensive or relatively expensive, with less and less in between.

Many good attempts are being made to resolve the energy-efficient, low-cost residence. Yet in contrast, the mid-to-high range market moves on with "business as usual" in spite of economic recession, and many, if not most of these types, still exude an obese and wasteful opulence.

This paper attempts to show the inroads passive solar is making into responsible and responsive development of these "separatist" single-family detached residences, hopefully giving their owners a "nudge in consciousness" to their role in local and national energy scenarios.

The Umbach Residence (Fig. 1) located in Saginaw, Michigan, (43.3°N, 7,400 heating degree days[1] and less than 50% average annual sunshine) is such a house. Designed for a sucessful, young and growing family, it encloses 2,800 square feet of living space and employs energy conserving and passive solar features throughout.



Fig.1 . South Elevation

## 1. INTRODUCTION

In a common pattern of urban development, these owners purchased a lot in a newly developed subdivision on the outskirts of the city. Only twenty or so homes were planned to be built there, with "quality" insured by the developer through conditions requiring minimum floor areas and one premier builder to construct all the homes.

All too often in this type of development, the homes end up with attractive facades of high quality materials, but with little regard for solar orientation and other energy conscious criteria.

In this case too, the builder prepared a plan that did not exactly fit the owner's needs, as well as those of the site, and had minimal energy features (e.g., inadequate wall insulation, a major southwest building orientation, no thermal mass or night insulation, and zoning which did not take full advantage of the heat circulating fireplace located at one end of the house on an outside wall).

Untypically however, the Umbachs decided not to use the builder's plan, and having heard of a passive solar residence nearby, contacted its owners. They became convinced that they should employ the same architects to design an energy conserving, passive solar home which would be more responsive to their needs and their particular site.

## 2. DESIGN CONSIDERATIONS

The site is flat and wooded (deciduous) with a good clearing in which to set the house. (Selective cutting and pruning provided good solar exposure.) The owners wanted a "contemporary feel" to the exterior and a mix of "contemporary and traditional" on the inside. Their scrapbook of magazine cut-outs and a well thought out building program conveyed these ideas extremely well.

Energy strategies were studied and blended

with the building program through a series of meetings with the owners, the builder, and the architect. In a cooperative process, a design evolved which "fit like a glove" to their site, and met their needs for area, views, and lifestyle.

## 3. ENERGY CONSERVATION

Overall space zoning facilitated energy conservation. The basic layout (Fig.2) has a centrally located "Great Room" with an efficient wood burning stove (Vermont Castings) and masonry hearth. Flanking this room are the other major living areas, all with a southern exposure.

The central wood stove is adequate to meet all the back-up heatong load. One problem (discussed in more detail below) occurred when early plans for the Master Bedroom gradually closed off this area from the wood stove to the point where this became a separate thermal zone of the house.

The Garage, Mudroom, Laundry, and seldom used Dining Room (a program requirement which could not be compromised) provide northside buffers. Dense trees to the north also shelter the house at the entrance (Fig.3).

Exterior walls are comprised of 2x6s @ 16 in. o.c., R-19 fiberglass batts, 4 mil poly vapor barrier, rigid insulation sheathing (R-7), with horizontal 1x3 stripping for a vent space and nailers for the vertical siding.

Roofs over the flat ceiling areas have 15 in. of fiberglass batt insulation (R-49). Roofs at cathedral ceilings use 2x12 rafters with 2x2 sleepers providing a vent space over 11" of fiberglass batt insulation (R-38).

All south windows are double glazed with night insulation (Thermal Technology, Inc.) on an automatic mode. Upper bedroom south windows are triple glazed without night insulation. All other windows and skylights are triple glazed without night insulation.

The builder paid special attention to details such as caulking at all exterior joints, using two inches of rigid insulation at slab perimeters,and carefully insulating all under slab ductwork.

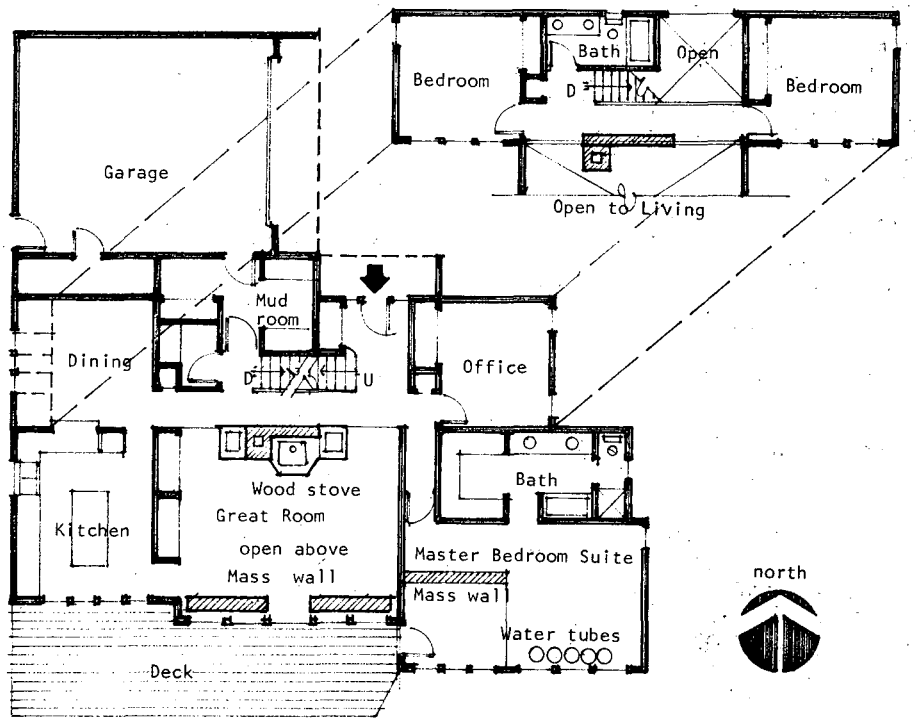



Fig. 2 . Floor Plans

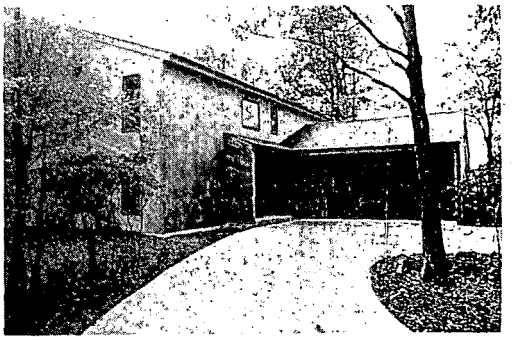


Fig. 3 : North Elevation

## 4. PASSIVE SOLAR

Since every major living space was planned for good solar access, the final solar concept for each room was determined primarily by the owner's desires for various finish materials and also by their "aversion" to some solar concepts (e.g., "no water tubes in the Great Room."). [2]

The "solar solution" for the Great Room is a modified, vented Trombe wall allowing for view, maintainability, and performance. A 12 inch filled block and brick mass wall (Fig.4) is open around the top and sides for daylighting and perforated in the center sections for view and ventilation. A 20 foot wide by 10 foot wide automatic, motorized insulating curtain is serviced over the top of the mass wall, and is deployed between the glass and the wall. A combination of interior crank operators and exterior key-latched windows permit full access to the exterior painted wall for cleaning to insure optimum system performance for the life of the residence. [3]

The Kitchen and eating area is a direct gain space with no wall cabinets on the south to block solar gain. The floor is ceramic tile on a 6 in. concrete slab, insulated below with 2" of rigid boards. Against the architect's advice, the owners have installed vertical fabric blinds instead of insulating curtains in the Kitchen. Wall openings allow warm air to circulate into the Dining area.

At the east end of the house, the Master Bedroom receives morning sunlight and employs a dual solar solution. The carpeted sleeping area has a soft, transluscent water wall of 12 in. dia., 8 ft high tubes, and an automatic insulating curtain (Fig.5). The sitting area employs tile on slab (as in the Kitchen) with an additional 3 ft high double-wythe brick mass wall. This area has access to an outdoor deck and pool. Here again, the owners opted for vertical blinds instead of insulating curtains.

## 5. ACTIVE SOLAR

A roof-mounted, four panel, flat plate, drain back solar water heating system was designed and bid for the house, but since the maximum state and federal tax credits were already used by the passive solar components, the added cost of the active system (and its long payback without tax credits) was not justifiable to the owners. It was omitted until a future date.

## 6. SOLAR PERFORMANCE AND AUXILIARY HEATING

The energy conservation measures described keep the maximum heating load to 57,000 Btuh. The calculated solar savings fraction [4] is 35%. This is reasonable in a location of less than 50% average annual sunshine. However, auxiliary heating is still a major factor in a 7,400 heating degree day climate. Energy costs can vary greatly depending upon the back-up system selected. The builder installed an Amana 60,000 Btuh output gas-fired furnace with electronic ignition and vent damper. The average annual energy costs for space heating with this unit are $300-350 (at $0.50 per CCF). This is one third the energy costs of "conventionally built" homes in the area. Varying internal heat gains and the use of a wood stove have reduced the annual energy costs even further.

## 7. PROBLEMS ENCOUNTERED

Some of the problems which arose after occupancy took some time to trouble shoot, but provided a valuble learning experience to be shared.

The main problem centered around heat distribution to the Master Bedroom. The "cool" situation appears to have been caused by many factors :

*Late design changes separated this area from the main part of the house, making it a separate thermal zone, yet the back-up furnace remained a single zone unit.

*The furnace thermostat was originally located



Fig. 4 : Great Room Mass Wall

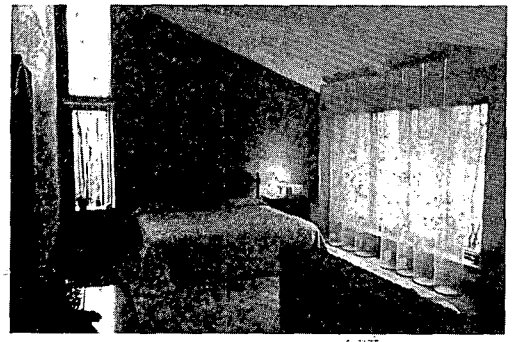


Fig. 5 : Master Bedroom Water Wall

in the main part of the house near the wood stove. When the stove was "stoked up," keeping the furnace off, the Master Bedroom remained quite cool even though every other room was very comfortable.
*A high cathedral ceiling in the Master Bedroom made it difficult to heat with a forced-air back-up system, even with a ceiling fan to circulate warm air.
*Although ductwork was sized properly, the 3-speed furnace blower was factory set at the lowest RPM, about two-thirds of what was required.
*The single return air grille for the Master Bedroom was installed smaller than specified.
*Further problems occurred with a great deal of condensation occurring at night between the insulating curtains and windows.

## 8. SOLUTIONS

Some problems were readily solvable :
*The furnace blower was adjusted to a higher RPM.
*The return air grille was replaced with the proper size.
*The insulating curtain was adjusted to allow it to drop slightly lower and "billow-out" more and better seal at the sill and jambs.
*All the exterior, south, key-latched windows were re-weatherstripped and the latch was replaced to allow for a tighter seal and reduce cold air infiltration.
*The ceiling fan RPM was increased for better air circulation.
*The single thermostat was replaced with two thermostats in different locations. One was relocated in the main part of the house, away from the wood stove, near the Office and Master Bedroom, and the other was placed in the Master Bedroom itself. Adjustable supply air registers in the main part of the house were partially closed for a better air distribution balance with no loss in interior comfort. The furnace blower was also wired to circulate room air even when the burner was off, allowing warm air from the wood stove area to be better circulated.

The combination of all these improvements has resulted in a much better thermal performance and seems to be a reasonable solution for the interface between passive solar, wood burning stove, and auxiliary furnace heating.

We had not encountered similar difficulties in other passive solar houses with wood stoves and back-up furnaces. However, the lessons learned here have already contributed to better performance in other houses.

## 9. CONCLUSION

All things considered, the Umbach Residence is delightful and comfortable. It is one of the few, relatively expensive, large custom homes being built today which is responsive to site, owner, and energy criteria. Its process of balance and cooperation between owner, builder, and architect shows in the overall quality of the finished product. The house serves as a positive example for others to learn from as the joys and difficulties of solar and energy conscious buildings are realistically faced.

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[2] Appleyard, Wayne; "Water Tubes?...Not in MY Living Room : Homeowner Attitudes Toward Passive Solar Aesthetics," Proceedings of the 8th Passive Solar Conference, Santa Fe, NM, September 5-11,'83.
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[4] Balcomb, et.al., Passive Solar Associates Workbook, 1980.

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0731-8626/83$3.00

# THE VAN TEECKELENBURGH RESIDENCE

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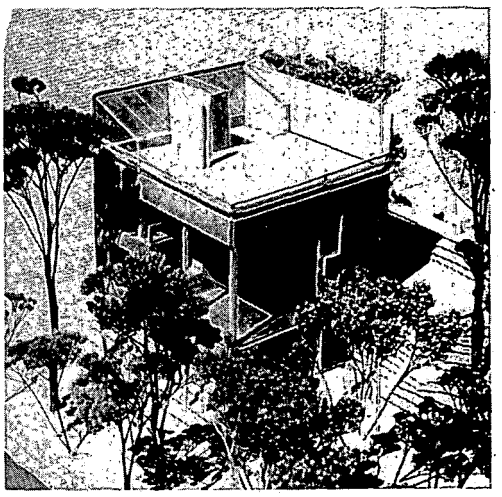


Figure 1. View from South.

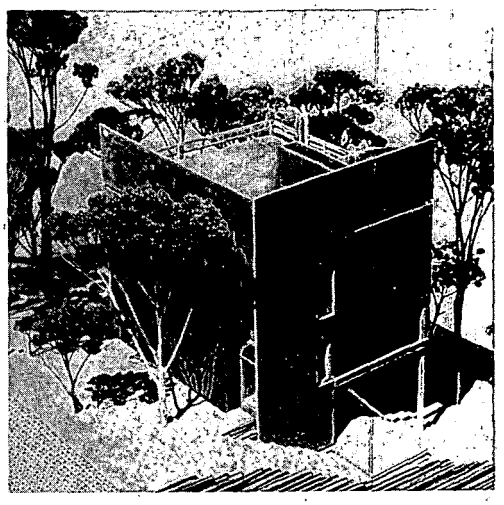


Figure 2. View from North.

## ABSTRACT

The description and analysis of a passive solar residence with double, southeast and southwest, orientation. The design includes automated sun tracking insulation, supplementary phase change heat storage system, mass sod roof and interior ventilation systems. Testing and computer assisted thermal modeling indicate unique advantages for the dual orientation design.

## 1. INTRODUCTION

Energy conservation is not the most important issue of housing or any architectural design. The energy issue provides a means by which our interior world becomes more sensitive and responsive to the many variations of climate and site, which are so intrinsically related to our sense of well being. Energy efficient theories are neither additive to architecture nor benign to the form and function of a building. They provide a set of attitudes through which architectural situations and opportunities may be expressed and evaluated.

## 2. PROGRAM

Three years ago we were approached by a young professional couple to design a small private residence in a rural area in Northern New Jersey. They sought a home of informal living and relative self-sufficiency. Both clients were fond of outdoor activities and choose a site of striking natural character. It was immensly important to maintain the character of the site and to relate interior spaces closely to the special site characteristics. Although their spatial needs were modest, they preferred large, open spaces. They desired to have a home which would be naturally heated and

cooled, sheltered from the winter winds, have cross ventilation in all spaces, be able to hear the adjoining brook, sense the changes of weather and time of day, and change in character as the seasons changed from winter to summer. Because both clients were away from the home during the day, and during extended vacation periods, it was important that the home manage itself during unoccupied periods.

## 3. SITE

The wooded three acre site is bisected by two small streams. Both river banks rise steeply from the wetlands between the two streams. The terrain is covered by rock outcroppings and large boulders. Located in one of the highest portions of New Jersey, the winter climate is relatively severe for the region with an average of 5200 degree days per year. Winter winds come from the northwest and are effectively blocked by the rising terrain. Summer breezes are of low velocity, but prevail from the southeast following the stream valley. Solar path variation is $47^{o}$ altitude and $120^{o}$ bearing, providing significant seasonal variation during the heating and cooling periods. Zoning setbacks, conservation easements, wetlands and soils revealed an extremely limited area for construction. The site chosen is located on a sloped enbankment of the stream, with southwest orientation, overlooking the stream valley.

## 4. SOLAR ACCESS

Integrating the site characteristics and client needs led to the development of a design which broke from many traditions in the area of natural heating. Combining the needs of two major views to the site, and the desire to maintain the existing tree cover, which reduced winter solar gain by 20%, the house was designed with two interacting solar orientations. Summer tree cover for the southeast and southwest orientations permitted this non-south design. The double solar orientation permitted increased solar gain which offset the onsite shading and enhanced the main living space with two complimentary views and site relationships. It was immediately clear that the double solar orientations would require the home to track the path of the sun throughout the day, insulating the glass wall which was not receiving significant solar gain. Early energy consumption and temperature studies

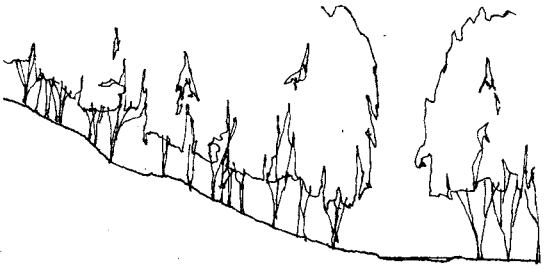


Figure 3. Site Section.

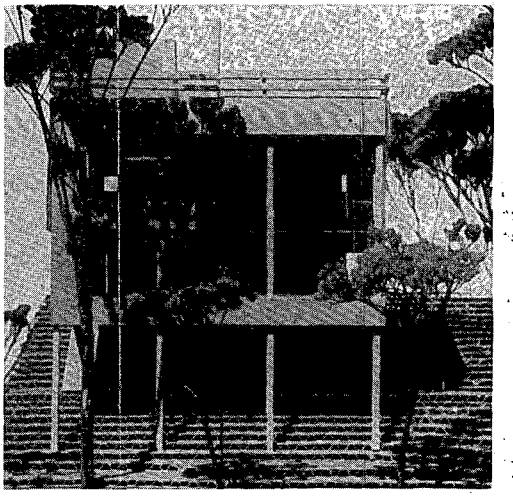


Figure 4. Southwest Elevation.

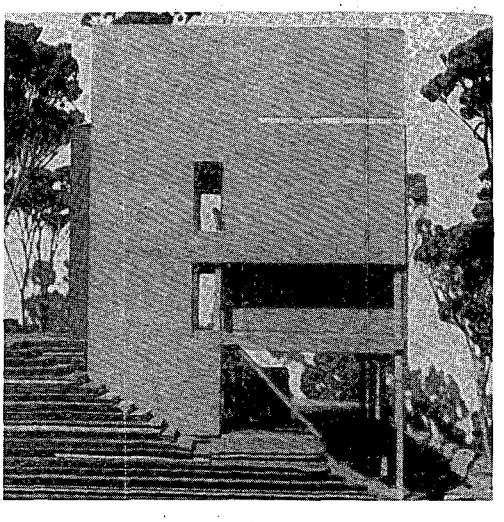
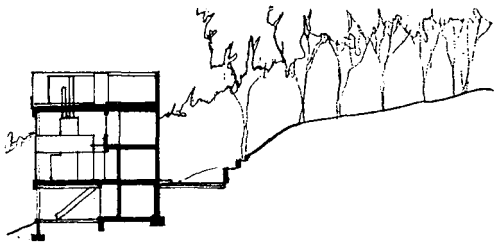


Figure 5. Northwest Elevation.



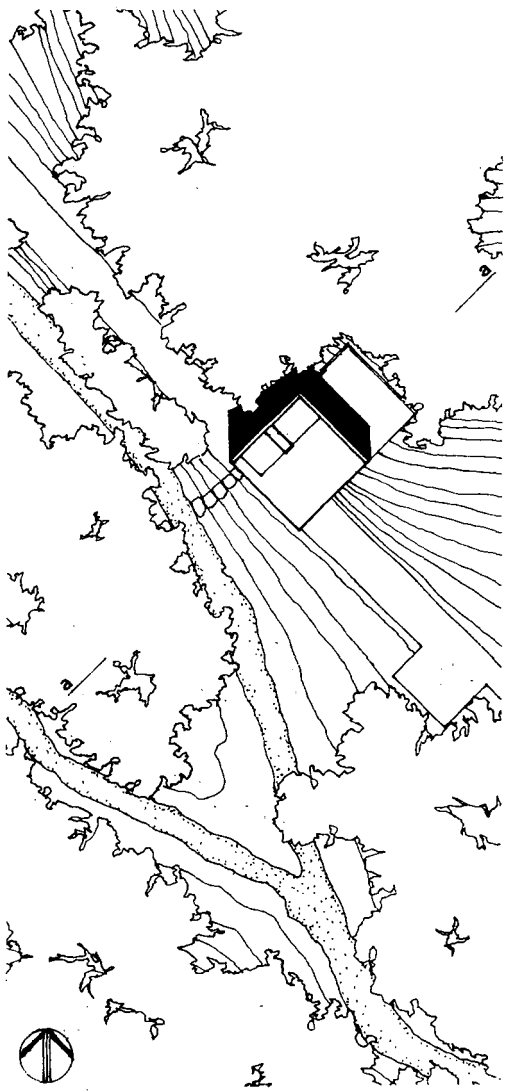


Figure 6. Site Plan.

illustrated that with automatic insulation, including site shading, the two orientation approach compared favorably to the traditional south orientation direct gain model. The ability to open the building selectively for solar gain, to insulate nonproductive glazed areas, to extend the vailable solar access hours, and to have the large solar aperture only at the midday hours proved a significant advantage over the south orientation design. Hour by hour thermal simulation illustrated that the dual orientations had increased solar gain under conditions of varying clear and cloudy skies.

## 5. BUILDING ORGANIZATION

The sloping site, limited construction area and desire to minimize conductive heat flow suggested a cubic building form. Orienting the exterior walls 45 degree from the compass points resulted in the two solar orientations, with relatively unglassed walls to the northeast and northwest. Services and bedrooms were located along the northeast wall and open into the main living space via sliding insulated panels. The moving panels permit the bedrooms to receive the benefit from daytime solar gain, while becoming isolated thermal zones with independent supplementary heating during the evening hours.

The home is organized on four levels including the roof. A workshop is located on the lower level and is a seperate thermal zone with insulation on all sides. The adjacent carport area can be used for large workshop projects or for informal parties adjacent to the stream in the shade of the building above. The main living space has two entries, one leading via an exterior stair from the carport to the kitchen and dining area. The main entry is at the northeast patio, one level above the driveway. The northeast patio is a shaded summer living area, partially enclosed by both the building wall and rising terrain beyond. It is isolated from the stream, quiet, shaded and private.

The main living space includes a living area which is open to the dining and loft spaces. A central fireplace opens to each of these areas and provides supplementary heating through a thermostatically controlled ducted air distribution system. The loft and dining areas are oriented to the southwest for evening sun. The fourth level is the only location on the site open

to sunlight throughout the year. It includes a solarium and spa and sodded exterior lawn area. The roof living spaces are sheltered from the north prevailing winds by the enclosing walls. Summer solar gain to the interior spaces is minimized by the time lag characteristics of the soil of the sod, as well as the evaporation of the water from the sod. Temperature of the soil stays at or below the exterior air temperature during the summer months.

## 6. INSULATION

The home is conventional post and beam framing with infill 2x6 stud wall construction totalling R-27. The floor of the living space is insulated to R-52 (joist weighted average). The roof construction includes sod, soil, sand, urethane insulation, liquid applied rubber waterproofing, laminated wood decking with a total insulation of R-54. Major solar glazing includes a multilayed insulating system, edge sealed with a total in place insulation of R-12.

The shading and insulation system of the southeast and southwest walls can be manually controlled to open either orientation, as well as permitting the lower and/or upper set of shades to operate independantly. This variation of choice permits the control of view, privacy, shading and daylighting within the main living space. The interior of the home can vary in spatial quality from an open space with wide panoramic views to an isolated space turning its attention to the central fireplace. Beyond the maximization of natural heating, this variation is immensely important in a relatively small open interior to provide a changing spatial quality.

Automatic control of the movable insulation system is accomplished through thermal sensors at each orientation with an alternative time-clock system. Under average day January conditions the solar glazing averages R-11 throughout the twenty-four hour period. The insulation system also provides an increased measure of thermal comfort increasing the mean radiant temperature of the walls in the winter. The non-solar glazing is conventional insulating glass with manually operated rigid interior insulation panels.

The infiltration rate is estimated at 3/4 air changes per hour and accounts for 45% of the conductive heat exchange. As thermal simulations and Solar Saving

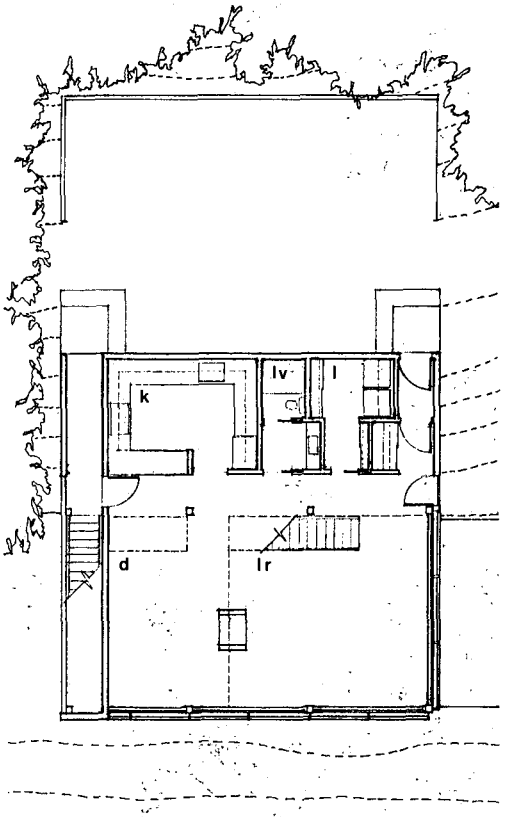



Figure 7. First Floor Plan.

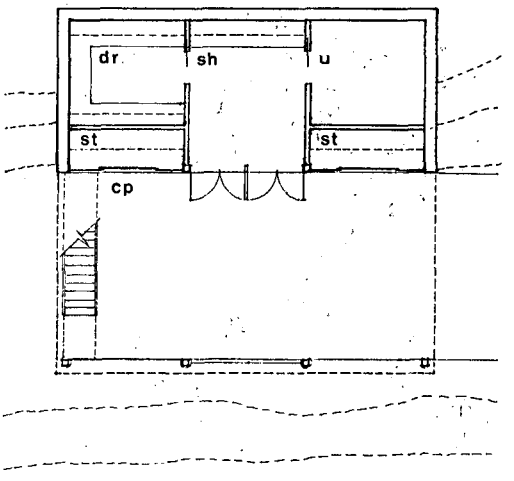



Figure 8. Ground Floor Plan.

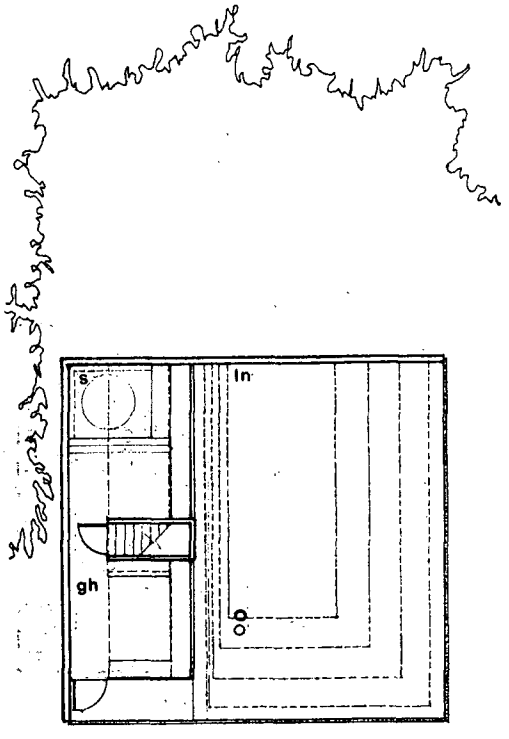



Figure 9. Roof Plan.

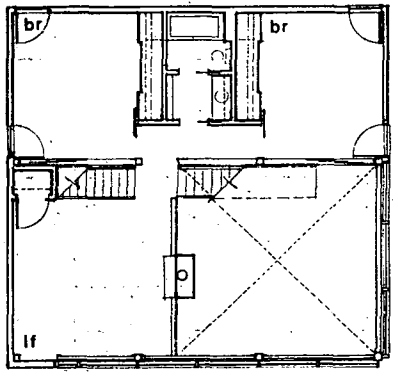



Figure 10. Second Floor Plan.

Fraction analyses tend to underestimate the overall natural heating performance.

## 7. THERMAL STORAGE

Primary thermal storage is accomplished by a concrete and quarry tile floor in the living and dining areas. Approximately 600 square feet in area and in sun 2/3 of the daylight hours, the floor provides 40% of the total conventional diurnal heat storage. Secondary thermal mass includes sheetrock walls and ceilings, exposed joists and decking with a total contribution of 12,000 Btu/$^{o}$F day (January). The total heat storage capacity of the home is 24,000 Btu/$^{o}$F day and is sufficient for average day conditions.

Heat storage for cloudy day carryover situations will be provide by ceiling mounted 72$^{o}$F phase change material with a total storage capacity of 74,000 Btu/day. This additional heat capacity is fully charged during two consective average January days, or by 2/3 of the excess heat received during one clear January day. During early and later winter months the charge of the phase change materials occurs more quickly due to the southeast and southwest orientations. The maximum temperature of the interior spaces under all winter weather conditions is held to approximately 74$^{o}$F and occurs during the unoccupied mid-afternoon period.

During the unoccupied periods heat is permitted to stratify, raising the ceiling temperature. When occupied small convective fans destratify the air and bring heat from the phase change material to the floor. The cycle of stratification and destratification assists in the charging of the phase change material.

Excess heat produced by the fireplace is also permitted to raise the air temperature at the ceiling. This stores the auxiliary heat for night time hours.

## 8. VENTILATION

All interior living spaces are designed to include both natural and fan assisted cross ventilation. Although the insulating shades are time-clock controlled for the overheating periods of the summer, auxiliary fans can exhaust excess heat if the shades are manually

overridden. Two exhaust fans are located at the ceiling of the main living space. They pull air from the lower horizontal strip windows in the main living space and assure cross ventilation during all weather conditions. The difference in height of the bedroom windows and lower horizontal strip windows results in a natural stack effect which produces natural ventilation throughout the home. This, combined with the prevailing southern summer breeze guarantees interior temperatures at or below the exterior air temperature.

## 9. SHADING

Early and late summer shading is provided by the time-clocked insulating shades. Their light exterior color reflects most of the solar gain. The double solar orientation permits the main living space to have a view to the site on the shaded side of the building at almost any hour. Closing only the upper set of shades protects 3/4 of the living space floor area. Although marginally increasing the solar gain, this maintains a panoramic view to the entire site.

Thermal simulation suggests that the 72°F phase change material will reduce the average summer interior temperature. During the day excess heat will be absorbed by the heat storage material. In the evening the main living space is isolated from the bedroom areas. Fans bring in cool night air which takes heat from the heat storage material, thus making them available for daytime cooling. The sub 72°F night time temperatures occur frequently during the early and late summer months and permit natural cooling. Although isolated from the main living space in the evening, the bedrooms have cross ventilation.

## 10. UTILITIES

A preheat solar hot water system is planned to supplement the existing domestic hot water system. A fin tube panel will be located inside the solarium and spa glazing on the roof. It will preheat well water and provide permanent summer shading for the rooftop living spaces.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

## 11. STATISTICS

UD = 590 Btu/°F
UN = 430 Btu/°F
US = 2,450 Btu/°F/hour
MC = 24,000Btu/°F/day
MC (aux) = 74,000 Btu/day
$A_{glass}$ = 749 ft² (total)
Floor Area = 1884 ft²
$Q_{internal}$ = 122,000 Btu/day
LCR = 10.2
S/DD = 25 (January)
S.S.F. (annual) = 78% (B-3, modified)

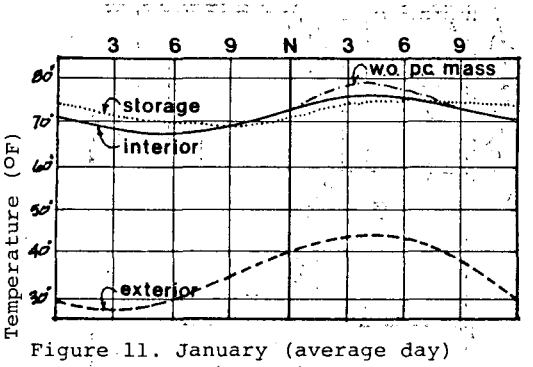


Figure 11. January (average day)

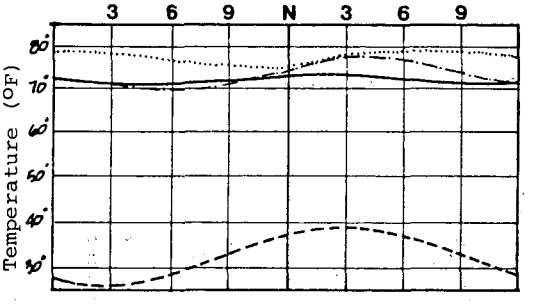


Figure 12. January (clear day)

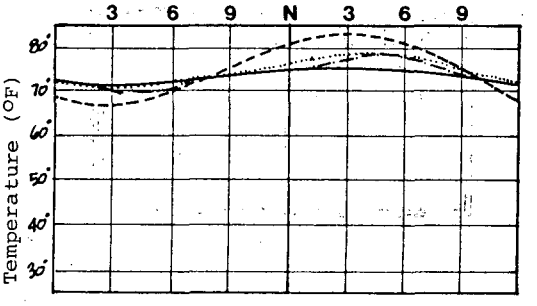


Figure 13. July (average day)

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# SMITH HOUSE, TANNERSVILLE, NEW YORK

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## ABSTRACT

At the beginning of the design process, the clients proposed three priorities: (1) a space and use program for a young, growing family, (2) an urge toward energy self-sufficiency using conservation, solar, wood and wind in the most cost-effective applications, (3) a profound sensitivity to the Art of the local home building traditions which include High Victorian, Stick and Shingle and the Arts and Crafts Movement.

The project has been in progress for 15 months. Site visits were made in each season and extensive microclimatic data were gathered or recorded. Construction began June 1, 1983

## 1. THE SITE

The 15 acre site rises to a high windy plateau known as Star Rock. The access road traverses the heavily wooded hillside and arrives at a row of stone columns and free-standing walls of a former home. This plateau affords spectacular views - paticularly to the south and the northwest. The first ruin, with its southerly orientation and protection from the winter winds, establishes the setting and the stone forecourt for the new house.

## 2. THE HOUSE

The entrance to the house is from the axial path to the east and up to the partially covered court. This stone-paved area extends to the south where the courtyard is defined by three stone walls. The entrance doors, artifacts provided by the clients, open first to a small vestibule and greenhouse and then into the main space. The central fireplace defines the living room and courtyard access to the south and the kitchen along the north. To the west is the dining alcove and the outdoor dining area combined with two bathrooms, two fireplaces and three outside porches. The third level houses the painting studio.

The most extreme aspect of the heating season brings below zero temperatures, high winds, prolonged cloudy periods and 5 to 7 foot snow drifts. The primary energy consideration is the reduction of heat loss and the supply of renewable energy sources.

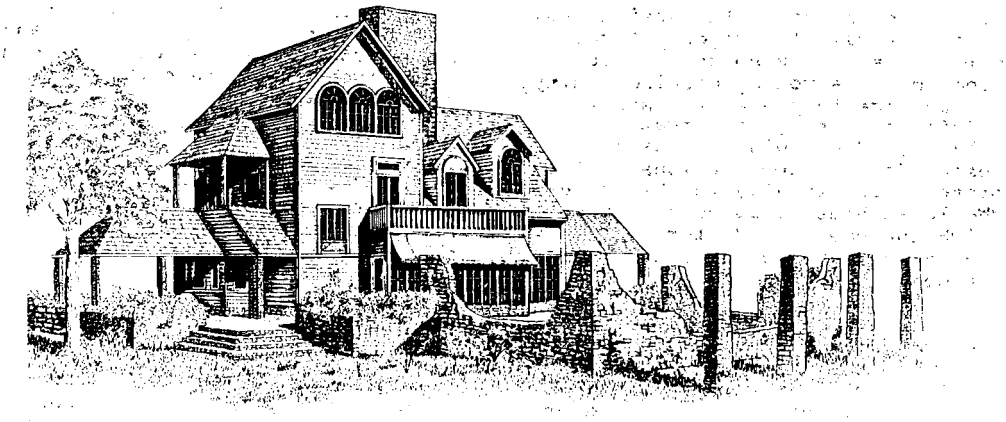
The house is heavily insulated, but not superinsulated; it is designed for one-half an air change per hour. The south facade integrates the major glazing aperatures for the direct gain system.

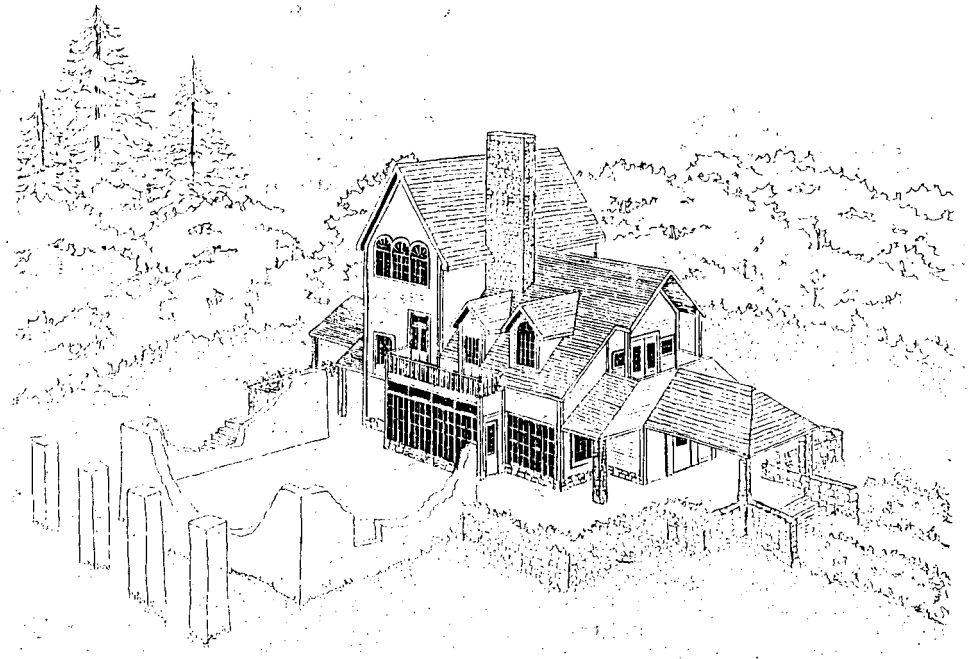
The house is sited along the east-west axis. The north side is largely protected from the winter winds by the high timber of the adjacent State land. At the crest of the ridge on the northeast corner of the site, the 4 kW induction WECS will stand on a 90 foot tower to see the winds (annual average 12 m.p.h.).

The direct gain heat warms the primary living spaces and is stored in the directly irradiated mass of the floor and chimney. Overheating is prevented by distributing the heat through the central forced air heating system which is fed by a wood-burning furnace; the furnace also

preheats the domestic water. In unoccupied periods, a 12 kW two-stage coil is primarily fed by the wind generator which is interconnected with Central Hudson Gas and Electric Company.

The summer brings warm, sunny days with constant breezes and clear, often chilly nights. Exterior decorative awnings shade the South glazing and will be adjusted for solar control throughout the spring, summer and fall. Natural ventilation is assisted by strategically located casement windows acting as windscoops. The open stairwell and cross- ventilated studio level will encourage the warm air to rise and be ventilated at the peak.





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# SAN PASQUAL BATTLEFIELD STATE HISTORIC PARK
## AN EARTHBOUND VISITORS' CENTER

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ABSTRACT

The State of California for the last several years has actively supported the design and construction of particularly energy conscious buildings. This policy has been embraced by the State Parks and Recreation Department. Firms with backgrounds in "energy design" from throughout the state were interviewed for this project which had two basic requirements:

1. Design a culturally sensitive facility preserving archaeological sites within a 50+ acre tract and provide an interpretive display showing three cultures involved in an important historic battle.
2. Develop an energy program that would significantly reduce operation costs in an all-electric, inland valley near San Diego.

This paper presents the generally more important overall design development issues as they relate to the energy program which culminated in an on-site budget of 8,500 Btu/ft$^2$/yr. Major features include earth integrated structure; wind scoops for venting; nocturnal cool-down; hybrid "breadbox" space heating; high-efficiency lighting (HPS and dimmable fluorescent); motion sensors; point-of-use and passive DHW; water conservation (ultra-low flush toilets-2 quarts and indigenous landscaping); and rammed earth walks and drive.

## 1. DESIGN PURPOSE

The purpose of this State Parks and Recreation project is to establish a permanent location for the preservation of archaeological sites within park boundaries, and to develop an interpretive display of the cultures, personalities and historical events surrounding a tragic skirmish that was lost in the larger events of the Mexican-American War (1846-1848). It is important to note that three ethnic cultures were involved in the battle - Native Americans (Indians), Mexicans (Californios), and Anglos (Americans), and there is much disagreement as to whose story is accurate. Historically the Indians, who have inhabited this region as far back as the 13th century, were made to be trespassers on their ancestral lands and have received neither citizenship nor cultural recognition; yet they maintain strong ethical ties with the local community.
The Californio community feels its interests have been misrepresented by the war-time victors (even though they won the battle). Resolution of these and "American" interests within an acceptable format (sequence of experiences and visual image) was given roughly equal importance with energy conservation and low maintenance factors by the State.

## 2. RESPONSE

Early site visits with the client resulted in reconsideration of the initial building location proposed by the State and advisory committee members (made up of various cultural and civic user groups). This move was accomplished largely to facilitate handicapped access, view and constructibility. It should be noted that roughly a one year process to develop a detailed program had been undertaken by the State Parks and Recreation Department and the advisory committee with two especially strong formal criteria: that the final building be of a low profile and "earth integrated". These guidelines were born of a concern that a large prominent structure would end up being an undesired monument to values not shared by the users.

Programmatic elements were schematically developed to establish both architectural and energy base cases. From a cultural standpoint we felt that if we could respect the Indians' spirit of the land that all users would be happy. Research into the Indians' relationship with the environment revealed a central animistic belief that man shared his existence with all things - plants, animals and minerals - and felt responsible for them. They believed that "by respecting other forms of life man did not abuse his relationship to them. Conservation of resources helped insure the continued supply of all things man needed, so waste...was rare..." (Taken from Handbook of North American Indians, Vol. 8, by Robert Heizer.) It was also discovered that many of

their rituals and practices appear to have been organized management techniques for necessary exploitation of resources. Hence, we felt that to the greatest extent possible, our design responsibility for the overall project (and especially the main structure) included making use of on-site opportunities to the fullest.

Since cooling was predicted to be the largest component of annual energy use (and expense), the envelope was conceived as being a membrane which could selectively reject or admit ambient weather conditions. It was discovered through extensive computer modeling that in this region a structure of this occupancy, with external insulation and high, distributed thermal capacitance has an internal cooling load that can be met largely through nighttime venting. The magnitude, direction, and temperature of the breezes that nightly flush through the San Pasqual Valley were felt to be sufficient for natural ventilation (see figs. 1-4 ). A major design effort was therefore made to devise scoops of sufficient size to effectively capture the breezes, yet hopefully not become imposing elements. Further computer simulation of thermal behavior revealed that "earth integration" was a marginally effective conservation strategy, although its primary impetus was partly in response to initial desires for a "low profile" design. It evolved mainly as a device to minimize potential visual impact of a large roof area from planned pathways along the adjacent hillsides. The structure incorporates an underfloor, "earth coupled", air distribution plenum which, along with the use of solar gain for selective heating and daylighting of appropriate spaces, contributes to the total passive heat exchange between building and environmental setting.

These major design strategies - the use of large wind scoops to facilitate night cooldown, and extensive earth integration to minimize the impact of ambient conditions - were supported by the Indian advisors who felt that although the structure was larger than their pre-conceived ideas, the sense of respect for and response to the natural setting was **strong;** that the project does not impose, but rather shares the spirit of the land, to our pleasure, other client/user groups feel similarly.

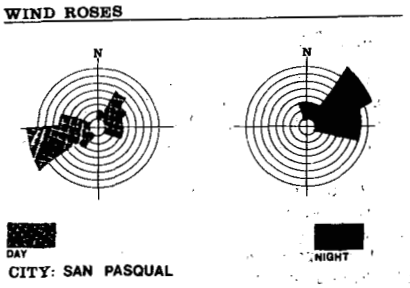



Fig. 1.

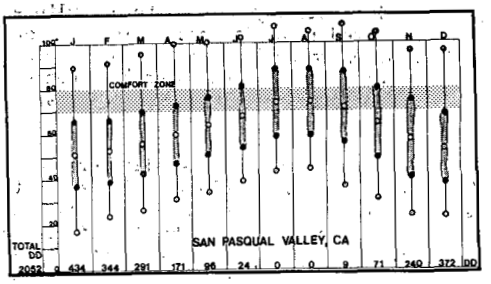



Fig. 2.

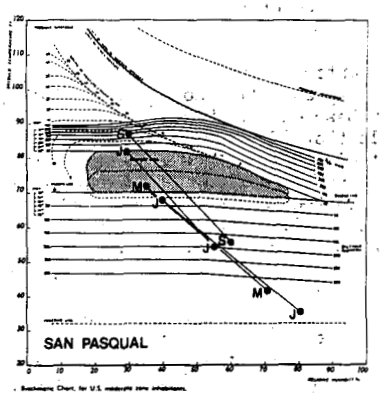



Fig. 3.

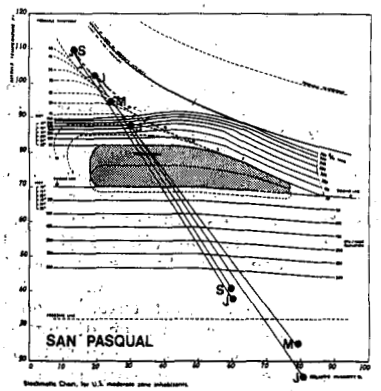



Fig. 4.

Upon arrival to the center a visitor's experiences are modified by passage via a low foot bridge through a newly planted grove of Sycamore trees which provides an emotional filter between automobile and memorial. This process is enhanced by walking as much as possible on pathways of rammed earth, stabilized by a non-cementitious emulsified resin binder. The clear colored binder, often used for dust control on back coutry haul roads, can be sprayed over packed earth surface, leaving an unobtrusive, "natural" earthen walkway. (It was felt that this was a fair compromise between cultural sensitivity and the cost for permanent paving.) An amphitheater opposite the main building (near the parking lot) provides a setting for more secular activities on the public side of the grove. (see Fig. 5).

Water conservation is a very important consideration for drought-prone Southern California. While still in the schematic design phase, analysis of four major options to standard waste water treatment (septic tank to leach field) was undertaken. The first three involved different levels of "reclamation" systems assuming normal effluent flows for a small museum occupancy. They included:

1. septic to trees
2. reuse/reclamation
3. evapotranspiration

The first option, although untested, was the best of the three, but was still almost 40% more expensive than a standard system on a first cost basis; with water savings during the winter being of marginal value. The major alternative to "reclamation" was to significantly reduce effluent water flow in the first place with low-flush toilets. When a comparison was made for total yearly water/cost savings, significantly reduced <u>demand</u> techniques clearly won. This result seems to coincide with other lessons learned in passive design, namely, that conservation is usually the best first effort!

1 Entrance Gate
2 Water Well
3 Bus Parking
4 Future Parking
5 Parking
6 Bus Loading
7 Trash Enclosure
8 Vehicle Storage
9 Amphitheater
10 Pedestrian Bridge
11 "Sacred" Grove
12 Memorial Plaque
13 Vehicle Turnaround
14 Visitor Interpretive Center

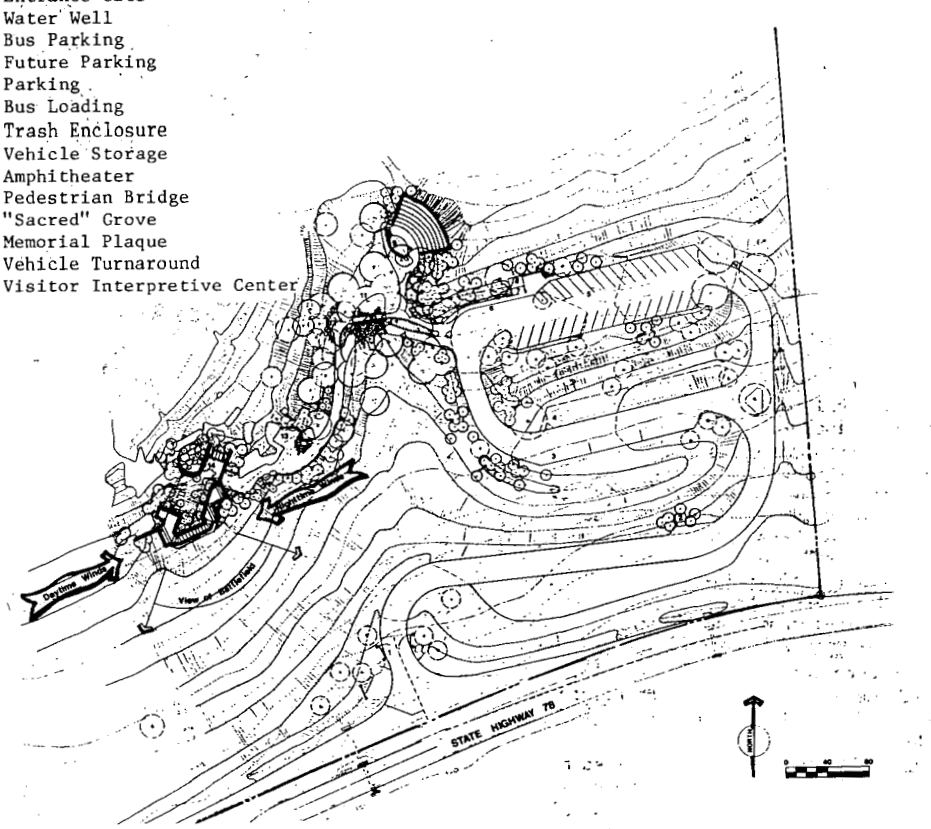



Fig. 5.

## 3. MAJOR ENERGY CONSERVING FEATURES AND BUILDING OPERATION

The major features of this building include:

1. High internal thermal capacitance
2. Effective distribution of thermal mass, including use of concrete waffle-slab ceiling as a major radiative heat sink
3. Under-floor "earth-coupled" cool air distribution plenum
4. Exterior insulated concrete masonry walls using a new, integrated product - "SolarStone"
5. Large, natural ventilation air inlets ("scoops")
6. "Earth integration" to buffer interior from ambient conditions (and minimize visual impact on site)
7. Daylighting at major public areas, with photoelectric controlled fluorescent dimming; motion sensors control all other lighting
8. Skylight "soffit" acts as hybrid air heater for all average heating
9. Breadbox DHW provided at restrooms
10. Mechanical refrigeration is eliminated.

Computer simulation confirmed that night flushing could largely satisfy cooling loads, and that a short term (2 hour peak) winter skin heating load can be satisfied by a hybrid air heater at a skylight/plenum. Four operation modes have been scheduled to accomplish the required space conditioning:

A. Night Ventilation: 4-7 mph breezes "drain" the site (a valley) from the East, enter the building through two large scoops, flow through openings in the waffle slab ceiling to flush and cool occupied space and underfloor plenum and then pass into the mechanical room through large interior louvers or a "grate" floor to then be exhausted at the low-pressure, west scoop.

B. Passive/Hybrid Cooling: A recirculation fan in the mechanical room directs air through the underfloor plenum to occupied space, with the pre-cooled structure absorbing most internal heat.

C. Daytime Ventilation: 8-14 mph winds are directed by the western scoop through the mechanical room, with most air flowing directly to occupied space; the easterly scoops become leeward outlets. Air volume and circulation routes are controlled by roll-up overhead doors at scoops.

D. Heating: Hybrid heating is supplied by fan-circulated warm air from the skylight/plenum over the Diorama (typically only a 2 hr. need). Back-up is met by electricity via insulated ducts in the underfloor plenum.

## 4. ENERGY PERFORMANCE COMPARISON

Based on computerized analysis and estimated daylight contributions (from L.O.F.), the following differences can be seen:

| | Btu/ ft$^2$-yr | |
|---|---|---|
| | Site | Source |
| Conventional | 33,000 | 117,000 ("code") |
| High Mass Only | 30,600 | 91,800 |
| FINAL DESIGN | 8,500 | 25,500 |

It should be noted that internal energy use for display lighting accounts for over 90% of the total energy use in the final design, as opposed to roughly 40% in the base case (Figs. 6-7).

## 5. CONCLUSION

It appears that a high-mass, bermed structure is a reasonable architectural solution to this type of occupancy in a mild climate. Where reasonable daily temperature swings occur simultaneously with fair night breezes natural ventilation can satisfy a significant portion of (or all) cooling requirements. Space heating can be virtually eliminated, with simple hybrid techniques ample for morning "pick-up". Lastly, once other energy loads are significantly reduced, the proper integration of daylighting into major use areas is the key design issue to be solved in the development of energy responsive buildings.

## 6. ACKNOWLEDGMENTS

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LSW Engineers, (Mechanical/Electrical)
Stedman & Dyson (Structural)
AWB (Landscape)
Solar Aqua Systems (Water)

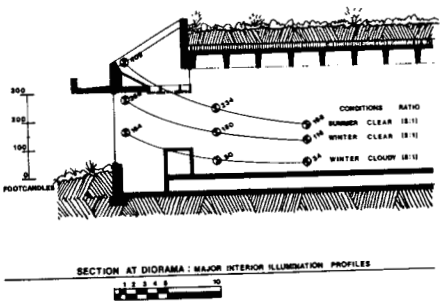



Fig. 6.

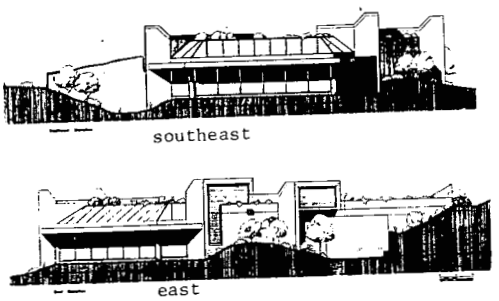
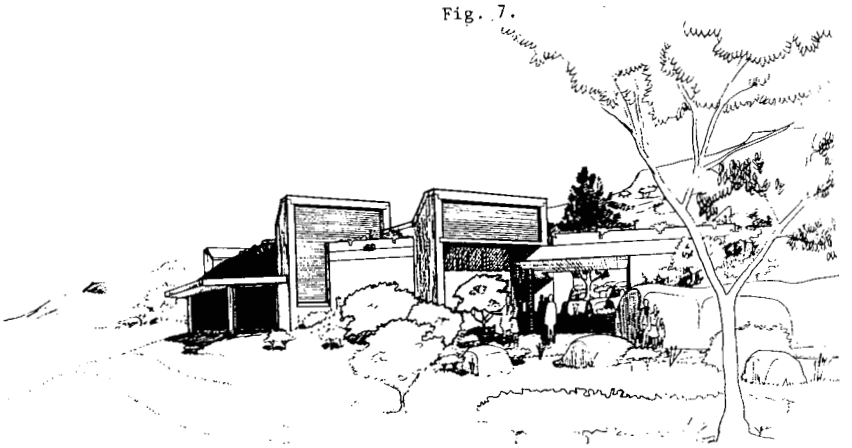
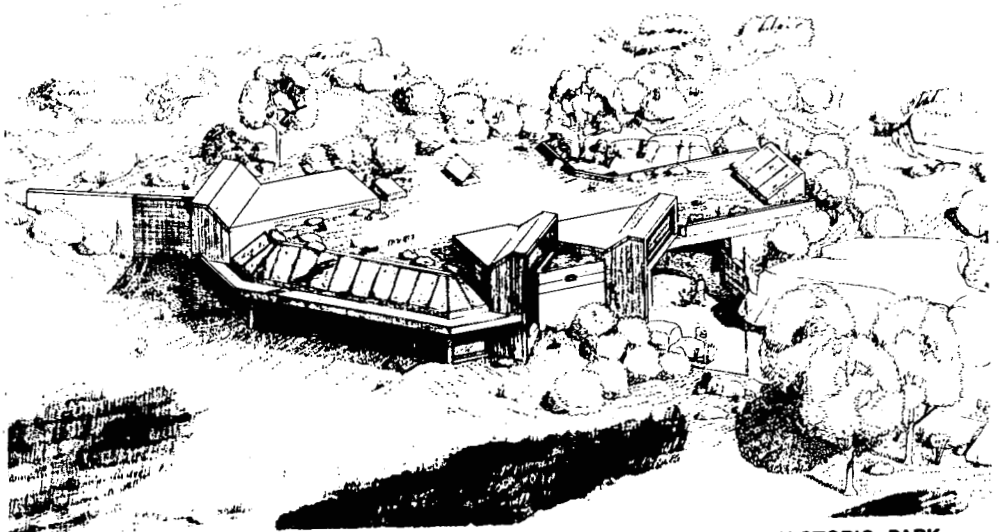



Fig. 7.





SAN PASQUAL BATTLEFIELD STATE HISTORIC PARK
VISITOR INTERPRETIVE CENTER

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# ENERGY-CONSCIOUS DESIGN FEATURES FOR NEW CALIFORNIA STATE OFFICE BUILDING - SITE 1-C

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## ABSTRACT

This paper describes the energy-conscious features used in the design of a new 160,000 square foot California State Office Building (Site 1-C). The building represents an integration of a series of simple and proven energy-conscious design concepts that contribute to an extremely energy efficient end result. Covered are implications in building configuration, office space layout, fenestration and shading device design, and electric lighting/control alternatives. The various energy-conscious design features considered are discussed and particular solutions highlighted.

## 1. INTRODUCTION

By the mid 1970s there was considerable disagreement as to the best approach to energy-conscious commercial building design. The majority opinion seemed to suggest that this building type should be thermally very tight, with as little surface area and penetrations as possible. Standards like ASHRAE 90-75 and buildings such as the then recently designed Norris Cotton Federal Building in Manchester, New Hampshire best typify this approach. Yet others tended to disagree, arguing that the issue in this building type was one of internal load reduction rather than one of increasing the thermal integrity of the building skin. Those taking this position suggested that commercial buildings should have large surface areas and be as responsive as possible to the various flows of energy to and from the building.

One client who allowed its designers to explore this latter point of view was the State of California, who in 1977 embarked upon a major building program to provide the State with 1,500,000 square feet of "energy efficient" office space. This building program resulted in eight buildings with similar functions ranging in size from 100,000 to 350,000 square feet and totaling nearly $100 million in construction. Each of the buildings stressed a slightly different combination of energy-conscious design strategies, thus making the California building program one of the largest building research activities ever undertaken. It is hoped that this experiment will not end when the buildings are completed, but will carry on to evaluate in-situ energy usage and occupant satisfaction, providing the building research and design communities with a tremendous data base.

## 2. THE SITE 1-C BUILDING

Of the eight State buildings, the 160,000 square foot headquarters of the Water Resource Control Board (Site 1-C) is the most recently completed. The Site 1-C building is located in downtown Sacramento two blocks south of the State Capitol. Site 1-C consists of a city block bounded by 9th, 10th, "P", and "O" Streets in which the north-east quarter is occupied by an existing parking garage (see Figure 1). Across 9th Street is the Site 1-B State Office Building and diagonally across the intersection of "P" and 9th Street is

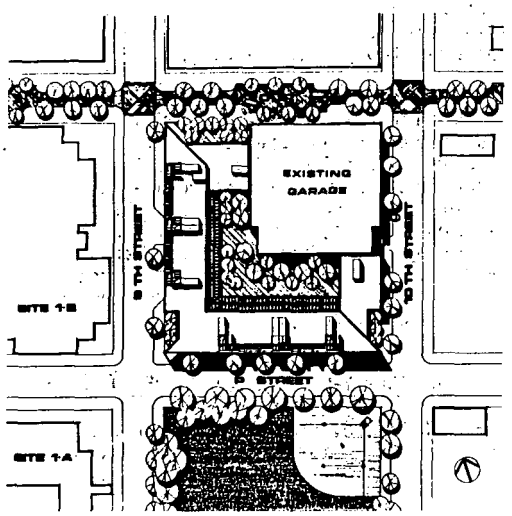



Fig. 1. Site plan for Site 1-C

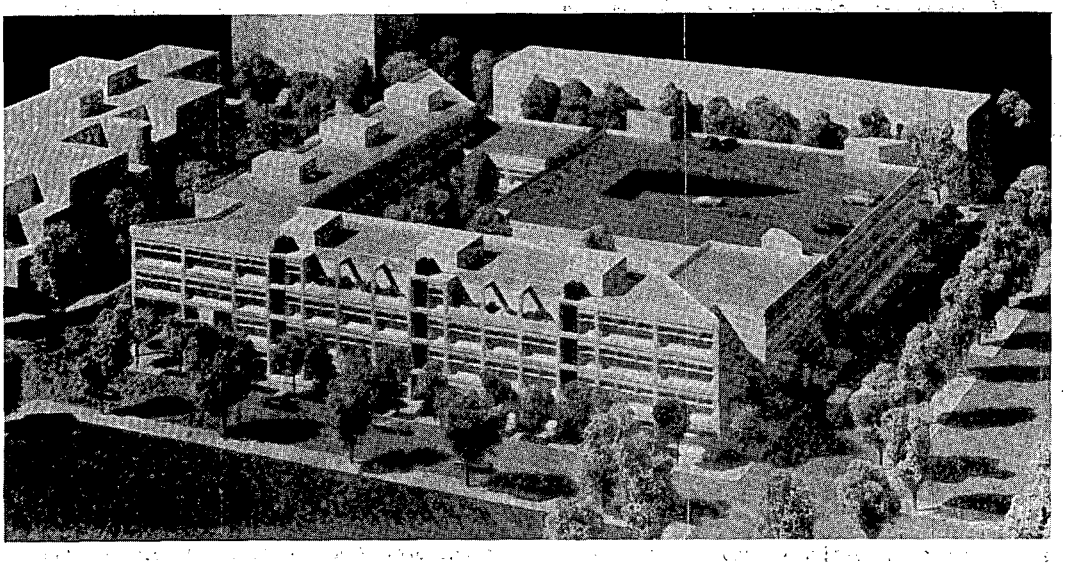


Fig. 2. Photograph of the Site 1-C model

the Site 1-A Building. The northern edge of the site along "O" Street is being developed into a pedestrian mall while the southern edge along "P" Street offers excellent solar exposure and view to an existing park.

The Site 1-C building accommodates program requirements by providing both open and enclosed space through a simple "L" shaped configuration. The building is four stories high with two smaller wings of three stories. The building's "L" shaped form and narrow depth help create a courtyard which uses the four story wall of the existing parking garage for part of its defination. The courtyard is extensively landscaped to provide a retreat area for the building occupants hidden from the street and accessible only by passing through the building.

The building is steel framed and clad in cement plaster. The exterior is highly textured, varied, and shaded on all sides except the north (see Figure 2). There is a four foot recess between the structure and the building enclosure which houses the sun shading devices, light shelves, and the air handling ducts. Such a textured facade provides a human scale and constantly changes character as the sun moves around the building (see Figure 3).

## 3. THE ENERGY-CONSCIOUS FEATURES OF SITE 1-C

In a 1977 study that analyzed a hypothetical State office building in Sacramento, designed to the State Energy Conservation Standards for New Nonresidential Buildings (Title 24), it was discovered that approximately 50% of this building's energy use was attributable to lighting, 30% to cooling (with lighting as the largest contributor to this load), and the remaining 20% divided between equipment and heating.[1] From such information, it became apparent that if Site 1-C was to go beyond Title 24 (an objective of the client), a major emphasis had to be placed on lighting load reduction. After investigating a number of lighting conservation strategies, daylighting proved to offer the most savings at the least cost. Thus, the requirement for the efficient use of daylighting became one of the major energy-conscious design features of the building. The building's "L" shape, narrow depth, office space layout, large windows, clear glazing, shading devices, light shelves, high ceilings and light reflective surfaces (both inside and out) are design

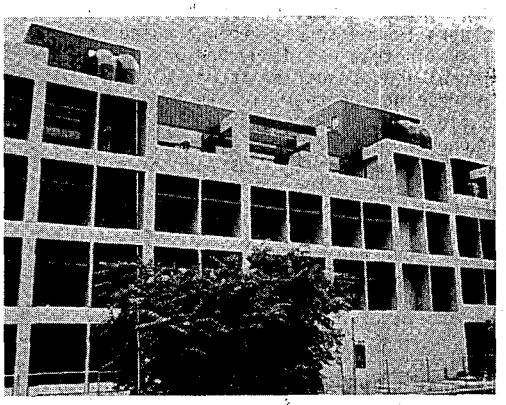


Fig. 3. Photograph of west facade showing shading devices, light shelves and air handling ducts

features that were directly generated by the daylighting analysis.

### 3.1 The Design Process

The organization of the Site 1-C design team and the processes used in generating daylighting information are some of the most hidden but most noteworthy aspects of the project.

Organization. Several of the design team members had previously worked together on The California State Energy Efficient Office Building Competition,[2] and were familiar with many of the design issues that would be encountered with Site 1-C. The design team met frequently to discuss design issues and excellent communications existed between the client, architect, engineer and consultants. All parties were aware of the innovative nature of Site 1-C and were extremely conscientious in resolving the tasks at hand.

Schematic Design. Daylighting analysis during this phase provided information concerning building configuration (and related site planning issues), building depth, and arrangement of interior space. Of particular importance to the design team was determining the overall energy effect of a deep vs. narrow building. This analysis was accomplished by manipulating the electric lighting schedule of the DOE-1.4 program:[3] the lighting load was reduced in the area along the perimeter that was within a distance of two times the window height - the maximum depth to which daylighting (from a side source) can provide good illumination. Although crude results are often derived from such an approach, it proved sufficient for this stage of design by giving the design team information as to the relative values of each of the options under consideration. The narrow "L" shaped configuration was the major result of this phase.

Design Development. Daylighting analysis during this phase provided information concerning window sizing, shading device/light shelf design, ceiling height, surface reflectances and integration with the electric lighting design. Methods of analysis included the construction of physical scale models,[4] manual,[4] and automated calculation procedures.[5] Potential energy savings for the various options were once again analyzed by manipulating the electric lighting schedule of the DOE-1.4 program; however since detailed daylighting information had now been generated, much more discrete lighting schedules could be analyzed. Again crude results are often derived from such an approach, however, each of the various methods used in comparing identical parameters suggested similar trends. Thus, the design team felt confident of the results the analyses were providing.

Construction Documents. Daylighting activities during this phase involved preparing details and specifications for the various energy-conscious features of the building. Considerable time was expended detailing the windows and shading device/light shelves, while specifications involved determining standards that the electric lighting and lighting control system were required to perform. The lighting control system specifications proved to be the most arduous task, since no system on the market at that time operated to the stardards that were required.

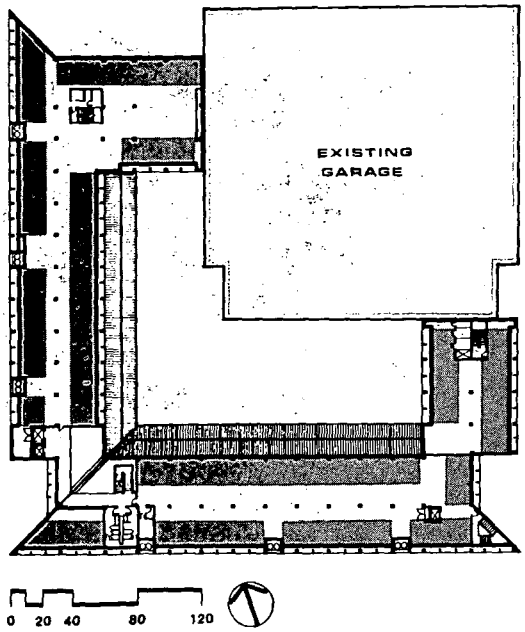



Fig. 4. Third floor plan showing the daylighting zones of the building (the shaded areas)

### 3.2 The Daylighting Specifics

Seven specific daylighting features were proposed and incorporated into the final design. Although many of these features are unique to Site 1-C, they do provide an excellent check list of items that need to be considered by anyone who is involved in the design of a large commercial building.

Building Shape and Depth. The building's "L" shape and narrow depth are its most important daylighting features. The building shape places 62% of the building's gross area within 20 feet of a window, while its narrow depth, usually no more that 60 feet, with occupant circulation down the middle, allows work stations to be never more than 30 feet from a window. A building with such a high percentage of perimeter (typical office buildings have about 25% to 30% of their area within 20 feet of the perimeter) assures maximum use of daylighting. Thus, daylighting

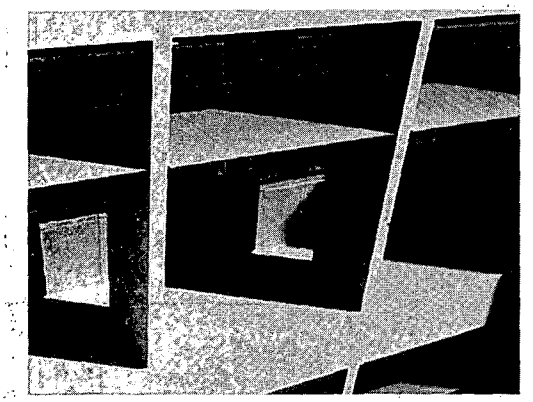


Fig. 5. Detail of Shading Device/Light Shelf

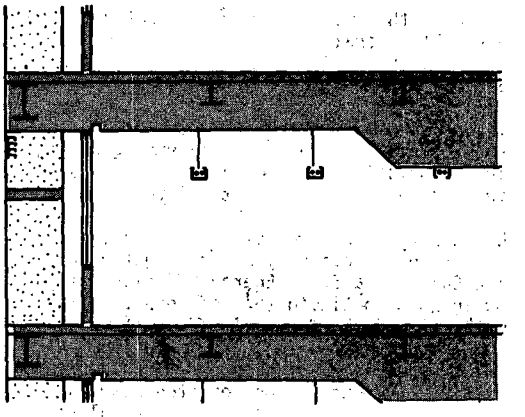


Fig. 6. Section through perimeter zone

became Site 1-C's most important form determining element (see Figure 4).

Interior Layout. The majority of Site 1-C's office space will be open plan with work stations defined by low partitions. Within the perimeter are located office activities that most benefit from daylighting, whereas non-critical daylighting functions and spaces that require enclosure are placed in the interior. Thus, work stations are organized along the perimeter while corridors, conference and storage areas occupy the interior. The viewing direction of each work station is positioned to be parallel to the window-wall in order to eliminate the presence of sky glare within the occupant's field of view.

Windows and Glazing. Integrated daylighting and thermal analyses of various glazing options showed that well shaded single pane clear glass provided the best energy performance. Such information allowed Site 1-C to make ample use of glass by providing the building with a .55 window to wall area ratio, a high value considering that California's Title 24 prescriptive section (the ASHRAE 90-75 based portion of the code) would have restricted Site 1-C to approximately a .20 window to wall area ratio (the prescriptive section would also have required the use of double pane glass). Fortunately, the California code included a performance section where compliance can be met via an energy budget approach (the method used to certify Site 1-C). In addition, the windows used in Site 1-C permit ample natural ventilation (20% of the window area is operable) as well as providing excellent views.

Shading Device/Light Shelf. The sun shading features of Site 1-C utilize carefully designed fixed horizontal and vertical elements (see Figure 5). The horizontal elements provide sun protection during the majority of the midday hours, whereas the vertical elements shade the windows from low morning and afternoon sun. The overall shading design permits the sun to strike the windows when direct solar gain actually reduces heating load (winter mornings) or when it has no direct effect on building operation (after working hours). A portion of the shading devices were also designed to function as a light shelf, a simple device that consists of a white diffusing horizontal plane that reflects diffused natural light toward the ceiling (see Figure 6), thus providing a more uniform distribution of natural light within the perimeter zone.

Interior Daylighting Cavity. All the interior surfaces of Site 1-C are highly reflective. The perimeter zone has been made as unobstructed as possible by incorporating an open plan office concept (using low partitions) with a ceiling height of 10.5 feet, which is 2 feet higher than those used in interior zones of the building. These features contribute to daylighting performance by increasing the interreflected efficiency of the perimeter zone (see Figure 7).

Electric Lighting. Site 1-C's electric lighting levels were designed to conform to GSA Standards, which suggest a 50±10 footcandle range for the type of tasks that occur in this building. Several alternative lighting designs were analysed using the Lumen II computer program.(6) These analyses took advantage of Lumen II's ability to assess Equivalent Sphere Illumination (ESI), Visual Comfort Probability (VCP), illuminance as well as the total watts per square foot in choosing the most appropriate lighting design. The results of this suggested an electric lighting solution which incorporates indirect fluorescent fixtures running parallel to the windows in the high ceiling perimeter (daylit) zones (this solution integrated extremely well with the daylighting concept) while the low ceiling interior zones would use direct fluorescent lighting. Thus, the electric lighting design provides a comfortable and visually pleasing environment that integrates well with daylighting and has a connected

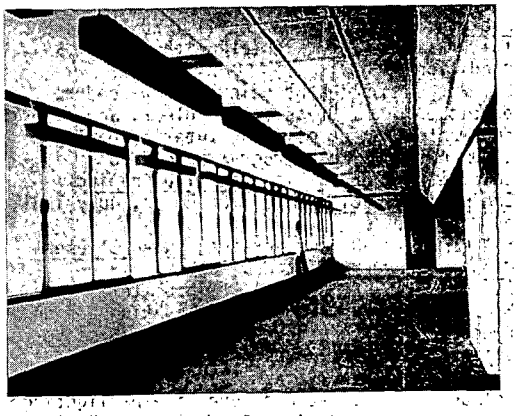


Fig. 7. Photograph of perimeter zone

lighting load of 1.7 watts per square foot (see Figures 6 and 7).

Lighting Controls. Lighting controls offer a tremendous range of system performance, complexity and cost. Several levels of control were analyzed: dimmable, stepped and on-off. The dimmable system provided the best performance and was originally specified, however it was later eliminated for cost reasons. Its replacement became an on-off system intelligently wired to perform like a stepped system. This system uses standard off-the-shelf components: 1) Central Controller (an Intel 8085A microprocessor) for automated lighting control (programmed for start-up, lunch-time, shutdown, etc.) and monitoring, 2) Data Line to connect the controller to the transceiver, and 3) Transceiver which receives signals from the controller or from switches (photocell relays) when lights are to be turned on or off.

The on-off control was made acceptable for daylighting by having all perimeter lighting split wired--ballasts were wired to lamps running in series (running parallel to the windows) rather than the conventional practice of wiring ballasts to parallel lamps. Such a technique allowed the on-off system to be stepped in 25% increments within the perimeter zone (which consists of 2 indirect fixtures with 2 lamps each).

## 4. PERFORMANCE IMPLICATIONS

The potential energy savings associated with the use of daylighting were analyzed by modifying the lighting schedule of DOE-1.4 with data derived from the daylighting calculations. The resulting lighting savings within the perimeter zone were found to be approximately 80% for the summer months, 30% for the winter months, with an annual savings of 58%.

These results are significant. If no daylighting was assumed, the user area of Site 1-C (130,000ft$^2$) would consume 552,500Kwh of electrical energy for lighting. Site 1-C's use of daylighting within the user area consumes only 353,820Kwh of electrical energy for lighting, a 36% savings (in an already efficiently lit building). The cost savings for electricity associated with daylighting based on an electrical rate of $0.05/Kwh would be $9934 per year. In addition to electrical energy savings, a significant portion of the reduced use of electric lighting can also be converted into reduced space cooling requirements. Thus, the cost savings for cooling based on fuel cost of $8/million Btu's and an average Central Plant cooling coefficient of performance (COP) of .8 would be $6746 per year.

The use of daylighting not only produces significant energy savings but also reduces peak demand on both the Central Plant (cooling demand) and local electrical utility (power demand). The peak demand for both cooling and power occur on summer afternoons which coincides with Sacramento's most ideal daylighting conditions. Thus, assuming 100% daylighting of the perimeter zone, peak cooling demand will be reduced by 47 tons while peak power will be reduced by 137 kW. This phenomenon will incur additional cost savings to the State. Reduction of the peak cooling demand would reduce the cost of equipment installation to the Central Plant by approximately $35,250 (assuming $750/ton of installed refrigeration). Reduction of the peak power demand would reduce the cost of equipment installation to the local electrical utility by approximately $137,000 (assuming $1000/KW of installed capacity). A portion of this latter savings will be returned to the State in the form of savings in demand and time-of-day charges.

## 5. CURRENT STATUS

Site 1-C was occupied in the spring of this year. Construction costs have come in below the client's projected budget of $13.4 million, thus dismissing any notion that energy-conscious design need be expensive. Preliminary daylighting measurements have proven to be slightly higher than daylighting calcualtions suggested, which is probably due to the unoccupied state of the building when the measurements were taken. The several occupants that have been interviewed have commented on the natural lighting qualities and openness of the office space. The State was planning to install monitoring equipment in the building, however recent changes in State Administration (which has been less than supportive of the previous administration's building program) may preclude any serious monitoring effort.

## 6. GENERAL COMMENTS

In this paper, we have discussed the form-generating effects that daylighting has had on a particular office building design. The energy-conscious design features of Site 1-C represent an integration of simple and proven daylighting concepts that contribute to significant lighting and cooling savings as well as peak load reductions. Many of the daylighting design techniques used during the design of Site 1-C (circa 1978-79) have been made obsolete by recently developed design tools,(7,8) which today would automate and compress much of the daylighting design effort that went into Site 1-C. In addition, codes like the new ASHRAE 90A-1980 place less restrictions on the use of daylighting, thus allowing more designers to successfully use daylighting as a design strategy. Finally, we hope that this discussion has helped this process in some way.

## 7. ACKNOWLEDGEMENTS

The work described in this paper was funded by: State of California Department of General Services, Office of the State Architect. Barry Wasserman, Former State Architect.

Design Team included:

MBT Associates, Principal Architect
Frank Tomsick, Project Principal
Lyrinda Snyderman, Project Manager

Sam Davis, Consultant Architect

URS/Blume Associates, Structural Engineers

Syska & Henessy, Mechanical and Electrical Engineers

Vladimir Bazjanac, Ph.D., Energy Consultant

Harvey Bryan, Daylighting Consultant

Arbegast, Newton & Griffith, Landscape Architects

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2. Four of the seven team members of the third place submission to The California State Energy Efficient Office Building Competition were members of the Site 1-C design team.
3. Only the loads portion of the DOE-1.4 program along with simple zoning of the building were used during the schematic design phase.
4. The BRS Tabular method was used for calculating the overcast sky conditions, and a manual method developed by H. Bryan and documented in "A Simplified Procedure for Calculating the Effects of Daylight from Clear Skies," Journal of the Illuminating Engineering Society, Vol. 9, No. 3, April 1980, pp. 142-151, was used for calculating the clear sky conditions.
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# SENIOR CITIZEN HOUSING PROJECT AT ROOSEVELT, N.J.

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## ABSTRACT

The 21 units of Section 8 Farmer's Home senior citizen townhouses is Kelbaugh & Lee's first multi-family housing design to have been built and one of the first examples of low-rise, high density passive solar housing in the Northeast. It was designed in 1980-1981 and construction completed in summer 1983. Each unit in the project includes: (1) a small attached greenhouse with massive floor and back wall, (2) a small stagnant Trombe wall with selective surface and direct gain clerestory in each of its one or two bedrooms, (3) a small array of five Big-Fin preheaters in each greenhouse, (4) movable insulation on all but the clerestory windows, (5) a 16SF skylight in the living room for daylighting and direct gain and (6) a solar and wind assisted ventilation chimney for natural ventilation in summer. The central community building incorporates an attached greenhouse with an array of 20 Big-Fins for preheating hot water for its washing machines, dishwasher and lavatories. The solar chimney is designed to obviate the need for air conditioning.

The site plan strings the units in four east-west rows for solar access while creating small courtyards. The architects addressed the design problem of providing both north and south-facing front doors, fundamental and critical to fostering a sense of community in any street or courtyard configuration. The architectural style is a modern interpretation of shingle style, beach houses with the passive solar features carefully integrated. It was an award winning design in the 1981 NY AIA Energy Design Competition and has been the subject of a feature article in Solar Age (October, 1982).

## 1. INTRODUCTION

During the Great Depression, the Federal Government created the planned town of Roosevelt on potato fields 15 miles east of Princeton, New Jersey. Jewish immigrants, most of them garment workers in New York City, settled there in 200 architecturally designed flat-roofed concrete block single storey houses. In all, 160 committed families moved in for the cooperative experiment to form an ideal community with a school, a store, farms and one needle trades factory in the middle of nowhere.

Intended as a self-sustaining community, the idea was to produce cloaks in the winter for sale to New York manufacturers and clothing co-ops, and in the off-season, the same people would work in the farmlands. Each house was built on a half-acre lot in a carefully planned town with greenbelts still left green. The town has not grown too much, but among Roosevelt's original settlers who



arrived some 47 years ago, quite a few stayed and have grown old together. Physically and financially less able to maintain their three or four bedroom homes (many of the original flat-roofed houses have been modified) many of these elders faced the prospect of having to sell and move away. Very few wanted to leave the town if they had a place to retire.

With the help of David Davies, a housing consultant and a former resident of Roosevelt, these senior citizens formed a non-profit housing corporation and started their acts together to apply for a funding from the Farmers Home Administration (FmHA) for a modest senior citizen housing of their own.

Solar was not an objective, but Kelbaugh & Lee was selected out of 10 architects interviewed after a visit to Kelbaugh House in Princeton. They saw the greenhouse and Trombe walls as an experiment worthy of a town that was itself an experiment.

After choosing the site, two acres of regressing farmland about a five minute walk from the center of town, a questionnaire was circulated to find out what the future occupants wanted. The seniors wanted their project to be a continuation of the existing neighborhood, but they asked for an architectural style "completely new and different" from the original Roosevelt stock. Almost all wanted one-story, one-bedroom units, and they unanimously did not want flat-roofs. True to their community's heritage, they did not want fences around individual yards, favoring instead "only a common lawn."

## 2. SITE PLANNING

The gently sloping site borders on woods to the north and south, farmland to the east, and a residential neighborhood to the west. It was decided to put in a one-way loop lane around the housing project. Autos are to be kept out of the interior of the site. Perimeter parking will be used instead.

On the south side of the lot, the buildings are set back 100 feet from the lot line because the woods across the street are dense. To keep landscaping costs down, as many trees as possible were maintained on the site.

The project has the ambience of a small village. A low trellis fence surrounds the attached cottages on three sides. The fourth side opens to a view of farmlands. Typically English country details such as an entrance pavilion, archways and gates within the fence underscore the sense of place. There are eight residential dwellings: four one-bedroom duplexes, two two-bedroom duplexes, and two one-bedroom quadruplexes. A Community Center in the midst of the enclave, houses commercial washing machines, lockable storage space, a kitchen and a community room.

Wandering walkways and a mix of open and confined spaces sculpt an informal, personal landscape. The spacing between buildings is irregular, the courtyards separating them vary in size and proportion. One large open area can be used for a community garden, while a smaller common area to the south of the Community Center will be left in its natural

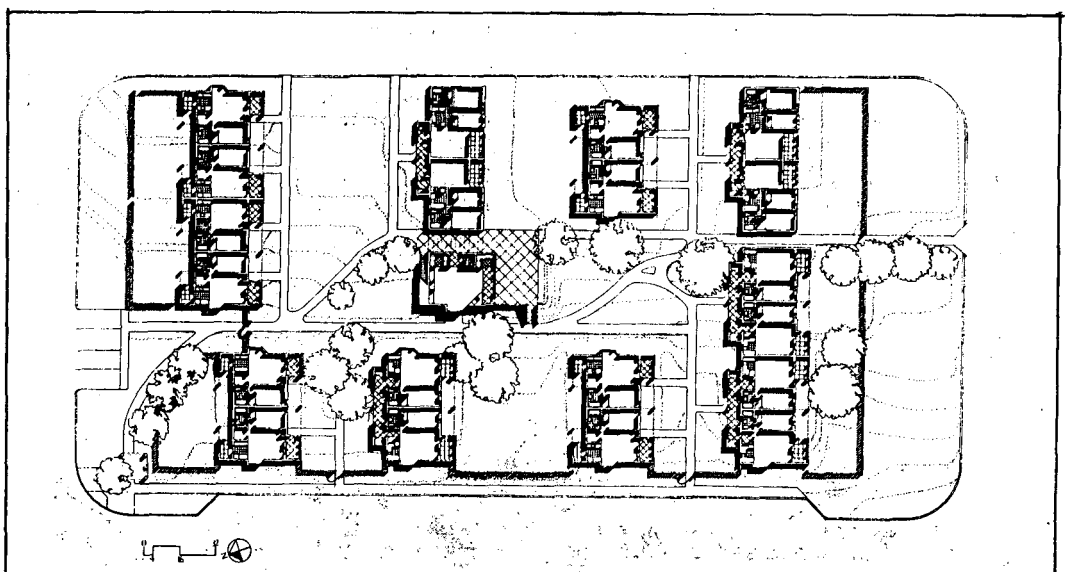


Fig. 1. Site Plan.

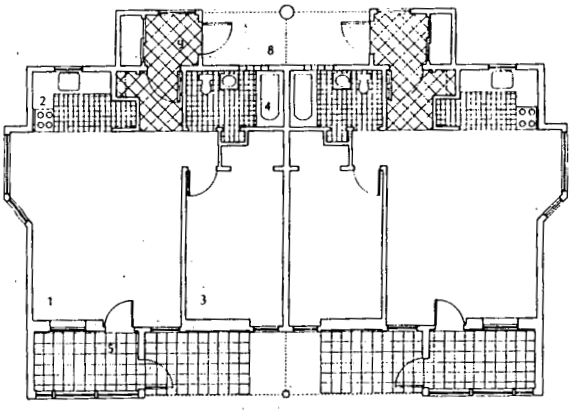
state, a little wooded park. All the townhouses are distributed across the site in east-west strips for solar and barrier-free access. But we tried to avoid the feeling of regimented rows of houses. And residents can walk throughout the project without encountering steps.

## 3. RESIDENTIAL DESIGN

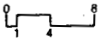
The atmosphere is enhanced by the scale of the buildings, their porches and lattices, and windows with cross bar mullions. The design has regularity but diversity. We aimed to get maximum diversity with a minimal number of architectural moves. FmHA funding constrained the number of architectural moves. Generally, FmHA allows no-frills design. Some items such as cedar shingle siding and large glass areas, took considerable effort to convince FmHA officials that they were necessary.

At first, all the homes had front doors facing south, until we realized that this meant each front door faced a neighbor's back door. So a new unit was designed, one with its front facing north to create a courtyard between front doors to bring neighbors together. Now the backyards are more private, uninterrupted by walkways. In all, five different units were developed: south-facing one-bedroom, north facing one-bedroom, north-facing two-bedroom, and two different handicapped units.

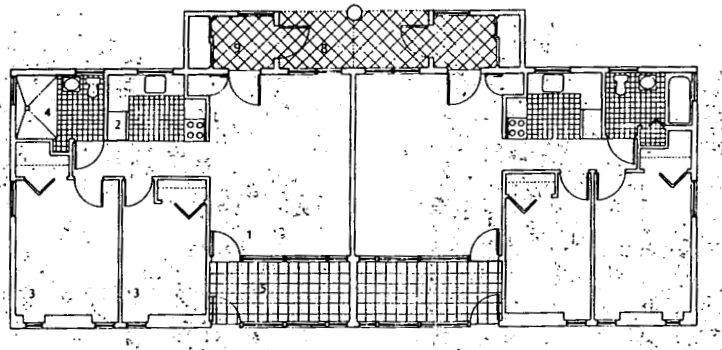
A social and architectural focus for the project, the brick-veneered Community Center rises three stores tall, above the one-story shingled dwellings. The feeling that this building needed to be prominent led us to



1 BR Units, North-facing



1. Living/Dining
2. Kitchen
3. Bedroom
4. Bathroom
5. Solarium
6. Storage
7. Back Porch
8. Portico
9. Vestibule



2 BR Units

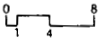


Fig. 2. Each Unit has a sunspace, a luxury for housing for the elderly, but one that senior citizens will use for more than its energy benefits. Care is given to organizing the living space to the south. Support spaces are buffers on the north.

suggest adding an extra residential unit atop it, a cathedral ceiling studio apartment.

The 21-unit housing development is composed of 16 one-bedroom units, four two-bedroom units and a studio apartment for a managerial tenant atop the Community Center. The sizes of units are modest; 700 $ft^2$ for one-bedroom unit and 850 $ft^2$ for two-bedroom unit.

## 4. SOLAR ENERGY

The living/dining area receives heat and light from a skylight overhead and from the mass wall heated by the solarium. The window in the mass wall opens up a view from the living area into the solarium. Each solarium has a quarry tile floor and Exolite glazing overhead. Hung across the solarium roof beneath the glazing are five Big Fins, a solar hot-water preheat system consisting of a black-painted, extruded aluminum strip snapped on to a copper tube. Solar-heated water circulating through the copper tube then thermosiphons to a small 55-gallon heater/storage tank in the attic. Made unnecessary by Big Fin, the lower heating element in the tank is removed. (For three months in summer, Big Fin should provide 100% of the hot water). Twenty Big Fins are installed in the Community center for its washing machines, dishwasher and lavatories. The south wall of each bedroom is a stagnant Trombe Wall flanked by a casement window required by code. A clerestory atop the wall introduces additional light. The heavyweight concrete block wall is filled with mortar and covered with black chrome selective foil. Standard glass patio doors, one-inch thick, are used for glazing. Unvented walls were used for several reasons: less expensive construction without vents, no circulation of dirt through vents or deposits on the glazing, and less floor space lost with just a one-inch space between the glass and the wall.

Stagnant Trombe walls deliver a warmer wave of radiant heat at night. Since there is no way to vent themselves, these walls will be well shaded under canvas awnings in summer.

Electrical resistance was chosen for backup instead of a central heating system, because it has a low initial cost and is easy to operate and maintain. Little backup heat will be needed. Since the electricity can be individually metered, homeowners have more incentive to operate their solar systems properly.

In the guise of a decorative cupola, a solar chimney is used to cool the residences. During the summer, operable louvers in the living room and bedroom ceilings can be electrically opened to vent hot air into the attic. The air will then be pulled into a black-painted, 30-inch-diameter pipe that leads up to the rotary on the cupola. Venting through the turbine can be wind or heat induced, or both. On windy days, the motion of the turbine will flush hot air out of the attic. To ensure ventilation on still days, the east and west sides of the cupola are glazed to admit the low-angled rays of the morning and afternoon summer sun. This heats up the black pipe and the air inside, which then rises through the turbine (which may or may not be turning). This action pulls the house air up to the attic and circulates air in the living spaces. On windy, clear summer days, the solar chimney will move about as many cfm as an electrical fan of equivalent diameter. To give residents a choice, air conditioner sleeves have been installed during construction.

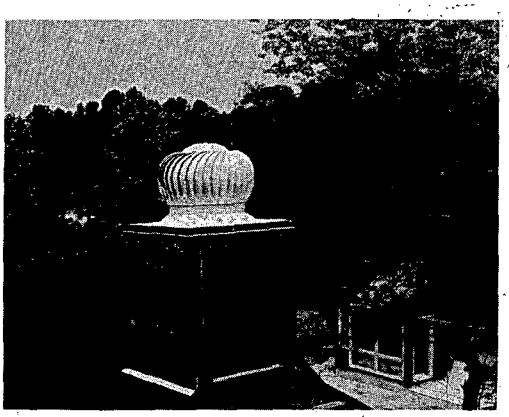


Fig. 3. Wind Turbine/Solar Chimney.

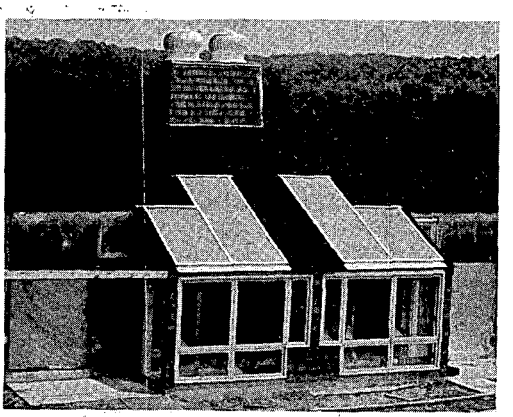


Fig. 4. Adjoining One-bedroom Units Showing Extended Skylight Over Living Room.

During the summer, an interior shade can be drawn over the living room skylight, and the rows of Big Fin should provide enough shade within the solarium.

Airlock entries are on the front and back. Walls are insulated to R-25, roofs R-40 and Window quilt night insulation will be installed on all double-glazed apertures. SSFs for interior units and end units is estimated to be 43% and 38% respectively. Annual auxiliary heating load would be 7.31 MMBtu for inside units, and 9.98 MMBtu for outside units. A typical unit will consume $160-$260 worth of electricity for heating in the 5,000 degree-day climate and use no electricity for summer cooling.

Total Energy Consumption estimates are shown in Table 1.

TABLE 1 ROOSEVELT SENIOR CITIZEN HOUSING ENERGY CONSUMPTION ESTIMATES, OCTOBER 15, 1981

| | Space Heating (kWh/yr) | DHW Heating (kWh/yr) | Electrical (kWh/yr) | Total (kWh/yr) |
|---|---|---|---|---|
| 1 BR Unit | 2141-2923 | 350 | 1800 | 4291-5000 |
| 2 BR Unit | 3500 | 500 | 2000 | 6000 |
| 0 BR Unit | 2500 | 330 | 1800 | 4630 |
| Community Rm | 5 MMBtu gas | 8 MMBtu gas | 2400 | 13 MMBtu 2400 kWh |

Thus, two bedroom unit will consume 6000 kWh./yr. or 20484 MBtu/yr. This is equivalent to 26.6 MBtu/ft$^2$/yr. This is considerably lower than BEPS Energy Budget Level for Multi-family Low-Rise Units which is 109 MBtu/ft$^2$/yr.

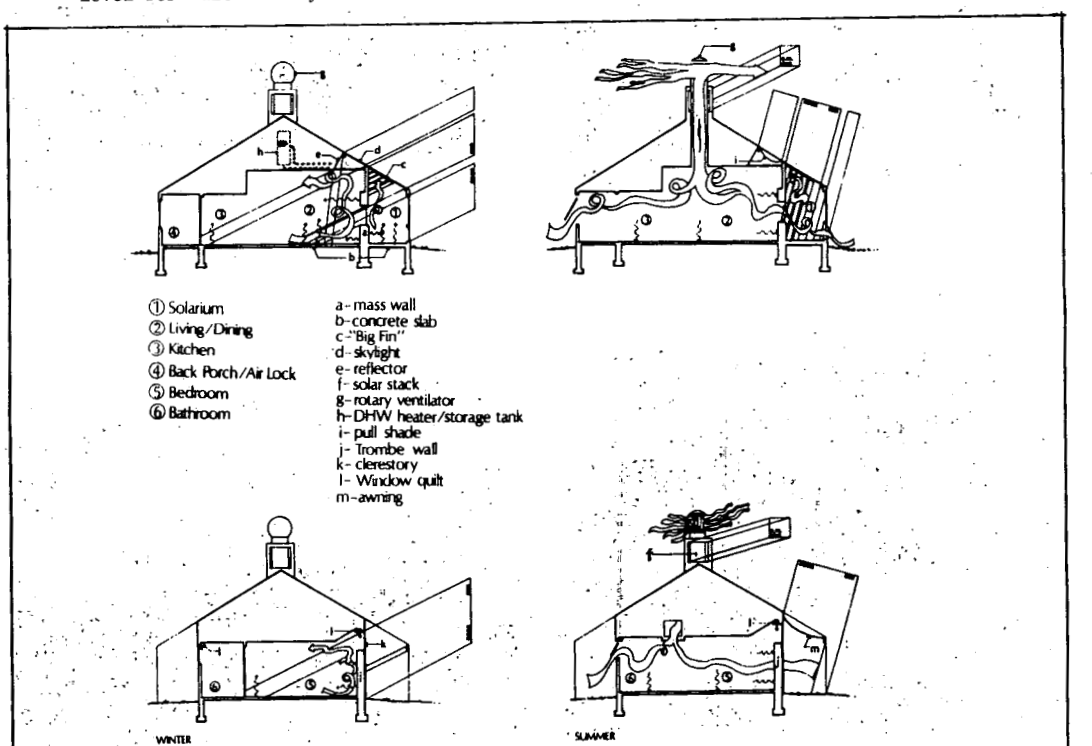



Fig. 5. Solar design: Windows are placed carefully to maximize direct gain. The Trombe walls are small since much of the south side is glazed.

## 5. SUMMARY

Total construction cost amount to be approximately $50/ft$^2$, still in the upper range of government standard. Without full support of innovative senior citizens and great interest and cooperation by FmHA Architect, the project would not have been realized. In addition, the project was kept alive during its design phase with $5,000 seed money from the now defunct Northeast Solar Energy Center and $25,000 from the State of New Jersey. After two years of design and approval procedures, and one year of construction, the community is anxiously waiting for its completion. Meanwhile, the design has already garnered the only award given in the 1981 NY AIA Energy Design Competition for the tri-state region, New York, New Jersey and Connecticut.

Although it is certainly sensible to utilize solar design for multi-family housing, not many have been built. As government assistance programs become more scarce for both solar designs and housing, the elderly of Roosevelt timed their housing project well. We hope that this project will bring about satisfaction to these well-deserved old citizens, and an incentive for those who are contemplating similar projects elsewhere.

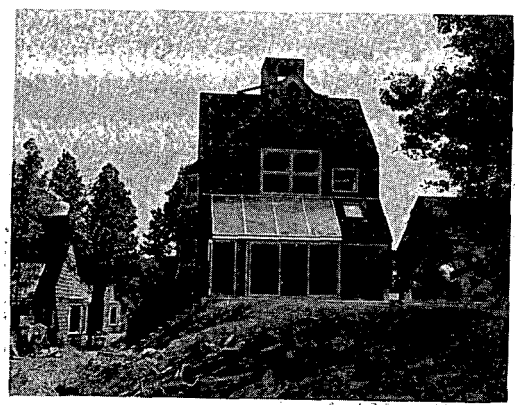


Fig. 6. South View of Community Center.

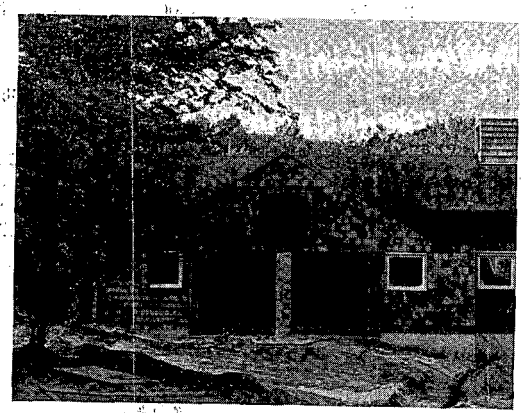


Fig. 7. Elevation of North Facing One-bedroom Unit.



Fig. 8. Side Elevation of South Facing One-bedroom Unit.

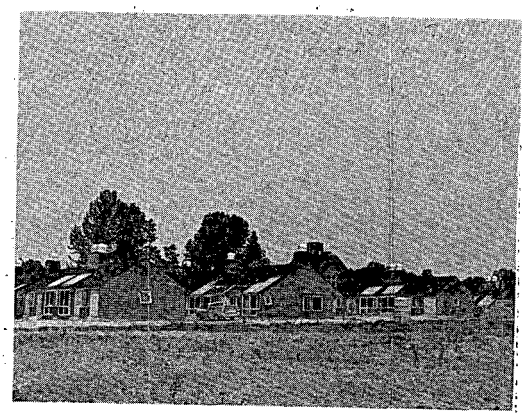


Fig. 9. View of Development from East.

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# PERFORMANCE OF THREE AIR ENVELOPE RESIDENCES IN IOWA USING MASS FLOOR STORAGE

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## ABSTRACT

Since the introduction of "air envelope" structures as a concept in energy conscious design, a continual controversy has evolved questioning nearly every aspect of their construction and performance. This author agrees with the general concept of air envelope structures, but very much disagrees with the concepts of using earth as a storage media, using concrete culverts as a means of natural cooling, using double vapor barriors in the envelope walls. This paper describes the performance of three homes that differ markedly from those that have gained more notoriety, without the problems of moisture condensation, or large temperature swings.

## 1. INTRODUCTION

In early 1979 after reading a few articles on the Tom Smith home at Lake Tahoe, this author obtained the Ekose'a design manual and the Case Study by Tom Smith. It seemed unbelievable the claims that were put forth concerning their performance. After studying the Butler's manual, it became quite evident that a number of claims were grossly distorted. Tom Smith's manual seemed much more believable however this author was still in disagreement with the value of a crawl space for either storage media or its geo-thermal contribution to heating the envelope. Other points of disagreement were the use of vapor barriors in both interior and exterior walls of the envelope, and the placement of a majority of south glass in the roof.

Ed. Note: A list of metric-English-metric conversion values appears immediately preceding the Author Index.

With this in mind, this author began design of a number of air envelope homes reflecting what appeared to be a more affective way to deal with envelope air flow.

## 2. ADJUSTMENTS TO THE ENVELOPE DESIGN

The following is brief discussion of each component of the air envelope describing the differences between those using more nationally recognized techniques.

### 2.1 The Mass Floor

This author has never agreed that a crawl space recieves enough benefit from geo-thermal contact or acting as a storage mass to justify its use. This has been evidenced through testing of crawl spaces in existing air envelopes. Because it is ineffective as a storage mass, high and low temperature swings within the envelope are quite probable.

In order to deal more directly with the storage needs, this author used what is termed a Mass Floor Storage system. It is simply a concrete slab cast around pipe running in a north/south direction connecting the north air chamber with the sunspace. Under the slab is 2 in. rigid board insulation, reducing the conductive heat loss through the bottom of the slab.

This large amount of storage capability allows the potential high and low temperature swings in the envelope to stabilize, effectively storing heat during sunny days and releasing it night. In comparison to a crawl space, there is no question of whether the heat will adequately be stored. With this type of mass floor, there is no other place the air can flow; it must be pass through the concrete encassed pipes.

The insulation under the slab also reduces the possibility of sweating floors during months of warm weather because the surface temperature of the slab is a few degrees warmer than if it was in direct contact with the earth beneath. The author uses this same type of slab insulation in all slab on grade structures, whether or not an air envelope design. Moisture condensation might not be a concern in more arid climates, but its a big concern in Iowa where the mean annual relative humidity is 73%.

It is the feeling of this author that if a mass floor storage system of some type is not employed, the air envelope concept is not worth using.

## 2.2 Placement of South Glass

The location of south glass is critical to the speed of air flow through the envelope. One of the mistakes that have been made in envelope design is to locate the majority of south glass in the tilted roof of the sunspace. The majority of south facing glass should be in the vertical walls and not in the roof. Then as the cool air is warmed by the sun, it will become lighter and rise, creating a positive airflow. If the majority of heat is generated in the upper level, that warm air has no where to go since it is already nearly to the top of the envelope. This merely reduces or stops the natural air flow that is the whole basis of envelope design. This lack of air flow unfortunately has been prevelant in a number of air envelope homes that have recieved some national attention.

Note: Probably the most stupid comment I've ever heard concerning air flow in an envelope and how to maximize it was at the 1980 air envelope workshop in Amherst, Mass. during the 5th National Passive Conference. A speaker stated that one way to increase air flow was to increase the amount of glass on the north side of the envelope. This would increase the amount of heat loss causing more cold air to drop into the lower north wall, thus pushing air from the crawl space into the sunspace. That's like opening a window in the winter time when the house gets too warm. The envelope designs presented in this paper all have very positive air flow. This will be discussed later.

## 2.3 Vapor Barriors and Condensation

One of the most severe problems with air envelope construction has been high humidity and moisture condensation on glass in the outer walls of the envelope. This author believes it is caused by two practices: using vapor barriors in both walls of the envelope and by using a crawl space as an air chamber.

The homes presented in this paper use only one vapor barrior in the envelope; on the interior face of the inside wall. None of the homes presented ever had any problems with moisture condensation on the glass, not even light fogging. Two of the three have been through the 1981-1982 winter when it reached 25 $^{o}$F below zero.

A lot of designers don't believe use of one vapor barrior is a wise decision. This author however, believes it much wiser than two. Double vapor barriors are never used on double wall construction with dead air spaces in superinsulated homes so why should they be used in air envelopes? It is true that hot tubs or growing plants will encrease the humidity level within the envelope, however, the ratio of glass to floor area of the envelope is so high that the incoming sunlight helps dry from the inside out, reducing the possibility of accumulating moisture in the outer wall.

## 2.4 Summer Cooling

Another point of disagreement this author has with more standard air envelope construction is use of below grade culverts or pipes to cool the envelope area. If adequate roof vents are provided at the top of the sunspace or in the attic, the envelope will exhaust sufficiently without them. The three homes in Cedar Rapids exhaust adequately without cooling tubes, the air temperature being no more than a few degrees warmer than ambient. If the sunspace is to be considered part of the living space, control from glare is much more important than cooling.

Earth tube cooling is much more valid directed to the actual living space of the structure than the sunspace. Systems can be connected to the conventional furnace or separately operated. This will be discussed later in this paper.

## 3. THE THREE PROJECTS

The follwing is a brief description of the three projects currently operating in Cedar Rapids, Iowa. Photos of each project are on the right side of this page.

### 3.1 The Lippisch Addition

Mrs. Lippisch requested the design of a separate living quarters for just herself, attached to the existing two story home in which she raised her family. The existing house would be used for her family or friends from Europe who might stay for extended periods of time. She requested that the addition not only make use of passive solar energy as the major heat source but that the design be an air envelope if at all possible.

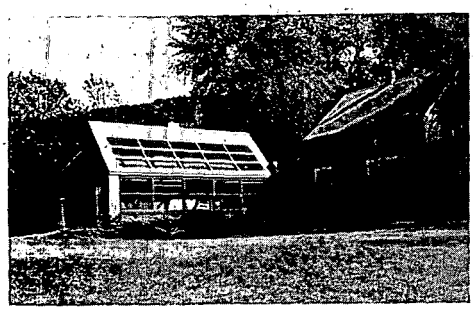
Because the addition was single storey with not the vertical height in the sunspace conducive to rapid air flow, this architect recommended that three fans be installed in the attic assist air flow during the sunny winter days. These fans are controlled by a thermostat in the sunspace allowing either automatic or manual control. Although there is a positive air flow during the sunny days, the fans give the added ability of "super storing" heat in the floor.

The mass floor of this design is comprised of 8 in. cored slab concrete planks with a 3 in. concrete topping over. The planks run from north to south connecting the double north wall with the sunspace. Below the planks is rigid board insulation.

Glass in the bottom of the south wall of the sunspace are operable awning windows, all glass above and in the roof are tempered 1 in. replacement units for sliding glass doors. Insulated vent doors at the top of the north wall of the sunspace are opened to exhaust air from the sunspace during the warm months.

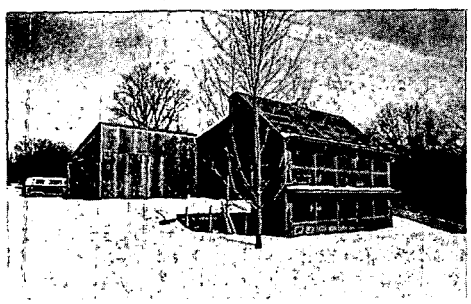
The auxilliary heating system for the addition is electric baseboard. Of the 1,012 $ft^2$ of heated area, approximately 350 $ft^2$ is the connecting link between the addition and the existing house along the north side.

The actual performance of this addition is discussed in Section 4 of this paper.



**The Lippisch Addition**

South Glass Area: 424 $ft^2$
Heated Floor Area: 1,012 $ft^2$
Glass to Floor Ratio: 0.42



**The Olsen Home**

South Glass Area: 569 $ft^2$
Heated Floor Area: 1,900 $ft^2$
Glass to Floor Ratio: 0.30



**The Speers Home**

South Glass Area: 656 $ft^2$
Heated Floor Area: 2,360 $ft^2$
Glass to Floor Ratio: 0.28

### 3.2 The Olsen Home

The Olsen home was the second air envelope design constructed in Cedar Rapids. The Olsens requested the design of a passive solar home reflecting their immediate and future living needs. They were very interested in the air envelope concept. Because the site was conducive to air envelope design, that type was used. The upper level consists of the main living areas; bedrooms walkout to the sunspace on the lower level. Bathroom, closet, utility, and storage rooms comprise the rest of the lower level.

The mass floor storage system on this home is a bit different than the Lippisch Addition. Because of the two story design a floor system was chosen that would not require the use of a crane for installation. A different floor was also chosen to reduce the cost. The final solution was to use thin wall plastic pipe cast into the concrete slab. Pipes are spaced at approximately 8" on center running north and south.

As with the Lippisch design, the south wall has awning windows at the bottom and 1 in. insulated glass above. On both designs and added benefit of the glass in the roof is that domestic water collectors can be installed in the upper level of the sunspace directly under the roof glass. This can result in a collector system without a glass cover over the absorber plate since the air temperature in the sunspace is so much warmer than normal ambient air temperature.

The auxiliary heating system for the heated space is an electric forced air furnace. The water heater and all appliances are electric. Performance data on the house is discussed in Section 4 of this paper.

### 3.3 The Speers Home

The Speers' requested the design of a passive solar home using the envelope concept. Because they are both retired, low maintenance was a key factor in not only selection of materials, but also in the decision not to use glass in the roof of the sunspace. Another design parameter was to have an exterior appearance that would blend in with the existing "ranch style" homes in the sub division. The upper level consists of the main living areas; bedrooms walkout to the 12 in. wide sunspace on the lower level. The furnace and utility areas are also on the level.

The mass floor storage on this design uses the same thin wall plastic pipe encased in concrete. Two inches of rigid board insulation is beneath the slab.

The glass placement of the sunspace consists of 46 in. wide, 1 in. insulated replacement units installed vertically in the south wall. Ventilation of the sunspace is achieved by four 8' sliding glass doors, two in each level. In warm months, air exhausts from the sunspace up through the attic and out the gable end vents. These vents have insulated hinged doors that can be opened and closed via a rope and pulley system extending down from the attic into the upper level of the sunspace. The vents are normally opened in the spring and closed just before the heating season begins.

This particular design has a earth cooling system connected to the auxilliary furnace which is forced air natural gas. The system consists of 360 feet of 10 in. corrugated drainage tile that is connected to the main return plenum on the furnace. When cooling of the living areas is desired, the furnace blower is turned on and a damper is flipped, bypassing all of the air from the living areas out underground. This air is cooled down as it passes through the pipe, returning to the furnace and is then blown through the normal supply ducts in the house. The piping was sized to supply one ton of cooling capacity to the house. The system as designed works very well.

## 4. PERFORMANCE

The following is a brief description of the operation of the three homes during the last two winters.

### 4.1 Auxiliary Heat

The Figures 1-4 on the following page represent the performance of the houses in relation to each other. The performance of each design is evaluated in terms of its own Thermal Integrity Factor. The Integrity Factor is the number of Btu of heat consumed per square foot of heated floor area per degree day. The formula for calculating it is below:

Thermal Integrity Factor=

$$\frac{\text{MMBtu Aux.Heat} \times \text{Furnace Efficiency}}{\text{Deg.Days} \times \text{Heated Floor Area}}$$

Because the Integrity Factor deals in Btu per square foot, it is a figure that can be used for comparison of any type of design regardless of the type of heating system, conventional or solar.

The net energy consumption for space heating in the three envelopes presented in this paper was derived by averaging their base utility demand in the warm months and then subtracting it from the total consumption shown on the utility bill as supplied by the power company. Although this is not the most exact method of analyzing the consumption, it is about as close to actual as can be done without use of sophisticated, expensive monitoring systems.

The last two winters in Iowa have been characterized as two of the worst when compared to the averages for solar insolation and heating degree days. The 1981-1982 winter was nearly 20% colder than average with nearly the same reduction in solar radiation. The 1982-1983 winter had considerably less heating degree days but was was very humid with a lot of cloud cover and a large reduction in the amount of radiation.

The last page of this paper presents four different graphs concerning the auxilliary consumption of the houses. In looking at Figures 1 & 2, it is interesting to note that although the 1981-1982 winter was much colder than this last winter, the Lippisch and Olsen homes still performed better. This is mainly because of the lack of solar radiation this last winter. The amount of heat loss from the house during cloudy days was evidently proportionally greater than during the colder but sunnier 1981-1982 winter.

Another reason that these particular air envelopes would not perform quite as well during winters of reduced radiation is because no night time insulation on the windows is used. With total heat cost so low, the economics of "store bought" insulation does not make it worth buying.

In comparing the three houses during the 1982-1983 winter, it is quite evident that the Speers was superior in performance. This is mainly due to the lack of roof glass. This author does believe, however, that during a winter with more normal sunshine the Olsen house would be closer to equaling the performance of the Speers home.

Although efficient in performance, this author does not believe that the Lippisch addition can really compete with the performance of the other two. It is a single story not two which reduces the air flow. It is also totally above grade which proportionally increases the heat loss to ambient. Because of the "walk out" lower levels on the Olsen's and Speers' homes, the overall performance of the building shell is better.

This is evidenced by comparing the month by month Integrity Factors graphed in Figures 3 & 4. It is quite apparent that because of its physical design, the Lippisch Addition is much more sensitive to ambient air temperature.

## 4.2 Conclusions & Recommendations

With the experience gained by the actual construction of the homes and by being able to evaluate their performance, this author is very convinced that the air envelope concept worthy of use in the design of energy efficient structures. It is not however a design that can be or should be used in all cases. It's worth is questionable when designing on a flat site that would be conducive to a slab on grade construction. The air envelope is best suited to a site sloping down to the south.

The use of glass in the roof is also questionable from a strict cost efficiency standpoint. It is benefical however, if a domestic water system is incorporated into the upper level of the sunspace.

In the future this author intends to continue designing air envelope structures but will most likely back away from using glazing in the roof. The performance of the Speers home has convinced me that a highly efficient design can be accomplished without roof glass.

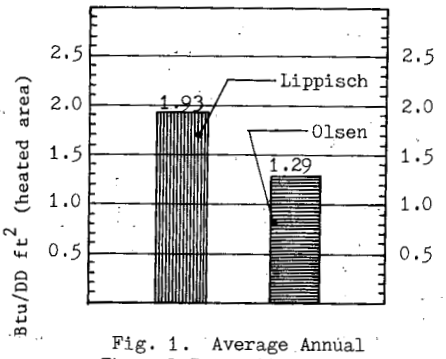



Fig. 1. Average Annual Thermal Integrity Factors 1981-1982 Winter(7,300 DD)

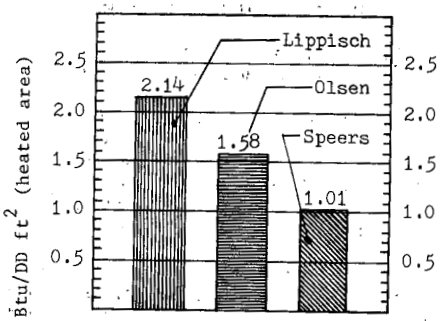



Fig. 2. Average Annual Thermal Integrity Factors 1982-1983 Winter(6,000 DD)

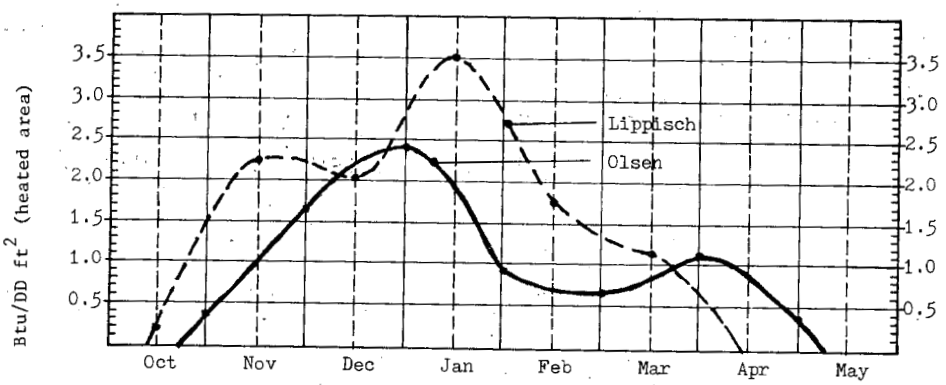



Fig. 3. Monthly Thermal Integrity Factor Graph 1981-1982 Heating Season (7,300 DD)

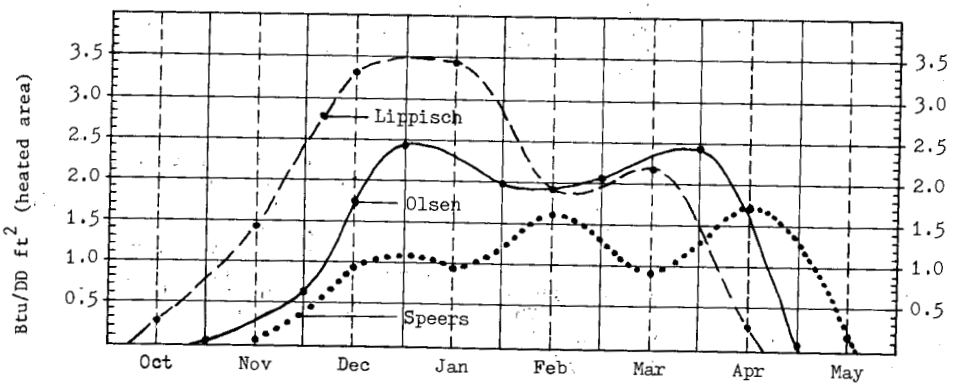



Fig. 4. Monthly Thermal Integrity Factor Graph 1982-1983 Heating Season (6,000 DD)

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# PASSIVE SOLAR PERFORMANCE OF A LARGE MIXED BUILDING COMPLEX ST. ENOCH SQUARE, GLASGOW, SCOTLAND

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## ABSTRACT

The objective of this study is to assess the environmental behavior of the St. Enoch Square Development. The architectural concept comprises a glass envelope enclosing a variety of structures, with the objective of attempting to maximize the passive use of the natural environment in order to reduce the demand for auxiliary energy and consumption of fossil fuels. The study consists of a calculation of temperature and humidity for representative spaces within the envelope exposed to both "typical" conditions (95% of the time), and to "design" or extreme conditions (2-5% of the time). From this, requirements for natural or mechanical ventilation, auxiliary heating and cooling have been determined for each typical space, together with requirements for solar control or shading. On this basis annual energy consumption and operating costs have been established for various different approaches to the relationship between the internal structures and the envelope, and have been compared to the likely consumption of a "conventional" building with the same internal contents.

Daylighting studies and physical model testing has been carried out on several proposed arrangements for fenestration in the offices to provide an empirical base for daylighting performance estimates and benefits.

On the basis of the study an overall 20% reduction in annual operating costs for the proposed design can be achieved as compared to a conventionally designed shopping mall.

## 1. INTRODUCTION

The key to a successful energy efficient design is early problem definition which should lead to the "correct" solution. Early problem definition is best accomplished in the predesign stage of the project before final architectural and engineering decisions are made. Adequate methods and analysis techniques must be readily available, easy to use, inexpensive and sufficiently accurate to give useful and credible results. This paper will deal with energy-efficient design of the proposed St. Enoch Square Development Complex.

The project is a glass enclosed atrium 250 meters long by 45 meters wide and 25 meters high located in Glasgow, Scotland. The St. Enoch Square Mall designed by British Architects GMW & Reiach & Hall is a multi-use structure including five stories of offices, stores, leisure areas, ice rink and car parking. The current scheme shown in Figures 1 & 2 is located on the site once occupied by the old St. Enoch Train Station. The scheme has developed towards an all-encompassing structure in the grand tradition of the old St. Enoch Station, thus, giving historical continuity and a unifying force to enhance the surrounding spaces.

The glass envelope concept provides a flexible and aesthetically pleasing structure to facilitate internal programming while providing an effective means of environmental control by using direct solar gain and thermal mass in winter and natural ventilation in summer. The glass skin is constructed with 6mm of Georgian wire glass and will be shaded to prevent overheating in summer. Careful design to alleviate undesirable solar gain in summer through

the clear glass envelope will be a major consideration. The design goal is to maximize the use of the natural environment for heating, cooling & lighting while minimizing the use of auxiliary energy & fossil fuels.

## 2. CLIMATE ANALYSIS

Glasgow, Scotland lies at a latitude of 55°, elevation of 149 ft and is 23 miles inland from the Firth Of Clyde. The climate is relatively mild despite its latitude due to the Gulf Stream in winter. Outdoor peak design temperatures for winter and summer are -4°C and 24°C, respectively. The winds in winter & summer are southwesterly averaging 5 - 7 m/sec. Design conditions occur only 2% of the time during the year. Average minimum winter temperatures are 1.0°C and average summer maximum temperature are 19°C.

Winter - The amount of solar radiation avaiable is very low in winter (only 1 hour/day in January). Direct normal clear sky solar intensity averages only 200-250 $W/m^2$-hr and skies are overcast 46% of the time in January. The sun angle on December 22 for a southern exposure is only 10° above the horizon and only 15°-25° during October, November, February and March.

Average tempeatures in winter are 0°C with average humidity 85%. There are approximately 6388 degree-days (English units) in Glasgow.

Summer - Summer temperatures average between 10-18°C. Direct normal clear sky solar intensity averages between 600-700 $W/m^2hr$ and skies are clear 84% of the time in July. The wind speed is less than 2 m/sec 18% of the time. Average humdities are 75% in July. The sun angle is 58° above the horizon on June 21 for a southern exposure.

In summary, the lack of solar availability in winter minimizes the amount of direct solar gain that can be used for heating in a passive building. However, a well designed passive & energy conserving building can utilize both diffuse daylighting and direct & diffuse solar radiation for partial daytime heating, especially, since outside temperatures are only moderately low. A commercial office structure would benefit from a design scheme which maximizes the use of diffuse daylighting to reduce artificial lighting and can utilize natural & mechanical ventilation to cool interior spaces and the building envelope.

The current envelope design scheme is open to the entire sky dome & thus, enchances the availability of daylighting. However, sufficient solar control/shading and must be incorporated to minimize unwanted heat gains especially in summer.

## 3. BACKGROUND

Both manual and computer calculations where performed to estimate the performance of various alternative designs for the St. Enoch Square Mall. The Building Loads Analysis and System Thermodynamics (BLAST) program and ASHRAE methods for calculating loads and ventilation rates were employed in the analysis. Features incorporated in the BLAST program which were of particular importance to this project include:

A heat balance is carried out on each side of each room surface. This includes the calculation of surface temperature and room mean radiant temperature which proved to be important indicators of design performance for the St. Enoch Square project.

Heat conduction and diffuse radiant solar energy transfer through the glass doors which are proposed for use between offices and glass enclosed walkways (office gardens) in St. Enoch's was simulated. This allowed for simulation of the thermal coupling between these adjacent spaces.

Air mixing between zones and natural or forced ventilation is modeled. This allowed for the study of ventilation cooling and a determination of how ventilation air would be warmed as it moved from intlets near the bottom of the structure to outlets near the top. It also allowed the simulation of the tempering effect of air moving from offices and stores into the unheated open areas of the mall.

Basic optical physics provides modeling of solar and long wave energy transfer. This feature allowed precise modeling of the impact of solar shades and the effect of surface absorptivities.

## 4. RESULTS & FINDINGS: A. OFFICE/WALKWAY ANALYSIS

Assumptions - In the exterior office/walkway areas, peak lighting and equipment use

for the office was assumed to be 27 watts per square meter (2.5 watt/square foot). Peak occupancy was based on nine (9) square meters per penson (97 square feet per person). No artificial lighting was simulated in the walkways. In the adjacent offices, varying amounts of forced ventilation were assumed to be available for natural cooling up to a maximum rate corresponding to 0.0075 cubic meters per second per square meter of floor area (1.5 cfm per square foot). No auxiliary heating or air conditioning was provided as long as the spaces remained between 20 °C and 23 °C (68 °F AND 73.4°F). If the office spaces dropped below 20°C or went above 23 °C, auxiliary heating or air conditioning was added to the space. During the unoccupied period, heating was not provided to the offices unless the space dropped below 16°C (60.8°F).

No heating or cooling was provided to the walkways. However, auxiliary (fossil fuel or waste heat) heating and/or office air dumping will be required during a few hours of the year to maintain temperatures above freezing. Some air was assumed to flow from the offices of the walkways (0.5 liters per second per square meter of floor area of .1 cfm per square foot) during the working day. An amount of infiltration which varies with temperature and wind speed was also assumed, based on data provided by the Design Team.

Ventilation for the walkways was assumed to enter at the ground floor and travel upward along the glass roof in an opening provided by the space required for the roof support structure. It was assumed that ventilation would be controlled through dampers so that flow can be reduced to avoid over-cooling. The maximum flow simulated was calculated based on stack effect (natural convection) only. See Figures 3 & 4 for typical schematics.

Results:

We considered various options for the design of office/walkway areas, assuming that the structure supporting the roof provides an open area for ventilation to pass from the bottom inlet to outlet vents at the top of the structure. One design option which was considered was the use of a medium colored carpet on the walkway floor and no solar control. Results for summer design condition for this option are shown in Figure 5 for the fourth floor walkways. The solid lines are the estimated floor temperatures, the short dashed lines are the estimated mean radiant temperatures (the area-emissivity weighted average surface temperature for the walkways) and the long dashed line is the room air temperature.

The plotted results show that the air temperature in the walkways can be kept reasonably comfortable without solar control and without special attention to the floor covering (the floor receives most of the direct sunshine). However, the mean radiant temperature and the expected floor temperatures are clearly unacceptable.

It should be noted that in actuality, floor temperatures would not reach 97°C due to convective and conductive heat transfer to adjoining spaces. For comparsion purposes, a model was used which did not fully account for heat transfer to all spaces. The relative change in temperatures between cases is important, not the absolute value. However, we expect temperatures could be as high as 60°C.

Figure 6 show results for the summer design extreme for the fourth floor walkway with a floor covering with 0.3 absorptivity (the floor covering in the previous case had an absorptivity of 0.75). These results clearly show the beneficial effect of using a non-absorbing floor covering (white glazed tile, for example). Even with no shading floor temperatures remain below 50°C, the mean radiant temperature is below 40°C and the air temperature is only a few degrees warmer than the outdoors. This is in sharp contrast to peak floor temperatures of nearly 100°C and mean radiant approaching 55°C (see expanation of modeling constraints).

To further reduce floor and mean radiant temperatures, light colored flooring was retained and highly reflective shades were added, covering tow thirds of the glass roof of the walkway.

Results for the top walkway are shown in Figure 7 for the sunny summer day. Note that the estimated peak air temperature is a comfortable 26°C and the surface temperatures reamin at resaonable levels.

Finally, we consider the second design alternative where the offices are moved within 1 - 2 feet of the glass envelope. Figure 8 shows the result for the case with a light colored floor and with ventilation corresponding to the reduced area and effectiveness of the ventilation openings.

This space will be about 35°C and increase the cooling load on the offices.

B. MALL ANALYSIS

Asuumptions:

An interior mall with pyramid shaped glass roof elements (with and without shading) was a key space modeled in analyzing the St. Enoch Square Complex. This space was assumed to be 45 meters long (150 feet), 15 meters wide (50 feet) and 27 meters high (90 feet). Two interior office areas, each of the same dimensions as the Mall but containing 5 stories of floor space were assumed to adjoin the Mall. Air is transfer from the adjacent offices to offset winter losses (.5 liter per second per square meter of office floor area).

Forced ventilation was assumed for the mall because it appeared that natural ventilation would be difficult to achieve given the mall's deep interior location. Two rates were studied: 0.015 cubic meters per second per square meter of mall floor area (3 cfm per square foot) and 0.030 cubic meters per second per square meter (6 cfm per square foot). The first rate corresponds to about 3.3 air changes per hour and the second to 6.6 air changes per hour.

Results:

Figures 9 & 10 show the inside and outside air temperature for a typical and design (summer and winter) day. No auxiliary heating or air conditioning is needed during normal operating periods. However, extended unoccupied periods would require heating to maintain temperatures above freezing.

For typical winter days during occupied hours the mall can be maintained at 60 - 63°F. in the summer the mall can be maintained below 80°F.

C. LIGHTING AND DAYLIGHTING ANALYSIS

A study was conducted by the Princeton Energy Group of office lighting for the purpose of evaluating the annual energy consumption and operating cost of various daylighting and artifical lighting schemes for the proposed offices in the building complex.

Five office lighting schemes were developed for comparing the amount of the auxiliary lighting required and overall-impact on energy consumption and operating cost. See Figure 11. The following is a description of each office scheme: Scheme A has full-height glass and is shaded by a light-colored Venetian blind. Schemes B and C open the perimeter-office facades with overhead sloped glazing. In B the glass is protected from the sun on clear days by manually-operated pivoting louvers. Scheme C uses a light-colored window shade with a transmittance of 50 per cent which excludes solar heat, but lets daylight through. The shade is raised on overcast days. Scheme D has an overhead skylight to bring light into the interior. A white translucent shade for solar control is suspended from the trusses. Scheme D is the same as D, and E is the same as A, except for replacing overhead fixtures with task lighting.

Results:

The annual lighting costs for each scheme is shown in Figure 12. It is evident that Scheme E has nearly identical lighting cost as Scheme D. Therefore, the architectural strategy of skylighting is nearly equivalent to the equipment oriented strategy of task lighting. If one considers incorporating both strategies the results is the annual lighting cost for Scheme D'.

D. ANNUAL ENERGY CONSUMPTION ANALYSIS

To fully evaluate the cost and performance of selected design stategies proposed for St. Enoch Square Development Complex, a comparsion is made between the glass envelope building and a conventional "Base Case" building. Total building energy and lighting, and annual operating costs were determined by simulating six building configurations over an entire year. This dyanamic analysis uses an hour by hour weather tape input to the BLAST computer program. Selection of appropriate mechanical systems (i.e., fans, pumps, chillers, controls, etc.) along with climate data and design criteria provides the basic performance calculations of the complete building system.

Results:

The results of the annual energy requirements is shown in Figure 13 and indicates that the glass envelope (Scheme D consumes 33% less energy than the Base Case (5.8 x $10^6$ kWh. Almost 50% reduction in heating energy is realized with smaller reductions for cooling energy due to the use of out-

side air in all schemes. Heating energy required by the offices of leisure areas account for almost 40% of the total. Actual chiller energy for all schemes is small, compared to overall electrical consumption. Fan energy is slightly higher in Schemes A-E than in the Base Case, due to the higher ventilation rates in the mall and leisure areas. Lighting energy for the base case offices is almost double when comparing the Base Case to Schemes D and E. Lighting energy for the malls is less than the Base Case in Schemes A-E, due to the daylighting from the glass roof. Also, it is obvious that lighting and electrical consumption is the largest component of energy. This is due to store and shop lighting equipment and pumps and office equipment.

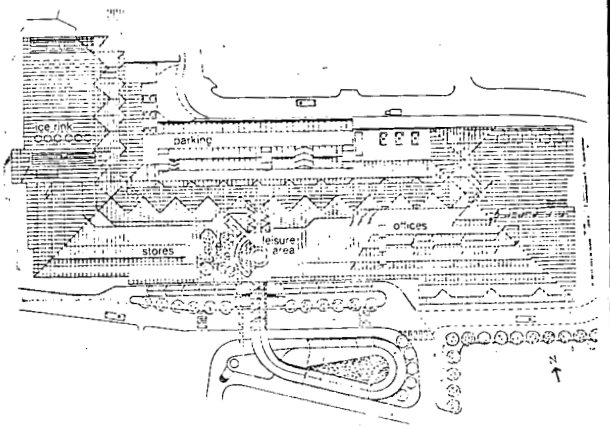



Fig. 1.

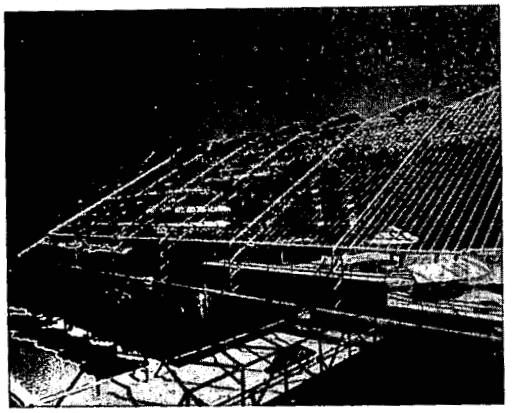


Fig. 2.

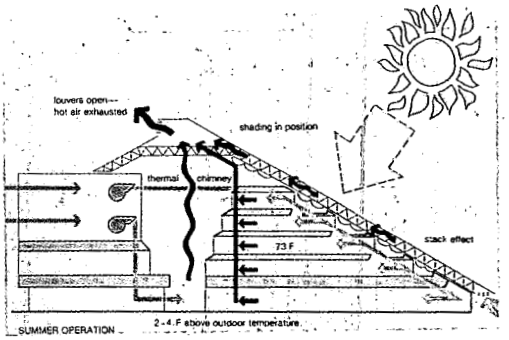



Fig. 3.

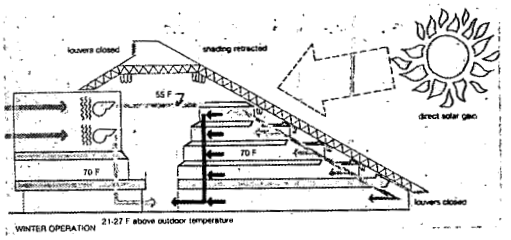
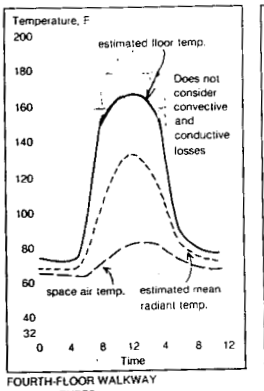
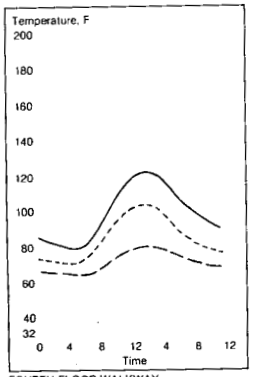



Fig. 4.



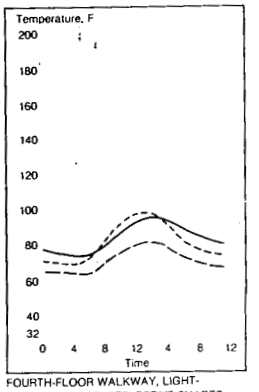

FOURTH-FLOOR WALKWAY TEMPERATURES

Fig. 5.



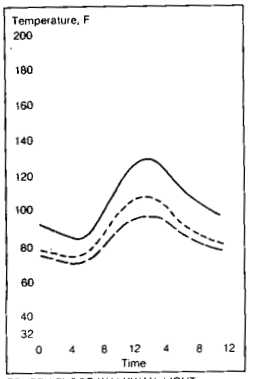

FOURTH-FLOOR WALKWAY, LIGHT-COLORED FLOOR

Fig. 6.




FOURTH-FLOOR WALKWAY, LIGHT-COLORED FLOOR, REFLECTIVE SHADES

Fig. 7.




FOURTH-FLOOR WALKWAY, LIGHT-COLORED FLOOR, LOW VENTILATION

Fig. 8.

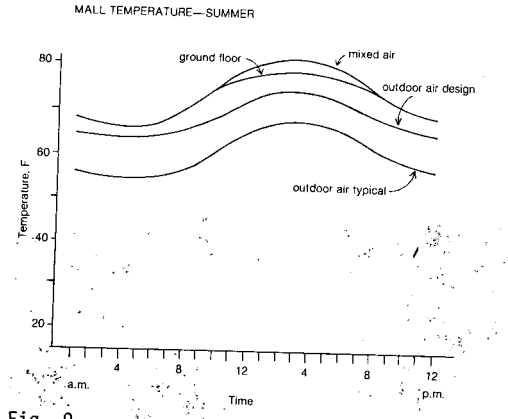



Fig. 9.

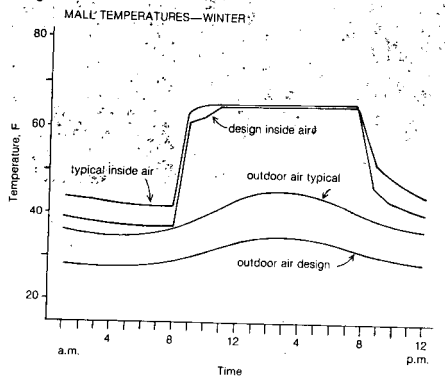
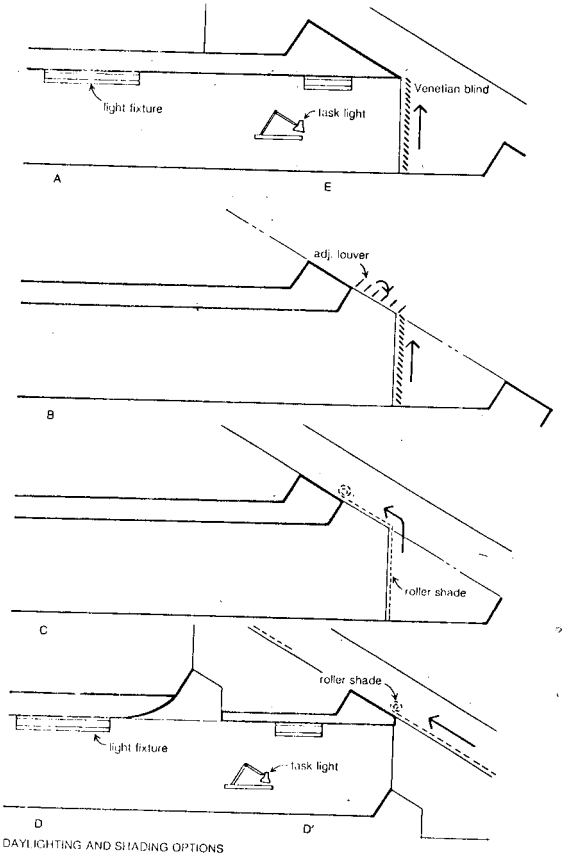
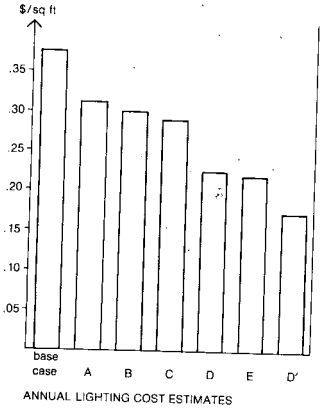



Fig. 10.



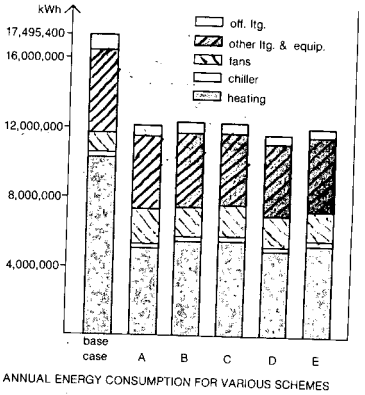

DAYLIGHTING AND SHADING OPTIONS

Fig. 11.




ANNUAL LIGHTING COST ESTIMATES

Fig. 12.




ANNUAL ENERGY CONSUMPTION FOR VARIOUS SCHEMES

Fig. 13.

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0731-8626/83$3.00

# TRANSFORMATIONS:
# THE DESIGN PROCESS IN RESIDENTIAL RETROFIT
# ACTIVE HAND / PASSIVE DESIGN

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## ABSTRACT

The author's experience as owner, designer, and builder in the architectural and energy renovation of an early 1800s farmstead in Central New Jersey. Innovative passive design concepts were carefully integrated with the traditional features of an old fieldstone farmhouse to achieve an 85% reduction in the non-renewable energy use. The study documents the processes and quantitative effects of the energy conserving strategies employed, from insulation and caulking to the addition of a two-story "sunspace" which utilizes the stone mass of the structure as an integral heat storage medium. Emphasis is placed upon the integration of the "new" with the "old" and the importance of user/client involvement in the design choices made. In addition to design and details, cost and performance data are presented where appropriate.

## 1. INTRODUCTION

In the summer of 1979, the author purchased a 30 acre farm in rural New Jersey. Located atop a ridge outside Hopewell, the primary feature of the property was a 150 year-old stone farmhouse which had, over the years, acquired woodframe additions on the east, north, and west sides and a single storey screened porch on the south. With its longest side oriented 10° east of solar south, the farmhouse seemed a prime candidate for renovation/restoration. It also was an opportunity for the author to demonstrate that five years of architectural design theory and professional practice in passive solar design had not thoroughly alienated him from the concerns and skills of construction craftsmanship. In a very real and immediate sense, it was an opportunity to create and personally inhabit the kind of project allowing one to measure theory against reality, pursue an ideal goal while maintaining a finite budget, and evole a synthesis of traditional form and new technology. This was not the first renovation project the author has undertaken. However, it was the first such project to combine his skills and experience as a builder with the knowledge of solar design he had developed at Princeton University School of Architecture and subsequently as a designer, energy analyst and project manager with the Princeton Energy Group.

This project has occupied the author's "spare" time over the past four years and has been a continuing source of personal satisfaction and professional growth. The purpose of this paper is to provide an account of the major elements of the design, the process by which they were developed and chosen, and their net effects in reducing the consumption of non-renewable energy sources. The data presented here provide an opportunity to evaluate the quantitative and economic effects of each successive step in the renovation process as a clear demonstration of the resources which lie untapped in residential energy renovation. In addition, it is hoped that the graphic material presented here will demonstrate the very positive synthesis which can be achieved when traditional forms are blended with new technologies and applications.

## 2. DESIGN PROCESS

The design process for this project developed from both theory and experience. A designer-owner-builder occupies an enviable position, for the quality of his concepts may be realized and enjoyed as a product of his own skill and commitment. To the extent that a particular technique is intriguing or one's skills limited, the design may be directed to fulfill curiosity or needs. By the same token, if something goes wrong at any point in the process, he has no one to blame but himself. For this reason, it is important to work within a design framework which is highly self-critical and where each choice is evaluated from as many perspectives as possible. Criteria of cost and durability must have equal weight with thermal performance and aesthetic delight. For the designer

whose instinct is to charge ahead with insulation and insolation, contemplation and evaluation are states of being which are often difficult to achieve. Luckily, financial circumstance often outweighs precocious exuberance, and one is afforded the luxury of spending long winter evenings contemplating the host of potential opportunities which exist for the enterprising energy saver. In retrospect, it is this part of the process which is often most productive, for the mistakes which are made in dreaming, when recognized, require no physical effort to correct. As the saying goes, "Measure twice, cut once."

The logic and deliberation which is so apparent in hindsight is often difficult to perceive in the midst of the process. It is for this reason that an outline of the important milestones in the renovation process is an essential element in the development of a design strategy. In the present case, the first step was clearly to improve the thermal integrity of the building envelope, and then to develop alternative heating sources. Economic considerations and time commitments limited the options the second year. Only after three years of occupancy was a sunspace a possible project. Specific elements of the design choices are discussed in the sections following.

## 2.1 Insulation and Thermal Upgrading

The first step in the retrofit design process must be to assess the existing thermal integrity of the building and develop an affordable plan for reducing the heating load to a level where a solar addition or comparable alternative system can make a significant contribution to comfort and energy cost. In the farmhouse at Sunstone, the intermittent aggregation of additions made at various times in the past one hundred years had resulted in a thermal envelope whose U-value was difficult to analyze theoretically. Insulating materials ranged from rock wool in the attic applied with differing degrees of attention, fiberglass batts in the newer sections, to collections of nuts left in the otherwise empty study spaces that had been home to vaious rodents and other uninvited guests over the intervening years. Two sides of the original stone farmhouse had been incorporated into the interior of the aggregate so that only the south and west walls were exposed to the exterior.

An effective insulation strategy had to be devised which whould preserve the exterior appearance of the stone and frame elements which gave the house its character while providing an economical and practical application techniques. Various foamed-in-place products were considered and rejected as being either too expensive, complicated, unreliable in application integrity, or potentially toxic. The manhour cost of removing the interior finish surfaces of plaster and wood panelling and replacing them in order to install fiberglass batts and a vapor barrier in the existing stud cavities was prohibitive and intrusive upon the interior living space which was to remain occupied during all phases of the project. Time constraints as well as material cost eliminated the use of an exterior insulating skin of rigid board insulation and new siding. The final choice was a recycled cellulose insulation which was treated for fire retardance and rodent resistance.

Wall cavities were completely filled at 3 psi, and 12" of loose material was blown into the attic. Factors which clearly influenced the choice of cellulose were cost per unit of effective U-value, ease of installation (application to wall cavities was through 1" holes drilled in the exterior wall and then plugged with cork seals), the perceived effectiveness of the system in limiting the potential for air infiltration, and the applicability of the material to the wide range of existing conditions in the building. Even cavities which had been previously insulated with other materials were re-insulated with cellulose without the necessity of removing the earlier insulation. A drawback of the system which had the potential to cause significant problems, water vapor migration, was handled through the application of vapor resistant paint finishes on the interior walls and ceilings. Semi-gloss, eggshell, and gloss enamels were applied with special attention being given to areas of high humidity generation such as the bathrooms and kitchen.

The insulation system was installed by the owner and several friends over the course of a single weekend using simple portable equipment and hand tools. The materials cost $990 in the fall of 1979. This step, combined with general measures to further reduce air infiltration, weatherstripping of doors, reglazing of cracked windows, caulking and the insulation of heating supply pipes, reduced the actual heating use to 50% of the previous year's level. These results are presented in Table 1. The insulation strategy reduced the normalized energy use from 11.81 Btu/ft$^2$/degree day (Btu/ft$^2$/DD) to 6.24 Btu/ft$^2$/DD.

## 2.2 Sunspace Addition

From the outset of the renovation project, the possibility of adding a heat-producing sunspace to the house was appealing. The south elevation of the house presented several design related problems and opportunities. Among the problems were a lack of natural light on the interior sections of the first floor. The undistinguished single story



Fig. 1. Sunstone 1983 Showing Aggregate Nature of Farmhouse.

screen porch which was creating this condition was in relatively poor shape and detracted from what might otherwise have been a very attractive facade. Design configuration, dimensions, and thermal and structural details which addressed these problems were evolved over the two year period of occupancy before the actual beginning of construction.

A clear advantage of the sunspace strategy was that it would resolve the problem of how to insulate the southfacing stone wall of the original structure. By including the entire stone face in a two-story sunspace, not only was this problem overcome, but additionally, being directly irradiated by the sun, the stone wall provided the required thermal storage of the solar strategy at virtually no added cost. Another advantage was that the stone would be preserved in its original condition. The attached sunspace concept also allowed a thermally driven flow of heated air from the sunspace to the second floor bedroom, and a return flow down the internal stairhall.

The spatial effect of the sunspace has been to unify the disparate elements of the house and to create an intimacy between spaces which might otherwise be isolated from the life in the house. Although the house is small (1880 $ft^2$ including addition) the degree to which the sunspace is visually open to the surrounding land has increased the perceived space and light in the building.

Because of the age of the building and considerable uncertainty about the integrity of the existing conditions, a decision was made to have the sunspace be structurally freestanding, rather than a lean-to configuration. This was a definite advantage when we commenced the construction phase, for it was only after the demolition of the existing single storey screened porch that it was possible to establish the fact that the stone wall was six inches out of square, had a large bulge in the middle, and provided no convenient place for the attachment of a ledger beam which would have been required for the lean-to structure. By using rough-sawn, oversized timbers for the construction of the rear supporting frame and rafters, the design achieved a genuine rustication which helped make the transition between the old and the new in both a figurative as well as structural sense.

The details of the structure, materials used, and construction methods employed in the sunspace were developed in collaboration with the co-author, Charles Katzenbach, and other members of the Princeton Energy Group (PEG) as a direct product of the design build work of that firm. A major objective of PEG's activity in this field has been to develop high-quality, low-cost building system designs which can be adapted easily to site specific building conditions. In large measure, this objective has been achieved by utilizing commonly available construction grade materials and then detailing their application with great attention to the quality of fabrication in the field. This places the responsibility for final quality in the hands of the construction carpenters which is where it ultimately belongs. It has been the authors' repeated experience that many of the performance shortcomings of passive systems can be directly attributed to poor quality execution of otherwise sound designs.

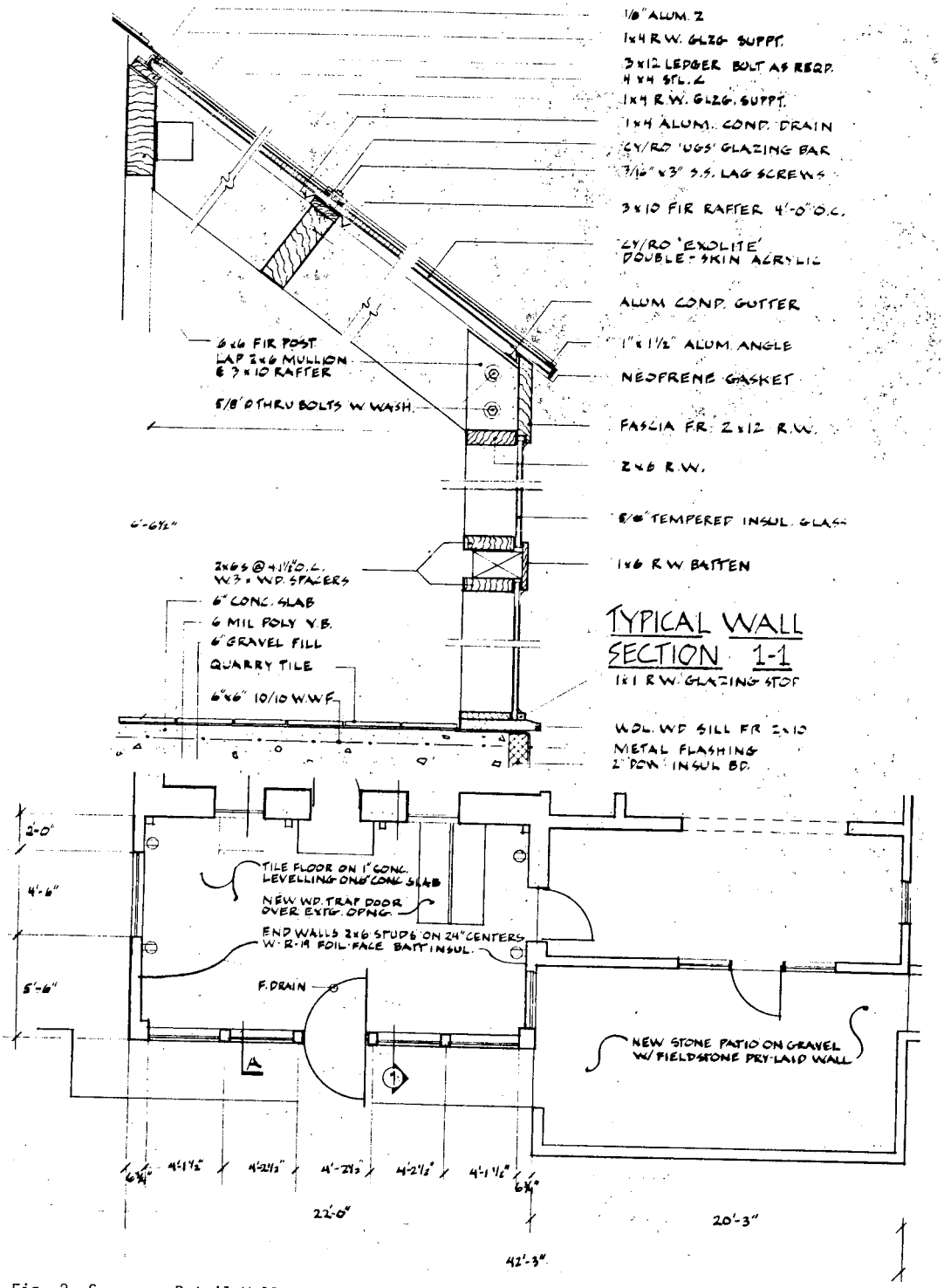



Fig. 2. Sunspace Detail Wall Section and Floor Plan.

TABLE 1. SUNSTONE SUNSPACE ANALYSIS

| | 78-79 | 79-80 | 80-81 | 81-82 | 82-83 |
|---|---|---|---|---|---|
| Heating Degree Days | 4992 | 4747 | 5085 | 5064 | 4730 |
| Total Gallons of Oil | 1300 | 803 | 778 | 557 | 453 |
| Domestic Hot Water Load | -300 | -300 | -300 | -300 | -300 |
| Net Heating Load (Gallons) | 1000 | 503 | 478 | 257 | 153 |
| Net Heating Load (MM Btu) | 97.3 | 48.94 | 46.5 | 25.0 | 14.8 |
| Total Cost | $1200. | $ 739. | $ 907. | $ 675. | $ 524. |
| Heating Cost | $ 923. | $ 463. | $ 557. | $ 311. | $ 177. |
| Total Square Feet | 1650 | 1650 | 1650 | 1880 | 1880 |
| Btu/ $ft^2$ / Degree Day Auxiliary | 11.81 | 6.24 | 5.54 | 2.62 | 1.16 |
| Cost of Improvement | --- | $ 990. | $1400. | $ 4,000. $12,500 | --- |
| Milestones | Previous Owner | Insulate | 2nd Wood-Stove | Sunspace | -Kitchen + Fireplace |
| $/MM Btu | $ 9.48 | $ 9.46 | $11.97 | $12.40 | $11.95 |
| MM Btu Saved Total | --- | 48.36 | 50.80 | 72.30 | 82.50 |
| $ Saved Over Base | --- | $457.48 | $608.07 | $896.52 | $985.87 |
| $ Saved Cumlative | --- | $457.48 | $1065.55 | $1962.07 | $2947.94 |

Notes to Table 1

-Heating degree days are to a 65° base and are from actual Trenton, NJ readings except for 1981-83 data which are extrapolated from a different, correlated degree day base developed for Nassau Oil Co. by Johnson Control.

-DHW load represents 100 gal of oil measured use for a period from June- August discounted 25% for periods of joint demand in winter months

-Net Heating Btu values are for #2 heating oil burned at 70% efficiency or 97,300Btu heat delivered /gallon of oil

-Oil cost is directly from applicable rate at period represented

-Although data is comparing the energy use patterns of two different owners/occupants the author is satisfied that the energy use patterns of each party were significantly similar, maintaining a maximum temperature in the house of 65° or slightly lower and supplementing the oil-fired boiler system with an occasional fire in a wood stove.

## 3. COST AND PERFORMANCE

Table 1 summarizes the performance, costs and savings achieved with each successive renovation step. Somewhat unintentionally, each major change was undertaken in a separate year so that the cumulative results represent separate and distinct effects of each strategy.

Quite clearly, insulation and general upgrading of the thermal envelope of the building in 1979-80 was the single most effective strategy both quantitatively as well as economically. Oil consumption and cost were reduced by 50% at an expenditure which was repaid in realized savings before the second year of operation. The addition of a more efficient woodstove and a new chimney in the living room was the major energy renovation change in 1980-81. The savings attributable to this step were only 5.8MMBtu, equivalent to $70 in reduced energy cost, but the stove, a Vermont Castings "Defiant," significantly improved the perceived level of user comfort in that section of the house. The cost of wood has not been factored into heating calculations since it is provided from the farm

by the author's labor. Firewood consumption has remained at a constant level of 1-1 1/2 cords per season for each year of the project.

The sunspace addition in 1981 increased the actual square footage of the house by 13% while reducing the use of non-renewable energy for heating from 6.24Btu/ft$^2$/DD to an average of 2.14Btu/ft$^2$/DD, a 65% passive solar contribution.

Finally, in 1982, several changes were made to the layout of the downstairs spaces. These included moving the kitchen to the north wall of the downstairs space, creation of an airlock entryway, and rebuilding of an existing chimney and hearth to provide for a more efficient fireplace. The costs of these measures have not been included in the calculations since they would have been carried out in any case, and their energy savings effects are simply a by-product. They are mentioned however because their effects are significant, reducing the energy load by 8.5 MMBtu, a saving of just over $100.

In a structure whose energy retrofit cost has been calculated at $6400, the energy saving to date equal $2947.94. At the current rate of savings, the remaining $3400 should be recouped in 4 years or less. It is important to note that these savings in energy cost could be justified solely on the basis of considering them to be a form of "untaxable" income. However, no amount of calculated or real savings could warm up a cold house. The author is pleased to report in this regard that the perceived comfort of the house has improved noticeably over the years as each successive improvement has been made.

## 4. CONCLUSION

By conscientiously applying basic energy design strategies and passive solar principles and techniques in the renovation of an existing house, significant and immediate energy savings can be realized. An integral part of the strategy in such cases is the utilization of existing features and properties of the buildings to their best thermal advantage. In this case the physical mass of the original stone house has provided a substantial thermal storage capacity at no additional cost while the added sunspace allows the features of the stone to be exposed and enjoyed visually as well as thermally. From an architectural viewpoint, this strategy has also brought into being a transparent zone on the "exterior" southern exposure of the house which is simultaneously an occupied "hearth", a focus of interior activities, and a feature which also involves one's attention to the landscape and climate outside the sunspace.

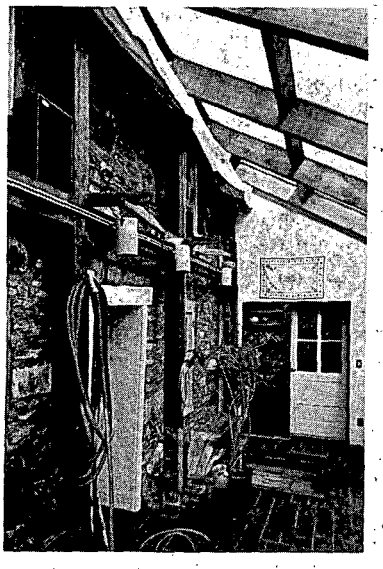


Fig. 3. Freestanding structure of sunspace, exposed stone face of house.

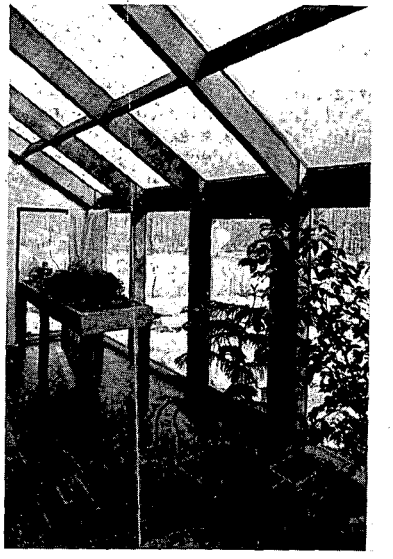


Fig. 4. View to South-East & Kneewall Framing.

# METRIC-ENGLISH-METRIC CONVERSION VALUES

## CONVERSION FACTORS

| TO CONVERT | INTO | MULTIPLY BY |
|---|---|---|
| British thermal unit (Btu) | cal | 252 |
| Btu | joules (j) | 1.055 |
| Btu | kilowatt-hours (kWh) | $2.93 \times 10^{-4}$ |
| Btu | megawatt-years (MW yr) | $3.34 \times 10^{-11}$ |
| Btu | langleys (cal/cm$^2$) | 0.271 |
| Btu/ft$^2$ | Btu | $3.97 \times 10^{-3}$ |
| calories (cal) | ft lb | 3.09 |
| cal | J | 4.18 |
| cal | watts (W) | 0.0698 |
| cal/minute (cal/min) | inches (in.) | 0.394 |
| centimeters (cm) | meters | 0.305 |
| feet (ft) | cal | 0.324 |
| foot-pounds (ft lb) | J | 1.36 |
| ft lb | kilogram-meters (kg m) | 0.138 |
| ft lb | kWh | $3.77 \times 10^{-7}$ |
| ft lb | liters | 3.79 |
| gallons (gal) | lb | 0.00220 |
| gal | W | $1 \times 10^{9}$ |
| gigawatts (GW) | acres | 2.47 |
| hectares | kW | 0.745 |
| horsepower (hp) | Btu | $9.48 \times 10^{-4}$ |
| J | cal | 0.239 |
| J | ft lb | 0.738 |
| J | W hr | $2.78 \times 10^{-4}$ |
| J | Btu | 3.97 |
| 1000 cal (Kcal) | kW | 0.0698 |
| Kcal/min | ft lb | 7.23 |
| kg m | lb | 2.20 |
| kg | tons | 0.00110 |
| kg | hp | 1.34 |
| kilowatts (kW) | Btu | 3.413 |
| kWh | ft lb | $2.66 \times 10^{6}$ |
| kWh | W hr | $1 \times 10^{3}$ |
| kWh | Kcal/min | 14.3 |
| kW | Btu/ft$^2$ | 3.69 |
| langleys | W/sc cm | 0.0698 |
| langleys/min | Btu | $3.41 \times 10^{6}$ |
| megawatt-hours | Btu | $2.99 \times 10^{10}$ |
| MW yr | meters | 1,609 |
| miles | ft$^2$ | 0.00108 |
| cm$^2$ | in.$^2$ | 0.155 |
| cm$^2$ | in.$^2$ | 144 |
| ft$^2$ | m$^2$ | 0.0929 |
| ft$^2$ | cm$^2$ | 6.45 |
| in.$^2$ | ft$^2$ | 10.8 |
| m$^2$ | mile$^2$ | $3.86 \times 10^{-7}$ |
| m$^2$ | acres | 640 |
| mile$^2$ | ft$^2$ | $2.79 \times 10^{7}$ |
| mile$^2$ | m$^2$ | $2.59 \times 10^{6}$ |
| mile$^2$ | kg | 907 |
| tons (short) | lb | 2000 |
| tons (short) | tons (short) | 1.1025 |
| tons (metric) | tons (metric) | 0.907 |
| tons (short) | J | 3600 |
| W hr | °C | subtract 32 and multiply by 0.555 |
| F | | |
| °C | F | multiply by 1.8 and add 32 |
| cal/cm$^2$-sec-°C | Btu/ft$^2$-hr-F | 7380 |
| Btu/ft$^2$-hr-F | cal/cm$^2$-sec-°C | $1.35 \times 10^{-4}$ |

# METRIC-ENGLISH-METRIC CONVERSION VALUES

## UNITS AND CONVERSION FACTORS

***Weight***

1 kilogram (kg) = 1000 grams (g) = 1,000,000 milligrams (mg) = 1,000,000,000 micrograms (ug)
1 kg = 2.205 pounds (lb); 1 g = 0.035 ounce (oz)
1 lb = 453.6 g = 0.4536 kg
1 metric ton = 2205 lb = 1000 kg
1 short ton = 2000 lb = 907.2 kg
1 megaton = 1,000,000 tons

***Length***

0.001 kilometer (km) = 1 meter (m) = 100 centimeters (cm) = 1,000 millimeters (mm) = 1,000,000 microns (u)
1 km = 0.6214 statute mile; 1 m = 39.37 inches (in.) = 3.281 feet (ft); 1 cm = 0.3937 in.
1 mile = 1.609 km; 1 ft = 0.3048 m; 1 in. = 2.54 cm

***Area***

1 hectare = 10,000 square meters ($m^2$)
1 hectare = 2.47 acres = 0.003861 square mile
1 square mile = 640 acres = 259 hectares

***Volume and Cubic Measure***

1 cubic meter ($m^3$) = 1,000,000 cubic centimeters ($cm^3$)
1 $m^3$ = 35.31 cubic feet ($ft^3$); 1 $cm^3$ = 0.061 cubic inch ($in.^3$)
1 liter (l) = 1000 $cm^3$
1 l = 61.02 $in.^3$ = 0.2642 gallon (gal)
1 $ft^3$ = 0.02832 $m^3$ = 28.321; 1 gal = 231 $in^3$ = 3.785 l

***Energy and Work***

1 British thermal unit (Btu) = 252 calories (cal) = 0.0002931 kilowatt-hour = 1055 joules (kWh)
1 joule = 1 watt-sec = $10^7$ erg = 0.73 ft lb
1 gm-cal = 4.184 joules
1 kWh (kilowatt-hour) = 3.6 X $10^6$ joules = 3412 Btu
1 watt-yr = 3.15 X $10^7$ joules = 3 X $10^4$ Btu
1 hp = 550 ft lb/sec = 746 watt

***Power***

1 megawatt (MW) = 1000 kilowatts (kW) = 1,000,000 watts (W) = 3,413,000 Btu/hour (Btu/hr) = 1341 horsepower (hp)

***Pressure***

1 atmosphere (atm) = 76 cm mercury = 14.70 $lb/in.^2$ = 1,013 millibars (mb)

| | Absolute Zero | Ice Point (water) | Steam Point (water) |
|---|---|---|---|
| Degrees Fahrenheit (F) | -459.7 | 32 | 212 |
| Degrees Celsius or Centigrade (°C) | -273.15 | 0 | 100 |
| Degrees Kelvin (°K) | 0 | 273.15 | 373.15 |
| Degrees Reaumur (°R) | | 0 | 80 |

## TERMINOLOGY AND ABBREVIATIONS

The following terms were frequently used in papers employing the metric system of units.

1 billion — 1000 million = $10^9$
1 trillion — 1000 billion = $10^{12}$

1 kcal — 1 kilocalorie = 3.968 Btu (British thermal units)
1 therm — $10^5$ Btu = 25,200 kcal
1 thermie — 1000 kcal

1 metric ton — 1000 kilograms = 0.985 ton = 1.1023 short ton
1 toe — 1 ton of oil equivalent = $10^7$ kcal
1 Mtoe — 1 million metric tons of oil equivalent = $10^{13}$ kcal
1 tce — 1 ton of coal equivalent = 0.7 toe
1 Mtce — 1 million tons of coal equivalent = 0.7 Mtoe

1 cubic foot — 0.0283 cubic meter
1 Mcf — 1 thousand cubic feet = 28.3 cubic meters
1 TCF — 1 trillion cubic feet = 28.3 X $10^9$ cubic meters
$1 per Mcf — is approximately equivalent to $40 per toe

The typing guidelines requested that the following terms be used in papers also using the English system of units:

MBtu — 1000 Btu
MMBtu — 1,000,000 Btu
F — degrees Fahrenheit
°C — degrees Celsius
kWh — kilowatt-hour

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