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SOLAR-ENERGY-SYSTEM PERFORMANCE EVALUATION

COLORADO SUNWORKS
SINGLE-FAMILY RESIDENCE,
LONGMONT, COLORADO

NOVEMBER 1978 THROUGH MAY 1979

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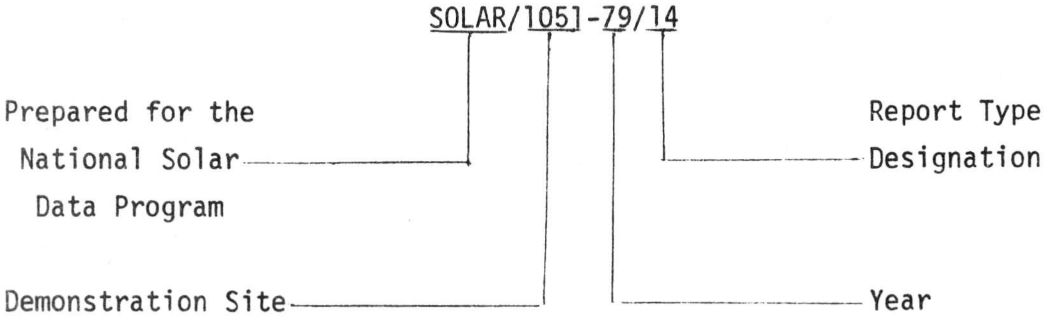
NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under a specific format. For example, this report for the Colorado Sunworks system project site is designated as SOLAR/1051-79/14. The elements of this designation are explained in the following illustration.



- Demonstration Site Number:

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- Report Type Designation:

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  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December).

  - Solar Energy System Performance Evaluations are designated by the number 14.

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  - Solar Project Cost Reports are designated by the number 60.

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1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy under the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to accelerate the establishment of a viable solar energy industry and to stimulate its growth in order to achieve a substantial reduction in nonrenewable energy resource consumption through widespread applications of solar heating and cooling technology.

Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate, and may include such topics as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- Monthly Performance
- System Performance Evaluation

The International Business Machines Corporation is contributing to the overall goal of the Demonstration Act by monitoring, analyzing, and reporting the thermal performance of solar energy systems through analysis of measurements obtained by the National Solar Data Network.

The System Performance Evaluation Report is a product of the National Solar Data Network. Reports are issued periodically to document the results of analysis of specific solar energy system operational performance. This report includes system description, operational characteristics and capabilities, and an evaluation of actual versus expected performance. The Monthly Performance Report, which is the basis for the System Performance Evaluation Report, is published on a regular basis. Each parameter presented in these reports as characteristic of system performance represents over 8,000 discrete measurements obtained each month by the National Solar Data Network.

This Solar Energy System Performance Evaluation Report presents the results of a thermal performance analysis of the Colorado Sunworks passive solar energy systems. Analysis covers operation of the system from November 1978 through May 1979. The Colorado Sunworks solar energy system (Figure 1-1) provides space heating and domestic hot water heating to a single family residence located in Longmont, Colorado. A more detailed system description is contained in Section 3. Analysis of the system thermal performance was accomplished using measurements and a system energy balance technique described in Section 4. Section 2 presents a summary of the results and conclusions obtained, while Section 5 presents a detailed assessment of the system thermal performance.

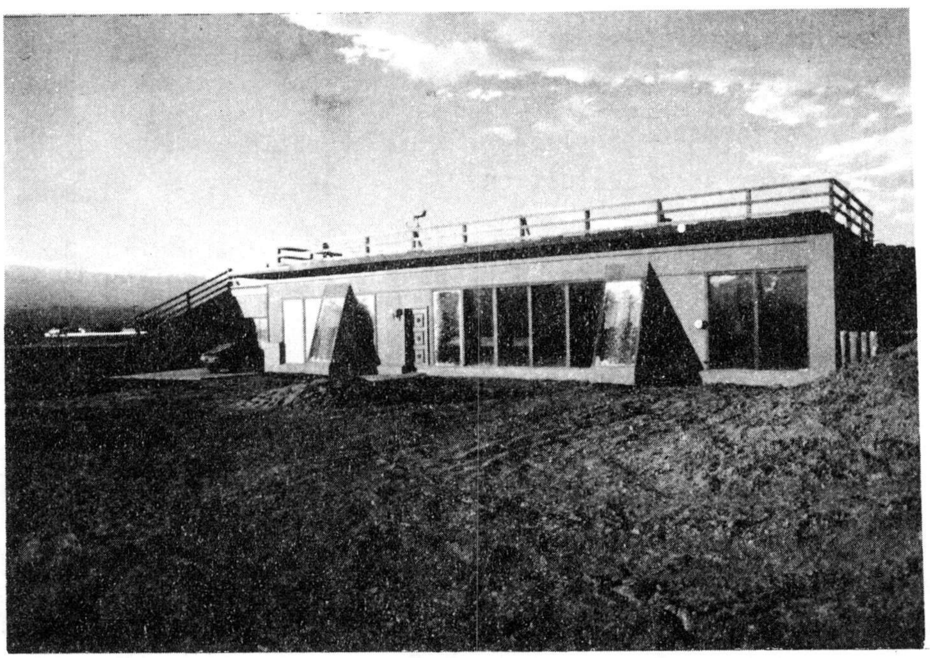

Figure 1-1. Colorado Sunworks Solar Energy System

2. SUMMARY AND CONCLUSIONS

This system Performance Evaluation Report provides an operational summary of the solar energy system at the Colorado Sunworks site, a single family residence located in Longmont, Colorado. This analysis is conducted by evaluation of measured system performance and by comparison of measured weather data with long-term average climatic conditions. The performance of major subsystems is also presented.

Features of this report include: a system description, a review of actual system performance during the report period, analysis of performance based on evaluation of meteorological load and operational conditions, and an overall discussion of results.

The Colorado Sunworks passive solar space heating system satisfied 74 percent of the building heating energy requirements during the time period November 1978 through May 1979. The remainder of the building heating energy requirements were provided by the occupants, their use of electrical energy, and by incidental use of the fireplace. The natural gas-fired auxiliary system was used for space heating on only two days.

The passive solar domestic hot water system satisfied 25 percent of the hot water thermal energy requirements. No hot water system malfunctions were observed.

Significant amounts of non-renewable energy were saved by both the passive space heating and domestic hot water solar energy systems. Using a conservative evaluation of the space heating system savings, almost 55 million Btu of fossil energy was displaced by solar energy at a cost of only 3.06 million Btu of operating energy.

Comfort levels inside the building were acceptable to the occupants over the majority of the winter. Minor comfort related difficulties were encountered. However, these difficulties are more of an inconvenience than a major problem. The awareness of system operation by the occupants and their resultant actions caused an increase in energy savings. These actions are described, along with detailed discussions of system thermal performance, in Section 5.

3. SYSTEM DESCRIPTION

The Colorado Sunworks solar energy system [1] is a passive solar energy system used for both space heating and domestic hot water preheating at a single family dwelling located in Longmont, Colorado. The building is a three bedroom single story house with approximately 1,800 square feet of living space as illustrated in the drawings of Figure 3-1.

The passive space heating system, illustrated schematically in Figure 3-2, is a combination drum wall and direct gain system. Sunlight enters the double glazed windows (approximately 300 square feet) on the south side of the building where the majority of the energy is absorbed by the black painted 55-gallon water filled drums (54 drums total). The remainder of the energy is either absorbed in the six-inch thick concrete slab floor or used to satisfy the daytime space heating demand. The eight-inch thick exterior insulated reinforced concrete building walls also serve as a secondary solar storage mass.

At night, or during periods of low incident solar energy, heat losses through the glazing are reduced by using movable insulation in the form of a Beadwall*. The Beadwall is constructed using the two panes of glass spaced five and one-half inches apart. Beads of white colored rigid insulation are blown into the space between the glass or sucked out using electrically driven blowers. When not used for south wall insulation, the beads of insulation are stored in tanks located in the garage. Operation of the Beadwall is automatically controlled based on sensors which measure incident solar energy and inside and outside temperature. This automatic operation may be manually overriden.

Collected solar energy is distributed to the house by both convection and radiation. A unique feature of this building is the technique used for distribution of collected solar energy from the drums to the north side of the house. The vertically stacked drums near the south wall form a drumwell

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* Beadwall is a registered trademark of the Zomeworks Corporation, Albuquerque, New Mexico.

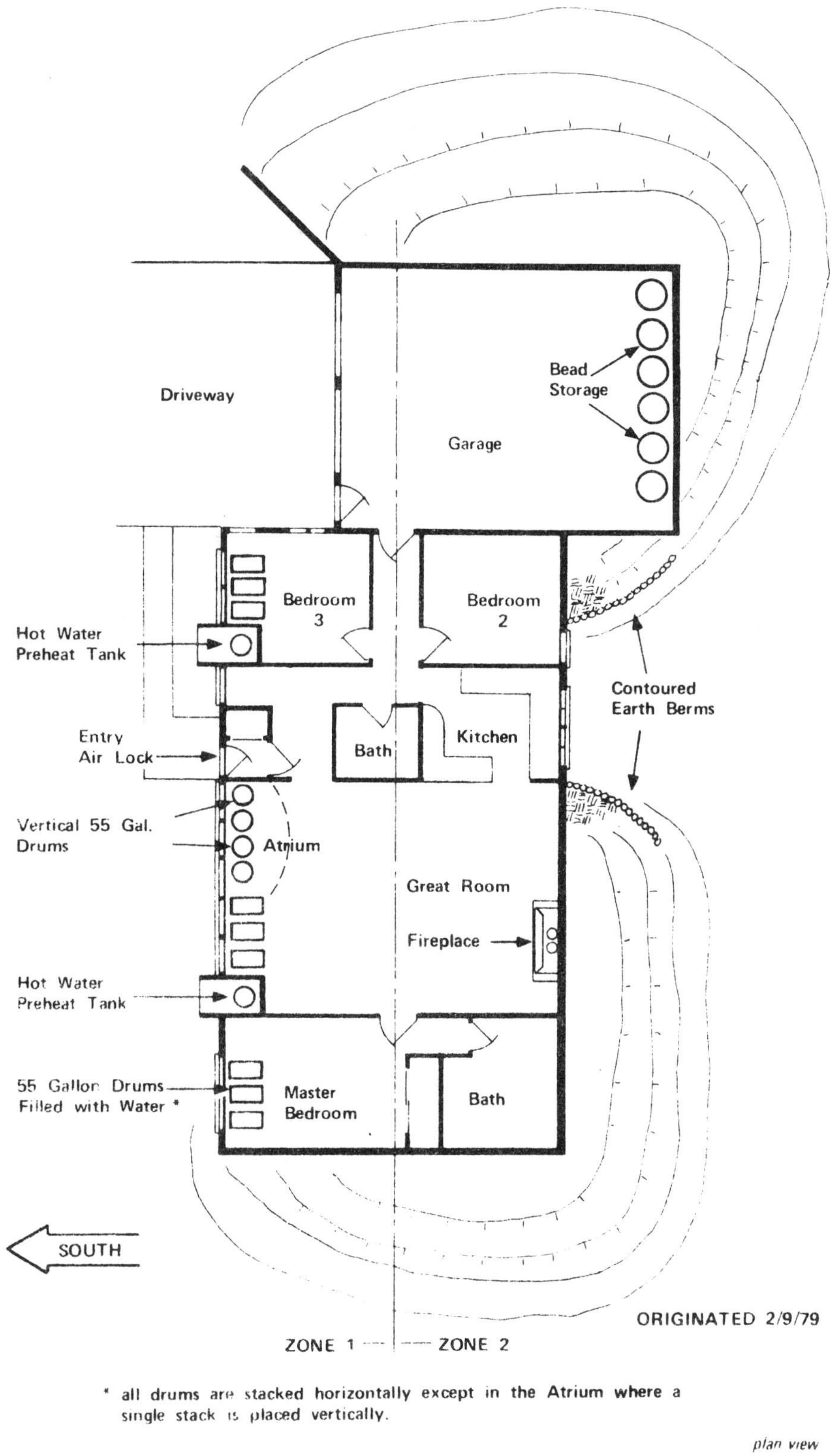

Figure 3-1. Colorado Sunworks Passive Solar Space Heating System

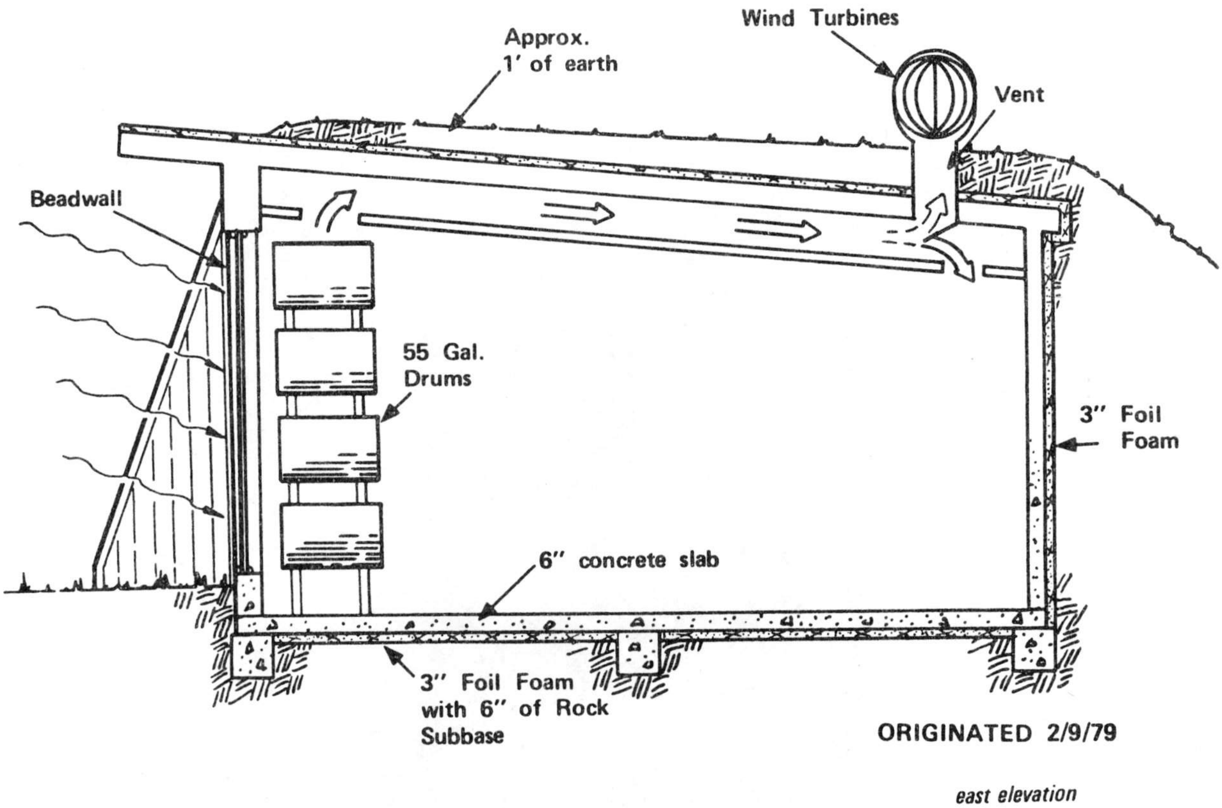

Figure 3-2. Colorado Sunworks Solar Space Heating System Schematic

chimney (Figure 3-3) where heated air rises through ceiling vents above the drums into an open plenum area between the roof and the ceiling of the rooms. Additional vents from this plenum on the north side of the house provide a path for the warm air into the room thus providing for a thermosiphon flow around the inside of the building.

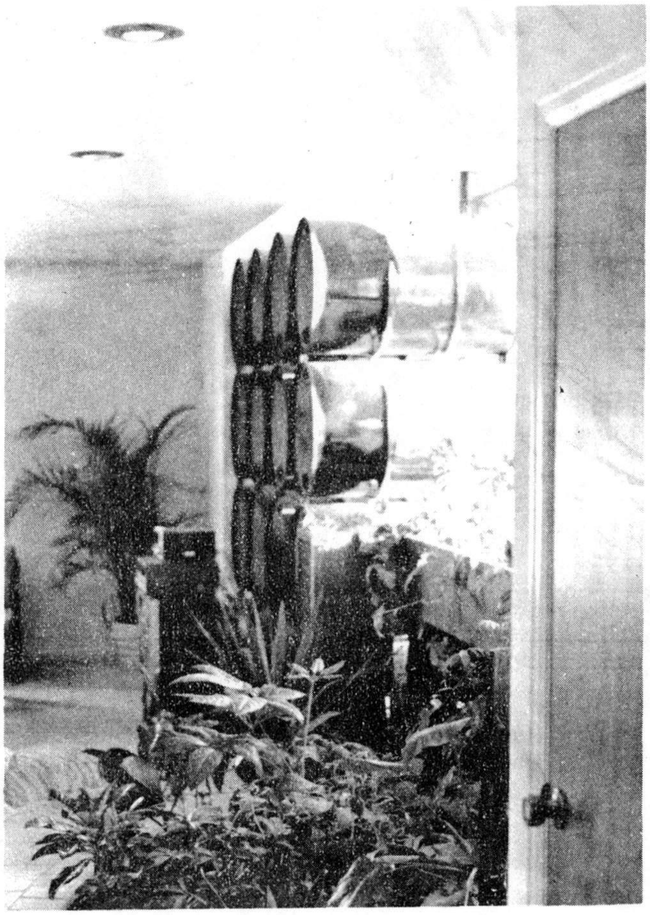

Figure 3-3. Living Room Drum Well

The building design and construction makes use of a number of energy conserving features. The exterior skin of the building (including the bottom of the slab floor) is well insulated and sealed. Earth berms on the north, east, and west sides of the house (Figure 3-4) provide additional insulation along with a damping of the extremes in temperature variation of the outside skin of the house. The roof is also covered with approximately one foot of earth. Additional energy conserving features include the use of an entry vestibule which serves as an airlock and the placement of the garage to the northwest to serve as a windbreak.

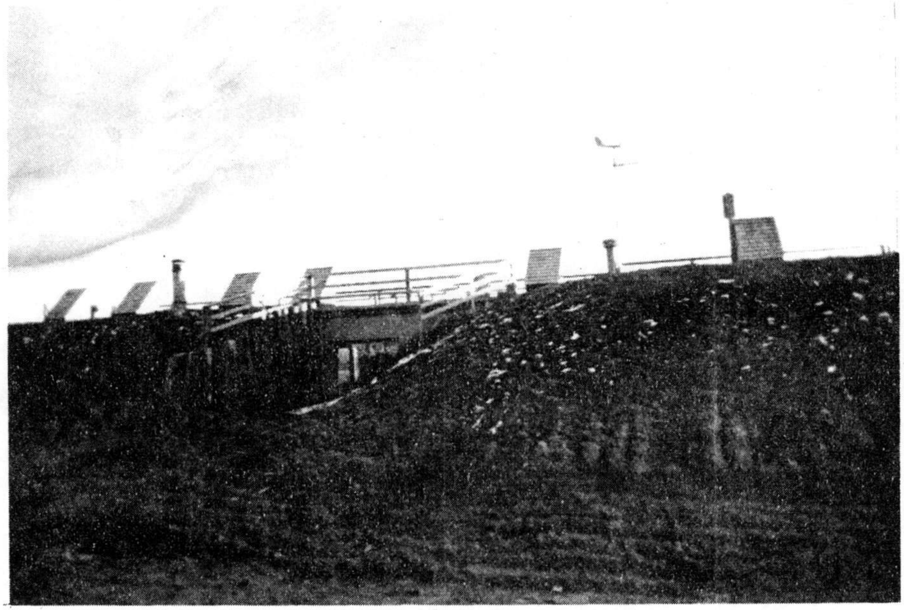

Figure 3-4, Northwest View

Auxiliary space heating energy is provided by either natural gas-fired hydronic baseboard units or by a wood burning fireplace. The fireplace has a provision for recirculation of room air. Outside air is used for combustion.

The passive solar domestic hot water system (Figure 3-5) consists of two 30-gallon tanks which have been stripped of their insulation, painted black, and positioned next to the south wall (Figure 3-1). Domestic hot water is

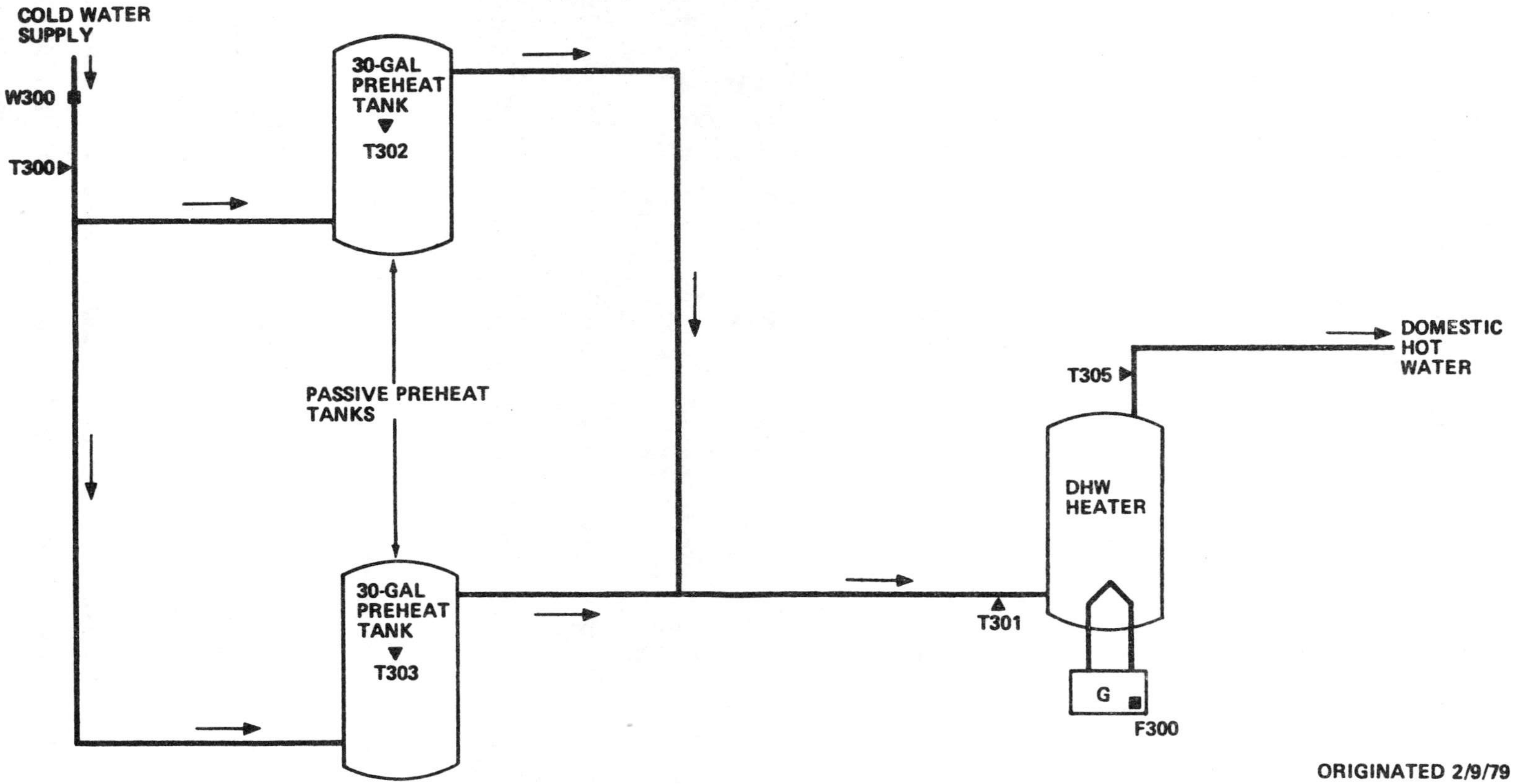

Figure 3-5. Colorado Sunworks Passive Solar Domestic Hot Water System Schematic

preheated in these tanks before passing, on demand, to the natural gas-fired domestic hot water tank where it is raised to operating temperature. The preheat tanks are insulated from the living space by interior walls, and are insulated from the outside conditions at night by the Beadwall movable insulation. Reflective surfaces inside the insulated spaces enhance the absorption of incident solar radiation.

Summer overheat protection is provided by several means. A roof overhang over the south wall provides shading from the high summer sun. The Beadwall movable insulation can be closed during the day to prevent solar radiation from entering the building. Cooling of the building is enhanced by the use of night time ventilation. Cool outside air can enter the house through open windows, passing over the solar storage masses and removing energy before exiting the building through roof vents located in the plenum area between the ceiling and roof. This natural flow is enhanced by the use of wind turbines above the roof vents as illustrated in Figure 3-2. When the house is closed during the daytime hours, the cooled solar storage masses absorb energy, thus tempering conditions inside the living space.

The predicted solar contribution for this system is 65 percent of the energy requirements for space heating and domestic hot water. The building is located near Longmont, Colorado (north of Denver) on a plain at least 10 miles east of significant changes in the terrain elevation. The average annual heating requirement for this area is over 6,000 heating degree-days. Long-term monthly average outside ambient temperatures range from 30°F in January to 73°F in July. Relative humidity is generally quite low. The average annual percentage of available sunlight is 64 percent. The most significant local climate effects are the high surface winds typically encountered during periods of changing weather conditions.

4. PERFORMANCE EVALUATION TECHNIQUES

The thermal performance of the Colorado Sunworks solar energy systems is evaluated using data from monitoring instrumentation located at the site. Performance factors which represent the thermal performance of the system are computed using this measurement data. Definition of the performance factors used follows the general outlines of the intergovernmental agency report, "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program," [2]. The analysis technique used is outlined in another report, "Performance Evaluation Reporting for Passive Systems," [3]. This section addresses the application of the passive system thermal evaluation technique to the Colorado Sunworks system along with a description of the measurements used to monitor the system performance.

4.1 Instrumentation and Data Acquisition

Measurement data is provided for analysis using the IBM-developed Central Data Processing System (CDPS), [4]. Data from sensors is sampled approximately once each five minutes by a microprocessor controlled device located at the site and recorded on cassette tape. Approximately once per day a processor at the CDPS automatically accesses the on-site microprocessor via telephone to collect the data stored on tape. This data is further processed by another computer to provide the measurement data in a form compatible with both visual and automated data analysis procedures. The measurement data is scanned by the analyst either in tabular or plot form on a frequent basis in order to detect significant changes in solar energy system or instrumentation/data acquisition system operation. The measurement data is also available to the software which provides for the computation of the performance factors discussed in the remainder of the report.

System thermal performance at the Colorado Sunworks site is monitored using 70 different measurements of conditions at the site. The monitoring measurements sampled at the site are summarized in Table 4-1. The measurement identification number used in Table 4-1 follows the system defined in Reference [2] where the prefix I is used for insolation measurements, T for temperature measurements, EP for electrical power, W for air or liquid flow, V for wind velocity, and D for switches or wind direction. Units used for the measurements are Btu/ft^2-hr for insolation, degrees F for temperature, kilowatts for electric power, feet per minute for air flow, miles per hour for wind speed and degrees for wind direction.

Table 4-1. Colorado Sunworks System Sensor Locations

MEASUREMENT ID	DESCRIPTION
T001	Outside ambient air temperature.
RH001	Outside relative humidity.
RH600	Indoor relative humidity measured in the great room area.
D001	Wind direction.
V001	Wind speed.
I001	Total insolation measured in a vertical south-facing plane below the south wall overhang.
I002	Total insolation measured in a vertical south-facing plane on the outer edge of the south wall overhang.
T300	Cold water supply temperature.
T302,T303	Surface temperatures of the two domestic hot water preheat tanks.
T301	Temperature of water delivered from the preheat tanks to the domestic hot water heater.
T304	Temperature of the outer surface of the domestic hot water heater.
T305	Temperature of the hot water delivered from the hot water heater.
W300	Flow of water through the domestic hot water system.
F300	Fuel used by the domestic hot water heater.
D101	Mode of the domestic hot water system beadwall.
F403	Auxiliary heating system fuel use.

Table 4-1. (Continued)

T407	Water temperature at the outlet of the auxiliary heating system boiler.
T406	Water temperature at the inlet to the auxiliary heating system boiler.
W403	Auxiliary hydronic system flow rate.
EP401	Power consumed by auxiliary system circulating pump.
EP600	Total building power.
D100,D101,D102, D103,D104,D105	Mode of each Beadwall insulation section.
EP100	Total electrical power used by Beadwall system motors.
D405	Mode of the great room fireplace.
T200,T201	Water storage drum surface temperatures in bedroom three.
T202,T203	Water storage drum surface temperatures in the entry hallway.
T204,T205	Water storage drum surface temperatures in the atrium.
T206,T207,T208, T209,T210,T211, T212,T213	Water storage drum surface temperatures in the living room area of the great room.
T214,T215	Water storage drum surface temperatures in the master bedroom.
T400,T401,T402, T403,T404,T405	Air temperatures at the bottom and the top of the drumwell chimneys in bedroom three, the living room, and the master bedroom.
T600,T601,T602, T603,T604,T605, T606,T607	Temperatures in the great room and master bedroom of the floor measured near the surface, at the styrofoam/gravel interface and in the earth one foot below the floor surface.

Table 4-1. (Continued)

T608	Concrete floor surface temperature in the kitchen.
T609,T610,T611, T612,T613,T614	North wall temperatures in the great room and in bedroom two on the inside and outside of the styrafoam and on the wall outer surface.
T615,T616	Roof temperatures on the inside and outside of the styrafoam layer.
T617,T618,T619, T620,T621,T622, T650,T651,T652, T653,T654	Ambient air temperatures in each room of the building including the garage and the entry air lock.
D400,D401,D402, D403,D404	Mode of the ceiling vents on the north side of the building.

4.2 Energy Balance Technique

The basis for the analysis technique is an energy balance concept developed for use in the National Solar Data Network. All significant sources of energy entering and leaving the system, along with the change in energy inside the system are accounted for. The details of the derivation of the technique used are presented in References [3] and [5]. The equations used are listed in Appendix B of this report.

The space heating load used in this report and in References [6] through [18], is the building load minus the other sources of energy generated inside the building which would cause a reduction in the equipment load of an active solar energy system or a conventional heating system. As such there may be periods of time when significant amounts of energy are supplied to the building from non-renewable energy sources other than solar energy. Consequently there may exist periods of time when the reported load appears small in relation to the building load since the reported load is actually an equivalent equipment demand.

Using the energy balance concept the solar energy used is found as the difference between the space heating load and the auxiliary energy supplied to the building. As such both the load and the solar energy used represent the energy requirements of the building being analyzed and do include the energy which is lost back through the solar glazing area. All other primary performance factors including energy savings are computed with respect to these load and solar energy used values (Appendix B). However, the energy savings, particularly when used for comparison with another solar energy system, can be misleading if a comparison is made between a passive system analyzed by this technique and an active sytem. Consequently other energy savings comparisons must be made.

The building savings, or the energy savings for the system as built, are presented first. The building savings is the difference between the energy required to maintain the measured building interior environment and the auxiliary energy used. As such, the building savings represents the difference between the homeowner's utility bills with and without the use of incident solar energy.

The comparison savings represents the difference between the energy which would be required to maintain the measured interior environmental conditions in a comparison building and the auxiliary energy used by the system. The comparison building is a building model which has thermal characteristics identical to the passive system on all exterior surfaces except the glazed south wall area. For the comparison building load determination, the solar glazing is replaced by a wall with thermal characteristics similar to the other passive system building walls. Thus the comparison savings represents the savings realized in a comparison to a building with the same energy conservation characteristics which does not make use of incident solar energy for heating. In effect, the comparison savings is the building savings reduced by the high losses through the glazed south area on a passive system.

The third savings, the comparison set point savings, is the energy savings compared to the energy requirements of the comparison building under conditions when the temperature inside the comparison building is controlled to a set point. This would be the case if a conventional heating system was used for control of the building environment. To determine the comparison set point savings, a two degree range of building temperature (from 68° to 70°F) is used as the set point. When the building temperature is below the lower set point temperature of 68°F, the comparison set point savings are reduced by the additional energy which would be required to maintain the lower set point temperature in the comparison building. Although this energy would not decrease the actual savings, it is applied as a penalty to the comparison savings for convenience, rather than creating a new performance factor. When the building temperature is above the upper set point temperature (70°F), the assumption is made that the additional energy used to maintain the higher temperature is excess energy. Consequently, the comparison set point savings are reduced by this excess energy unless all or part of this excess energy was derived from a renewable energy source such as wood. If the excess heating energy requirements could be totally satisfied from other renewable energy sources, then no reduction is made in the solar comparison set point savings.

Otherwise the savings are reduced by the difference between the excess energy and the other source of renewable energy (wood).

Presentation of the three concepts of energy saved allows the reader to observe the effect of more constrained operation of the passive space heating system through successive levels of more severe constraints. It should be noted that both the comparison savings and the comparison set point savings for a well designed and well built passive system will be relatively low. However, if the use of auxiliary energy is also low, then the relatively low magnitude of the savings reflect only the energy conservation features of the system. For a building where the glazing is an integral part of the building (i.e., a direct gain system) the comparison savings most adequately describe the energy savings realized. However, as the glazing and area of collection becomes more isolated from the living space, the building savings become more meaningful. A greenhouse falls in between -- that is, it is a livable part of the building when greenhouse temperatures are high, but less usable when temperatures are lower. Consequently, both the building savings and the comparison savings have periods of applicability for the greenhouse system. No attempt is made in this report to quantify the energy savings resulting from the application of energy conserving construction techniques. That is, the energy savings presented in the report are savings resulting only form the use of the incident solar energy.

More complete definitions of the performance factors used for system analysis are presented in Appendix A. The equations used to generate these performance factors for the Colorado Sunworks system are present in Appendix B.

5. PERFORMANCE ASSESSMENT

During the winter of 1978-1979, the Colorado Sunworks passive solar space heating system satisfied 74 percent of the building heating load and almost 100 percent of the space heating demand. The passive solar hot water system satisfied approximately 25 percent of the hot water demand. Winter weather conditions, both in terms of available solar energy and outside ambient temperature, were more severe than the long-term average conditions for the area. Significant amounts of energy savings were realized by both solar energy systems. Comfort conditions produced by the space heating system were acceptable to the occupants during all periods of the winter and spring with the exception of several periods in January and May.

Weather conditons in the Longmont area during the winter, as shown in Table 5-1, were such that significantly larger than average heating loads were encountered. Measured incident solar energy was only 80 percent of the long-term average value. The measured average outside ambient temperature was less than the long-term average during all months of the heating season except March and April. Weather conditions were particularly severe during December and January when measured outside ambient temperatures were more than 10°F less than the long-term average temperature. Weather conditions during May also produced a severe test of the heating system capability since the incident solar energy was only 60% of the expected value. Wind speed, which normally averages near 10 miles per hour was significantly lower during the winter, averaging only 5 miles per hour for the heating season. However, a number of days were observed when the average daily value of wind speed exceeded 10 miles per hour. Outside relative humidity was slightly high during the winter, averaging over 60 percent, providing yet another indication of the severity of the winter weather conditions in terms of precipitation. A number of periods of time were encountered during this unusually severe winter when only a small amount of solar energy was incident on the glazing for several consecutive days.

TABLE 5-1

WEATHER CONDITIONS

Month	Daily Solar Energy Incident Per Unit Area (Btu/Ft^2-Day)		Ambient Temperature (°F)		Wind Speed (MPH)		Relative Humidity (Percent)
	Measured	Long-Term Average(1)	Measured	Long-Term Average	Measured	Long-Term Average	Measured
Nov 78	1,257	1,712	35	39	4.4	8.7	63
Dec 78	1,601	1,690	20	32	5.1	9.0	62
Jan 79	1,493	1,856	16	30	3.7	9.2	62
Feb 79	1,488	1,769	31	32	4.9	9.4	55
Mar 79	1,126	1,496	39	37	5.5	10.1	64
Apr 79	1,019	1,106	49	48	6.2	10.4	53
May 79	584	890	53	57	5.4	9.6	69
Average	1,226	1,502	35	39	5.0	9.2	61

(1) Long-term weather data derived from Denver, Colorado measurements.

Collection of incident solar energy at the Colorado Sunworks system occurs through the double-glazed glass windows on the south side of the building. The collection process is operational at any time the Beadwall system is open and solar energy is incident on the glazing. Control of the operation of the Beadwall system is automatic based on a sensor measuring a combination of the incident solar energy and the outside ambient temperature. The effectiveness of automatic control of the Beadwall movable insulation system is illustrated in Figure 5-1 where the percentage of the total incident solar energy available when the Beadwall is open is shown. Over the heating season more than 80 percent of the total incident solar energy was available to the space heating system. Also shown in Figure 5-1 for comparison purposes is the same information for another passive system monitored in the National Solar Data Network. The movable insulation in the second system is manually operated with the result that a substantially smaller percentage of the total incident solar energy is available to the space heating system.

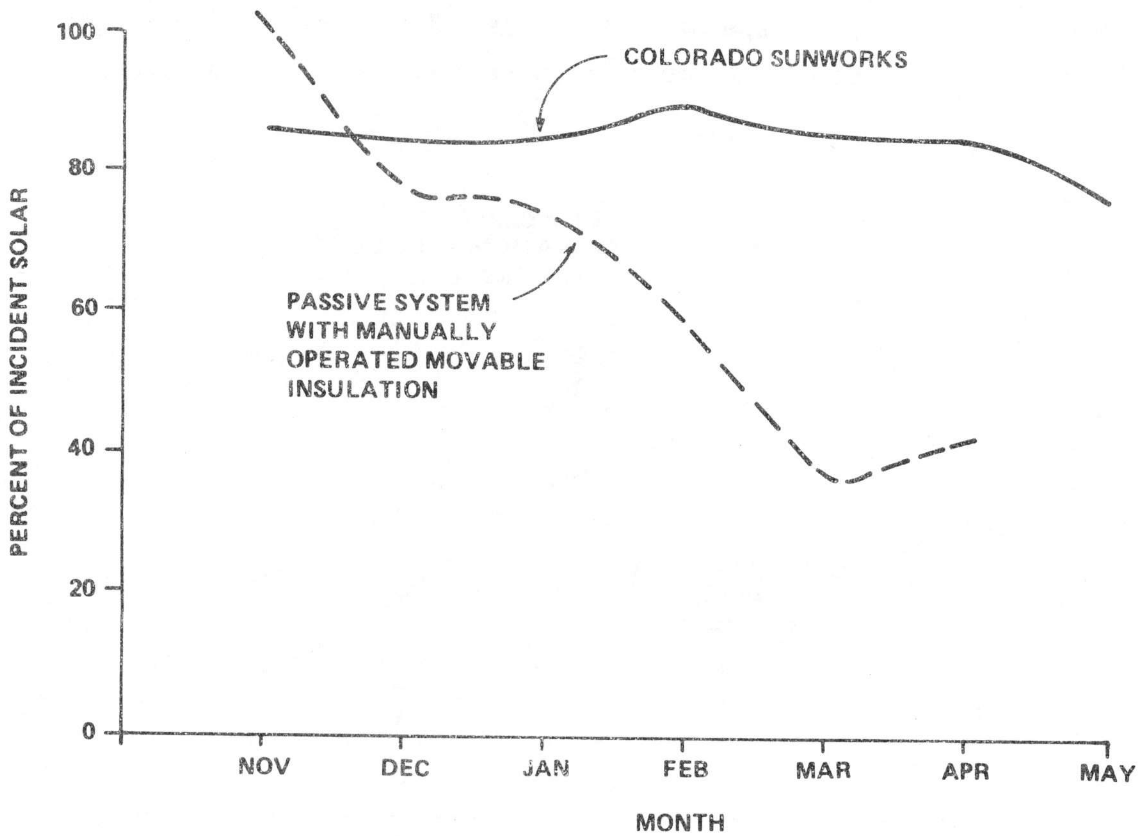

Figure 5-1. Percentage of Solar Energy Incident When Beadwall is Open

Only during November 1978 did the manually operated system percentage exceed the automatic system percentage at Colorado Sunworks. The 100 percent value during November at the other system was due to lack of operation of the movable insulation. (The movable insulation was open day and night over the entire month.) During May, the lowest value of the heating season was observed at the Colorado Sunworks system. The low value is due to the use of the Beadwall for shading during several days and to a temporary failure of an electrical component in the control system which disabled the Beadwall for several days. This component failure was the only abnormal Beadwall operation observed over the heating season. The Beadwall system was inoperative for a few days while temporary repairs were accomplished. Full automatic operation of the Beadwall system resumed within 3 weeks.

The efficiency of solar energy collection, illustrated in Figure 5-2, is presented with respect to both the total incident solar energy and the operational incident solar energy (incident solar energy when the Beadwall is open). The similar shape of both curves illustrates the consistent performance of the Beadwall automatic control system. The maximum

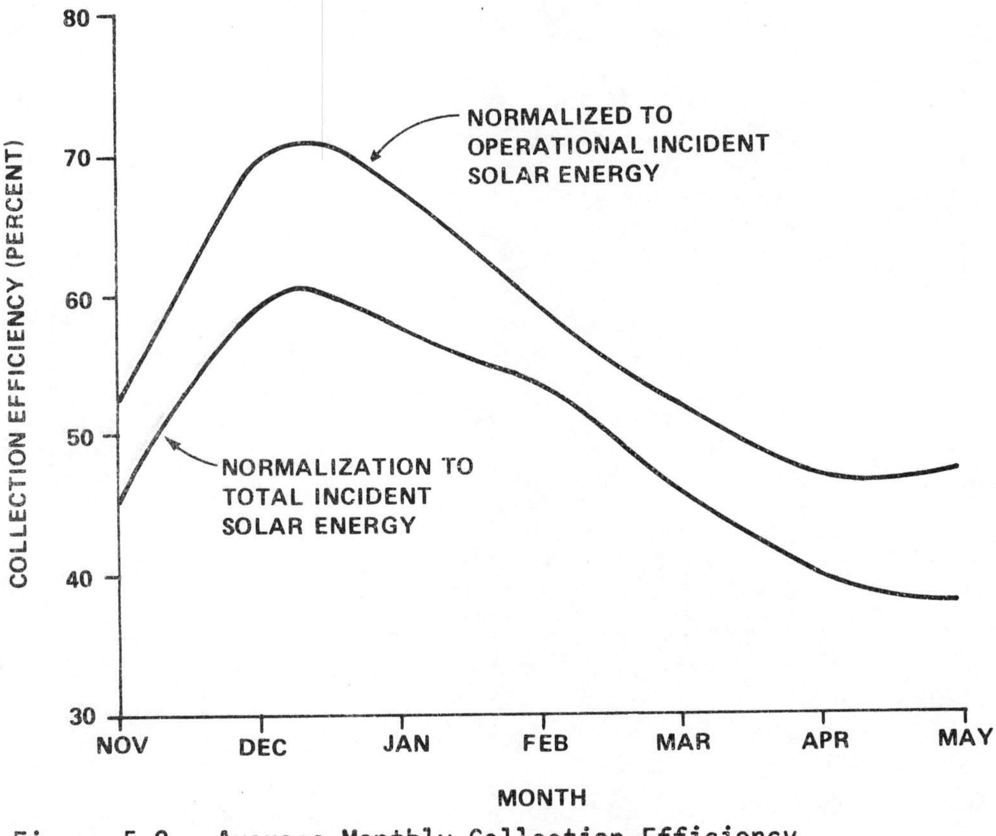

Figure 5-2. Average Monthly Collection Efficiency

difference in the two curves occurs during the coolest months and is due to the cold weather encountered, since the sensor used for Beadwall operation senses both incident solar energy and outside ambient temperature. As a result, the ratio of operational incident energy to total incident energy, shown in Figure 5-1, is lower during cold weather causing the larger difference in the curves of Figure 5-2 during December and January. Since the sun is at its lowest point in the sky during late December and early January, the incident solar energy is most normal to the vertical glazing during this time period. Consequently, the collection efficiency is the highest during this period. Both before and after this time the collection efficiency decreases as the incident solar energy is less normal to the glazed areas. It should be noted that the values of the collection efficiency presented do not include thermal losses through the south-facing glazed areas. Thermal losses through these areas are included as a part of the building heating load, since the glazed areas are a portion of the exterior of the building.

The Colorado Sunworks passive solar domestic hot water system operated reliably over the entire heating season while saving more than 6 million Btu (7,000 cubic feet) of natural gas. No significant system failures or abnormal system operation was observed during the time period covered by this analysis. Incident solar energy collected in the two preheat tanks and delivered on demand to the domestic hot water tank satisfied approximately 25 percent of the domestic hot water load. As shown in Table 5-2, the four member family used an average of 88 gallons of hot water per day over the heating season. Solar energy system performance in terms of the solar fraction was reasonably consistent from month to month with a season low solar fraction of 19 percent in November and a season high of 27 percent in February. Variations in the performance from month to month are caused in part by the seasonal variations in available solar energy but are more significantly influenced by the hot water use patterns of the occupants.

TABLE 5-2

DOMESTIC HOT WATER SYSTEM THERMAL PERFORMANCE SUMMARY

Month	DHW Load (Million Btu)	Auxiliary Thermal Used (Million Btu)	Solar Energy Used (Million Btu)	Hot Water Used (Gallons)		Solar Fraction of Load (Percent)	Hot Water Temperature (Degrees F)	Cold Water Inlet Temp (Degrees F)
				Total	Avg per Day			
Nov 78	1.81	1.97	0.41	2,709	90	19	137	57
Dec 78	2.22	2.34	0.56	2,935	95	21	141	47
Jan 79	2.14	2.27	0.55	2,828	91	21	136	42
Feb 79	1.89	1.83	0.59	2,484	89	27	134	41
Mar 79	1.66	1.76	0.51	2,270	73	25	131	42
Apr 79	1.87	1.80	0.57	2,687	90	26	132	46
May 79	1.79	1.86	0.43	2,731	88	21	131	50
Season Average	1.91	1.98	0.52	2,663	88	--	134	46

To obtain maximum use of the collected solar energy, the timing of water use is more important with the passive hot water system than with an active hot water system. In the passive system, the maximum temperature in the preheat tanks under no load conditions occurs during the middle of the afternoon of a sunny day. The area around the preheat tanks, even with an operational Beadwall, is a much less effective tank insulation than the tank insulation on a typical active system storage tank. Consequently, if the warmed water in the preheat tank is not used before late evening, then the majority of the collected solar energy will be lost to the area surrounding the preheat tanks. Therefore, if activities which require the use of hot water can be scheduled in the afternoon and early evening hours when maximum preheat tank temperatures occur, more efficient use of the collected solar energy can be realized, and the need for auxiliary hot water fuel will be reduced. Also, the number of occurrences when the hot water output temperature falls noticeably below the set point can be reduced.

Occasionally the temperature of the water delivered from the hot water heater falls below the thermostat set point temperature. The lower temperatures generally occur when a large amount of hot water is used over a short period of time (i.e., during clothes washing) and are due principally to the small domestic hot water tank used. If, as discussed in the previous paragraph, these large amounts of hot water are used when the preheat tanks are hot, than the hot water temperature is less likely to drop below the set point temperature.

As shown in the monthly reports for this system (References [6] - [13]), the solar contribution to the domestic hot water load never reaches zero, even after a period of several cloudy days. This is due to energy transferred from the warm building to the cold incoming city water. Even though the preheat tank enclosures are rather well insulated from the remainder of the house, some energy still transfers from the house to the enclosures. As a result, even after cloudy day sequences during the coolest months, the temperature of the water in the preheat tanks is near 60°F, representing for example in February, a nearly 20 degree rise in water temperature.

Collected solar energy satisfied almost 100 percent of the space heating energy demand as shown by the data presented in Table 5-3. Reasonably comfortable living conditions were maintained over the analysis period. More than 74 percent of the building thermal heating load was satisfied by the use of solar energy. Other energies used to satisfy the building heating load were derived from use of electricity (appliances, Lights, etc.), body heat from the occupants, and incidental use of the fireplace.

The reported load is an equivalent equipment demand. As illustrated in Table 5-3, this space heating equipment demand is the difference between the building load and the sum of the wood and internal energy gains. This demand is the amount of energy which would be required to maintain the measured building environmental conditions. Almost 100 percent of this space heating subsystem demand was satisfied by collected solar energy.

Operation of the wood burning fireplace produced 1.56 million Btu of useful thermal energy. Based on occupant reports of the amount of wood used, this 1.56 million Btu represents less than 10 percent of the energy available in the wood. As discussed in Section 3, the fireplace should be reasonably energy efficient due to the use of glass firescreen doors and outside air for combustion. However, late in the winter the occupants discovered that the outside combustion air source was not operating properly. Thus, combustion air for fireplace use had been entering the fireplace through the building rather than directly into the fireplace, causing lower fireplace efficiencies. This combustion air apparently entered the tightly sealed building around the closed summer vents in the roof area. Indication of this is provided by the plots of the drum well air temperature in the master bedroom presented in Figure 5-3. Normally, due to air stratification effects around the heated water-filled drums, the air temperature at the top of the drum well was several degrees warmer than the air temperature near the floor. However, as indicated in Figure 5-3, when fireplace operation was observed, the air temperature near the floor was warmer than the air temperature near the ceiling, indicating a flow of air from the roof

TABLE 5-3

Heating System Thermal Performance Summary

Month	Building Load (Million Btu)	Fireplace Energy (Million Btu)	Internal Heat Gain (Million Btu)	Space Heat Demand (Million Btu)	Solar Fraction Of Load (Percent)	Solar Fraction Of Demand (Percent)	Average Building Temperature (Degrees F)	Average Ambient Temperature (Degrees F)
Nov 78	6.9	0.40	1.51	4.99	72	100	73	35
Dec 78	10.15	0.14	1.76	8.25	81	100	71	20
Jan 79	9.55	0.55	1.65	7.35	81	100	66	16
Feb 79	7.69	0.04	1.42	6.23	81	100	71	31
Mar 79	6.03	0.23	1.43	4.37	72	100	70	39
Apr 79	4.44	0.02	1.39	3.03	68	100	70	49
May 79	3.36	0.18	1.47	1.71	51	100	70	53
Season	48.12	1.56	10.63	35.93	74	100	70	35

vents, through the ceiling plenum area and down around the vertically stacked drums. Furthermore, the difference in temperature was porportional to the intensity of the fire in the fireplace. These effects were not observable in the southwest bedroom due to the distance from the fireplace and were masked in the great room area by local heating from the fireplace.

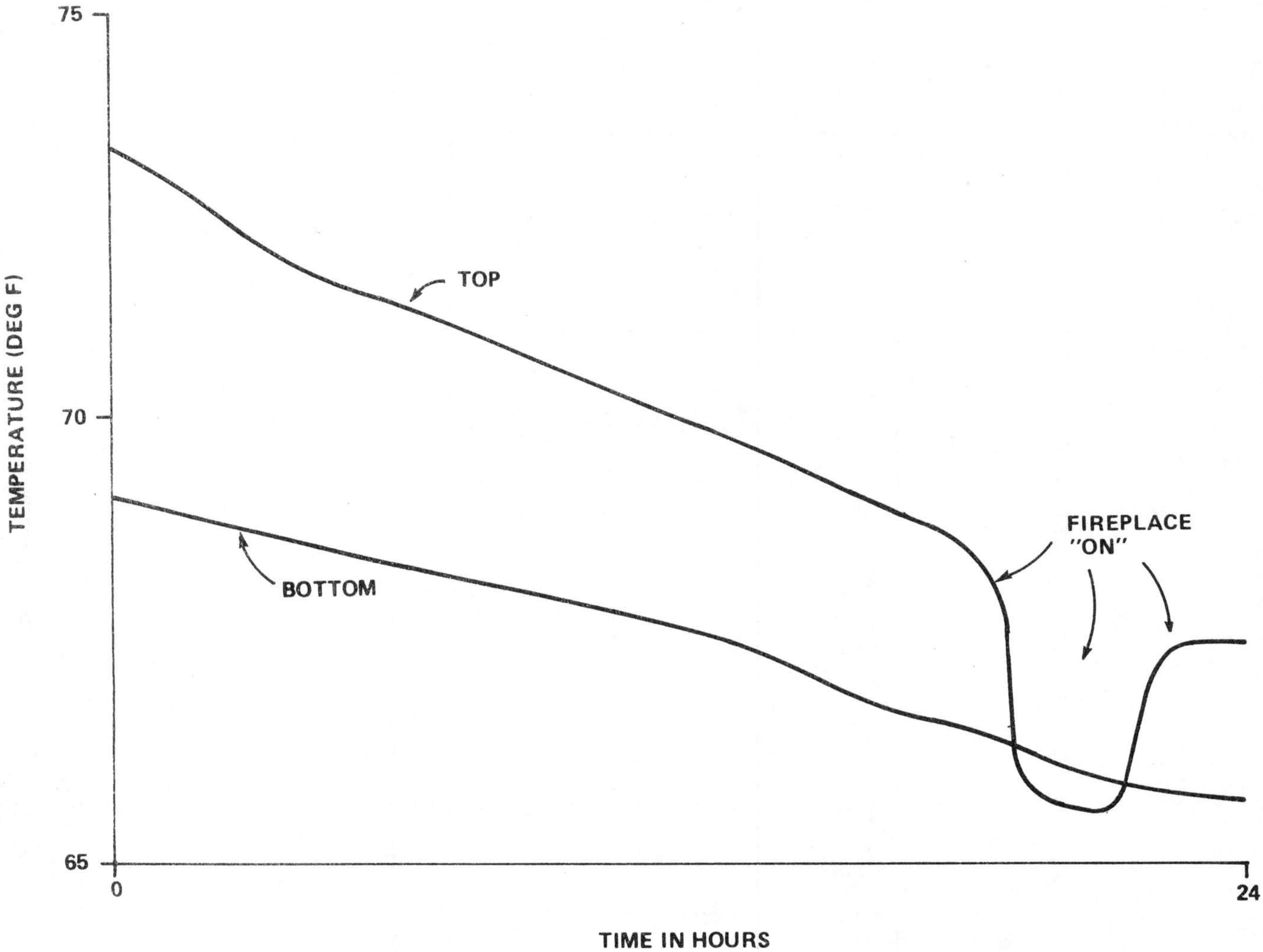

Figure 5-3. Master Bedroom Drum Well Chimney Temperatures - January 22, 1979

Storage of collected solar energy is provided primarily by the 54 water-filled drums. However, both the mass in the slab floor and the mass in the walls provide some additional storage capacity. The storage masses provided both adequate damping of daily building temperature variations and substantial long-term energy reserves.

As illustrated by the monthly average building and storage temperature data presented in Figure 5-4, the average temperature of the storage mass was consistently above the average building temperature thus maintaining the capability to transfer energy from the storage mass to the conditioned space. This reserve storage capability is further illustrated in the data presented in Figure 5-5, where daily average temperature data is presented.

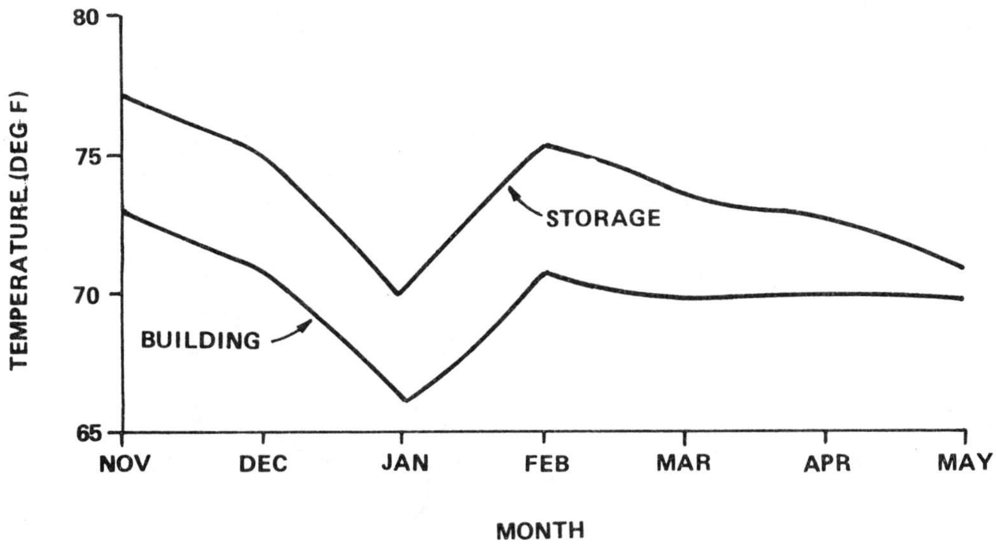

Figure 5-4. Monthly Average Building and Storage Temperatures

The storage mass in the Colorado Sunworks system provided a several day reserve energy capacity for space heating on many occasions throughout the winter. During several periods of cloudy weather, the storage masses were able to supply energy to the conditioned space for a four-day period. One such time period is illustrated by the plots presented in Figure 5-6. During the period illustrated (March 18, 1979 through March 21, 1979) available energy from the sun qas quite low, averaging only slightly greater than 100 Btu/ft^2-day. The Beadwall movable insulation system remained closed for the entire period. Outside ambient temperature during this four-day period was nearly constant at 32°F. For several days prior to this time period, levels of incident solar energy had been sufficient to increase the amount of stored energy to a point where the temperature of the water in the drums was almost 80°F at the beginning of the period (Figure 5-5). As can be seen from Figure 5-6, the temperature of the energy storage mass dropped

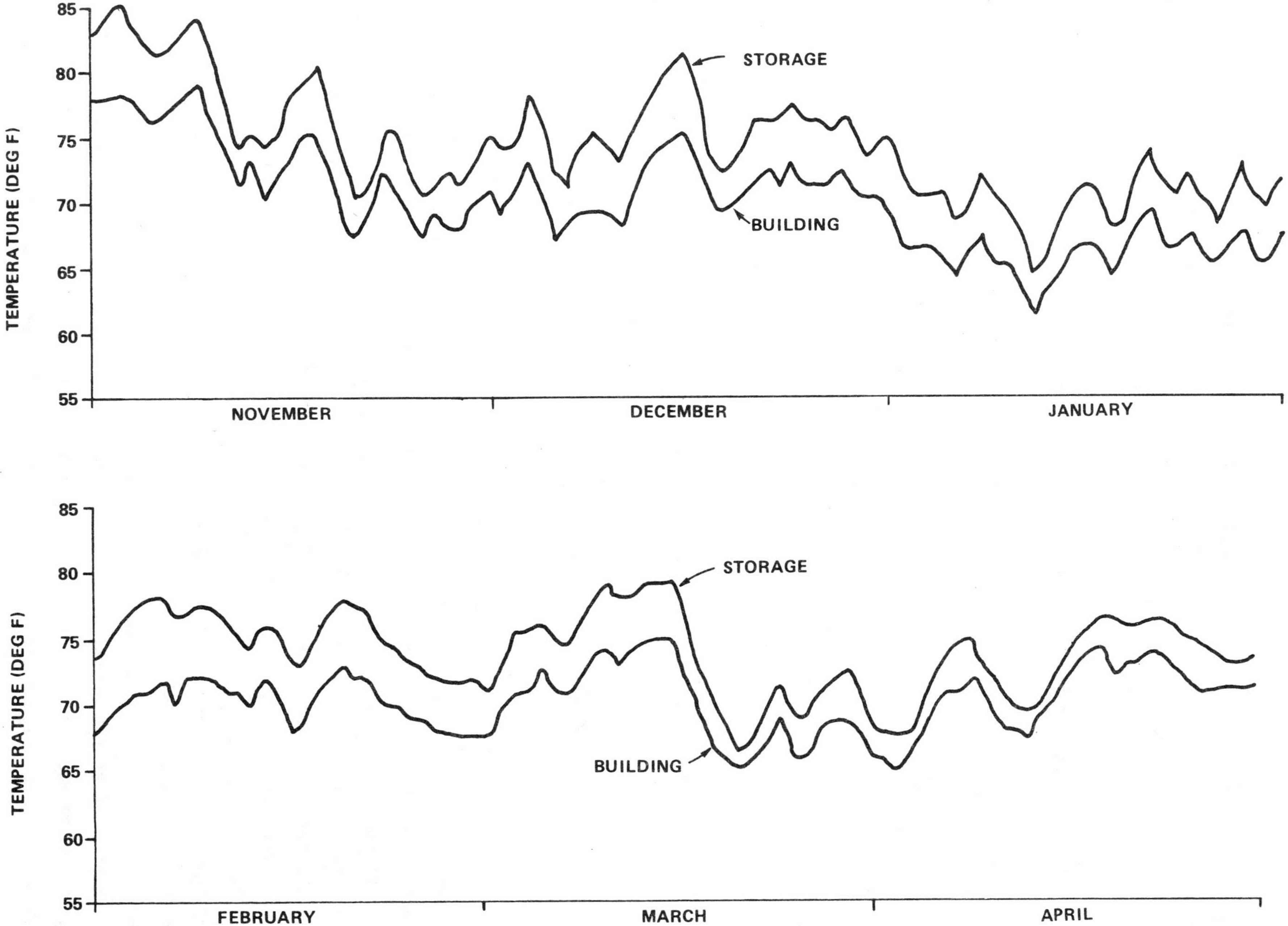

Figure 5-5. Daily Average Building and Storage Temperatures

steadily over the four-day period, reaching a low of 67°F at the end of March 21. The average building temperature also dropped steadily, reaching a low of 65°F. Since the average storage temperature was higher than the average building temperature, the storage mass was able to effectively supply energy to the conditioned space over the entire time period. Slight increases in building temperature noted during each day are due to energy generated inside the building as a result of energy use or activity by the occupants. The more substantial building temperature increase which occurred late on March 21 was the result of fireplace operation.

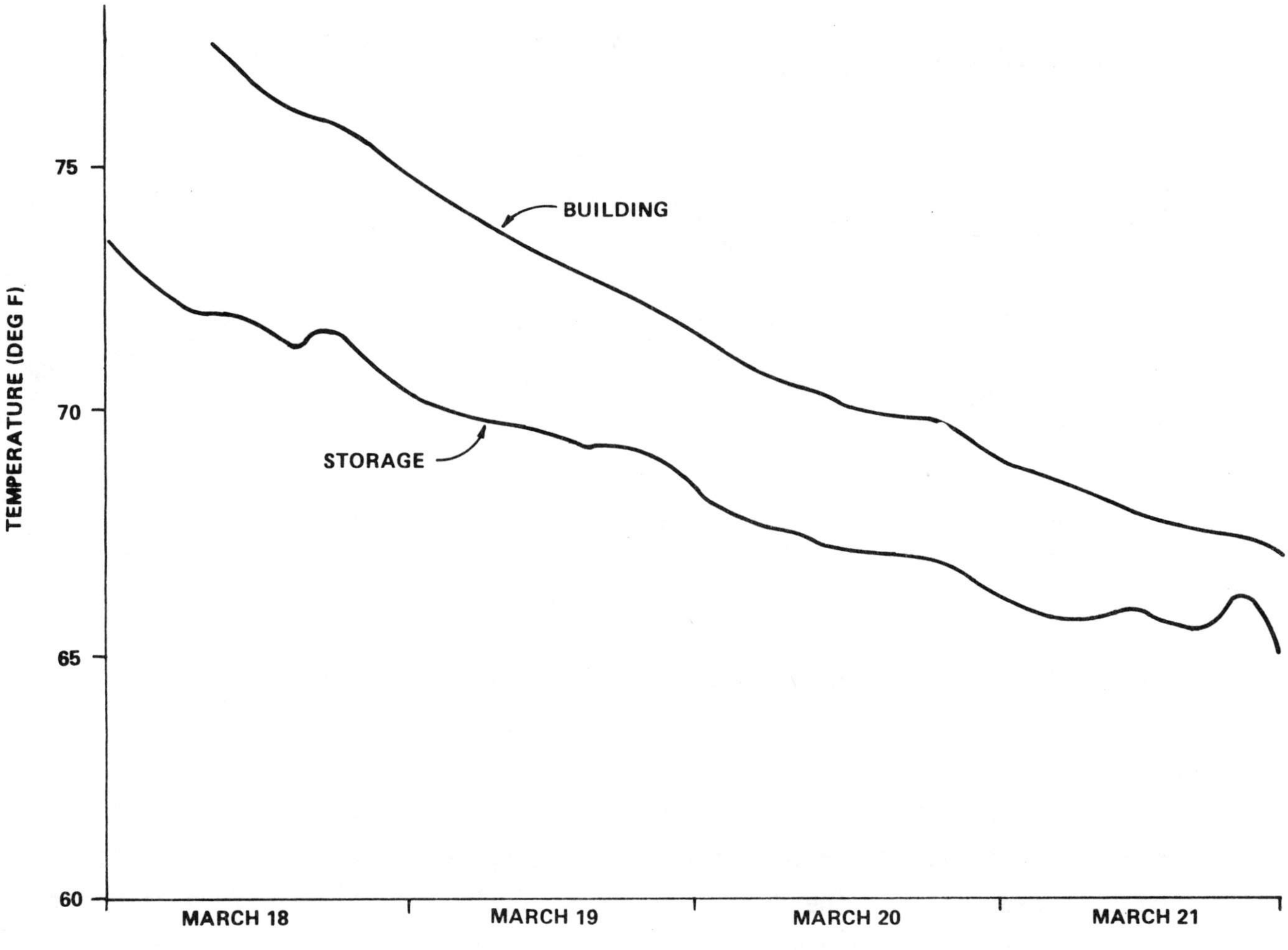

Figure 5-6. Building and Storage Temperature - March 18 - 21, 1979

The storage masses were also able to provide adequate damping of temperature variations inside the building as illustrated by the plots presented in Figures 5-7 and 5-8. The data presented in Figure 5-7 illustrates the building temperature response on a cloudy day when the outside air temperature varied considerably. Average building temperature varied by only 3 degrees while the outside ambient temperatures varied from a low of 27°F in the morning to a high of almost 65°F in the afternoon. This illustrates the capability of the storage masses to moderate the building temperature when outside temperature conditions vary considerably.

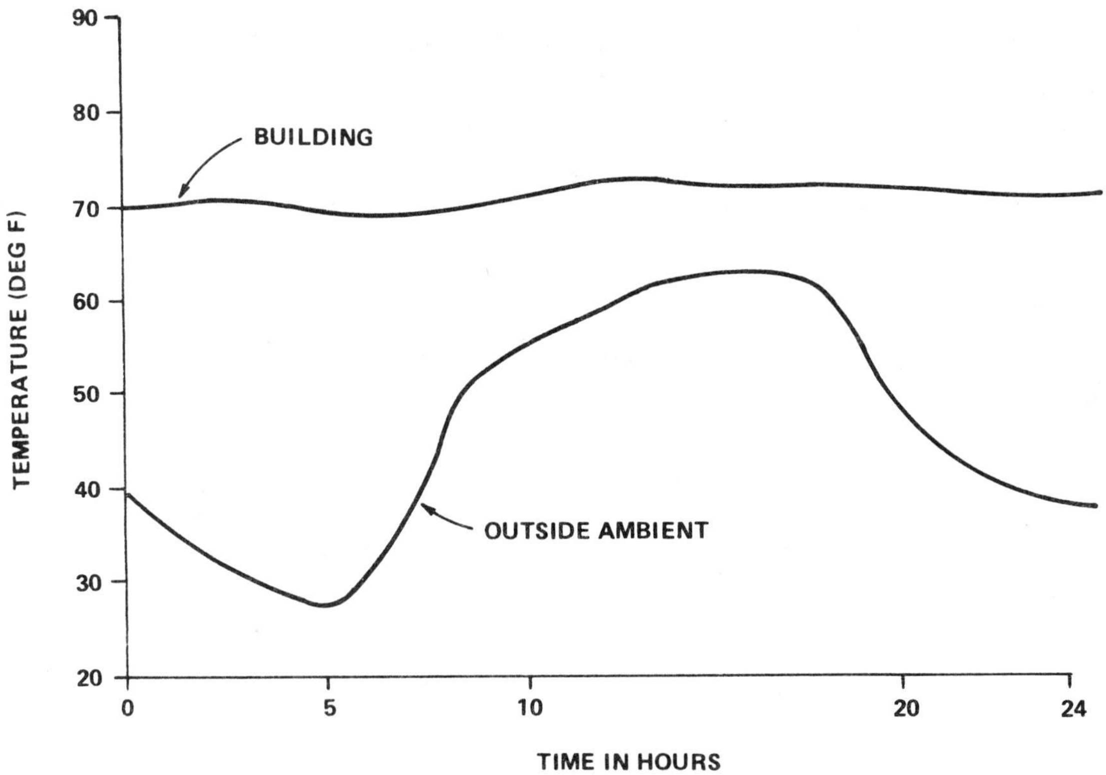

Figure 5-7. Building and Outside Ambient Temperatures - May 8, 1979

The storage masses also provided moderation of building temperatures on sunny days as illustrated by the data presented in Figure 5-8. Outside air temperature averaged 35°F for the day while almost 2,200 Btu/ft^2-day of solar energy was incident on the glazed are. Building temperature varied by only 9 degrees even with the considerable amount of solar energy available, while the average storage mass temperature increased by 6 degrees.

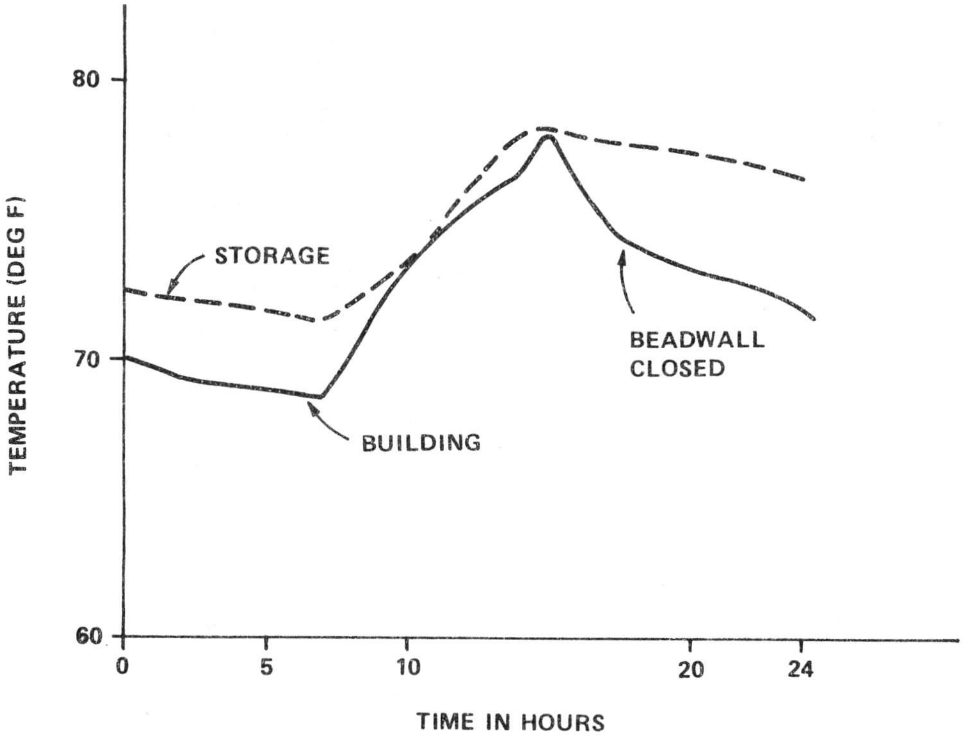

Figure 5-8. Building and Storage Temperatures - November 13, 1978

Mass for storage of collected solar energy is also present in the building walls and floors. Although this additional mass contains significant storage capacity, it has not been as dramatically effective as the mass in the water drums. However, energy stored in the walls and floor is generally available to the conditioned space during long cloudy periods. The temperature of both the wall interior surface and the floor surface is generally slightly higher than the air temperature near the surfaces, thus providing the capability to transfer energy to the conditioned space.

The use of mass to provide beneficial effects is not limited to the interior of the building. Exterior mass, in the form of earth berms around the walls and a layer of earth on the roof, provides some additional thermal insulation. However, as illustrated in Figure 5-9, another effect of the exterior mass is a reduction in the magnitude of the variations in roof external surface temperature along with a time lag in the maximum variation. This effect, which is manifested by an approximately 10 hour lag, serves to reduce the night time heating load and increase the daytime load, thus helping to provide load conditions more in phase with the available solar energy.

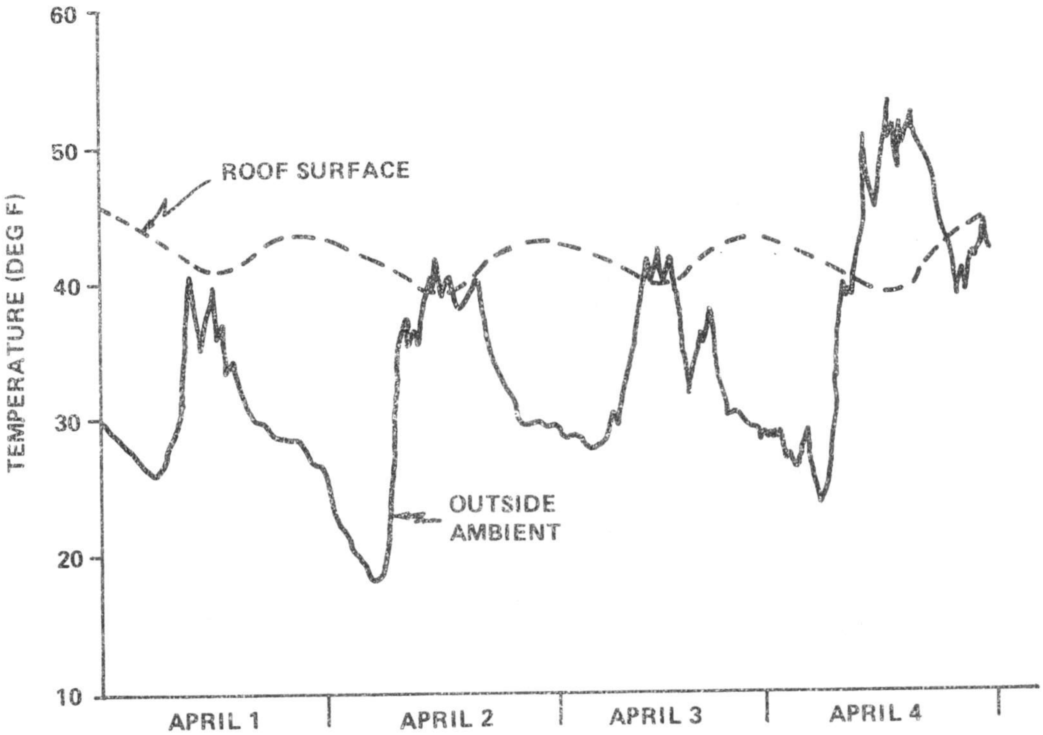

Figure 5-9. Roof Surface and Outside Ambient Temperatures

Energy savings for the heating season, as presented in Table 5-4 were substantial. Building savings were over 70,000 cubic feet of natural gas while savings compared to a conventional south wall building (comparison savings) were reduced to only 59,000 cubic feet. Savings of fossil fuel compared to a conventional south wall building where temperatures were controlled to a set point range of 68 to 72°F (comparison set point savings) were more than 51,000 cubic feet. Also presented in Table 5-4 is the estimated savings of natural gas resulting from the use of the fireplace - 2,000 cubic feet. The domestic hot water system produced savings of more than 7,000 cubic feet of gas.

TABLE 5-4

ENERGY SAVINGS

Month	Space Heating Demand (Million Btu)	Space Heating Load (Million Btu)	Fireplace Energy (Million Btu)	Fireplace Energy (Cu.Ft. Gas)	Building Energy Savings (Million Btu)	Building Energy Savings (Cu.Ft. Gas(1))	Comparison Energy Savings (Million Btu)	Comparison Energy Savings (Cu.Ft. Gas(1))	Comparison Set-Point Energy Savings (Million Btu)	Comparison Set-Point Energy Savings (Cu.Ft. Gas(1))	DHW Energy Savings (Million Btu)	DHW Energy Savings (Cu.Ft. Gas(1))	Beadwall Operating Energy (Million Btu)	Beadwall Operating Energy (kwh)
Nov 78	4.99	6.90	0.40	476	8.29	9,869	6.86	8,166	5.25	6,250	0.68	809	0.14	41
Dec 78	8.25	10.15	0.14	167	13.75	16,369	11.45	13,630	10.57	12,583	0.93	1,107	0.18	53
Jan 79	7.35	9.55	0.55	655	12.26	14,595	9.95	11,845	9.14	10,880	0.91	1,083	0.18	53
Feb 79	6.23	7.69	0.04	47	10.39	12,369	8.50	10,119	7.64	9,095	0.98	1,166	0.15	44
Mar 79	4.37	6.03	0.23	273	7.28	8,667	5.95	7,083	4.92	5,857	0.85	1,012	0.12	35
Apr 79	3.03	4.44	0.02	23	5.05	6,011	4.10	4,880	3.42	4,071	0.94	1,119	0.14	41
May 79	1.71	3.36	0.18	214	2.74	3,262	2.01	2,932	1.91	2,273	0.72	857	0.10	29
Season Total	35.93	48.12	1.56	1,855	59.76	71,142	48.82	58,655	42.85	51,009	6.01	7,153	1.01	296

(1) assumes 840 Btu per cubic foot

Operating energy for the Beadwalls, which must be charged as a burden to the system, was only 296 kwh of electricity for the entire season. If a 33 percent conversion efficiency is assumed for conversion of fossil fuel to electrical power and transmission of the power to the site, then the 296 kwh becomes an estimated 3.06 million Btu equivalent fossil energy. Considering the solar hot water fossil energy savings and the comparison savings for the space heating system, then 54.8 million Btu of fossil energy was saved at the expense of 3.06 million Btu of equivalent fossil energy. This results in a total savings of fossil resources of 18 Btu for each Btu required from the utility company.

Fossil energy was used by the space heating system in both November and May. During November, the furnace pilot light was on, thus causing a consumption of fossil fuel. However, only a very small amount of this fossil energy was actually used for space heating. This use occurred only for a few minutes as the auxiliary system was exercised in order to verify that it was operating properly. During May the furnace was used for two days, providing only 64,000 Btu to the conditioned space. The furnace was used due to a need for increased temperature levels by one of the occupants. One of the children sustained an injury, temporarily limiting the childs mobility. As a result, the furnace was used to maintain a lower bound on building temperature for the child until she could regain normal mobility and activity levels.

Comfort conditions inside the building, presented in Table 5-5 were acceptable to the occupants over the majority of the heating season. Occasionally, during long periods of cloudy weather, the building temperatures became low enough to cause slight discomfort. However, with the exception of two days during May, the occupants chose not to use the furnace. Occasional use was made of the wood-burning fireplace during afternoon and evening hours to maintain comfortable conditions. Interior relative humidity levels were within acceptable limits for the occupants over the entire heating season. Interior relative humidity seldom exceeded 50 percent.

TABLE 5-5

BUILDING COMFORT LEVELS

Month	Building Temperature (°F)			Zone 1 Comfort Index (°F)			Zone 2 Comfort Index (°F)			Storage Temperature (°F)			Interior Relative Humidity (Percent)
	Average	Average Daily Minimum	Average Daily Maximum	Average	Average Daily Minimum	Average Daily Maximum	Average	Average Daily Minimum	Average Daily Maximum	Average	Average Daily Minimum	Average Daily Maximum	
Nov 78	73	70.5	75.8	74	72.1	77.0	72	70.3	73.9	77.0	74.9	79.2	34
Dec 78	71	67.9	73.9	72	69.7	75.2	70	67.8	71.8	75.1	73.1	77.6	41
Jan 79	66	62.4	68.8	67	64.1	70.0	65	62.5	66.7	69.8	67.5	72.2	39
Feb 79	71	67.9	73.8	73	70.3	75.6	69	67.5	71.3	75.6	73.6	77.7	44
Mar 79	70	67.7	72.5	72	69.5	73.8	69	67.4	70.5	73.6	71.8	75.4	50
Apr 79	70	68.3	72.4	72	69.7	73.2	69	68.0	70.5	72.8	71.6	74.0	48
May 79	70	68.1	71.7	70	68.7	71.6	69	68.2	70.7	70.7	69.8	71.6	48

The comfort index used in this analysis is the operative temperature, which is defined as the average of the space dry bulb and mean radiant temperatures. For this analysis, the space mean radiant temperature is defined as the average surface temperature of all radiating surfaces bordering the space, except the fireplace, since a surface temperature measurement of the hearth area is not available. The building is divided into two comfort zones. Zone 1 is the south part of the building, while Zone 2 is the north part of the building. While relative humidity does play an important part in the perception of comfort, it is not presently included in the comfort index.

Differences in the comfort index value between the two building zones were generally quite small, (Figure 5-10) averaging 2 to 3 degrees F over each month. This low difference is due to the capability of the system to effectively transfer collected solar energy from the south side of the building to the rooms on the north side. As illustrated in Figure 5-10 comfort levels in both zones of the building were near 70°F in all months except January, when the very severe weather conditions encountered caused the substantial reductions in the comfort index values.

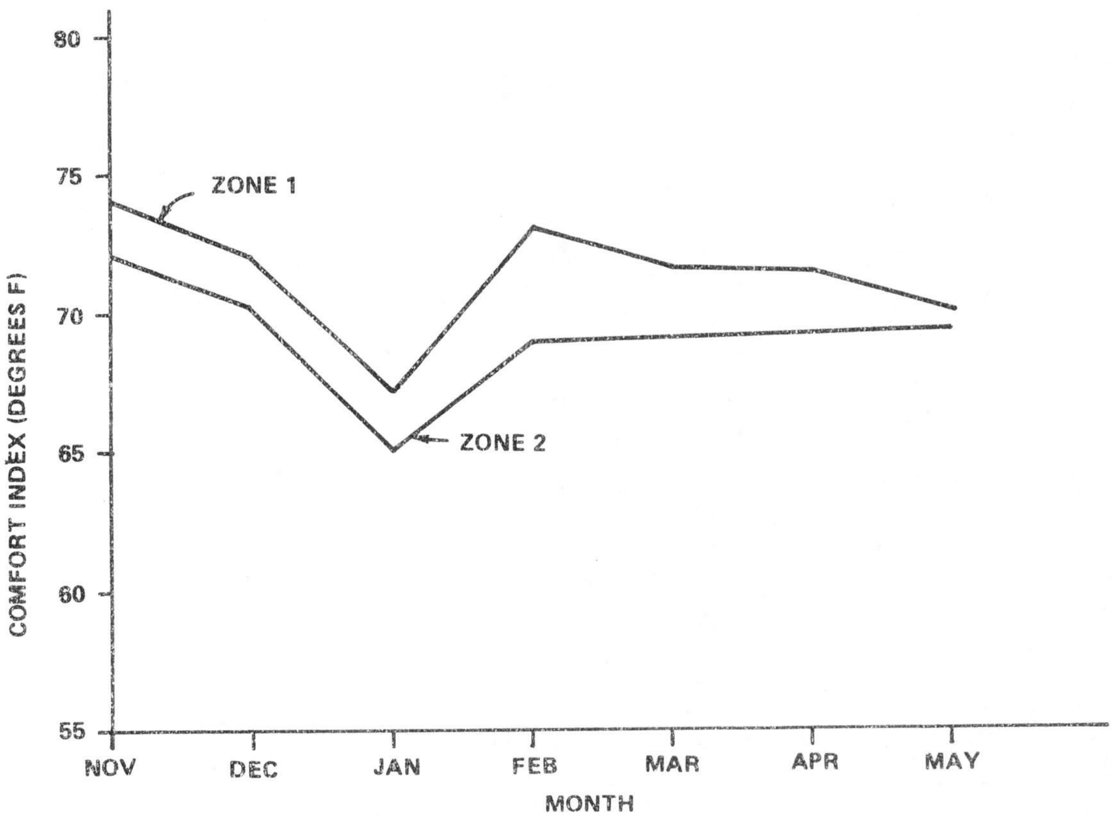

Figure 5-10. Average Comfort Index

Daily variations in comfort conditions presented for zone 1 (Figure 5-11) and zone 2 (Figure 5-12) were within acceptable limits. The average change of 5°F shown for zone 1 is slightly higher than the average variation seen in zone 2. The larger variation in zone 1 is due to the proximity of the zone 1 areas to both the solar gains and higher losses of the glazing system.

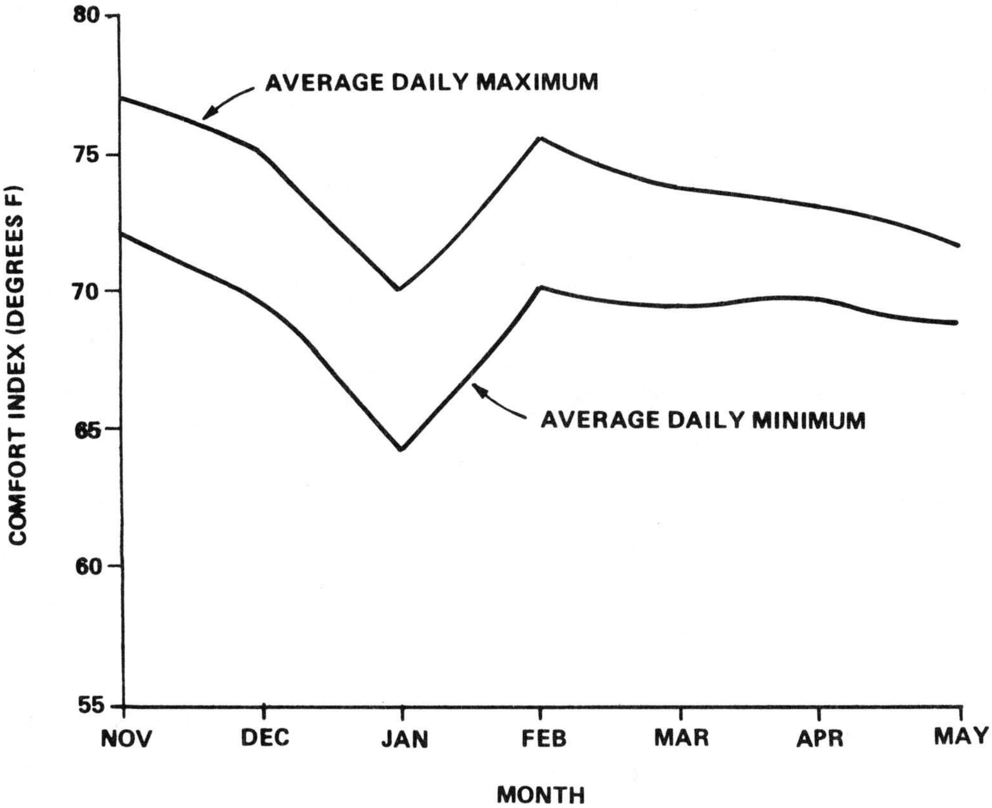

Figure 5-11. Zone 1 Minimum and Maximum Comfort Index

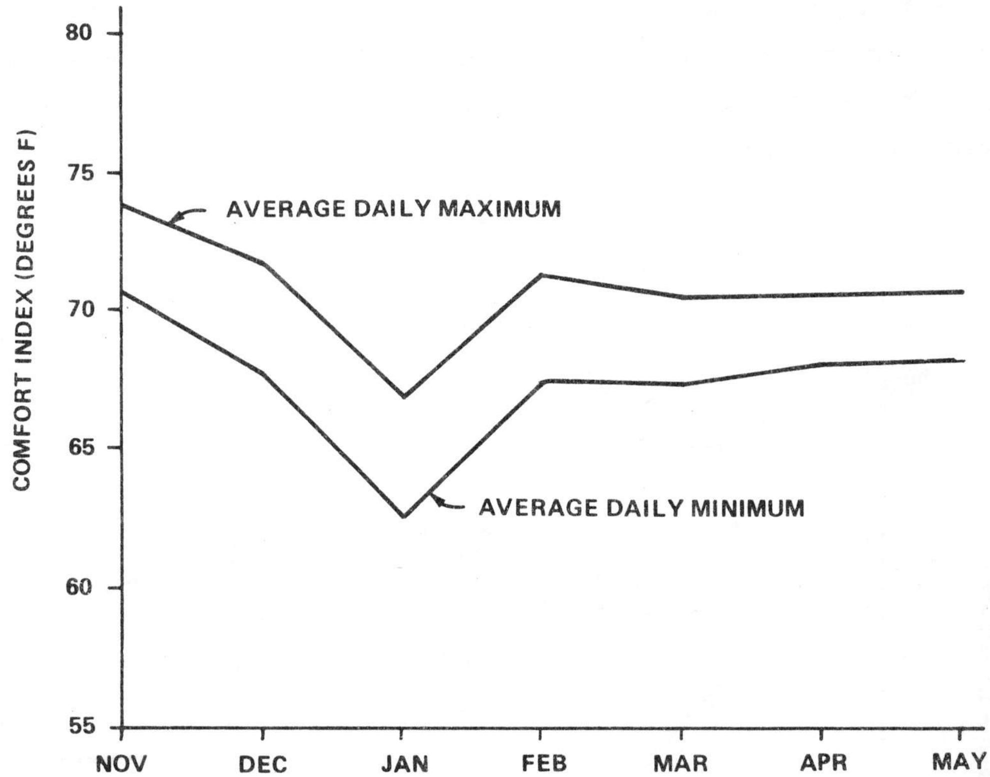

Figure 5-12. Zone 2 Minimum and Maximum Comfort Index

Two comfort related problems were encountered during the heating season. The first is the temperature level in the northwest room. This room is generally 2 or 3 degrees cooler than the room on the northeast corner of the building, even though it is partially sheltered from outside conditions by the garage area. The temperature difference between the two rooms appears to have been caused by the lack of earth berming on part of the north outside wall of the northeast corner room. The effect of the earth berm on the outside of the northeast room has been to moderate the severity of the temperature conditions at the wall insulation layer, thus producing less variation of temperatures and warmer conditions inside the northeast room.

The second problem is that of large temperature variations in the southwest bedroom. This bedroom is typically the warmest room in the house during late afternoon on a sunny day and frequently is the coolest room in the building shortly before sunrise. The cause of this variation is a west-facing window in the southwest bedroom (Figure 5-13). As illustrated by the plot

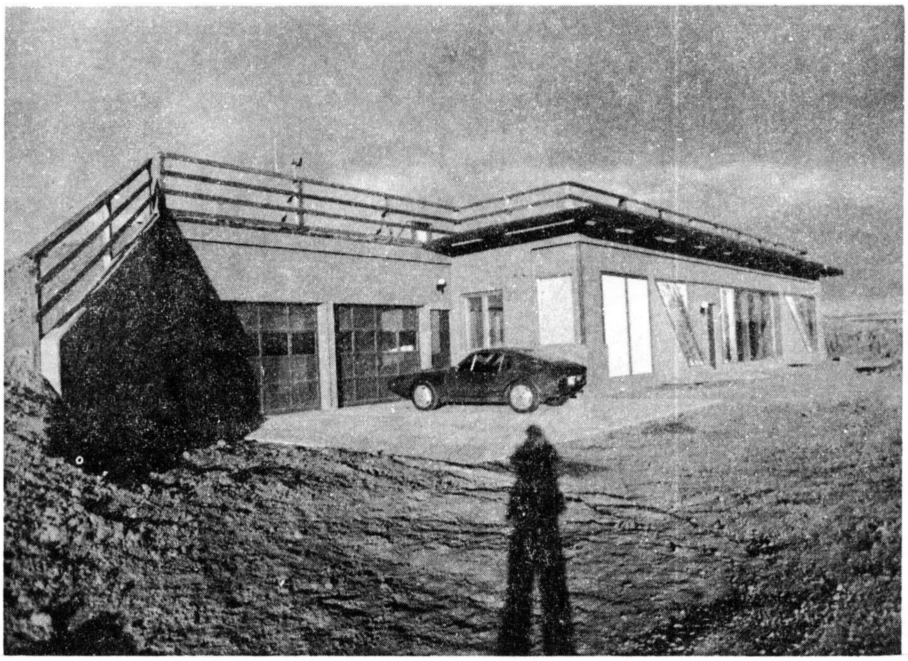

Figure 5-13. Southwest View

of temperatures in the two west rooms presented in Figure 5-14, the southwest room is cooler at night and warmer during the late afternoon. Energy is lost through the west window at night causing the cooler early morning temperatures.

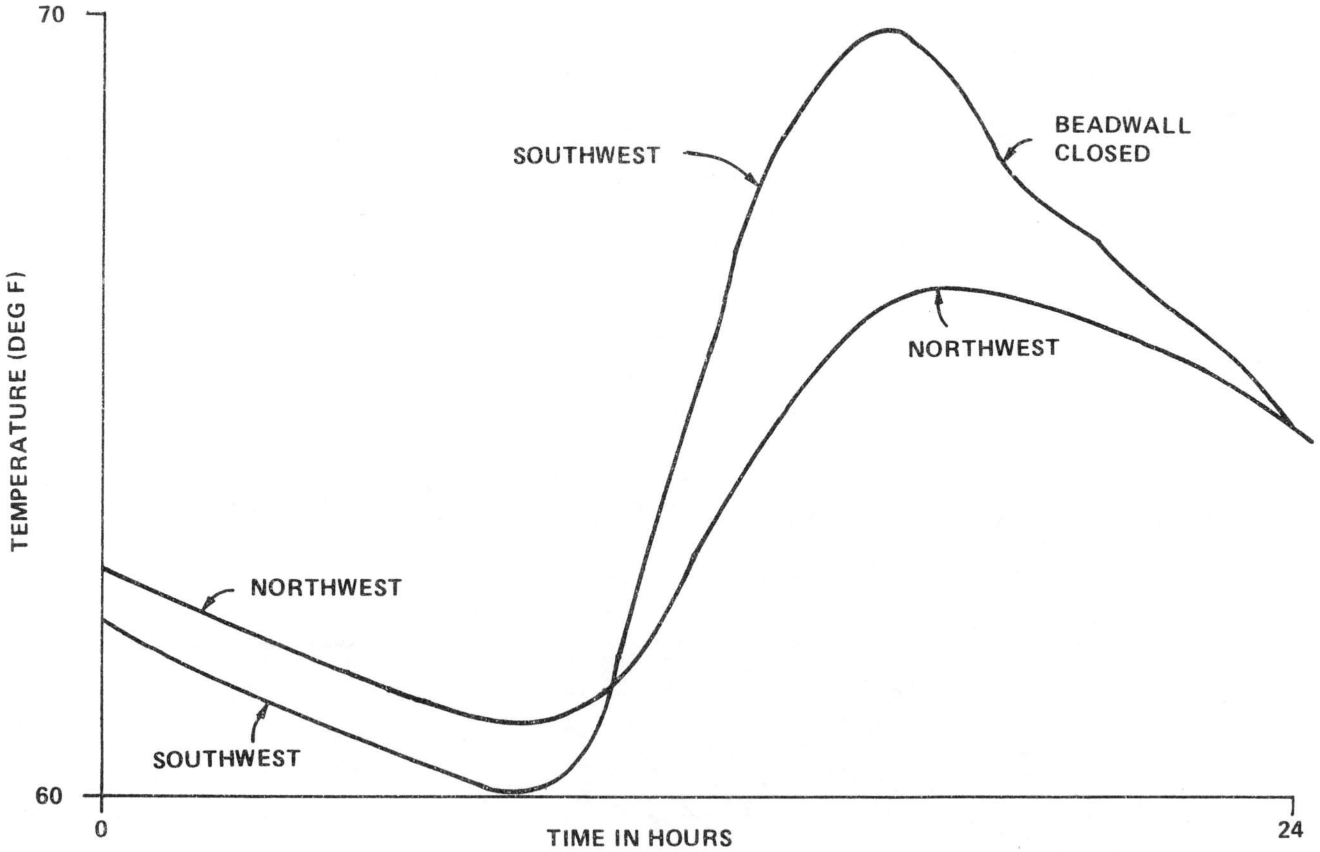

Figure 5-14. West Room Temperatures - January 30, 1979

Additional solar energy collection occurs through the window in the afternoon causing the warmer afternoon temperatures. Contrasting with the effect of the west-facing window is the data presented for the two east rooms in Figure 5-15. East-facing glazed area does exist in the southeast room (master bedroom). However, since the building is cooler in the morning hours when sunlight is incident on east facing glazing, then energy collection through the east glass is not as apparent. Higher night time losses in the master bedroom are not apparent since less non-south facing glazed area in porportion to the room size is contained in the master bedroom than in the southwest room.

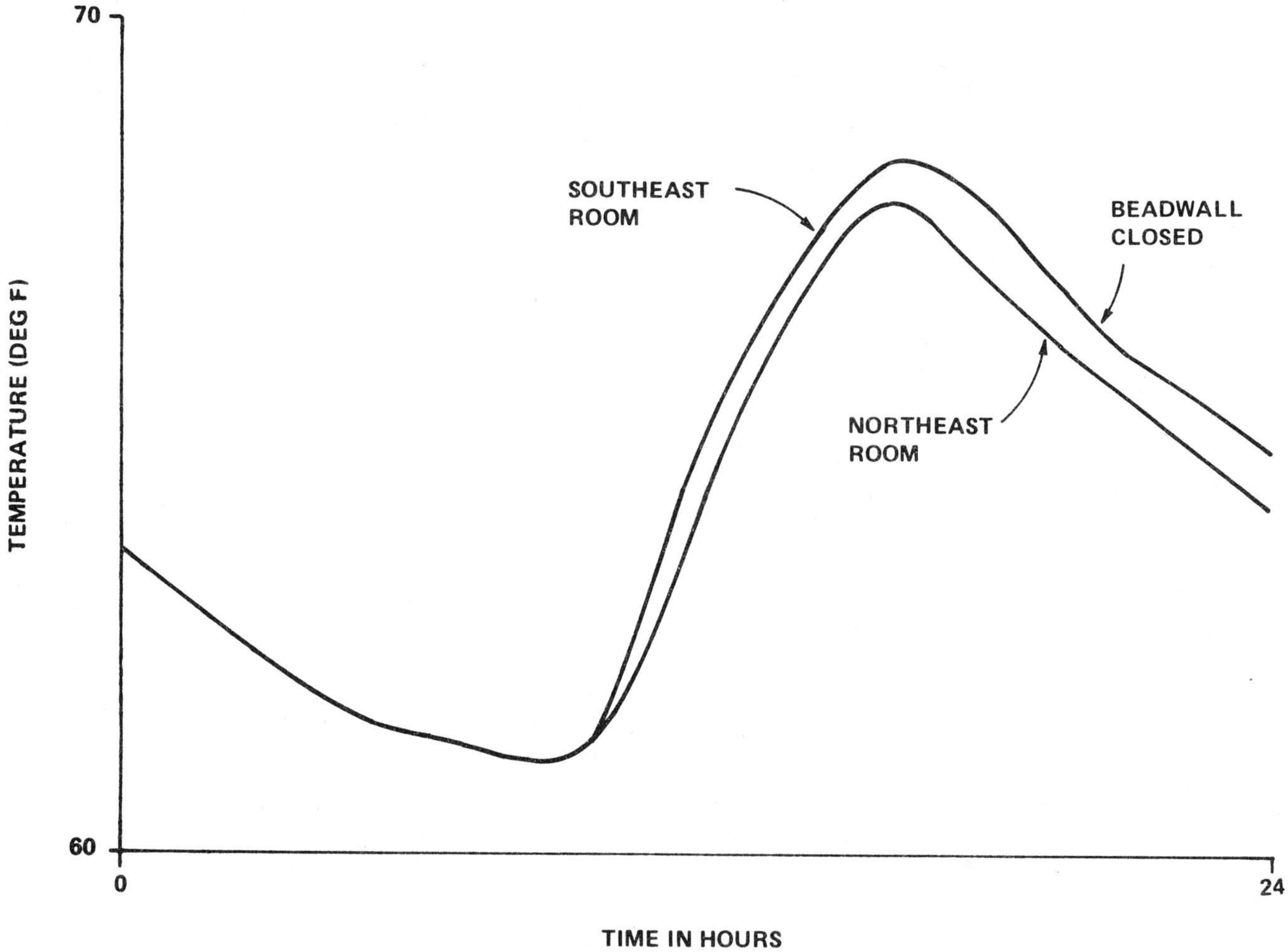

Figure 5-15. East Room Temperatures - January 30, 1979

One of the reasons that the performance of the Colorado Sunworks passive space heating system has been successful is the degree of awareness of system operation demonstrated by the owners. Performance improvements in the domestic hot water system have been obtained by the owners simply by appropriate planning of the use of hot water. Large uses of hot water frequently occur in the afternoon on sunny days allowing maximum utilization of the energy stored in the preheat tanks. Space heating energy savings have been increased by the owners' willingness to tolerate slightly cool temperatures during early morning hours. Although not necessary for satisfactory performance, this reluctance to use the auxiliary system has led to additional energy savings. During the sequences of cold, cloudy days encountered, the occupants were willing to accept slightly cool temperatures. Again, this was not necessary for satisfactory performance, but does identify ways in which the occupants can increase the savings realized.

6. REFERENCES

1. "The Sunearth Home," Paul Shippee, Proceedings of the Second National Passive Solar Conference, March 16-18, 1978, Philadelphia, Pennsylvania.

2. "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program," NBSIR-76-1137, Washington: National Bureau of Standards, August 1976.

3. "Performance Evaluation Reporting for Passive Systems," April 17, 1979, SOLAR/0018-79/35.*

4. U. S. Department of Energy, "National Solar Data Network," prepared under Contract Number EG-77-C-01-4040, by IBM Corporation, December 1977.*

5. A Thermal Performance Analysis Technique for Passive Solar Space Heating Systems," proceedings of the Third National Passive Solar Conference, January 11-13, 1979, San Jose, California.

6. "Monthly Performance Report, Colorado Sunworks," November 1978, SOLAR/1051-78/11.*

7. "Monthly Performance Report, Colorado Sunworks," December 1978, SOLAR/1051-78/12.*

8. "Monthly Performance Report, Colorado Sunworks," January 1979, SOLAR/1051-79/01.*

9. "Monthly Performance Report, Colorado Sunworks," February 1979, SOLAR/1051-79/02.*

10. "Monthly Performance Report, Colorado Sunworks," March 1979, SOLAR/1051-79/03.*

11. "Monthly Performance Report, Colorado Sunworks," April 1979, SOLAR/1051-79/04.*

12. "Monthly Performance Report, Colorado Sunworks," May 1979, SOLAR/1051-79/05.*

13. "User's Guide to the Monthly Performance Report of the National Solar Solar Data Program," February 28, 1978, SOLAR/0004-78/18.*

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* Copies of these reports may be obtained from Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

This section contains the definitions of performance factors used in the Colorado Sunworks monthly reports (References [6] - [12]). These performance factors used to described the thermal performance of solar energy systems are described in Reference [13].

SITE SUMMARY

The overall system performance is characterized by monthly summations and averages of appropriate daily and hourly performance factors.

- INCIDENT SOLAR ENERGY (SE) is the total insolation available on the gross collector array area. This is the area of the collector energy-receiving aperture, including the framework which is an integral part of the collector structure.

- COLLECTED SOLAR ENERGY (SEC) is the thermal energy removed from the collector array by the heat transfer medium.

- AVERAGE AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- AVERAGE BUILDING TEMPERATURE (TB) is the average temperature in the controlled space of the building which the system serves.

- ECSS SOLAR CONVERSION EFFICIENCY (CSCEF) is the ratio of the solar energy delivered to the load subsystems to the total energy incident on the collector array.

- ECSS OPERATING ENERGY (CSOPE) is the electrical operating energy required to support the ECSS heat transfer loops.

- TOTAL ENERGY CONSUMED (TECSM) is the sum of the collected solar energy, the total system operating energy, the total fossil fuel energy, and the total electrical fuel energy. This performance factor represents the total energy demands of the system from all outside sources.

- SYSTEM PERFORMANCE FACTOR (SYSPF) is the ratio of the total system load to the equivalent fossil energy required to support the system for the month. The equivalent energy, as used in this context, is the sum of the actual fossil fuel and (1/.3) times the electrical requirements (for operating energy and fuel). This multiplication factor results from the estimation that, on the average, the efficiency of extracting fossil fuels from the ground. converting to electricity, and transmitting the electrical energy to the site is about 0.3.

- LOAD is the amount of energy required for the month for each of the respective subsystems.

- SOLAR FRACTION is the percentage of the load demand during the month for each subsystem which was supported by solar energy.

- SOLAR ENERGY USED is the total amount of solar energy supplied each subsystem for the month.

- AUXILIARY THERMAL USED is the amount of energy supplied, during the month, to the major components of each subsystem in the form of thermal energy in a heat transfer medium. This term also includes the converted electrical fuel energy supplied to the subsystem.

- AUXILIARY FOSSIL FUEL is the total amount of fossil energy supplied directly to each subsystem during the month.

- FOSSIL SAVINGS is the estimated difference between the fossil energy requirements of an alternative conventional system (carrying the full load) and the actual fossil energy required by each subsystem.

- ELECTRICAL SAVINGS is the savings/penality arising from the use of electrical energy in support of the solar energy systems.

COLLECTOR ARRAY PERFORMANCE

In addition to parameters previously presented on the summary page as monthly values, the operational incident solar energy is also presented.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the total amount of solar radiation incident on the south facing glazed areas when the beadwall is open.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow into and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of auxiliary fossil fuel, and electrical auxiliary thermal energy, and the operating energy for the subsystem. In addition, the solar energy supplied to the subsystem, along with solar fraction, is tabulated. The load of the subsystem is tabulated and used to compute the estimated electrical and fossil fuel savings of the subsystem. The load of the subsystem is further identified by tabulating the supply water temperature, and the total hot water consumption.

- HOT WATER LOAD (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.

- SOLAR FRACTION OF LOAD (HWSFR) is the percentage of the load demand which is supported by solar energy.

- SOLAR ENERGY USED (HWSE) is the amount of solar energy supplied to the hot water subsystem.

- <u>AUXILIARY THERMAL USED</u> (HWAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- <u>AUXILIARY FOSSIL FUEL</u> (HWAF) is the amount of fossil energy supplied directly to the subsystem.

- <u>FOSSIL ENERGY SAVINGS</u> (HWSVF) is the estimated difference between the fossil energy requirements of an alternative conventional system (carrying the full load) and the actual fossil energy required by the subsystem.

- <u>SUPPLY WATER TEMPERATURE</u> (TSW) is the average inlet temperature of the water supplied to the subsystem.

- <u>AVERAGE HOT WATER TEMPERATURE</u> (THW) is the average temperature of the outlet water as it is supplied from the subsystem to the load.

- <u>HOT WATER USED</u> (HWCSM) is the volume of water used.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by an accounting of the energy flow into and from the subsystem. In addition, the savings in energy attributable to the use of solar energy are presented.

- <u>SPACE HEATING LOAD</u> (HL) is the energy demand on the space heating subsystem, generally less than the building heating load.

- <u>SOLAR FRACTION OF LOAD</u> (HSFR) is the percentage of the space heating demand satisfied by solar energy.

- SOLAR ENERGY USED (HSE) is the amount of solar energy used by the space heating subsystem.

- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY FOSSIL FUEL (HAF) is the amount of fossil energy supplied directly to the subsystem.

- FOSSIL ENERGY SAVINGS (HSVF) is the estimated difference between the fossil energy requirements of an alternative conventional system (carrying the full load) and the actual fossil energy required by the subsystem.

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the program. It is tabulated in this data report for two purposes -- as a measure of the conditions prevalent during the operation of the system at the site, and as an historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is accumulated total solar energy incident upon the gross collector array measured at the site.

- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.

- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.

- WIND SPEED (WIND) is the average wind speed measured at the site.

- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

- RELATIVE HUMIDITY (RELH) is the average outside relative humidity.

PASSIVE SPACE HEATING

In addition to the characterization of the space heating subsystem previously mentioned, several other parameters are reported for passive space heating systems.

- CHANGE IN STORED ENERGY (STECH) is the change in energy level of all components of the solar energy storage mass.

- DIRECT SOLAR UTILIZATION EFFICIENCY (CSCEF) is the ratio of the solar energy used to the incident solar energy.

PASSIVE SYSTEM ENVIRONMENT

In addition to the environmental summary performance factors presented earlier, additional performance factors describing the interior environment of a passive space heating system are presented.

- BUILDING COMFORT ZONE 1 (COM1) is an index relating to the comfort conditions on the south side of the building. The index is formed as an average of the average dry bulb and mean radiant temperatures inside the zone.

- BUILDING COMFORT ZONE 2 (COM2) is an index relating to the comfort conditions on the north side of the building and is defined similar to the other comfort index.

- BUILDING TEMPERATURE MIDNIGHT (TMID) is the average building interior temperature at midnight local solar time.

- BUILDING TEMPERATURE 6 A.M. (T6AM) is the average building interior temperature at 6 a.m. local solar time.

- BUILDING TEMPERATURE NOON (TNOON) is the average building interior temperature at local solar noon.

- BUILDING TEMPERATURE 6 P.M. (T6PM) is the average building interior temperature at 6 p.m. local solar time.

- INTERIOR RELATIVE HUMIDITY (RELHIN) is the average relative humidity inside the building.

- AVERAGE STORAGE TEMPERATURE (TST) is the mass weighted average temperature of all solar storage masses.

APPENDIX B
SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR COLORADO SUNWORKS

INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by,

$$\text{SOLAR ENERGY AVAILABLE} = (1/60) \times \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

Where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by,

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [\text{W100} \times \text{CP} \times \text{RHO} \times (\text{T150} - \text{T100})] \times \Delta\tau$$

Where W100 is the flow rate of the heat transfer fluid in gal/min, CP and RHO are the specific heat and density, and T100 and T150 are the temperatures of the fluid before and after passing through the heat exchanging component. Frequently this temperature difference is referred to as simply TD100. The product W100 x RHO is often combined and represented as M100.

For electrical power, a general example is,

$$\text{ECSS OPERATING ENERGY} = (3{,}413/60) \times \Sigma\ [\text{EP100}] \times \Delta\tau$$

Where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and 3,413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [2]. This document was prepared by an interagency committee of the Government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of operation of systems. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

All energies are expressed in Btu's, while temperatures are expressed as degrees Fahrenheit. Efficiencies are expressed as dimentionless ratios.

Location and definition of the measurements used is contained in Table 4-1 of Section 4.

EQUATIONS USED IN MONTHLY REPORT

HOT WATER SYSTEM MASS FLOW RATE

$$M300 = RHO(T300)*(W300-W300p)/\Delta\tau$$

MASS WEIGHTED COLD WATER TEMPERATURE

$$TSW1 = \Sigma M300*T300*\Delta\tau$$

MASS WEIGHTED HOT WATER TEMPERATURE

$$THW1 = \Sigma M300*T305*\Delta\tau$$

DHW PREHEAT TANK TEMPERATURE

$$STHW = (1/120)*\Sigma(T302 + T303)*\Delta\tau$$

TOTAL HOT WATER CONSUMED

$$HWCSM = \Sigma WD300*\Delta\tau$$

HOT WATER LOAD

$$HWL = \Sigma M300*HWD(T305,T300)*\Delta\tau$$

HOT WATER SOLAR ENERGY

$$HWSE = \Sigma M300*HWD(T301,T300)*\Delta\tau$$

AVERAGE AMBIENT TEMPERATURE

$$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$$

DAYTIME AVERAGE AMBIENT TEMPERATURE

$$TDA = (1/360) \times \Sigma\ T001 \times \Delta\tau$$

For $\pm$ THREE HOURS FROM SOLAR NOON

AVERAGE BUILDING TEMPERATURE

$$TB = (1/540) \times \Sigma\ (T618 + T619 + T620 + T621 + T622 + T651 + T652 + T653 + T654) \times \Delta\tau$$

TIME OF DAY BUILDING TEMPERATURES (ONCE PER DAY)

TMID = TB

AT 12 HOURS FROM LOCAL SOLAR NOON

T6AM = TB

AT 6 HOURS BEFORE LOCAL SOLAR NOON

TNOON = TB

AT LOCAL SOLAR NOON

T6PM = TB

AT 6 HOURS PAST LOCAL SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT

$$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$$

OPERATIONAL INCIDENT SOLAR ENERGY

$$SEOP = (1/60) * \Sigma\ I001 * [B3AREA * (1-D100) + DHWAREA * (1-D101) + HWAREA * (1-D102) + ATAREA * (1-D103) + LRAREA * (1-D104) + MBAREA * (1-D105)] * \Delta\tau$$

AVERAGE DRUM STORAGE TEMPERATURE

$$TST = (1/960) * \Sigma\ (T200 + T201 + T202 + T203 + T204 + T205 + T206 + T207 + T208 + T209 + T210 + T211 + T212 + T213 + T214 + T215) * \Delta\tau$$

EXTERIOR WALL AVERAGE STORAGE TEMPERATURE

$$TSTWALL = (1/120) * \Sigma\ (T609 + T612) * \Delta\tau$$

CONCRETE FLOOR AVERAGE STORAGE TEMPERATURE

$$TSTFLOOR = (1/180) * \Sigma\ (T604 + T605 + T608) * \Delta\tau$$

ECSS OPERATING ENERGY (BEADWALL)

$$CSOPE = (3,413/60) * \Sigma\ EP100 * \Delta\tau$$

EAST SIDE HEAT LOSS

$$HTE = (1/60) \times \Sigma\ (EAREA \times UWALL + EGLASS \times UGLASS) \times [(T160 + T613)/2 - (T614 + T611)/2] \times \Delta\tau$$

WEST SIDE HEAT LOSS

$$HTW = (1/60) \times \Sigma\ [(WAREA \times UWALL + WGLASS \times UGLASS) \times [(T610 + T613)/2 - (T614 + T611)/2] + GARAREA \times UGARAGE \times (T619 - T617)] \times \Delta\tau$$

NORTH SIDE HEAT LOSS

$$HTN = (1/60) \times \Sigma\ [NAREA \times UWALL \times [(T610 + T613)/2 - (T614 + T611)/2] + NGLASS \times UGLASS \times (T620 - T001)/60] \times \Delta\tau$$

SOUTH SIDE HEAT LOSS

$$HTS = (1/60) \times \Sigma\ [B3AREA \times (UGLASS \times (1-D100) + D100 \times UBEAD) + DHWAREA \times (UGLASS \times (1-D101) + D101 \times WBEAD) + HWAREA \times (UGLASS \times (1-D102) + D102 \times UBEAD) + ATAREA \times (UGLASS \times (1-D103) + D103 \times UBEAD) + LRAREA \times (UGLASS \times (1-D104) + D104 \times UBEAD) + MBAREA \times (UGLASS \times (1-D105) + D105 \times UBEAD) + SAREA \times UWALL] \times [(T400 + T401 + T402 + T403 + T404 + T405)/6 - T001] \times \Delta\tau$$

FLOOR HEAT LOSS

$$HTFL = (1/60) \times \Sigma\ FLAREA \times UFLOOR \times [(T601 + T605)/2 - (T602 + T606)/2] \times \Delta\tau$$

ROOF HEAT LOSS

$$HTRF = (1/60) \times \Sigma\ RFAREA \times UROOF \times (T615 - T616) \times \Delta\tau$$

INFILTRATION HEAT LOSS

$$NCHANGE = (1/60) \times \Sigma\ (K1 + K2 \times (TB - T001) + K3 \times V001) \times \Delta\tau$$

IN AIR CHANGES PER HOUR

$$HINF = NCHANGE \times VOLUME \times [H(TB) - H(TA)] \times RHO$$

IN BTU WHERE H IS AIR ENTHALPY FUNCTION AND RHO IS AIR DENSITY

INTERIOR RELATIVE HUMIDITY

$$RHIN = (1/60) \times \Sigma\ RH600 \times \Delta\tau$$

FIREPLACE ENERGY

$$HFIRE = (1/60) \times \Sigma\ FIRERATE \times \Delta\tau$$

IF FIREPLACE IS IN USE

AUXILIARY HEATING SYSTEM OPERATING ENERGY

$$HOPE = (3{,}413/60) \times \Sigma\ EP401 \times \Delta\tau$$

OTHER INTERNAL ENERGY GENERATED

$$HINT = [(3{,}413/60) \times \Sigma\ EP600 \times \Delta\tau] - HOPE - CSOPE$$

$$HINT = HINT - 3 \times 3{,}413/60$$

IF EP600 - EP100 < 3 (REMOVE CLOTHES DRYER)

OUTSIDE RELATIVE HUMIDITY

$$RELH = (1/60) \times \Sigma\ RH001 \times \Delta\tau$$

WIND DIRECTION AND SPEED

$$WNS = (1/60) \times \Sigma\ V001 \times COSINE\ (D001) \times \Delta\tau$$

$$WEW = (1/60) \times \Sigma\ V001 \times SINE\ (D001) \times \Delta\tau$$

$$WDIR = INVERSE\ TANGENT\ (WEW/WNS)$$

$$WIND = (1/60) \times \Sigma\ V001 \times \Delta\tau$$

DRUM WALL INSIDE SURFACE TEMPERATURE

$$WALLSURF = (1/9) \times (T200 + T202 + T204 + T205 + T206 + T207 + T208 + T209 + T214)$$

ZONE 1 COMFORT INDEX

$$COM1 = (1/120) \times \Sigma\ [WALLSURF + (1/8) \times (T618 + T622 + T650 + T651 + T620 + T621 + T653 + T654)] \times \Delta\tau$$

ZONE 2 COMFORT INDEX

$$COM2 = (1/120) \times \Sigma\ (T619 + T652) \times \Delta\tau$$

COLD WATER TEMPERATURE

$$TSW = TSW1\ [\Sigma\ M300 \times \Delta\tau]$$

HOT WATER TEMPERATURE

$THW = THW1 / [\Sigma\ M300 \times \Delta\tau]$

TOTAL SOLAR ENERGY AVAILABLE

$SEA = SE \times CLAREA$

PRIMARY STORAGE ENERGY CHANGE

$STECH = STOCAP \times [RHO\ (TST) \times CP\ (TST) - RHO\ (TST_p) \times CP\ (TST_p)] + 70$

$\times [RHO\ (STHW) \times CP\ (STHW) - RHO\ (STHW_p) \times CP\ (STHW_p)]$

WHERE THE SUBSCRIPT $_p$ INDICATES A PAST VALUE

HOT WATER AUXILIARY FOSSIL ENERGY

$HWAF = FOONST \times (F300 - F300_p)$

HOT WATER AUXILIARY THERMAL ENERGY

$HWAT = 0.6 \times HWAF$

HOT WATER FOSSIL ENERGY SAVINGS

$HWSVF = HWSE/0.6$

HOT WATER SOLAR FRACTION

$HWKRAUX = TANKE \times (1 - HWSFR_p /100) + HWAT$

$HWTKSE = TANKE \times HWSFR_p /100 + HWSE$

$HWSFR = 100 \times HWTKSE / (HWTKSE + HWTKAUX)$

HEATING AUXILIARY FOSSIL ENERGY

$HAF = FCONST \times (F403 - F403_p)$

HEATING AUXILIARY THERMAL ENERGY

$HAT = 0.6 \times HAF$

CHANGE IN NON-SOLAR BUILDING ENERGY LEVEL

$HSTECH = TMASS \times (TB - TB_p)$

BUILDING HEATING LOAD

$BHL = HTN + HTS + HTE + HTW + HTFL + HTRF + HINF$

HEATING SUBSYSTEM DEMAND

HL = BHL - HINT + HSTECH - HFIRE

HEATING SOLAR ENERGY USED

HSE = HL - HAT

HEATING SOLAR FRACTION

HSFR = 100 x HSE/HL

SOLAR ENERGY COLLECTED - TOTAL AND PER UNIT AREA

SECA = HSE + STECH + HWSE

SEC = SECA/CLAREA

HEATING FOSSIL ENERGY SAVINGS

HSVF + HSE/0.6

COMPARISON BUILDING FOSSIL ENERGY SAVINGS

DELE = HTS - (1/60) x Σ [(B3AREA + DHWAREA + HWAREA + ATAREA + LRAREA + MBAREA) x UWALL x (T400 + T401 + T402 + T403 + T404 + T405) /6 - T001] x $\Delta\tau$

COMHSVF = (HSE - DELE) /0.6

COMPARISON BUILDING SET POINT ENERGY SAVINGS

UACOMP = (HL + HFIRE - DELE + HINT) / (TB-TA)

OVER = UA x (TB - 70)

IF TB IS GREATER THAN 70

UNDER = UA x (68 - TB)

FIRE = MINIMUM OF HFIRE AND OVER

SETHSVF = EQHSVF - UNDER - (OVER-FIRE)

SYSTEM LOAD

SYSL = HWL + HL

SYSTEM SOLAR FRACTION

SFR = (HWSFR x HWL + HSFR x HL) /SYSL

SOLAR ENERGY TO LOADS

SEL = HSE + HWSE

SYSTEM OPERATING ENERGY

SYSOPE = HOPE + CSOPE

SYSTEM AUXILIARY THERMAL ENERGY

AXT = HWAT + HAT

SYSTEM AUXILIARY FOSSIL ENERGY

AXF = HWAF + HAF

TOTAL SYSTEM ELECTRIC ENERGY SAVINGS

TSVE = - CSOPE

TOTAL SYSTEM FOSSIL ENERGY SAVINGS

TSVF = HWSVF + HSVF

TOTAL ENERGY CONSUMED

TECSM = SYSOPE + AXF + SEL

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