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Energy

SOLAR

DESIGN AND CONSTRUCTION OF A PASSIVE COOLING EXPERIMENTAL FACILITY FOR A HOT/ARID CLIMATE

Appendices I–XI

By
John F. Peck

August 1983

Work Performed Under Contract No. AC03-80SF10816

The University of Arizona
Environmental Research Laboratory
Tucson, Arizona

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APPENDICES I - XI

for

DESIGN AND CONSTRUCTION of a PASSIVE COOLING EXPERIMENTAL FACILITY for a HOT/ARID CLIMATE

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APPENDIX I

ClearView Solar Collector^R Description

1. "The Hybrid ClearView Solar Collector^R and Complementary Evaporative Cooling" by John F. Peck, T. Lewis Thompson, Helen J. Kessler and Carl N. Hodges
2. "Recent Design and Performance Data for the Hybrid ClearView Solar Collector^R System" by John F. Peck, T. Lewis Thompson, Helen J. Kessler and Carl N. Hodges
3. "Hot Air Solar Collectors" by Helen J. Kessler

THE HYBRID CLEARVIEW SOLAR COLLECTOR® AND COMPLEMENTARY EVAPORATIVE COOLING-PERFORMANCE PREDICTION METHODOLOGY AND RESULTS

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ABSTRACT

The hybrid form of the ClearView Solar Collector® -- a transparent, site-built, wall-mounted hot air solar collector -- has been retrofitted to a home in Tucson, Arizona. This collector uses dark colored venetian blinds located between the south wall and the exterior glazing to absorb solar radiation. A small fan distributes the hot air produced by the collector through the house where the heat is stored in solid masonry walls. Results of a computer analysis are presented. A method for predicting the performance of hybrid and passive solar homes in desert regions of the Southwest is discussed and is verified with data collected from this retrofit home. The use of the thermal mass of such a home to improve the comfort attained with evaporative cooling is also discussed. An economic analysis presented here shows that simple hybrid heating systems are cost effective today in comparison to electric heating for residential uses in desert regions.

1. INTRODUCTION

The ClearView Solar Collector® system is a family of solar heating systems that range from totally passive to unabashedly active.[1] All forms include complementary evaporative cooling systems which are appropriate for use in many of the desert climates of the Southwest. The active form uses a large rockbed to store heat in the wintertime, as do most conventional active hot air systems In the summer, the rockbed has been successfully used in several prototype installations and homes to store coolth and provide a second stage to enhance the performance of evaporative coolers.[2] In contrast, the hybrid and passive forms store both heat and coolth in the massive construction of the solid masonry walls which preferably are insulated on the outside. These simpler passive and hybrid forms of the ClearView Solar Collector® system use optimized evaporative cooling.

Two types of ClearView Solar Collector® are being developed, one with venetian blinds which are dark on the slat top and white on the slat bottom, and the other with heat absorbing glass*[3] as the "absorber plate." The hybrid venetian blind form will be the primary subject of this paper.

Figure 1 is a view through a portion of a venetian blind ClearView Collector, adjusted for the winter. Normally, during the winter, monthly adjustment of the slat angle is required. The dark blinds absorb approximately 80% of the sunlight in the almost horizontal position shown, and transmit approximately 20% of the insolation as diffuse light to the room. If the blinds are closed, they absorb almost all the light. While the collector could be made entriely of transparent panels, we prefer to use opaque panels in areas where windows are not required.

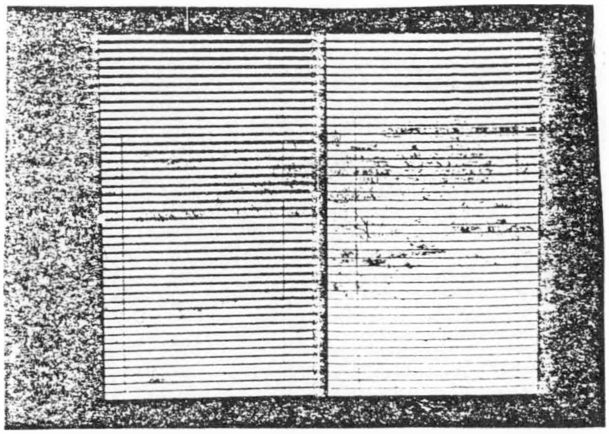

Fig. 1. View through venetian blind type ClearView Solar Collector, winter orientation. The right-hand blind is white on the lower, convex surface; the left-hand blind is dark on both sides.

During the summer, the blinds are also oriented with the dark side up, effectively shading the inner wall of the collector and obviating the need for an overhang. In the late summer and fall, when the sun is lower in the sky, the blinds may be turned white side out to reflect incoming insolation. Waste evaporatively cooled air is exhausted through the collector, thereby removing the modest amount of heat absorbed during the warmer months.

2. SYSTEM DESCRIPTIONS

The simplest passive form of the ClearView Solar

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*U.S. Patent #4,050,443, for fan-driven models.

Collector® is the ClearView window solar absorber which preferably uses bi-colored venetian blinds that are dark on the slat top and white or reflective on the slat bottom. They are located in south facing windows and collect solar heat in a variation of the direct gain method. (See Figure 2.) By using venetian blinds, furniture fading is reduced considerably, and the hot air produced by the collector can be distributed throughout the house to equalize temperatures.

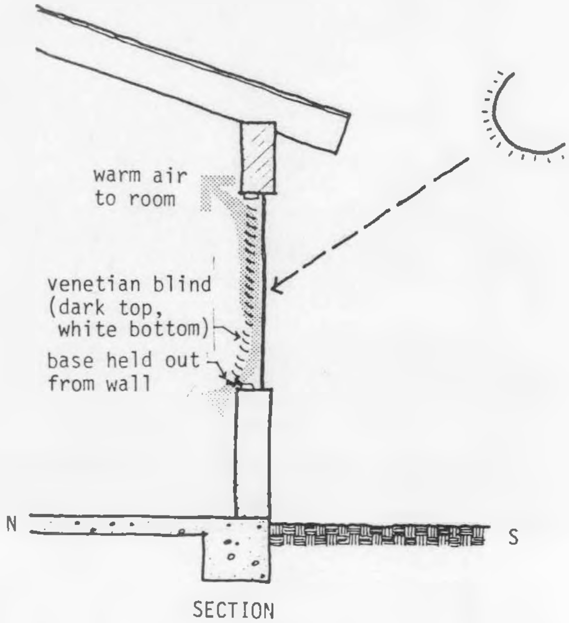

Fig. 2. ClearView window solar absorber with venetian blinds located in south-facing windows.

Heat is transferred to all the massive interior walls by convection. We have found, through computer analyses and experience, that in mild climates such as those of the desert southwest, convection gains are sufficient to heat the walls and that the more efficient direct gain systems are not necessary.* Unfortunately, the use of natural convection to distribute this heat in conventional tract home designs is severely impeded by ducts in furred down ceiling areas ("hot air dams"). This problem is solved by the use of a small fan, as illustrated in Figure 3.

However, once one starts using fans, along with venetian blinds and easily operated nocturnal window insulation devices, one might consider moving on to the hybrid ClearView system which is the main topic of this paper, and which we feel is the most generally applicable form of the ClearView Solar Collector®.

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*Also, summer comfort is enhanced by convectively cooling the masonry walls at night, when evaporative coolers produce their coolest air. Thus, the extra mass required to store heat by the convective heat transfer mode is predicated by summer cooling requirements as well as the winter heating requirements of conventional tract homes.

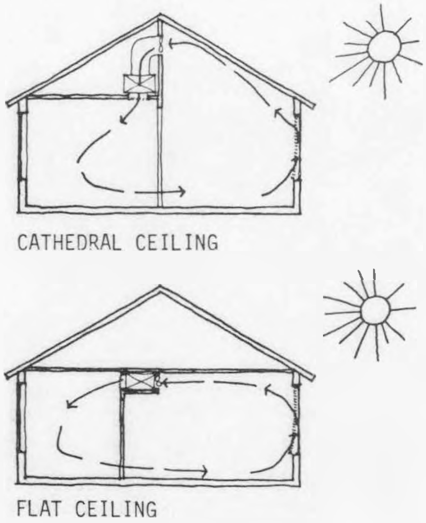

Fig. 3. Fan distribution systems for ClearView window solar absorber. Conventional tract type home with rooms located on north and south sides of house.

The hybrid ClearView Solar Collector® shown in Figure 4 uses dark venetian blinds (heat-absorbing glass could be substituted in transparent areas), which are placed over the masonry south wall. Windows may be located wherever desired.

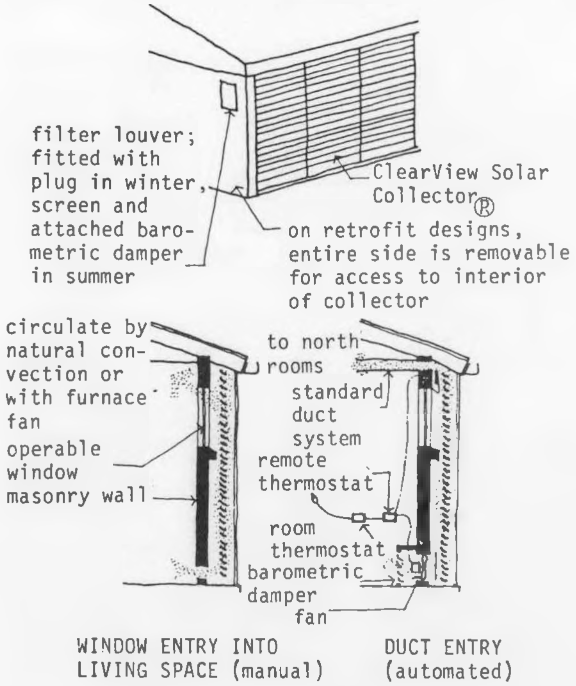

Fig. 4. Hybrid ClearView Solar Collector® schematic drawings showing sections through manual form on left, automated form on right.

In new construction, we use double sliding, double glazed patio doors which provide convenient access to the collector. The exterior surface of the collector is made of standard double 1.22m x 2.44m (4' x 8') patio door glass.* Both a passive and an automated version are shown in Figure 4, and both were constructed on a home in Tucson as a retrofit.

Although the passive form works very well, the hybrid form is greatly preferred by the household manager. It is completely automated with two thermostats, one standard and one remote, wired in series with a 100-watt fan. The fan, which is located diametrically opposite the warm air duct, turns on when the house needs heat and the collector is warm, thereby distributing hot air evenly throughout the home. Overheating of the house is avoided because the fan will only turn on when the house needs heat, and otherwise, excess heat is absorbed by the masonry interior wall of the collector and eventually returns to the home interior in the evening. On average nights when the outside ambient temperature falls to about 4.5°C (40°F), the home slowly cools, reaching 18-20°C (65-68°F) by early morning. Heat lamps with timers can heat localized areas of the home in the early morning, pending the arrival of the sun. Figure 5 is a view of the Tucson retrofit home showing the two collectors. In spite of the fact that it was a retrofit, and therefore not an ideal solar house, it performed as designed, as will be shown.

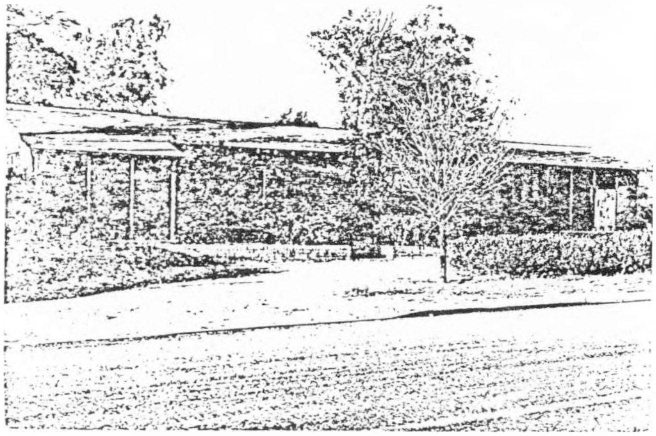

Fig. 5. Tucson home retrofitted with two hybrid ClearView Solar Collectors®.

3. PERFORMANCE PREDICTIONS, DESIGN METHODOLOGY

We have devised some simple calculation techniques which predict the performance of hybrid solar heating systems for desert regions.

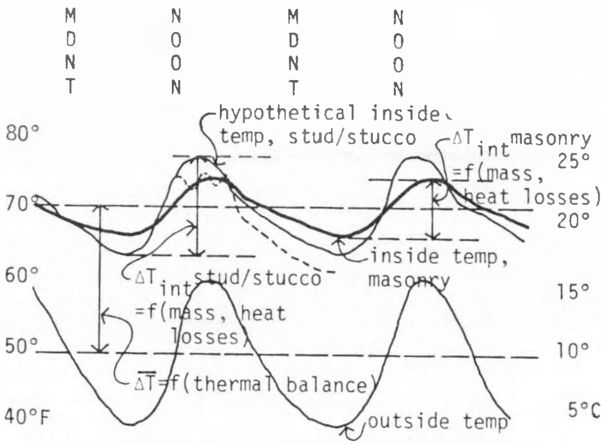

Fig. 6. As shown here, the $\overline{\Delta T}$ of a house (the difference between the 24-hour average inside temperature and the 24-hour average outside temperature) is a function of the thermal balance of the home. Thus, in long-term equilibrium, heat inputs must equal heat outputs. The greater the heat input to the interior of a given home (solar + people + appliances + auxiliary), the higher the $\overline{\Delta T}$ will be if the home is of massive construction. Also shown is the ΔT_{int} which is a function of the heat losses and the effective mass of the home. The greater the quantity of effective mass in the home and the lower the heat losses, the smaller ΔT_{int} will be.

To begin, it is important to discuss two ideas which are illustrated in Figure 6. First, in all homes, over a period of time greater than 24 hours, the hourly interior and ambient temperature fluctuations cease to be important in thermal loss calculations. The $\overline{\Delta T}$ value is used, which is defined as the difference between the 24-hour average interior temperature and the corresponding exterior average temperature. So, in a passive solar home where heat from pulsed sources is stored within the structure of the home, the $\overline{\Delta T}$ is a function of the thermal balance of the home. That is, the heat losses at the average interior design temperature will be balanced by the intrinsic passive heat input, the solar collector heat input, the people and appliance heat inputs, as well as any auxiliary heat used. If any of the heat inputs are increased, the average internal temperature will rise until the consequent greater heat losses balance the larger heat inputs.

The other point is that in a solar house of heavy masonry construction, only the phase and amplitude of the internal temperature swing will be affected by the thermal mass, but the $\overline{\Delta T}$ will not be. We have measured a very acceptable 10° internal temperature swing in the Tucson retrofit home, as shown by the heavy black trace in Figure 6. We call this the interior temperature variation, ΔT_{int}, which is generally a function of the effective mass and heat losses of the home. If the home has outside insulation on masonry walls, as well as interior masonry walls, the ΔT_{int} is still less than that shown in Figure 6. If the home were made of lighter materials, such as frame construction, the internal temperature swing would be

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*Actual size - 46" x 92"

greater and the house would have a tendency to overheat. With our automated hybrid system, the collector fan would be turned off more often than in the masonry home and the eventual result, assuming auxiliary heat is not used, would be lower temperatures in the home, as shown by the dashed line in Figure 6.

Using the heat loss calculation method of Prof. John A. Reagan of the Electrical Engineering Department of the University of Arizona, we have devised a simple technique for predicting the performance of a hybrid solar home on sunny days in the desert regions of the Southwest.[4] Prof. Reagan has derived wintertime Total Equivalent Temperature Difference (TETD) values for Tucson and has verified them as ASHRAE has done for the summertime.[5] When these TETD values are used along with window thermal gains, which he has also verified for Tucson conditions, the solar heat gain is automatically included in the heat loss calculations. If the heat loss is calculated for several different average indoor temperatures, a characteristic "load line" describing the thermal behavior of the house may be constructed as shown in Figure 7. This load line will cross the zero heat loss/gain line at a $\overline{\Delta T}$ that will indicate the interior temperature relative to the average ambient temperature about which the house will cycle without solar collectors or auxiliary heat. We call this the "intrinsic passive and internal heat $\overline{\Delta T}$." The intrinsic passive component of this heat gain is due mainly to windows in the home which ideally -- both from the house design and a calculation viewpoint -- are distributed throughout the house so that no one area receives a massive heat gain.* With this load line, then, one can determine the additional amount of heat input required to shift it downward and achieve a $\overline{\Delta T}$ which is adequate to maintain the house interior at the desired average temperature. If the average heat output of each ClearView Solar Collector® panel is known (21,000 kJ/day (20,000 BTU/day) in Tucson), the minimum number of automatically controlled solar panels needed may be easily calculated. Ideally, the intrinsic passive and internal heat $\overline{\Delta T}$ should be that required to heat the home on the very warmest January days as shown in Figure 8.

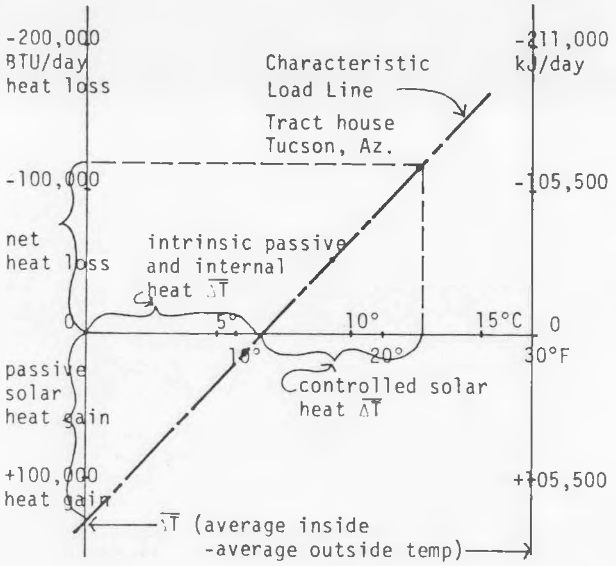

Fig. 7. The characteristic "load line" of a Tucson home based on heat loss calculations. The intrinsic passive and internal heat $\overline{\Delta T}$ is indicated where the load line crosses the zero heat loss/gain line. This signifies that without controlled solar collector or auxiliary heat inputs, the house will maintain this intrinsic $\overline{\Delta T}$ above the average ambient temperature. The remaining amount of heat needed to offset the heat loss and keep the house at the interior design temperature is indicated by the dotted line which intersects the load line at the desired $\overline{\Delta T}$. This heat loss is used to calculate the minimum number of hybrid ClearView panels needed to maintain the interior design temperature for average conditions.

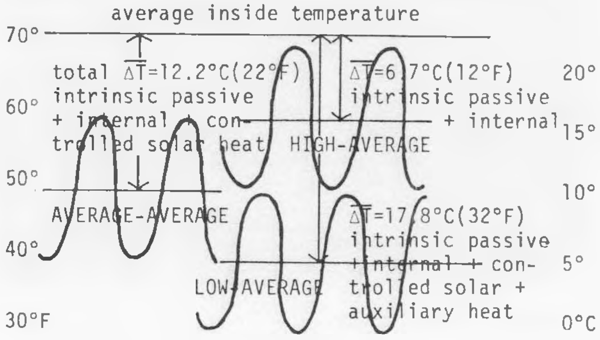

Fig. 8. High, average, and low average ambient temperatures in Tucson, Arizona.

On colder days, the automated ClearView Solar Collector®, along with the intrinsic passive gains, will heat the home. And on the coldest days, both solar heat plus auxiliary heat will be needed, or the occupants must be willing to don sweaters.

The Tucson retrofit house has been analyzed using this characteristic load line. It should be remembered that this is not an ideal solar house; it has too many north-facing windows, all of which are single-glazed, and not enough facing south; the walls are uninsulated bonded brick and the ceiling has R-19 insulation. As shown in Figure 9, the calculated intrinsic passive gain of this house only indicates a $\overline{\Delta T}$ of 3.3°C (6°F), not enough even for warm January days. However, when one adds seven hybrid ClearView Solar Collector®

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*Such windows could use dark venetian blinds in order to avoid fading furnishings. Or, alternatively, inverted reflective blinds could be used to scatter insolation about the room as in the MIT house.[6] In this way, the intrinsic passive heat component would be used as a direct gain. Obviously, if a totally passive house is desired, the window areas could be increased so that the intrinsic passive and internal heat $\overline{\Delta T}$ is adequate to maintain the house at any desired design $\overline{\Delta T}$.

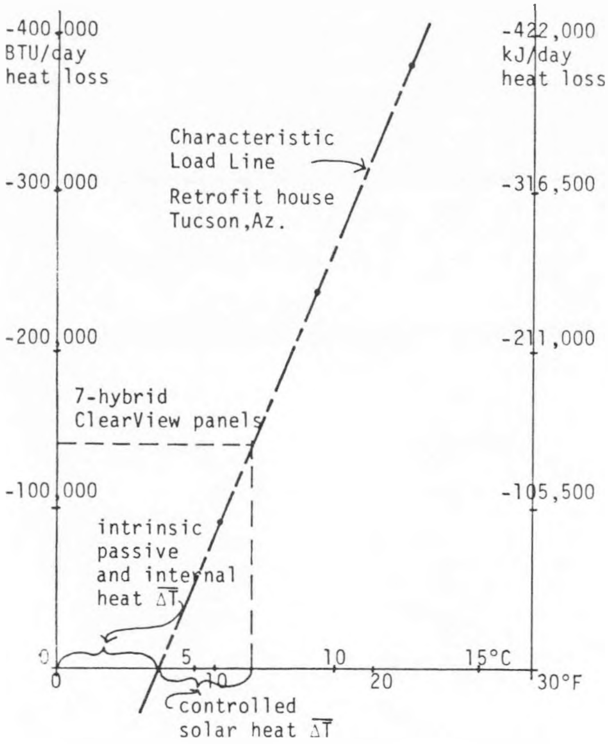

Fig. 9. Characteristic load line for house in Tucson retrofitted with two hybrid ClearView Solar Collectors (7 panels total). The load line crosses over $\overline{\Delta T}$ at about 3.3°C (6°F) indicating a 3.3°C (6°F) intrinsic passive heat gain. With the 7 hybrid ClearView panels rated at about 20,000 BTU/day each, the home has a calculated $\overline{\Delta T}$ of 6.7°C (~12°F).

panels, this home has a predicted $\overline{\Delta T}$ of 7°C (12-13°F). And, indeed, on the sunny week shown in Figure 10 and all other sunny days in January and February, the $\overline{\Delta T}$ was approximately 7°C (12°F) This trace also shows that the home had an internal temperature fluctuation of 5.5°C (10°F). During the week shown here, it ranged from 18-24°C (65-75°F). Regarding comfort conditions in passive homes, the occupants of this home found an 18-24°C (65-75°F) daily variation quite acceptable and 15.5-18°C (60-65°F) temperatures tolerable on weekdays during the early morning hours.

Figure 11 illustrates a computer simulation of an ideal hybrid solar home constructed of solid masonry exterior walls, insulated on the outside and located in Tucson. About one-third of the interior walls are also solid masonry. (As a general rule, as many interior walls as possible should be masonry.) This simulation indicates that a 3.3°C (6°F) internal temperature variation is quite possible with this kind of construction, even with convective heat transfer. Evidently, as shown by the graph, the wall begins to give heat back to the house in the early morning. Figure 12 shows an interior wall, which stores heat

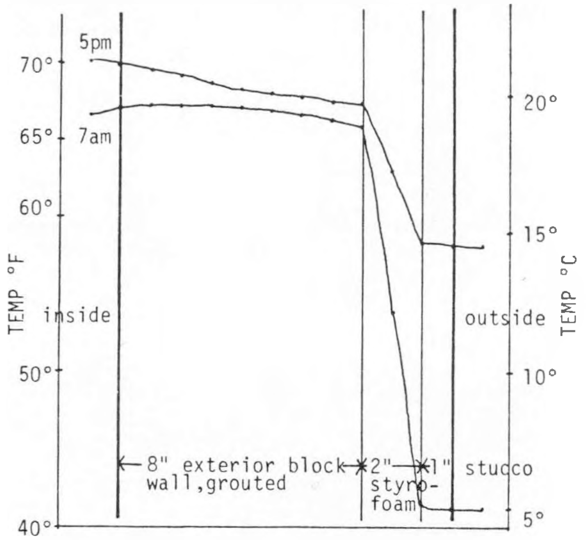

Fig. 11. Computer simulation of the temperature variation in the exterior wall of an idealized hybrid solar home in Tucson, Arizona. The exterior walls are 8" grouted block with 2" of styrofoam insulation on the outside. The house was held at 22.7°C (72°F) between 8 a.m. and 4 p.m. The concrete floors are uncarpeted and 30% of the interior walls are 8" solid masonry.

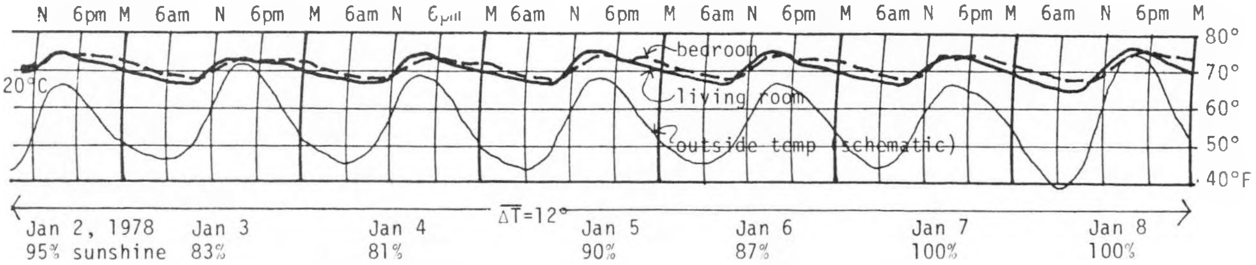

Fig. 10. Winter performance data for retrofit home using seven hybrid ClearView panels. The exterior temperatures are schematically drawn from maximum and minimum temperatures at the Tucson Weather Bureau. Two thermographs, calibrated daily from mercury thermometers, recorded the interior temperatures. Interior temperature fluctuations (ΔT_{int}) are only 5.6°C (10°F) in this home, which has an uninsulated bonded brick wall, single glazed windows and R-19 insulation in the attic.

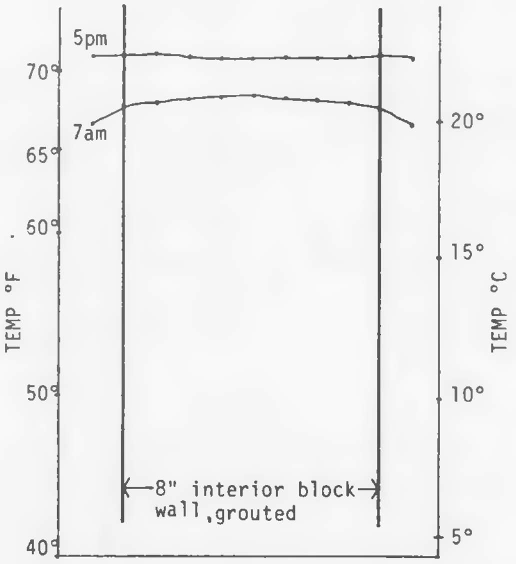

Fig. 12. Computer simulation of the temperature variation in the interior wall of an idealized hybrid solar home in Tucson, Arizona. The construction is the same as in Fig. 11.

more efficiently than the exterior walls, giving more heat back to the home than the exterior wall in Figure 11.

Any other automatically controlled hot air solar collector, located either on the wall or on the roof, could be substituted for the hybrid Clear-View Solar Collector®. We prefer to use the Clear-View Solar Collector® for its obvious advantages, including architectural acceptability, simplicity, and ease of construction and maintenance.

4. OPTIMIZED EVAPORATIVE COOLING

All the hybrid solar homes which we have designed for the desert Southwest use optimized evaporative cooling. This is achieved by introducing the cooled air into the main daytime living areas through a short, wide duct, and exhausting the house air out through the bedrooms, the kitchen, and the bathrooms. In this way, the homeowner will not need to turn off the evaporative cooler during the early morning hours, when it produces the coldest temperatures, because the bedrooms will no longer get too cold. Thus, the outside insulated solid masonry walls in the daytime living areas of the passive or hybrid house may be evaporatively cooled at night by convective heat transfer (or coolth transfer), taking advantage of the cool nocturnal temperatures. Then, during part of the day, the cooler may be turned off, letting the house "coast through the day," just as it "coasts through the night" during the heating season.

Performance data (Figure 13) for the previously discussed non-ideal Tucson retrofit home with an optimized evaporative cooling installation, shows that the bedroom areas did not vary more than 2.2°C (4°F) at night, as indicated by the heavy line. On many days, it was noticed that at 2 p.m. the input temperature approached the output temperature, indicating that thermal gains of the house were compensated by the coolth from the walls as the air passed through the house. In a solid masonry house with outside insulation, we would expect to see a cross-over at this time of day, when the input air temperature is actually warmer than the output air temperature.

There may be occasions when one will want to cool the bedroom areas at night, especially in climates that are warmer and more humid than Tucson's. We have devised a system of flexible zoning for this purpose, where, with the use of a simple extractor located in an essentially normal duct system, one can introduce the cooled air into either the main living areas or divert it to the bedrooms. In Figure 14, we show how this is achieved in a new solar home to be built in Tucson as part of a tract home development.

The duct configuration guides the air into either the bedroom areas or the main living areas, depending on the extractor location. In a home with a straight duct where the daytime areas are located on one side of the home and bedroom areas on the other (a fairly typical tract home layout), extractors may also be used to divert the cooled air to either area. (See Figure 15.)

Another aspect of optimizing an evaporative cooler installation includes locating the cooler on the ground where it is easily maintained, and where it is shaded from the sun at all times. It should, however, be located in dry areas and in such a way as to allow plentiful air flow around it.

In all evaporative cooling systems, eliminating heat before it heats air in the home itself can

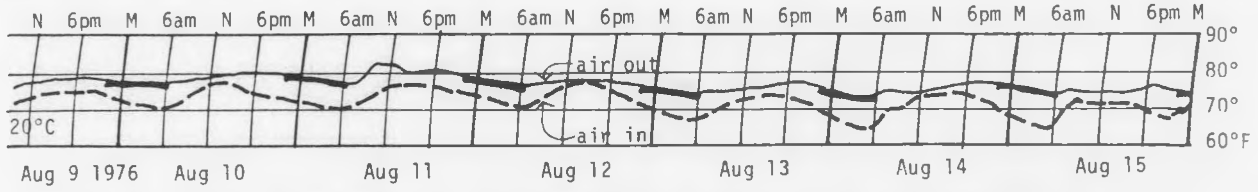

Fig. 13. Summer performance data for optimized evaporative cooling installation on the hybrid ClearView retrofit house in Tucson, Arizona. The heavy line indicates relatively stable nighttime temperatures in the bedroom areas (air out).

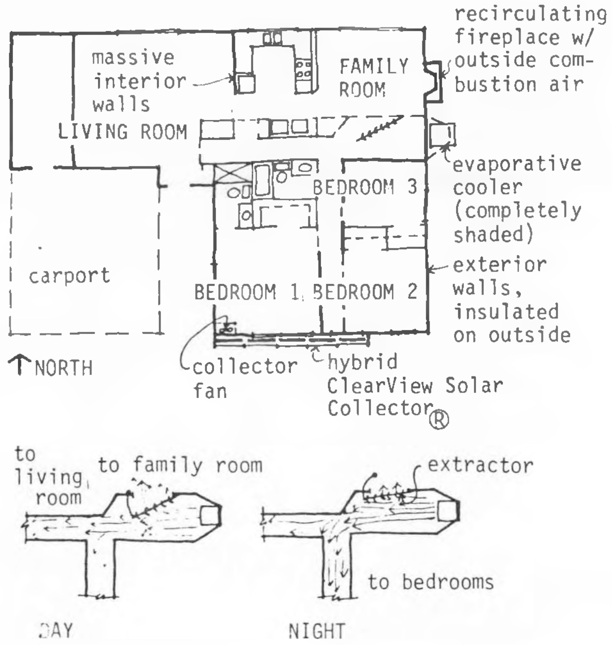

Fig. 14. Schematic drawing of tract home "retrofitted" with hybrid ClearView Solar Collector® and optimized one-stage evaporative cooling. Bottom diagrams illustrate flexible zoning which is used for evaporative cooling. An extractor diverts the coolest air into either the bedroom areas or the daytime living areas as desired.

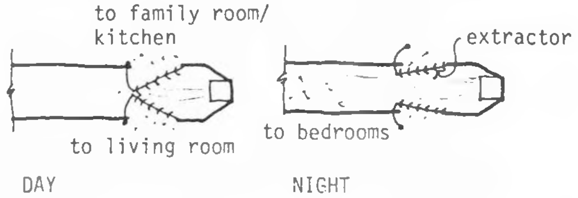

Fig. 15. Flexible zoning as it would be used in a typical tract home with a straight duct.

improve comfort. When a ClearView Solar Collector® is used, any heat collected is exhausted by the stream of evaporatively cooled air flowing from the house through the collector to the outside. If the home has an attic, cooled air may also be vented out through the ceiling, into the attic and to the outside, thus negating the solar gain of the roof. Cooled air may furthermore be exhausted out of standard windows by venting air past white-lined drapes, or over venetian blinds or shutters, thereby exhausting absorbed heat before it enters the house. Also, venetian blinds (dark on the top, white on the bottom) could be enclosed between two standard windows to allow absorbed heat to be exhausted, or to allow heat collection during the winter.

5. ECONOMIC ANALYSIS

The two components which add to the cost of a hybrid solar heating system are the solar collector and the thermal mass of the walls. Compared to a passive direct gain system, the hybrid ClearView Solar Collector® may be regarded as being significantly more expensive. However, when venetian blinds, an automated fan system and easily operable insulated shades are added to the large window area required for a passive solar house, the cost advantages of such simple systems rapidly diminish. Thus, unless we have a very elemental direct gain system, the relatively trouble-free hybrid systems are not much more expensive.

We have estimated the cost of five 1.22m x 2.44m (4' x 8' nominal) completely automated hybrid ClearView Solar Collector® panels at $1,000 for materials (May 1978). We assume these panels will be installed by the builder, and we include the large discount available when glass and venetian blinds are purchased in bulk. The cost of labor, overhead, and profit, etc., roughly equals the cost of materials, so that the installed cost of this device should be approximately $2,000. This cost is significant, but has been reduced from what it might be by including comparatively low cost intrinsic passive heating in the home.

The next major cost of the system is the added cost of the mass in the home. If the interior partition walls are solid or filled masonry, they can cost $\sim \$12.90/\mathrm{m}^2$ ($\sim\$1.20/\mathrm{ft}^2$) (May, 1978) more than framed partition walls. This substitution does not involve any major changes in standard construction techniques in Tucson. If care is used, for example, the extra cost of electrical conduit in filled block walls may be avoided if some cores are left unfilled and used as a wire chase to the attic. Exterior solid masonry walls insulated on the outside surface can cost $\sim \$10.80/\mathrm{m}^2$ ($\sim\$1.00/\mathrm{ft}^2$) (May, 1978) more than block walls with equivalent insulation on the inside surface. The cost of adding these walls to a typical Tucson tract home varies from $1,000-$2,000, depending on the fraction of standard wall replaced. This cost could also be partially or entirely charged against cooling, since it improves the performance of evaporative cooling by providing massive walls for the storage of nocturnal coolth. Considering that cooling is the major problem in the desert, we would prefer to charge most of the wall mass to the cooling system, since it will be used to increase summer comfort. This decision is best made by the owner, his tax lawyer and a practitioner of the manipulative art of accounting; thus we have not taken advantage of this factor in our analysis.

Figure 16 illustrates an economic analysis of the hybrid ClearView Solar Collector® using the economic portion of the f-Chart method.[7] As shown on the graph, the hybrid ClearView Solar Collector®, when installed on new homes with evaporative cooling, is more cost-effective for winter heating on a life cycle basis than the two electric alternatives (electric resistance heating and the heat pump). This is based on a $2,000 contractor-installed cost for the 5 ClearView panels minus the

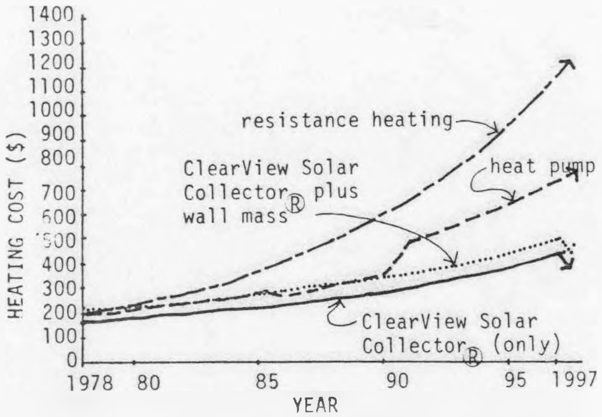

Fig. 16. Economic analysis comparing the hybrid ClearView Solar Collector®, the ClearView plus wall mass, a heat pump, and electric resistance heating. The analysis assumes a 10% electrical inflation rate, a 6% general inflation rate, a $2,000 collector cost, $1,000 for the additional cost of the massive walls, $2,300 for the heat pump cost (1/3 for heating), and a 105,500 kJ/day (100,000 BTU/day) January heat loss. The home is 80% solar heated. This also takes into account the 30% Arizona solar tax credit for 1979. No federal tax credits are used.

1979 30% Arizona State tax credit. If one adds the additional costs of constructing the heavy masonry wall with outside insulation, one still pays less for heating energy on a life cycle basis, as shown by the dotted line.

6. CONCLUSION

We have shown that the hybrid ClearView Solar Collector® with complementary optimized evaporative cooling is a viable method for heating and cooling in desert areas of the Southwest. Performance data for a home in Tucson, Arizona retrofitted with this hybrid solar collector shows that a fairly comfortable 5.5°C (10°F) diurnal temperature swing may be achieved on a poorly insulated but high mass home. A method for predicting the performance of passive and hybrid solar homes has been verified using this retrofit home. An advantage of predicting performance using this variation of standard heat loss calculations is that one can determine the amount of intrinsic passive and internal heat entering the house and thus its overall performance characteristics.

For desert climates, optimizing the performance of evaporative cooling has been shown to be an effective method for increasing summertime comfort without the use of expensive air conditioning.

These are all simple site-built systems which can be constructed by anyone with some carpentry skills ranging from the do-it-yourselfer to the tract home builder. We have shown that, compared to two electric alternatives, the hybrid system is economical today on alife cycle cost basis. All components of these systems are presently mass-produced, and thus can be readily purchased, with large discounts for bulk purchases.

Our goal is to demonstrate to tract homebuilders that it is profitable to build simple yet effective solar homes for the general public. We are presently in the process of introducing these techniques to several homebuilders in Tucson.

7. ACKNOWLEDGMENT

The authors would like to acknowledge the input of Prof. R. Larry Medlin from the College of Architecture, University of Arizona, who participated in developing the concept of the venetian blind type solar collector.

8. REFERENCES

[1] Peck, John F., Insulation, Solar Heating and Improved Evaporative Cooling, Environmental Research Laboratory, University of Arizona, Tucson, Arizona (1976 and 1977).

[2] Peck, John F., et al, "A Greenhouse-Residence Utilizing a ClearView Solar Collector and Two-Stage Evaporative Cooling," Proceedings of a Conference on Solar Energy for Heating Greenhouses and Greenhouse-Residential Combinations, Cleveland, Ohio (1977).

[3] Thompson, T. L., et al, "Environmental Control and Vegetable Production in a Combined Solar Collector-Greenhouse," Proceedings of a Conference on Solar Energy for Heating Greenhouses and Greenhouse-Residential Combinations, Fort Collins, Colorado (1978).

[4] Reagan, J. A., Energy Conservation for the Home or How to Lower Your Utility Bill, EE45 Report, Department of Electrical Engineering, University of Arizona, Tucson, Arizona (1975).

[5] ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., New York (1976) pp. 410-413.

[6] Wellesley-Miller, Sean, "Weather Responsive Building Skins: Concepts and Configurations," Passive Solar: State of the Art, Proceedings of the 2nd National Passive Solar Conference, American Section of the International Solar Energy Society, ed. by Don Prowler, Philadelphia, Pennsylvania (1978) p. 497.

[7] Beckman, William A., Sanford A. Klein, John A. Duffie, Solar Heating Design by the f-Chart Method, John Wiley and Sons, New York (1977).

RECENT DESIGN & PERFORMANCE DATA FOR THE HYBRID CLEARVIEW SOLAR COLLECTOR® SYSTEM

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ABSTRACT

The hybrid ClearView Solar Collector® has been built into two new houses and retrofitted onto three existing houses in Tucson, Arizona, Heat from the automatically controlled, site-built, wall-mounted, transparent hot air solar collector is stored primarily in the mass of each house. Predicted performance is calculated using a heat loss analysis which has been programmed into a TI-59 programmable calculator. This interactive calculator program, which is suitable for hybrid and passive solar homes, allows prediction of intrinsic passive interior temperatures as well as the number of ClearView Solar Collector® panels necessary to achieve a desired temperature difference between average inside and average outside temperatures. It is verified based on performance data obtained from these homes during the winters of 1977-78 and 1978-79. The process of introducing this solar heating system to tract homebuilders, as well as some design details are also discussed.

1. INTRODUCTION

The hybrid ClearView Solar Collector® system is part of a family of solar collecting systems designed for the desert Southwest that range from passive to active. All use the wall-mounted transparent ClearView Solar Collector® together with some form of complementary evaporative cooling. Heat and coolth are stored in either the mass of the home or a large rockbed. These systems have been discussed in previous papers [1, 2, 3, 4]. There are two types of ClearView Solar Collectors®. One uses duo-tone venetian blinds and the other uses heat absorbing glass* to absorb solar radiation. Since the venetian blind form is well documented in previous papers, the heat absorbing glass version will be described in detail in this paper. (Both are applicable to cold climates in addition to the relatively mild climates of the desert Southwest.)

The hybrid ClearView Solar Collector® is a versatile and aesthetically pleasing solar collector that can be integrated into new home designs or be retrofitted to many existing homes. On a well-insulated 1500 sq. ft. home in Tucson with an average number of windows, five ClearView panels, each a standard 4' x 8' (1.22m x 2.44m), will normally heat the house well during sunny periods.

Since a small (100 watt) fan is used to distribute solar heat throughout the house, a large variety of home designs are possible. The collector is automatically controlled with two thermostats that turn the fan on when the house needs heat and when the collector is hot. Thus, the system is quite suitable for those who are accustomed to letting the thermostat control their house heating needs. During colder than normal times, a back-up heater or recirculating fireplace may be used (or sweaters donned!).

In the process of building a prototypical installation at ERL and of introducing this solar heating system to a major tract homebuilder, various construction techniques have been investigated. These include variations in masonry construction and outside wall insulation as well as different collector design details.

Five very different houses have now been constructed using the hybrid ClearView Solar Collector® system. They range from single family detached homes to townhouses, and from new to retrofit. All have different wall types, with different forms of outside insulation. The performances of three of these houses have been predicted and verified based on data collected during the winters of 1977-78 and 1978-79.

2. CONSTRUCTION DETAILS

2.1 The Solar Collector

The hybrid ClearView Solar Collector® (See Fig. 1) is an entirely site-built hot air solar unit that is constructed from mass produced, off-the-shelf parts and materials. Solar radiation is absorbed by either venetian blinds or heat absorbing glass located between the exterior glazing and the inner wall of the collector. Exterior glazing is normally double 4' x 8' (1.22m x 2.44m) tempered patio door glass. The interior wall of the collector, which is the exterior masonry wall of the house, has windows wherever desired. These windows are preferably double sliding in order to provide easy access to the interior of the collector for cleaning and maintenance as well as

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*U.S. Patent No. 4,050,443, for fan-driven models.

access to venetian blind controls, if used. A small propeller fan, located diagonally opposite the house duct, is used to distribute heated air from the collector to the rest of the house. The ends of the collector have louvers which allow heated air to be exhausted to the outside during spring, summer and fall, when solar heat is not needed.

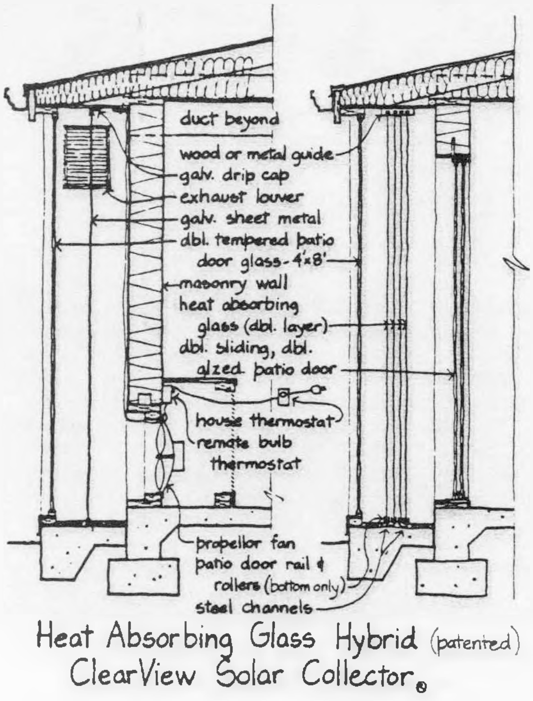


Fig. 1. Section through heat absorbing glass hybrid ClearView Solar Collector®.

In the two prototypical ClearView units located at the Environmental Research Laboratory, the heat absorbing membrane consists of two layers of 1/4" (6.4mm) "solar bronze" glass. This provides ~25% visible transmission through the collector. At some time in the future, a single layer of heat absorbing glass with 25% visible transmission, or less, may be developed (the view through "solar bronze" with 12-1/2% visible transmission is very acceptable).

In an 8' (2.44m) wide transparent section of collector, four pieces of 4' x 8' (1.22m x 2.44m) heat absorbing glass are used, two per 4' x 8' section. These are mounted in the bottom rail of a patio door, complete with rollers. Two low cost steel tracks are ramset (or bolted) to the floor of the collector and allow the four panels of glass to glide past one another for ease of cleaning or to roll beyond the field of vision (this also allows the collector to become an objet d'art, as shown in Fig. 2). The tops of the glass panels are held in place by a set of wood or metal tracks attached to the roof of the collector. Ideally, an 8' x 6'-8" (2.44m x 2.05m) double sliding double glazed patio door is located in the wall behind the heat absorbing glass for access.

Where there is no need for a view, the collector is opaque. The inside wall is constructed of masonry and the absorber panel is low cost galvanized sheet metal, painted a dark color on the south side. The sheet metal is held in place along the top of the collector by a channel system formed by a set of two roof drip caps, placed inside one another. A similar installation contains the sheet metal along the collector's bottom. The sheet metal is suspended from the upper channels by a single screw, allowing for complete freedom of expansion and contraction. To stiffen the sides of the sheet metal, standard S-bends, used for joining ducts, are used.

By using sheet metal wherever a view is not desired, the heat absorbing glass ClearView Solar Collector® can be no more expensive than the venetian blind form. Also, if the sheet metal is placed in the panel at the point where the fan blows air into the collector, it will help even out the collector temperatures before the cool house air blows over the heated glass, thus avoiding temperature differentials across the glass which may cause heat cracks.

The exterior glass of the solar collector may be framed in various ways. For the do-it-yourselfer, 2 x 4 wood mullions work well. For commercial homebuilders, standard aluminum extrusions may be preferable, since they reduce field labor.

One detail to be wary of is the duct design. It is important that pressure drops be very low, so a low wattage propeller fan can be used. In a hybrid system, a comparison of the fuel equivalent of electrical power used with the usable solar heat produced can be quite embarrassing sometimes. Also, if venetian blinds are used, a standard ceiling-type diffuser should be used over the air entry into the collector to avoid excessive swaying of the blinds.

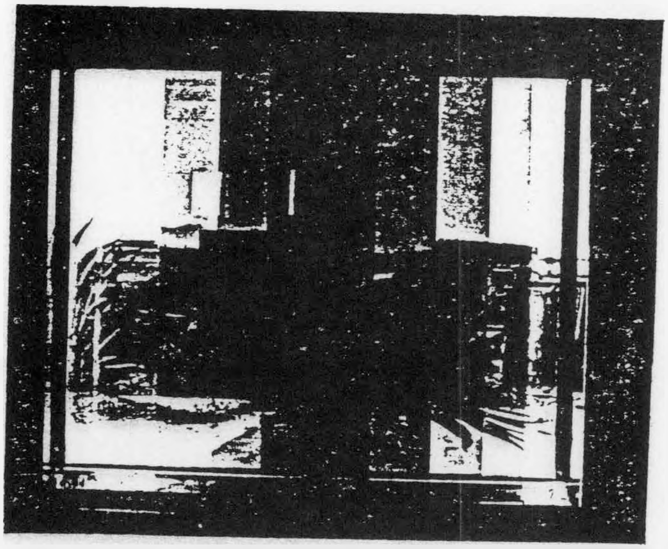


Fig. 2. View through heat absorbing glass ClearView Solar Collector® retrofitted to solar office located at the Environmental Research Laboratory (optional art-deco arrangement).

Various propeller fans have been tried -- some with metal blades; others with plastic. Molded plastic blades are recommended since they make considerably less noise and can now be fairly easily obtained in a 3-speed standard window ventilation fan. Generally, the fan draws between 75 and 150 watts, depending on the size of the house and the pressure drops in the system. It is automatically controlled by two standard thermostats, as mentioned previously.

It is important that the back wall of the solar collector be made of masonry. In this way, any excess heat from the collector is absorbed by the wall and enters the house in the evening in the same manner as with a Trombe wall.

The sides of the collector may be constructed of wood or masonry, depending on the desired architectural effect. Near the top of the sides, standard filter-type louvers are used to exhaust heat from the collector during warm weather. In the winter, these vents are plugged with styrofoam insulation, and the edges sealed with tape.

2.2 The Masonry Walls

A different type of exterior masonry wall has been used in each of the hybrid solar homes. These include bonded brick without insulation, vermiculite filled slump block with 38mm (1-1/2") of urethane foam on the outside, 203mm (8") burnt adobe with 38mm (1-1/2") of urethane foam on the outside, a combination of 203mm (8") burnt adobe, 51mm (2") UFC foam and another 102mm (4") of burnt adobe on the outside and hollow concrete block with 2 x 6's furred out on the inside and R-19 fiberglass batt insulation. A tract home, currently under construction will be built with concrete masonry units filled with grout or packed dirty sand and with 51mm (2") of styrene foam insulation on the exterior surface.

For tract homes, a flat masonry unit such as a standard or scored concrete block, is preferable to the irregular slump block or burnt adobe. This allows for the use of board stock exterior insulation such as styrene foam insulation. Although urethane foam has been sprayed onto the exterior walls of two of the homes where it was not possible to use styrofoam, it is more expensive both as a material and because it needs special preparation (smoothing) before application of the exterior finish coat. The scored and colored concrete block (called RMU) eliminates the need for interior plaster, and thus can reduce costs.

Various materials for covering outside insulation are available. Names and addresses of manufacturers are given in the Appendix. We have found that the most reliable seem to be those with a continuous fiberglass or metal mesh in them.

3. PERFORMANCE DATA AND ANALYSIS

A relatively simple method for predicting the average inside temperature of a hybrid solar home on sunny days has been devised and reported [1, 2]. Briefly, it consists of determining the heat losses (or gains) of a home at both a 22°C (72°F) and a 17.8°C (64°F) average inside temperature and a common average outside temperature, using the TETD concepts of ASHRAE, together with solar gains through windows. These heat losses are then translated from these specific temperatures to the differences between them called $\Delta\overline{T}$, and are plotted on a graph, as shown in Fig. 3. The "characteristic load line" intercepts the heat loss line at a $\Delta\overline{T}$ which is the intrinsic passive and internal heat gain interior temperature rise. That is, the house will maintain itself at an average inside temperature of that many degrees above the average outside temperature without added heat input from a solar collector. If the net heat losses at an average January $\Delta\overline{T}$ for a given location (12.2°C (22°F) for Tucson) are divided by the average heat output of each solar collector panel, we can establish the number of collector panels needed to heat the house on average sunny days. This has been reduced to a TI-59 program which will calculate the heat losses at the average inside temperatures, the intrinsic passive $\Delta\overline{T}$, and the minimum number of ClearView panels when the appropriate TETD's, solar gains, U-values and areas have been stored.

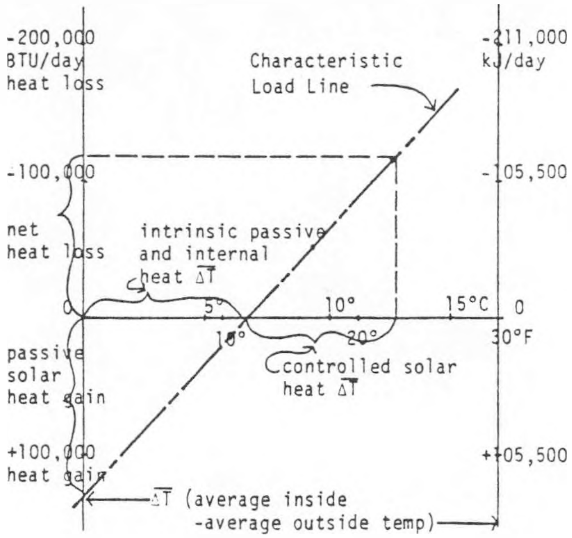


Fig. 3. The characteristic "load line" of a home derived from heat loss calculations. The intrinsic passive and internal heat $\Delta\overline{T}$ is indicated where the load line crosses the zero heat loss/gain line.

The above technique has been tested on 3 combinations of homes and heat loss levels, as shown in Table 1. In general, the actual $\Delta\overline{T}$ is 1.1-2.2°C (2-4°F) above the calculated value. The calculated $\Delta\overline{T}$ for the new house (#3) is not given, since the house has several features that are different from our established performance values, and auxiliary heat was used in the early morning hours. However, the actual $\Delta\overline{T}$ of 13°C (23.5°F) does not seem out of line with an estimated $\Delta\overline{T}$ in the mid-teens°C (mid-20°F) range.

TABLE 1

HOUSE		CONSTRUCTION	CALCULATED $\Delta\overline{T}$	ACTUAL $\Delta\overline{T}$	INTERIOR TEMPERATURE VARIATION
1. TUCSON RETROFIT HOUSE	a.	Uninsulated double bonded brick walls, R-19 ceiling, single glazed windows	12°F 6.7°C	12-15°F 6.7-8.3°C	~Δ10°F ~Δ5.6°C
	b.	same, but most north windows have 2" styrofoam plugs	15°F 8.3°C	17-19°F 9.4-10.6°C	~Δ9-10°F ~Δ5.5-6°C
2. ERL SOLAR OFFICE		unfilled block walls w/outside insulation, R-19 ceiling, double glazed windows	20.5°F 11.4°C	22-24°F 12.2-13.3°C	~Δ14-17°F ~Δ7.8-9.4°C
3. TUCSON NEW HOUSE		block walls w/inside insulation, R-30 ceiling double glazed windows	--	23.5°F 13°C	~Δ10-14°F ~Δ5.6-7.8°C

Data from the retrofit house has been reported [1, 2] and is shown in Fig. 4. This year, the north windows were insulated with 51mm (2") styrofoam panels (with taped joints), and the house performance was recorded. No furnace heat was used during sunny days. Fig. 5a shows the temperatures in the living room which had only convective gain from the collector, but no uninsulated windows, and no direct gain. The $\Delta\overline{T}$ of this room was 11.7°C (21°F), 3.3°C (6°F) above the calculated value, and quite acceptable for almost all Tucson weather. When contrasted with prior data, when the windows were not insulated ($\Delta\overline{T}$ = 6.7°C (12°F)), the advantage of easily used, effective movable insulation in windows is shown. (The fixed insulation used in this test did not lead to a divorce, but did cause certain strains!).

Some areas of the retrofit house which were dependent solely on passive natural draft airflow through specially designed ducts are generally 2.8-3.3°C (5-6°F) lower in temperature than other parts of the house. This points out the usefulness of small fans for temperature equalization. Also, these cooler areas decrease the overall average $\Delta\overline{T}$ in the retrofit home to a level of 1.1-2.2°C (2-4°F) above the calculated values.

The daily temperature variations of ~Δ5.6°C (~Δ10°F) in this home at both heat loss levels were quite acceptable.

Fig. 5b shows data from the ERL solar office. The collector fan is turned off automatically by the interior thermostat at approximately mid-day. Then, after a temperature drop, the west windows and natural draft from the collector maintain the internal temperatures. The calculated $\Delta\overline{T}$ = 11.4°C (20.5°F) is in apparent excellent agreement with the 11.7°C (21°F) actual $\Delta\overline{T}$. However, if the collector fans operated all day, the actual $\Delta\overline{T}$ would be 12.2-13.3°C (22-24°F), illustrating the conservative nature of the calculations.

This office has vermiculite-filled block walls with exterior insulation and no interior walls at present. Its daily interior temperature variations of 7.8-9.4°C (14-17°F) are not as good as in the retrofit home with poorer insulation, but with more mass (double bonded brick walls, interior walls and internal heat gain!). This is consistent with our prior computer model of convective gain homes [2] which indicate that interior mass is necessary. Furthermore, the shape of the temperature curve of the unoccupied office (Fig. 5b) is different from

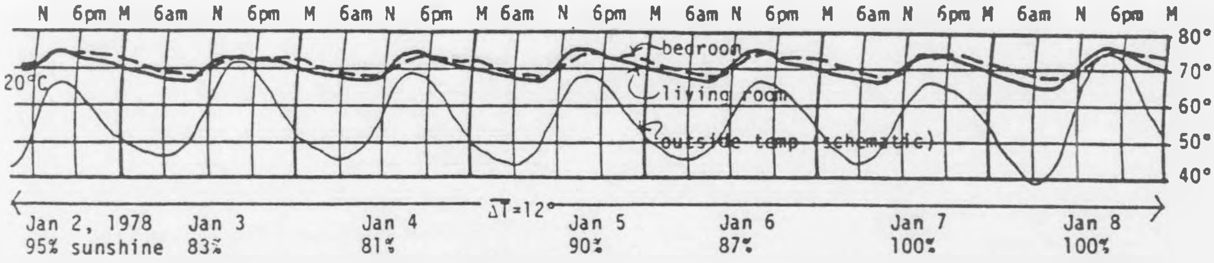
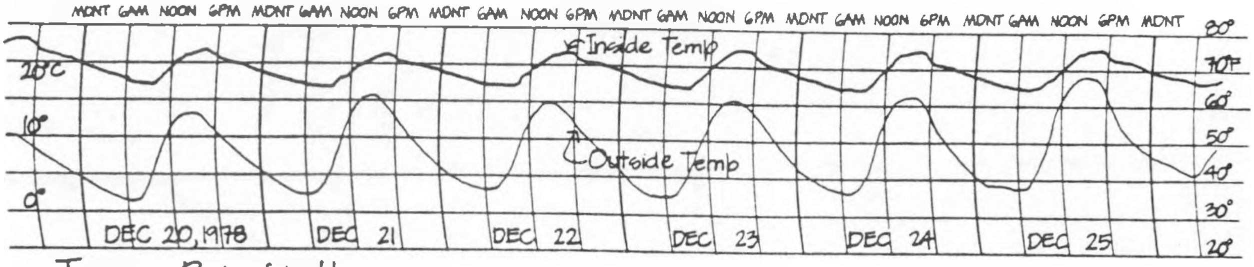
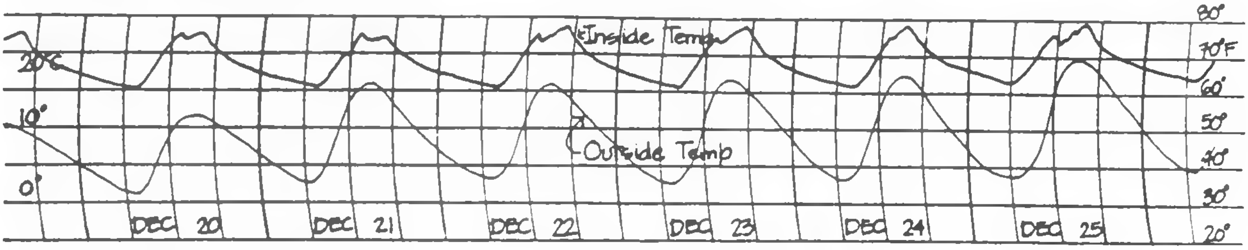


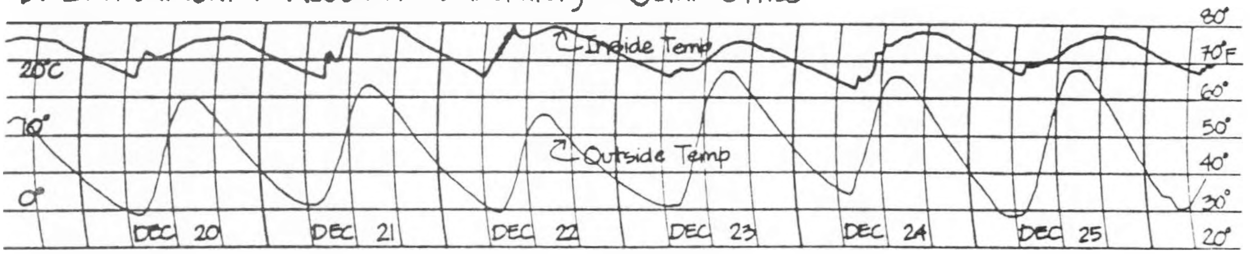
Fig. 4. Performance data for Tucson retrofit home during winter of 1977-78. Indoor temperatures were recorded on thermographs, outside temperatures are from the Tucson Weather Bureau.



a. Tucson Retrofit House



b. Environmental Research Laboratory - Solar Office



c. Tucson New House

Fig. 5. Performance data for three hybrid ClearView solar homes in Tucson during winter of 1978-79. Both indoor and outdoor temperatures recorded at the site.

that of the retrofit home (Fig. 5a). The occupied office drops asymptotically toward its early morning value, while the occupied residence levels out in the evening, and then drops. This is probably due, at least in part, to the heat from lights, people, cooking, etc. This is an important factor in the comfortable conditions attained in this home. Unfortunately, the house occupants refuse to eliminate all internal gain (in other words, move out) so that the relative effects of this and internal mass can be assessed.

Data from a new home is shown in Fig. 5c. The well-insulated, low interior mass exterior walls apparently counterbalance the higher mass, poorer insulation of the walls of the retrofit home somewhat, since the interior temperature variations are similar. However, this home was warmed in the early morning by a furnace. as shown by the rapid initial rise, followed by a temporary drop in temperature when the collector takes over.

4. INTRODUCTION TO TRACT HOMEBUILDERS

A goal of the Environmental Research Laboratory's solar program is to introduce simple to use relatively inexpensive solar heating systems together with complementary evaporative cooling to the tract home industry of the desert Southwest. In order to work successfully with tract homebuilders, it is important not to change too many details at once. We found that one way to achieve success is to simply modify an already popular tract home with an automatically controlled hybrid, hot air ClearView Solar Collector. This allows for heat distribution to all rooms, no matter what the floor plan, yet also provides a site built solar collector that can be constructed by the homebuilder's subcontractors, using standard off-the-shelf parts.

Six tract homes will be built, using the hybrid ClearView Solar Collector®. It is now important to monitor and optimize the effect of thermal mass for convective heat transfer in these homes. The process of developing an effective design tool has been started as discussed in this paper.

Most tract homebuilders are not familiar with the intricacies of building with interior masonry walls, although the technology exists and is being used by many for varying purposes. Sand filling of the cores of concrete block walls is already common for party walls. Outside insulation techniques have been used on stud walls in tract home developments in Tucson. But it takes a great deal of hand-holding to proceed from even these ordinary construction practices to the solar house. Details that seem relatively minor can result in financial surprises. For example, some interior masonry wall finishes can add $1500 or more to the cost, and be charged as a solar extra. This can easily upset economic analyses.

The most effective way to introduce future home buyers to the benefits and comforts of passive and hybrid solar homes is to let them experience such homes. Building significant numbers of homes can only be accomplished by initially using both familiar materials and designs. In the long term, it is hoped that these small changes might lead to the acceptance of more radical designs, and a greater solar consciousness in the home building industry.

5. REFERENCES

[1] Peck, John F., et al., "Passive Forms of the ClearView Solar Collector®," Proceedings of the 1978 Annual Meeting, American Section of the International Solar Energy Society, Inc., ed. by K. W. Böer and G. E. Franta, Denver, CO (1978) pp. 180-186.

[2] Peck, John F., et al., "The Hybrid ClearView Solar Collector® and Complementary Evaporative Cooling-Performance Prediction Methodology and Results," Passive Solar: 1978, American Section of the International Solar Energy Society, ed. by Jeffrey Cook, to be published 1979.

[3] Peck, John F., et al., "A Greenhouse-Residence Utilizing a ClearView Solar Collector and Two-Stage Evaporative Cooling," Proceedings of a Conference on Solar Energy for Heating Greenhouses and Greenhouse-Residential Combinations, Cleveland, Ohio (1977).

[4] Thompson, T. L., et al., "Environmental Control and Vegetable Production in a Combined Solar Collector-Greenhouse," Proceedings of a Conference on Solar Energy for Heating Greenhouses and Greenhouse-Residential Combinations, Fort Collins, Colorado (1978).

6. APPENDIX

The following are manufacturers of various outside insulation techniques. Doubtless, there are others we have not heard of. These companies can be consulted for local distributors.

1. INSUL-FLEX

El Rey Stucco Company, Inc.
4100-1/2 Broadway, E.
Albuquerque, New Mexico 87102
(505) 873-1180

2. DRYVIT

DRYVIT System, Inc.
420 Lincoln Avenue
Warwick, Rhode Island 02888
(401) 463-7150

3. NU-WALL

George Newland
8616 North 32nd Drive
Phoenix, Arizona 85021
(602) 943-0510

4. SUREWALL

W. R. Bonsal Company
P. O. Box 38
Lilesville, North Carolina 28091
(704) 848-4141

Hot-air solar collectors suited to desert climate

First of a two-part series

Helen J. Kessler

Hot-air solar collectors provide an effective means of heating the air inside your desert home.

There are many types of hot-air solar collectors. Some are mounted on the south wall of a house, others on the roof. Some provide a view while others do not. And some are stick-built at the site while others are manufactured and transported complete to the site. In new houses, they become an integral element of the design.

A hot-air solar collector can be part of a passive, active or hybrid solar heating system.

As part of a passive system, it would be mounted on the south wall of a house and would provide heat by natural convection. Manufactured units called thermosiphoning air panels (TAP) are passive systems. Passive systems also can be built from scratch at the site. Heat is stored in the mass of the house.

The heat from an active hot-air system is distributed with fans. Usually a rock bed (installed beneath the house) is used for storage. Sometimes water is used, but this requires air-water heat exchangers and increased complications. When heating the space inside a home, it is much more natural to provide direct hot-air heating. Solar collectors for active systems can be located either on the roof or on a south-facing wall.

Hybrid systems use only a small amount of energy, enough to run a 100-watt propeller fan. They usually are mounted on a south-facing wall. They are turned on and off automatically with thermostats, which makes them the simplest and most easily controlled solar heating systems. As with the passive systems, heat is stored in the mass of the house.

Since hybrid systems are the most convenient to use, especially in desert climates, they will be described in more detail.

The University of Arizona Environmental Research Laboratory has experimented with hybrid systems using two types of solar collectors, the ClearView and the NoView.

The idea for the ClearView originated with John F. Peck and Carl N. Hodges of the research laboratory and R. Larry Medlin of the UA College of Architecture.

As its name implies, the ClearView allows you to see through it. It can be retrofitted to an existing home or incorporated into a new home. Generally it is built at the site with readily available off-the-shelf parts.

It uses dark-colored Venetian blinds or solar bronze heat-absorbing glass to absorb solar radiation. That means you can place it over existing windows along the south wall of your house and still enjoy the view. Dark-painted sheet metal can be used as the absorber if a view is of no importance.

A word of caution: If the solar collector is placed over an existing bedroom window, there still must be an exterior means of escape in case of fire.

A 100-watt propeller fan (we generally use the Dayton 4C528 window ventilation fan because it has three speeds and is very quiet) is used to distribute hot air from the collector into the house. The fan is connected to two thermostats, which are wired in series.

One is a standard house thermostat that triggers the fan when the temperature inside the house drops below a given point, such as 75 degrees.

The other thermostat has a remote bulb (a temperature sensor) that is located in the hottest spot near the top of the collector. When the collector air temperature is above a given point, such as 85 degrees, that thermostat will turn on and the house can be solar heated.

This scenario only takes place when the house really needs heat. If it is already warm enough, the fan won't turn on and most of the heat in the collector will either remain or dissipate to the outdoors.

Storage of the solar heat is usually in the mass of the house. In a new home, the mass can be solid masonry interior walls or exterior masonry walls that are insulated on the outside. In existing homes, adding mass is often difficult and you sometimes have to make do with whatever you have.

The collector is constructed of standard off-the-shelf parts. It is usually between 14 inches and 2 feet wide to allow access for cleaning and maintenance. In a new house, access can be provided with a patio door from inside. In an existing house, it might be easier to install an insulated custom-made door on one end of the collector.

The north wall of the collector is the wall of the house. The south wall is glazed. For this, we usually use standard size, double-pane, tempered patio door replacement glass in 4-by-8 foot sheets. This works well with 8-foot-high exterior walls, giving you as much collection area as possible in the space available.

Either wood or aluminum mullions can be used to retain the glazing. Wood has the advantage of not conducting heat or cold very well, thus providing better insulation. Aluminum has the advantage of being essentially maintenance free.

In the next article, the ClearView Solar Collector and other hot-air systems will be described further.

Kessler is an architect with the University of Arizona Environmental Research Laboratory.

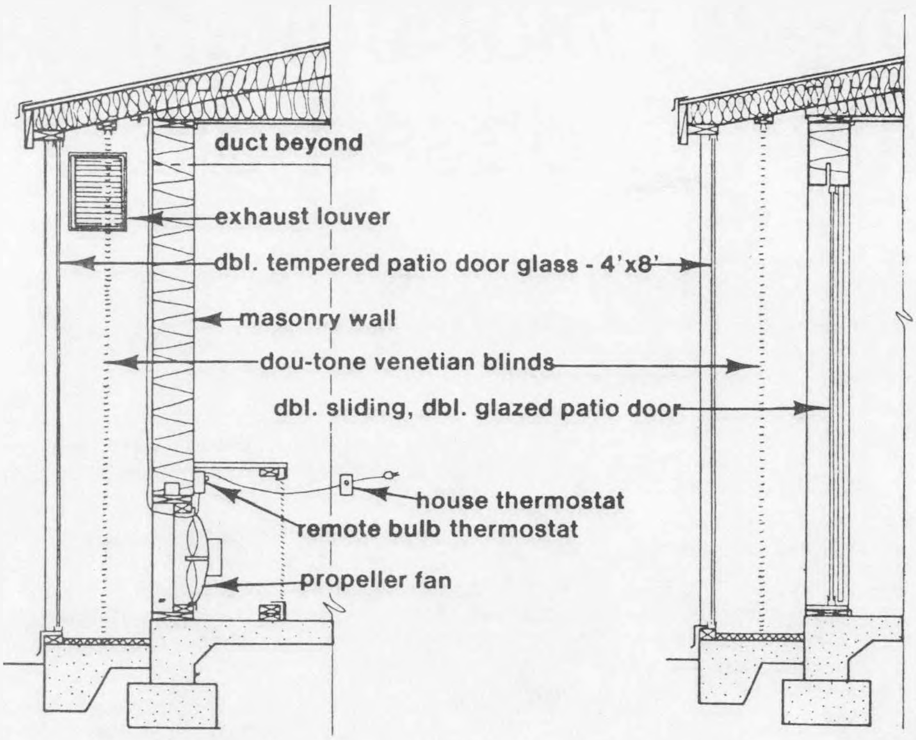


figure 1

Venetian Blind Hybrid
ClearView Solar Collector

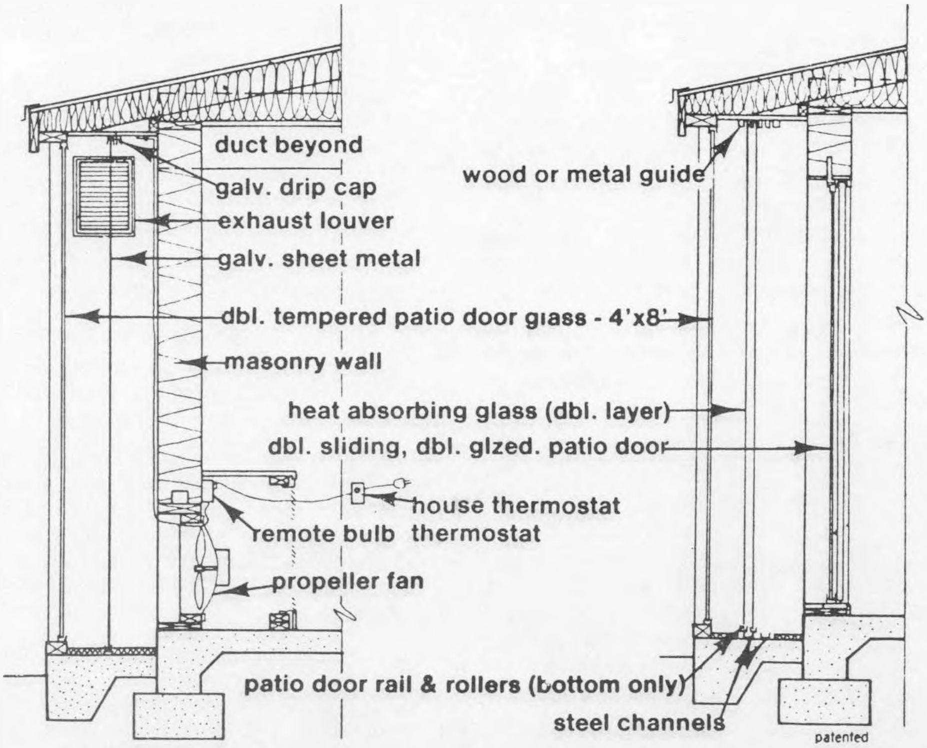


figure 2

Heat Absorbing Glass Hybrid
ClearView Solar Collector

UA works mainly on two types of hot-air solar collectors

Helen J. Kessler

Second in a two-part series

Hot-air solar collectors can heat your home this winter and reduce your utility bills.

Among the many types of collectors available, the University of Arizona has experimented with two: the ClearView and the NoView. Components of these systems were discussed in a previous column on Nov. 14. This week, the collectors are described in further detail.

The collector system consists of a glazing, an absorber, thermal storage and a distribution system. The absorber is installed in the air space between the glazing and the wall. It can be made of several materials. Absorbers for the ClearView Solar Collector are either duo-tone (dark top, white bottom) Venetian blinds or two layers of ¼-inch solar bronze heat absorbing glass.

Where no view is desired, a 4-by-8 foot sheet of galvanized sheet metal painted a dark color on the side facing the sun is used as the absorber.

The blinds are installed so they can be operated from inside the house (we usually have all the controls put on one side of the blind.) The optimum configuration is with the blinds turned upside down so that the concave side faces up. That side can then be a dark color, such as dark bronze, while the bottom convex side is white.

If you find that these are too expensive, blinds that are dark bronze on both sides also will work. They just don't have the same flexibility.

The solar bronze glass absorbers are standard-sized tempered patio-door glass. They are mounted on rollers, and slide on a steel track to make them easier to clean. They are held at the top in a wood track.

Since the heat absorbing glass is quite expensive (though it does provide a wonderful view), it makes sense to use sheet metal as the absorber where you cannot see through the collector. The sheet metal is installed on a track made of two pieces of galvanized drip cap mounted at the top and bottom of the collector. It is held at one point at the top so it can expand in all directions.

As you are putting in the solar collector, it is very important that it be well-caulked and insulated to keep heat losses to a minimum. Many different kinds of caulking are available. Silicone is probably the best and the most expensive, but could be well worth it in terms of reduced maintenance costs.

The collector should allow for exhausting heat during the summer. This is accomplished by putting vents with barometric dampers near the top of the collector on each side. The vents are Fra-FF return air filters which can be plugged with one inch Styrofoam board in winter to keep heat from escaping.

Barometric dampers are simply light weight cloth flaps that allow air flow in one direction only. A damper also is used in front of the distribution fan so that house air can flow into the collector, but collector air is prevented from flowing backwards into the house.

In either a new or retrofit design, it is best if the solar heating system is totally separate from the back-up heating or house furnace system. In new, properly designed homes, a few baseboard heaters, heat lamps in the bathrooms and perhaps over the breakfast area, and an energy efficient recirculating fireplace with outside combustion air may be the only back-up needed.

Hybrid ClearView and NoView solar heating systems have been in use since about 1976 in Tucson. They have worked extremely well, keeping new houses with high mass construction between 68 and 75 degrees during average winters and keeping older homes between 58 and 75 degrees without back-up heating. (The latter may sound cold, but the homeowner just wanted to see how the house would work without turning on the furnace.)

In high mass homes, the temperature swing is usually about 6 degrees from morning to evening. This means that the temperature changes very slowly from perhaps 68 degrees in the morning to 74 degrees in the late afternoon.

Now that you know what a hybrid solar heating system can do, you may want to know how large a system you need. In Tucson, based on analyses carried out at the University of Arizona Environmental Research Laboratory, a 4-by-8 foot panel should provide about 20,000 Btu's per day. Thus, if you calculate your home heat loss to be 100,000 Btu's per day, you will need five panels.

To calculate heat loss (or gain), get a copy of a booklet called "Energy Conservation for the Home" by John Reagan from the UA Electrical Engineering Department. The procedures are quite simple to follow, although somewhat time-consuming. However, they can help you learn where you are losing heat from your house.

For further details on how to build a hybrid ClearView Solar Collector, Rodale's New Shelter magazine published an article I wrote, called "The See-Through Solar Wall" in their January 1981 issue.

Helen Kessler is an architect with the University of Arizona Environmental Research Laboratory.

APPENDIX II

Klos Window Description

1. "Low-Cost Key to Year-Round Comfort May Be Klos Window" by Helen J. Kessler
2. "Windows for Accepting or Rejecting Solar Heat Gain" by John F. Peck, T. Lewis Thompson and Helen J. Kessler

Low-cost key to year-round comfort may be Klos window

Helen J. Kessler

One of the finest devices for staying comfortable in the summer and collecting solar heat in the winter is the Klos window.

A solar heating and heat rejection device similar to the ClearView Solar Collector developed by John Peck and his colleagues at the University of Arizona Environmental Research Laboratory, it was introduced to the research lab by Stanley Klos of Tucson.

What makes the Klos window so fine is its extreme simplicity. It consists of two standard single-glazed windows with a Venetian blind installed in between.

The windows, which should be installed a minimum of 3 to 4 inches apart, open in opposite directions.

Actually, you have a choice. The least expensive outside window is a horizontal sliding aluminum residential grade window. The inside window can be either the same type of window, but open in the opposite direction, or it can be a storm window that opens in both directions and allows for easy removal of both panes of glass.

The surprise about the Klos window is that the two single-glazed windows cost only a small percentage more ($10 to $15 for a 4-by-4-foot window) than a double-glazed window of the same quality.

The Venetian blind can either be perfectly ordinary or slightly special. Either way, it costs about the same. We prefer to use a slightly special blind, which has the slats installed upside down. Normally, the convex side faces up; we usually face the concave side up. The up side is a dark color, usually a dark brown, but a dark green, red, blue or black would also work; and the down side is a white.

This allows the blind to conveniently absorb solar radiation on the dark side. The white side seems to obstruct the view somewhat less than a dark slat does and can be used to reflect sunlight back out the window during spring, fall and winter. Also, dust on the upper surface does not seem to be as noticeable with this configuration.

Blinds can be purchased with either 1- or 2-inch slats, although the 1-inch miniblinds usually are preferred. It is most important, however, that the ladders be made from polyester strings, rather than cotton, rayon or nylon tape, which don't hold up in the sun as well.

OK, so why are we going through all this trouble with a window? Because it provides good solar control in both summer and winter.

In its simplest mode of operation — closed — it offers

See KLOS WINDOW, Page 2J

Klos window grabs winter heat

Continued from Page 1J

slightly better insulation than a standard aluminum double-glazed window because it provides a thermal break between the aluminum window frame on the outside and the frame on the inside. A great deal of heat can pass through the aluminum frame because it is an excellent conductor of thermal energy. Also, by using two windows, air infiltration is reduced, since the wind has to pass through two windows instead of one. However, on the debit side, two windows mean more glass surfaces to clean.

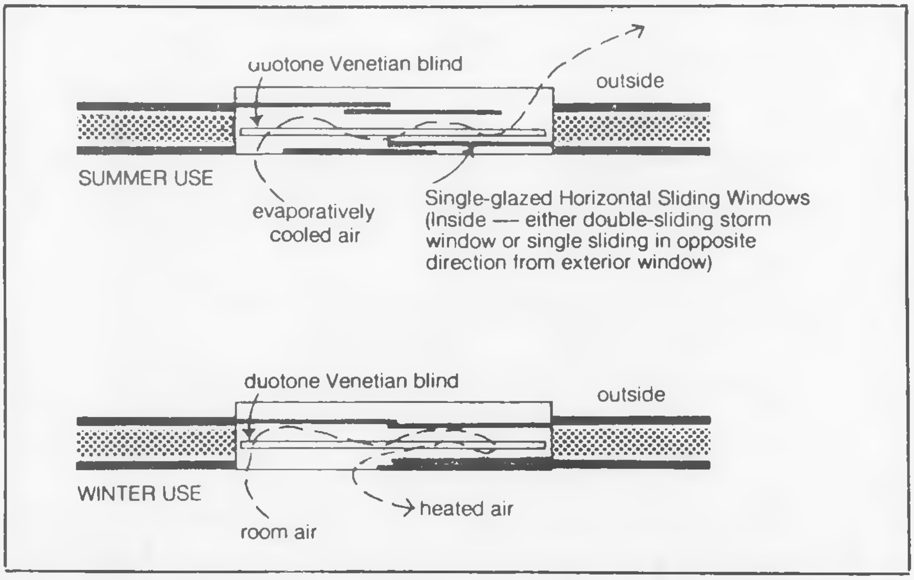
In the winter, the Klos window can be used as a controllable means of collecting solar heat. When you want heating and the sun is out, simply open the inside window and tilt the blinds so that no sunlight strikes the floor. They do not need to be closed. As long as no sunlight is hitting the floor, most of the solar radiation will be absorbed by the Venetian blinds. That also means that you can avoid fading your furniture and carpet.

The sun heats up the blinds and the heat is transferred by natural convection to the air inside your house. If the house gets too hot, just close the inside windows. And if it's still too hot, open the outside window.

Where the Klos window "shines" even brighter is in an evaporatively cooled house during the summer. When the evaporative cooler is on, you can open the inside window several inches and the outside window several inches on the opposite side and evaporatively cooled air will flow out between the two windows, exhausting any solar heat absorbed either by the blinds or the glass.

This actually provides a cool surface between you and the hot outside air and significantly lowers the radiant temperature inside the house. In fact, according to tests made at the research lab, the Klos window reduces the solar heat gain by up to 90 percent — better than any window shade. And it still provides a good view.

Because it does such a good job of reducing summer heat gain, we put it on north, south, east and west windows. The north windows are the only ones on which you might think it is not needed. But north windows can gain almost as much heat in the summer as south. The window also works in an air-conditioned house, just not as brilliantly. To reduce solar heat gains, the outside window can be opened completely and the blinds lowered. They will help keep solar heat out, before it enters the window and is cooled by the ambient air. However, in an air-conditioned home, exterior window shades would keep solar heat from entering windows more effectively. (The Klos window would continue to provide the other advantages mentioned previously.)



Besides being a good energy-saving window, the Klos window has several other features worthy of note.

If you use two single sliding windows that slide in opposite directions with one fixed pane of glass in each, you can easily leave them open when you leave the house. They will provide as much protection from intruders as a closed window.

Why? Well, there just aren't very many 4-inch-wide burglars around. So if an intruder wants to get in, he would have to break the glass. If you use a storm window on the inside (which many prefer), you can secure — from the inside — the window that doesn't need to slide, and provide yourself with similar protection.

The advantage of the storm window is that it is easily removable so that you can clean the blinds and glass. It also provides a possibility for escape through the window in case of fire, because you can open both panes on one side of the window. If two single sliding windows are used, then — just like the burglars — you would have to break a pane of glass to get out.

The Klos window is available either as a pre-manufactured unit or as something that can be assembled at the site. The latter is less expensive, but takes a certain amount of thought to make sure they are installed correctly.

The window is least expensive when installed in a new home, especially if the individual components are installed on the job. It can also be retrofitted to an existing home with aluminum sliding windows. Again, be sure to try to get a minimum of 3 to 4 inches between the two windows.

Double-hung Klos windows also work well, probably better than horizontal sliding windows. Unfortunately, they cost a lot more and are more difficult to obtain. Wood may work better than aluminum, too — but again, cost is a limiting factor.

The Klos window is truly an energy-saving device for all seasons. In the winter, it allows for controllable solar hating. In the summer, it effectively keeps out unwanted solar heat gains. And at all times it provides better insulation than a standard double-glazed window. Best of all, it is simple and relatively inexpensive.

Kessler is an architect with the University of Arizona Environmental Research Laboratory. She welcomes your questions, and while she cannot respond to you individually, she will try to answer them in future columns. Write to her in care of The Arizona Daily Star, Box 26807, Tucson 85726.

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WINDOWS FOR ACCEPTING OR REJECTING SOLAR HEAT GAIN

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Abstract

Ordinary windows may be modified at low cost using various combinations of windows, duotone venetian blinds, and drapes to control the solar heat gain. In the winter, solar radiation may be absorbed by dark blinds and transferred to the air, minimizing fading of furnishings while collecting useful energy. In the summer, 95 percent of the total potential window heat gain may be rejected by exhausting evaporatively cooled air over the blinds.

1. Introduction

There is a need for low-cost window designs in hot arid climates which allow winter-time solar heat gain to controllably enter the house in the form of hot air, and which allow summer-time window heat gain to be exhausted by evaporatively cooled air flowing out of the window. Such treatments should allow solar heat to enter the house without fading the furnishings, and permit significantly more solar heat gain during the winter than do closed white drapes. The view out the window should also be relatively unimpeded by such window treatments.

These studies have been conducted as a small part of the broader LBL window program (1).

2. The Klos Window

The Klos window (2), satisfies these requirements. It can be composed of two half-slider (horizontal movement) windows which open on opposite sides and which enclose venetian blinds, as shown in plan view in Fig. 1. The blinds have a dark concave upper surface, and a white convex lower surface. Sunlight is absorbed by the dark upper surface, while the white lower surface is visible from the inside of house, decreasing the visual impact of the blinds.

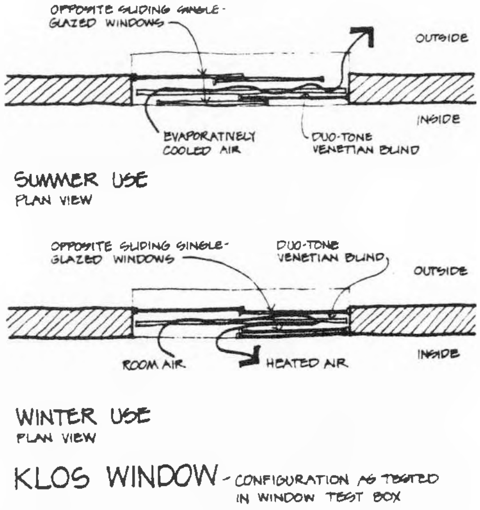


Fig. 1

During the winter, the interior window is open while the exterior window is closed (Fig. 1). The venetian blinds heat air flowing over them by natural convection, which then enters the house. To prevent overheating, the windows may both be closed, the white side turned out, or the inside window closed and the outside window opened.

During the summer, windows are opened at opposite ends. Evaporatively cooled air flows out over the solar heated venetian blinds, carrying this heat outside without blocking the view. Additionally, a layer of cool air is interposed between the hot ambient and cool interior air. Thus the window heat gain is greatly reduced, since radiation, conduction, and convection heat gains are all affected by this window treatment.

Klos windows must be properly designed. The two windows must be set apart as far as possible, approximately 3-5 inches, to permit air flow through the window and allow the blinds to be removed. Any fixed panes in the windows must be accessible for cleaning, and no area of a fixed pane should be more than 0.6M (2 ft) from an opening for cleaning and air access to the blinds.

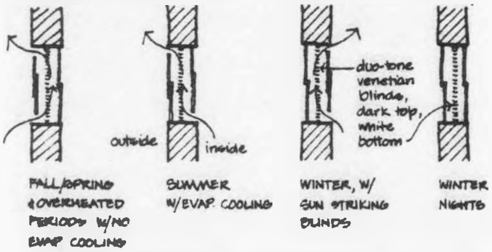
When a Klos window is installed in an exterior mass wall with outside insulation, heat stored during the day in the mass adjacent to the window can reduce nocturnal heat losses from the occupied areas of the house. The masonry must not be insulated from the space between the windows in this case.

Each blind should be no wider than the height of the window, to allow their removal. The use of storm windows with "lift out" panes as the interior window improves accessibility.

Surprisingly, the cost of two single glazed windows is little more than a double glazed window of equal quality. If two half-slider windows are used and opened as shown in Fig. 1, entry into the house is not possible without breaking the window. If a Klos window is installed in a bedroom, a double-sliding window (some storm windows are double sliding) should be used so that the window can be completely opened on one side for egress in case of fire. However, unwanted entry is not prevented as easily with this type of window.

Using polished aluminum venetian blinds may be advantageous if their glare problem is controlled (3).

As shown in Fig. 2, vertical-sliding, double-hung windows can be also be used, and would be more efficient than horizontal-sliding windows.

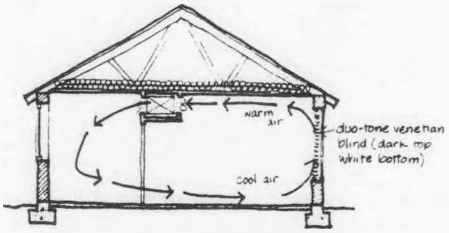


KLOS WINDOW OPERATION (DOUBLE HUNG)
SECTION VIEW

Fig. 2

3. ClearView Solar Absorber

This design uses an ordinary window with a duotone venetian blind like that used in the Klos window. The insolation absorbed by the dark upper surface of the venetian blind heats air, which is convected upward into the house, as in Fig. 3.



ClearView Window Solar Absorber
w/automatically controlled fan to distribute heat

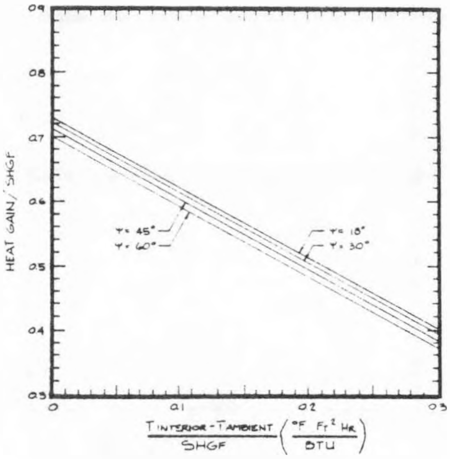
Fig. 3

During the summer, white lined drapes can be used to direct evaporatively cooled air along the venetian blind slats between the drape and the window. This reduces window heat gain in a manner similar to that of the Klos window. The drape edge must be pinned back along the edge opposite the opening so that airflow is permitted along the drape and out the window. The drape liner must be prevented from blowing against the window. Also, in some cases it will be advantageous to enclose the top of the drape with a valance. This technique has not yet been formally tested as part of this program, but it does appear to work well if properly adjusted

4. Estimating Heat Gain Values

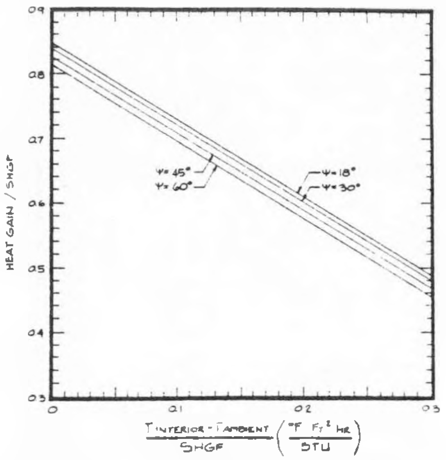
Hourly winter heat gain values for these window treatments are easily estimated using the graphs in Figs. 4 and 5, and the readily accessible ASHRAE (4) Solar Heat Gain Factors (SHGF) for the appropriate latitude, orientation, date, and time of day. The SHGF values give the insolation transmitted through single glazed windows in English units, which we have conformed with in this instance for the convenience of those using the ASHRAE tables. Thus the variables affecting light transmission through the windows are accounted for, and we only need one graph for each window treatment.

The graphs in Figs. 4 and 5 are based upon a computer model of each window treatment, and are essentially Hottel-Whillier-Bliss (5), (6) solar collector efficiency curves, since properly oriented windows are solar collectors. Note that the curves in Fig. 4 and 5 are based on transmitted radiation, not insolation striking the exterior window surface. The efficiency of the window at various blind tilt angles (from the horizontal) is given on each graph, which are valid only when all direct sunlight is absorbed by the slats. As long as this is



KLOS WINDOW HEAT GAIN BASED ON THE ASHRE SHGF VALUES

Fig. 4



CLEAR VIEW SOLAR ADSORBER WINDOW HEAT GAIN (SINGLE GLAZED) BASED ON THE ASHRAE SHGF VALUES

Fig. 5

true, the effect of the blind tilt angle appears to be minor.

To estimate the winter heat gains or losses for various window treatments, choose the graph for the appropriate window treatment.

1. Calculate the (T Int. - T amb.)/ SHGF factor for the appropriate design temperatures and the ASHRAE SHGF values for the desired window orientation and date for each hour of the day, or for selected hours.

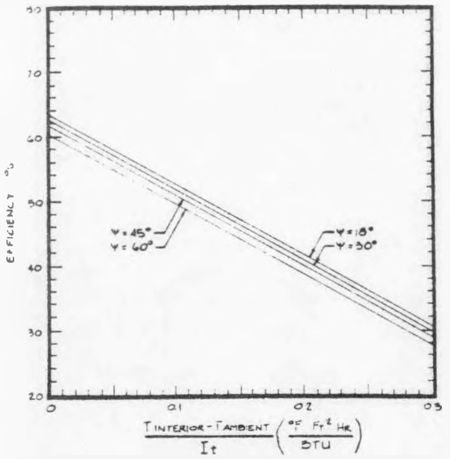
2. Determine the heat gain-SHGF ratio for each hour from the graph, and multiply it by the SHGF for that hour. This is the net hourly heat gain from the window, including conduction and convection heat losses or gains.

Winter heat gains are often calculated over a 24 hour period, and the solar heat gains are calculated independently of conduction and convection losses. Since the above hourly heat gain combines these two terms, it must be modified if it is to conform to this calculation procedure. Thus, the hourly conduction and convection losses must be calculated from the interior temperature, the ambient temperature, and the window U value, and added to the above solar heat gain terms for each hour with significant solar gain. These modified solar gain terms are summed over the entire day, and are used in the 24 hour heat loss or gain calculations for a house. The conduction and convection values added to form the modified SHGF are subtracted along with the rest of the conduction and convection losses in the final calculation. Once determined, this modified value of the SHGF for a specific treatment, window orientation, date, and design temperature for a given location can be used repetitively for design purposes.

Similar graphs of window efficiency are given in Figs. 6 and 7. These graphs are based on the insolation striking the outside surface of a window, not the transmitted radiation given by the SHGF value. Figures 4,5,6, and 7 were based on 5 cm (2 in) wide blinds; a blind width of 2.5 cm (1 in) gives efficiencies from 0.5 to 1.0% higher, due to slightly higher convection heat transfer coefficients.

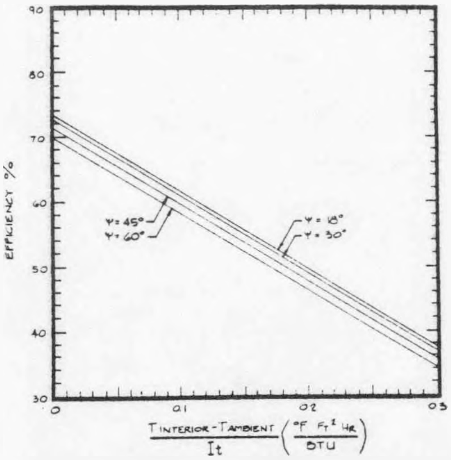
The measured total summer heat gain in full afternoon sun from the west facing 1.22x1.22 M (4 ft x 4 ft) Klos window tested in this program is only 2-5% of the insolation striking the window, depending on the flow rate of evaporatively cooled air through the window. The test air flow rates varied from 0.3 to 0.1 $M^3 sec^{-1}$(630 to 240 $Ft^3 min^{-1}$).

Thus, the hourly heat gain in the summer for the Klos window may be conservatively estimated by ignoring conduction/convection heat gains, and using a 0.05 transmission factor for the SHGF. The tilt angle of the blinds is not an important variable, so long as all direct sunlight is intercepted.



KLOS WINDOW HEAT GAIN BASED ON INSOLATION STRIKING WINDOW EXTERIOR, 12 NOON, DEC 21 AT 32° N LATITUDE

Fig. 6

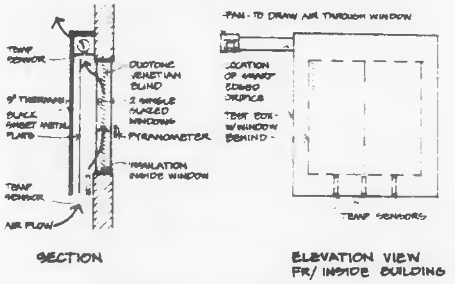


CLEAR VIEW SOLAR ABSORBER WINDOW HEAT GAIN (SINGLE GLAZED) BASED ON INSOLATION STRIKING WINDOW EXTERIOR, 12 NOON, DEC 21 AT 32° N LATITUDE

Fig. 7

5. Verification of Results

The curves presented in figures 4-7 are based on correlations in the literature (7) (8) (9) (10), and data obtained from a window calorimeter, which consisted of an insulated box attached to the window, as in Fig. 8. Air was drawn through the box vertically at a low velocity, over the interior window surface and a black absorber plate into a plenum in the upper section of the box. It is important that low air velocities are used, so that free convection conditions prevail.



WINDOW TEST BOX

Fig. 8

The air flow was measured with a sharp-edged orfice at the outlet. Temperatures were measured with thermocouples, shielded where necessary from thermal radiation. Energy input was determined from the temperature rise of of the air, while solar radiation was measured with pyranometers.

The rate of natural draft airflow into the closed portion of the Klos window during the winter, see figure 1, proved difficult to calculate, although the equations given by Brown, et.al. (10) were quite useful. Ultimately, a constant was determined for a convective heat flow equation which gave calculated efficiencies and temperatures consistent with experimental results.

During the summer test of the Klos window, the insulated box was moved sideways, so that the window could be opened slightly, to allow evaporatively cooled air to be exhausted through the window. The heat gain through the remaining glazed area was measured, and the radiant heat gain through the opened portion calculated from the measured slat temperatures in the open area. The measured heat gain, corresponding to heat gain through the glass into the room, was from 2.5 to 5% of the outside solar radiation, depending on the air flow. Analyses of similar geometries are given in the literature (11).

6. Conclusions

The Klos window and The ClearView solar absorber controllably transmit significantly more usable heat to a house in the winter than a window with a white lined drape, closed to prevent fading. When used in a mass wall, the Klos window can reduce heat losses from the occupied space in a house, at the expense of less daytime heat gain.

The Klos window virtually eliminates summertime window heat gain when used in evaporatively cooled houses.

The cost of these window treatments can be minimal.

Acknowledgements

We would like to acknowledge the support of DOE-LBL for the support of this program, as well as the understanding management of the program by the DOE administrator, Mr. Richard Johnson. A complete report and bibliography covering this work will be available in the near future.

References

1. Window and Lighting Program, Lawrence Berkeley Laboratory, University of California Berkeley, Calif. 94720
2. Stanley Klos of Tucson, Arizona is the first person, to the authors' knowledge, to have used this design.
3. Rosenfeld, A.H. and Selkowitz, S.E., 1977. Beam Daylighting: An alternative Illumination Technique. Energy and Building, vol. 1, p 43-50
4. 1977 ASHRAE Handbook of Fundamentals. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., 345 E. 47th Street, New York, NY 10017.
5. Hottel, H.C. and A. Whillier, 1955, Evaluation of flat-plate solar collector performance, Trans. Conf. on Use of Solar Energy, 3, Tucson, Arizona, p 74-104.
6. Bliss, R.W., 1959, The derivations of several "plate-efficiency factors" useful in the design of flat-plate solar heat collectors, Solar Energy, Vol III, No.4, p 55-64.
7. Parmelee, G.V. and D.J. Vild, 1953. Design Data for Slat-Type Sun Shades for Use in Load Estimating. . .ASHVE Research Report No. 1485, ASHVE Transaction, Vol. 59, pp 403-434.
8. Raithby, G.D. and K.G.T. Hollands, 1975. A General Method of Obtaining Approximate Solutions to Laminar and Turbulent Free Convection Problems. Advances in Heat Transfer, Vol II, Academic Press, Inc., New York, NY, pp. 26-345.
9. Elenbaas, W., 1942. Heat Dissipation of Parallel Plates by Free Convection. Physica IX No. 1, pp. 1-28.
10. Brown, W.G., Wilson, A.G., and Solvason, K.R., 1963. Heat and Moisture Flow Through Openings by Convection. ASHRAE Transactions. Vol. 69, 1963. pp. 351-357.
11. Peck, J.F., et al. , 1977. A Greenhouse Residence Utilizing a ClearView Solar Collector and Two-Stage Evaporative Cooling. Proceedings of a Conference on Solar Energy for Heating Greenhouses and Greenhouse Residential Combinations, Cleveland, OH.

APPENDIX III

Evaporative Cooling Description

1. "Evaporative Cooling for Hot Arid and Semi-Arid Regions" by John F. Peck and Helen J. Kessler

EVAPORATIVE COOLING FOR HOT ARID AND SEMI-ARID REGIONS

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ABSTRACT

Various methods of using evaporative cooling to enhance comfort are discussed. Simple direct evaporative cooling methods, as well as the more complex two-stage, indirect and recuperative (regenerative) cooling systems have been used. By combining evaporative cooling with other passive cooling strategies such as earth integration or mass, rejecting heat before it enters a space and flexible zoning, greater comfort, potentially at less cost, may be obtained. Use of the psychrometric chart, as well as some sizing guidelines are also discussed.

INTRODUCTION

Various forms of evaporative cooling have eased the travail of life in hot arid regions for much of mankind's existence. The medieval Arab's view of paradise was a garden, evaporatively cooled by fountains and water transpired from the leaves of green plants. Natural drafts through openings in walls filled with wet twigs, or through damp chimneys and tunnels in the earth have also been used. The latter also incorporates the beneficial effects of the lower temperatures present in the earth itself and points out the advantages of integrating evaporative cooling and other methods of passive cooling in order to maximize their cooling effects.

Modern direct evaporative cooling is simple and convenient and is available in a compact manufactured box. A fan draws ambient air through wet fiber pads, cooling the air by evaporation before blowing it into the house. The air is exhausted out through windows and other openings, preferably through sources of heat gain, so that solar heat is rejected before it enters the occupied spaces. However, during particularly hot and relatively humid conditions, direct evaporative cooling may not provide desired comfort levels.

Since the 1930's, innovative technologists have been devising methods of using two evaporative cooling processes in series to produce still colder or drier air. These are called "two stage, indirect, or recuperative evaporative cooling systems". Two basic evaporative cooling devices were available to designers, a cooling tower, which produces cold water or an evaporative air cooler, which produces cool air.

Unfortunately, simply blowing air from one evaporative cooler into another does not produce significantly colder air. Two stage evaporative cooling is only achieved by pre-cooling air without humidification before further cooling by evaporation. The first stage can be a cooling tower, an ordinary evaporative cooler, or any other cooling effect, such as nocturnal radiation. A heat exchanger then uses the cool fluid or cooled air from the first stage to precool (without humidification) outside air entering the second stage evaporative cooler, thus producing lower output air temperatures. The cool air flows through the house, and out, preferably through sources of heat, as in direct evaporative cooling. We have developed a system where a large rockbed is cooled at night. The following day, the rockbed is used to precool air without humidification before further cooling by evaporation. The thermal storage inherent in this system has several advantages, including two stage evaporative cooling output temperatures lower than those produced in systems which do not have thermal storage.

Indirect evaporative cooling, another evaporative cooling method, does not humidify the air in the structure. An evaporative cooling device, commonly a cooling tower, is used to cool the air in the house indirectly through an air-water heat exchanger over which interior air is recirculated. This prevents the house air from being humidified. However, heat exchangers cannot cool the house air to the temperature of the cooling tower water or air in them, and very dry conditions are required for this system to work well.

To circumvent the above limitation, indirect recuperative (regenerative) evaporative cooling systems were developed. Instead of recirculating house air through a heat exchanger, as in the above indirect system, outside air is continuously cooled by the heat exchanger as it enters the house. Since air leaving the house is considerably cooler than the outside air, and has not been humidified, it can be used as the input air to the evaporative cooling device. This lowers the output temperature of the evaporative cooling device, thus lowering the temperature of the heat exchanger, and lowering the temperature of the house below that which would be attained by a non-regenerative system. (This is not perpetual motion!). Many systems of this type use a cooling tower as the evaporative cooling device. One uses a dual rockbed, and another uses a rotating wheel which alternately cools outside air and is cooled by an evaporative cooler.

The following discussions about these forms of evaporative cooling do not cover all of the possible systems. The particular variation which you think of may not be strictly original, but it is your idea if you independently thought of it. Conditions in our changing world, new materials, or even methods of algae control may make it an idea whose time has come.

For a thorough description of evaporative cooling and evaporative cooling devices developed before 1963, see John Watt's book, Evaporative Air Conditioning (1).

I. Direct Evaporative Cooling

A. Evaporative Cooling Devices

Many kinds of direct evaporative cooling devices are commercially available. Some are used on residences, while others are used on commercial buildings where low maintenance is a factor. Others are site-built and used primarily on greenhouses.

1. Drip-Type Direct Evaporative Air Coolers

This is the ubiquitous residential and light commercial evaporative cooler used throughout dry areas of the southwest. It consists of a metal box containing a fan with fiber pads on 3 or 4 sides of the box. While city water pressure can be used to drip water through the pads, in most installations a pump recirculates water through the pads in order to improve the efficiency.

The fan in such drip-type coolers blows air out the bottom or the side of the box. Units that blow the air upwards have advantages in ground mounted installations and are commercially available on special order.

These economical units are easily maintained by the homeowner. The large areas of fiber pad on each unit (and consequent low air speeds) make them efficient coolers.

Most manufacturers publish certified curves of airflow vs the duct pressure drop. These, rather than the so-called "nameplate" airflow rates, are used for design purposes since the cooler never produces the nameplate airflows, even without any external resistance to airflow.

2. Spray Type Evaporative Air Coolers

In some cases, fine misting nozzles are installed in a large corrosion resistant duct. Air is blown through the duct, and is evaporatively cooled by contact with the fine water mist. CSIRO, in Australia used such a cooler, but report that due to the lack of mist eliminators, the mist carries over into the ductwork.

3. "Slinger" and Horizontal Pad Evaporative Air Coolers

The "slinger" is a commercial type of evaporative cooler which combines the drip and spray types. A rapidly rotating wheel throws a sheet of water in the air, which is broken up into droplets by the incoming air, cooling the air somewhat before wetting a fiber pad like those in the drip-type cooler. This wetted pad further cools the air. These devices have fewer clogging and scaling problems than drip-type coolers.

The horizontal aspen pad evaporative cooling devices installed on some greenhouses are similar. Water is sprayed over horizontal aspen pads. Cooling occurs both by evaporation from the misted water as well as from the wet pads, which serve as a mist eliminator. As in the slinger, clogging and scaling are greatly reduced as compared to vertical pads, and the pads do not tend to sag and form air leaks. The efficiency of the system improves as the droplet size of the sprayed water decreases.

4. The Rotary Pad Evaporative Air Cooler

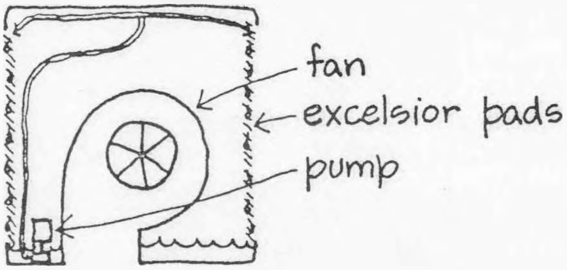


Figure 1. Direct Evaporative Cooler

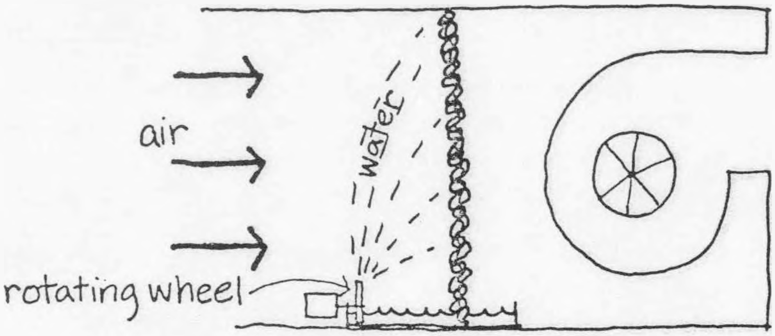


Figure 2. "Slinger" Evaporative Air Cooler

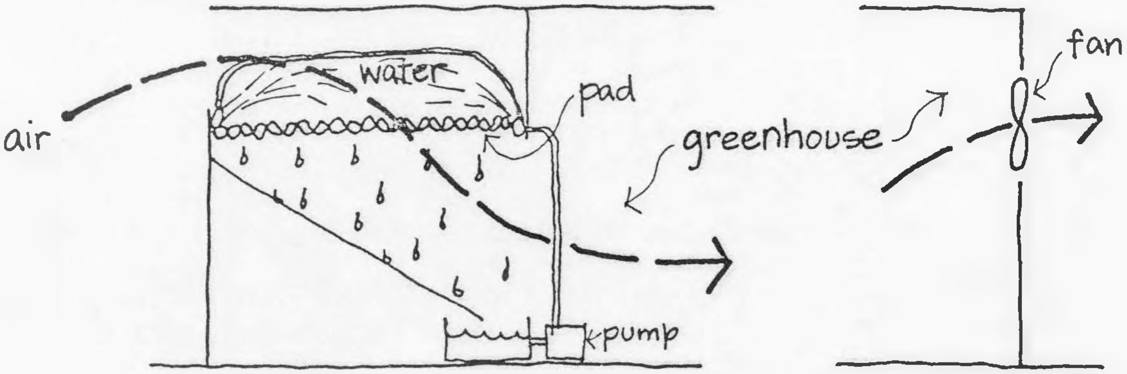


Figure 3. Greenhouse Evaporative Cooler

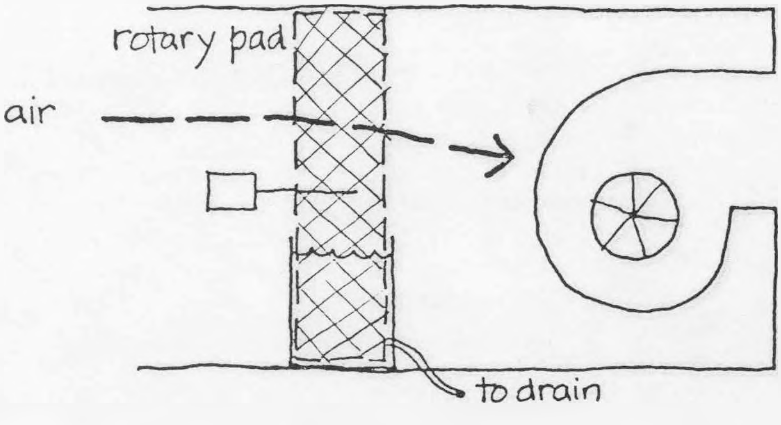


Figure 4. Rotary Pad Evaporative Cooler

This device is considered to have the lowest maintenance requirement of all the evaporative coolers and is very quiet during operation. It is also the most expensive. A rotating piece of wire mesh (generally copper) passes through a water tank, and then rotates slowly into the airstream entering the building, cooling the air as the water on the wires evaporates. Both its shape and the lack of mist from the rotating drum make this cooler useful.

The water tank is drained periodically by a timer. Clogging and scaling are almost non-existent. Rotary pad coolers can also be easily used in multiple groupings. We have operated one at ERL for three years. No maintenance has been required.

B. Use of the Psychrometric Chart

The Psychrometric Chart, available in the ASHRAE Handbook (2) and many mechanical systems texts, is used to depict the changes in the state of the air as it is cooled evaporatively. In a direct evaporative cooling system, the psychrometric chart is used as follows:

When ambient air enters the evaporative cooler at A (see figure 5), the evaporative cooler cools the air along the constant wet bulb temperature line to B. This is because most evaporative coolers will cool the air approximately 70% ± 10% of the distance from point A to the curved line at the extreme left of the psychrometric chart. In the process of evaporation, latent heat has been substituted for sensible heat. If the temperatures in the structure can be maintained in the low 70's, the amount of latent heat in the air does not effect comfort until it almost reaches saturation levels.

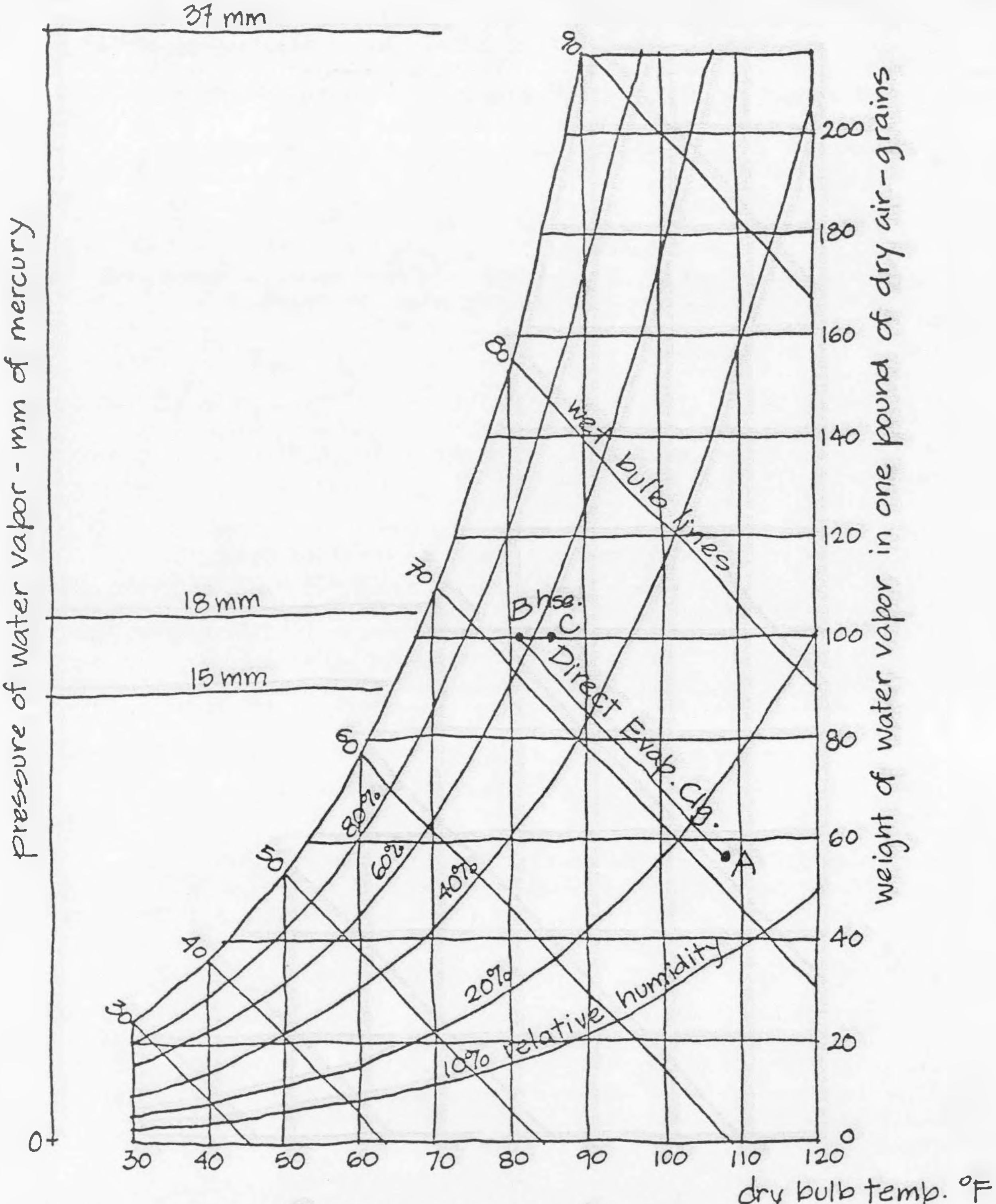
C. Ambient Weather Requirements for Evaporative Cooling.

ASHRAE tables of design wet bulb temperatures are helpful in determining areas where evaporative cooling will be useful (3). In general, if the location has wet bulb temperatures of less than 70 F most of the time, direct evaporative cooling will work very well all the time. If the maximum wet bulb temperatures are greater than 75 F, relief is all that can be expected for significant periods of time.

A direct evaporative cooler will cool the air approximately 70% ± 10% of the difference between the dry bulb and the wet bulb temperature along the wet bulb line on the psychrometric chart. This can be applied to the ASHRAE coincident dry bulb temperature/wet bulb temperature data to arrive at an approximation of the output temperature of a direct evaporative cooler in a particular area.

D. Sizing Direct Evaporative Coolers

Always use a two-speed cooler where possible since the low speed position uses 2/3 as much air at 1/3 to 1/2 the power cost. Size the cooler so that the house air is changed (on high speed) every 2 1/2 minutes in a poorly insulated house with lots of glass, and up to every four minutes or slightly more if the house is well insulated, and the windows



PSYCHROMETRIC CHART

Direct Evaporative Cooling A→B→C

Figure 5

are shaded. This rule is for climates similar to Tucson. Modify these values accordingly for a climate different from Tucson, using the ASHRAE weather table. Local practice can often be a very good guide to the sizing of coolers. If you want to calculate hourly heat gains for the average or maximum days, you can calculate the approximate temperature rise of the air as it passes through the house from the formula $\Delta T(^{\circ}F)=\frac{\text{BTU/hr(heat gain into house)}}{\text{ft}^3\text{/min(airflow thru house)}}$ When combined with estimated cooler output temperatures, this approximate equation allows the temperature of the air as it leaves the house to be estimated. If the temperatures are too high, the airflow can be increased and the ΔT decreased.

Always use the biggest cooler and the smallest motor, unless you are forced to use a duct system with a high pressure drop. For example, a "5500" cooler comes with a 1/2 hp motor. A "6500" cooler is exactly the same size, but has a 3/4 hp motor installed. Since the pad size is the same, the faster airflow rate through the "6500" cooler results in less evaporation efficiency.

E. Ducts

The maximum airflow rate in ducts can be up to 1500 ft per min., but 1000-1200 ft per min is preferable to avoid high pressure drops and excessive noise. Keep ducts as straight as possible, and use turning vanes in elbows and extractors in outlets. Extractors are a set of turning vanes, and are relatively low in cost. They guide the air from the duct through the register. They can be moveable if desired, so they can selectively direct the air into occupied areas of the house. This is illustrated in Fig. 6.

These extractors are not expensive. A 10"x24" unit recently cost $13. Installations detail are in Fig. 7.

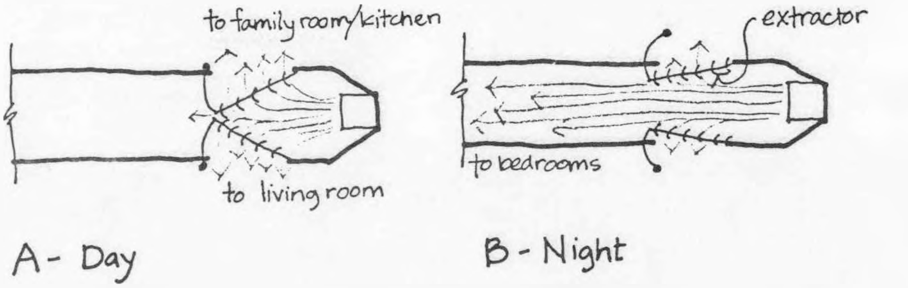
Evaporative cooling uses large volumes of air, and forcing this air through small ducts, around sharp corners, and out small outlets costs money.

In some cases, the best duct system is none. Just blow the air into a large daytime occupancy room, and through the house and out bedrooms, bathrooms, and kitchens.

F. Rejecting Heat Before it Enters the House

Since evaporatively cooled air may not be recirculated, but must be exhausted from the house, it can be used to reject incoming solar heat. Areas where heat may be rejected include the attic, hot air solar collectors and Klos windows.

Louvers with fire dampers may be installed in the ceiling of a home with an attic to exhaust air out vents on the gable ends or under the soffit. Each one square foot louver should be used to exhaust about 500 cfm of airflow. The gable ends should also have about the same area of opening. Such louvers should be put in all rooms except the kitchen. In addition to keeping the attic cool, they also allow one to keep the cooler on without opening windows.

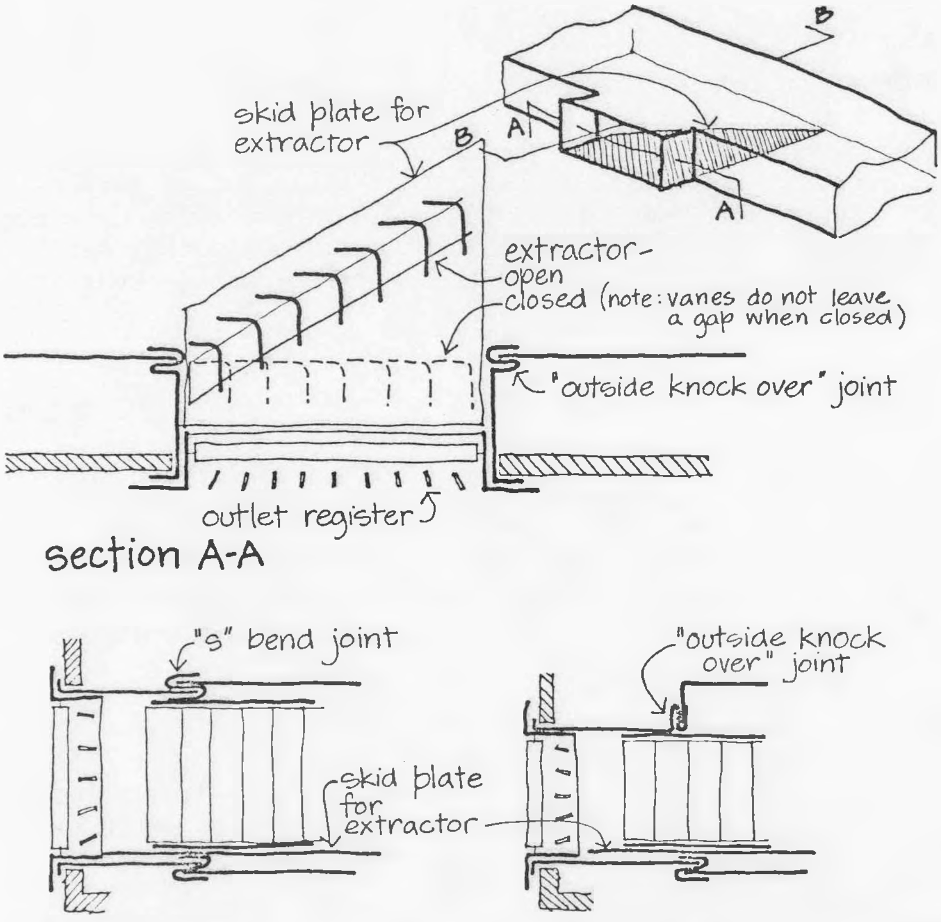


A- Day

B - Night

Flexible Zoning - extractor used to divert the coolest air as desired

Figure 6



section B-B
outlet same height as duct

section B-B
outlet height less than duct

note: do not use "inside knock over" joints

Flexible Zoning Extractor Installation

Figure 7

A second source of heat, are hot air solar collectors such as the ClearView Solar Collector (5). When such collectors are vertical, very little heat enters them in the summer. The heat that does penetrate the glass is absorbed by the absorber plate (venetian blinds, tinted glass, or metal plates which shade the wall) and is efficiently removed by the cool air flowing through the collector. Due to this self-shading feature, no overhang is needed. Barometric dampers, shown in Figure 8, allow the air to pass through the collector in one direction but prevent hot outside air from entering the house.

Klos windows are also useful for rejecting heat (as well as for collecting solar heat in the winter). They are made up of two windows with a duotone venetian blind hung in an air space in-between. The windows open on opposite ends and evaporatively cooled air is exhausted through the airspace to the outside. See Figure 9. During the summer, the window can effectively reject 95% of the incoming heat, including both radiation and conduction gains. (6).

G. The Use of Fans to Improve Comfort

The key to improved comfort in most evaporatively cooled homes is the use of small fans which keep the air moving in localized areas. Several such fans may be purchased and placed in various rooms of the house where the occupants spend the most time. The fans should be located where they can easily be turned on when one enters a room and turned off when one leaves the room. They are especially useful in homes where the cooler has been used to cool the mass of the home at night and where it is turned off during the following day.

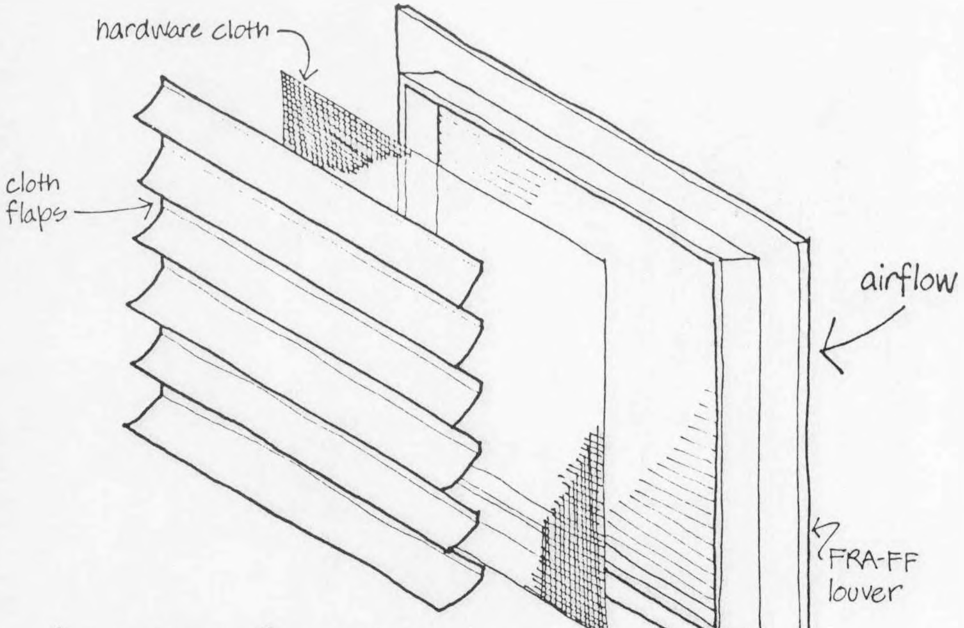
H. Cooler Location

Direct evaporative coolers can be located on the roof or on the ground. Maintenance, a frequent requirement of most direct evaporative coolers, is easier in the ground location. However, a ground mounted cooler should be under a large shaded area, and must have free air access. If the cooler is surrounded by high fences and vegetation, put the cooler on the roof. If a duct is used, it will cost more with a ground mounted cooler, since larger ducts are required. When a roof mounted cooler is used, the airflow can be split immediately after it leaves the cooler, thus reducing the duct size required.

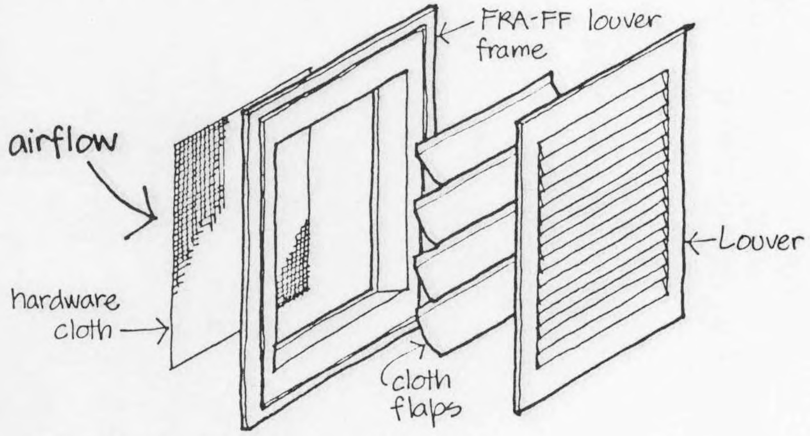
I. Alternate Non-Duct Systems

As mentioned previously, it is possible to blow the air from an evaporative cooler directly into a large daytime occupancy room. This is especially useful in retrofit situations, since ducts in existing homes are generally under sized for evaporative cooling. This method introduces the coolest air into the areas occupied during the day, and allows the cool air to flow through the house (the largest duct system available) and out unoccupied bedrooms, bathrooms, or sources of heat such as the kitchen. If additional cooling is desired in the bedroom areas at night, a second cooler can be installed for these areas.

J. Mass In Direct Evaporatively Cooled Homes

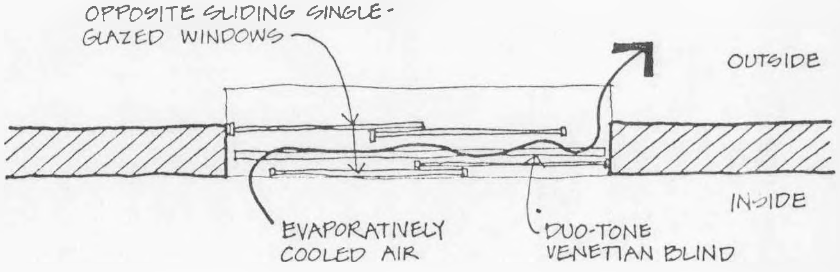


Louver and Barometric Damper for Fan Box

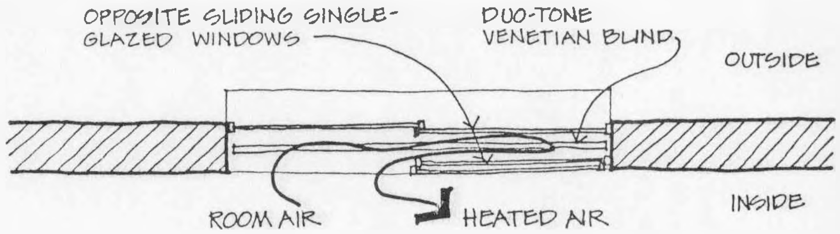


Detail for Collector Ends

Figure 8. Barometric Damper

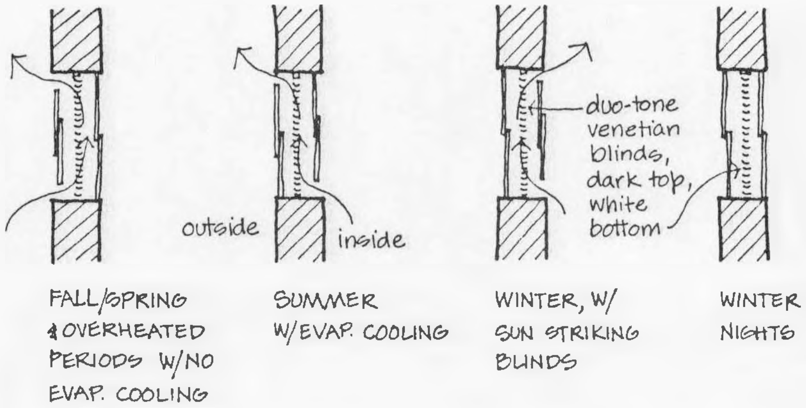


SUMMER USE
PLAN VIEW



WINTER USE
PLAN VIEW

(HORIZONTAL SLIDERS)



KLOS WINDOW OPERATION (DOUBLE HUNG)
SECTION VIEW

Figure 9

The above airflow patterns are especially useful in high mass homes (7). The cooler cools the mass in the daytime occupancy areas at night. The mass in those areas warms the air flowing out the bedrooms slightly, preventing excessive cooling (and reducing one's tendency to turn the cooler off at night). The next day, the cooled mass reduces the peak temperatures in the house, compared to those in a low mass house with the same evaporative cooling facilities. Figure 10 compares the interior conditions in a high mass (left side) and a low mass home with identical floor plans. Figure 11 illustrates the effect of mass in stabilizing interior temperatures, in the same two homes.

Such high mass homes also provide an opportunity to utilize dessicant systems to improve comfort. Although not experimented with yet, theoretically, one could use a dessicant to help dry out the air in an evaporatively cooled home. Since the air is heated only slightly as it dries, this minimal amount of heat could be absorbed by the cool walls of a high mass house. The dessicant would then be regenerated in a solar heater.

K. Cooler Maintenance

An evaporative cooler will perform well and last much longer if a schedule of weekly and yearly maintenance is carefully adhered to. Some tips for cooler maintenance are enumerated below.

1. The inside of the cooler should be completely tarred with black asphalt before it is ever used. This will extend its life significantly.

2. The cooler should be cleaned and retarred once a year, preferably at the end of the cooling season.

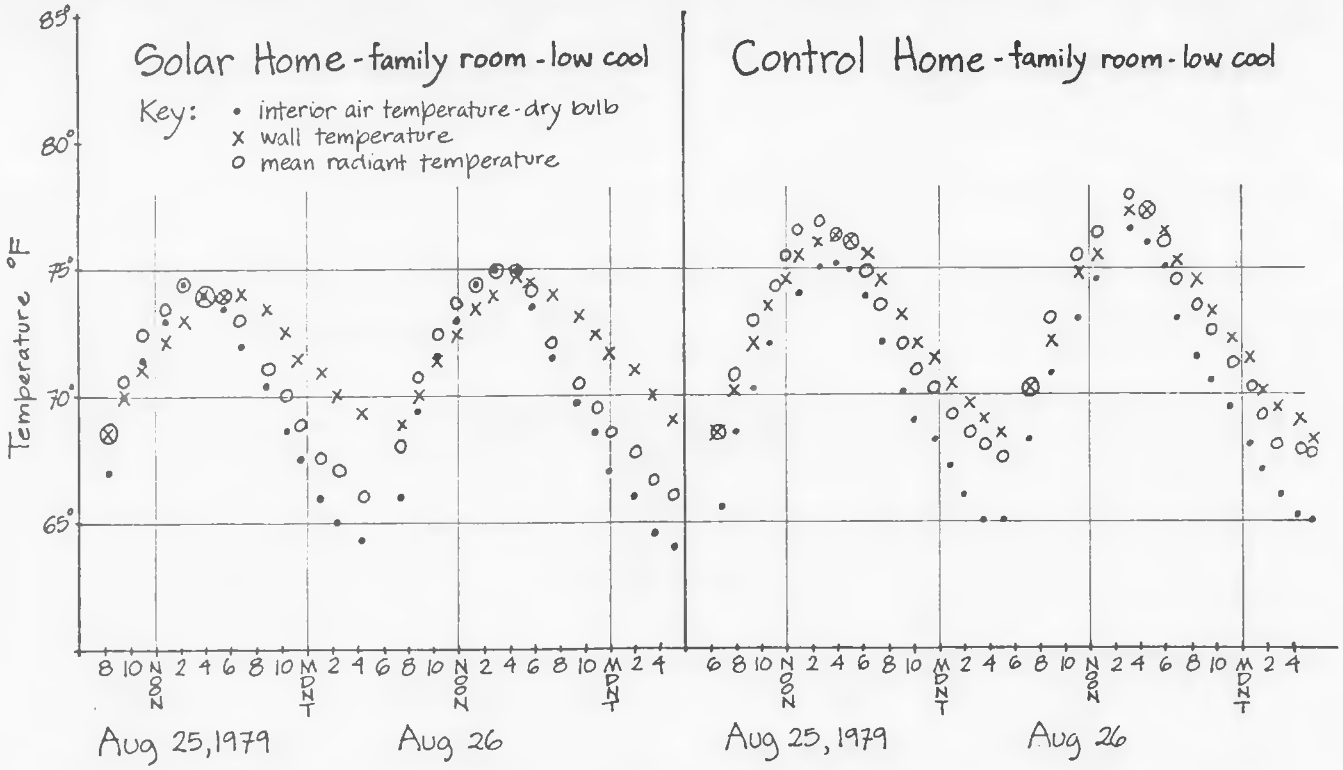
3. The excelsior pads should be changed at least once a year. Although it's more convenient to replace them when the cooler is being cleaned in the spring or fall, it may be more effective to change them in late June, just before the high heat of the summer. Pads with a cheesecloth covering should be avoided since they promote clogging by scale on the outer surface.

4. If a regular thumping sound is heard, the belt is cracked and should be replaced immediately -- before it breaks at some inconvenient moment.

5. In order to reduce scale build-up on the pads (from minerals dissolved in the water), a "bleed off" kit may be installed. The kit allows a small amount of water to be removed constantly while the pump is on. Scale may also be controlled by draining the sump at least once a month.

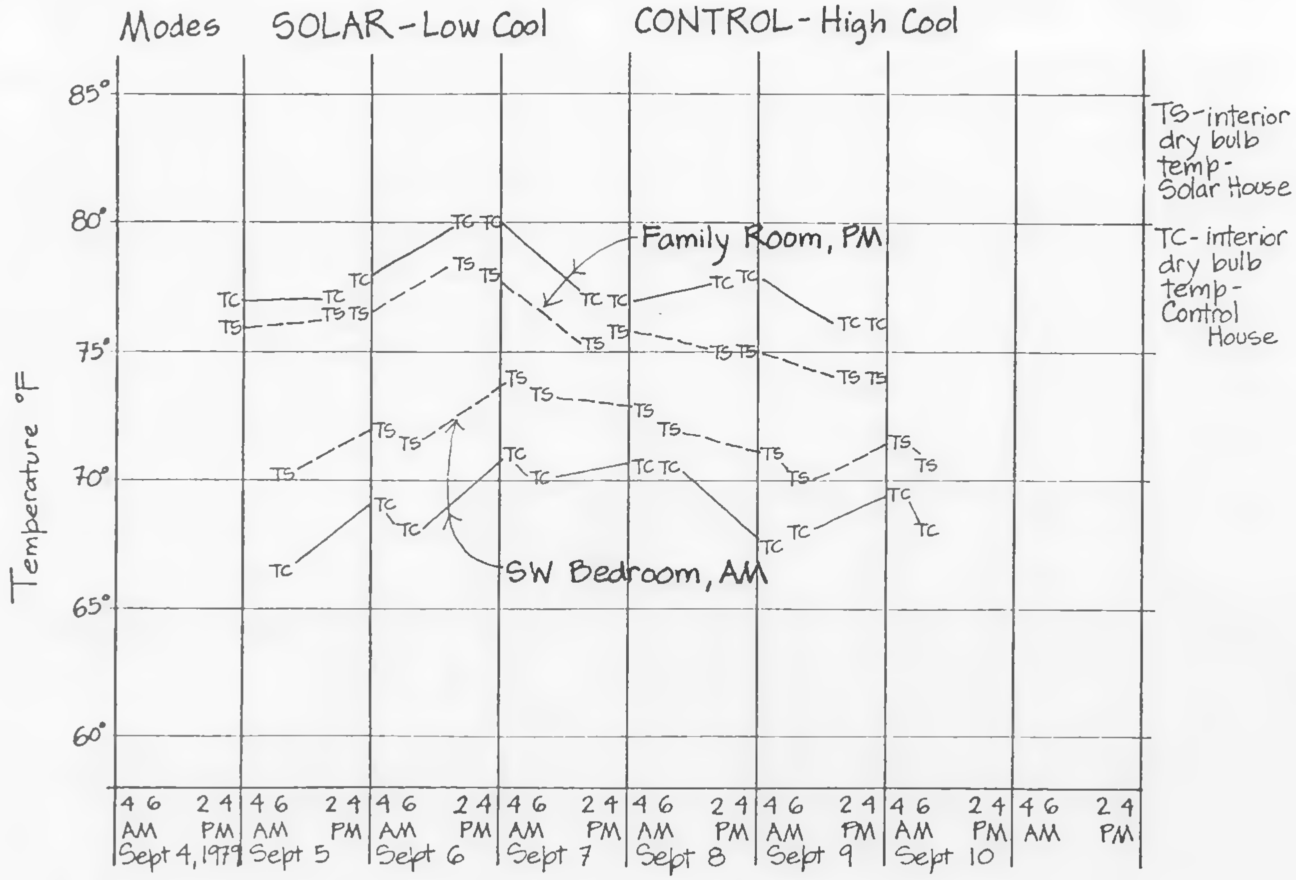
6. The blower bearings should be oiled at least monthly.

7. When the pads are only partially wet, they may produce a fishy smell. This can generally be avoided by either being sure the



Effect of High Mass Walls on Interior Air, Wall and Mean Radiant Temperatures

Figure 10



Interior Dry Bulb Temperatures - Massive Solar & Standard Control House

Figure 11

pads are fully wetted before the blower is turned on or by using chemical tablets which destroy the biological growths causing the smell.

II. Two Stage Evaporative Cooling

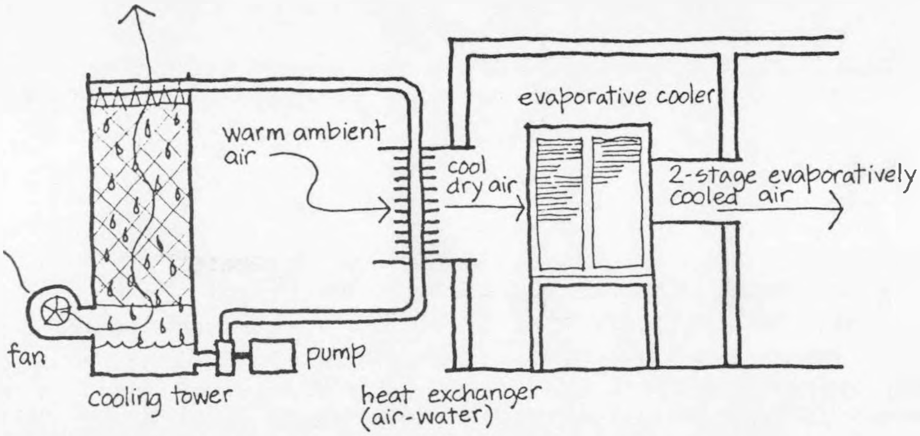
A system which precools air without humidification before evaporatively cooling it further is called a two-stage evaporative cooling system. A common type of two-stage evaporative cooling system uses a cooling tower as the first stage (8). The cool water from the cooling tower flows through an air-water heat exchanger (like a car radiator), and cools fresh air flowing over it without humidification. This precooled air is then cooled in an evaporative air cooler. See figure 12. The air washer (rotating drum type) of evaporative cooler or a spray type evaporative cooler (section I) have advantages over the standard box type evaporative cooler using aspen

Such systems produce cool air although some complaints about the humidity level have been noted during abnormally hot, humid weather. One was operated successfully at the Environmental Research Laboratory (ERL) for three years. It used a large water tank from a solar heating system to allow the coolth produced at night by the cooling tower to be stored for daytime use. Since we did not want to mix the cooling tower water with the water in the large storage tank, a water-to-water heat exchanger was placed between the cooling tower and the water tank. This system performed as designed, producing output temperatures approximately 6^{o} below that of a standard evaporative cooler. The limitations of this type of design are the approach temperatures of the various heat exchangers and the cooling tower.

When designing such systems, the power requirements of the entire system must be considered carefully, especially when fractional horsepower pumps and fans are used. A seemingly low sum of motor horsepower can draw surprisingly large amounts of current.

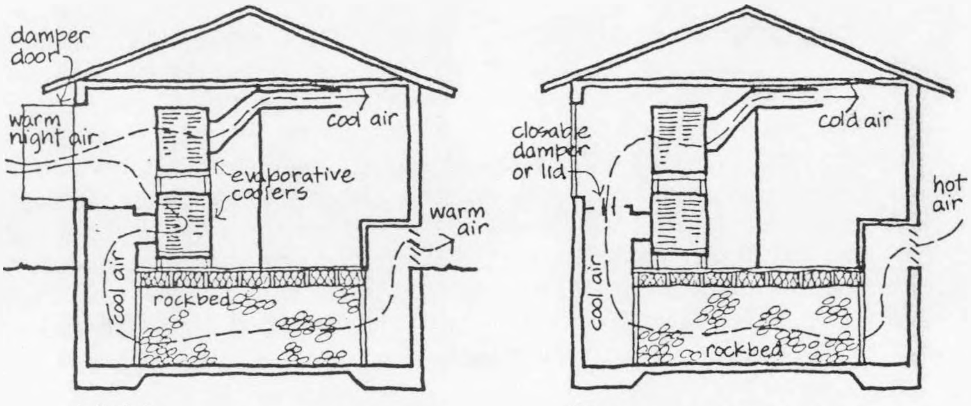
It is also possible to use an air-to-air heat exchanger to couple two evaporative coolers using the cool air from the first one to indirectly cool the air entering the second cooler. Unfortunately, air-to-air heat exchangers are relatively inefficient, and are rather difficult to obtain. Thus, a cooling tower has been preferred in systems described in the literature. An air-to-air heat exchanger is similar to the heat exchanger in a furnace, where the hot combustion gasses are separated from the warmed house air by a series of metal tubes.

Two-stage evaporative cooling systems using large rockbeds have been independently developed at CSIRO in Australia (9) and at the Environmental Research Laboratory (10). See figure 13. In this system, a large rockbed is evaporatively cooled at night and is used to precool air without humidification during the following day. Total power requirements can be quite small if the duct system and the rockbed are properly sized. Since the rockbed is an extremely efficient heat exchanger due to its large surface area, the out-put air temperatures of the rockbed are virtually identical to the rock temperatures themselves. Thus, the rockbed cools the



Two Stage Evaporative Cooling System using Cooling Tower

Figure 12



Night

Day

Schematic Diagram of Two Stage Evaporative Cooling w/ Rockbed

Figure 13

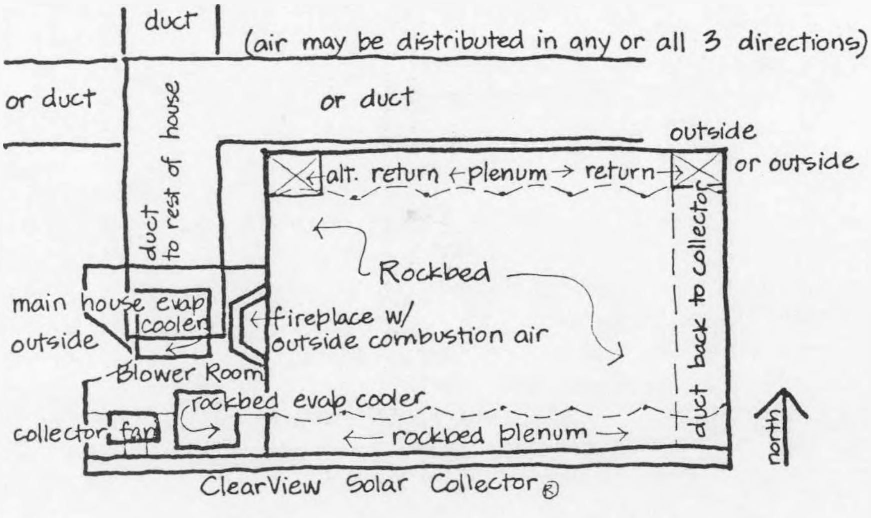


Figure 14

air passing through it during much of the day to temperatures available only at night. Systems without such thermal storage can only precool air to temperatures limited by daytime conditions. Thus, this system is actually more than a two-stage system.

On the debit side, this method does require a very large rockbed (which may be minimized through proper house design). Also, ordinary one stage evaporative cooling is used at night. However, this need not be a serious problem, since ordinary cooler output temperatures are lower at night because nocturnal radiation reduces both ambient dry and wetbulb temperatures. Because of the necessity of locating large openings near the rockbed for access to outside air, as well as locating evaporative coolers with outside air access near the rockbed, constraints are placed on the design of the house. A schematic layout of how one might incorporate a two-stage system in a house is shown in figure 14.

Data from the system at the Environmental Research Laboratory, which uses standard evaporative cooling, is shown in figure 15.

The psychrometric chart should be used at all times to analyze the effect of changing air conditions in these systems. While, as a rule of thumb, precooling the air 10 F will cause an approximately 3 F decrease in the output temperature of an evaporative air cooler, the improper use of this rule can lead to errors in judgement when analyzing the results of changing conditions.

The psychrometric chart in figure 16, schematically shows the changes in air as it passes through the various stages of a rockbed type two-stage cooling device. As the air is cooled without humidification, it moves from A to B along a constant moisture content line. Then it is evaporatively cooled from B to C along a constant wet bulb temperature line. If the ambient air had only been cooled by direct evaporative cooling, it would have been cooled from A to D along a constant wet bulb temperature line. Note that while the humid two-stage evaporatively cooled air is below the critical 15 mm Hg partial vapor pressure line mentioned by Olgyay (11), the direct (1-stage) evaporatively cooled air is above this level, and a fan is required for comfort. While one-stage or direct evaporative coolers have been deemed unsatisfactory during much of the hot and somewhat humid summers in Phoenix, two-stage cooling has been found to be comfortable, albeit a bit humid, some of the time. (In Tucson, the majority of people are satisfied with direct evaporative cooling except for about two weeks during the summer).

The two stage evaporative cooling systems described above do not directly use the relatively cool air exhausted from the home to improve the performance of the system. However, as has been described in Section I-G, this cool air can be exhausted through the hot air solar collector, windows and the attic so as to intercept heat before it heats the air inside the home. This reduces the size of the system required.

III. Indirect Evaporative Cooling

Indirect evaporative cooling is a very attractive form of evaporative

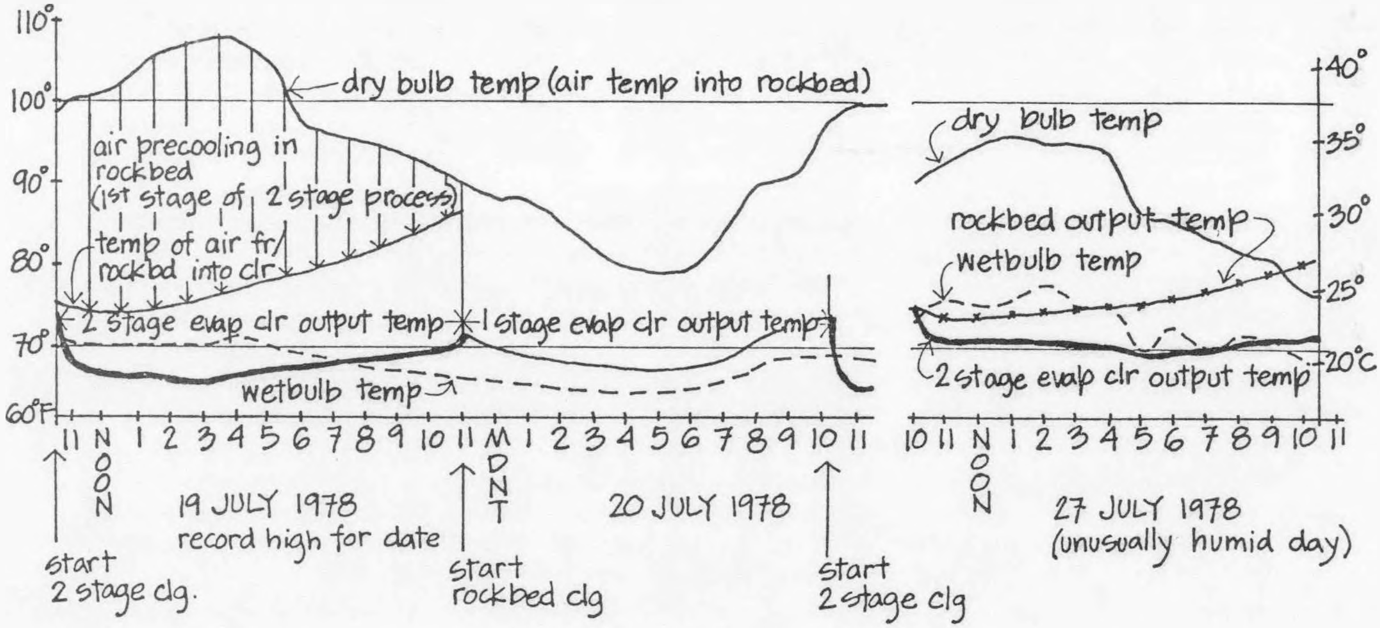
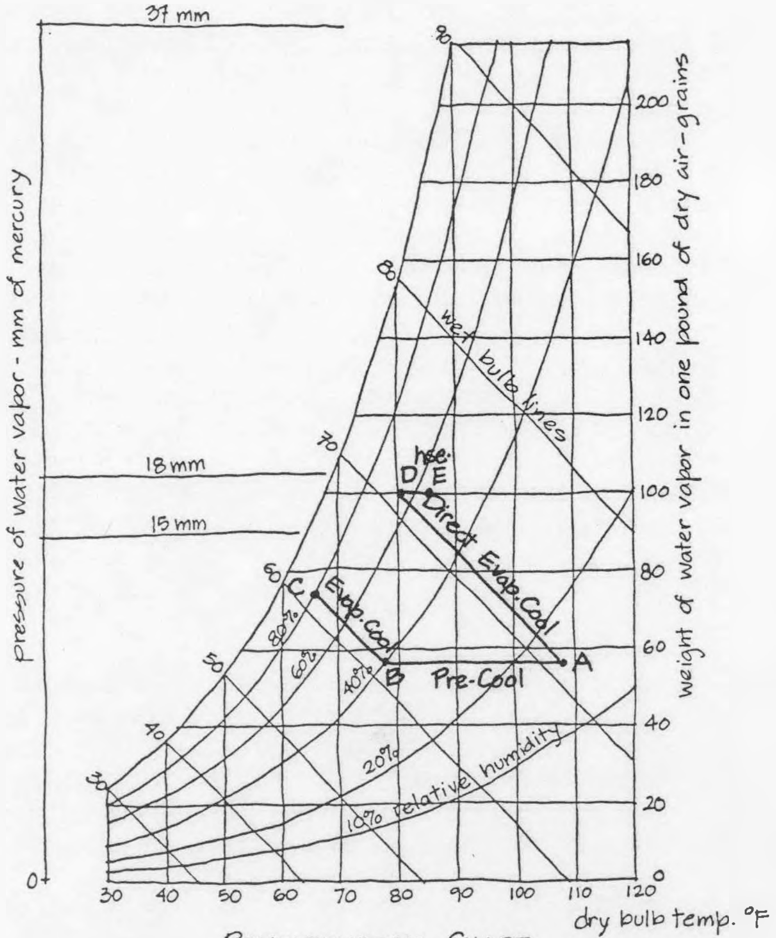


Figure 15



PSYCHROMETRIC CHART

Two Stage Evaporative Cooling A→B→C
(rockbed type)

Direct Evaporative Cooling A→D→E

Figure 16

cooling, since the air is not humidified. However, since fluid cooled by an evaporative cooling device only approaches the wet bulb temperature, and since the house air only approaches the temperature of this cool fluid, the wetbulb temperature must be quite low (approximately 65 F or less) to keep the house interior at less than 80 F. This means that the method generally does not work well during humid summer weather. However, it was appreciated in the 1930's, since it was one of the few available methods of cooling.

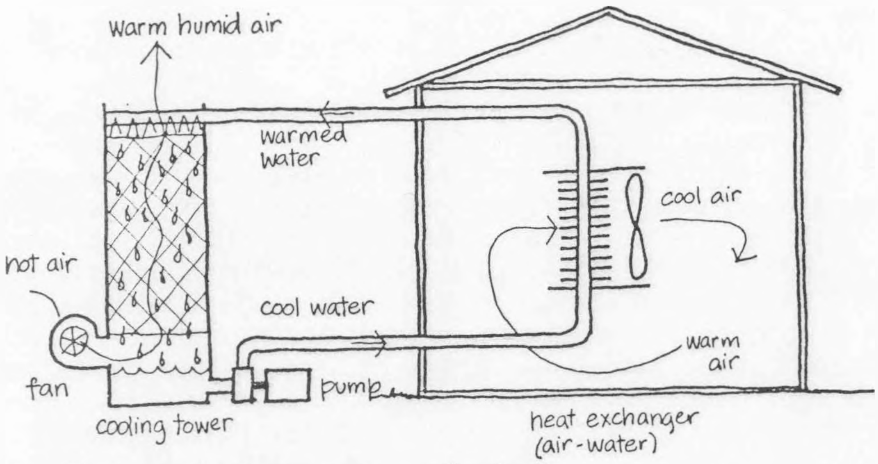
In the classic form of this system, water from a cooling tower is circulated through an air-water heat exchanger over which house air is recirculated (Fig. 17) (12). It is possible to design this system so that it is used for indirect evaporative cooling during drier weather, and two-stage cooling during humid weather, as was done at the Environmental Research Laboratory installation in 1974. In at least one case, the outside air was cooled by the heat exchanger and blown out through windows (13), instead of recirculating home air through the heat exchanger.

We have also used indirect evaporative cooling in our rockbed installations. As with two-stage evaporative cooling, the rockbed is cooled at night. Then, outside air is drawn through the rockbed during the day and enters the house without further cooling. During the dry periods in June and September, the output air is quite cool (Fig. 18 - "Dry Cool" on June 20 and 21). A further option would be to recirculate house air through the rockbed, which requires more power dampers.

IV. Recuperative (Regenerative) Evaporative Cooling Systems.

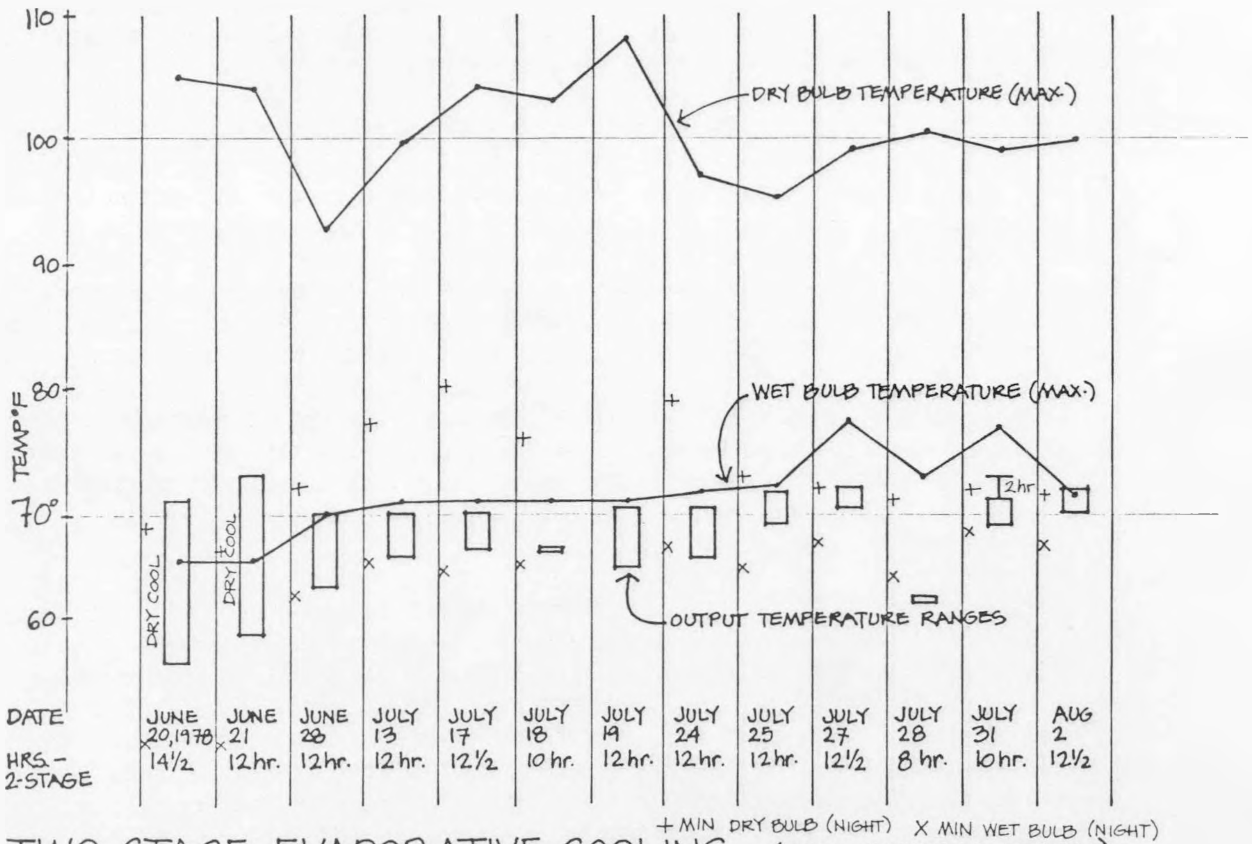
In a recuperative evaporative cooling system, outside air entering the house is cooled in a heat exchanger, flows through the house, and is exhausted through the evaporative cooling device that provides the cool fluid pumped through the heat exchanger. Since the house air exhausted through the evaporative cooling device is precooled and not humidified, the evaporative cooling device produces colder fluids for use in the heat exchanger and thus lowers the input temperature to the house. See Figure 19. Unfortunately, since air entering the house must be exhausted through the evaporative cooling device, the possibility of exhausting air so as to eject heat before it reaches the inner parts of the house is reduced. However, some installations exhaust the relatively cool air from the cooling tower through the attic (14).

One form of this device uses a cooling tower to produce the cool water flowing through the air-water heat exchanger, which cools the outside air entering the home. This air is precooled but not humidified, and exits through the cooling tower water, lowering the output temperature of the cooling tower water as compared to a cooling tower using outside air. For example, if the air rises 5 F as it passes through the house, if the heat exchanger has a 7 F approach temperature, and if the cooling tower has a 4 F approach temperature, the following would occur: Ambient air at 100 F drybulb/71 F wetbulb (A) entering the home is cooled to 76 F drybulb/63-1/2 wetbulb (B) (69 F water in the heat exchanger), and warms up to 81 F dry bulb/ 65 F wetbulb (C) as it passes through the house (5 F above the temperature of the air entering the house). The house air is then exhausted through the cooling tower which cools the water to 65 F (D). The



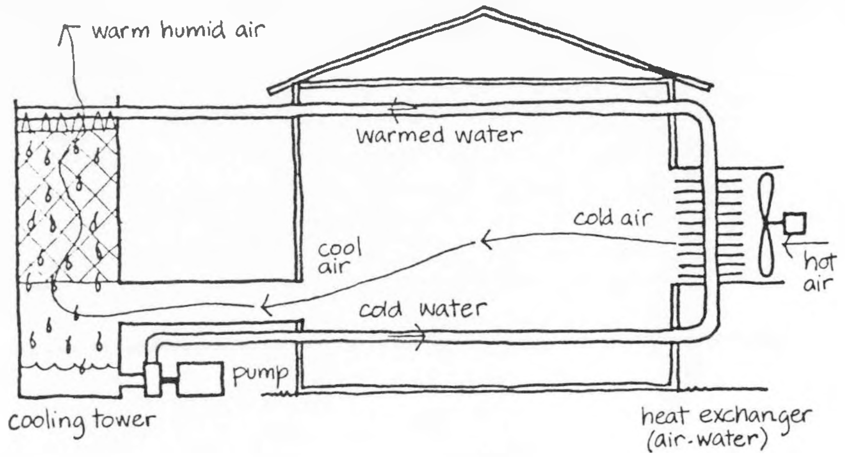
Indirect Evaporative Cooling

Figure 17



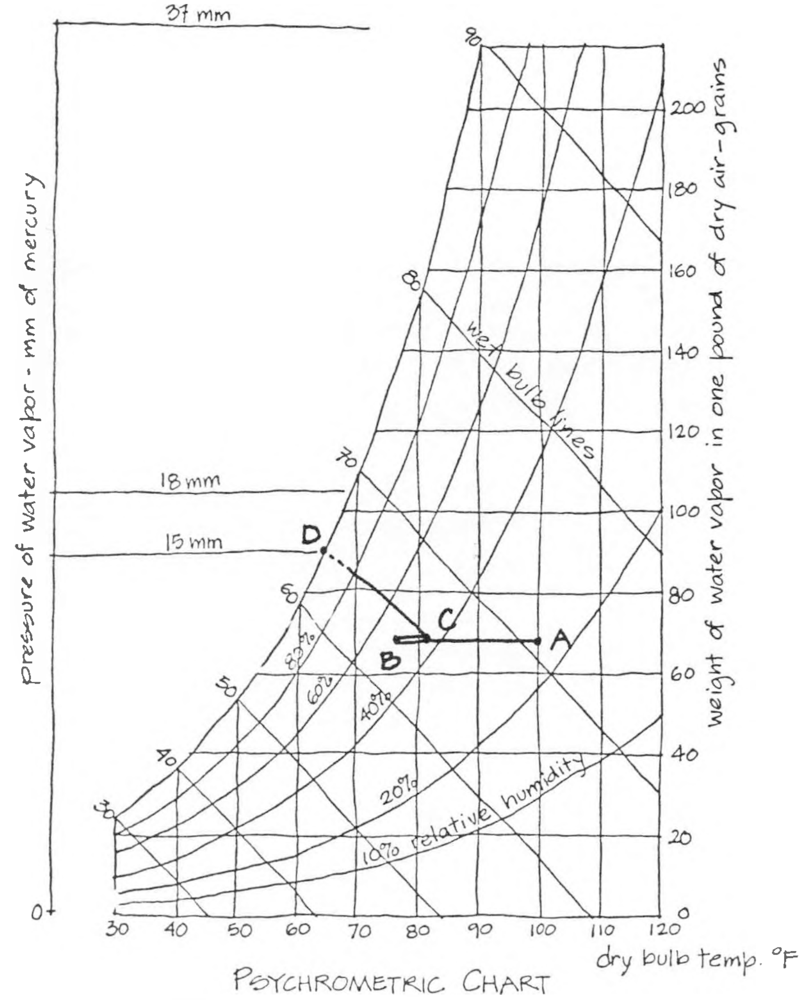
TWO STAGE EVAPORATIVE COOLING - (ERL INSTALLATION)
OUTPUT TEMPERATURE RANGES AND AMBIENT CONDITIONS

Figure 18



Regenerative Evaporative Cooling using Cooling Tower

Figure 19



Recuperative Evaporative Cooling
(w/cooling tower & air/water heat exchanger)

Figure 20

cool water is circulated through the heat exchanger and the cycle begins again with the hot ambient air being cooled to 76 F drybulb/63 1/2 F wetbulb. See Figure 20. Thus, reasonable conditions (since the air is not humidified) can be maintained. However, in hotter and more humid climates, such as Phoenix, AZ, this system may occasionally produce less than the ideal conditions. However, they may still be quite acceptable when compared to ordinary air conditioners operated at high temperatures to minimize costs, or when compared to ordinary evaporative cooling systems. Closer approach temperatures can be used, but at greater capital and operating costs. (It should be noted that it is not possible to depict the temperature changes exactly on a psychrometric chart when a cooling tower and an air system are combined since the chart deals only with the properties of air).

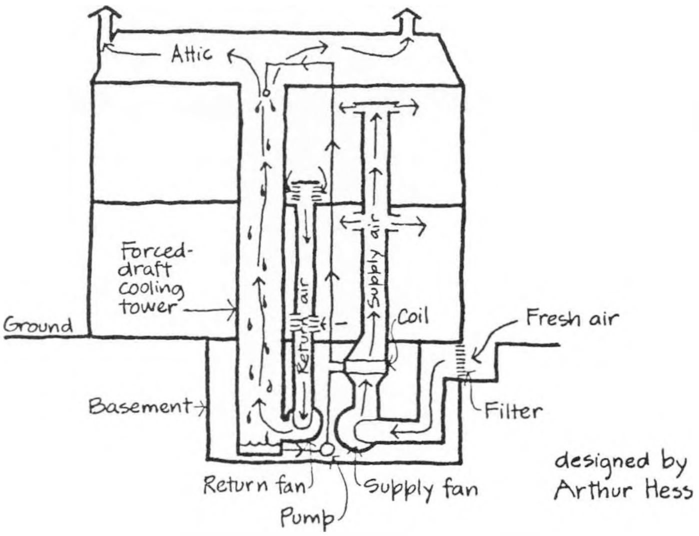
While it may be possible to use only one fan to blow air into and out of the house in this system, this can result in an objectionable pressure difference between the inside and the outside of the home. If properly balanced, two fans can reduce this effect.

The cooling tower water needs regular chemical treatment and "blowdown" (either constantly bleeding off small amounts of water or periodic changes of the water). This necessity to "blowdown" the cooling tower makes chemical treatment a continuous process.

Watt describes a regenerative cooling system built into the old Administration Building at the University of Arizona (15). The cooling tower was a central shaft in the building itself (Fig. 21) to facilitate exhausting all the cooled air in the building through it. The cooling tower air was exhausted through the attic to reduce heat flow from the roof to the rooms below. Otherwise, the system operated as previously described. Such a system with a built-in cooling tower might be useful in a home if the architect is willing to let the system influence the design of the house. Each room might have a heat exchanger in it with individual airflow controls.

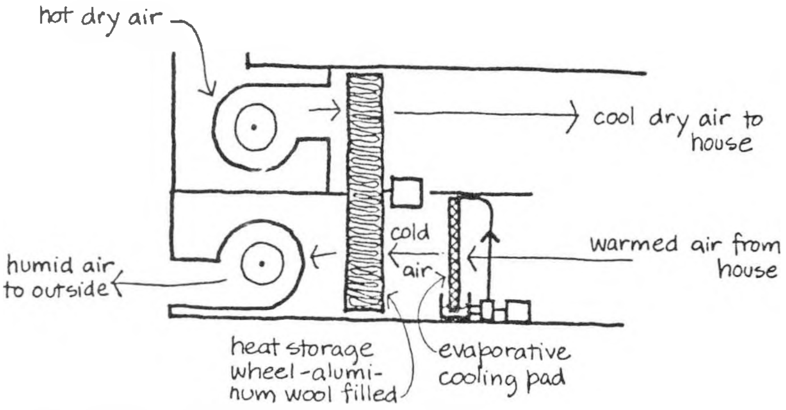
Regeneration wheel techniques have also been tested. Neal Pennington of Tucson used a rotating heat storage wheel one foot thick and filled with fine "aluminum wool" (Fig. 22) (16). The aluminum wool is cooled by air from an ordinary excelsior pad, drip type evaporative cooler, in the lower section. As it rotates into the upper section, it cools outside air drawn through the aluminum wool without humidification. The air cools the house, and exits through the evaporative cooling pads in the lower section, thus utilizing regeneration. Watt was impressed by the system, whose scaling and spray nozzle clogging problems are only those of a standard evaporative cooler. It has counter flow heat exchange, and in winter the heat storage wheel can be used to recover heat from ventilation air. Watt mentions that a calcium chloride desiccant wheel was added later, which partially dried the cool air entering the home (this does heat the air, however). This desiccant wheel was dried later in the process with fossil fuel derived heat. However, it could possibly be dried by a solar heated hot air device.

The famous Australian regenerative rockbed (RBR) uses the same principles, but has the advantage of the low approach temperatures inherent



Schematic diagram - University of Arizona Administration Building regenerative dry-surface system, 1936-52

Figure 21



Pennington heat storage wheel regenerative evaporative cooling device

Figure 22

in rockbeds due to their large surface area. Design equations and graphs are presented by Dunkle (17).

An older RBR (1965-1968), schematically illustrated in Fig. 23, (18), is used to explain the system initially, since it is simpler to understand than the newer version. Ambient air is drawn by the first fan through a 5" deep layer of closely sized 1/4" gravel (left side), which has been previously cooled. Then the air flows through a thinner 2" deep layer of the same size rock, also precooled. This cool unhumidified air enters the house and rises slightly in temperature as it cools the house. It is then exhausted by the second fan on the opposite side through a 2" layer of rock which was sprayed for a few seconds with water, at the start of the cycle. This layer of rock functions as an evaporative cooling pad.

The cooled air then cools the 5" layer of rock above the evaporative cooling layer. Since the air entering this side from the house is not humidified and is much cooler than the ambient air, these rocks are cooled more than would otherwise be possible. After five minutes, when the 2" rock layer on the right has dried out, the airflow is reversed. The outside air is then cooled without humidification by the right side, and the left side is cooled, or regenerated.

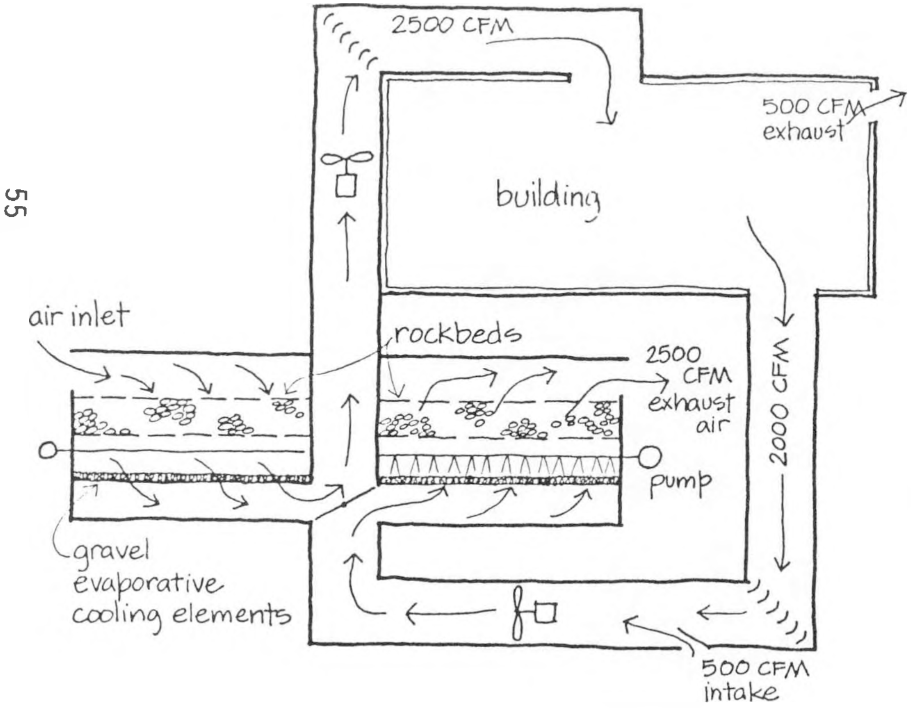
The newer Mark IV system is schematically illustrated in Fig. 24 (19). It is an 8'x12' x 2 1/2' deep metal box, divided into two compartments. A continuously wetted evaporative cooling rock layer is on one side only, and cools the 5" rockbed on either side, controlled by the dampers in the center. All rocks (gravel) are coated with a bituminous compound to reduce moisture absorption.

The path of the air on a psychrometric chart as it passes through a rockbed regenerative or recuperative evaporative cooling system is shown in Figure 25. Air at point A is cooled in the heat exchanger to point B where it enters the house. As it passes through the house, it warms slightly from B to perhaps C. As it is exhausted through the evaporative cooling pad and out through the rockbed being regenerated, it passes from C to D. Thus the house is essentially maintained at a temperature between B and C. If ordinary direct evaporative cooling were used, air at state point A would be cooled along a constant wet bulb line to state point E where it would enter the house and warm slightly to perhaps F.

This system appears to be quite good. Performance reports include mention of successful use in hard water areas, and that they have had no odor problems. Hogg (20) reports that the RBR produces output drybulb air temperatures approximating the ambient wetbulb temperature, without humidification.

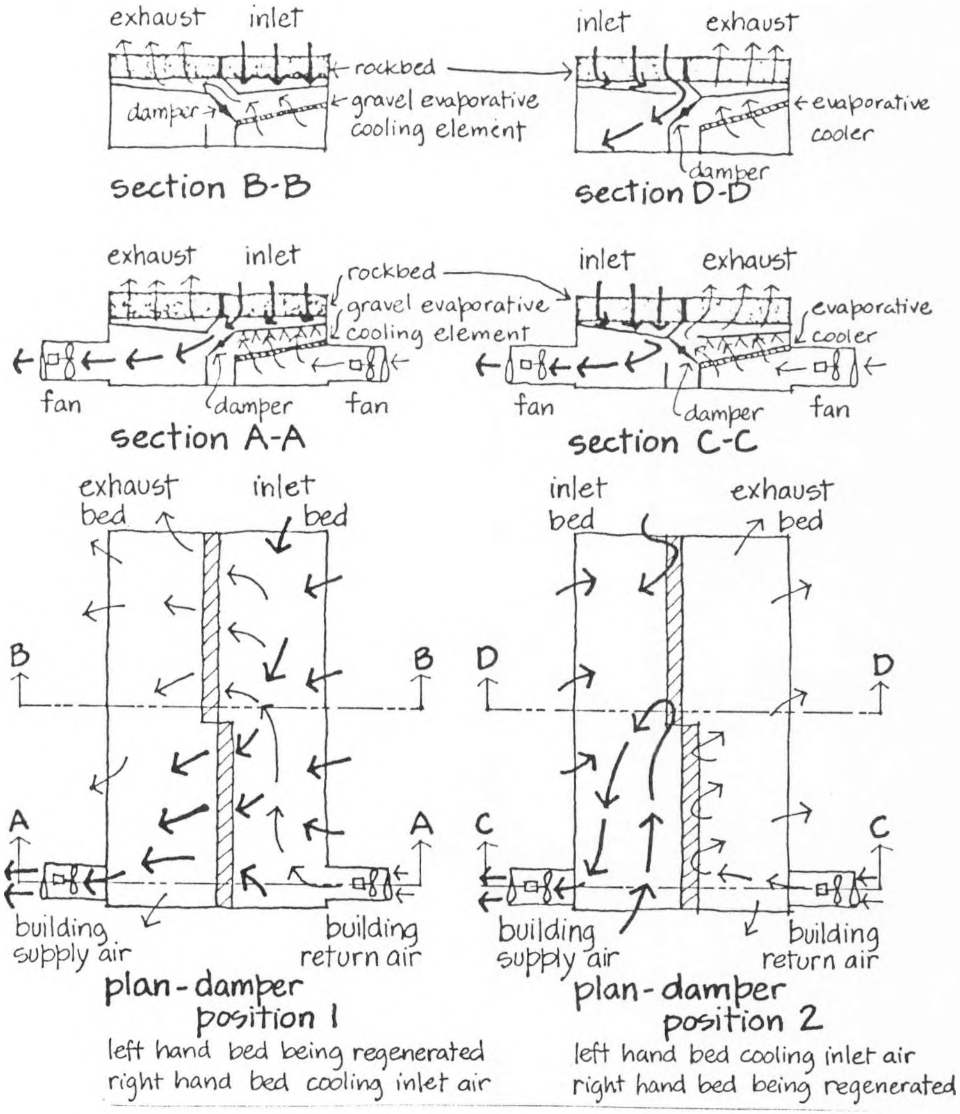
The RBR, as designed by CSIRO, does not appear to be immediately useful as a rockbed for a solar heating system. Design changes might allow this. However, since the CSIRO group is noted for its solar work, and did integrate their larger two-stage rockbed with solar heating, it is likely that no simple designs were evident for linking the RBR to a solar heating system.

The CSIRO group also used two fans in the system, so that the house is



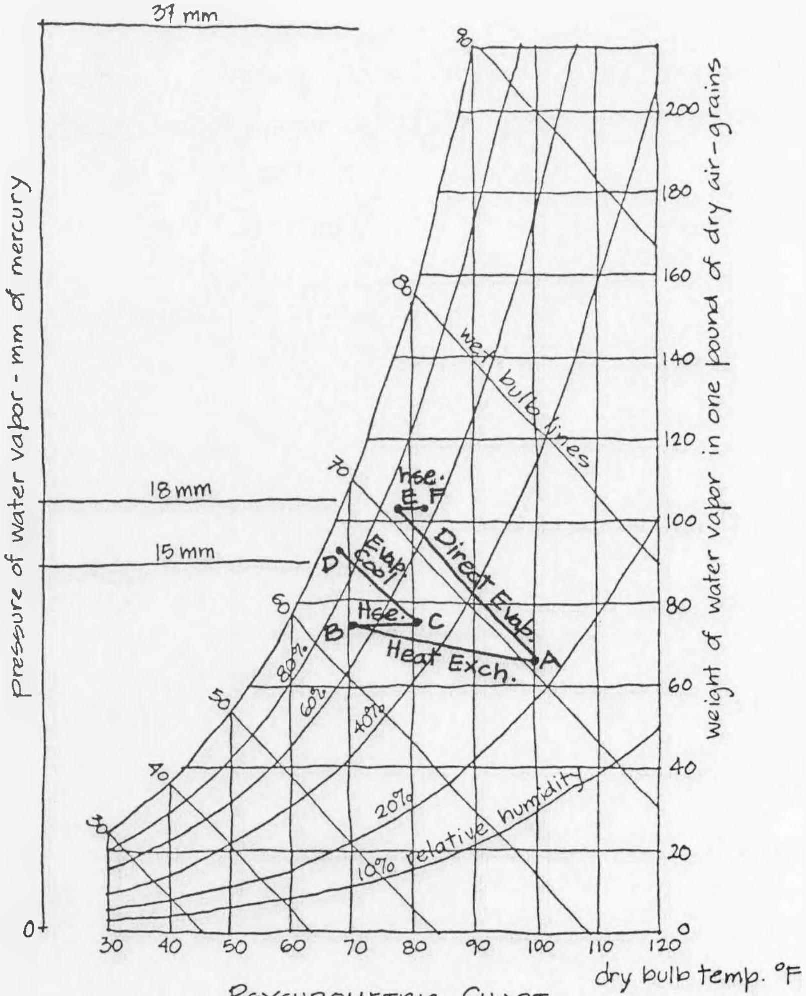
Schematic Diagram of Rock Bed Regenerative Cooling System (designed by CSIRO, Australia)

Figure 23



Rock Bed Regenerative Airflow Diagram (Mk IV) (designed by CSIRO, Australia)

Figure 24

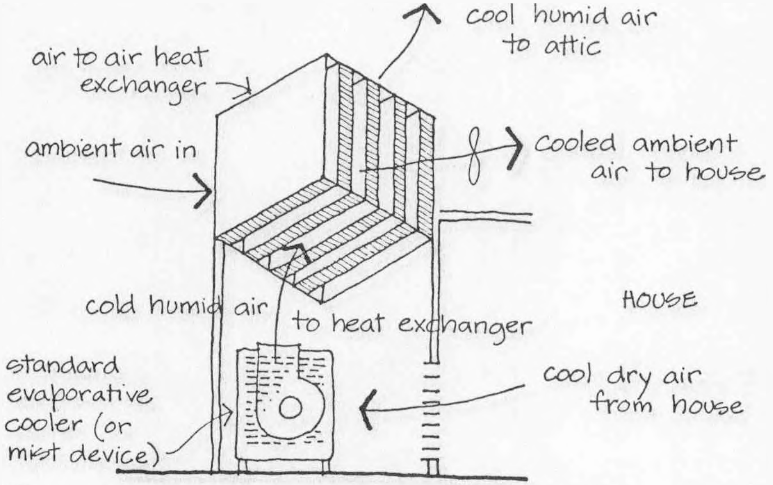


PSYCHROMETRIC CHART

Recuperative Evaporative Cooling A→B→C→D
(rockbed type)

Direct Evaporative Cooling A→E→F

Figure 25



Schematic Diagram of Recuperative Evaporative Cooling System w/air to air heat exchanger

Figure 26

neither under positive or negative pressure during operation of the system. If one fan were used, then the house would be under positive or negative pressure, depending on whether the fan is at the exit or the intake to the house.

Dr. Stanley Mumma of Arizona State University has done work on a system similar to the RBR in principle, but using standard evaporative coolers instead of the evaporative cooling rockbed. (21).

Pescod, of Australia (22), has developed a regenerative evaporative cooler that uses a plastic heat exchanger, which is a combination of a cooling tower and the air-water heat exchanger previously mentioned. Similar devices are made in the U.S. at this time. In the latter, ambient air flows across the dry surface of plastic tubes, which cool the air. This cooled ambient air passes into the house as before, warms slightly, and is exhausted over the wet outside surface of the aforementioned plastic tubes (covered by a fabric cylinder) onto which water is sprayed. Since, as in all regenerative systems, the air entering the tubes is cooled and has not been humidified, it can then lower the water spray to temperatures below those normally reached with ambient air. Thus, the ambient air entering the house is cooled to lower tempertures. Unfortunately, we could not obtain any reports with detailed drawings of the Pescod device. All these devices require a very large number of small tubes to attain sufficient surface area.

Pescod reports that he regularly achieved output dry bulb temperatures in his device equal to the ambient wetbulb temperature. The U.S. made devices achieved drybulb temperatures within 4 F of the wet bulb temperatures in a Phoenix, AZ installation. With lower airflow rates, the performance may have equaled that of the Pescod device.

Watt reports similar devices made of very large areas of parallel plates of metal which separate the air being cooled from the surface cooled by a water spray (23). Such units were built by Pernot and Rich. They did not use regeneration. Apparently, 100% outside air was cooled without humidification, or building air was partially recircuated through these units.

Watt reviews several devices similar to the above which he tested. He calls them "plate type" indirect or regenerative evaporative coolers. He showed that regeneration is effective, where air that has cooled the house is used as the air input into the water spray cooled chambers. However, if cool dry air from the device itself is immediately used as input air to the spray chambers, performance is reduced. This is due in part to the large total volume of airfow required to maintain a given flow rate through the house, and to the small incremental temperature reduction achieved by such practices. He also notes that the water sprays should be directed downward in "plate type" coolers, since water mist is not reliably carried far by air flowing horizontally.

It should also be possible to use parallel plate air to air heat exchangers coupled with the standard evaporative cooling devices described in section I.A. Ambient air would be cooled by one set of heat exchange surfaces, blown through the house, evaporatively cooled and blown through the other set of heat exchange surfaces (see Figure 26.). If this air enters the attic, it can be exhausted out in an area remote from the ambient air intake of the system, avoiding inadvertent recirculation of air, but without using an expensive duct system.

V. Other Evaporative Cooling Systems

Evaporative cooling may be used to cool air directly or to cool surfaces which cool air inside a space. For instance, as B. Givoni has suggested, an earth integrated house (which already takes advantage of the stabilizing effect of the earth), could be cooled further if the earth surrounding the structure is evaporatively cooled. One way this could be achieved is by irrigating the soil surface around the building. The surface could be covered with plants or pebbles (or both) for shade. (24). Kusuda has measured the effect of various surfaces on the seasonal temperature changes in the earth, noting that grasses lower the seasonal maximum temperature, and raises the seasonal minimum temperature. (25).

Porous earth tubes have also been used. Outside air is cooled by a combination of earth contact and evaporative cooling (by water in the soil diffusing to the surface of the tubes). Due to the length of the tubes that are used, the output temperatures are quite uniform. (26).

These systems would take advantage of both the stabilizing effects of the earth and evaporation.

Another evaporative cooling system which needs further study is the downdraft wind tower. A water mist is sprayed in the wind tower. As hot air is evaporatively cooled by the water, it flows downward into the structure. The airflow is aided by any wind present. The actual performance of a small unit tested at ERL by Charles Moody conformed quite well to his predicted performance. However, large well-insulated multi-directional wind towers will be needed for this cooling system. A solar chimney which passively vents air out of the opposite side of a structure may potentially improve the performance of the wind tower.

In relatively milder (cooler) arid climates, such as Las Cruces, night ventilation over a fountain such as the system in Dr. Ed Lumsdaine's home are effective in addition to being aesthetically pleasing and quite soothing. We have now returned to the paradise of the medieval arab mentioned in the introduction.

CONCLUSION

The large and extremely varied types of systems for evaporative production of "coolth", are a monument to the explosive inventiveness of mankind when a basic principle bearing upon a universal problem becomes widely known. However, we believe that due to cost, direct evaporative cooling (modified in some cases by the improvements described in section I) will be the predominant system in most hot arid regions.

REFERENCES

(1) Watt, John R., *Evaporative Air Conditioning*, The Industrial Press, New York 13, N.Y. (1963).

(2) *ASHRAE Handbook, 1977 Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York (1978) p. 5.6.

(3) *Ibid.*, pp. 23.3 - 23.22.

(4) Peck, J.F., H.J. Kessler and T. Thompson, "Optimized and Advanced Forms of Evaporative Cooling", *Proceedings of the 1979 Conference on Technology for Energy Conservation*, Information Transfer, Inc., Tucson Arizona (1979) pp. 113-118.

(5) Peck, J.F., H.J. Kessler and C.N. Hodges, "The ClearView Solar Collector System," *Proceedings of the 1979 Conference on Technology for Energy Conservation*, Information Transfer, Inc., Tucson, AZ (1977) pp. 208-212.

Peck, John F., T. Lewis Thompson, Helen J. Kessler and Carl N. Hodges, "The Hybrid ClearView Solar Collector and Complementary Evaporative Cooling -- Performance Prediction Methodology and Results, "Passive Systems '78, American Section of the International Solar Energy Society, ed. by Jeffrey Cook and Donald Prowler, Newark, Delaware (1979) pp. 116-123.

(6) Peck, J.F., T.L. Thompson and H.J. Kessler, "Windows for Accepting or Rejecting Solar Heat Gain", Proceedings of the Fifth National Passive Solar Conference, AS/ISES, to be published (1980).

(7) Peck, J.F. and H.J. Kessler, "Integrating Optimized Evaporative Cooling Systems with Passive Homes", *Proceedings of the 1980 Annual Meeting*, AS/ISES, Newark, Delaware (1980) pp. 952-956.

(8) Heckman, A.R., "Two-Stage Evaporative Systems Can Save Energy", *Actual Specifying Engineer*, Vol. 32, No. 2 (August 1974) pp. 80-82.

(9) Close, D.J., Dunkle, R.V. an Robeson, K.A., "Design and Performance of a Thermal Storage Air Conditioning System", reprinted from the *Mechanical & Chemical Engineering Transactions of the Institution of Engineers*, Vol. MC4, No. 1 (May 1968) pp. 45-54.

(10) Peck, J.F., Hodges, C.N., Jensen, M.H. and Thompson, T.L., "A Greenhouse-Residence Utilizing a ClearView Solar Collector and Two-Stage Evaporative Cooling", *Proceedings of a Conference on Solar Energy for Heating Greenhouses and Greenhouse-Residential Combinations*, Cleveland, Ohio (March 1977) pp. 14-52.

Peck, John F., Helen J. Kessler and T. Lewis Thompson, Monitoring, Evaluating, and Optimizing Two-Stage Evaporative Cooling Techniques, report prepared for the Arizona Solar Energy Commission (1979).

(11) Olgyay, Victor, *Design With Climate*, Princeton University Press, Princeton, NJ (1963).

(12) Watt, pp. 205-207.

(13) Ibid, p. 205.

(14) Ibid, p. 208.

(15) Ibid, pp. 207-208.

(16) Ibid, pp. 215-218.

(17) Dunkle, Robert V., "Randomly-Packed Particulate Bed Regenerators and Evaporative Coolers for use in Solar Systems, *"Proceedings of the Second Southeastern Conference on Application of Solar Energy*, Baton Rouge, Louisiana (1976) pp. 131-147.

(18) Morse, R.N., "A Rockbed Regenerative Building Cooling System", presented at CSIRO Conference on Thermodynamics and Fluid Mechanics, Brisbane, Australia (December 1967) p. 1.

(19) Robeson, K.A., "Evaluation of Evaporative Rockbed Regenerative Coolers", AIRAH Transactions, presented at AIRAH Conference, Brisbane, Australia (May 1969) p. 2.

(20) Hogg, F.G., "A Switched-Bed Regenerative Cooling System", Proceedings of the XIII International Congress of Refrigeration, Vol. 4, Washington, D.C., (1971).

(21) Mumma, Stanley A., "Rockbed Regeneration as a Means of Indirect Evaporative Cooling", ASHRAE Transactions, Vol. 85, Part 2 (1979).

(22) Pescod, D., "Energy Savings with Evaporative Cooling in Australia", CSIRO (1976).

(23) Watt, pp. 212-219.

(24) Givoni, B., "Earth Integrated Buildings -- An Overview", prepared for the DOE International Expert Group on Passive Cooling of Buildings, Miami (1980).1

(25) Kusuda, T., "The Effect of Ground Cover on Earth Temperature," The Use of Earth Covered Buildings, National Science Foundation, U.S. Government Printing Office 0-254-963 (1978) pp. 279-303.

(26) Acevedo, M.L., "The Letcher House," Solar Greenhouse Digest, Flagstaff, Az (June/July 1979) pp. 10-12.

APPENDIX IV

Habitability of Below Grade Spaces

1. "A Discussion of the Habitability of Below Grade Spaces" by Les Wallach

LINE AND SPACE

A DISCUSSION OF THE HABITABILITY OF BELOW GRADE SPACES

A paper written for the Environmental
Research Laboratory, University of
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I would like to thank the University of Arizona and the Environmental Research Laboratory for funding this paper. In particular I would like to thank Dr. John Peck and Ms. Helen Kessler for their support.

Les Wallach

For the purpose of this paper, below grade spaces will be defined as structures which have earth along their exterior walls above the finish floor level. This includes basements, earth integrated, buried and bermed construction. Habitability of these structures depends upon criteria which will be discussed following.

In addition to discussion, criteria will be related to one or more examples of solutions to specific problems. The examples will all be located in Pima County, Arizona and are the Coleman residence[1] (Coleman), the 'Cabeza' Prieta Wildlife Game Refuge Ranger Housing[2] (Cabeza), the Quimby residence[3] (Quimby) and the Line and Space Architectural Office[4] (Line and Space).

Construction of below grade space is an attractive and rewarding approach to conserving energy.

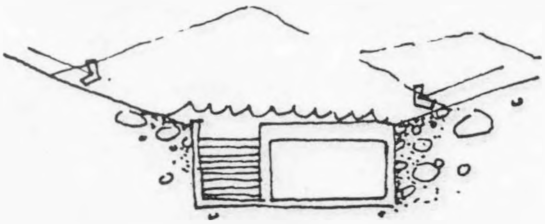
In the early part of this century, people in Tucson instinctively recognized the advantages of a basement space for relief from summer heat. The Lovejoy House, constructed in 1928, is an excellent example of this. Three rooms were constructed below grade and were often as much as 10° cooler than the main floor. Natural light entered through light wells. No special precautions were taken for moisture and dampproofing, however, and this space was subject to periodic flooding and ground moisture.

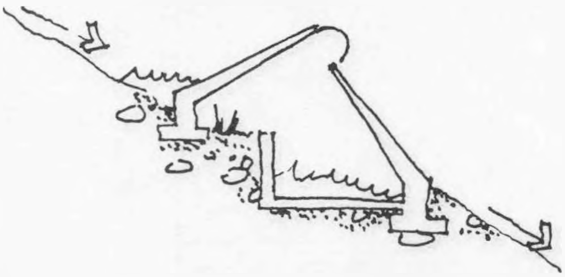
1- 2350 square foot urban residence.
   1200 square feet bermed to six feet
   high on perimeter--
   flat site.
2- 1350 square foot rural residence, earth
   integrated and bermed sloped site
3- 1700 square foot rural residence--
   earth integrated--sloped site
4- 500 square foot basement conversion--
   flat site.

With the advent and acceptance of mechanical equipment for environmental control, basement spaces remained much as in the example above until the 1970's. With costs rising one of the alternatives for conservation of energy is to utilize the sheltering mass of the earth with below grade spaces.

To enhance habitability and usability of below grade spaces a number of critera must be considered. These generally fall under the following headings.

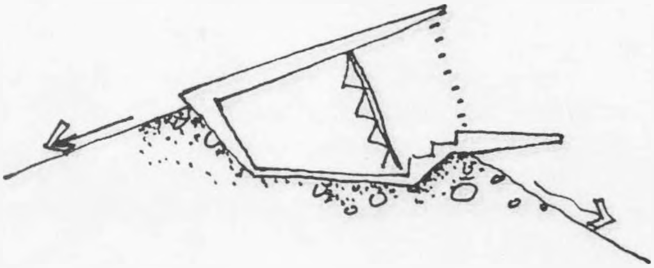
.Site Selection
.Codes
.Access
.Quality of Space
.Light
.Temperature and Ventilation
.Sanitation
.Water and Moisture





Site Selection

Proper site selection is of primary importance in assuring habitability of below grade space. Site drainage, flood potential, utility locations and depths, views, vegetation, solar and breeze obstructions as well as compass orientation are all important. Generally speaking sites sloping to the south are good. The ideal condition would be a ridge gently sloping north and south. Views would be to the north; vegetation would be east and west and utilities would be below on the north or south.



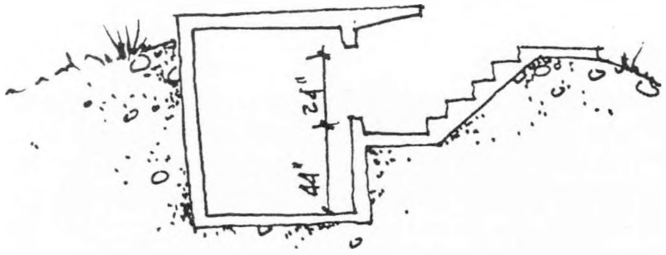
Site Selection Examples

Coleman: A flat site was purchased. Above grade berming allowed flexibility and control over portions of house to be in earth contact.

Quimby: A site sloping gently (about 10%) to the south and east was chosen.

This allows maximum cover on the west and passive solar design on the south.

Line and Space: This office was converted from the Lovejoy Basement mentioned previously. It required special mechanical solutions for drainage and is precluded from waste disposal by existing relationship to the city sewer.



Codes

The Uniform Building Code is in effect in Pima County. It is primarily concerned with health and safety, strictly defining by law certain criteria for habitability. General structural requirements are prescribed but will not be discussed here.

For residences under 3000 square feet (UBC - 33A) one exit is required plus at least one operable window or exterior door must be provided from each sleeping room (UBC - 404 and 3302). Windows are to have a minimum net clear opening of 5.7 square feet with minimum heights and widths of 24" and 20" respectively. Finished sill height may be no more than 44" above the floor.

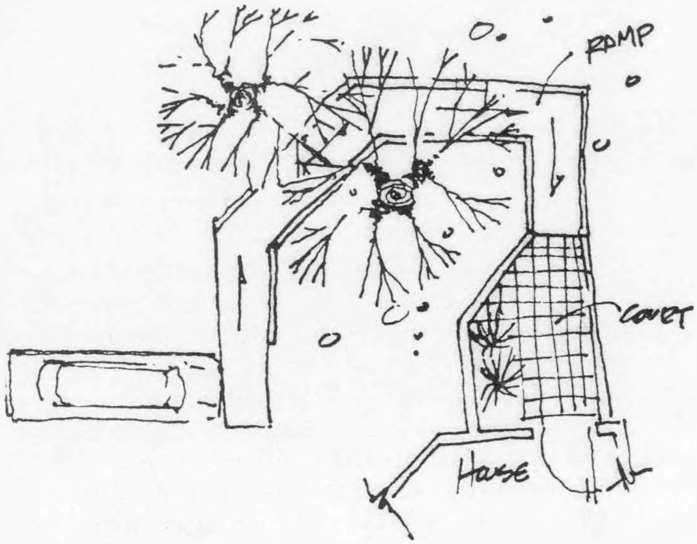
Minimums for natural light (UBC 1405) require window areas equal to 10% of floor area. Natural ventilation is required but mechanical ventilation may be substituted.

Additional code requirements which are required for habitability of spaces are a minimum ceiling height of 7'-6", minimum room sizes of 70 square feet, a fire warning system, bathroom and kitchen facilities.

Code Compliance Examples

Coleman: Exits from bedrooms are through minimal size sliding glass windows opening into light wells which penetrate surrounding earth berms. The light wells are formed from concrete block and extend in depth below sill height.

Quimby: Exits from bedrooms are into sunken court yards. These court yards are defined by retaining walls and exit from these spaces is by stairs or ramps.



Access

Access to underground spaces must take into effect planned entry sequences and transitional areas to avoid the abrupt feeling of "going below." Users with special needs should be considered. Stepped entries are a barrier to many persons.

Access Examples

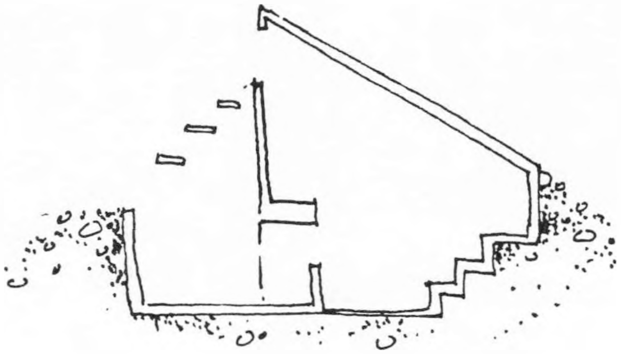
Coleman: An open walk leads through a high, open, exterior covering--compression of space upon entry to the house is achieved by a low ceiling. Thereafter one may go to high open public spaces or lower introverted bermed spaces. This house is generally one level.

Quimby: A ramped entry from the desert is taken to a below grade greenhouse. A diagonal walk through this area precedes going into the house proper. An oasis like feeling is achieved below grade.

Line and Space: A ramp leads past a large light well. This allows a glimpse of the below grade space, preparing one for transition. Entry is into an interior space for transition and then descent follows.

Quality of Space

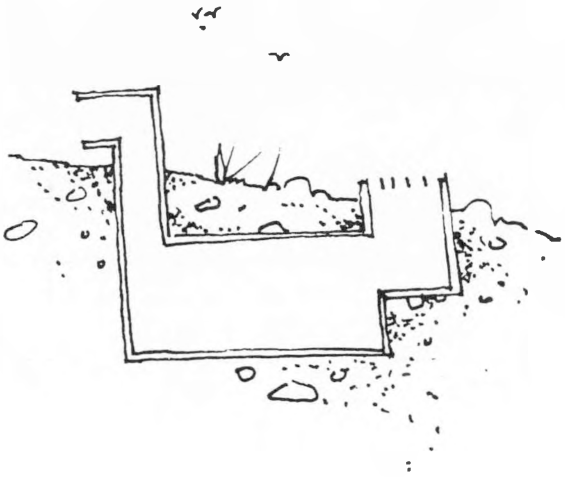
Quality of space deals with the aesthetic idea that a habitable volume may be judged to be better or worse relative to other spaces. This may be rooted in psychology or other specialized areas but as an aesthetic determinate includes the use of light, texture, form, materials, color and configuration. One of the most effective ways of improving quality of space below grade is to design spatial layering and extended vistas.



Quality of Space Examples:

Quimby: Space is compressed at the entry with immediate release by extension. There is an open plan with low wall layering. There are multiple views to sunken gardens and courts. There is minimal use of doors as barriers. Zoning and privacy is achieved by configuration.

Line and Space: Walls were removed to allow extended vistas from existing space. This includes views to gardens and into other rooms.

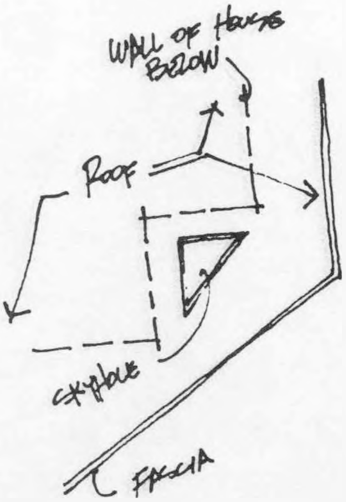


Light:

Introduction of natural light enhances habitability of earth integrated spaces. This often goes hand in hand with code provisions for exit requirements. Techniques include the use of skylights, light wells, clerestory windows and courts.

Light Examples:

Quimby: Light is introduced into every room through conventional windows or sliding glass doors which open into sunken courts, gardens or the greenhouse. Clerestory windows were used to allow penetration of winter sun into the main activity area. They are shaded by overhangs during summer months. A linear skylight with high thermal properties was used to add to the general lighting.



Coleman: The Coleman residence utilizes shading of berms through large overhangs. This reduces light available at window light wells. To relieve the dark feeling "skyholes" were cut through the roof at strategic locations in the overhang. This allows light in while keeping heat out.

Line and Space: To introduce light into an existing subterranean work space, a large sunken garden was constructed adjacent to an existing wall. This wall was restructured and removed opening the room on to the garden.

Temperature and Ventilation:

Temperature of underground spaces may be controlled by conventional mechanical means as well as passive and active solar techniques. Natural ventilation, required by the Uniform Building Code when mechanical systems are not used may be achieved through high-low window combinations, thermal chimneys and other techniques.

Temperature and Ventilation Examples:

Coleman: Conventional cooling and heating are used. The house is divided into two zones. Each is cooled by an evaporative cooler or a Carrier high efficiency split refrigeration system. Heating is by gas heated forced air. The bermed portion of the house requires less than one ton per 800 sf of living area for cooling.

Quimby: Cooling and ventilation are achieved through the use of an evaporative cooler, high-low windows and day night temperature differentials in conjunction with thermal mass. Heating is dependent upon passive mass walls with movable insulation backed up by electric baseboard units.

Sanitation:

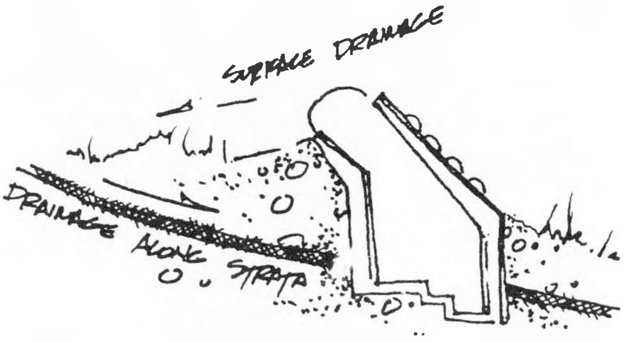
Bathroom and kitchen facilities are required in a habitable space by the Uniform Building Code. If sewers are available the invert elevation of the HCS limits the depth a habitable space may be placed below grade. If a septic tank may be used practical limitations place the depth of the top of the tank at 6 or 7 feet below grade.

Examples of Sanitation:

Coleman: The residence is bermed above existing grade and no problem was encountered in utilizing the existing sewer.

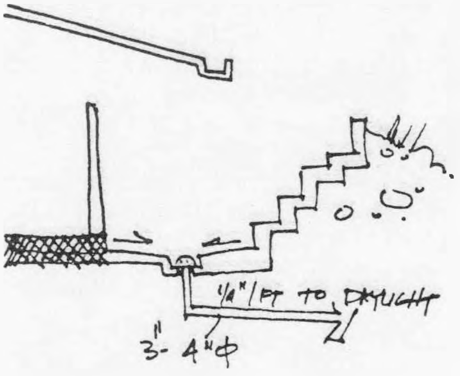
Quimby: A septic tank was used here. Location on the downhill side was imperative to keep depths from becoming excessive and to prevent possible flow of fluids from the leach field to the house. The top of the tank is less than 3' below grade as the largest portion of earth contact at this part of the house is achieved through earth berming above existing grade.

Line and Space: The existing depth of finished floor of basement offices was below the city sewer. This required bathrooms to be utilized above grade.



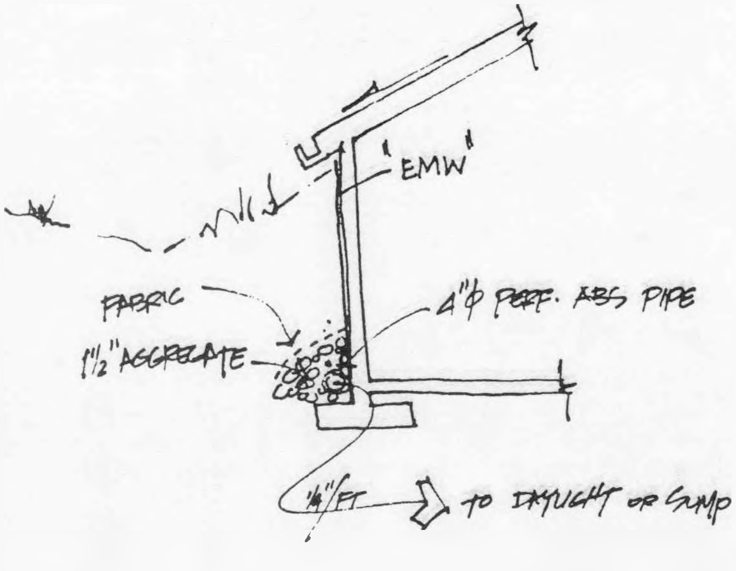
Water and Moisture:

The traditional basement has been damp making it a poor place to reside. This is easily cured. In Pima County the probability is that water problems will coincide with rainy periods and not originate in the ground. Walls should be sealed from the outside by a proven method such as Bentonite panels, waterproof plasters or membranes. Over excavation is required so that there is enough room for proper application after walls are completed. If there is a possibility of flowing water against one or more walls due to intersection of an impermeable strata, etc., then provisions for drainage at the base of the wall should be made.



Sunken courts are subject to water from direct rain. This can be dramatic and has been known to exceed 3 inches in one hour. General solutions involve area drains and flow to daylight or drywells. Finish floors of habitable space should be 4"-8" above court floors and care must be taken to prevent sheet flow from roofs or terrain into these spaces.

Water and Moisture Examples:



Coleman: Membrane waterproofing conforming to Flintkote specification "E-M-W" was used. This consists of layers of asphalt emulsion and glass fabric applied per manufacturers recommendation. Light wells are covered by a roof and not subject to rain.

Quimby: Membrane waterproofing conforming to Flintkote specification "E-M-W" was used. Footings are drained by the use of perforated 4" pipe layed in two feet of 1 1/2" aggregate. The drained footing was required due to downslope drainage and intersection of the residence's north wall with an impermeable layer of cemented decomposed granite. Courts are drained by area drains in catch basins. The drain line is 4" in diameter and daylights at a drywash about 100 feet away.

Cabeza: Solutions are similar to above.

Line and Space: A sump pump is used to drain the sunken garden from rainfall as well as to dispose of condensate from the buildings refrigeration system.

Conclusion:

Consideration of the criteria listed is important in effecting a truly livable below grade space. Other factors may apply and each situation must be examined for its own determinants. The examples listed are all fairly recent in construction and must stand the test of time before performance can be judged.

APPENDIX V

Geotechnical Investigation

1. "Geotechnical and Foundation Investigation" by Robert L. Sogge

November 1, 1980

Environmental Research Laboratory
Tucson International Airport
Tucson, Arizona 85706

Re: Geotechnical and Foundation Investigation for Passive Cooling Experimental Facility at Environmental Research Lab, Tucson, Arizona

Dear Helen Kessler,

We are pleased to submit our report covering design recommendations relating to the soil and foundation aspects of the above captioned project. The scope of this investigation was provided in our conversation of October 13, 1980.

Conclusions and recommendations contained in this report are predicated upon a field investigation made October 15 and upon laboratory tests performed on the field samples. The existing soil profile was evaluated in order to determine the most feasible foundation system for the walls and interior slabs of the five structures.

We wish to thank you for the pleasure of being associated with you on this project and we look forward to a continued association with you. If we can be of any further assistance to you please call us.

Very truly yours,

Bob Sogge

R. L. Sogge P.E.

4228 E. Grant Rd.
Bldg. 3B
Tucson, Arizona
85712
(602) 326-1121

DESERT EARTH ENGINEERING

GEOTECHNICAL AND FOUNDATION INVESTIGATION
for
PASSIVE COOLING EXPERIMENTAL FACILITY

Environmental Research Lab
Tucson International Airport

John Peck, Project Engineer
Helen Kessler, Architect
Richard Ebeltoft, Structural Engineer

November 1, 1980

4228 E. Grant Rd.
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Tucson, Arizona
85712
(602) 326-1121

Desert Earth Engineering

Registered Professional Engineer (Civil)
Certificate No.
10296
ROBERT L.
SOGGE
Date Signed 11/3/80
Arizona, U.S.A.

INDEX

INTRODUCTION AND SCOPE

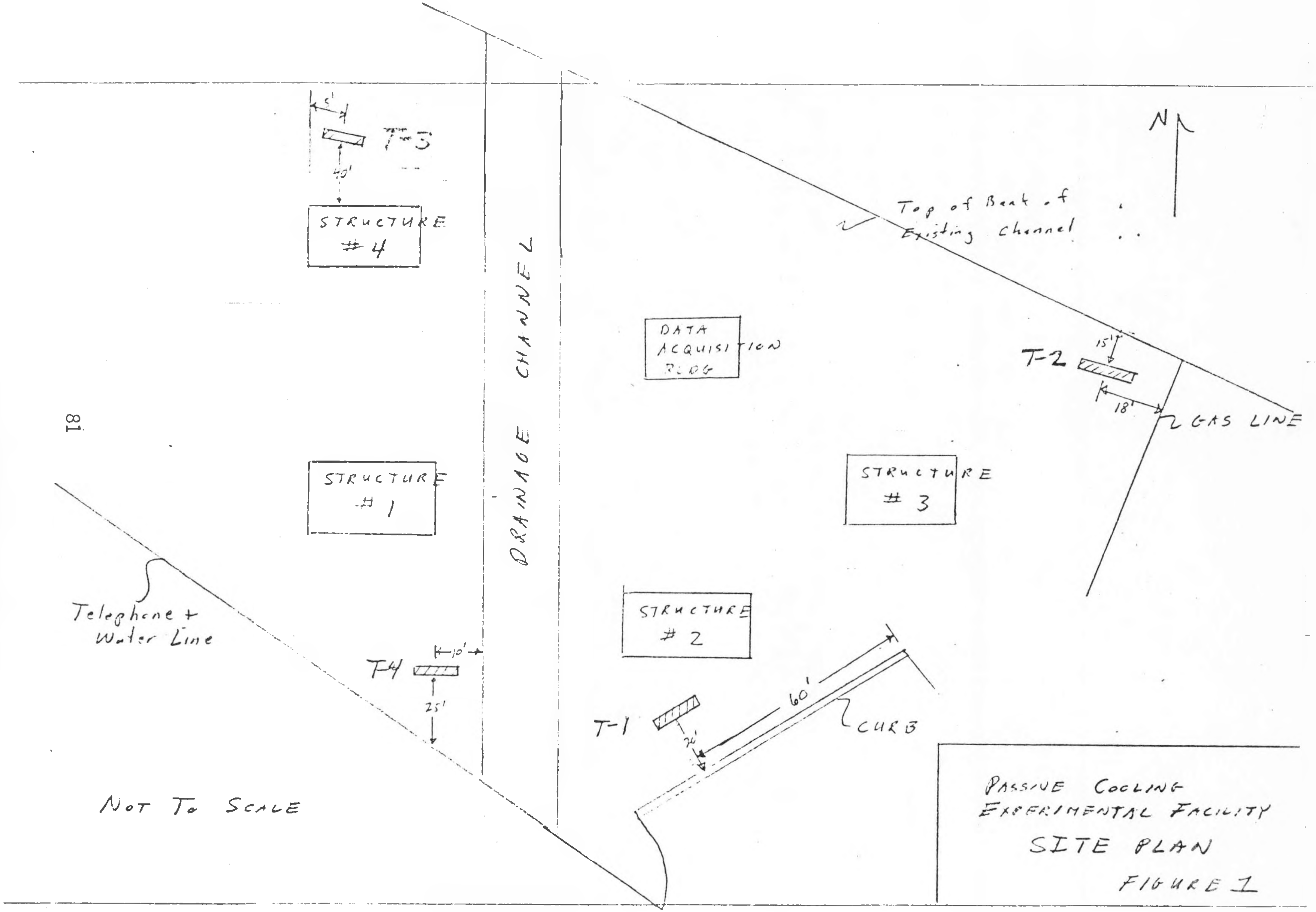
This report describes a geotechnical and foundation investigation at the subject site and it presents the results along with recommendations relating to the design of the foundations. The study is intended to determine the most suitable type of foundation, the required foundation depth, and the allowable soil pressures to be used in the design. The lateral earth pressures for use in the design of retaining walls, as well as a discussion of settlement and groundwater problems are presented.

The field investigation for the project was performed October 15, 1980 and consisted of excavating four backhoe trenches. Laboratory tests were performed on samples taken from the trenches. An interpretation and evaluation of these test results in conjunction with a technical analysis led to the design recommendations.

SITE DESCRIPTION

The subject site is located at the Tucson International Airport and is bounded by the existing ERL facilities on the south and east, on the north by a channel, and on the west by the road providing public access to the airport. The approximately 2 acre site is essentially flat with a very slight slope toward the channel bounding the north side. The site plan is shown in Figure 1.

The site is divided into two portions by a feeder drainage channel running directly north into the main northwesterly flowing channel. The smaller feeder [illegible] is fed by surface drainage areas of the airport facility and has water flow predominantly during times of substantial rainfall funoff. Its banks are not maintained and presently it is a habitat for dense weed vegetation.



PASSIVE COOLING
EXPERIMENTAL FACILITY
SITE PLAN
FIGURE 1

The main channel is a maintained channel. It carries surface flows from a large drainage area east of the airport. At no time during the large floods which Tucson has experienced in the last two years have the banks of this channel been breached by the waters.

It appears that until channelization of this drainage way was conducted, that the flow meandered over a broad area encompassing much of the site. Confirmation of this theory is given later in the report.

The present use of this land is varied. The portion of the site west of the small feeder channel is planted with low vegetation while the eastern portion has been cleared.

PROPOSED STRUCTURE

The proposed structures are five in number and will encompass approximately a total of 4330 sq ft. The locations of these structures are shown on the site plan, Figure 1. Structures numbered 1, 3, and 4 will be conventional above ground units.

The Data Acquisition Bldg is approximately 16 ft by 21 ft in plan and will have concrete block walls. It is anticipated that at a future date a berm will be placed to an elevation of 8 ft above grade along the east, north and south walls of the structure. Grade will be approximately the existing ground surface level at the south end of the site.

Structure #2 at the south end of the site is a 2 story concrete block building approximately 20 ft by 38 ft in plan. A 19 ft by 20 ft eastern portion of the building is to be buried 1 story or 8 ft below grade. The western portion of the structure is to be constructed 1/2 story or 4 ft below grade. The two stories for each half are staggered, therefore the grade elevation around the structrue will not need to be varied.

FIELD EXPLORATION

A subsurface investigation was performed on October 15 using a backhoe to excavate 4 trenches. The locations of these trenches are shown on Figure 1. Trench #1, near Structure #2, was excavated to a depth of 10 ft, Trench #2 to 9 ft, Trench #3 to 8½ ft, and Trench #4 to 8 ft below the exisiting ground surface.

Field logging of the soils was performed. Samples of the soil at various levels of the soil profile exposed by the trench walls were taken. The classifications including density characterizationsof the soils in each trench are presented in Appendix A.

Groundwater was not observed in any of the trenches. This occurence is expected for the dry time period in which the trenches were excavated. During long periods of intense rainfall transitory perched water may exist.

All the trenches have been located by orange flagged stakes. After sampling, the trenches were backfilled but not compacted.

LABORATORY TESTING

For the purpose of foundation evaluation, laboratory test were conducted on samples of soil taken during the field exploration. These tests were confined to gradation tests since strength estimates can be made from the density characterizations made in the field.

The gradation curves are presented as Figures B-1, B-2, and B-3 of Appendix B. The material can generally be classified as a well graded sand with some silt. Due to the lack of fine material the Unified Soil Classification symbol is SW or SP.

A calcium carbonate verification test on the cemented material gave a positive reaction. The presence of some slight caliche type cemented material was thus confirmed.

CONCLUSIONS AND RECOMMENDATIONS

It is apparent from the field exploration that the soils at the site have been deposited by waters overflowing the banks of the channel bordering on the north. The material closest to this channel is generally slightly coarser than thematerial found at some distance away. The appearance of gravel at some depths indicated that the channel has not always been confined to its present location. In general, the material which comprises this site can be described as a well graded brown sand with some silt which is slightly moist and medium dense to dense throughout.

These soils have all the strength characteristics of good bearing soils that can support appreciable loads by means of shallow foundations. Therefore it is recommended that the masonry walls be supported by continuous strip (wall) footings embedded in this soil. Interior floor slabs can be placed on this material in a manner to be specified.

Bearing Capacities

The allowable bearing capacity of the brown sand (SW) layer existing in the top 1 to 2 ft is 1600 psf. The reddish brown to brown sand at depths of 6 to 7 ft can support 3000 psf. The layer of grey brown sand at deeper depths can support 4000 psf. These bearing capacities for these soil layers assume that the structures are buried a minimum of 18 inches or the depth from the surface to these soil layers, whichever is greatest.

Any footings should not be founded at a depth less than 18 inches below the nearest adjacent final grade. The minimum width of such a footing should not be less than 18 inches and they should have a thickness of at least 10 inches.

Due to the low magnitude of the applied dead and live load intensities in the interior of the building, the bearing capacity of slabs-on-grade are not critical.

Footings and slabs should not be poured on foundation soils which have become saturated. Such soils should be dried to the point where the Soil Engineer can certify that it is safe to place the foundations.

Settlements

The total settlements associated with these recommended bearing capacities and foundation schemes will be less than 1/2 inch. Maximum differential settlements throughout the length of the structures will be less than half of the total settlements. These determinations are based upon the uniformity and density of the materials present.

Slab-On-Grade

The interior floor slabs can be supported on the existing material provided that 4 inches of clean gravel material is placed and compacted below them. This material forms the subgrade for the slabs and will break any capillarity caused by moisture below the slab.

The slabs should be at least 4 inches thick. They should be reinforced with at least 6 in x 6 in x 12# welded wire mesh.

In order to provide a moisture proof seal between the slabs and wall footings these components of the Data Acquisition Bldg and Structure #2 can be poured monolithicly. For the other structures which are founded a short distance below exisiting grade, the slabs should be isolated from the walls by thin mastic strip providing a sealer to moisture. In the former case reinforcement should be continuous through the slab and wall footings and in the latter it should not extend through these components.

Lateral Soil Pressures

The concrete block walls of the buried Structure #2 and the Data Acquisition Bldg with berms placed against its walls will be subject to lateral pressures. The pressure which acts on these walls is a function of the soil strength, the movement these walls will undergo, and the drainage conditions. The structural support system anticipated by preliminary drawings indicate a two point support of the walls at the bottom and at the top. This restraint will not allow the walls to rotate or translate adequately to relieve the at-rest pressure to the point where full active pressures develop.

Thus the walls of Structure #2 should be designed for bending and shear using equivalent fluid pressures of 42 psf. The lateral pressures which the berm surrounding the Data Acquisition Bldg will impose can be determined by using an equivalent fluid pressure of 35 psf. Both of these pressure diagrams will be essentially triangular in shape. Slight increased intensities above this shape will appear at the top and bottom of the walls.

It is essential that no buildup of hydrostatic pressures occur along the walls. Measures which should be taken to insure this condition are specified in the following section.

Groundwater Control

The following drainage considerations must be addressed in order to control the detrimental effects of surface and subsurface groundwater. Such effects can include a reduction in the woil bearing capacity, an increase in settlement potential, an increase in hydrostatic forces, as well as the possibility of having a damp foundation.

The design of the Data Acquisition Bldg and Structure #2 are such that the walls adjacent soil will be used to monitor thermal conductivity through the soil and building. Any backfill material different from on site material would alter the values obtained from those for a wall against the indigenous material. Another aspect of the design is that there will be no sinks or drains in the depressed 'basement' areas.

For these reasons no drainage pipe embedded in gravel backfill leading to a sump is recommended for Structure #2. Instead, moisture migration can be prevented by the placement of an impermeable membrane on the buried walls and surface flow can be controlled by grading. Backfilling can be performed by using material existing on site. The ground surface around the periphery of the buildings should be sloped away from the structures as soon as the backfill is placed.

JOB NO.	CLIENT	LOCATION
	ERL	Airport

LOCATION OF BORING

South side of Site

See site Plan Fig I.

DATUM

ELEVATION

DRILLING METHOD & EQUIPMENT

Backhoe - John Deere

SAMPLING METHOD

CASING DEPTH

BORING NO. T-1

SHEET 1 OF 1

DRILLING

START	FINISH
TIME	TIME
DATE	DATE
10/15/80	

DRILLING CONTR.

CHKD BY

DATE

SAMPLER TYPE	INCHES DRIVEN / INCHES RECOVERED	SAMPLE NO. / SAMPLE DEPTH	BLOWS/6" SAMPLER	DEPTH IN FEET	SOIL GRAPH	WATER LEVEL	SURFACE CONDITIONS
							Cleared ground surface
				0			SW Brown SAND with some Gravel well graded slightly moist
				1			medium dense to dense, some cementation slight
				2			SP Reddish Brown SAND fine-medium moist dense, no cementation
				3			
				4			
				5			
				6			
				7			
				8			SW Grey Brown SAND w/ trace Silt well graded, dry, very dense
				9			Some slight carbonate cementation Top 1 ft of this soil layer is more
				/0			Brown in color than grey brown
				1			Bottom of Trench 10 ft
				2			
				3			
				4			
				5			
				6			
				7			
				8			
				9			
				0			

	JOB NO.	CLIENT	LOCATION
		ERL	Airport

LOCATION OF BORING

Northeast side of site

See site Plan Fig I

DRILLING METHOD & EQUIPMENT

Backhoe - John Deere

BORING NO. T-2

SHEET 1 OF 1

DRILLING

START TIME	FINISH TIME
DATE 10/15/80	DATE

SAMPLING METHOD

DATUM

ELEVATION

CASING DEPTH

SAMPLER TYPE	INCHES DRIVEN / INCHES RECOVERED	SAMPLE NO. / SAMPLE DEPTH	BLOWS/6" SAMPLER	DEPTH IN FEET	SOIL GRAPH	WATER LEVEL	SURFACE CONDITIONS
							Cleared ground surface
				0			SW Brown SAND with some Gravel well graded, slightly moist medium dense to dense
				1			
				2			SP Brown SAND, fine-medium, slightly moist, dense
				3			
				4			trace silt at lower depths
				5			SW Grey Brown SAND medium-coarse dense slightly moist
				6			Cementation begins at 6ft depth
				7			SP Uncemented loose 8" thick seams some small roots present
				8			SW Brown Gravelly SAND conglomerate structure
				9			
				0			Bottom of trench - 9 ft
				1			
				2			
				3			
				4			
				5			
				6			
				7			
				8			
				9			
				0			

DRILLING CONTR. ____

CHKD BY ____

DATE ____

Water migration from the channels adjacent the buildings will be prevented by the density and silt content of the soil as well as the distance between buildings and the channels.. Dampness and moisture below the interior slabs is prevented by the gravel layer which breaks any capillarity.

Precautions should be taken to insure that seepage from the watering of planted areas adjacent to the foundations will not reach the foundation soil below the bottom of the footing level. Either a sheet of impermeable lining placed 18 inches below planted areas or a well compacted stratum of clayey soil above the bottom of the footing will insure that this requirement is met.

APPENDIX A

FIELD INVESTIGATION

JOB NO.

CLIENT: ERL

LOCATION: Airport

LOCATION OF BORING: North west portion of site

See Site Plan Fig I

DRILLING METHOD & EQUIPMENT: Backhoe - John Deere

BORING NO. T-3

SHEET 1 OF 1

SAMPLING METHOD

DRILLING

START TIME	FINISH TIME
DATE	DATE
10/15/80	

DATUM

ELEVATION

CASING DEPTH

SAMPLER TYPE	INCHES DRIVEN / INCHES RECOVERED	SAMPLE NO. / SAMPLE DEPTH	BLOWS/6" SAMPLER	DEPTH IN FEET	SOIL GRAPH	WATER LEVEL	SURFACE CONDITIONS
							Plant cultivation less than 3ft in height
				0			SW Brown SAND with some Gravel well graded slightly moist
				1			medium dense to dense gravel amount approx 25%
				2			SP Brown SAND fine-med, slightly moist, dense
				3			
				4			
				5			
				6			
				7			SW Grey Brown SAND trace Silt dense, slightly cemented by carbonates, dry
				8			SW Brown Gravelly SAND moist dense
				9			
				0			Bottom of trench 8'-6"
				1			
				2			
				3			
				4			
				5			
				6			
				7			
				8			
				9			
				0			

DATE ______ CHKD BY ______

JOB NO.

CLIENT ERL

LOCATION Airport

LOCATION OF BORING

Southwest portion at Site
See Site Plan Fig I.

DRILLING METHOD & EQUIPMENT Backhoe - John Deere

BORING NO. T-4

SHEET 1 OF 1

DRILLING

START TIME

FINISH TIME

SAMPLING METHOD

DATE 10/20/80

DATE

DATUM

ELEVATION

CASING DEPTH

SURFACE CONDITIONS Plant cultivation - less than 3ft in height

SAMPLER TYPE	INCHES DRIVEN / INCHES RECOVERED	SAMPLE NO. / SAMPLE DEPTH	BLOWS/6" SAMPLER	DEPTH IN FEET	SOIL GRAPH	WATER LEVEL	
				0			SW Brown SAND with some Gravel well graded, slightly moist medium dense to dense
				1			SP Reddish Brown SAND
				2			fine-medium dense no cementation
				3			
				4			
				5			
				6			
				7			
				8			SW Grey Brown SAND w/ trace silt
				9			well graded dry very dense with some carbonate cementation finer than SW in layer above
				0			
				1			Bottom of Trench at 8ft.
				2			
				3			
				4			
				5			
				6			
				7			
				8			
				9			
				0			

DRILLING CONTR

CHKD BY

DATE

APPENDIX B

LABORATORY INVESTIGATION

GRAIN-SIZE DISTRIBUTION
(UNIFIED SOIL CLASSIFICATION SYSTEM)

JOB NO. ERL BY RLS DATE 10/20/80

KEY	BORING	DEPTH	ELEV.	SOIL CLASSIFICATION
—	T-1	0-9ft		(SW) SAND with trace silt well graded

Symbol	Depth ft
⊙	1
X	2½
•	6
□	7
△	7+
●	9

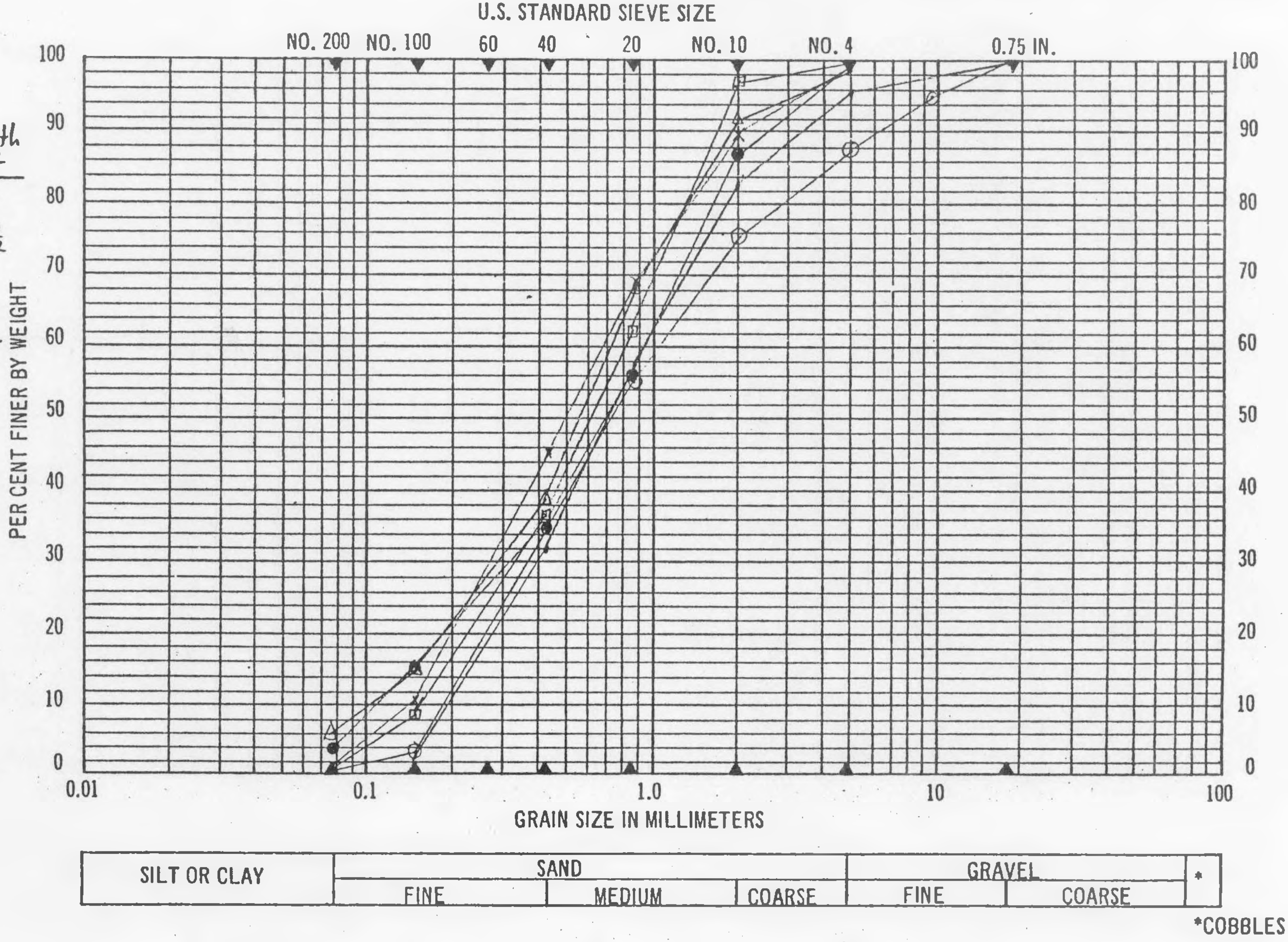


Fig B-1

GRAIN-SIZE DISTRIBUTION

(UNIFIED SOIL CLASSIFICATION SYSTEM)

JOB NO. ERL BY RLS DATE 10/20/80

KEY	BORING	DEPTH	ELEV.	SOIL CLASSIFICATION
⊙	T-2	7'		SW SAND trace silt
Δ	T-2	8'		SW GRAVELLY SAND trace silt

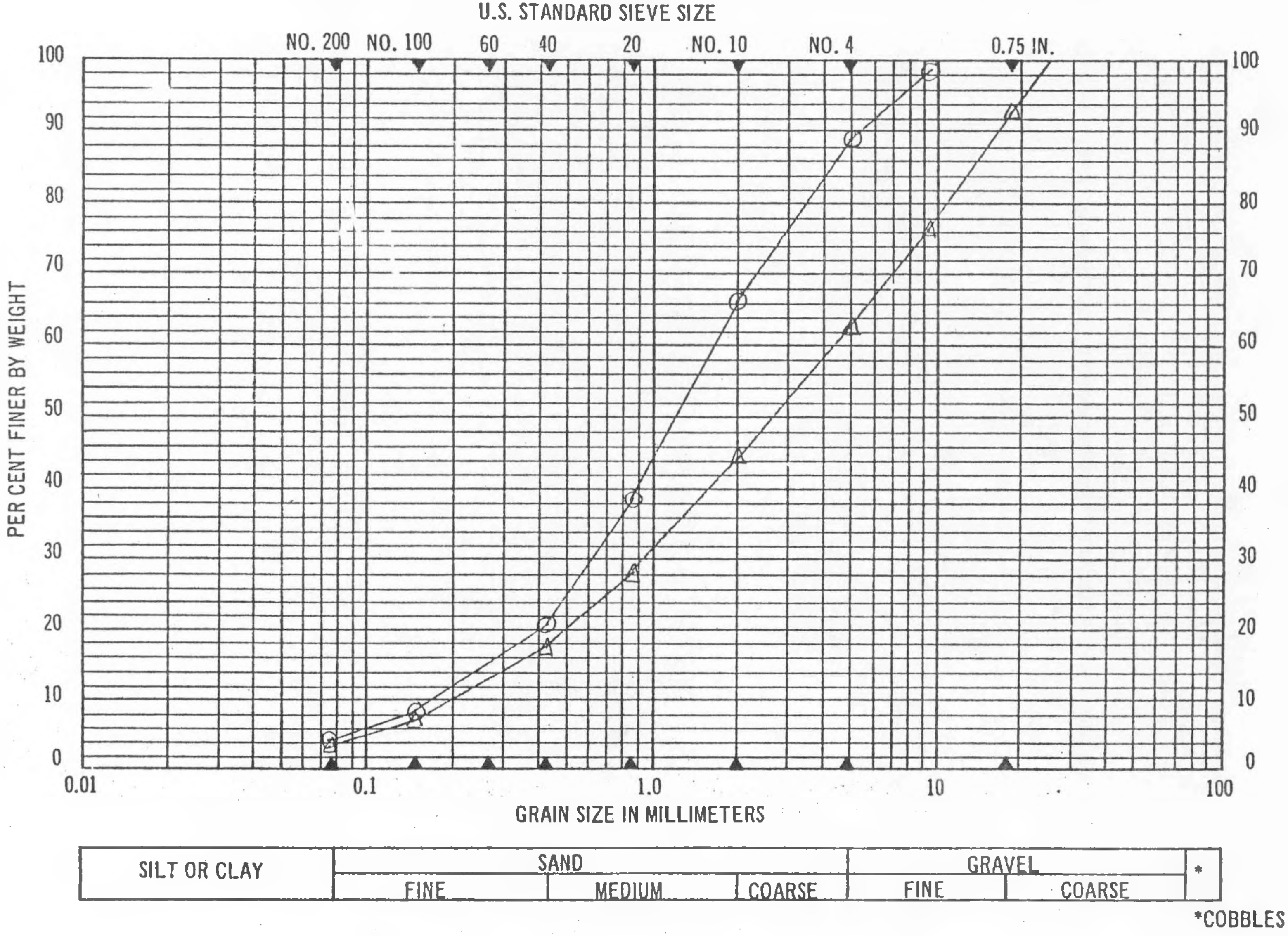
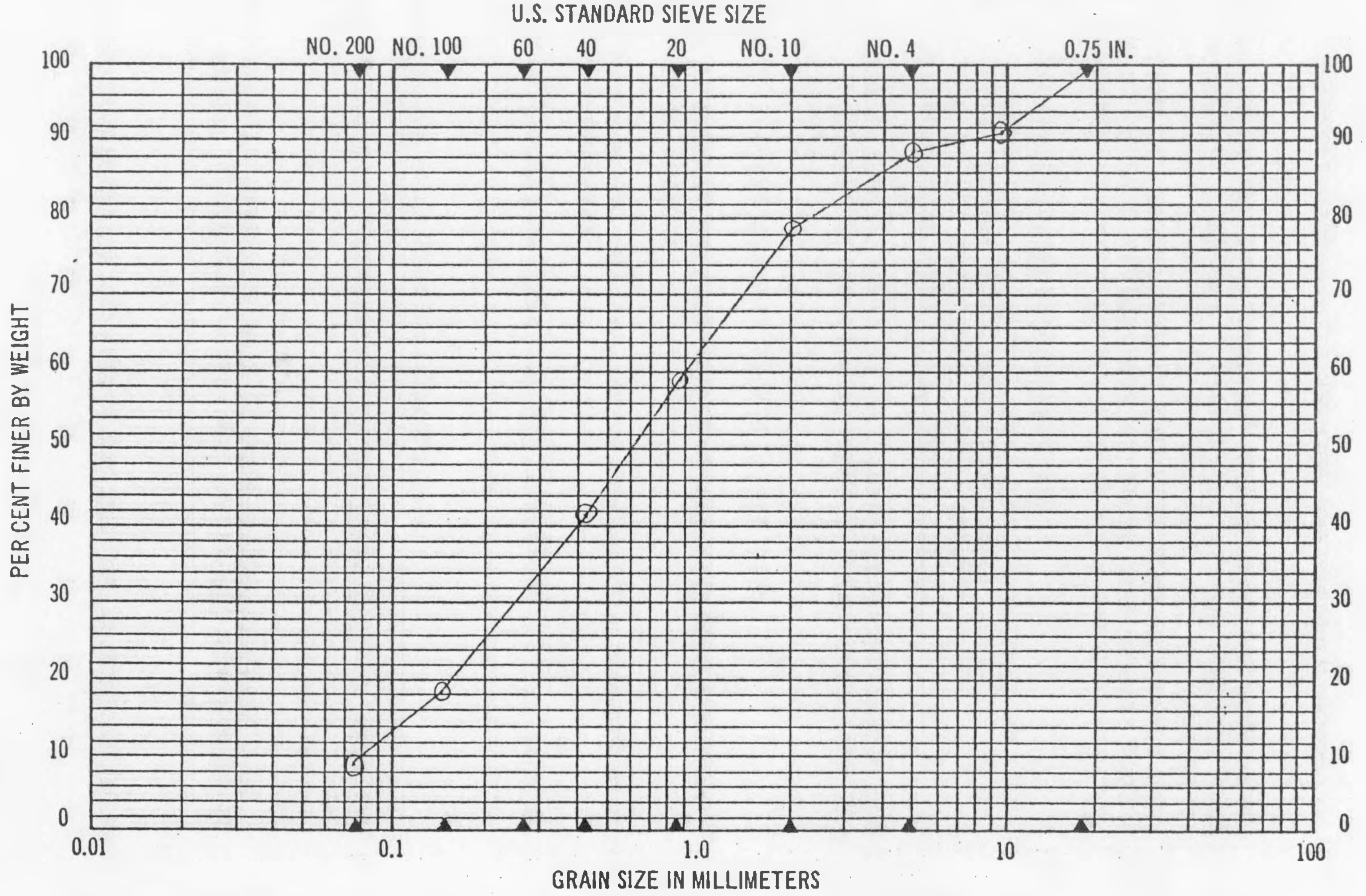


Fig B-2

NO. ERL BY RLS DATE 10/20/80

KEY	BORING	DEPTH	ELEV.	SOIL CLASSIFICATION
⊙	T-3	6-8'		SW SAND with trace silt and f. Gravel



SILT OR CLAY	SAND			GRAVEL		*
	FINE	MEDIUM	COARSE	FINE	COARSE	

*COBBLES

GRAIN-SIZE DISTRIBUTION
(UNIFIED SOIL CLASSIFICATION SYSTEM)

Fig B-3

APPENDIX VI

Waterproofing Discussion

1. "Analysis of Waterproofing Methods for Basements" compiled by Helen J. Kessler

Analysis of Waterpoofing Methods for Basements
Compiled by Helen J. Kessler

February 1981

Waterproofing in desert areas may seem like a trivial matter since the water table in most areas is several hundred feet below the surface. However, basements that are not waterproofed do get wet, primarily because of capillary action which allows water from the soil to seep through basement walls. This action is the primary reason why gravel is placed below concrete floors - to prevent water from seeping up into the floor.

For the Passive Cooling Experimental Facility, we looked at several methods for waterproofing walls which we felt would be appropriate for desert areas. Many other methods do exist, but seemed to be more than adequate and thus too expensive for the average desert dweller.

Two asphalt materials and variations thereof were studied. One is an emulsion and the other is a liquid "cutback". These materials can be used with or without a fiberglass mesh and other protective coatings.

The first three materials/systems in the following list will be used on various underground walls of Structure #2 of the Experimental Facility. The other systems were also discussed as possibilities. (Amounts are given for a 100 square foot area)

1. Flintkote E-M-W

Asphalt emulsion primer ($1^1/2$ gal./100 sq. ft.)
First course C-13-E (Asphalt emulsion) (3 gal.)
Second course Yellow Jacket glass fabric over entire wall
Third course C-13-E (3 gal.)
Fourth course C-13-E (3 gal.)
Protection board (We may use asphalt paper or no protection instead)

This system uses a non-fibrated asphalt emulsion reinforced with a fiberglass fabric and protected before backfilling. Other companies such as Johns-Manville, Henry, etc., recommended similar waterproofing systems.

2. Sonneborne Hydrocide Mastic

Hydrocide Mastic - 8-9 gal./100 sq. ft. (1/8" thick)

The Hydrocide Mastic is a "cutback" asphalt material made with a petroleum solvent. It is a "heavy bodied non-sag coating, reinforced with long asbestos fibers." Fiberglass mesh will be used as a reinforcement at corners such as where the stem wall meets the footing. Other companies such as Flintkote and Henry make similar materials for other purposes.

3. Two coats Henry fibrated asphalt emulsion

Asphalt primer ($1^1/2$ gal./100 sq. ft.)
First course asphalt No. 307 (3 gal.)
Second course asphalt No. 307 (3 gal.)

Henry fibrated asphalt emulsion is reinforced with asbestos fibers. It is easily available to the general public. Other companies make similar products.

4. One coat of asphalt emulsion over a primer coat.

5. One coat of asphalt emulsion over a primer coat with fiberglass reinforcing at corners.

6. Two coats of asphalt emulsion over a primer coat, with asbestos felt as a protective membrane.

7. One coat of Sonneborne Hydrocide Mastic without further reinforcing.

Materials: (Descriptions from Flintkote Catalogue):

1. Asphalt Emulsions: Manufactured in two basic types - "chemical" and "clay".

Chemical type is primarily used in road construction and soil stabilization. It is also suited for use in the manufacture of adhesives.

Clay-type is especially recognized for its use in conjunction with waterproof membrane systems.

Clay-type emulsion is a mechanical mixture of finely sub-divided particles of the soft, better weathering types of asphalt, suspended in a non-flammable, odorless vehicle by means of a mineral colloid which keeps the asphalt particles in uniform suspension to prevent their coalescing while in the liquid state.

When exposed to the air, the vehicle evaporates, allowing the asphalt particles to form into a homogeneous film having stability superior to the original asphalt from which the emulsion was made. Films deposited from a mineral colloid suspension have properties not possessed by the original asphalt such as a breathing film resistance to blistering, alligatoring, cracking and heat flow.

The emulsion is flowed on, rather than brushed in. When the vehicle evaporates, a weatherproof film of asphalt remains... a film that is actually a reinforced structure and the non-hazardous vehicle gives clay-type asphalt emulsions outstanding superiority over other forms of asphalt coatings.

2. Cutback Asphalts: Asphalt prepared as liquid, semi-liquid or plastic material by blending with petroleum solvents, or other volatile dilutents is referred to as a "cutback." A wide range of products is made from this form of asphalt, often with two or more types of asphalt blended together with asbestos fibers, mineral fillers, pigments and other compatible ingredients.

   The introduction of cutbacks was the first progressive step in making bituminous materials more adaptable to industrial uses. The desirable attributes of asphalt were retained in a workable form that permitted its use as a plastic and for adhesives, coatings and sealers. This group of asphalt products, while eliminating the necessity of heating, also retains many inherent drawbacks of solid asphalt in its original form.

3. Solid Asphalt: Must be heated and used while in a fluid state. It sets quickly as it cools. This is the form of asphalt commonly used for cementing sheets of roofing felts. It is manufactured by refining petroleum derivatives to specified degrees of hardness, ductility and softening point. There are many grades of solid asphalt. It has a long history of successful low cost use.

   In order to obtain maximum efficiency from its use, the CHARACTERISTICS OF SOLID ASPHALT must be thoroughly understood.

1. Overheating changes its physical and chemical qualities, therefore close temperature control is essential.

2. It does not bond to a wet surface.

3. Being a photo-sensitive material, it must be protected from the actinic rays of the sun in order to prevent deterioration.

4. It oxidizes rapidly when exposed to the weather, with resulting untimely cracking and spalling - the familiar "alligatoring". It is not a suitable base for reflective coating.

5. The fire required to melt it involves a hazard.

6. The material in place is not static at high temperature.

7. The fumes of hot asphalt are often objectionable. Most Air Quality Management Districts have restrictions on smoke and air pollutants from asphalt kettles.

Advantages and Disadvantages of Systems:

The emulsion may be used on damp surfaces while the cutback must be used on a dry surface. The emulsion must be used when the outdoor temperature is above $60^{O}F$ while the cutback may be used at lower outdoor temperatures. The latter makes it popular in cold climates. Both materials are cold applied which makes them easier to apply than hot asphalt, especially on vertical basement walls. The cutback materials are more expensive than the emulsion, but may be applied in fewer coats, thus reducing labor costs.

A description of waterproofing materials from the Flintkote catalogue as well as specification sheets from the W.W.Henry Company and Flintkote are enclosed.

APPENDIX VII

Exterior Insulation Techniques

1. "Exterior Insulation Techniques for Masonry Walls" by Helen J. Kessler and John F. Peck
2. Articles for Arizona Star

Exterior Insulation Techniques for Masonry Walls

(Methods that have been tried or observed by the
Solar Group at the Environmental Research Lab,
University of Arizona)

Helen J. Kessler
John F. Peck

Applying insulation to the exterior surface of a masonry wall is an effective technique for constructing a wall that is used to stabilize temperatures inside a home. It is particularly useful in passive solar homes where heat is stored in the mass of the home and in homes which are cooled at night and allowed to coast through the day on the coolness stored in the walls. In many cases, insulating older uninsulated masonry homes may be easier and better when outside insulation is used.

The following are some concerns which should be addressed when outside insulation is being considered.

1. How is the insulation attached to the wall? Is it held on by glue, nails or by some other method? Does the glue react with the insulation? How long will the glue last? If glue is used, does it have a positive bond to the masonry? If nails are used, are there enough nails and do they penetrate the masonry properly? Is the masonry flat or irregular -- this will help determine the method of attachment.

2. What kind of exterior coating (stucco) is being used? Very thin acrylic modified reinforced coatings (fiberglass cloth, etc.) may need few if any expansion joints, since they are somewhat flexible. However, such coatings are more susceptible to damage, such as from a rock being thrown at them or from woodpeckers. They are easily repaired with the same materials. Thicker coatings such as full thickness stuccos generally need expansion joints and are reinforced with chicken wire or expanded mesh. Interestingly, in many cases, the full stucco costs no more, or very little more than the thinner stuccos, even though much more material and often more labor is involved.

3. What types of insulation should be used or do you want to use? How high is the R-value?

   a. Beadboard type styrene foam (R-4 per inch)

   b. Styrofoam - blue extruded from Dow Corning (R-5 per inch).

   c. Sprayed on urethane (R-7 per inch)

   d. Board stock isocyanurate or polyurethane foam (R-7 or 8 per inch)

   See manufacturers specifications for more accurate R-values.

4. Is the price of the insulation and stucco quoted together or separately? Is the stucco specially imported from far away? If so, the price may be quite a bit higher than locally made stucco. Hauling sand 1000 miles is like taking "coals to Newcastle".

5. All outside insulation should be brought all the way down below grade to the footings.

We and several others in Tucson have tried various different outside insulation techniques. These include the following:

1. Insul-flex or Dryvit - A two-coat process approximately 1/8" thick applied over beadboard styrene foam insulation. The insulation is attached to a smooth masonry surface with a modified portland cement/acrylic glue mixture. The same mixture is then troweled onto the exterior of the styrofoam. While it is wet, a fiberglass mesh (plastic coated for alkali resistance) is imbedded in the modified portland cement/glue. This is then allowed to dry. The final coat is a thin sand stucco, mixed with acrylic glue and water.

   Because the coating is thin and somewhat pliable, few expansion joints are needed. However, cracking may occur at sharp corners and where the stucco is used over wood corners. In those areas, corner beads, extra fiberglass, or a more rounded corner should be used. In our installation at the Environmental Research Lab, we have also had a problem with woodpeckers. We're not sure whether the pesky birds like the stucco or the insulation below it, or even how they know to start pecking there in the first place.

   Insul-flex may be obtained from the El Rey Stucco Company, Inc. 4100 1/2 Broadway, E. Albuquerque, New Mexico 87102 (505) 873-1180.

   Dryvit is almost identical to Insul-flex and may be obtained from Dryvit System, Inc., 400 Lincoln Avenue, Warwick, Rhode Island 02888 (401) 463-7150.

   Several Tucson and Phoenix homes and businesses have used each and are satisfied with them.

2. Therm-clad

   Therm-clad is an acrylic stucco reinforced with chopped fiberglass roving. It is significantly harder than standard stucco. The Therm-clad process includes 1" of extruded styrofoam , 20 ga. steel mesh and a 3/8" - 1/2" "stucco" finish. The fabricators of this material have developed some special chemicals which they mix into the sand and cement mixture along with the alkali resistant fiberglass and acrylic. They point out that it is very important to use alkali resistant fiberglass, that this fiberglass is exactly 1/2" long and blue in color, and that only one company makes it, Dow Corning.

As with the other fiberglass reinforced acrylic stuccos, Therm-clad is quite a bit more flexible than standard stucco. This means that fewer expansion joints, if any, are needed on residential construction and the material is much more resistant to cracking.

The insulation is attached to the masonry with case hardened nails. At first it is tacked up with just a few nails. It is then firmly secured as the stucco mesh is being nailed on. The people who use Therm-clad avoid glue since they don't trust its lifespan.

It appears that Therm-clad is a good material. However, in spite of its thickness and hardness, it is susceptible to woodpeckers.

Therm-clad may be obtained from Johnson Plastering, 3371 E. 36th Street, Tucson, AZ 85713, (602) 624-1769.

3. Surewall

Surewall and NuWall are also acrylic stuccos reinforced with fiberglass roving. We have applied Surewall in a 1/8" thickness directly over insulation with no wire reinforcement and have observed significant cracking. We have also observed it being used with chicken wire reinforcement in 1/4"- 1/2" thickness. In this mode cracking also occurred, but was not as significant. One Tucson house has a wire reinforced NuWall coating over styrofoam , and the owners are quite pleased with it.

Surewall is available from the W.R. Bonsal Company, P.O. Box 38, Lilesville, NC, 28091 (704)848-4141.

NuWall is available from George Newland, 8616 N. 32nd Drive, Phoenix, AZ 85021 (602)943-0510.

4. Another type of stucco is just the standard three-coat stucco over wire mesh. This appears to work well, although it has similar cracking problems inherent in any standard stucco.

Attaching the insulation and stucco to the wall is perhaps the biggest question. If the wall is flat, board stock insulation may be glued on (as with Insul-flex) or nailed on. If the wall is bumpy, as with adobe or slump block, the insulation must be nailed on. A further method is to prepare for the insulation while the house is under construction. Durawall (a steel reinforcing ladder placed between the courses of concrete block) may be used every second course (at 16" intervals). Every second leg of the Durawall is cut and bent out so it sticks out a bit more than 2" from the surface of the wall. The insulation can then be impaled on the Durawall spikes (or ties) and held in place with round washer like discs which once put on can't come off. The stucco mesh is then held onto the wall using the same Durawall ties and discs.

Another insulating method is to blow on urethane foam. This is an expensive method and gives an undulating finish, which when completed makes the wall appear similar to plastered mud adobe.

When used over masonry walls, the insulation value of the outside insulation should be at least R-8 if possible, although some in Tucson find R-5 satisfactory.

This is just a listing of the outside insulation methods we at the Environmental Research Lab are familiar with. Undoubtedly there are others.

Protect outside of your house

Helen J. Kessler

This is the first of a two-part series.

When was the last time you took note of the walls of your house? Maybe, it was just the other day when you noticed how cold they were.

Cold walls make cold houses, and big heating bills.

There is something you can do to make masonry walls more efficient. And as a side benefit, it also might help you turn your house into a solar home.

That something is outside insulation. Although not cheap, insulation on the exterior of your house can be installed to keep the cold out in the winter, and also keep the heat out in the summer.

A few years ago nobody knew what you were talking about if you said you wanted to insulate the outside of your masonry walls. But now, a whole slew of companies have formed to sell the very product you were looking for to make a solar home work properly. (As I discussed in the last column, solid masonry walls, insulated on the outside, help stabilize the temperatures inside your house.)

Standard flat concrete block walls, either stuccoed or exposed, are the easiest to insulate on the outside because they are smooth and their appearance won't be significantly changed by the addition of the outside insulation. If you are building a new house, using dirt-, rock- and sand-filled concrete block is a good idea.

Other masonry or solid walls also can be insulated on the outside. Some include burnt adobe or mud adobe (both of which have the advantage of already being solid and have the disadvantage of being so good looking that most people don't want to cover them up). Other good massive walls include rammed earth and poured concrete (which we may be seeing more of in the coming years).

Outside insulation is made up of two basic components, the insulation itself and the material protecting the insulation from the elements. There are several types of insulation that can be used. The most effective come in large boards. They include extruded polystyrene and beadboard, polyurethane (this can also be sprayed on but that is usually more costly) and polyisocyanurates.Others might also be available.

The insulation can be applied in several ways:

- It can be glued on. But not just any glue will work. The glue has to stick to both the insulation and the masonry wall. Those that contain Portland cement, acrylic glue and some additional chemicals work well for this application.

- It can be nailed on. If nails are used, they need to be long enough and strong enough for a firm bond. If your walls are concrete block or poured concrete a mechanically-powered gun will be needed to embed the nails. If you find that an overabundance of nails are needed to do the job, you may start losing heat through those nails. They provide an excellent conduit for heat to travel through.

- A truly elegant system for attaching outside insulation on new homes was developed by Tucson solar enthusiast Milton Anderson when he built his solar home. Before he laid up the concrete block wall of his house, he prepared pieces of Dur-O-Wall (a metal reinforcement shaped like a ladder used to strengthen the mortar joints of masonry walls) so that it could be used to install the insulation. He cut the Dur-O-Wall ladder at every other rung on opposite sides, making two comb-like pieces that appear to be missing every other tooth. Then as the block was layed he put the pieces of cut Dur-O-Wall in every other course such that the cut ends would stick out about 2¼ inches from the surface of the wall. Two inch polystyrene insulation was then impaled on the ends of the cut Dur-O-Wall. Wire mesh, which is used to reinforce the stucco, was then attached to the ends of the Dur-O-Wall with one-way washers (once they're on, they don't come off).

- Other commercially available methods for attaching insulation to the outside of masonry walls can also be used. One involves installing metal or wood furring strips directly to the masonry. The insulation is then installed between the furring strips. The wire mesh for the stucco is attached to the strips.

In addition to various ways of attaching the insulation to the wall, there also are a number of ways of attaching the stucco to the insulation. Different types of stucco systems are available as well. I will discuss these in the next column.

Helen Kessler is an architect with the University of Arizona Environmental Resarch Laboratory. Kessler welcomes your questions. Although she can not answer them individually, she will try to respond to them in future columns. Write to her in care of The Arizona Daily Star, Box 26807, Tucson, 85726-6807.

Insulation goes outside

Helen J. Kessler

This is part two of a series.

Let's assume you've decided to save some money and energy by putting insulation on the exterior of your masonry house. Or maybe you've decided to build a new house with outside insulation.

By adding this outside insulation, you can expect to significantly reduce the amount of energy needed to heat your house in midwinter and you might possibly be able to eliminate the need for heating in spring and fall. Your cooling bills will be reduced as well.

The big question is how do you do it? What kind of insulation and stucco should be used?

Many different insulation materials are available. Unfortunately price ranges and qualities vary widely, which naturally helps to complicate your decision-making.

The most common types of outside insulation are polystyrenes. There are two types: extruded and expanded (beadboard).

The extruded is much denser, has a higher impact resistance and is waterproof, making it ideal for underground applications and for use in wet and freezing climates.

The expanded is similar to the material used in styrofoam cups. It is considerably less expensive than extruded polystyrene and seems to work well for many applications in desert areas.

Extruded polystyrene has an R-value of 5.4 per inch and beadboard has an R-value of 4 per inch. In warm climates, a minimum R-value of 8 is suggested. Thus, either material is suitable.

Other types of insulation include polyisocyanurate foam and board stock with sprayed-on urethane foam. These materials have R-values between 6 and 8 per inch, so less thickness is needed. However, they are quite expensive. From our observations, they also don't seem to be quite as compatible with stucco as are polystyrene insulations. We have noted some cracking of the stucco, especially in applications where sprayed-on urethane is used.

Just a few years ago, finding someone willing to put stucco over outside insulation was a major challenge. Now you can go to many plasterers and actually get a choice of stucco materials. There are essentially three generic types:

- The most common type is put on in three coats over a wire mesh. It is approximately ⅞ inch thick. Although it has been used for years, there are many reasons to look for other solutions. It takes several days to apply a three-coat stucco, which tends to slow down the construction process. It also is heavy and thus needs greater support (which is sometimes inconvenient) than some of the newer stuccoes. And perhaps most importantly, it has little flexibility and thus has a tendency to crack easily without proper expansion joints. The insulation and stucco must be firmly attached to the wall with nails, furring strips or the Dur-O-Wall system described in the previous column.

- A relatively new ⅜-inch-thick stucco, applied in one thick coat with a texture coat, is becoming more common. Like the full-coat stucco, it uses wire mesh for reinforcement. However, the stucco itself contains acrylic glue and ½-inch fiberglass roving. These materials give it considerable elasticity, which means it needs fewer expansion joints and is generally less likely to crack than the regular stucco. Attachment techniques are similar to those for a full stucco.

- A very thin multistep process (approximately ⅛ inch thick) is another relatively new alternative. It was developed more than 20 years ago in Germany. In this process, the polystyrene is glued to the wall (the wall must be smooth) with a Portland Cement/acrylic glue mixture. This same mixture (which has various additives depending on the brand) is then troweled onto the polystyrene and a fiberglass mesh is embedded into it. After this application dries, a finish coat with integral color is troweled on. The finish coat contains fine sand, Portland Cement and acrylic glue.

Because the use of stucco over insulation has become so common, many brands with descriptions similar to those above are now available. In general, the thinner the material the more flexible and less likely to crack it will be. However, those same materials then become more susceptible to damage from other forces, such as baseball bats and woodpeckers. So tradeoffs will have to be made.

We have used all of these materials at the Environmental Research Lab with few problems except for woodpeckers and some cracking (where urethane foam was used). So if you want to build an energy-efficient high-mass house, consider outside insulation a key ingredient.

Helen Kessler is an architect with the University of Arizona Environmental Research Laboratory. Kessler welcomes your questions; although she cannot answer them individually, she will try to respond to them in future columns. Write to her in care of The Arizona Daily Star, Box 26807, Tucson 85726.

APPENDIX VIII

Two Stage Evaporative Cooling

1. "Two Stage Evaporative Cooling Using a Rockbed Associated with the Active ClearView Solar Collector^{R}" by John F. Peck, Helen J. Kessler and T. Lewis Thompson

TWO STAGE EVAPORATIVE COOLING USING A ROCKBED ASSOCIATED WITH THE ACTIVE CLEARVIEW SOLAR COLLECTOR$_R$

by John F. Peck, Helen J. Kessler, T. Lewis Thompson
Environmental Research Laboratory
University of Arizona
Tucson International Airport
Tucson, Arizona 85706

ABSTRACT

Two stage evaporative cooling is an effective alternative to refrigerated air conditioning in many of the desert regions of the Southwest. It is attained by precooling air without humidification before further cooling by evaporation. Both a new home and a retrofit attached office-greenhouse installation located at the Environmental Research Laboratory (ERL) have been constructed using the active ClearView Solar Collector$_R$ and two stage evaporative cooling. Data was collected at both locations during the summer of 1978. The performance of the ERL solar office/greenhouse is discussed.

1. INTRODUCTION

In the desert Southwest where cooling is as costly, if not more costly than heating, it is advantageous to design space conditioning systems for buildings from the point of view of both heating and cooling. By integrating a two stage evaporative cooling system with an active hot air solar space heating system, many of the same components may be used during the entire year. In this case, the storage medium, a large rockbed, is used to store heat during the winter and coolth in the summer [1]. Similar concepts have also been developed at CSIRO in Australia [2].

In this paper, two stage evaporative cooling, the design, behavior and performance of the rockbed and the integration of such systems into single family homes are discussed.

2. THE TWO STAGE EVAPORATIVE COOLING SYSTEM

Two stage evaporative cooling is attained by precooling air without adding humidity before further cooling by evaporation. A system consisting of two evaporative coolers and a large rockbed is used. At night, one evaporative cooler cools the rockbed while the other cools the house with standard one stage evaporative cooling (See Figure 1). During the day, hot outside air is drawn through the rockbed where it is precooled before entering the main house evaporative cooler (See Figure 2). During dry weather in June, no further evaporative cooling of the rockbed air is needed before it is introduced into the house. The system also includes other modes of operation, such as heating and ventilation. All modes are thermostatically controlled and

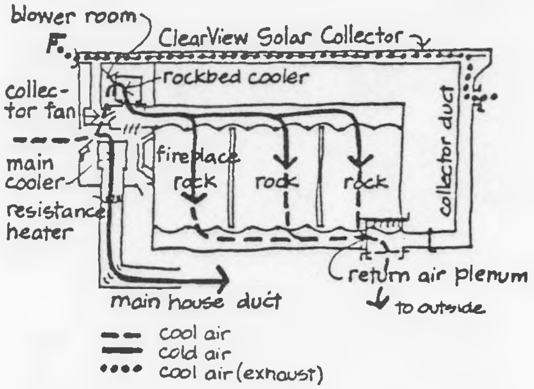


Fig. 1. *Operation of two stage evaporative cooling system at night showing rockbed evaporative cooling and one stage cooling of house.*

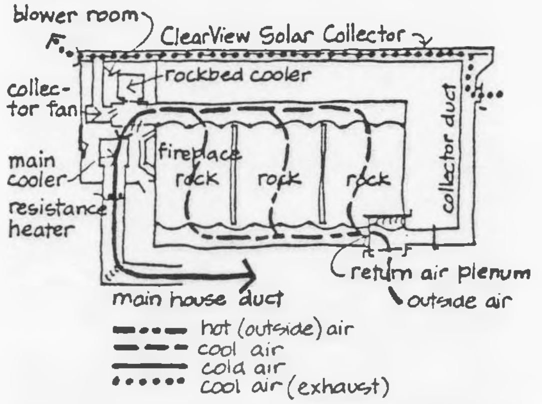


Fig. 2. *Operation of two stage evaporative cooling system during the day. Hot outside air is precooled by rocks before entering evaporative cooler. Cooler pump may be off and dry cooling utilized during part of the less severe portion of summer.*

are operated by the homeowner with either a set of pushbuttons or manually. It should be noted that all items, including the evaporative coolers, are standard off-the-shelf parts.

2.1 The Rockbed

The rockbed is constructed similarly to a standard 1.4m (4'-8") deep basement (See Figure 3). The 8cm-13cm (3"-5") rounded river rock is held in place by a sturdy chainlink fence which is used to form an air chamber approximately 60cm (2') wide on either side. The chainlink fencing is allowed to bow out 15cm (6") from the posts retaining it in order to alleviate high stresses in it from the rocks. Airflow is horizontal across the 4.5m (14'-8") width of the rockbed.

Concrete block walls constructed across the width of the rockbed support the floor joists above. The joists are placed perpendicular to the airflow in order to help prevent air from short-circuiting across the top of the rockbed. When the rockbed is located below the living areas of the house, 15cm (6") of fiberglass insulation is used between the rocks and the floor. During the winter, the large mass of heated rock below the floor can heat the home and helps stabilize the interior house temperatures for periods of a week or more.

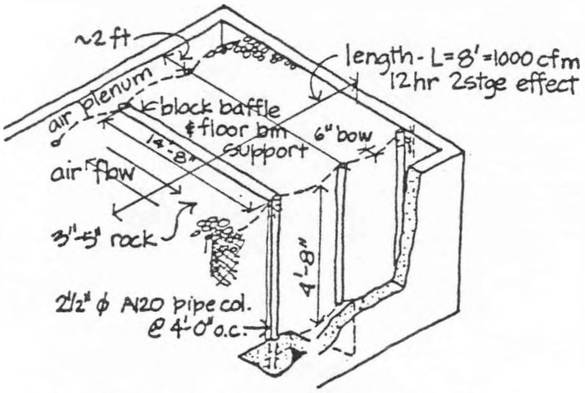


Fig. 3. *Rockbed Construction Details*

2.2 Rockbed Behavior and Performance

The rockbeds we have constructed have been designed for a 12-hour cycle of two stage evaporative cooling, followed by a 12-hour cycle of rockbed cooling at the same airflow. For a relatively well insulated 139m^2-230m^2 (1500-2500 sq ft) house without excessive window heat gains, a typical rockbed size might be 7.3m (24') long by 1.4m (4'-8") deep with a 4.5m (14'-8") airflow path length. This would accommodate a 1416 liter/s (3000 cfm) airflow at 7.9m/min (26 ft/min) face velocities and low static pressure drops (12-20Pa) (.05"-08" H_2O) through the 8cm-13cm (3"-5") rock.

The movement of heat through the rockbed can be thought of as a thermal wave. At night, evaporatively cooled air is blown through the rockbed, gradually exhausting the heat stored during the daytime two stage operation to the outside. At the end of the rockbed cooling period, the temperature of the output air decreases as the "wave" of "coolth" passes through the rockbed. During the daytime cycle, hot outside air is drawn into the rockbed in the opposite direction. The cool rocks absorb heat from the air, thus cooling the air which is drawn into the main evaporative cooler. At the end of the two stage cooling cycle, the rockbed output air warms up as the wave of heat gradually penetrates the rockbed.

The time required for a thermal wave to traverse the rockbed was measured at ∿ 13-1/2 to 14 hours. This data was obtained by blowing ambient air through the rockbed for several days. Input and output temperatures were recorded as shown in Figure 4.

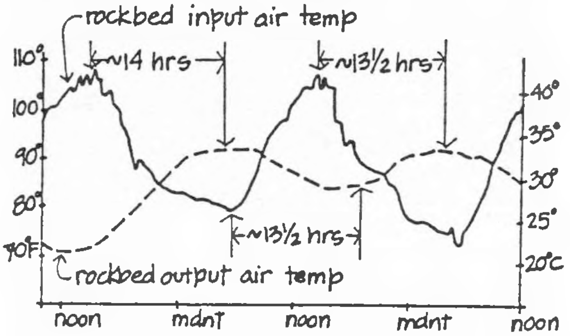


Fig. 4. *Thermal wave through rockbed. Ambient air was blown through ERL rockbed during 48-hour period. Rockbed input and output temperatures are shown.*

2.3 Rockbed Sizing Using the Thermal Wave Concept

While examining experimental data, it was noted that the time required for a thermal wave to penetrate the rockbed was a function of the volumetric heat capacities of air and rock, as well as the rockbed air path length and the air velocity in the rockbed.

Riaz [3] shows that if the volumetric heat transfer coefficient is large and the axial conduction is negligible, and

$$\rho_a \, Cp_a << \rho_b \, Cp_b$$

then the rockbed equations reduce to the purely convective motion of a thermal wave traveling at the velocity

$$V = V_a \, \frac{\rho_a \, Cp_a}{\rho_b \, Cp_b}$$

If the bed length is L, then the time required for the thermal wave to travel through the rockbed is θ = L/V. The equation for the lag time of the rockbed is then

$$\theta = \frac{\rho_b\ Cp_b\ L}{\rho_a\ Cp_a\ V_a}$$

Using handbook values Cp of rock = .88 KJ/KG°C (.21 BTU/# °F) and ρ_b = 1538 kg/m^3 (96 #/ft^3) and Cp air = 1.0 KJ/kg°C (.24 BTU/# °F) and ρ_a = 1.07 Kg/m^3 (.067 #/ft^3), a 4.6m (15') airflow path length, and the measured face velocity of 7.9m/min (26'/min), an ∿ 12-hour thermal pulse is calculated. This agrees reasonably well with the measured values. Thus, this may be a simple method for determining the time for a thermal wave to pass through a rockbed, a useful parameter for designing rockbeds.

2.4 Results of Testing

Output temperatures generally start at approximately .56°-1.1°C (1-2°F) above the nighttime minimum wet bulb temperature and increase to 2.2°-3.3°C (4-6°F) above this minimum wet bulb temperature after 12 hours of operation. On the hottest day of the summer with a dry bulb of 42.2°C (108°F), output temperatures ranged from about 18.9°C (66°F) during the afternoon to 21°C (70°F) at 10 p.m., as shown in Figure 5. On the most humid day of the summer of 1978, a worst case condition with a 25°C (77°F) wet bulb temperature, the output temperature of the two stage cooler varied from 21-22.8°C (70-73°F) (See Figure 6). Since the rockbed is cooled at night, the performance during the next day is generally governed by the dry bulb temperatures of the night before. Figure 7 shows typical output temperatures, along with minimum nighttime wet and dry bulb temperatures from the ERL two stage installation during a representative set of summer days.

2.5 Alternate Two Stage Evaporative Cooling Operation

It is theoretically possible for the two stage evaporative cooling to be operated in the following assymetric manner:

(8 a.m.-2 p.m.) 6 hr two stage evaporative cooling @ 66% of "design" airflow.
(2 p.m.-10 p.m.) 8 hr two stage evaporative cooling @ 100% of "design" airflow.
(10 p.m.-8 a.m.) 10 hr of rockbed cooling @ 120% of "design" airflow.

The "design" airflow is the airflow used during the 12-hour cycle (12 hours of two stage evaporative cooling at 100% of design airflow followed by 12 hours of rockbed cooling at 100% of design airflow). In general, "low" speed operation of evaporative coolers results in airflows ∿ 66% of that at "high" speed. Further control is obtained by controlling the cooler with a thermostat. This cycle, and its variants, should allow the cooler output to match the heat gain of the house more closely. The rockbed at ERL will be operated in this assymetric mode during the summer of 1979 to verify the results of operating in this mode.

3. INTEGRATION OF TWO STAGE EVAPORATIVE COOLING INTO SINGLE FAMILY HOUSES

The ClearView Solar Collector with two stage evaporative cooling has been integrated into two single family homes in Tucson. One has been completed for over a year; the other is currently under construction. In the former house, the heating and cooling systems have been separated, but both use the large rockbed for heat and coolth storage. The heating system is completely automated.

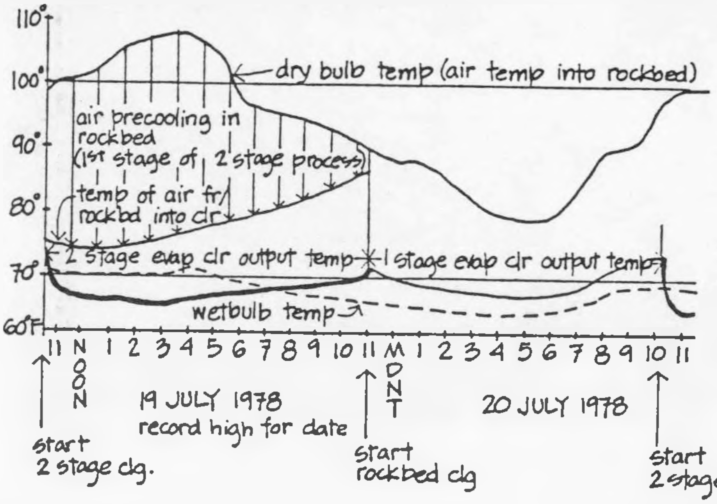


Fig. 5. *Two stage evaporative cooling performance at ERL installation during hottest day of summer 1978.*

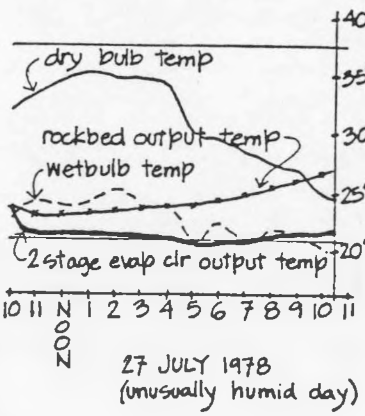


Fig. 6. *Two stage evaporative cooling performance at ERL installation during most humid day of summer 1978.*

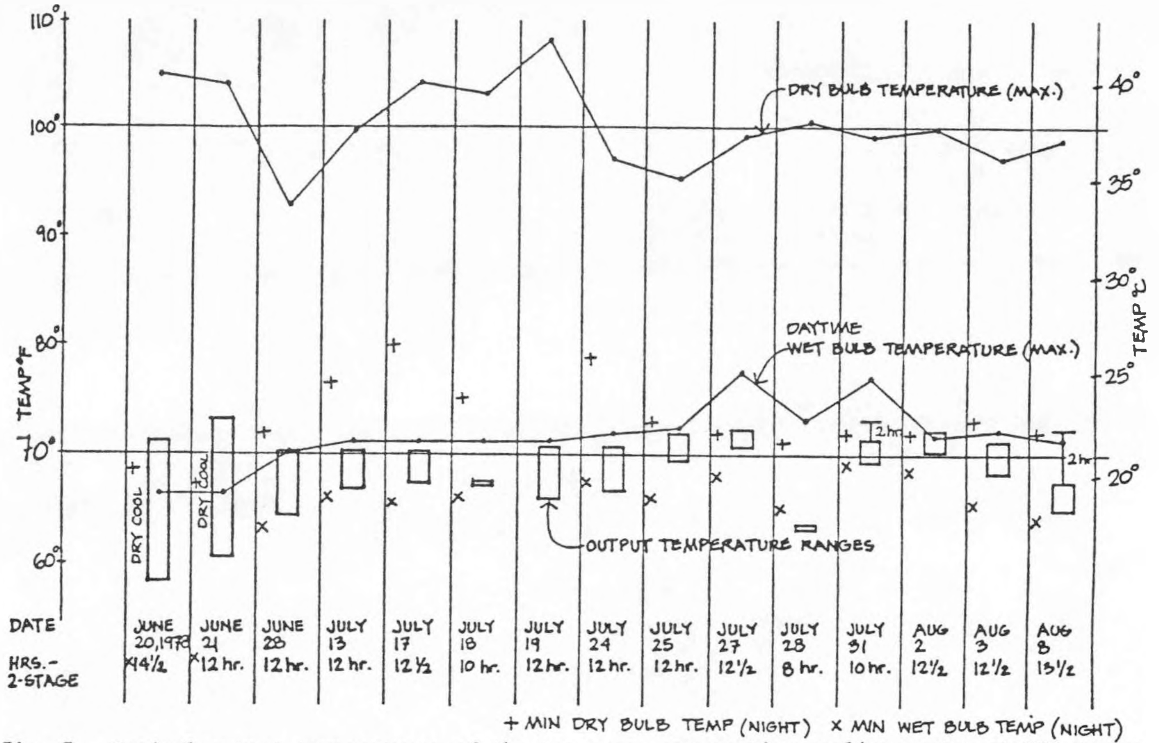


Fig. 7. *Typical output temperatures of the two stage evaporative cooling system at ERL during the summer of 1978.*

To operate the cooling system, the homeowner needs to open and close two manual dampers (doors) located in a storage room. During the past summer and winter, the homeowners have been very comfortable and have not needed any auxiliary heating or felt the need for improved cooling. During the past winter, one of the coldest and cloudiest in Tucson history, natural convection through the duct system from the rockbed located below the living room floor kept the interior house temperatures between 20.6°C (69°F) and 23.9°C (75°F).

In the home under construction, all fans and power dampers have been located in a single mechanical room. In this way, the extra heating fan in the former system may be eliminated. The main house evaporative cooler, with pads removed, is then used as a heating fan during the winter. The system is entirely thermostatically controlled and has been completely automated with three fans and three power dampers, and may include a recirculating fireplace if desired, as shown in Figures 1 and 2. (One of the power dampers is a power-operated insulated door with magnetic seals which allows air from outside to enter the mechanical room.) Some of the dampers may be manually operated if desired.

Various constraints are put on the house design by the system and will be included in a report to the Arizona Solar Energy Research Commission in June, 1979, together with sample house designs.

4. CONCLUSIONS

Two stage evaporative cooling has been shown to perform well in the hot and relatively dry climates of the Southwest. Although capital costs are quite high, operational costs are low, generally about $10/month more than standard evaporative cooling (considered the economical cooling method for this region). The performance of two stage evaporative cooling is similar to or better than that of refrigerated air conditioning, where most homeowners cannot afford to run their cooling system at the same low temperatures achieved by two stage cooling. As with most solar homes, introduction of the active ClearView Solar Collector$_R$ System and two stage evaporative cooling places certain limits on the design of homes, thus requiring an interactive communication between the architect and engineer.

Most importantly, this system combines heating and cooling in order to make best possible use of all components during the entire year. The large rockbed acts as a seasonal heat storage in the winter, because of its size. In the summer, it essentially adds a third stage to standard two stage evaporative cooling since it makes use of cool nighttime temperatures produced by nocturnal radiation.

5. REFERENCES

[1] Peck, John F., et al. "A Greenhouse-

Residence Utilizing a ClearView Solar Collector and Two Stage Evaporative Cooling," Proceedings of a Conference on Solar Energy for Heating Greenhouse Residential Combinations, Cleveland, Ohio (1977).

[2] Close, D. J., R. V. Dunkle and K. A. Robeson, "Design and Performance of a Thermal Storage Air Conditioning System," reprinted from the Mechanical and Chemical Engineering Transactions of the Institution of Engineers, Australia, Vol. MC4, No. 1 (May, 1978) pp. 45-54.

[3] Riaz, M., "Transient Analysis of Packed-Bed Thermal Storage Systems." Solar Energy, Vol. 21 (1978) pp. 123-128.

6. ACKNOWLEDGMENTS

This work has been carried out with funding from Pima County, Arizona; the City of Tucson; Tucson Gas & Electric Company; the Arizona Solar Energy Research Commission; the Energy Research and Development Administration; the University of Arizona Foundation, and the Agricultural Research Service, United States Department of Agriculture.

7. NOMENCLATURE

Cp_a	specific heat capacity of air, KJ/kg°C, or BTU/#°F
Cp_b	specific heat capacity of rock, KJ/kg°C, or BTU/#°F
L	airflow path length in rockbed, m or ft
ρ_a	density of air, kg/m^3 or #/ft^3
ρ_b	density of rockbed, kg/m^3 or #/ft^3
V_a	velocity of airflow in bed, m/min or ft/min
V	velocity of thermal wave through bed, m/min or ft/min
Θ	time required for thermal wave to travel through rockbed, hr.

APPENDIX IX

Construction Alert-Sensor Installation

TASK VI, APPENDIX 1

CONSTRUCTION ALERT, SENSOR INSTALLATION

The sensor installation locations listed by structure are:

A. Data Acquisition Building

1. After site preparation, before slab poured

   One vertical thermocouple array in the earth below the floor

2. After exterior walls are 2' high

   2 thermocouple rakes in the east wall

   2 thermocouple rakes in the north wall

3. After interior walls are 4' high

   1 thermocouple rake in the interior wall

4. After exterior walls are 6' high

   2 thermocouple rakes in the east wall

   2 thermocouple rakes in the north wall

B. Structure #1

1. After the floor site is prepared, before the bricks are placed

   1 vertical thermocouple array in the earth below the floor

2. After the walls are 4' high

   1 thermocouple rake in the west wall

   2 thermocouple rakes in the interior wall

   1 thermocouple rake in the north wall

C. Structure #2

1. After excavation, before foundation is poured

   1 thermocouple on the west foundation's outer edge

   1 thermocouple on the east foundation's outer edge

   1 vertical thermocouple array in the earth below the west foundation

   1 vertical thermocouple array in the earth below the east foundation

2. After excavation, before the slab is poured

   1 vertical thermocouple array in the earth below the center of the full basement

   1 vertical thermocouple array in the earth below the center of the half basement

3. After the full basement walls are 2' above the foundation

   1 thermocouple rake in the interior wall

   3 thermocouple rakes in the east wall

4. After the full basement walls are 6' above the foundation, and the half basement walls are 2' above the foundation

   3 thermocouple rakes in the east wall

   3 thermocouple rakes in the west wall

   1 thermocouple rake in the interior wall

5. After the walls are 2' above grade

   3 thermocouple rakes in the west wall

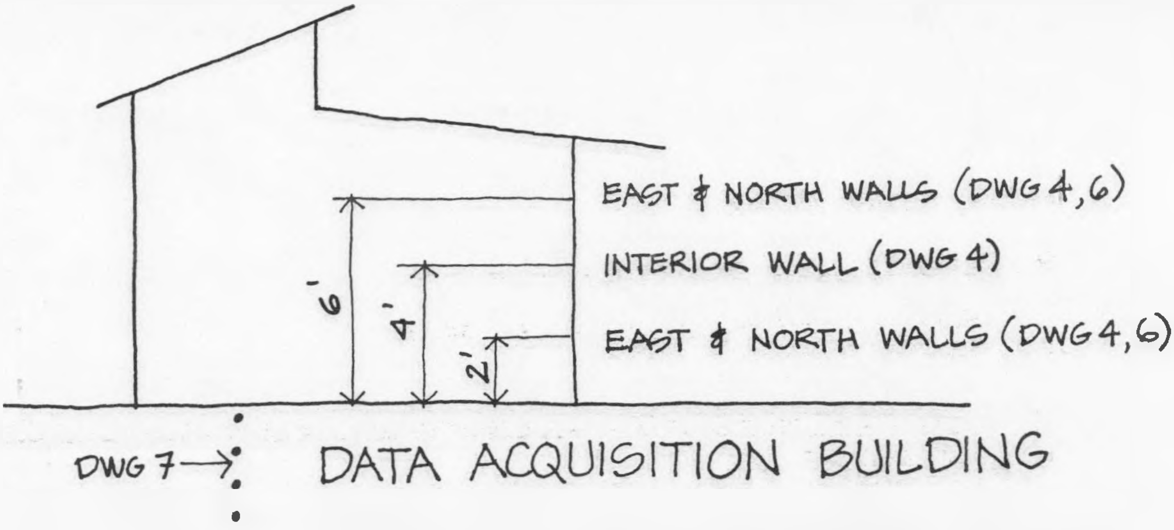
   1 thermocouple rake in the interior wall

6. <u>After the walls are 4' above grade</u>

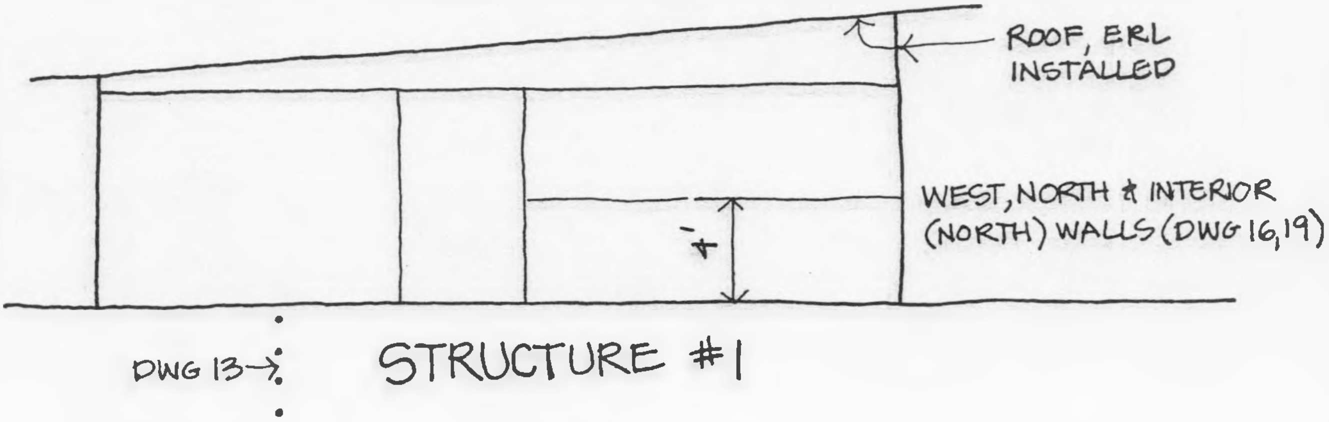
   1 thermocouple rake in the east wall

7. <u>After wall construction, insulation, and outside stucco, before backfilling</u>

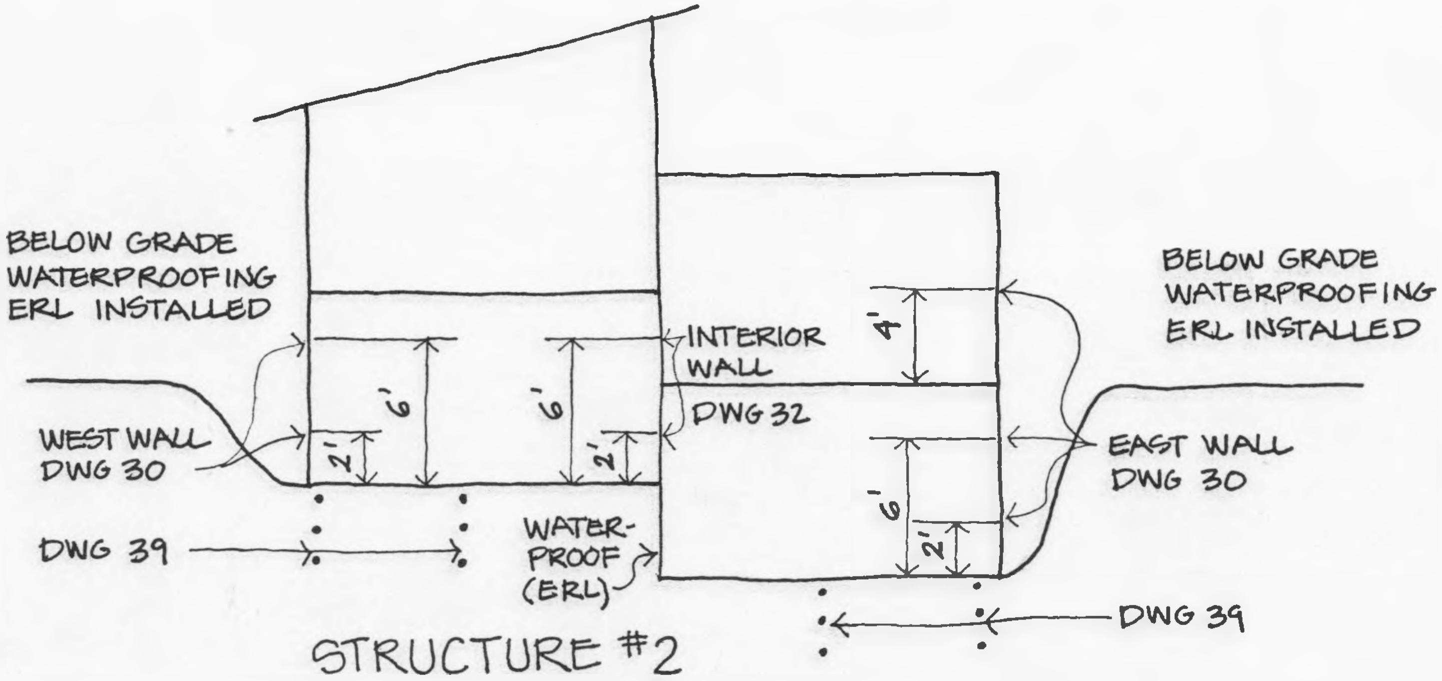
   ERL will waterproof the walls below grade



DATA ACQUISITION BUILDING



STRUCTURE #1



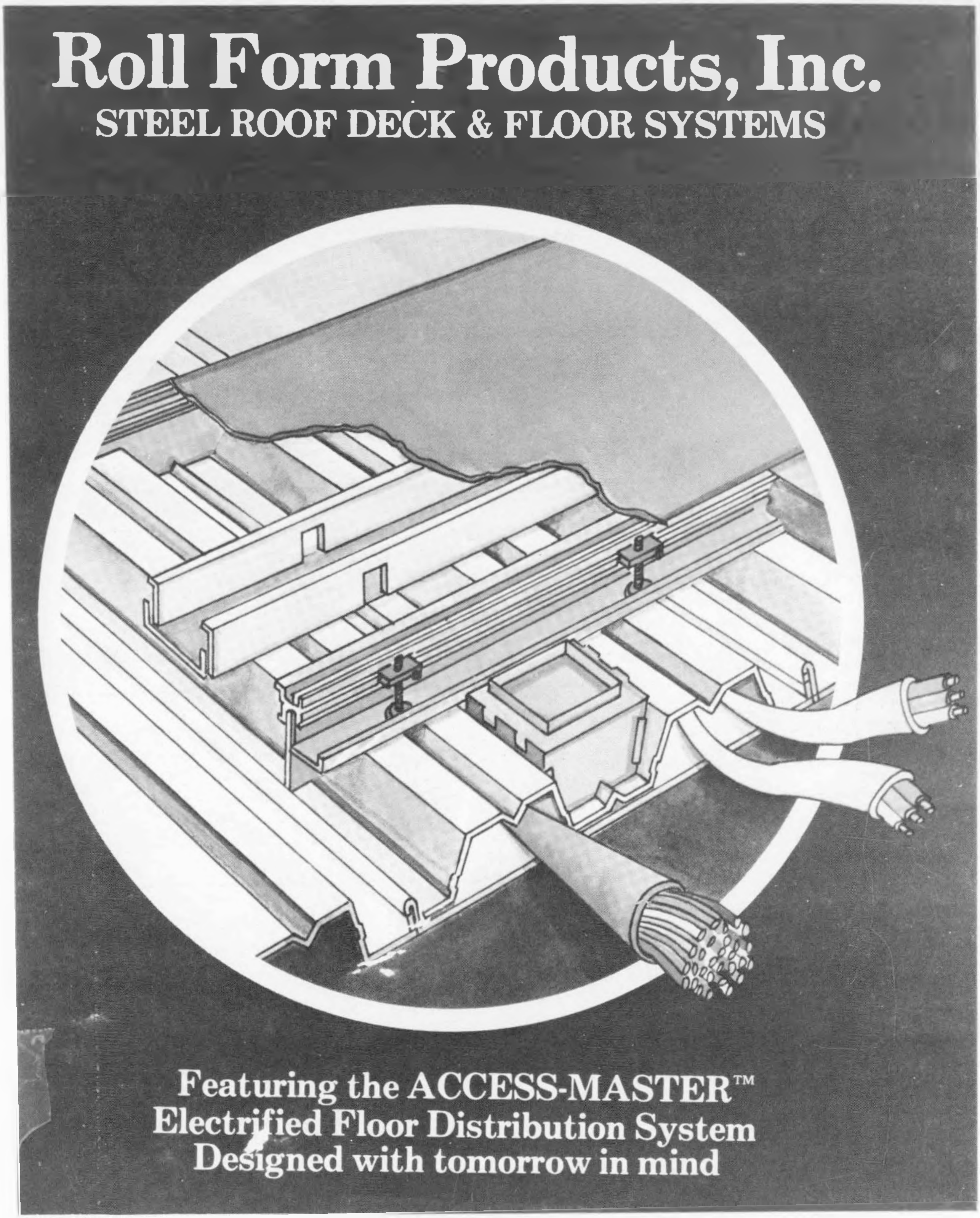
STRUCTURE #2

CONSTRUCTION ALERT

SENSOR INSTALLATION SUMMARY

APPENDIX X

Manufacturer's Specifications-Radiating Roof for Structure One



Roll Form Products, Inc.

STEEL ROOF DECK & FLOOR SYSTEMS

Featuring the ACCESS-MASTER™
Electrified Floor Distribution System
Designed with tomorrow in mind

Steel Roof Decking

Roll Form offers a complete line of steel roof deck to meet most project conditions. Steel roof deck is lightweight, incombustible, quickly and easily installed in any weather, and adds rigidity to the entire structure—especially when used as a shear diaphragm. Sections are available in a variety of gages and shop finishes.

Fluted deck in 24", 30" and 36" cover widths is available in lengths up to 40 feet. Cellular deck with 24" cover widths is fabricated in lengths based upon practical handling considerations.

In addition to the standard configurations shown here, Roll Form will custom fabricate steel roof deck to meet specific large-scale applications.

Acoustical Decking

Roll Form Acoustical Deck provides an economical solution to sound control in building construction. It is ideal for schools, auditoriums and theaters, and is especially suited for structures where in-plant noise levels are limited by OHSA regulations.

Roll Form combines permanent steel roof deck with attractive ceiling patterns and superior sound absorption properties, decreasing reverberation and excessive decibel levels.

Glass fiber insulation, made exclusively for Roll Form, is placed between the perforated webs of the fluted sections by the roofing contractor, or in the cells of the cellular sections by the deck erector.

The following acoustical decks feature one and/or two inches of insulation. Profile types correspond with steel deck configurations.

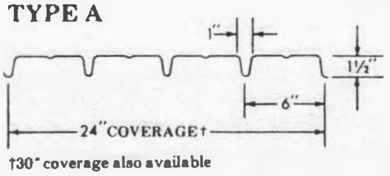
Sound Absorption Selection Table

		COEFFICIENTS*						
TYPE	in.	125	250	500	1000	2000	4000	NRC
B	1	.25	.59	1.07	.91	.56	.20	.80
	2	.52	.96	1.05	.91	.61	.30	.90
RFC1½	1	.14	.35	.77	.99	.75	.47	.70
BP1½	1	.19	.58	1.14	1.00	.59	.25	.85
BP3	1	.31	.75	1.01	.92	.55	.33	.80
	2	.54	.97	1.04	.91	.55	.31	.85
RFC3	1	.19	.47	.96	.92	.75	.53	.80
	2	.34	.80	1.15	1.00	.84	.61	.95

*Riverbank Acoustical Laboratories Tests

section properties

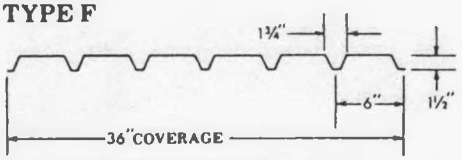
TYPE A



†30" coverage also available

gage*	weight* lbs. per sq. ft.		S_p—in.^{3}	S_n—in.^{3}	I—in.^{4}
	ptd.	galv.			
22	1.78	1.83	.10	.11	.11
20	2.14	2.19	.13	.14	.14
18	2.86	2.91	.17	.18	.20

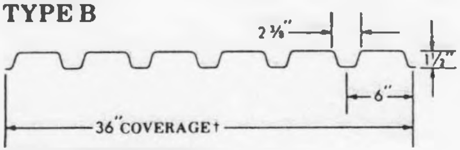
TYPE F



NOTE: Stretch rib in top flange optional

gage*	weight* lbs. per sq. ft.		S_p—in.^{3}	S_n—in.^{3}	I—in.^{4}
	ptd.	galv.			
22	1.67	1.72	.11	.12	.12
20	2.01	2.06	.14	.15	.15
18	2.68	2.73	.18	.19	.21

TYPE B

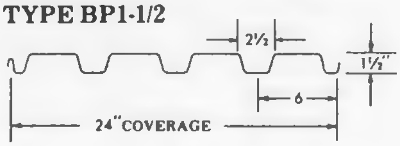


†30" coverage also available

NOTE: Stretch rib in top flange optional

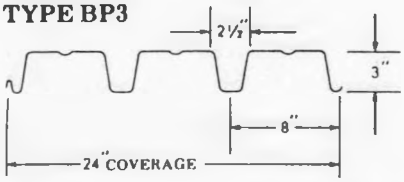
gage*	weight* lbs. per sq. ft.		S_p—in.^{3}	S_n—in.^{3}	I—in.^{4}
	ptd.	galv.			
22	1.67	1.72	.18	.19	.16
20	2.01	2.06	.22	.23	.20
18	2.68	2.73	.30	.31	.29

TYPE BP1-1/2



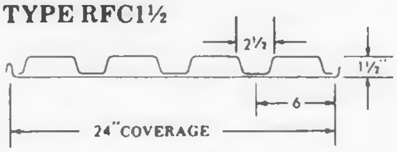
gage*	weight* lbs. per sq. ft.		S_p—in.^{3}	S_n—in.^{3}	I—in.^{4}
	ptd.	galv.			
22	1.78	1.83	.19	.20	.17
20	2.14	2.19	.24	.25	.21
18	2.84	2.89	.32	.33	.30
16	3.55	3.60	.41	.42	.40

TYPE BP3



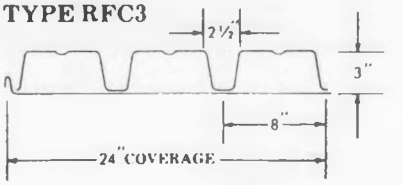
gage*	weight* lbs. per sq. ft.		S_p—in.^{3}	S_n—in.^{3}	I—in.^{4}
	ptd.	galv.			
22	2.10	2.16	.35	.40	.60
20	2.52	2.58	.43	.48	.76
18	3.36	3.42	.59	.64	1.12

TYPE RFC1½



gage*	weight* lbs. per sq. ft.	S_p—in.^{3}	S_n—in.^{3}	I—in.^{4}
	galv.			
20-20	3.69	.31	.44	.38
20-18	4.24	.32	.45	.41
18-20	4.34	.46	.56	.51
18-18	4.89	.47	.58	.56
18-16	5.44	.48	.60	.60
16-16	6.09	.66	.75	.77

TYPE RFC3



gage*	weight* lbs. per sq. ft.	S_p—in.^{3}	S_n—in.^{3}	I—in.^{4}
	galv.			
20-20	4.10	.60	.87	1.50
20-18	4.65	.62	1.04	1.52
18-20	4.89	.88	1.02	1.89
18-18	5.44	.90	1.25	2.06
18-16	5.99	.92	1.50	2.21
16-16	6.76	1.27	1.71	2.85

---

*All unit weights and gages referred to in this catalog are subject to commercial tolerances.

Steel Roof Deck Specifications:

1. SCOPE:
This section shall include all materials, equipment, and labor necessary for the installation of steel roof deck and accessories in accordance with these specifications and drawings. Requirements for deck supports, field painting, flashings, drains, gutters, downspouts, or other miscellaneous items are not part of this section.

2. MATERIAL:
Steel roof deck shall be as manufactured by Roll Form Products, Inc. Roof deck shall be formed from steel sheets conforming to ASTM A446 or ASTM A611 having a minimum yield strength of 33,000 psi. Type, gage and finish shall be as indicated on the shop drawings.

3. DESIGN:
Maximum fiber stress shall not exceed 20,000 psi under a total dead and live load of________psf. Deflection shall not exceed 1/240 of the span under a live load of ________psf. Section properties are to conform to the "Specification for the Design of Cold-Formed Steel Structural Members" as published by the American Iron and Steel Institute.

Where possible, deck sheets shall extend over three or more spans.

Acoustical Deck—Acoustic profiles will carry 5% less uniformly distributed load than the same profile without perforations.

Diaphragm Design—Where seismic or wind loadings are required, welding patterns, to develop maximum shear resistance, shall conform to Roll Form Products, Inc. specifications and the Steel Deck Institute Tentative Recommendations for the Design of Steel Deck Diaphragms.

4. SHOP FINISH (select one):
Prime Coat—Basic steel shall be thoroughly cleaned and pre-treated prior to painting. Following the pre-treatment, an oven cured prime coating shall be applied. Both applications shall be performed before fabrication. **The prime coat is intended to protect the steel for only a short period of exposure in ordinary atmospheric conditions and must be considered an impermanent and provisional coating.**

Galvanized—Basic steel, conforming to ASTM A446, shall have received a protective coating of zinc conforming to ASTM A525 and Federal Specification QQ-S-775d, Type 1.

5. ACCESSORIES:
Where indicated on drawings, ridge and valley flash, cell closure, cant flash, sump pans, drain plates, butt strip, finish strip and reinforcing channel shall be furnished by Roll Form Products, Inc. and shall be attached directly to the steel deck to provide a suitable surface for the application of insulation and roofing.

6: STORAGE:
Steel deck shall be stored off the ground with one end elevated to provide drainage and shall be protected from the elements by a waterproof covering ventilated to avoid condensation.

7. ERECTION:
Deck shall be installed and anchored directly through the bottom of the rib to all structural supports in accordance with Roll Form Products, Inc. specifications and erection standards.

Permaform

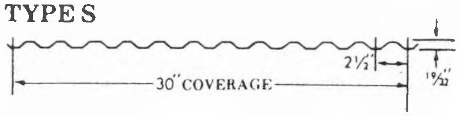
Roll Form Permaform is a high-strength steel unit designed as a permanent form for all types of concrete. Concrete topping utilizing normal weight, lightweight structural and insulating aggregates are all acceptable for Permaform.

Permaform sheets can be supplied with factory built-in vents to give positive vapor release and eliminate the field installation of vent clips.

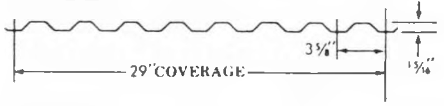
The combination of a Permaform unit and lightweight insulating concrete provides a fire resistant roof system. Refer to the latest *U.L. Fire Resistance Index* for current fire rated systems.

CAUTION: Galvanized Permaform shall be required when used as a structural support for lightweight aggregate or foam insulating fill. Concrete admixtures containing calcium chloride shall not be used over galvanized Permaform.

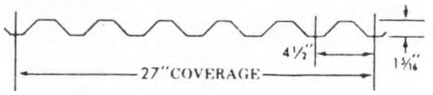
TYPE S



TYPE L



TYPE H



section properties

type	weight*—lbs. per sq. ft.		gage*	section modulus—in.^{3}	moment of inertia—in.^{4}
	black	galv.			
S	.75 .90	.84 .99	28 26	.036 .043	.011 .013
L	1.00	1.10	26	.072	.039
H	1.28 1.60 1.92	1.38 1.70 2.02	24 22 20	.131 .170 .203	.092 .117 .139

Permaform Specifications

1. SCOPE:
This section shall include all materials, equipment, and labor necessary for the installation of steel concrete form for floors and roof complete, in accordance with the specifications and drawings.

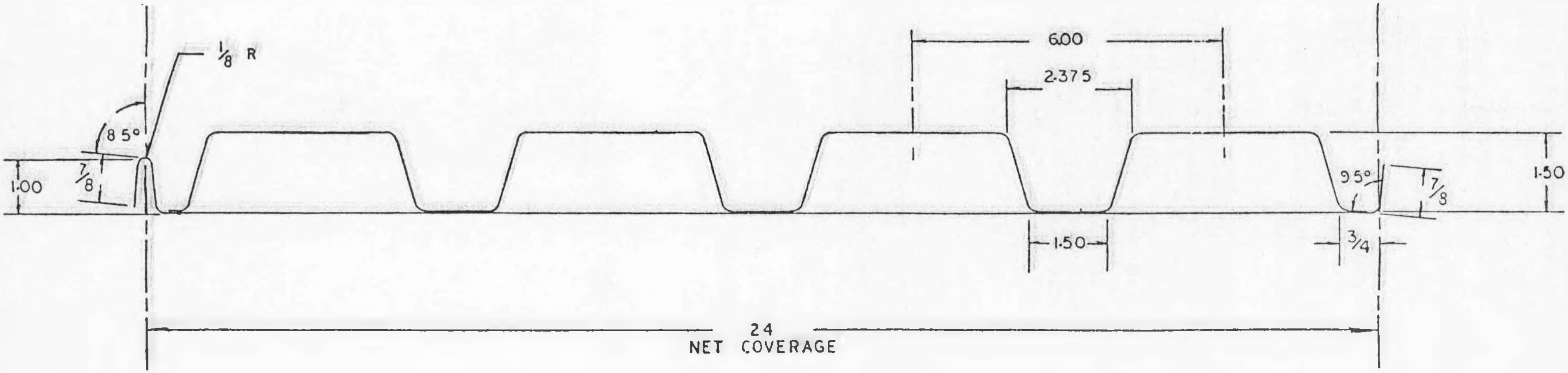
2. MATERIALS:
Steel concrete form shall be Permaform as manufactured by Roll Form Products, Inc. Permaform shall be fabricated from high strength steel sheets conforming to ASTM A446 or ASTM A611 having a minimum yield strength of 80,000 psi. Galvanized steel shall have received a protective coating of zinc conforming to ASTM A525 and Federal Specification QQ-S-775d, Type 1.

3. DESIGN:
Maximum fiber stress shall not exceed 30,000 psi under a total dead and live load of________psf. Deflection shall not exceed either 1/240 or 1/180 of the span under a live load of________psf.

4. ACCESSORIES:
Where required, welding washers shall be furnished by Roll Form Products, Inc.

5. ERECTION:
Permaform shall be placed with the ribs perpendicular to the supports. End laps shall be a minimum of 2 inches and shall always occur over supports. All sheets shall be welded to the structural supports in accordance with Roll Form Products, Inc. specifications and erection standards. CAUTION: Concrete admixtures containing calcium chloride shall not be used over galvanized Permaform.

Note: We reserve the right, without notice to make changes in specifications, construction, design, and details, at any time in such manner as we may consider necessary or advisable. Corrections to reflect any such changes shall be included in subsequent printings of this publication.



RFC1½ NOTES:

1. DO NOT MEASURE FOR DIMENSION-USE FIGURES AS SHOWN
2. ALL RADII 0.1875 INSIDE
3. RFC1½ MAY OR MAY NOT BE LOCK-FORM: SEE LOCK-FORM DETAIL
4. 20-20 TO 16-16 GAGE

ROLL FORM PRODUCTS, INC.

RFC1½ - 24"

DRAWN BY: RSL	DATE: 9-21-70	SCALE: 1/2 IN = 1 IN.
CHECKED BY: SAK	DATE: 10-2-70	70P-1

APPENDIX XI

Task I

INTERIM REPORT ON TASK 1
Passive Cooling Experimental Facility
Hot Arid Zone
DOE Contract Number DE-AC03-80SF-10816

Selection of Passive and Hybrid Cooling Options

by
John F. Peck
Helen J. Kessler
John E. Groh
T. Lewis Thompson

Environmental Research Laboratory
University of Arizona
Tucson International Airport
Tucson, Arizona 85706

November 10, 1980

TABLE OF CONTENTS

I. The objective of Task 1 is to select a set of passive and/or hybrid cooling options for testing in the experimental facility according to the following criteria.

1. Preference shall be given those options which have potential for utilization in both new construction and retrofit markets.

2. Options selected shall be those which have the greatest potential for affecting interior comfort conditions.

3. Selected options shall maximize the displacement of competing fuels and fuel specific utilization systems.

4. Preference shall be given those options with the lowest life cycle costs.

5. Selected options shall be susceptible to testing within the format of the experimental facility.

6. Selected hybrid options shall minimize the use of parasitic energy.

II. General format of the proposed structures, and the passive cooling options to be tested in them.

Since the immobile nature of many passive cooling options prevent reconfiguring the structure, we have chosen four different construction techniques, each of which allows different passive cooling options to be tested. They are:

Structure No. 1. High mass walls, interior and exterior

Structure No. 2. Below grade construction (earth contact)

Structure No. 3. Low mass, high insulation value, low infiltration type construction

Structure No. 4. Roof pond type construction

The capability of testing as many options as possible, which are compatible with the basic properties of the structures will be incorporated into each structure.

The passive cooling options we have chosen roughly fall into the following three categories:

1. "Appropriate technology" options.

These generally involve options similar to those used historically, but which are improved by modern technology. These incorporate such passive cooling options as massive or below grade construction, possibly with low mass (frame) adjunct structures, natural ventilation, roof decks, vegetation, etc. Modern techniques of outside insulation, stabilized earthen building materials, quiet low wattage fans, etc., greatly improve the utility of these techniques. It is interesting to note that many of the options which have the lowest parasitic energy use, and the lowest fuel use incorporated into the materials themselves, are those that were used historically. This is, of course, due to the high cost of energy and transportation during those times. Thus, solutions useful then are now useful again. While testing such options may seem redundant, it is not, because the building industry has forgotten how to use them, as well as the cooling effects produced by such options. We have to remind builders and homebuyers of these options, and furnish data on their performance, so they can have confidence in the performance of the systems they are buying.

2. Moderate power usage passive cooling options.

These are generally evaporation, earth tube, indirect nocturnal radiation, and ventilation processes, where fans are used to blow air over the fundamental source of coolth. The former two are moderately independent of daily cycles, and thus are retrofitable, but have less than top marks in parasitic power usage. It should be noted that while evaporative cooling can be used in any home, the performance can be improved when it is used in homes which have massive construction and use the cool air leaving the house to reject heat before the heat enters the occupied space.

3. Roof pond options

These consist of water either enclosed in containers on the roof or free to evaporate. In some cases, cool water is allowed to flow into tanks located inside the structure. Fixed or insulated moveable covers are generally used. These systems are not retrofitable, and require development and testing of the materials used in the system, and their maintenance. If water exposed on the roof becomes infested with algae, (especially if the water flows through tubes into containers inside the home) cleaning out the algae could be a serious problem. Because of potential difficulties, we have tenatively considered their utilization of roof ponds in the second building phase of the program.

III. Phase One options

The options we have chosen for the first two structures and the data acquisition building (not ranked in the order of preference) are:

1. Shading and Heat Rejection Techniques

Techniques of shading and heat rejection will be used wherever possible. Windows generally are the major source of heat gain and will be well shaded. Various exterior shading devices or vegetation will be used. However, the need to constantly exhaust relatively cool air from directly evaporatively cooled structures allows the use of techniques which interpose this cool air between the building interior and the hot, ambient air. They allow solar heat to be rejected into the ambient air, and keep interior window or drape surfaces cool, thus lowering the mean radiant temperature, as well as reducing heat gain. These techniques are shown in Fig. 1 and 2.

Most of these heat rejection techniques (including exhausting cool air through hot attic spaces and wall mounted solar collectors), are easily used on both retrofit and new construction. They will be included in the new passive cooling option classification category entitled COMFORT ENHANCEMENT.

2. Evaporation/ventilation

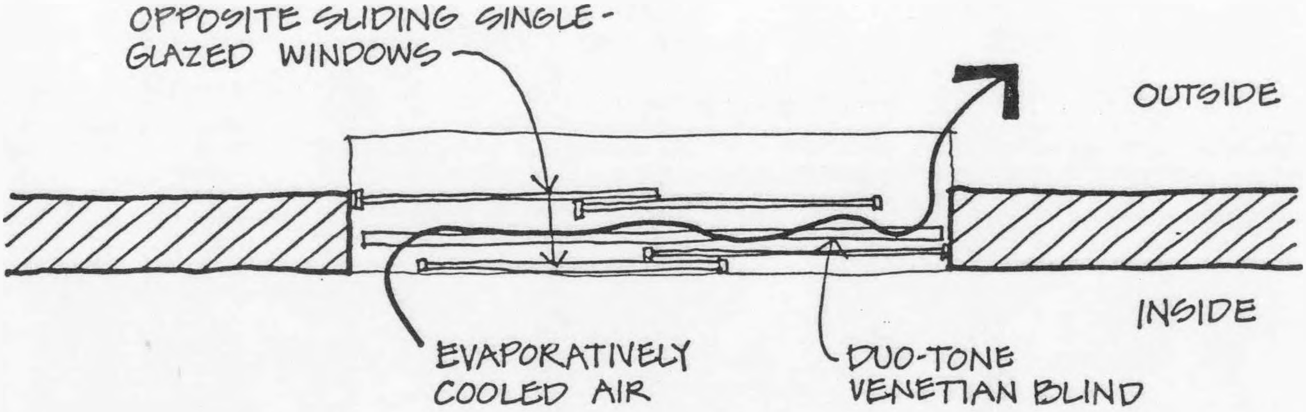
   a. DIRECT ATMOSPHERE - fan driven evaporation/ventilation

      Direct evaporative cooling is the simplest form and is very suitable for retrofitting. Ambient air is cooled by evaporation as it is drawn through wet, porous sheets of material. The air is usually cooled approximately 60% to 80% of the difference between the wet and dry bulb temperatures, although some media can approach 95% cooling efficiency. Relatively cool air is exhausted from the structure, since re-humidification is self-defeating. As mentioned previously, this relatively cool air can be exhausted through sources of heat to reduce heat gain into the structure. Massive construction can allow direct evaporative cooling to be used primarily at night, when it works most efficiently. The structure can then coast through much of the day on the stored coolness in the walls. Thus mass can help to improve comfort and reduce the power requirements of direct evaporative cooling.

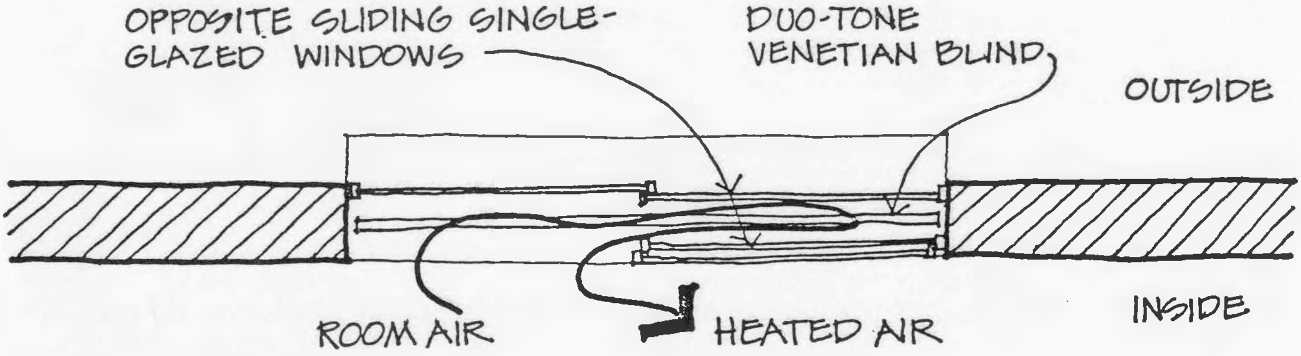
      Although direct evaporative cooling does use parasitic energy, it uses about one-fifth to one-third as much as refrigerated air conditioning (a common form of cooling in the warmest areas of this region). During the most humid periods, direct evaporative cooling is often not considered satisfactory; however, when many of the optimizing techniques developed at ERL are used, comfortable conditions may be achieved. These evaporative cooling devices will be used for ventilation when applicable.

      The low capital cost ($300-$500) of direct evaporative coolers, coupled with their relatively low power usage gives them a low life cycle cost, relative to other more capital intensive options. Such devices can easily be tested at the facility in conjunction will all the optimization techniques we have mentioned previously.

   b. DIRECT ATMOSPHERE - wind/convection driven evaporation/ventilation



SUMMER USE
PLAN VIEW



WINTER USE
PLAN VIEW

KLOS WINDOW - CONFIGURATION AS TESTED IN WINDOW TEST BOX.

Figure 1

A tower may be constructed that uses two complementary principles of natural convection: Cool, moist air flows down, while heated air flows up. Thus air cooled by a water mist in a tower above the structure flows down, while air heated in a solar heated attic will flow up through chimneys or other outlets, thus using convective forces in both directions. Since this system uses towers for air intake and exhaust, wind forces can easily be used to assist convection. The only parasitic power used is that needed to run the high pressure mist pump, which must be carefully chosen so its power usage is minimal. Such a cooling device was tested at ERL, and is called the Thompson-Moody tower, after the team that designed and tested it. This system has similar comfort constraints to standard direct evaporative cooling (high indoor humidity). It will probably work best during the day and on windy nights. Due to its unusual features, acceptance in the local community may not be rapid, although it can be constructed using standard materials. However, with proper presentation, and in the proper economic climate, it may find wide utility.

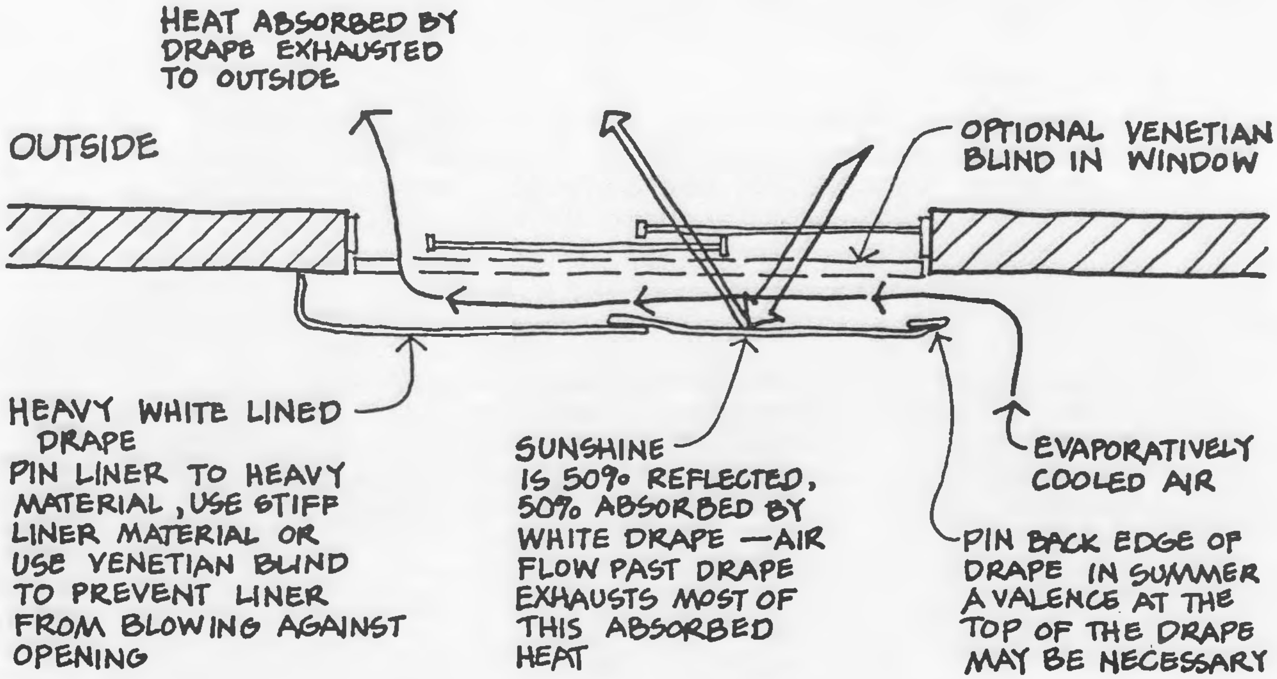
While such devices can be retrofitted to some present structures, they are not easily retrofitable. Their cooling potential is totally dependent on natural forces, and thus will vary. Their capital cost is much greater than a direct evaporative cooler. Thus to have a lower life cycle cost than a standard evaporative cooler, the energy savings of this wind power system have to be substantial. We will make the minimal modifications during phase I required to install and test this device later, when more careful consideration of the above factors can be made.

c. DIRECT ATMOSPHERE - convective ventilation

A clerestory will be used on the bermed high mass building to test natural convection ventilation. Since the cost of clerestorys is moderate, and they are used during both the heating and cooling seasons, the life cycle cost should be reasonable. No parasitic power is used. They are not easily retrofitted, unless extensive alterations are made to the house. We will also be able to test and demonstrate various techniques of controlling such high level windows. However, the effect of dust on the computer system housed in this structure will have to be carefully evaluated before testing this cooling option on this building.

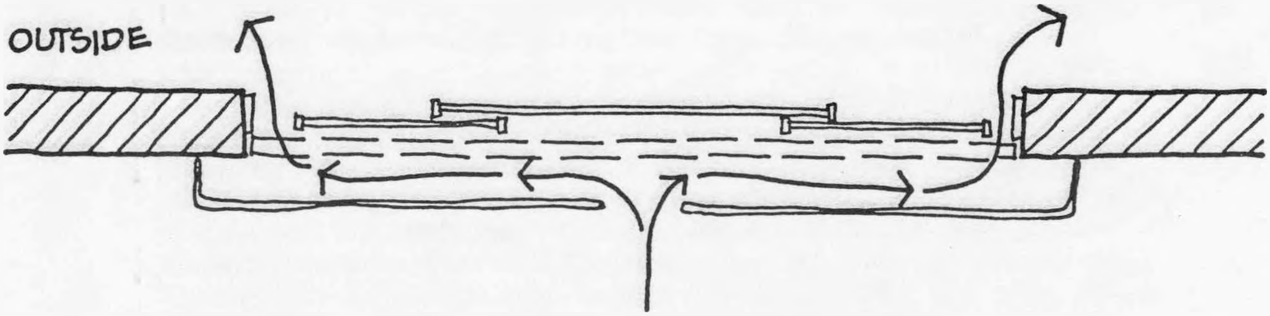
d. DIRECT ATMOSPHERE - wind driven ventilation

The utility of mass in structures has been discussed. The almost complete lack of mass is also useful; it is a traditional defense against heat when used as an adjunct to mass. Low mass frame porches cool rapidly at night by natural ventilation, while the massive portions of the structure are being cooled down. They can be screened or open. The "Solar/Screen Porch" that uses a removable glazing technique



ONE SIDE OPENING WINDOW/PATIO DOOR

PLAN VIEW



TWO SIDE OPENING WINDOW (OR CASEMENT WINDOW)

PLAN VIEW

EXHAUSTING WINDOW HEAT WITH EVAPORATIVELY COOLED AIR

Figure 2

developed at ERL makes this concept useful in all seasons, since when glazed, the porch can be used as a source of heat, a greenhouse, and a sunroom. The horticultural techniques developed by Dr. Merle Jensen of ERL are especially useful for such greenhouse/residential combinations. Such a grade level porch will be tested.

Additionally, a screen porch elevated from grade level will be tested. Natural ventilation will be especially effective in above grade porches.

The added cost of such structures is not great, and when they can be glazed in the winter to utilize solar heating, their life cycle cost should be very low. This porch is very retrofittable, since south facing porches can be added to many homes. Since many homes already have a south facing porch, the added cost of adding removable glazing is quite reasonable. It can be tested on the site, and uses no power in the summer. However it does use 100-200 watts in the winter to distribute heat throughout the house. It can be quite effective at night, and its utility during the day is increased by the insulated roof, which lowers the surface temperature of the porch ceiling, and increases comfort in the porch.

e. DIRECT ATMOSPHERE - Wind driven ventilation plus vegetation

Another similar technique that will be tested is a vine covered open ramada. Since leaves transpire, their surface temperatures are low compared to non-living materials, and result in lower mean radiant temperatures in the spaces below them. Since it is easily tested, low in cost, and uses no power, we will test such an area.

3. Earth Contact

a. DIRECT GROUND COOLING

Earth contact cooling will be tested in the high mass structure with a half buried basement, and in a smaller building that will be bermed on the east, north and west sides. The designs will test various methods of introducing daylight to such areas. While earth contact structures covered by several feet of earth may perform better, they are not usable as immediately by the building industry. One family in Florence, Arizona, whose house is bermed to the roof as above, experienced comfort conditions during almost the entire summer without other cooling.

Semi or entirely-buried structures act as a thermal diode for cool air. When the air in the structure is hotter than the ambient air, it rises and is replaced by the cooler ambient air. When the interior air is cooler than the ambient air, it remains in the below grade section, since there is no way for it to flow down and out. However, when night temperature minima are above 27 C (80 F), such effects are not useful, and comfort is dependent on heat flowing into the surrounding soil, and the low interior mean radiant temperatures induced by the cool walls of the structure.

The use of simple forms of ground contact cooling has the potential for the greatest comfort with the least amount of parasitic energy use. Construction materials are standard. It would primarily be used in new construction for both single family homes and townhouses, using standard construction techniques. If additions are made to the home, basements can be retrofitted.

Additionally, the modification of ground temperatures can be tested by using several different surface coverings such as grass, which has been shown to raise the minimum soil temperatures and lower the peak temperatures. Other soil temperature modification methods can also be tested, such as wells that act as thermal diodes. These wells are rockfilled pits constructed a short distance from the structure, which synchronize the minimum soil temperature with the cooling season as much as possible by using the thermal lag of the soil.

The cooling potential of such structures is great, and they are easily tested on the site. Since their added cost is moderate, and they are used during both the summer and winter season, their life cycle cost should be low, relative to the alternatives.

An attractive technique is a completely buried structure with a below grade courtyard atrium open to the sky, as was used in Southern Tunisia and the Chinese Loess soil belt.

Once again, a thermal diode effect will naturally ventilate the courtyard, and allow the coolest air available to fill the open courtyard like a well. This cool air will then enter the houses and cool them when the temperatures are sufficient for cooling. Unfortunately, the size of such structures make them difficult to test at this facility. They also will tend to be cold during the winter for the same reason they are cool in the summer.

b. ISOLATED GROUND - ground cooling via heat exchanger

Earth tubes (non-porous) may be used as heat exchangers for ground cooling. When soil temperatures are less than 70-80 F at depths greater than two meters, these effects can be significant if the interior heat gain of the structure is not great.

The parasitic power requirement of this system will be moderate (estimated at 400 to 600 watts) but not low. It is not retrofitable. It is easily tested on the site. Since this technique should be useable during the summer and during the heating season, its life cycle cost should be moderate but not one of the lowest.

4. Comfort Enhancement

a. COMFORT ENHANCEMENT - mass walls

The use of mass walls in conjunction with various fundamental sources of "coolth" (ventilation, evaporation, nocturnal radiation and earth contact) is necessary in many cases. Mass, and the almost total lack of mass, is the traditional defense against unwanted heat gain in the hot arid regions. Mass simply stabilizes the interior temperatures of a structure, and is not a passive cooling device by itself. Thus, it is used in combination with true cooling techniques such as nocturnal radiation, evaporation, and ventilation, and enhances comfort since it dampens the temperature swings of of cyclic sources of coolth. When the mass is adequately cooled at night, interior temperatures may be comfortable for much of the day. High mass and low mass structures can be combined so that nighttime living may take place in the rapidly cooled low mass portions.

The lowest cost high mass structure in terms of the displacement of competing fuels is one constructed of rammed earth or sun fired adobe, which are traditional building materials. Thus, one of the structures will use this material. Not only is rammed earth adobe inexpensive to make, it is relatively inexpensive to transport since the materials necessary for making it are often indigenous to most building locations. If earth walls cannot be made thick enough to provide adequate resistance to heat flow, they can be improved by insulating their exterior surface, which "captures" the mass inside. High mass construction is also useful because of its compatibility with wintertime passive heating. Since high mass structures must be cooled at night, which takes time on warm nights, a rapidly cooling, low mass structure is often a useful adjunct to a high mass structure.

The incorporation of mass into homes has immediate benefits. It can minimize the the peak power usage in mechanically refrigerated homes in problem cities such as Phoenix, lowering power bills when time-of-day billing is completely instituted (it has already begun in Phoenix). Mass will make it possible to retrofit such massive structures with more completely passive environmental control techniques at some later date. Peak power usage for evaporatively cooled structures can also be reduced in masonry buildings.

While mass is not easily retrofitted, modern outside insulation techniques allow mass already incorporated into present homes (such as brick, burnt adobe, and to some extent heavyweight concrete block), to be thermally "captured" inside the house, thus increasing the quantity of effective mass in the home. Paradoxically, this works best on homes with the least wall insulation, that is, homes with none on either side, since any insulation on the interior wall surface severly compromises the value of this technique in stabilizing periodic sources of warmth or coolth. We will test various outside insulation techniques over filled core concrete block walls in structure #2.

All these options, sunfired adobe, grouted or dirt/sand and rock filled block, and outside insulation processes are all easily tested at the site. In the sunfired adobe case, the fuel displacement is substantial. Massive homes tend to lower the parasitic power requirements of the cooling processes used. Since mass is useful both during the summer and winter seasons, but adds a significant small increment of the cost to the home, its life cycle cost should be moderate but not low. The data obtained in this project should be very useful in justifying the added cost of such techniques.

b. COMFORT ENHANCEMENT - air stratification

Mass (either earth contact or incorporated into the structure) can also be used with air stratification. The high (approximately 3.3 to 4 meters, 11 to 13 feet ceilings in many older structures were used as a reservoir for warm air, which was vented when ambient conditions made cooling by ventilation practical. The massive structure (including earth contact) is cooled at night by ventilation, evaporative cooling, or even "off peak" air conditioning, and coasts through the day on stored coolth. As the structure warms during the day, the warmed air rises to the ceiling, or to an upper story (also massive) where some of the warm air is cooled by the walls, and flows back down to the lower portions of the structure. The warmest air always remains at the highest level. It cannot be vented out during the day, since to do so would admit hot ambient air, and place added strain on the limited cooling capacity of the mass in the structure. This technique will be used on both above ground level and earth contact structures and would be inexpensive to use on a two story structure where the bottom level is used as the final refuge from the heat of the day.

Such stratification techniques are quite useful. Many people have observed the effects in two story homes, even in Phoenix, Arizona. This technique is not retrofitable, unless a sizable addition to the home is made. No parasitic power is used in the summer when stratification is used. However, a small 100 watt fan is used in the winter to direct warm air from the upper story to the lower story. Stratification is easily tested at the site, and since it is part of the structure, its life cycle cost should be relatively low.

c. COMFORT ENHANCEMENT - nocturnal evaporation, dessication and mass.

The use of solar regenerated, passive dessicant "cooling" techniques in arid climates may seem strange to some. However, direct evaporative cooling is, and will remain, the system of choice for an increasing number of desert dwellers. It is eminently retrofitable, and easily available commercially. However, evaporative cooling converts relatively dry, hot desert air into cool, humid air. If it is used to cool massive structures at night, which then coast through the day, the structure remains humid as the temperatures inside gradually rise. By removing 20 to 50% of the moisture in at least one area of the structure, with a solar regenerated, dessicant cart or fixed system, the structure will be more comfortable at a given temperature, and remain comfortable at higher temperatures. However, dessication of air heats the air (the opposite of evaporative cooling), thus requiring the removal of the energy. The nocturnally cooled mass of the structure can act as a sink for this heat which in a modest 140 square meter home could be as little as 4,200 - 8,400 KJ (4-8,000 BTU). Thus the combination of mass, dessication, and nocturnal evaporative cooling can, potentially, increase the comfort of such structures. Solar regenerated dessicant cooling techniques, if shown to work well, can be used in any high mass, nocturnally evaporatively cooled structure, new or old.

They would be retrofittable only in higher mass homes. They use little (if any) power, and are easily tested at the site. As an adjunct comfort enhancement method, their cooling potential is quite high.

We will test this technique in combination with automatic early morning ventilation of the structure when the ambient temperature is cool enough. This will assist in drying the air in the structure initially, and reduce the heat input to the house from the dessication process.

5. Nocturnal Radiation

a. INDIRECT SKY - night sky radiation cooling via heat exchanger

A low mass roof, cooled by nocturnal radiation, beneath which house air is circulated, will be used to cool a high mass structure. The thermal mass will be located in the walls of the structure. This method only uses a small amount of parasitic energy. It fits into standard construction practices quite readily. Moveable insulation panels on the roof are not required, since the roof is isolated from the structure, and may be vented during the day. This roof is also useable when direct evaporative cooling is used during the day because air from the evaporative cooler can be exhausted through the attic space and out, thus helping to reduce heat gain from the attic area. Retrofitting such a system is difficult.

When durable thin plastic films whose radiative and convection suppression properties enhance nocturnal radiation are available, they can be tested.

The cooling potential of such a system is dependent on the location, and will probably be effective in the early and late parts of the summer, when the air is cooler and dryer at night. The same system in its entirety is usable for space heating in the winter by operating the fan during the day. Thus, despite the extra capital cost of large quantity of mass, the additional cost of the roof and the fan cost, the life cycle cost of the system could be fairly attractive unless building codes impose too many restrictions. It is easily tested at the site, and easily adapted to many low cost new house designs.

b. INDIRECT SKY - night sky radiation via heat exchanger plus evaporation

The performance of the above system is greatly improved when the roof is periodically sprayed with water so that both evaporation and nocturnal radiation are used. This technique will also be tested.

c. DIRECT SKY - night sky radiation

Low mass roof decks open to the sky also cool rapidly at night and will be tested. A person on the deck is cooled by the combined effect of nocturnal ventilation and nocturnal radiation directly from the body. The latter is an especially powerful technique, since indirect effects are never as powerful as direct effects. This technique is surprisingly effective, and has been personally experienced in July in Tucson.

Installing a roof deck on a flat roof is low in cost. Roof decks are retrofittable on many homes. This system uses no power, can be easily tested, but it is useful only at night during the summer, as an adjunct to a high mass home in which coolth is stored for daytime usage. It is also a nice sun porch during mild winter days.

IV. PHASE 2 OPTIONS

The tentative choice of passive cooling options to be tested for structures 3 and and 4, organized by the fundamental source of coolth, are as follows:

1. Evaporative and Ventilation Cooling

a. DIRECT ATMOSPHERE - indirect evaporative cooling

Indirect evaporative cooling is accomplished by pumping evaporatively cooled water through an air/water heat exchanger in the structure. Air in the structure is circulated through the heat exchanger, and is cooled without humidification. The output temperatures are 3 to 6 C above the wet bulb temperature due to the approach temperatures of the cooling tower and the heat exchanger. Thus, this method is often not effective in times of high humidity, when wet bulb temperatures are above approximately 21 C (70 F). However, this technique can often be easily integrated with two-stage evaporative cooling systems, using the same equipment.

b. DIRECT ATMOSPHERE - recuperative and regenerative evaporative cooling

Recuperative and regenerative evaporative cooling options do not humidify the air in the structure, and use the relatively cool air exhausted from the structure to improve the performance of the evaporative cooling device. In one technique, evaporatively cooled water cools ambient air in an air-water heat exchanger, without humidification, as it enters the structure. The cool, dry air warms a few degrees as it passes through the structure, and exits through the evaporative cooling device (a cooling tower, in some cases). Since the exiting air is cool and dry, its wet bulb temperature is lower, and the water produced by the evaporative cooling device is cooler than if ambient air were used. Sometimes the heat exchanger and the evaporative cooling device are combined in one unit. Output temperatures approximately equal to the ambient wet bulb temperature in such devices have been reported.

c. DIRECT ATMOSPHERE - two-stage evaporative cooling

Two-stage evaporative cooling is accomplished by pre-cooling ambient air without humidification, before further cooling by evaporation. The cool air entering the structure is then exhausted, preferably through sources of heat gain. The pre-cooling step can be accomplished by a combined cooling tower/heat exchanger unit, by a nocturnally cooled rock bed (a method extensively investigated at ERL) or possibly by other methods. The second stage is accomplished by a standard commercial evaporative cooling device. Output temperatures below the wet bulb temperature are possible with this method. At the Environmental Research Laboratory, two-stage evaporative cooling has been combined with active and hybrid solar heating systems using the same storage (rock bed) system for both seasons. It is primarily suitable for new construction. It works well during hot, humid periods in Tucson or Phoenix, using only slightly more power than direct evaporative cooling. The comfort attained is similar to that with refrigerated air conditioning during much of the summer. The cost of the rock bed needs to be lowered, so a low cost shallow, under slab rockbed will be tested with such a system.

d. INDIRECT ATMOSPHERE - flat shaded storage roof with wind augmented evaporation

Another evaporative cooling method, which uses no parasitic power, is the shaded roof pond. The structure is cooled by radiation and convection to and from the cool ceiling. Interior "water walls" can be used to increase the interior cool surface area available for convection and radiant heat exchange. Cool water is allowed to thermosiphon into the water walls when the walls are warmer than the roof pond. As will be explained later, evaporative roof ponds are sometimes used in conjunction with nocturnal radiation. This system will provide dry cooling of the interior space and has the potential to be quite comfortable during humid periods while using no parasitic energy. It is primarily suitable for new one story (and possibly two story) construction, if water walls are used. However, it may take quite a while to be assimilated into the housing market.

e. DIRECT ATMOSPHERE - evaporatively cooling flourescent lighting fixtures

Flourescent lighting fixtures are responsible for 1/3 to 1/2 of the heat gain in mechanically refrigerated commercial buildings. By drawing evaporatively cooled air over such light fixtures through ducts enclosing them, 60-80% of their total heat input to the structure can be removed by low cost evaporative cooling.

This system could be tested in structure #3, and would be a useful adjunct to recuperative evaporative cooling systems. Other evaporative cooling systems which constantly exhaust air from the structure without reusing it can exhaust part of their air over the lights without using the separate evaporative cooling system required for refrigerated structures.

2. EARTH CONTACT

a. ISOLATED GROUND - ground cooling via evaporatively cooled heat exchanger

Ground contact cooling techniques can also be combined with evaporative cooling techniques. Long unglazed ceramic tubes buried in the earth permit soil moisture to penetrate to the interior surface. The soil is kept moist by drip irrigating "gray" water on to the soil over the tubes. Three mechanisms of cooling exist: heat transfer into the earth, using the earth as a large heat sink; damping of the ambient minima and maxima by thermal inertia of the surrounding soil; and evaporation of the surface of the tubes. Analysis is required to determine the relative effects of these mechanisms.

3. NOCTURNAL RADIATION

a. INDIRECT SKY - storage roof with movable insulation, night sky radiation

In this system the entire roof is used, both for the nocturnal radiation of heat upwards, and as a radiative/convective heat sink over the entire ceiling area. The roof is covered with water contained in flexible plastic containers, which are cooled by nocturnal radiation. Insulation and shading are required during the day. These techniques, which are primarily suitable for very well constructed, single story residences, may be quite costly due to the complexity of construction; however, some claim that their costs can be almost the same as those of a standard home. Since no parasitic energy is used and ventilation is generally not desired, oppressive conditions my occur by the end of the summer. These conditions might be alleviated by the use of small fans.

b. INDIRECT SKY - storage roof with movable insulation, evaporation plus night sky radiation

In such systems, the roof is flooded, is open to the night sky, and is insulated and shaded during the day. Thus nocturnal radiation and evaporative cooling combine to maximize cooling in this type of system. Interior thermosiphoning water walls will also be used with this technique. Since clouds reduce the effectiveness of nocturnal radiation, comfort conditions will probably not be achieved for significant periods of time in the hotter, more humid areas of the hot, arid zone. Contrary to the stereotyped picture of regular afternoon thundershowers, followed by clear nights, areas such as Tucson and Phoenix frequently have cloud cover at night. Thus, augmenting nocturnal radiation with evaporative cooling will be useful.

V. CONCLUSIONS

A wide range of passive cooling will be tested in this program. Not all will be totally successful during the entire summer in Tucson, since we are testing the upper climate limitations of many of them. None of these passive cooling techniques will attain the universal usage of mechanical refrigeration, which is being used by both rich and poor. This is assured by not only the weather and terrain in various areas, but also by the preferences, and financial capabilities of different people.

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