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Passive Solar Buildings

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PASSIVE SOLAR BUILDINGS

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Abstract

The description, successful operation, and performance estimate for each of 15 passive solar heated buildings are given. Technical evaluation methods and general economic factors are also considered.

ACKNOWLEDGMENT

This report is the result of a cooperative effort among several organizations and people. A major contribution to the report came from the Los Alamos Laboratories. Dr. J. Douglas Balcomb helped choose buildings for the report, and his group supplied original test data on buildings they monitored, as well as the recent papers on various passive solar subjects reproduced in the appendix. A consultant to Los Alamos Laboratories, Mr. Benjamin T. Rogers, supplied the performance estimate for each building.

Mr. Ed Mazria supplied the paper in the appendix which describes the sizing procedures for use in the preliminary design of a building.

A large number of owners and designers of the homes included in this report supplied information, allowed many photographs, and answered many questions in order to describe the buildings in the detail included in this report.

Special thanks are owed to Mrs. Balcomb, Dr. and Mrs. Ralph Williamson, Dr. T. J. Shankland and Mr. Gerrit Zwart, Mr. and Mrs. Bernardo Chavez, Mr. Mark Jones, Mr. James Kachadorian and Dr. A. O. Converse, Dr. D. C. Taff, Mr. Doug Kelbaugh, Mr. Scott Keller and Mr. Bruce Keller, Mr. Tim Maloney, and Dr. Dave Gunderson for their courtesy and cooperation.

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Dale Haskins
Robert P. Stromberg
Sandia Laboratories Solar Technical
Liaison Division

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SECTION 1

INTRODUCTION

"Passive solar heating and cooling" is a new name for an ancient craft. Socrates (circa 400 B.C.) described a passive solar heating and cooling technique: "Now in houses with a south aspect, the sun's rays penetrate into the porticos in winter, but in summer the path of the sun is right over our heads and above the roof, so that there is shade. If, then, this is the best arrangement, we should build the south side loftier to get the winter sun and the north side lower to keep out the cold winds."* American Indians used passive solar techniques as long ago as A.D. 1100 in the construction of dwellings in Chaco Canyon and Mesa Verde. These skills have long been neglected, and the design of modern buildings relies on cheap fossil fuels for heating and cooling. The sharply rising costs of fossil fuels make solar systems once again a desirable option. The art and science of passive solar building design has been rediscovered and is being rapidly developed.

Critics of solar energy have scoffed, saying that any building can be 100 percent solar heated if the occupants will agree to live in the cold. But it is hard to scoff at success. This report documents a selection of successful passive solar heating systems which not only derive the major part of their heating energy from the sun, but also provide a comfortable environment. As the price of heating fuels and electricity continues to escalate, add-on systems which can supply heat and reduce fuel bills for existing structure become more

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*Xenophon, <u>Memorabilia Socratis</u>

attractive. The greenhouse designs included in this report are in this category. Passive solar heating is not restricted to residential buildings; it can also be applied to commercial buildings. Several of these applications have been included.

Design Procedure

The buildings and solar systems described here illustrate the basic ideas and concepts of passive solar systems. Translating these ideas and concepts into firm plans for a new building is a difficult task. Designing a building with the single-minded purpose of saving energy is a mistake: the function of the building must take precedence; the solar system should complement the building and not dominate it. Since passive solar systems, by their nature, are so closely integrated with the building itself, the incorporation of the solar system must proceed step by step with the building design, starting with the initial layout. In the early stages of design, rough guidelines are needed to estimate the size and performance of the solar components without resorting to time-consuming calculations. Edward Mazria has prepared a design procedure which lists a set of rules-of-thumb for sizing the solar components. An introduction to this procedure is given in his paper, which is included in the appendix of this report. The complete details can be found in his book The Passive Solar Energy Book (Rodale Press, 1979).

Performance Calculations

Once a preliminary design is completed using the rule-of-thumb procedure, detailed performance calculations can be made. This can be an iterative process in which the preliminary design is adjusted and modified to correct deficiencies in performance identified by the detailed calculations. Then a second round of calculations checks out the effect of the modifications. This cyclic procedure is repeated until the desired performace is achieved or until it is determined that the basic building design cannot meet the performance specifications. In the latter case, a new preliminary design would be required.

Performance predictions inevitably involve the solution of a set of simultaneous equations in which the unknowns are the temperatures at critical locations in the building. The mathematical theory and computational methods available are more than adequate for this task, but it is tedious to "do it yourself" or expensive to "hire it out." Fortunately a short-cut method developed by the Los Alamos Scientific Laboratory (LASL) is available. The method is based on several hundred year-long, hour-by-hour performance calculations at 29 different cites and for 6 different building loads in each city.

Computer simulation analysis techniques were used to accomplish this huge task. The simplified method relies on the use of a correlating parameter, the Solar Load Ratio (SLR), and an empirical fit to the large ensemble of data from the computer analysis. The method is limited to thermal wall, waterwall, and direct-gain systems. The LASL papers describing this simplified performance prediction method are reprinted in their entirety in the appendix. The method has been applied to each of the buildings described in this report, and complete results are presented.

By combining under one cover the descriptions of a series of passive solar buildings, the rule-of-thumb design procedure, and the simplified performance prediction method this report presents a comprehensive background in passive solar technology.

An earlier report provided descriptions and performance data on five passive solar buildings and some general information on passive building design.* At that time, performance data was scarce. Most of the available data came from a series of buildings instrumented by personnel from the Los Alamos Scientific Laboratory (LASL). The purpose of that report was to document and publicize the attractive characteristics of passive solar buildings. The scope of this report has been expanded to include

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*R. P. Stromberg, and S. O. Woodall, Passive Solar Buildings: A Compilation of Data and Results, SAND77-1204 (Albuquerque: Sandia Laboratories, August 1977).

1. A larger number of buildings with more detailed information,
2. The rule-of-thumb design procedure by Edward Mazria,
3. The LASL simplified performance prediction method, and
4. Examples of performance prediction (supplied by LASL) for each building described.

Passive Versus Conventional Design Techniques

The methods described in the appendix for estimating the performance of passive solar buildings are far different from the conventional methods still commonly used to calculate the heating (and cooling) requirements of a building. The conventional method pictures a building as a closed but leaky box with a furnace which supplies heat at the exact rate necessary to keep the inside air at a constant temperature. Heat is lost from the box by conductance through the walls and by infiltration of air through the leaks. The rate of heat loss is proportional to the inside-to-outside temperature difference. The proportionality factor is called the "building loss coefficient." This model has proven useful in determining the size of a furnace needed in a house to meet the needs of the worst expected conditions (i.e., the "design day" conditions). The limitations of the model are best shown by using an actual-data example. The Bruce Hunn house (Section 10) has a building loss coefficient of 14,100 British thermal units per degree-day (Btu/dd). The indoor and outdoor temperatures during the period December 20-27, 1978 are shown in Figure 1-1. The average indoor temperature was 54°F. The average outdoor temperature was 27.5°F. According to the conventional model, the furnace should have been supplying 373,650 Btu's, or about 110 kilowatt-hours (kWh) of electric furnace heat, to the house each day. Being unoccupied, the house had no internal heat sources or unaccounted losses such as the opening of doors or windows. The house was for all reasonable purposes a closed box, just like the conventional model. Despite these ideal conditions, the conventional model fails to predict accurately the total energy needs of the house. This failure arises from the omission in the model of any means to account for the effects of solar energy and the ability of the house to store heat during the day for reemission at night. The performance prediction methods described in the appendix account for these effects and are capable of providing accurate predictions of total energy needs.

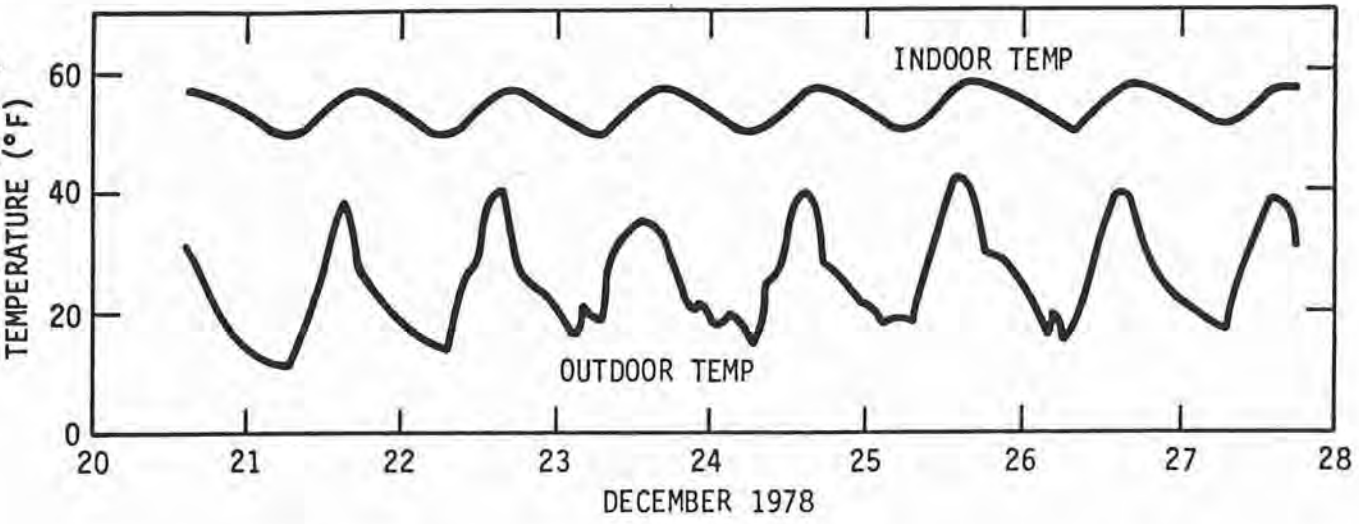


Figure 1-1. Indoor and Outdoor Temperatures for the Bruce Hunn House, December 1978

Passive Solar System Forms

It is instructive and convenient to categorize the various forms of passive solar systems. The buildings described in this report can all be classified as one of the following five forms or as combinations of these forms.

Direct Gain -- The simplest passive solar system is the direct-gain system, which consists of a well-insulated house with a large expanse of south-facing windows. The south windows admit the slanting rays of the winter sun. In summer, the high angle of the sun reduces the insolation admitted by the south windows, and a short roof overhang can exclude the sun completely. The house needs a large thermal mass to store heat during the day and to reemit it at night to keep the house warm. The thermal mass is usually in the form of masonry walls insulated on the outside or concrete slab floors with perimeter insulation. Heat can be transferred into the storage mass by thermal transfer with the air in the living space. This is a relatively inefficient process. If the sun shines directly onto the storage mass, more energy is stored and at a higher temperature. The latter case provides a more effective system.

Thermal Storage Wall -- In the thermal storage wall system, the thermal storage mass for the house is a south-facing wall. The outside surface is glazed to reduce heat losses to the outside air. The wall can be thick masonry construction or can be built as a water storage container (a waterwall). For masonry walls on a cloudless day, the outer wall surface temperature can exceed 140°F. The heat conducts slowly through the wall thickness. When it reaches the inner wall surface, it is transferred to the living space by radiation and convection. Vents can be placed at the top and bottom of the wall to allow prompt transfer of heat to the living space by convection currents. For a waterwall, the heat is transferred quickly through the wall by convection currents in the water; the temperature will be nearly uniform through the thickness of the wall. There will, however, be a vertical temperature gradient: the top of the wall will be warmer than the bottom. Because the heat is distributed rapidly through the entire mass of the wall, the outer surface temperature does not get as high as it does in a masonry wall, which makes the waterwall a more efficient solar collector. Water has the advantage of a high specific heat (about five times as high as concrete or brick) so that waterwalls can be smaller and lighter while having the same thermal mass as a masonry wall.

Greenhouse -- This form consists of a greenhouse built on the south side of a building, separated from the building by the thermal storage wall. The thermal storage wall serves to stabilize the temperature in both the greenhouse and the house. Normally, the greenhouse does not need to have its temperature regulated closely and is not supplied with any auxiliary heat. During the day, heat that builds up in the greenhouse can be transferred to the house. At night, the greenhouse can be closed off to prevent heat loss through it from the main building. The roof of the greenhouse admits sun all year long, and large vents high on the wall or in the roof are needed to flush out excess heat in the summer. Besides providing additional living space, the greenhouse can be used to grow food and flowers.

Roof Pond -- For this form, a flat roof is designed to hold and support a pond of water. The pond acts as the thermal storage mass and solar collector. Movable insulation is required. In the heating mode, the pond is exposed to the sun during the day, then covered by the movable insulation at night. The stored heat in the pond is transferred to the living space by radiation and convection from the ceiling which supports the pond. In the cooling mode, the insulation shields the pond during the day but is removed at night so that the water can cool itself.

Thermosiphon -- The thermosiphon, also known as a convective loop, consists of a solar collector and a thermal storage tank. The collector is at a lower elevation than the tank. Tubes connect the top of the collector to the top of the storage container. The bottoms are also connected. The whole system is then filled with water or antifreeze fluid. The sun shining on the collector heats the fluid, which expands and flows upward into the tank. Cold fluid is displaced from the tank back to the collector, where the sun warms it; the cycle continues as long as the sun shines.

Air can be used as the heat-transfer fluid, in which case the tank is replaced with a container filled with stones or pebbles. The movement of the air will be the same as for the water. As the heated air passes through the rock bed, the heat is transferred to the rocks, and the cooled air is recycled to the solar collector.

SECTION 2

UNIT ONE, FIRST VILLAGE

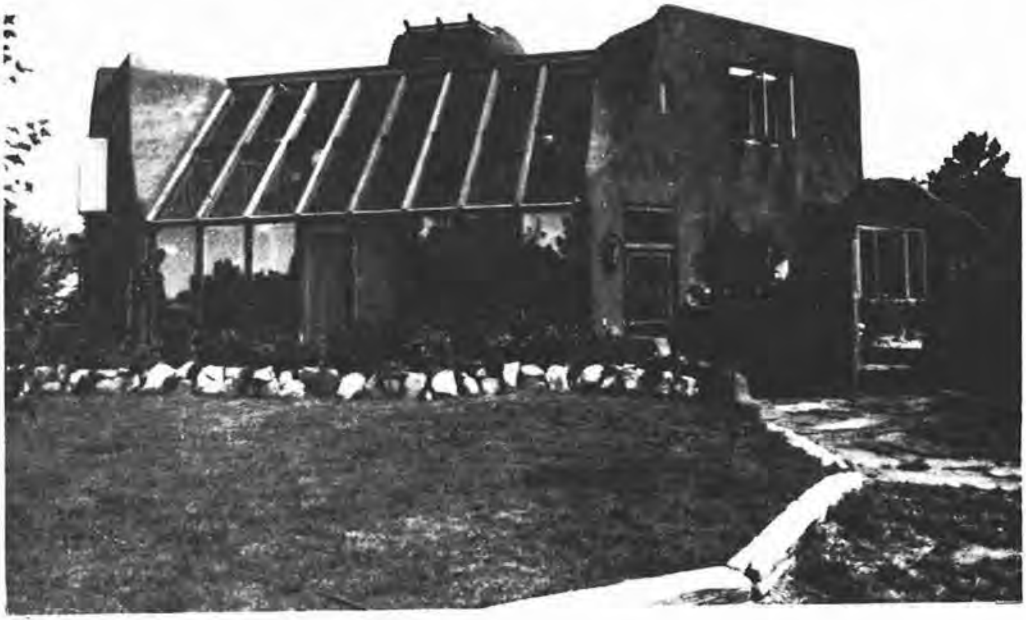


Figure 2-1. Exterior View of the J. Douglas Balcomb House

BUILDER: Wayne and Susan Nichols
DESIGNER: Susan Nichols, William Lumpkins
OWNER: J. Douglas Balcomb
TYPE: Single family, 1 unit
AREA: 2,300 square feet
GENERIC TYPE: Attached solar greenhouse, hybrid
LOCATION: Santa Fe, New Mexico
LATITUDE: 36°N.
ELEVATION: 7,700 feet
CLIMATE DATA: Annual heating degree-days (dd): 6,000
Design temp: 11°F
Horizontal insolation (January day): 1,090 Btu/ft^2

Figure 2-2. Interior of Greenhouse Looking Northeast toward Circular Staircase

Figure 2-3. Interior of Greenhouse Looking West

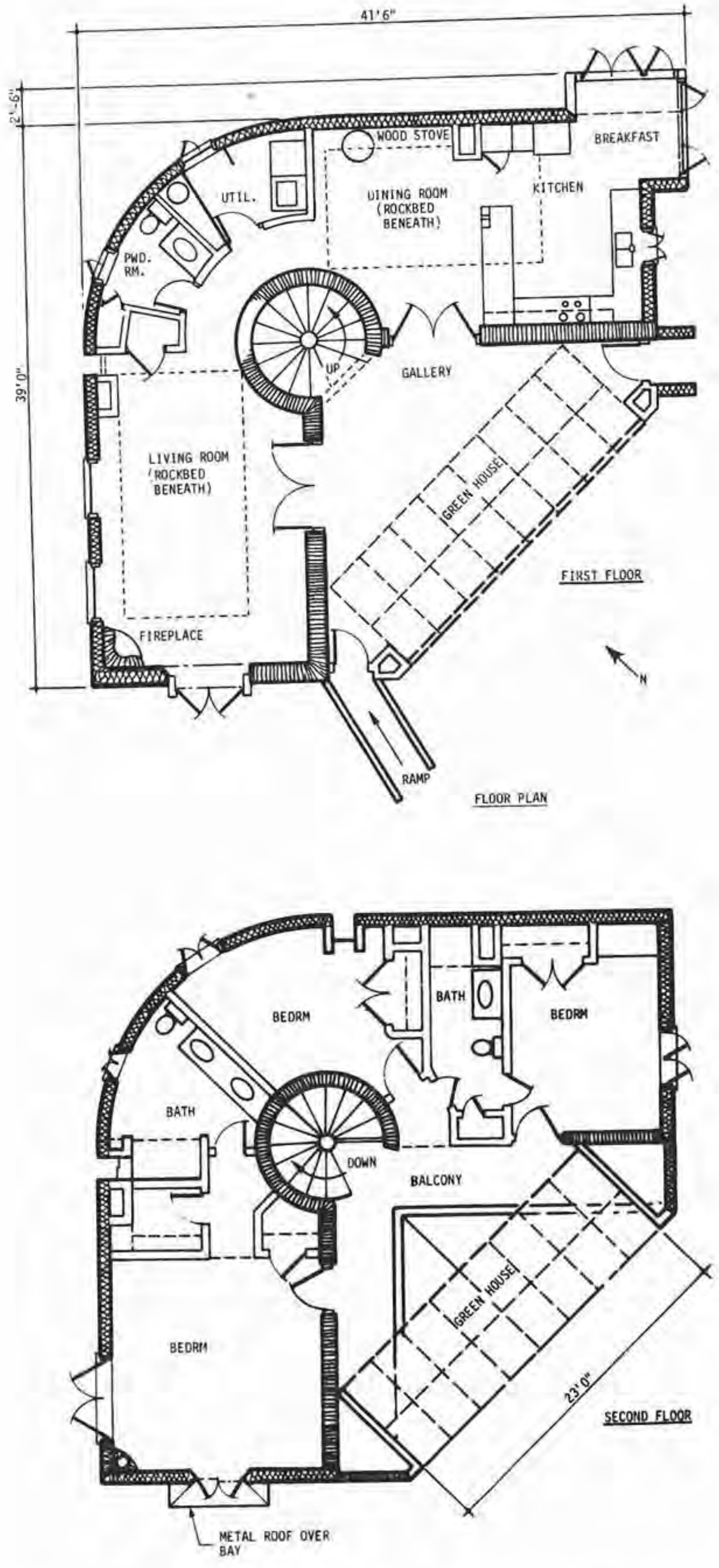


Figure 2-4. Floor Plan of Unit 1, First Village

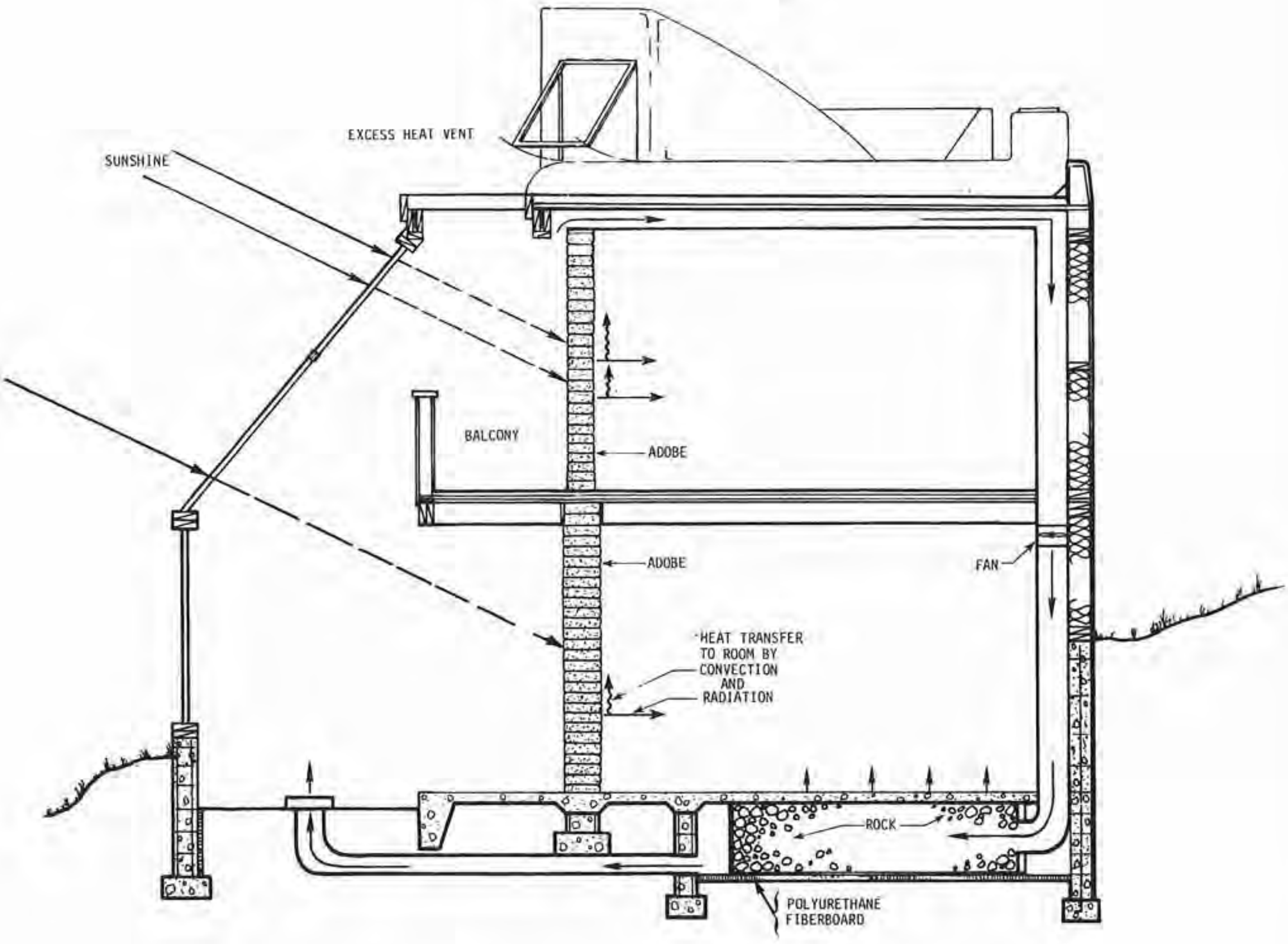


Figure 2-5. Thermal Flow Diagram

Collectors -- The south-facing greenhouse serves as a direct-gain collector. The total glass area of the greenhouse is approximately 412 square feet.

Storage -- The primary storage is the adobe mass wall which separates the greenhouse from the house and the floor of the greenhouse. Solar radiation incident on these surfaces is absorbed and stored directly. Secondary storage is achieved by two fan-powered ducts which pull heated air from the upper level of the greenhouse into two separate rock storage bins underneath the floor, with the exhaust air being returned to the greenhouse.

Distribution -- Distribution of heat to the greenhouse is by radiation and convection of absorbed solar heat from the floor and the back adobe walls. Primary distribution of solar heat to the house is by radiation and convection from the adobe wall, which functions largely as a Trombe wall. There is also some thermocirculation of warmed greenhouse air to the house through opened doorways during the day. Secondary distribution is by passive conduction of heat up through the concrete floor slab and subsequent convection and radiation to the groundfloor rooms.

Auxiliary Heat -- Baseboard electric heaters, a fireplace, and a wood-burning stove provide the auxiliary heat.

Domestic Hot Water -- A separate flat-plate collector provides preheat for the hot water supply.

Controls -- A differential thermostat controls the fan forcing airflow into rock storage beds. Individual thermostats control baseboard electric auxiliary heaters.

Description

First Village is a planned community of solar residences on a 40-acre tract of land in Santa Fe, New Mexico. The tract is subdivided into eight lots of 5 acres each. Unit 1, the first house constructed in the community, is a two-story house with an "L" shaped floor plan. The angle of the "L" encloses a greenhouse which is the major component of the solar heating system. On the first floor are the living room, dining room, and kitchen. The living room and dining room open onto the greenhouse area. The kitchen has a window opening into the greenhouse. A breakfast nook juts out from the kitchen on the east corner of the house and its large window area catches the early morning sun. At the angle of the "L" (the north corner of the greenhouse) there is a circular staircase which leads from the greenhouse to a second floor balcony which overlooks the greenhouse area and provides access to each of the three bedrooms on the second floor. The lot slopes slightly toward the south and the house is set below grade. The north corner is approximately 4-1/2 feet below grade, while the greenhouse floor at the south wall is on grade.

The south wall of the greenhouse is made of eight panels of tempered, double-glazed, sealed thermal glass units, each measuring 34 by 76 inches. The roof of the greenhouse slopes upward at an angle of 50 degrees from the horizontal. It is composed of 16 panels of double-glazed thermal glass units also measuring 34 by 76 inches each. This glass greenhouse roof meets, and is supported by, a flat, built-up roof which is an extension of the roof of the house. This arrangement provides 276 square feet of glass for the sloping roof and 136 square feet of glass for the vertical south wall.

The greenhouse space is separated from the living space by adobe walls 14 inches thick on the first floor and 10 inches thick on the second floor. A wall of adobe brick surrounds the circular staircase. These massive walls serve as thermal storage. Additional thermal storage is provided by two rock beds: one under the living room is 2 feet deep by 10 feet wide by 19 feet long (14 cubic yards); the other under the dining room is 2 feet deep by 10 feet wide by 15 feet long (11 cubic yards). These beds are filled with 3- to 5-inch round riverbed rock. Air ducts form a circuit from the top of the greenhouse, through the rock bed, and back to the floor of the greenhouse. Two 1/3-horsepower fans power these ducts.

The outer walls of the house are framed with 2- by 8-inch studs at 16-inch intervals. The space between the studs is insulated with a layer of 1-1/2-inch rigid fiberglass over a 6-inch fiberglass batt with the vapor barrier on the interior side. The outer surface of the wall is stucco. The below-grade portions of the wall are made of 8-inch concrete block with all the cells filled with cement. The wall is waterproofed with plastic roofing cement and insulated with 2 inches of rigid polystyrene.

Operation

During the day, solar radiation, direct and indirect, enters the greenhouse through the glass walls, and falls upon the interior adobe walls and floor. Part of the energy is absorbed by the adobe walls and floor, part is transferred to the air in the greenhouse, and another fraction is transferred back through the glass and lost. The heat absorbed by the adobe wall slowly conducts through the wall until it reaches the other side, where it is transferred by convection and radiation to the interior of the house. It takes 7 to 8 hours for heat to be conducted through the 14-inch adobe wall, so the heat of the day reaches the interior of the house during the evening hours when it is needed most. The heat absorbed by the floor of the greenhouse is reemitted during the night into the greenhouse space, keeping the space warmer than the outdoor ambient temperature.

Heated by the warm objects in the room, the air in the greenhouse rises and collects under the roof of the greenhouse and is pulled through the fan-powered ducts into the rock beds, where its heat is transferred to the rocks for storage. The cooled exhaust air is returned to the floor of the greenhouse to be recirculated. The heated rocks warm the 7-inch-thick concrete and tile floor slab and the living spaces above it. The fans are controlled by one differential thermostat which senses the temperature of the air at the top of the greenhouse and the temperature in the rock bed. The fans automatically turn on whenever the air temperature exceeds the rock bed temperature by 15°F. Override switches allow the fans to be turned on or off manually when desired.

Control of temperature within the living space of the house is not entirely automatic. The heat flow from the greenhouse to the living space is controlled by opening or closing the doors of the rooms which open onto the greenhouse. For example, as the morning sun raises the greenhouse temperature in the winter, the doors can be opened, allowing the warm air to heat the living space directly. When the sun sets and the greenhouse temperature drops, the doors are closed, trapping the heat within the interior of the house. It should be noted here that the greenhouse area in Unit 1 is not designed for use as a daylong living space. The large area of glass, while double glazed, is not shuttered or insulated, so the greenhouse temperature falls well below comfortable living temperature on cold nights. Conversely, on warm summer days, the solar input to the greenhouse provides an excess of heat which must be vented. Two of the glass panels on the south wall and the two access doors can be opened to let outside air enter the greenhouse. A window at the top of the circular staircase can be opened so that the staircase well acts as a chimney, venting excess heat from the greenhouse to the outside. During summer nights these vents are left open, and the doors to the rooms opening onto the greenhouse are also opened. In this way the entire house and the interior adobe walls are cooled. In the afternoon, the living space doors are closed, and the cool adobe walls act as an efficient (and quiet) air conditioner for the whole day.

A more subtle seasonal temperature control system is achieved by the greenhouse roof and the balcony. Both the greenhouse roof and the balcony floor are horizontal planes projecting out on the south side of the adobe wall. During summer, when the sun's midday altitude angle is high (or zenith angle is small), these projecting planes shade the adobe wall from direct incidence of the sun's rays. The low altitude angle of the sun during the winter allows the sun's rays to undershoot these projecting planes and fall directly onto the adobe wall, which then acts as an efficient solar collector and thermal storage system. The result for the annual seasonal cycle is that unneeded summer solar energy is largely prevented from entering the greenhouse or living spaces, while winter solar energy is efficiently collected, stored, and used to keep the living spaces at comfortable temperatures.

A two-panel, flat-plate collector array located northeast of the house provides preheat for the domestic hot water system. Propylene glycol is used as the heat transfer fluid to prevent freezing during the winter. A single wall heat exchanger transfers the heat from the propylene glycol to the water in the domestic hot water system.

Auxiliary heat is supplied by baseboard electric heaters in each room, controlled by individual thermostats. A wood-burning stove is used occasionally for both ambience and heat.

Performance

The dominant temperature control feature of Unit 1, First Village, is the massive adobe wall separating the greenhouse from the living space. It performs three functions: (1) its thermal mass moderates the temperature extremes, (2) it acts as a collector for solar energy, and (3) it distributes heat to the living space. Two arrays of temperature sensors (thermocouple rakes) have been imbedded within the walls to measure the temperature. The geometry of these rakes and their temperature records for the first floor wall and the second floor wall are shown in Figures 2-6 and 2-7, respectively. Each day, when the sun falls upon the wall, the outer surface temperature rises to 100°F or more. This energy is either transferred back into the greenhouse area by reradiation and convection, or it moves by conduction through the wall. As the conducted energy flows through the wall, the thermocouples register its passage as a temperature pulse. The thermocouple records show that the amplitude of the pulse is reduced and its width is broadened as it moves through the wall. The pulse takes 7 to 8 hours to travel from the outer surface to the inner surface. This means that the heat collected by the adobe wall from the midday sun is delivered to the living space in the evening--an ideal balance of the physical characteristics of the system with the human requirements.

Heat transfer from the adobe wall to the living space is convective and radiative. Convective transfer depends on the temperature difference between the wall surface and the air. The radiative effects of the adobe wall are important. The large area of the adobe wall continuously radiates energy to the other walls, which then reradiate. The room is filled with a low-level radiant energy flux, which warms the occupants of the room. A pleasant comfort level is achieved when the actual air temperature is significantly lower than would be required in a house heated by a forced hot air system. A secondary benefit is that, since the air temperature is lower, the house heat losses are reduced, and less energy is needed to keep the house comfortable.

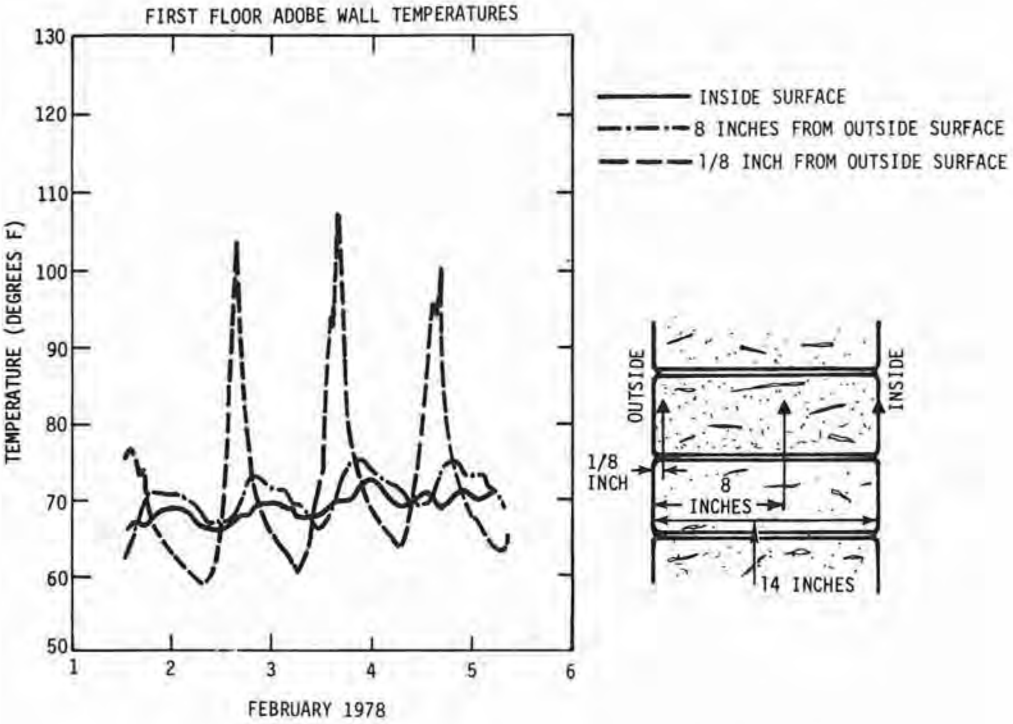


Figure 2-6. Temperatures within First Floor Adobe Wall

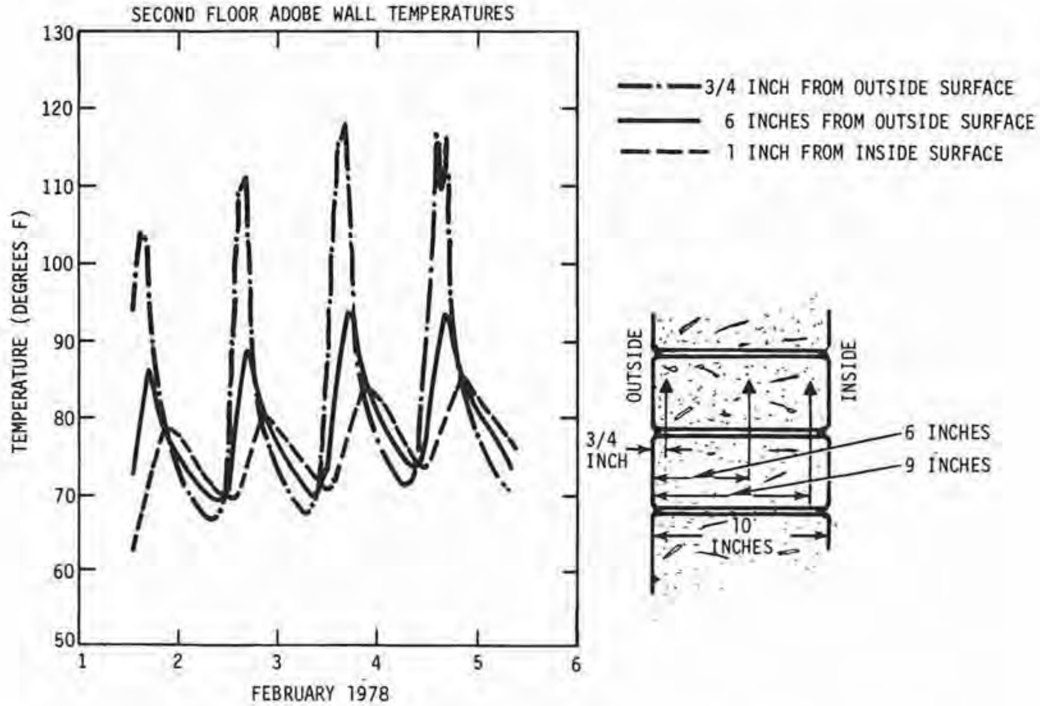


Figure 2-7. Temperatures within Second Floor Adobe Wall

Figure 2-8 is a compilation of data taken from the Balcomb house from December 26, 1978 to January 8, 1979. A few hours of data were lost on January 3, 1979, which accounts for the break in the records on that date. The period is characterized by extremely cold weather (down to -12°F) and a succession of days with poor insolation. It is a period of extreme test for a solar house.

The temperatures near the inside and outside surfaces of the adobe wall are the second pair of traces shown in Figure 2-8. This is the same type of data as shown in Figures 2-6 and 2-7, but with less detail. During the sunless days the wall loses heat steadily, and its temperature drops. Some of the heat flows into the house, but some is also lost to the outside through the greenhouse area.

The next pair of traces shows the temperature of the surface of the dining room floor above the rock bed. The same general characteristic shown by the adobe wall is repeated: temperatures rise rapidly during sunny days but fall steadily without the sun's heat. On the night of December 30 the floor temperature rises several degrees. This was caused by heat delivered from the wood stove in the dining room which was used on that night. The on-off periods of the circulating fan for the rock beds are shown on the very bottom edge of Figure 2-8. As would be expected, the rock bed temperature rises each time the fan is on.

The fourth set of traces shows the air temperatures for the greenhouse and dining room. The large temperature swings in the greenhouse are apparent. The temperature swing in the dining room is moderated to about 8°F. Over the winter of 1977-78, the interior temperature both upstairs and downstairs, normally remain in the mid- and upper-60's. During the period of cold and relatively sunless weather, the dining room temperature drops to the lower 60's and is maintained above 65°F by the auxiliary heating system. The last pair of traces in Figure 2-8 shows the total electric power consumed in the house and the power consumed by the baseboard heater (the auxiliary

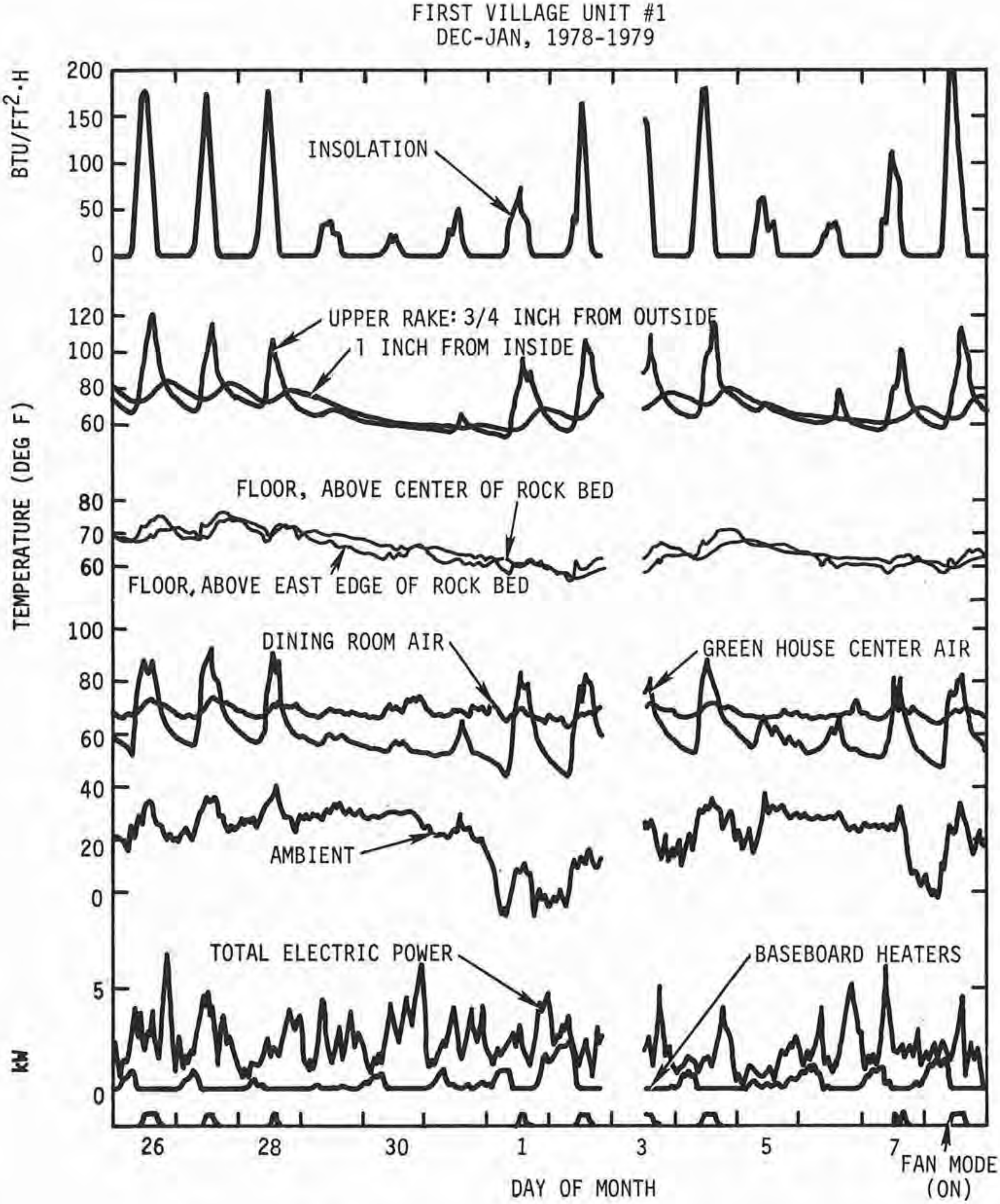


Figure 2-8. Recorded Data for the Balcomb House

heating system). The baseboard heaters turn on fairly consistently every time the dining room temperature drops below 65°F.

The greenhouse temperatures were recorded at a level of 8 feet above the floor at the center of the greenhouse. When the fan is on, circulating air through the rock bed, there is very little temperature stratification in the greenhouse. The greenhouse temperature shown in Figure 2-8 is essentially the temperature of the air entering the duct for delivery to the rock beds. At night, with the fan off, there is a 10°-15°F stratification between the floor and the roof of the greenhouse.

The electric utility (Public Service Company of New Mexico) installed two meters--a main meter which records all electricity used in the house and an auxiliary meter which records only the electricity used for auxiliary heat. The values recorded are shown in Table 2-I. The installed capacity of the auxiliary heating system is 9.5 kW, corresponding to the conventional design load of the house. Experience has shown that 3 kW is the maximum required.

Additionally, wood was burned in the fireplace and stove. The total wood consumption was not accurately monitored but amounted to about 1,200 pounds overall.

For the period shown in Figure 2-8, the total electric consumption was 728 kWh, with auxiliary heating system accounting for 79 kWh of the total. The average ambient temperature for this period was 22.7°F. These figures do not account for the hours during January 3, 1979, when data was lost.

Owner Observations and Comments

As noted earlier, one of the temperature control mechanisms for Unit 1 is the opening or closing of doors onto the greenhouse. Mrs. Balcomb, who has lived in the house for more than a year, indicates there is nothing critical about this operation; in fact, no particular attention is paid to it at all. The doors are left open when the

TABLE 2-I

Electric power consumption for the Balcomb house, 20 June 1977 to 19 April 1979

Meter Reading Date	Main, kWh	Auxiliary, kWh	
20 Jun 1977			
	787	0	
20 Jul 1977			
	578	0	
18 Aug 1977			
	805	0	
19 Sep 1977			
	802	0	
18 Oct 1977			
	1054	NOT AVAILABLE	
17 Nov 1977			
	1258	39	
20 Dec 1977			
	1671*	198	
20 Jan 1978			
	1663*	265	
20 Feb 1978			581 kWh
	1107	34	
21 Mar 1978			
	1046	30	
20 Apr 1978			
	1102	15	
19 May 1978			
	1104	0	
20 Jun 1978			
	795	0	
20 Jul 1978			
	826	0	
18 Aug 1978			
	1154	0	
19 Sep 1978			
	961	0	
18 Oct 1978			
	1152	8	
16 Nov 1978			
	1930*	243	
19 Dec 1978			
	1810*	222	
19 Jan 1979			745 kWh
	1534*	219	
19 Feb 1979			
	991	45	
20 Mar 1979			
	882	8	
19 Apr 1979			

*Solar water heater out of service during all or a portion of these months. A new, enlarged solar water heater was installed during February 1979.

greenhouse environment is agreeable and shut when it is not. The operation of the doors is natural and not a specific routine performed on a schedule.

The large area of greenhouse glass needs cleaning about once a year. Most of the inside glass can be cleaned while standing on the greenhouse floor or on the balcony. A ladder is needed to reach some areas. A long-handled brush and squeegee is all the equipment needed for the job.

During the winter the house is kept tightly closed, with little ventilation from outside air. No stuffiness or stale air has resulted. Mrs. Balcomb surmises that the circulation of air through the rock beds may be helping to freshen the house air, since the rock beds themselves may be acting as filters. The plants in the greenhouse probably also help. The greenhouse also adds humidity to the air, eliminating the problem of dryness which often occurs in the arid southwest region or in almost any region during winter months.

Mrs. Balcomb, a native of New Mexico, is familiar with the usual duties and complaints associated with a house in this area and has been pleased to find that Unit 1 is nearly free from all these duties and complaints--no thermostats to keep adjusting or drapes to open and shut, no water pipes to worry about freezing, no drafts from cold walls or leaky doors. The temperatures within the house are very uniform; there is no "warm part" or "cold part" in the house; it is comfortable throughout. Even after a year in the house, it still comes as a surprise to the Balcombs that the thermometer reads only 65°F while the house feels warm and comfortable. The house has not imposed itself on the Balcombs; instead, it has made it easier for them to maintain their lifestyle in greater comfort and satisfaction.

Mrs. Balcomb recommends one change: that the window at the top of the stairwell be modified so that it can be opened or closed without standing on a chair or ladder. Since the window only needs opening once a year, this is not a critical problem.

Designer/Builder Comments

During construction of Unit 1, there was some question about whether or not the greenhouse would overheat during the summer months. Accordingly, the window at the top of the stairwell was changed at this time from a fixed glass pane to an operable window. The venting effect of this window proved to be so efficient that the two manually operated vents planned for the greenhouse roof were eliminated.

The collector panels for the domestic hot water (DHW) system were shipped with the wrong size clips for the glazing. The collectors were placed on the ground to the east of the house rather than on the roof, as originally planned. The preheat water tank was defective and sprung a leak after about 18 months of service; it had to be replaced. Some difficulty was experienced in adjusting the controls for the hot water preheat system. There has been no difficulty with the collector itself or with the heat exchanger in the preheat tank.

The main air ducts as actually constructed had a smaller cross section than the original design. This caused the fans to be noisy. The fan size and model were changed, but they were still noisy. By custom-fitting the fan mounts and platforms, adding extra vibration isolators, and installing extra sound board around the fan closets, the noise problem was finally solved. These problems would never have arisen with properly sized ducts and bigger fan closets.

The differential thermostats used for fan control are difficult to adjust for an air system. Several probe locations were tested before proper on-off cycling was achieved.

Wooden mullions support the glass in the greenhouse. The mullions were difficult to custom cut. The original glass lites measured 34 by 76 inches; when fitted into the mullions, the net area was reduced to 29-1/2 by 73 inches. Sheet metal mullions would be better from a construction point of view, but would not be as satisfactory aesthetically.

The design of the solar system for Unit 1 was influenced by previous experience in the appraisal of solar homes. For one home with an air/rock system, the collector was mounted on the roof, and the hot air was pumped to the rock bed beneath the house. Although the system cost $9,000, the appraiser assigned it no value. In a second house of similar basic design, the collector was a greenhouse, and the appraiser assigned a value of $20 per square foot to the greenhouse because it was usable space. This anomaly in appraiser requirements resulted in the selection of the greenhouse design.

Construction and Cost

Construction of the house began in January 1976 and was completed in August 1976. The total cost was approximately $104,000, which includes $24,000 for the lot. An $8,000 grant, awarded directly to the builders by HUD during the first cycle of the 1974 Solar Demonstration Act, offset about two-thirds of the cost of the solar portion of the house.

The usable area inside the house is approximately 1,950 square feet. The greenhouse adds another 350 square feet, which are usable during the summer and during the daytime in the winter. The passive solar heating system is well designed. Once inside the house, it is difficult distinguishing it from an airy, nonsolar adobe house.

The cost of installing a conventional forced-air heating system in this house would have been approximately $12,000. The solar installation cost was $12,000, but additional living area in the form of a greenhouse has been provided. The passive solar heating system appears to be a wise investment for this property.

Performance Estimate

A standard heat loss analysis indicated that the total building loss coefficient is 15,920 Btu's per degree-day (Btu/dd), or 8.64 Btu/dd ft^2. (In this report, degree-days are heating degree-days: one degree-day is recorded for each Fahrenheit degree of departure below a certain standard during a single day.) The loss rate from the living space through the adobe wall, greenhouse, and greenhouse glazing was computed by assuming a steady-state heatflow in which the amount of heat lost from the living space through the adobe was equal to the heatflow through the greenhouse glazing to the outside. A performance estimate for Unit 1, First Village was made using the methods outlined in the appendix. The results are shown in Table 2-II. These methods cannot account for the heat delivered to the living space by the active transfer of heat from the greenhouse via the fan-powered ducts into the rock beds and thence into the living space. The method was, therefore, modified to include this heat source, as indicated in the last three columns of Table 2-II. The heat contribution credited to the rock bed system was a maximum of 47,000 Btu/day. The annual solar heating fraction (SHF) is 84 percent. The house appears to be performing at least as well as the performance estimate indicates, which is very well indeed.

TABLE 2-II

Performance Estimate for the Balcomb House

Month	Degree-Days	Gross (MBtu)*	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface (Btu/ft^2·mo)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Solar Heat Delivered (MBtu)		Aux. Energy (MBtu)
									Direct	Through Rockbed	
January	1,091	17.37	2.87	14.50	35,458	15.49	1.07	0.52	7.60	2.89	4.01
February	882	14.04	2.60	11.44	43,890	15.21	1.33	0.61	6.94	2.61	1.89
March	828	13.18	2.87	10.31	58,075	13.69	1.33	0.61	6.25	2.89	1.17
April	513	8.17	2.78	5.39	70,566	10.71	1.99	0.76	4.07	1.32	0
May	258	4.11	2.87	1.24	81,164	8.92	7.22	1	1.24	0	0
June	68	1.08	2.78	0	83,220	8.15	-	1	0	0	0
July	5	0.08	2.87	0	79,279	8.08	-	1	0	0	0
August	21	0.33	2.87	0	73,507	9.36	-	1	0	0	0
September	116	1.85	2.78	0	61,560	11.81	-	1	0	0	0
October	409	6.51	2.87	3.64	50,654	14.91	-	1	3.64	0	0
November	774	12.32	2.78	9.54	36,708	14.73	1.54	0.66	6.33	2.80	0.41
December	1,042	16.59	2.87	13.72	31,806	14.62	1.07	0.52	7.17	2.89	3.66
Annual				69.78							11.14

ANNUAL SHF = 0.84

*MBtu = million Btu

SECTION 3

MARK JONES HOUSE

Figure 3-1. Exterior View of the Mark Jones House

BUILDER: Mark Jones
ARCHITECT: Mark Jones
OWNER: Mark and Faith Jones
TYPE: Single family residence
AREA: 2,650 square feet
GENERIC TYPE: Hybrid/hot air thermosiphon to rock bed storage, with forced-air distribution
LOCATION: Santa Fe County, NM
LATITUDE: 36°N
ELEVATION: 6,750 feet
CLIMATIC DATA: Heating dd: 6,100
Design temp: 0°F
Horiz. insolation (Jan. day): 1,090 Btu/ft^2

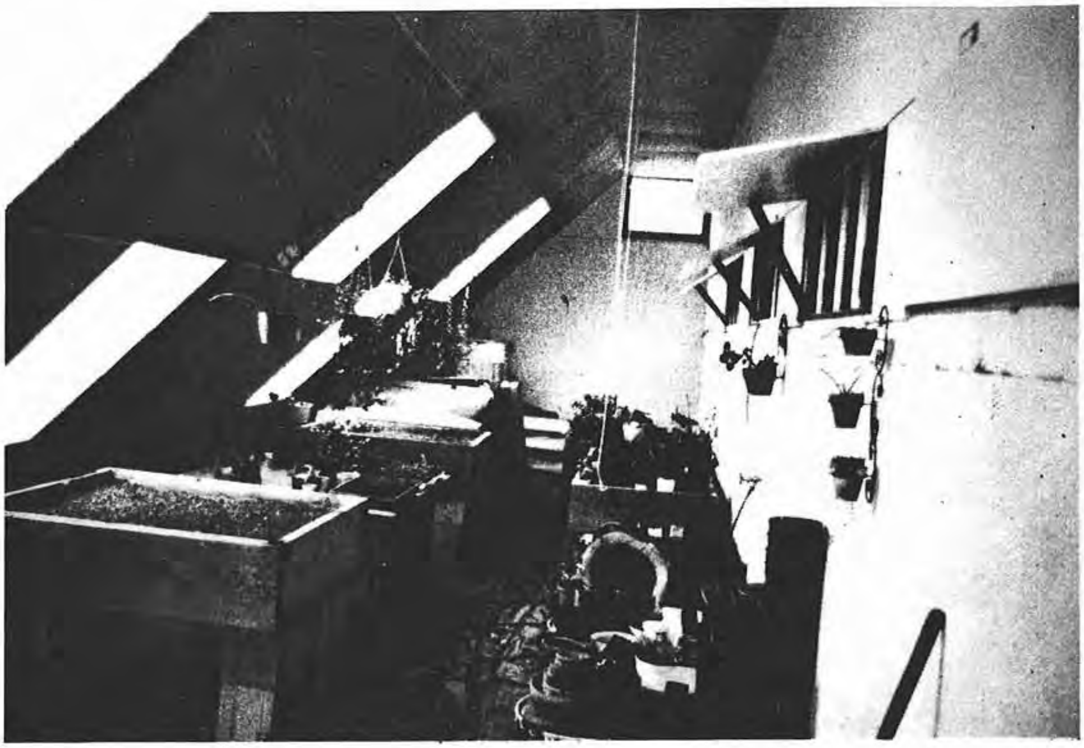


Figure 3-2. The Greenhouse in the Mark Jones House

Figure 3-3. View of the House from the West

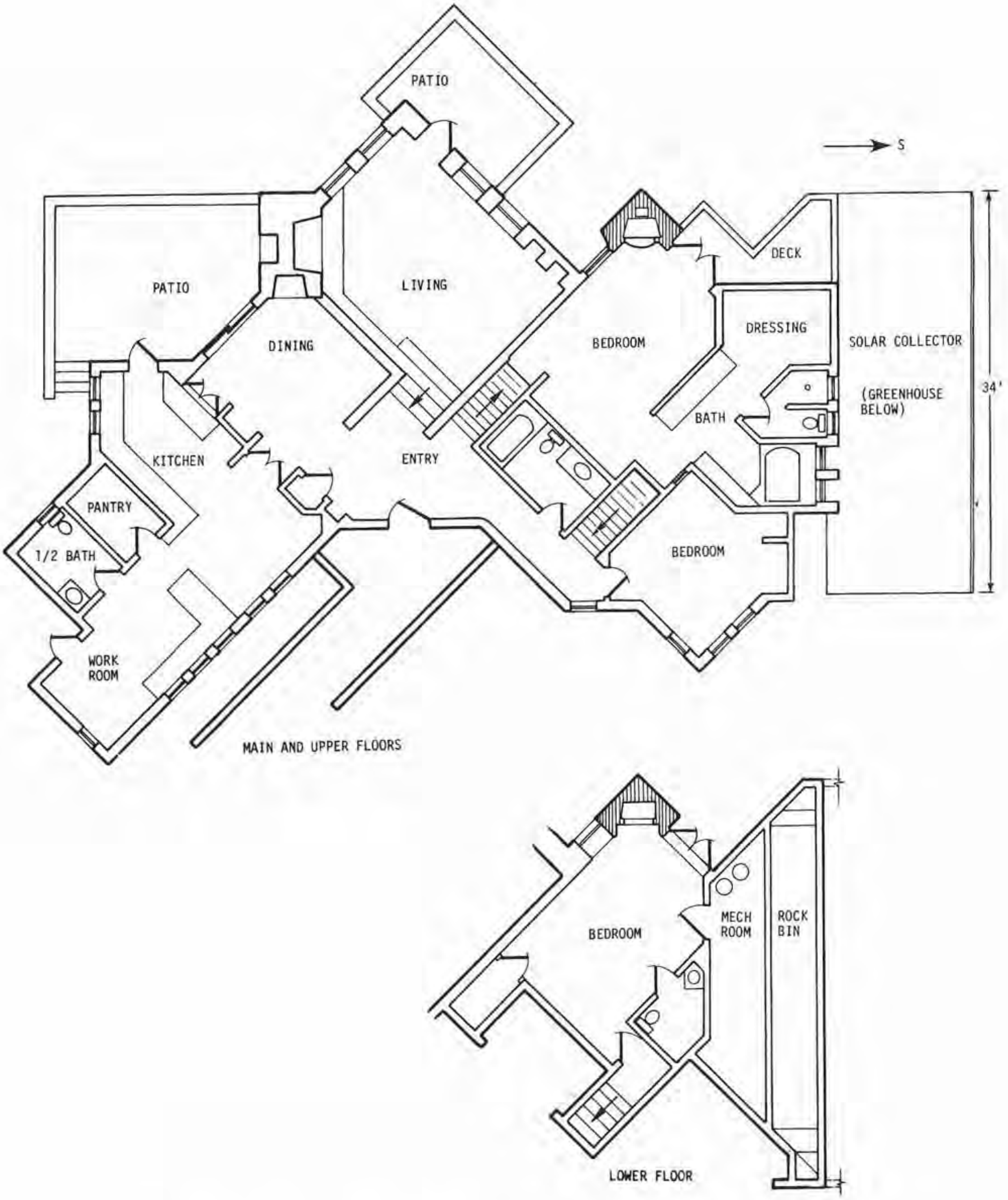


Figure 3-4. Floor Plan for the Mark Jones House

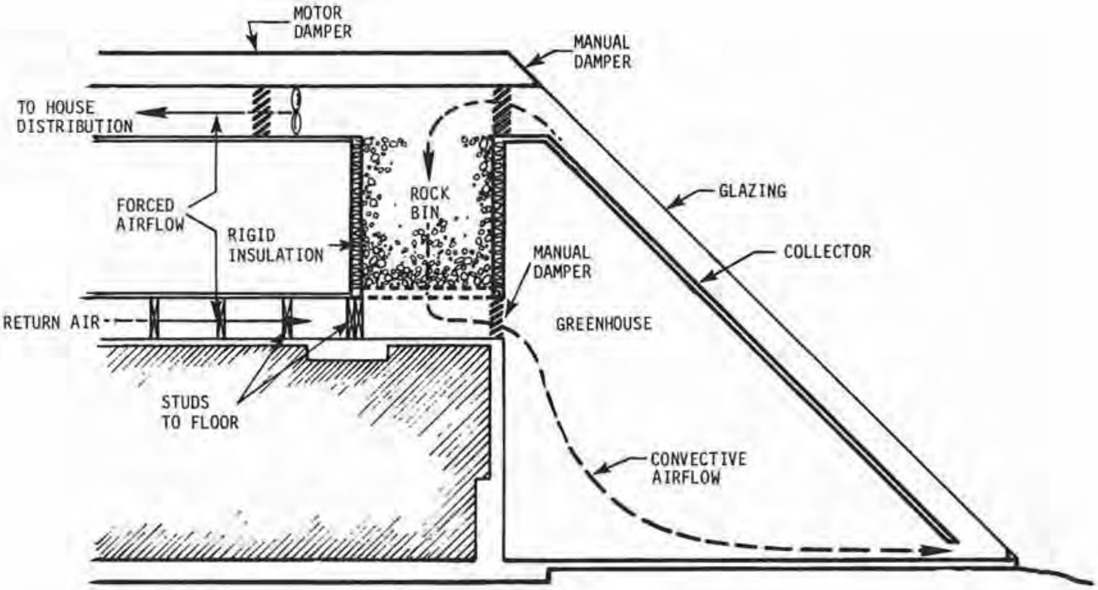


Figure 3-5. Thermal Flow Diagram of the Hot Air Thermosiphon System

<u>Collector</u> -- The collector for this system is a site-built, air-cooled, single-glazed flat plate tipped at 45 degrees from the horizontal. Net effective collection area is 532 square feet.

<u>Thermal Storage</u> -- 500 cubic feet (30 tons) of washed river rock (2 to 4 inch) provide thermal storage. The rock bin measures 4 feet by 32 feet in cross section and is 4 feet deep. Masonry interior walls provide additional storage mass within the house.

<u>Distribution</u> -- Hot air is supplied to the living areas through a conventional forced-air heat system driven by the fan in the auxiliary heater unit.

<u>Auxiliary Heat</u> -- A 50,000-Btu electric furnace supplies auxiliary heat.

Domestic Hot Water -- A liquid, flat-plate, thermosiphon solar heating system provides preheat for domestic hot water. The collector is an integral part of the collector array for the house heating system.

Controls -- Manual dampers prevent back siphoning through the rock bed. The fan and damper for the forced-air heating system are thermostatically controlled. The electric heating coils in the auxiliary furnace are controlled by a thermostatic sensor located within the rock bed.

Description

The Mark Jones house is located in Santa Fe County, New Mexico, several miles northwest of the city of Santa Fe. The site is on a knoll with excellent views to the east and northeast. The several interior levels of the floor plan follow the topography of the knoll. The collector array is on the south slope of the knoll and lies entirely below the upper floor levels of the house. This placement allows the use of the thermosiphoning system and prevents the large collector array from becoming the dominant architectural feature of the house.

The house has an "L" shaped floor plan. The north wing of the "L" contains a work room, kitchen-breakfast area, dining room, and, at a lower level, the living room. The many windows take advantage of the view to the east and northeast.

The south wing of the "L" is multi-level; the upper level contains the master bedroom and bath. Offset to the west, and at a lower level, is a second bedroom and bath combination. Beneath the master bedroom is a bedroom and bath. This level also contains the mechanical room for the heating system, the rock bed, and the greenhouse and solar collector array.

The walls of the house are a double-layer wood frame with 2- by 6-inch studs on the outside, 2- by 4-inch studs on the inside, and a

2-inch dead air space between. Fiberglass batt wall insulation is placed between the studs of both the outside and inside framing. The exterior and interior are finished with stucco.

Except for the master bath and hallways, the flat roof is supported on exposed 6- by 10-inch beams. The beams are overlaid with plywood, and a grid system of sleepers is laid on the upper surface. The space between the sleepers (10 inches deep) is filled with fiberglass batting for insulation. This is sheathed with another layer of plywood and the surface weatherproofed with built-up asphalt roofing. The roof over the master bath and hallway is conventional construction with 2- by 10-inch ceiling joists. The spaces between joists are filled with fiberglass batts. Both the walls and the roofs have a rated "R" value of 30. Part of the walls on the west and northwest are bermed. The below grade portions of the walls are concrete block insulated with 2-inch rigid polystyrene.

The foundation perimeter is insulated with 1 inch of polystyrene down to the depth of the footing.

Starting at floor level of the master bedroom, the solar collector slopes downward to the south at a 45-degree angle. The glazed area measures 18-1/2 feet by 34 feet. The glazing is a single layer of Kalwall® fiberglass-reinforced plastic sheeting. Beneath the glazing are metal pans which are inlaid with three layers of mesh wire lath. The lath and the pans are painted with a flat black, high-temperature enamel. The 2- by 10-inch joists supporting this solar collector array are sealed with high-temperature enamel to prevent outgassing from the wood. Part of the collector area is devoted to the water preheat system. The absorber in this part is copper sheeting with 1/2-inch copper tubing brazed to it. The tubing is filled with an antifreeze fluid which carries the collected heat to a heat exchanger in the preheat tank of the domestic hot water system. Some areas of the solar array have no collector at all; the sunlight is merely admitted directly into the greenhouse area beneath. The total glazed area is about 600 square feet. Of this, 476 square feet furnish hot air for the rock bed storage, 56 square feet are used in the water heating system, and about 70 square feet are direct gain into the greenhouse.

Operation

Sunlight transmitted through the glazing of the collector array is absorbed on the black-painted surfaces of the wire mesh and collector pan, raising the temperature of the metal. The layers of mesh provide a large surface area for the transfer of the absorbed energy from the metal to the air within the collector channel. As the air is warmed, it expands, its density decreases, and it tends to flow up the collector channel into the plenum above the rock bed. As long as the rocks are cooler than the air, they will absorb heat from the air, cooling it. The cooled air becomes denser, and it will flow downward through the rock bed back into the greenhouse where it is available for recycling through the collector. On each cycle, it picks up heat in the collector, transfers the heat to the rocks, and returns to the greenhouse. No blower or pump is needed to power this flow.

When the sun sets, the collector quickly cools below the temperature of the rock bed. The air in the collector channels is then denser than the air in the rock bed, and the thermosiphon flow will reverse itself. The effect of the reverse flow is to transfer heat from the rock bed back into the collector, where it is lost through the glazed surface to the outside. To prevent this loss, both the upper and lower plenums of the rock bin are fitted with manually operated dampers which, when closed, shut off the flow of air to the collector channels and the greenhouse.

Heat is transferred from the rock bed to the house by the auxiliary furnace fan, which draws air upward through the rock bed (where it is heated) and delivers it to the living spaces through ducts. Return air ducts from the living space to the lower rock bed plenum complete the circuit. When heat is being discharged from the rock bed into the house, the fan-powered flow is upward through the rock bed; when the rock bed is being charged, the thermosiphon-powered flow is downward through the rock bed. This pattern assures that the hottest air possible is delivered to the house. The electric heating coils in the auxiliary furnace are controlled by a thermostat located in the upper plenum of the rock bed. If the air exiting the rock bed is not hot enough to effectively heat the house, the thermostat turns on the electric coils to provide auxiliary heat. The fan itself is controlled by a thermostat located on the living room wall.

The solar preheat system for the domestic hot water supply is also a thermosiphon. Copper tubing forms a closed circuit which runs from the solar collector panels to a heat exchanger within the preheat water tank and back to the collector. The collector is a black painted copper sheet to which the tubes are brazed. Sunshine absorbed by the collector warms the antifreeze solution in the tubes, and it flows upward to the heat exchanger where its heat is delivered to the water in the tank. The cooled solution, now denser, flows out of the heat exchanger and back to the solar collector to be recycled. A check valve prevents reverse flow when the sun is not shining. The thermosiphon system is at atmospheric pressure, whereas the hot water supply system is pressurized so that antifreeze cannot contaminate the water supply even if a leak develops in the heat exchanger coils. Figure 3-6 diagrams the hot water system.

Performance

The solar system for this house has been well instrumented and monitored. Temperature data from 28 thermocouples in the collector, rock bin, and greenhouse, as well as the insolation and outside ambient temperature, have been recorded hourly.

Thermocouples installed at the center of one collector module on each of the three layers of wire mesh that form the absorber showed peak temperatures of 194°F while the system was in the charging mode on a clear February day. The maximum difference between the outer and inner mesh temperatures, which occurred during the peaks, was approximately 11°F. Under stagnant conditions (rock bin dampers closed so

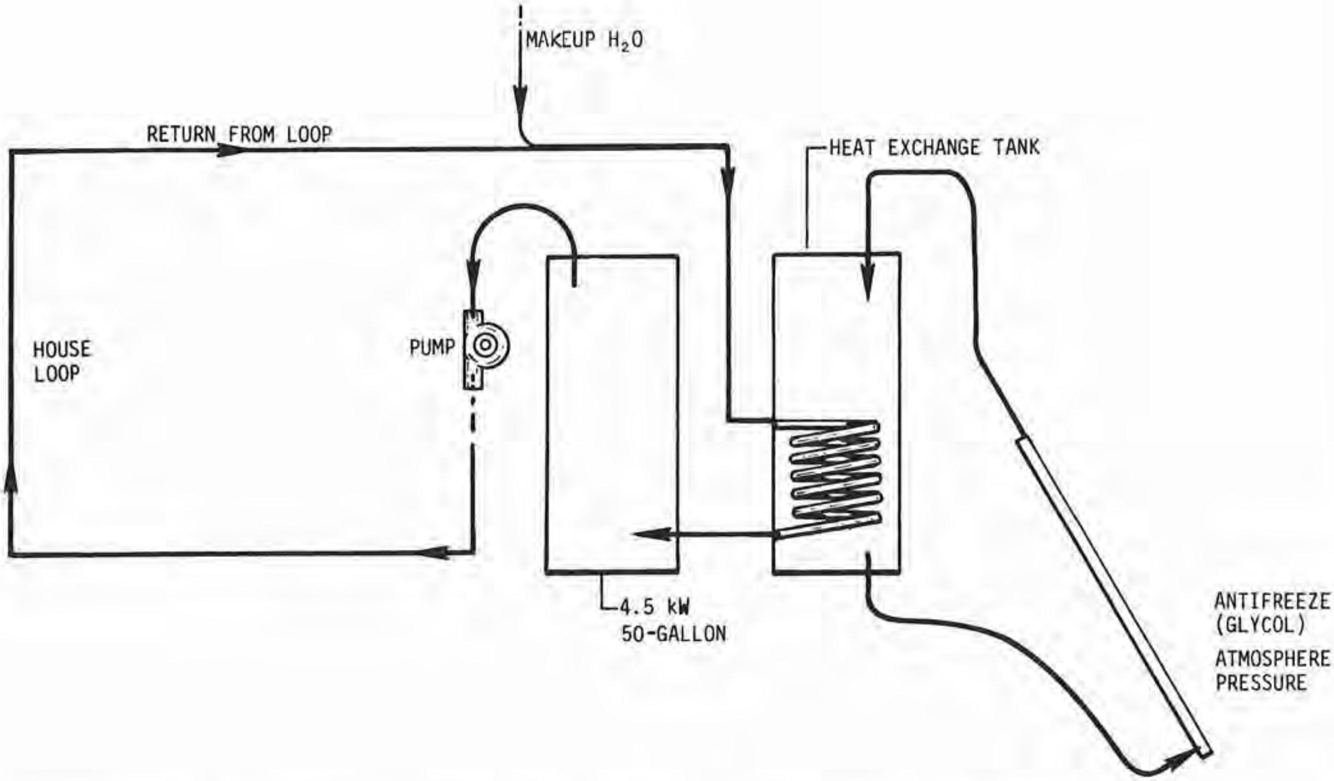


Figure 3-6. Domestic Hot Water Supply System, Mark Jones House

that there is no air flow through the collector) the peak mesh temperatures reached 220°F.

Temperature measurements were taken along the length and across the width of the rock bin to check uniformity of flow through the bin. The maximum temperature difference across the 30-foot length of the rock bin was 7°F, indicating uniform flow patterns in this direction. Across the 4-foot width of the bin, the maximum difference was over 22°F, indicating some "channeling" resulting from the collector discharge air flowing across the rock bed upper plenum to the rear (north) side before descending through the rocks.

Figure 3-7 is a compilation of data recorded at the Jones house during the period December 26, 1978 to January 8, 1979. The weather is shown by the insolation and ambient temperature graphs. It is a

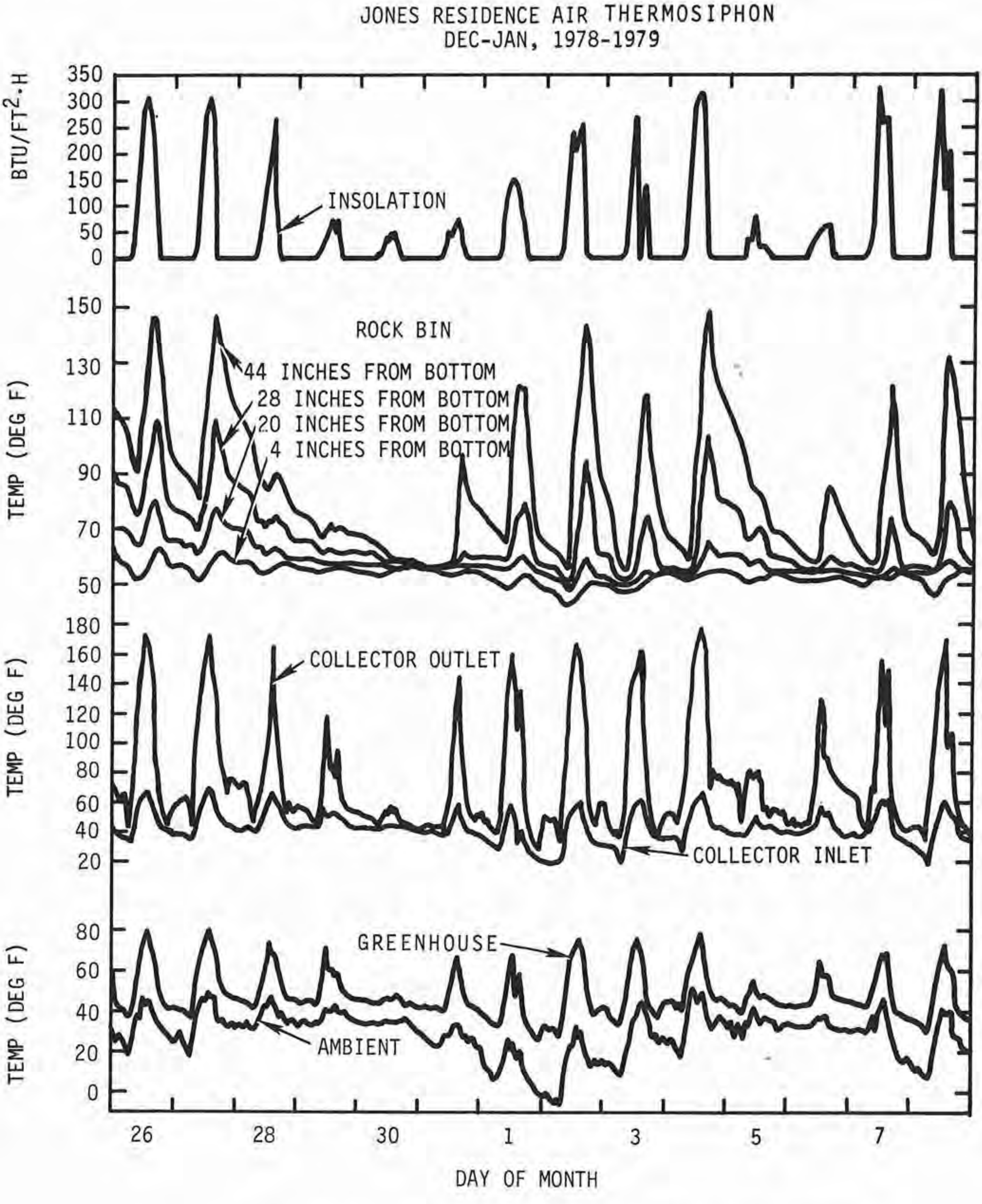


Figure 3-7. Recorded Data for the Jones House

period marked by several cloudy days and some very cold nights. The coldest night (January 1-2, 1979) follows a succession of cloudy days, a very demanding sequence for the solar system.

The temperatures at several levels within the rock bin are shown in Figure 3-7. The thermosiphon flow of air enters the rock bin at the top and exits at the bottom, transferring its heat to the rocks as it passes through. The top layers of rock are therefore the hottest. The characteristics of the thermosiphon system can be illustrated by observing the temperatures that occur along the flow path on a typical day. The week of December 20-27 was a succession of similarly sunny days. The ambient temperature ranged from 10° to 15°F at night to 45° to 50°F in the day. After a week of this type of weather, the long-term (over several days) transients have died out. Taking December 27 as the reference day, the following pattern is observed:

1. The wire mesh at the top of the solar collector reaches a peak temperature of about 182°F. This peak occurs at solar noon when the insulation rate is also at its peak (about 300 $\mathrm{Btu/ft^2 \cdot h}$).
2. The output air temperature of the solar collector reaches 172°F at this same time.
3. By solar noon the top rock bin zone has reached a temperature of about 105°F. The peak temperature of 146°F is reached about 5 hours past solar noon (within 1 hour of sunset). This peak occurs when the temperature of the outlet air from the collector has dropped to the same temperature as the rocks in the top of the bin.
4. The bottom rock bin zone reaches a peak temperature of 62°F. This peak coincides in time with the peak in the top zone.
5. From the bottom of the rock bin the air flows back to the greenhouse to be recycled. The temperature at the floor of the greenhouse, where the collector inlet is located, reaches a peak of 80°F about 2 hours past solar noon.

During the house-heating cycle, air is pulled upward through the rock bin by the furnace fan and then distributed to the living space. The return air ducts run under the floor in the crawl space and provide the air supply to the bottom of the rock bin. It appears that the return air reaches the rock bin at a temperature of about 50°F, since the lowest level of the rock bin drops to that temperature each night. On very cold nights, it drops even lower (e.g., on January 8 and 9, 1979).

Owner/Designer Comments

The hybrid passive/active air thermosiphon system described herein has been quite successful in operation over its first two heating seasons. Temperatures in the house were continually maintained in the 65° to 70°F range during the latter part of the 1977-78 heating season without the use of auxiliary heat. Some auxiliary heat was required in the 1978-79 heating season during cloudy and cold periods such as December 28-January 1, shown on Figure 3-7. The combination of the thermosiphon (passive) storage charging mode and the blower-driven (active) distribution mode simplified the air-handling design and currently saves significant blower energy.

The solar heating system is providing a very stable temperature range and more than adequate comfort. The space-heating characteristics of the system are essentially identical to those of a conventional forced-air heating system. There are no hot spots or cold spots because the ductwork is dampered to balance the distribution of heat throughout the house.

A major objective in designing this house was to incorporate the solar features such that they would not totally dominate other architectural features. Fitting the house into the topography of the site required a very complex framing plan.

Bruce Hunn performed the calculations for the solar system and assisted in the engineering design of the heating system.

Costs

The cost of the collector array (including domestic hot water collector) and greenhouse was $4,100. The rock bin, solar ductwork, damper, controls, and domestic hot water heat exchanger cost $2,400. The total cost of the solar system was $6,500, or $12.22 per square foot of collector surface.

Performance Estimate

The calculated modified building loss coefficient for the Jones house is 20,105 Btu/dd, or 7.59 $\text{Btu/dd} \cdot \text{ft}^2$. Since the methods for estimating performance (see appendix) cannot accommodate the collector/rock-bed system which is the major solar contributor in the house, the collector/rock-bed system performance was first analyzed separately. By using the measured changes in temperature through the rock bed, the daily energy flow through the system could be calculated. Comparing this to the solar energy incident on the collector array gave an estimate of the overall efficiency of the collector/rock-bed system in transferring solar energy into the house. The overall efficiency for the thermosiphon system in the Jones house was 31 percent. This contribution was then treated as an internal source of energy, as shown in Table 3-I. The performance estimate computations were then completed in the normal manner, treating the house as a direct-gain system. The windows provide the direct gain, and they contribute just 10 percent of the house heating requirements. The collector/rock-bed system provides 74 percent of the heating requirements for overall SHF of 84 percent.

TABLE 3-I

Performance Estimate for the Jones House

Month	Degree-Days	Gross (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Heat Supplied By Collector/Rock Bed System (MBtu)	Remaining Load (MBtu)	Solar Radiation on Horiz. Surface $(\mathrm{Btu/ft^2 \cdot mo})$	Solar Radiation Absorbed, Windows (MBtu)	SLR (Windows)	SHF (Windows)	Aux. Energy (MBtu)
January	1,091	21.94	3.13	18.81	10.83	7.98	34,410	3.62	0.45	0.27	5.81
February	882	17.73	2.82	14.91	10.22	4.69	39,732	3.07	0.65	0.39	2.86
March	828	16.65	3.13	13.52	11.56	1.97	58,358	3.09	1.57	0.78	0.43
April	513	10.31	3.02	7.29	11.20	0	68,460	-		1	
May	258	5.19	3.13	2.06	10.89	0	78,740	-		1	
June	68	1.37	3.02	0		0	80,760	-		1	
July	5	0.10	3.13	0		0	72,819	-		1	
August	21	0.42	3.13	0		0	71,331	-		1	
September	116	2.33	3.02	0		0	59,730	-		1	
October	409	8.22	3.13	5.10	11.78	0	49,135	-		1	
November	774	15.56	3.02	12.54	10.61	1.93	35,610	3.70	1.92	0.85	0.28
December	1,042	20.95	3.13	17.82	10.23	7.59	30,845	3.76	0.50	0.30	5.34
Annual				92.05							14.72

$$\text{ANNUAL SHF} = 0.84 \left(\begin{array}{l}\text{Direct Gain} = 0.10 \\ \text{Collector/Rockbed} = 0.74\end{array}\right)$$

SECTION 4

THE WILLIAMSON HOUSE

Figure 4-1. The Ralph Williamson House

BUILDER: Hamilton Migel and Assocs. (Tesuque)
DESIGNER: Dorothy Williamson, with Hamilton Migel and Jeffrey Acyrigg
OWNER: Ralph E. and Dorothy S. Williamson
TYPE: Single family residence
AREA: 1,265 square feet
GENERIC TYPE: Direct gain
LOCATION: Santa Fe County, New Mexico
LATITUDE: 36°N.
ELEVATION: 6,655 feet
CLIMATE DATA: Heating dd: 6,100
Design temp: 0°F
Horiz. insolation (Jan. day): 1,090 Btu/ft^2

Figure 4-2. Sunlight from Clearstory Windows Falling on Adobe North Wall of the Williamson House

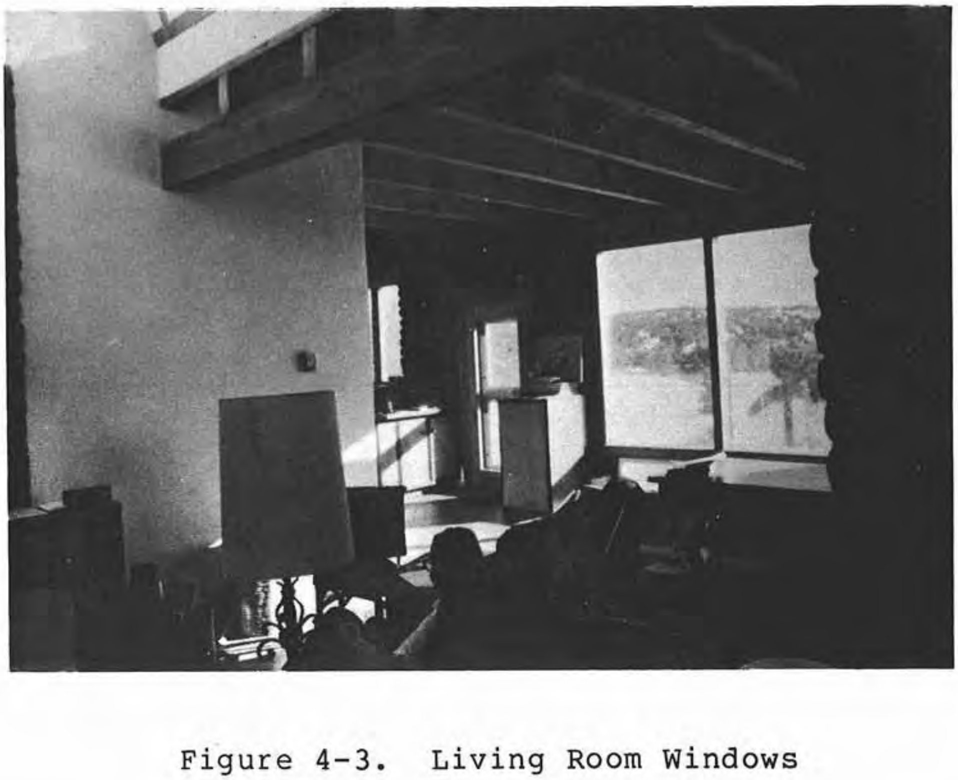


Figure 4-3. Living Room Windows

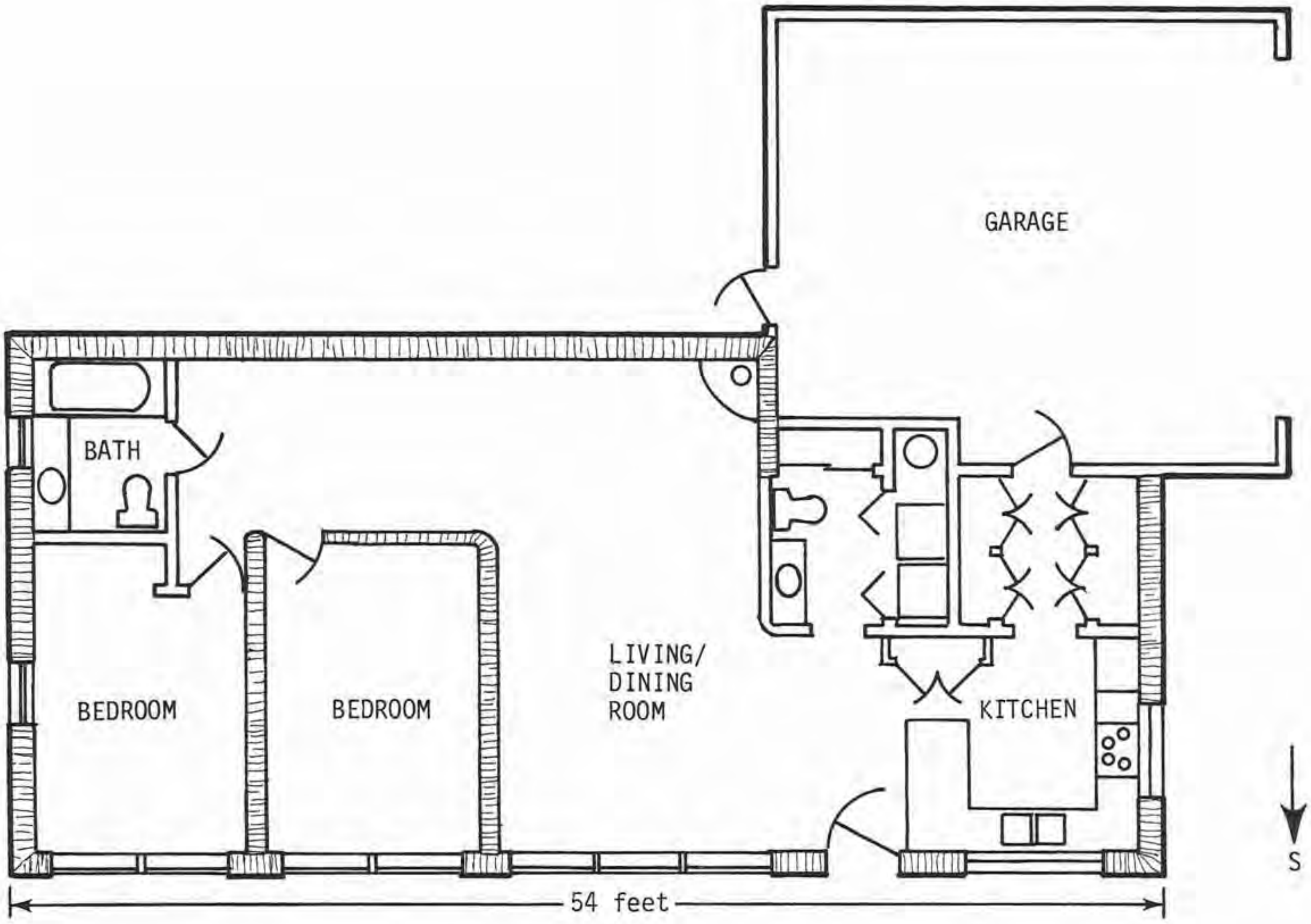


Figure 4-4. Floor Plan of the Williamson House

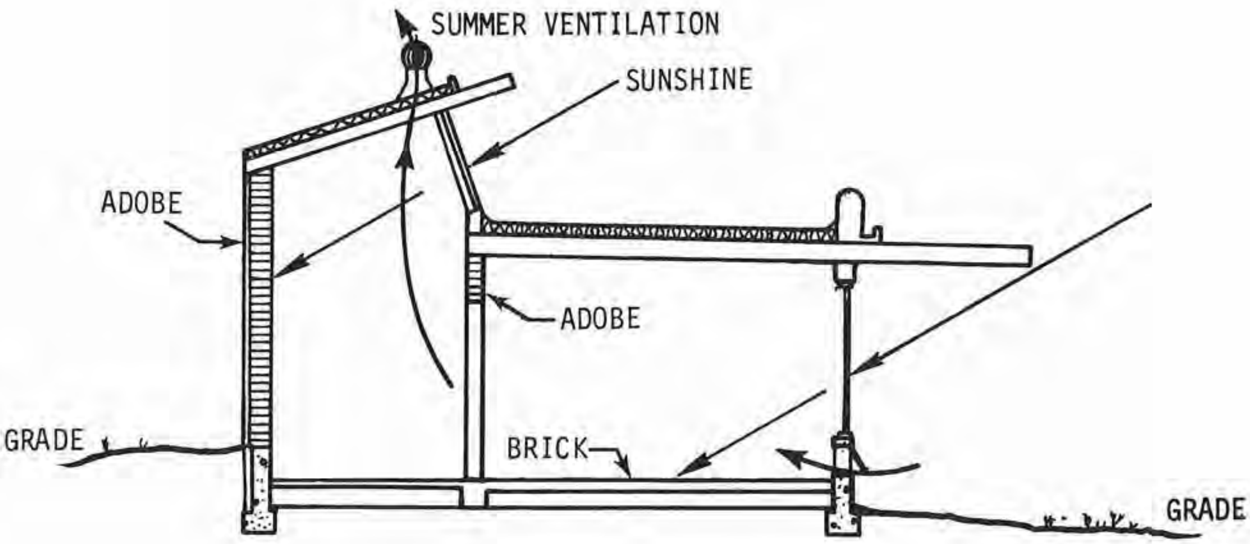


Figure 4-5. Thermal Flow Diagram of the Williamson House

Collectors -- South-facing windows serve as direct-gain collectors. The total south-facing glass area is approximately 310 square feet.

Storage -- The adobe walls and brick floor provide the thermal storage mass for this house.

Distribution -- The solar heat absorbed by the brick floor and adobe walls is distributed to the living space by convection and radiation.

Auxiliary Heat -- Electric baseboard heating units provide auxiliary heat.

Domestic Hot Water -- A flat-plate solar collector provides preheat for the domestic hot water system.

Controls -- Turbine-type ventilators allow venting of excess heat when desired. The auxiliary electric baseboard heating units are controlled by individual thermostats in each room.

Description

The Williamson house has a simple and straightforward floor plan. The basic shape is a rectangle with the long axis oriented east-west. The kitchen, a pantry, and a utility room with a half-bath are located on the east end of the rectangle. Two bedrooms and a full bath are on the west end. In the middle are a living-dining area and a study. The garage is on the north side with access through the pantry.

Running down the middle of the roof for over half the length of the house on the west end is a large clearstory window array. There are five windows in the array, each measuring 46 by 76 inches. The windows face south and are tilted approximately 20 degrees from the vertical. Sunlight entering through these clearstory windows falls on the north adobe wall of the house. Seven more windows of the same size (46 by 76 inches) are in the south wall. Sunlight entering these windows falls on the floor and furnishings of the house. There are no overhangs to shade any of these windows, but projecting roof beams provide the structural support for an overhang if it proves desirable. All windows are double glazed.

Underneath each of the seven major windows in the south wall are small (10- by 28-inch) operable windows for ventilation. The kitchen has standard wood-framed double-glazed windows on the south and east walls.

The exterior walls of the house are 10-inch-thick adobe. The north wall is insulated on the outside with 2 inches of polystyrene and 1 inch of urethane foam. The remaining exterior walls are insulated with 2 inches of polystyrene. The exterior finish for all walls is stucco. The interior walls for the bedrooms are also adobe, medium brown in color. The north wall is bermed to a depth of about 30 inches. The bermed part of the wall is constructed of cement block.

The roof is supported by exposed, rough-sawn 4- by 10-inch beams, decked with 1-inch-thick lumber. The roof insulation is 4 inches of polystyrene covered with Celotex and sealed with built-up asphalt coating. The floor is red brick laid in sand.

The house water supply comes from a well drilled on the property. A flat-plate collector provides preheat for the domestic hot water supply. The collector is a "drain-down" type. Some trouble has been experienced with this system failing to drain down, resulting in freezing and rupturing of the tubes in the collector. When functioning properly, the system preheats water to about 140°F.

A large Spanish-style fireplace is located on the north wall. The fireplace is provided with an outside intake for combustion air and is fitted with a metal faceplate, which is set in place to seal off the fireplace at night and to prevent the warm house air from escaping up the flue. The faceplate can be installed even if the fire is still burning.

Operation

The large expanse of south-facing glass admits a correspondingly large amount of sunshine into the interior of the Williamson house. The red brick floor and brown adobe walls absorb most of the energy and convert it to thermal energy, which is then transferred to the living space by convection and radiation. The large thermal mass of the walls and floor plays a vital role in this process. Due to this large thermal mass, the temperature change in the material is moderate, even when large amounts of solar energy have been absorbed. When the sun has set, the absorbed energy is slowly reemitted into the living spaces. The overall effect is to reduce the peak temperatures created by the sun and to spread the warmth of the day into the night and evening hours.

With such a large amount of direct-gain glass, overheating is a distinct possibility. By opening the small operable windows beneath the main glazings on the south wall and by opening the turbine vents in the roof, excess heat can be quickly flushed out of the interior of the house.

The circulation pump for the solar hot water preheating system is controlled by a temperature sensor on the flat-plate collector. When the sun is shining and the collector is warm, the circulation pump is turned on, pumping water from the preheat tank through the collector and back to the tank again. When the sun is not shining and the collector is cool, the pump remains off. A drain-down system clears the water out of the collector pipes when the circulation pump is off in order to avoid freezeup. A malfunction of this drain-down system resulted in damage to the collector. The electric hot water heater is a standard commercial 42-gallon, 3800-watt system.

The operation of the auxiliary heating system is automatic, requiring only the adjustment of thermostat settings.

Performance

Figure 4-6 is a compilation of data recorded at the Williamson house from December 26, 1978 to January 8, 1979. The period comprises sunny days and cloudy days, and includes some very cold nights, as shown in the insolation and ambient temperature records. The period was preceded by 5 successive sunny days with the ambient temperature ranging between 15° and 40°F.

The air temperature in the Williamson house was not recorded. Instead, the "globe temperature" was recorded. The globe temperature is the temperature registered by a thermocouple inside of a blackened hollow copper sphere. This sphere is suspended near the ceiling of the living room. The black sphere response to both the room air temperature and to any radiation incident on its surface, so the thermocouple inside is responding to both of these phenomena and not to the usual air temperature. The black sphere surface also emits radiation, so it can lose energy to a cold source and therefore be cooler than the surrounding air. This sensor is exposed on one side to the north wall of the house and on the other side to the windows along the south wall. During the day, radiation reflected from, and emitted by, the north wall probably causes the high peak temperatures shown. Likewise, at night, the lows may be below the actual room air temperature because radiant losses from the sphere to the cold windows. The sphere is never exposed to direct sunlight. However, it is close to

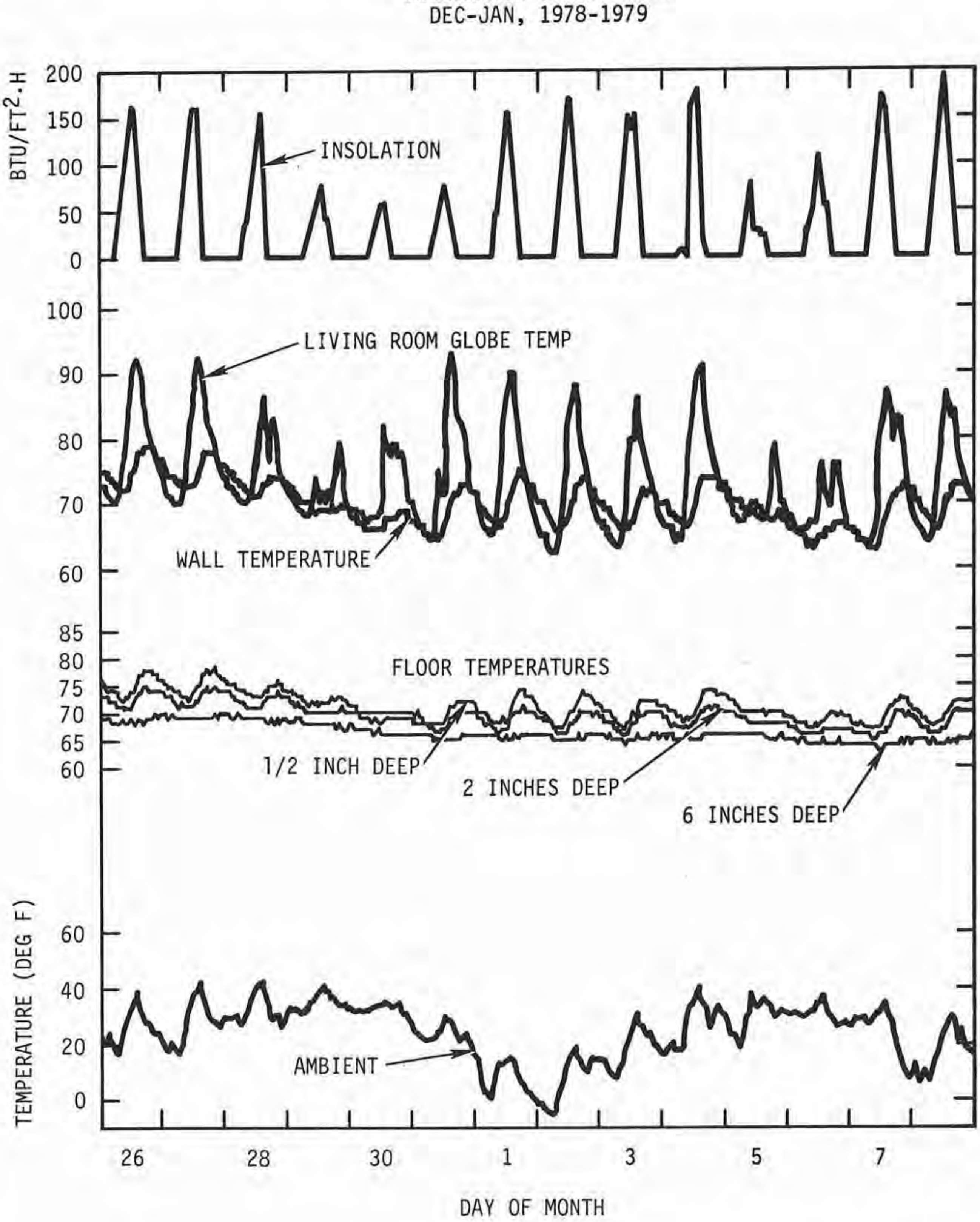


Figure 4-6. Recorded Data for the Williamson House

the fireplace and responds to the infrared radiation emitted whenever there is a fire (e.g., 7 p.m. on December 28, 1978, and 8 p.m. on December 29, 1978.

The temperature data for the back wall (also shown in Figure 4-6) was recorded from a thermocouple buried 2 inches deep in the north wall. This location is exposed to the sun entering through the clear-story windows at this time of year. The record shows the normal diurnal cycle for sunny days and the steady decay of temperature for cloudy days. This north wall is insulated on the outside to reduce heat loss.

The set of floor temperatures shown in Figure 4-6 were recorded at a point 7-1/2 feet from the windows on the south wall, where it is shaded by the placement of living room furniture from direct exposure to sunshine. The diurnal temperature cycle is, nevertheless, very clearly shown at the 1/2-inch and 2-inch depth levels. At the 6-inch level the temperature cycling is pretty well damped out. Other temperature sensors (not shown in Figure 4-6) set at the 1/2-inch depth level, but in a position exposed to direct sunshine, consistently show temperatures of 100°F on each sunny day.

Figure 4-7 shows the temperatures recorded at three different locations in the floor of the living room. The floor near the southern windows is exposed to the sun and is heated to a temperature of approximately 100°F on sunny days (solid curve in Figure 4-7). During the night the absorbed heat is given back to the room until the floor temperature is the same as the room temperature. December 17 and 18 were cloudy days with no sun, and the floor surface shows no temperature pulse on those days. The dashed curve in Figure 4-7 is also a floor surface temperature measurement, but at a point too far from the windows to receive any sun. The moderate daily temperature pulse is due to (1) heat transferred to the floor, (2) reradiation from the sunlit surfaces in the room, and (3) transfer from the warm room air. It is interesting to note that this part of the floor warms up on December 17 and 18 (the cloudy days). The warming is due to

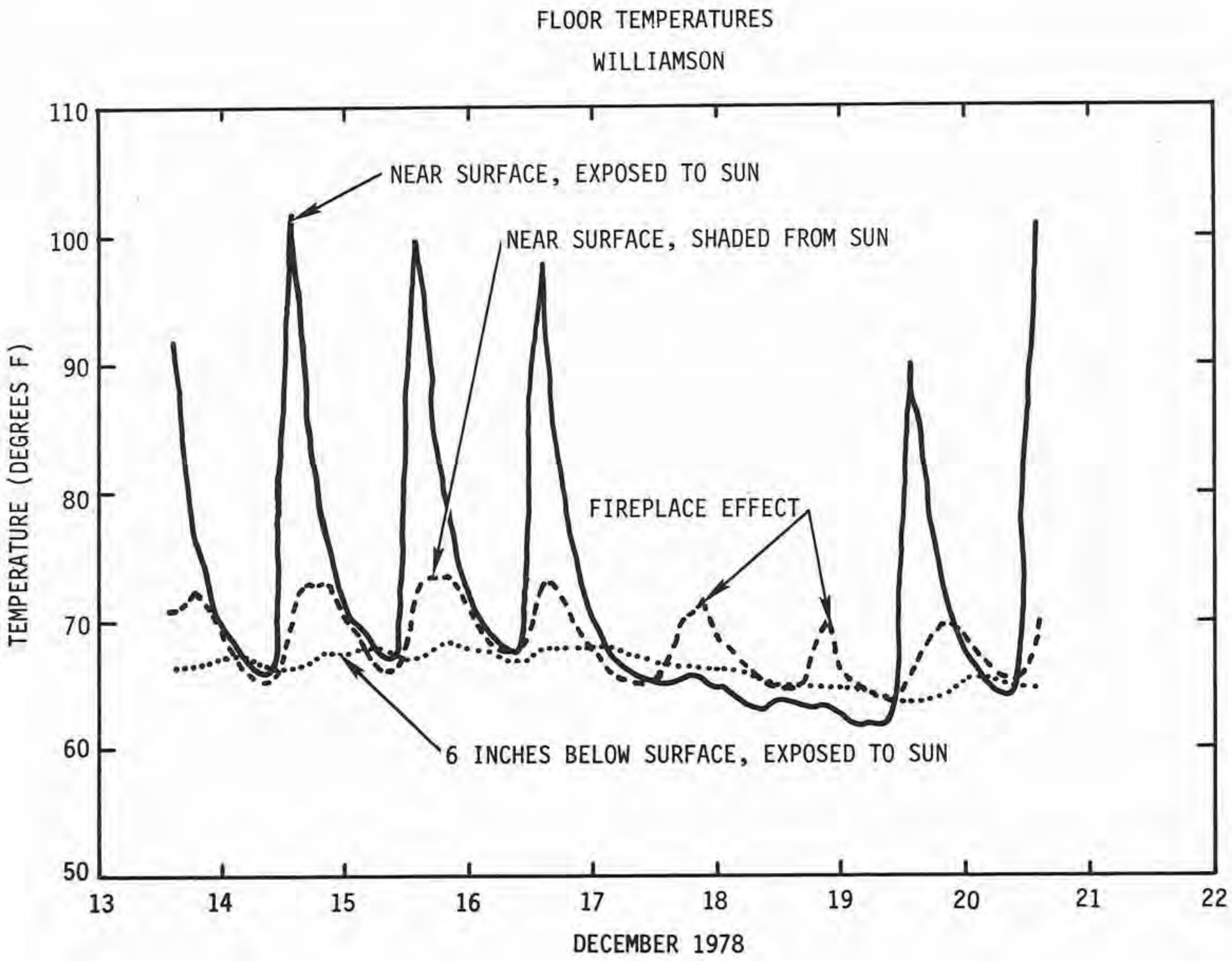


Figure 4-7. Floor Temperatures in the Williamson House

heat from the fireplace, which is used during the evening hours on each of these 2 days. The thermocouple location is about 10 feet from the fireplace. The dotted curve in Figure 4-7 shows temperatures at a depth 6 inches below the surface. Because of the large mass of material involved, only minor temperature changes occur, even on the sunless days.

In summer, this house has proved to be a very pleasant place to live. Even though the windows have no overhangs, little sun enters the house. A ventilation flow from the low operable windows on the south side through the turbine vents on the roof quickly flushes any excess heat. The cool air at this high altitude is essential to this ventilation feature. In late summer/early fall (near the fall equinox), the windows admit lots of sunlight, while the outside ambient temperature has not yet dropped significantly. The sunlight areas of the house get hot but the shady areas remain pleasant. This effect is not repeated during the spring equinox, probably because the outside ambient temperature is lower and there is more cloudiness.

In winter, the house is cool in the mornings, and the auxiliary heating system is sometimes used to warm it up. If the morning is sunny, the house warms quickly without the auxiliary heat.

An exceedingly severe storm struck the Santa Fe area in early December. Table 4-I lists temperatures recorded at the Williamson house during this extreme weather period. These are the lowest temperatures experienced in the house to date.

All utilities in the house are electrically operated. They include auxiliary heat, a TV, a frost-free refrigerator, the kitchen stove and oven, a washer-dryer, the lighting, and a 2-1/2 horsepower motor for the pump on the 600-foot-deep water well. The electric consumption runs between 400 and 500 kWh per month in both winter and summer.

TABLE 4-I

Temperatures Recorded at the Williamson House, December 7-10, 1978

Date	Time	Weather	Outdoor Ambient Temp. (°F)	Indoor Mean Radiant Temp. (°F)
7 December	0700	Snow	8	62
8 December	0700	Sunny	-1	55
9 December	0700	Sunny	-6	58
10 December	0700	Sunny	2	62

Owner Comments

Before occupying this house, the Williamsons were living in a condominium. The dramatic rise in fuel cost in the last few years, and resultant rise in utility bills, taught them the economy of keeping the thermostat turned down, living in a cooler house, and wearing sweaters. Their present house was designed to conserve on utility costs, and has proved a pleasant and satisfying place to live. Their habit of wearing extra clothes has continued during cold and cloudy weather. The improvement is that during periods of sunny weather, the house is comfortable and warm without running up the utility bill.

The designer and contractor for this house were not experienced in solar technology. There was difficulty settling on the construction plans, and the construction costs exceeded the initial estimates. Some problems have occurred. The drain-down system on the solar water heater failed, putting the system out of commmission and requiring repair. On two occasions, seals between glazings in the clearstory windows have ruptured. The caulking in one place around the clearstory windows is faulty and leaks water. The owners also have noted that the house is not tightly sealed and has air leaks that are noticeable on windy days.

Costs

The construction costs for this house were approximately $85,000, which considerably exceeded the construction cost estimate.

Performance Estimate

The modified building loss coefficient for the Williamson house is 14,008 Btu/dd, or 11.07 Btu/dd$\cdot$ft^2. An infiltration rate of one air change per hour was used. The performance estimate methods described in the appendix apply directly to the Williamson house without any modifications. The estimates indicate that the Williamson house receives 72 percent of its heating requirements from the sun. The performance estimate is detailed in Table 4-II.

TABLE 4-II

Performance Estimate for the Williamson House

Month	Degree-Days	Gross (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface ($Btu/ft^2 \cdot mo$)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	1,113	15.59	2.34	13.25	34,403	11.41	0.86	0.64	4.83
February	907	12.70	2.11	10.59	39,746	10.25	0.97	0.68	3.38
March	856	11.99	2.34	9.65	56,348	10.09	1.05	0.71	2.79
April	555	7.77	2.27	5.51	68,468	7.91	1.44	0.82	0.97
May	295	4.13	2.34	1.79	78,751	6.63	3.70	1	0
June	90	1.26	2.27	0	80,745	6.09	-	1	0
July	18	0.25	2.34	0	76,922	6.06	-	1	0
August	44	0.62	2.34	0	71,321	7.31	-	1	0
September	147	2.06	2.27	0	59,729	9.02	-	1	0
October	442	6.19	2.34	3.85	49,148	11.33	2.94	0.96	0.08
November	792	11.09	2.27	8.83	35,616	11.11	1.26	0.73	1.95
December	1,048	14.68	2.34	12.34	30,860	10.90	0.88	0.64	4.38
Annual	6,155			65.81					18.38

ANNUAL SHF = 0.72

SECTION 5

THE GUNDERSON HOUSE

Figure 5-1. The Gunderson House

BUILDER: Wayne Nichols
DESIGNER: Wayne and Susan Nichols and Bill Lumpkin
OWNER: Dave Gunderson
TYPE: Single family dwelling
AREA: 2,200 Square feet
GENERIC TYPE: Direct gain and waterwall
LOCATION: Santa Fe, New Mexico
LATITUDE: 36°N.
ELEVATION: 7,000 feet
CLIMATE DATA: Heating dd: 5,586
Design temp: 11°F
Horiz. insolation (Jan. day):
1,090 Btu/ft^2

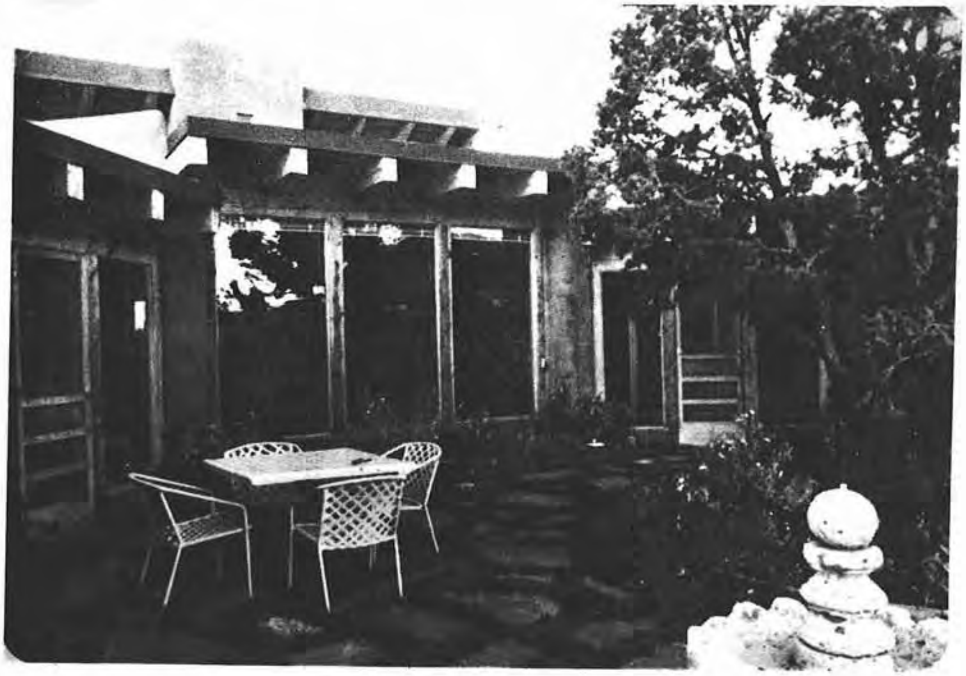


Figure 5-2. A View of the Direct-Gain Windows of the Living Room from the Patio

Figure 5-3. Interior of West Bedroom Showing Waterwall and Clearstory Window

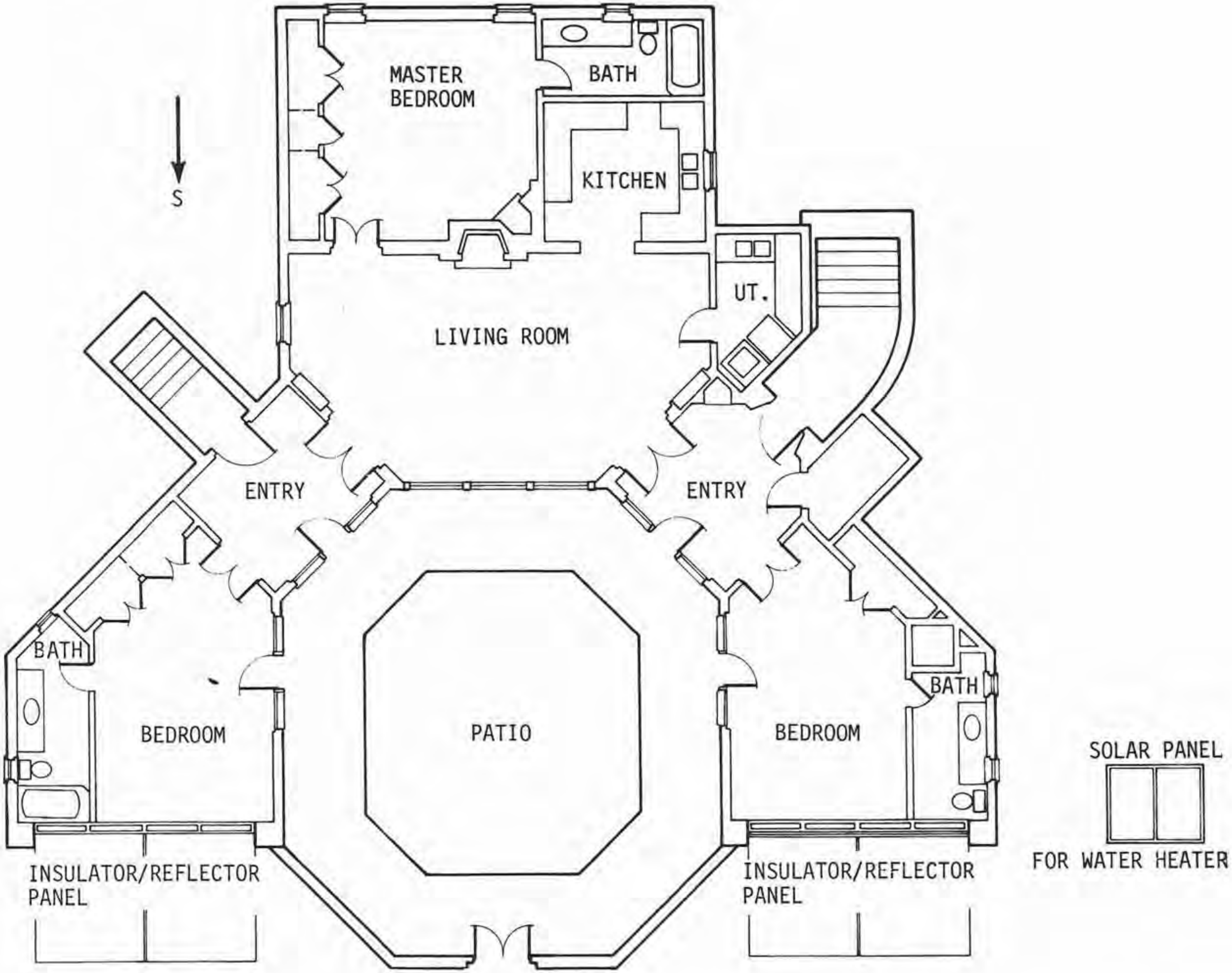


Figure 5-4. Floor Plan of Unit 4, First Village (the Gunderson House)

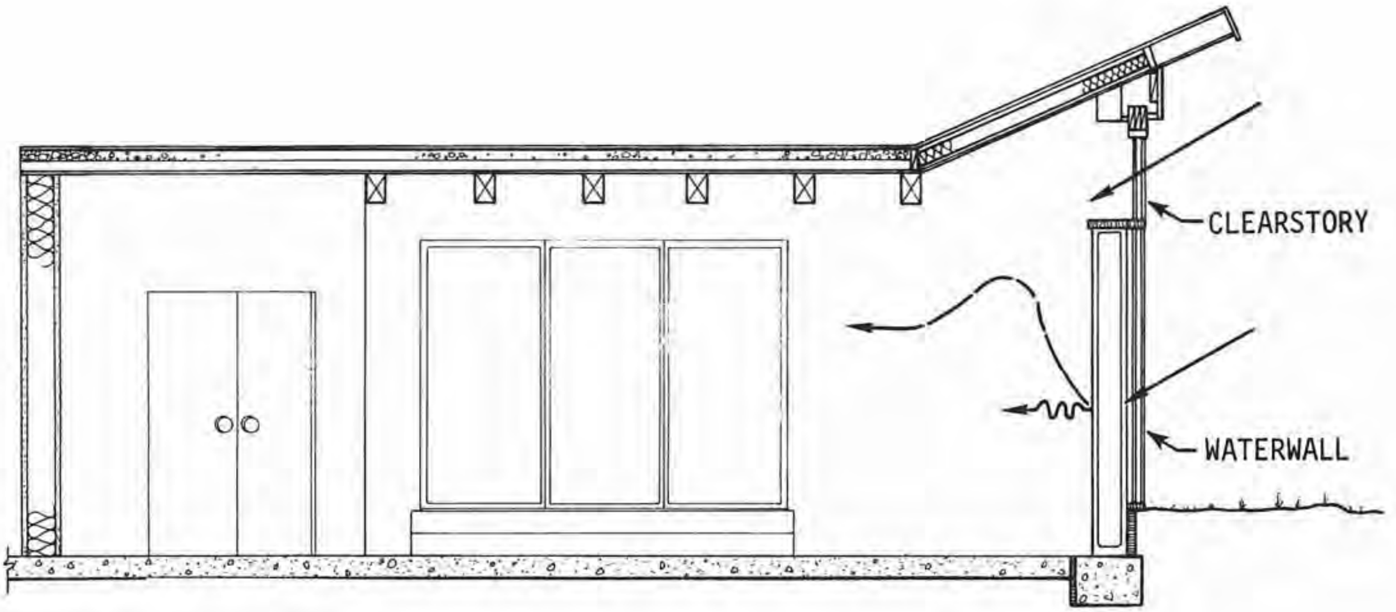


Figure 5-5. Thermal Flow Diagram of Waterwall

Collectors -- The south walls of two of the bedrooms are double-glazed waterwalls. These collectors have movable insulation. The windows facing onto the garden and the clearstory windows all serve as direct-gain collectors.

Storage -- The masonry interior wall, the masonry north wall, and the tile floors provide thermal storage for the direct gain. The two waterwalls are the thermal storage for the two bedrooms on the south side of the house.

Distribution -- The large surface areas of the thermal storage components (walls and floors) transfer heat to the living space by radiation and convection.

Auxiliary Heat -- Each room has electric baseboard heaters to provide backup heating.

Domestic Hot Water -- A flat-plate collector on the southeast side of the house provides preheat for the hot water supply.

Controls -- Movable shutters control the solar gain and thermal losses of the two waterwall systems. Manually operated vents located high on the wall of the living space provide, in conjunction with the windows, ventilation for dumping excess heat. Individual thermostats for each room control the electric backup heat.

Description

Dave Gunderson's house is located on a 5-acre lot 6 miles southeast of Santa Fe, New Mexico. The house is the fourth unit built in a planned solar community called First Village. The control section of the house comprises the living-dining room, kitchen, master bedroom and bath. The kitchen, master bedroom and bath are grouped on the north side of this section and are heated by direct gain through large clearstory windows. Part of the sunlight which enters the kitchen through this clearstory passes through a second, inner clearstory to enter the bathroom.

The south windows of the living-dining area look out upon a large garden and patio area. Two identical wings enclose the east and west sides of the patio. Each wing consists of a bedroom and bath, and each is connected to the central section through a small greenhouse. These two greenhouses serve as airlock entryways to the house and also thermally isolate the two bedroom wings from the central section. The south side of the patio is enclosed by a Spanish-style adobe wall and wooden gate.

The south wall of each of the two bedroom wings is constructed of four precast concrete sections. Each section has a 6-inch-thick cavity which is lined with a plastic bag and filled with water. The exterior side is painted black and double glazed. An insulating shutter, hinged at the bottom, is fitted over the glazing. The shutter is lowered during the day, and its inside surface of polished aluminum reflects the sunlight onto the waterwall to increase its thermal gain. The shutter is manually operated by a crank and cable system mounted on the bedroom ceiling.

The north wall of the house is 12-inch-thick concrete block, with the cells filled with concrete. The interior wall of the central section of the house is 8-inch-thick concrete block, again with the cells filled with concrete. The west wall of the central section is also 8-inch-thick concrete-filled concrete block, and its exterior is insulated with 2 inches of styrofoam. All the other exterior walls of the house are of stud frame construction, with 2- by 8-inch studs at 24-inch intervals. The outside is sheathed with 1/2-inch celotex sheeting and finished with stucco. The inside is sheathed with gypsum board and finished with a thick layer of plaster.

The floor is a 4-inch-thick concrete slab insulated by an 18-inch wide strip of 2-inch-thick styrofoam laid horizontally beneath the slab perimeter. The floor is set 2-1/2 to 4 feet below the grade to further reduce the perimeter heat loss.

The roof is supported by rough-sawn lumber laid over 8- by 10-inch exposed beams. The flat portion of the roof is insulated with 4-inch styrofoam covered with 2 to 4 inches of pumice graded for drainage and sealed with asphalt and gravel. The tilted portion of the roof has 2 by 10's on edge over the rough-sawn boards. This is sheathed with plywood and finished with cedar shingles. The cavities between the 2 by 10's are blown full of cellulose fiber.

The south-facing living room windows and the clearstory windows are thermopane units. All other windows are double-glazed, wood-frame units.

Operation

Unit 4, First Village is a strictly passive solar system, and its operation is correspondingly simple. The central section receives its solar heating from direct gain only. The south-facing living room windows provide 87 square feet of collector area. The clearstory provides 137 square feet of collector area for the master bedroom, bath, and kitchen. The masonry walls and tile floor provide the thermal sink for absorbing the major part of the solar energy admitted by these windows. When the sun sets, this energy is slowly released to the interior to maintain a stable temperature. Without these thermal sinks, the solar energy would be immediately converted to sensible heat, and this part of the house would be uncomfortably warm during the day. Conversely, at night, the temperature would fall to uncomfortably cold levels. The thermal masses modulate the temperature swing through the diurnal cycle. Excess heat can be flushed from the central section through vents located high on the walls near the apex of the tilted roof section. This ventilation can be enhanced by opening the small windows on the north wall, creating a chimney-like flow. Overhangs on all windows limit the solar collection during summer months, when the heat is not needed.

The solar systems for the two bedroom wings are unvented waterwalls. Sunshine passing through the vertical, south-facing double glazing is absorbed on the black absorbing surface. The glazing is unvented, and stagnant hot air builds up here. Part of the absorbed energy is reradiated or conducted back through the stagnant air space and glazings to the outside and is lost. The remaining energy is conducted through the 2-inch-thick concrete and heats the water contained in the wall cavity. The heat is rapidly transferred across the 6-inch water cavity by convection currents and delivered to the inner concrete shell, which is also 2 inches thick. After traversing this last layer of concrete, the heat is transferred to the bedrooms by convection and radiation from the inner wall surface. There is a narrow clearstory window above the waterwall section which admits some direct gain to the bedrooms. The bathrooms in these wings also adjoin the waterwalls and are heated in the same way as the bedrooms.

The movable insulating shutters for the waterwall systems are active (manual) control systems. During winter days, when they are lowered, their reflecting surfaces increase the solar gain to the waterwall, and at night, when they are raised, they reduce heat losses from the waterwall. In the fall and summer, the shutter can be left in the raised position during the day to prevent overheating. Opening doors and windows creates cross ventilation that flushes out excess heat from each bedroom wing.

The small greenhouse rooms which link the bedroom wings to the central section are airlock entryways and also isolate the wings, so that each of the three major sections of the house can be maintained at its own temperature level.

The solar hot water system is a standard commercial model with 33 square feet of collector and propylene glycol for the heat transfer fluid. An electric pump moves the fluid from the collector to the heat transfer coils in the 40-gallon preheat tank. The preheated water flows into a 40-gallon electric hot water heater before delivery to the hot water distribution pipes. The electric system is rarely used; it is turned on only on cloudy days. On the normal, sunny Santa Fe days there is plenty of hot water accumulated from the solar system to supply the household needs, and the housekeeping routine has adjusted to this timing.

The fireplace is a "Heatilator" model. One hot air vent from the heatilator opens to the master bedroom. The other hot air vents open directly into the living and dining area.

Performance

Data recorded at the Gunderson house from December 26, 1978 to January 8, 1979 is shown in Figure 5-6. The insolation and ambient temperatures shown are the same as for the Balcomb house, since the families are neighbors. The two bedroom wings are nearly identical in construction, and their thermal performances have been the same, so only the records of the west bedroom wing are shown. The week preceding the period of record shown in Figure 5-6 was a succession of sunny days with the ambient temperature ranging between 40°F during the day and 20°F at night. The water in the waterwall toward the end of this week was rising to a peak temperature of about 90°F and dropping to about 70°F during the night. Peak temperatures for the outer surface of the waterwall were consistently reaching 140°F. As the cloudy weather moves in, the temperatures in the wall gradually decay to a level of approximately 50°F. On December 31, 1978, a small bit of sun raises the wall temperatures a few degrees. It seems that the movable

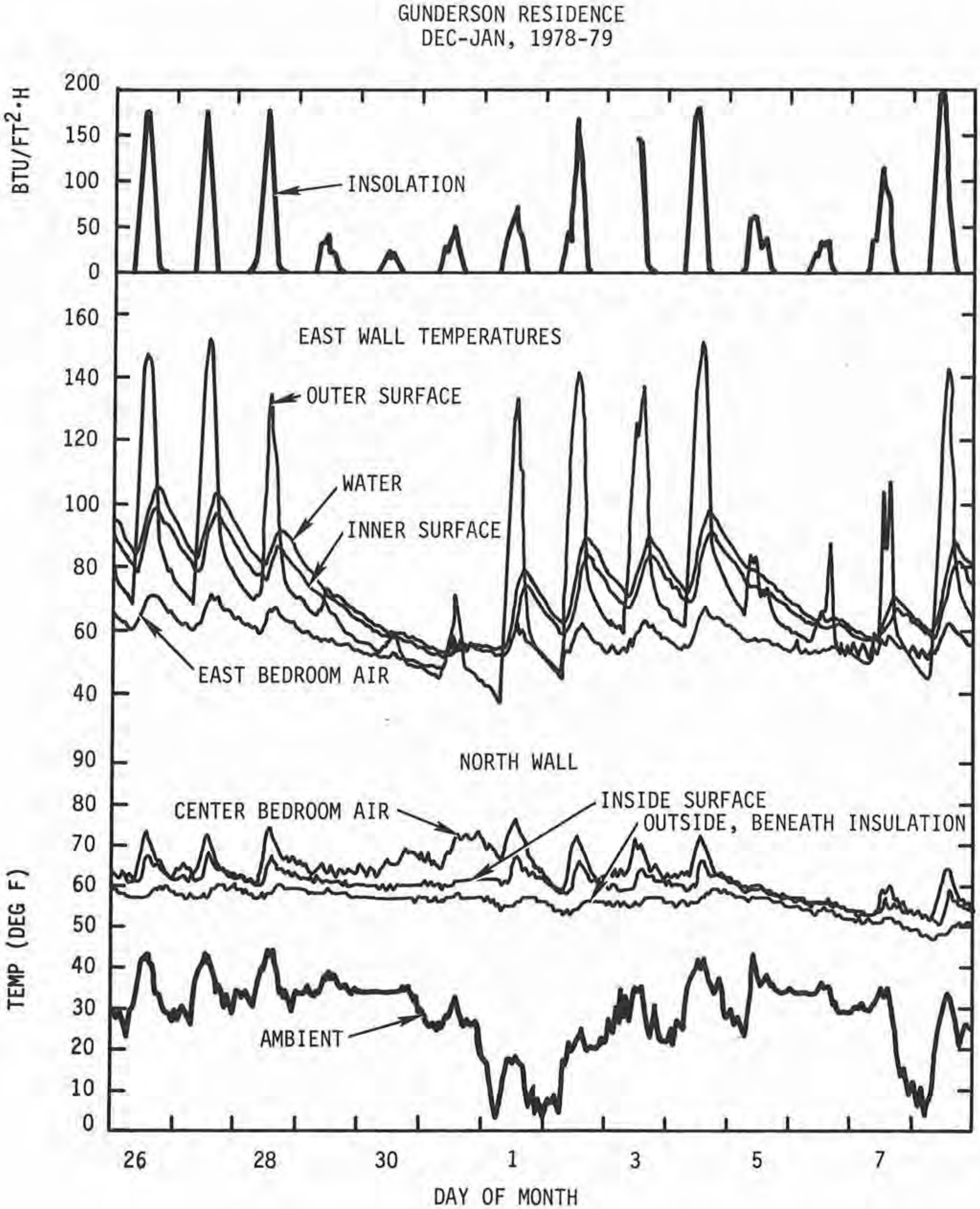


Figure 5-6. Recorded Data for the Gunderson House

insulation is not lowered until about noon, when the sharp spike appears in the outer wall temperature. The warming of the bedroom during the morning is from the direct gain through the clearstory and patio windows. On the night of December 31, 1978, the ambient temperature drops to 0°F, and the outer wall temperature drops significantly below the temperature of the water. During this period the waterwall is taking heat from the bedroom rather than providing it. Fortunately, the sun comes out on January 1, 1979 (Happy New Year!), and the wall is restored as a heating unit. A very similar pattern is shown for the period January 5-8, 1979.

The living room and master bedroom section of the Gunderson house is thermally isolated from the two wings. The solar system in this section is direct gain through the south windows into the living room and through the clearstory windows into the bedroom. The sun through the clearstory falls on the north wall, which is masonry, and acts as thermal storage for the master bedroom space. Figure 5-6 shows the temperatures for this wall as recorded on the inside surface and on the outer surface just beneath the outside insulation. The air temperature in the master bedroom is also shown. The clearstory provides a boost in temperature for the master bedroom each sunny day. The surface temperature of the storage wall is nearly always lower than the bedroom air temperature, and hence cannot contribute much to the heating of that space. The mass of the wall will assist in stabilizing the temperature.

Temperature records taken for the living-room space (not shown in Figure 5-6) are similar to those shown for the master bedroom.

Owner Comments

Dave Gunderson has found the house to be very comfortable through the year. The temperature varies diurnally by 10°F, which is more enjoyable than objectionable. The peak temperatures occur when the house is closed, especially during the fall months. These peaks are immediately reduced by opening doors and windows to vent the excess heat. During the summer, the waterwall shutters are kept closed, but no other actions are taken to exploit summer cooling capabilities. The house is cool enough at night all summer to require a blanket while sleeping. So far, the peak temperature during the summer has been 75°F, and the peak during the fall has been 78°F. The minimum temperature in the house during its recorded year of occupancy was 55°F, and this occurred during a prolonged period in February 1978 when the house (including the waterwall shutters) was closed up, the auxiliary heat was turned off, and the area suffered a series of cloudy days.

Living in this solar house has made Dave Gunderson very aware of the weather: the sun, the wind, the temperature, and cloudy skies. The weather has a definite psychological effect--cloudy days are not good days, they mean a cold house. No changes are recommended in the design. The house is comfortable and livable. It would be nice if the waterwall shutters were motorized and automated, but the expense for such a system is too great.

Performance Estimate

The modified building loss coefficient for the Gunderson house is 24,887 Btu/dd, or 11.31 Btu/dd·ft^2. The house combines direct gain with a waterwall system; the SHF was calculated for both types of systems and a weighted average taken of the two results. The weighting factor was proportional to the amount of energy absorbed by the two different types of systems.

TABLE 5-I

Performance Estimate for the Gunderson House

Month	Degree-Days	Gross (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface (Btu/ft^2·mo)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	1,113	27.70	3.28	24.42	34,403	20.70	0.85	0.63	9.04
February	907	22.57	2.96	19.61	39,746	18.62	0.95	0.68	6.31
March	856	21.30	3.28	18.02	56,348	18.33	1.02	0.71	5.28
April	555	13.81	3.18	10.63	68,468	14.38	1.35	0.82	1.97
May	295	7.34	3.28	4.06	78,751	12.03	2.96	0.99	0.06
June	90	2.24	3.18	0	80,745	11.03	–	1	0
July	18	0.45	3.28	0	76,922	10.99	–	1	0
August	44	1.10	3.28	0	71,321	12.95	–	1	0
September	147	3.66	3.18	0.48	59,729	16.39	33.92	1	0
October	442	11.00	3.28	7.72	49,148	20.58	2.67	0.99	0.05
November	792	19.71	3.18	16.54	35,616	20.17	1.22	0.78	3.67
December	1,048	26.08	3.28	22.80	30,860	19.79	0.87	0.64	8.21
Annual				124.28					34.59

ANNUAL SHF = 0.72

SECTION 6

THE SHANKLAND HOUSE

Figure 6-1. The Shankland House as Seen from the South

BUILDER: Ken Meyer
ARCHITECT: Gerrit W. Zwart
OWNER: T. J. and R. H. Shankland
TYPE: Single family residence
AREA: 2,000 square feet (living area)
GENERIC TYPE: Passive direct gain
Active storage rock bin
LOCATION: White Rock, New Mexico
LATITUDE: 35.8°N.
ELEVATION: 6,400 feet
CLIMATE DATA: Heating dd: 6,350
Design temp: −10°F
Horiz. insolation (Jan. day):
1,090 Btu/ft^2

Figure 6-2. The North Side of the Shankland House

Figure 6-3. The Living and Dining Area of the Shankland House

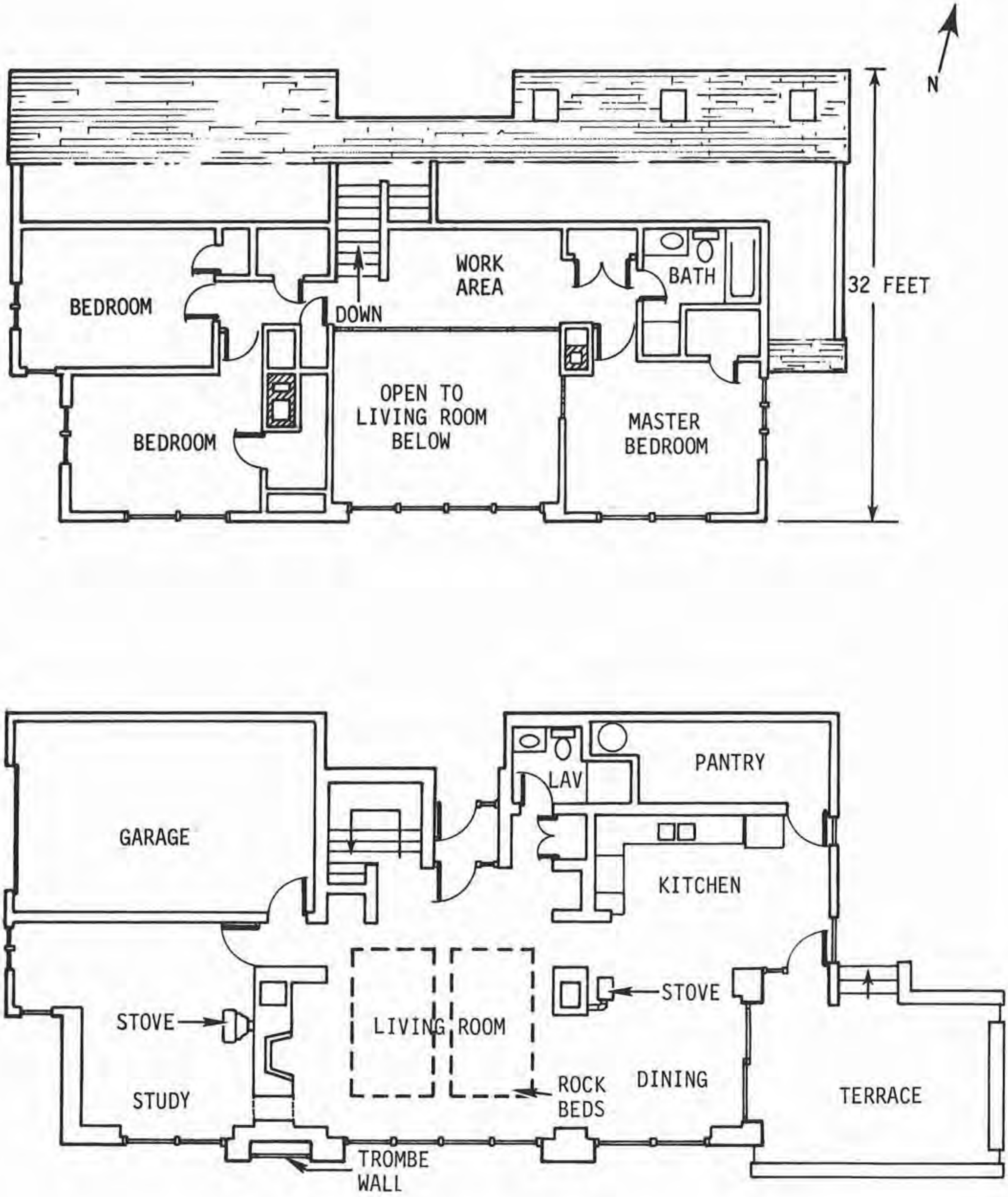


Figure 6-4. Floor Plan for the Shankland House

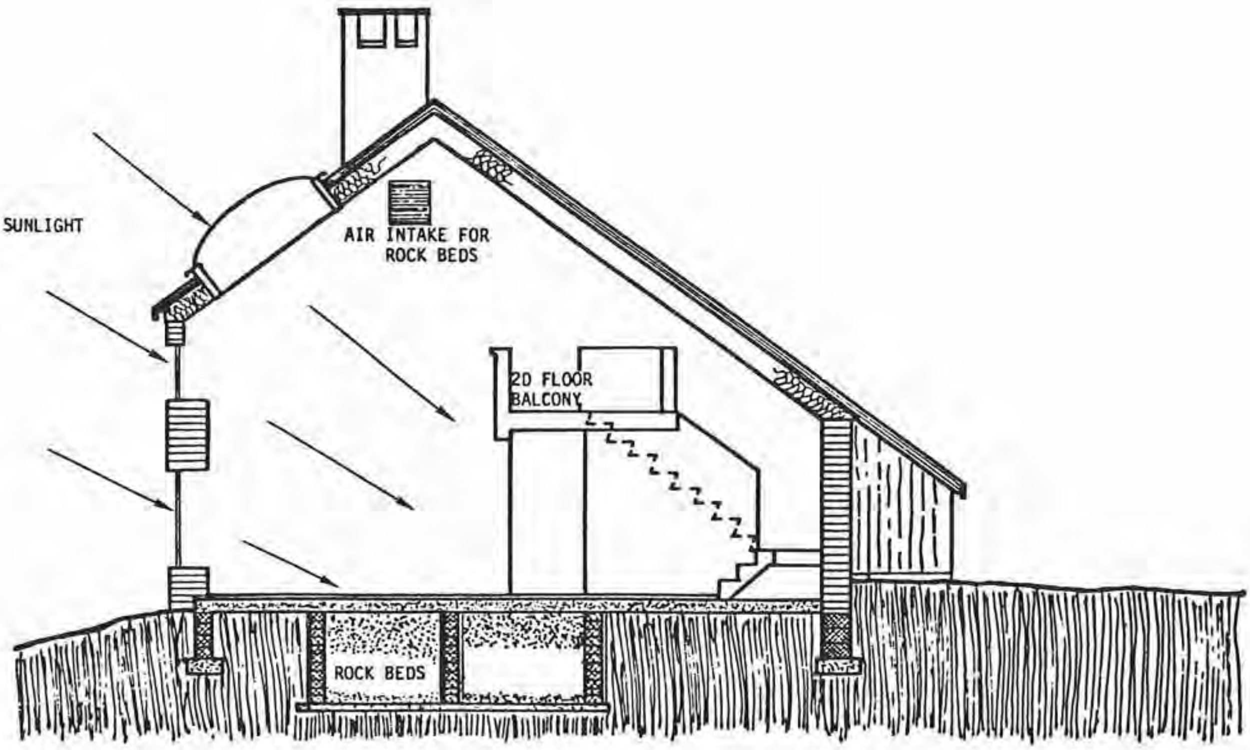


Figure 6-5. Thermal Flow Diagram for the Shankland House

Collectors -- The collectors for this house are direct-gain windows. The south wall has 270 square feet of windows, and the south slope of the roof has 75 feet of louvered skylights. A 30-square-foot Trombe wall supplements the direct gain.

Thermal Storage -- Primary storage consists of the adobe walls and brick floor of the first story. Two rock beds provide an active supplemental storage system. The rock beds are heated by warm air that collects at the apex of the loft.

Distribution -- Radiation and convection from the adobe walls and brick floor distribute heat from the passive storage. Two fans, coupled by ductwork to the two rock beds, distribute heat from the rock beds to the house.

Auxiliary Heat -- Two wood stoves and two electric furnaces can provide auxiliary heat when required.

Domestic Hot Water -- A standard commercial electric hot water heater provides hot water for the house. This system is not integrated with the solar system.

Controls -- A thermostat high in the loft of the house controls the fans for storing heat in the rock beds. A thermostat in the living room controls the forced hot air distribution and the auxiliary heat supply.

Description

The dining room, living room, and study are arranged along the south wall. On the north wall next to the dining room are the kitchen, pantry, and a half-bath. In the center of the north wall is the entryway and stairwell. The garage is located on the west end of the north wall and offers the house partial protection from winter winds. The living room ceiling extends up through the full two stories and is fitted with three skylights of 25 square feet apiece.

At the top of the stairwell, a wide balcony overlooks the living room and is used as a work space. The master bedroom and bath are on the east end of the second floor; there are two bedrooms on the west end. The floor space totals 2,000 square feet.

The first floor is a 6-inch-thick concrete slab surfaced with red brick. The walls, both exterior and interior, are adobe up to the level of the second story. The second story has 2- by 6-inch stud walls finished on the outside with 1-inch insulating sheathing and 5/8-inch plywood. The inside is finished with 5/8-inch wood paneling. The voids between the studs are filled with fiberglass batts.

The windows are all wood frame and double glazed. The skylights over the living room are fitted with a system of automatic operating louvres, manufactured by Zomeworks, called Skylids®. There are five small skylights on the north slope of the roof; they are double glazed with plastic domes. Glazing on the south wall includes 30 square feet of Trombe wall. The total glazed area of the house is 505 square feet, distributed as follows:

- South glass -- 270 square feet
- East glass -- 100 square feet
- West glass -- 30 square feet
- North glass -- 5 square feet
- Skylids® -- 75 square feet
- Skylights -- 25 square feet

It is worth noting that only 30 square feet, or about 6 percent of the total, face toward the north.

The roof is supported on 2- by 10-inch rafters covered with plywood, felt, and 1 inch of urethane insulation. The outside is finished with asphalt shingles; the inside, with sheetrock. The voids are filled with 8-inch-thick fiberglass batt insulation.

Two rock beds are built beneath the floor of the living room. Each bed is connected by ductwork to a grille located high in the loft over the living room. Two fans pull air from the loft, pass it through the rock beds, and exhaust it into the living room at floor level. The sides of the rock beds are insulated with 1 inch of polystyrene. The exhaust from the rock beds is distributed to both ends of the house.

Operation

The solar system of the Shankland house is primarily direct gain, and its operation is consequently very simple. The large glass areas admit sunlight which is largely absorbed into the thermal mass of the floor and walls. Later, when the sun sets, this heat is reemitted by radiation and convection to maintain the temperature in the living space. The kitchen, dining room, and master bedroom all have east-facing windows, and the morning sun warms these rooms early. The remainder of the house is dependent on south-facing windows for its direct gain.

The two-story height of the living room encourages temperature stratification of the air. As the sun pours in through the many windows and the three Skylids®, the warm air rises, with the hottest air collecting in the apex of the loft. The thermostats in the loft turn on the fans, and this hot air is pulled through ductwork down to the rock beds, where the heat is transferred to the rocks. The exhaust air flows back into the living room at floor level to be reheated and recirculated. The rock beds hold 16 tons of rock, which is a small thermal mass in comparison to the thermal mass of the floor and adobe walls (over 100 tons), but it is sufficient to moderate the temperature peaks during the day and provides storage for heat that would othewise be lost or vented.

In the summer the Skylids® are kept shut to exclude sunlight and prevent excessive temperatures. The small (30-square-foot) Trombe wall section was installed to provide heat storage and to shade part of the house from the glare of direct gain. The Trombe wall outlet is in the upstairs southeast bedroom and provides additional heat for that area.

When the house needs heat, the fans can be operated to pull heat from the storage rock beds and distribute it to the house. If the rock beds are too depleted to provide sufficient heat, the electric furnace is turned on.

Performance

This house has been monitored by LASL. Figure 6-6 is a graph of data recorded during the period February 21-25, 1978.

The wall and floor temperatures, shown in Figure 6-6(a), display the characteristic diurnal temperature oscillation. Also, the correspondence of temperature modulation to depth into the medium is apparent. In the case of the floor at a depth of 18 inches, the peaks are altogether wiped out, and only long-term, gradual trends can be distinguished.

Figure 6-6(b) shows temperature variations at various locations within the rock bed. Figure 6-6(c) shows the air temperatures in the loft and in the downstairs hallway. The most obvious characteristic is the strong daytime temperature stratification. Loft temperatures reach 80°F while the hallway temperatures are in the 60's. The upstairs hall is always warmer by several degrees than downstairs. At night the loft temperature drops into the 50's--sometimes lower than the downstairs hallway temperature.

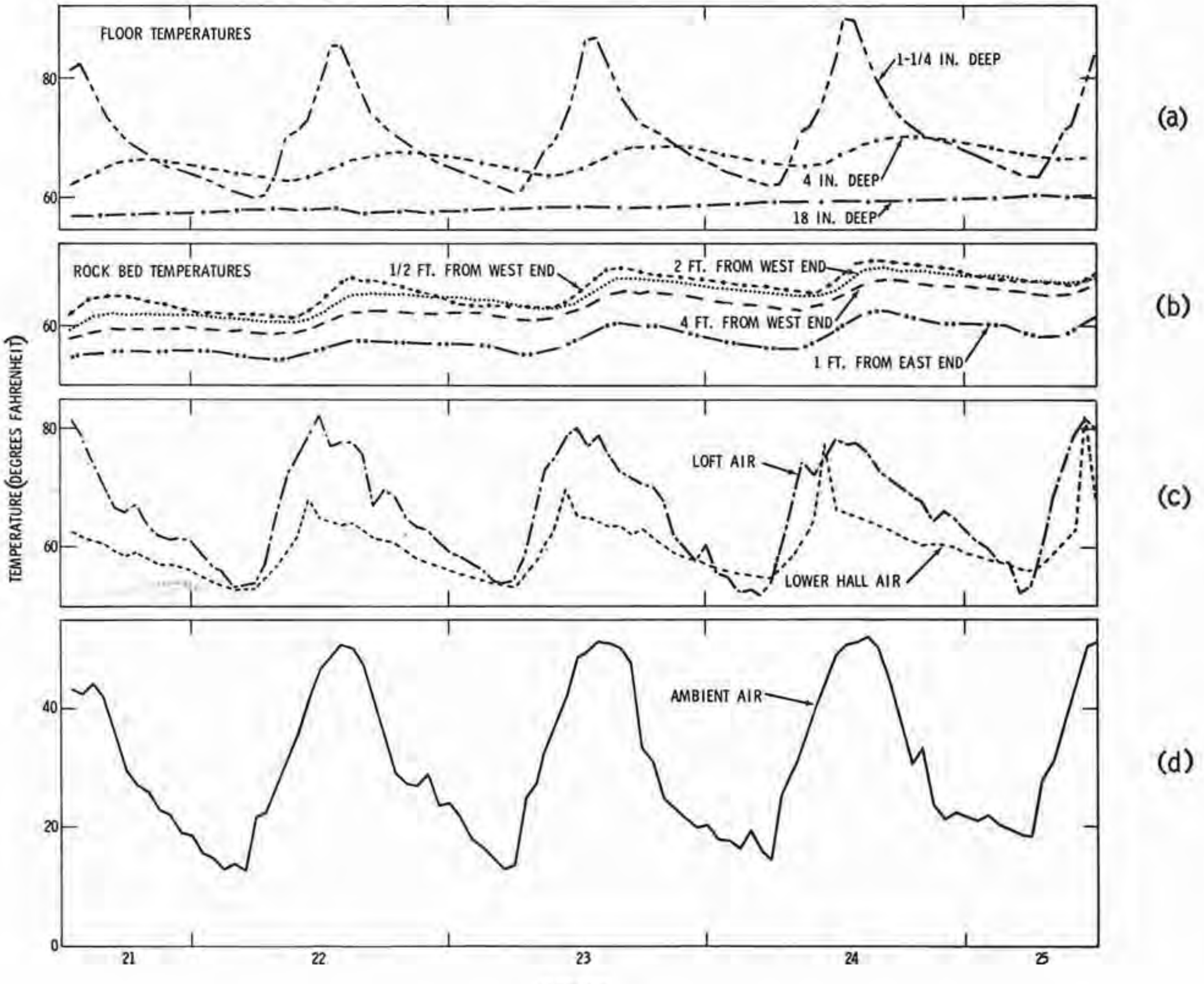


Figure 6-6. Performance Data for the Shankland House, February 21-25, 1978

The peak temperature in the house during summer was 85°F. The lowest temperature, which occurred after a severe winter storm in December 1978, was a very cool 44°F when the outdoor temperature was -15°F. The Shanklands have never used the auxiliary heating system in this house, even during the December 1978 storm, but they often use the wood stoves. The fireplace has seldom been used.

Owner Comments

Tom Shankland remarks that this "house follows the weather." The house is often cool, but the backup heating system has not yet been used. Draperies for the windows help conserve heat at night, but they were not hung until February 1978, after the dates for the data shown in the figures.

Very few changes in the design would be recommended. Water pipes are embedded in the north wall, and this is a mistake. The wall is cold, and the pipes are subject to freezing. As a solar house, the windows are the collectors, and the ratio of window area to floor area should be greater for an optimum solar system; but it would be difficult to increase the south facing window area over what is already in the house. The skylights on the north roof are noticeable heat leaks even though they are double glazed. It might be better to leave them out.

The house itself is of very tight construction and has an exceptionally low infiltration rate.

Designer Comments

> This project represents an effort to provide the basic housing needs of a family of four, to take advantage of a spectacular site and to make the sun the major source of heating in winter without overheating in summer and without the high costs associated with 'active' solar systems. Completed in July of 1977, this is basically a passive house with an 'active' circulation and storage system. The system results in reduction of the peak highs and lows of the temperature curve which are common to many passive designs.

The preceding is quoted from a report by Gerrit Zwart, A Hybrid Solar System in Los Alamos, New Mexico. Gerrit Zwart also indicates that in doing the design again he would make the rock beds larger, underlying the whole living room area, and would insulate them underneath.

Costs

The construction costs for this house were $65,000, excluding the land costs.

Performance Estimate

The modified building loss coefficient for the Shankland house is 21,181 Btu/dd, or 10.59 Btu/ft^2·dd. The rock bed contribution of 67,200 Btu/day was based on an average temperature swing in the rock bed of 15°F each day. This rock bed contribution was added to the heat absorbed by the direct-gain system before computing the solar load ratio (SLR). The gross load shown in the performance estimate is about 10 to 15 percent higher than that used by the architect in the design analysis. The internal source estimate used by the architect was 3.5 MBtu/mo. Also, the architect's calculation of solar radiation absorbed was 10 to 15 percent higher than what was calculated for the performance estimate, winter gains being higher and summer gains lower.

The performance estimate is summarized in Table 6-I.

TABLE 6-I

Performance Estimate for the Shankland House

Month	Degree-Days	Gross (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface $(Btu/ft^2 \cdot mo)$	Solar Radiation Absorbed (MBtu)	Rock Bed Contribution (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	1,113	23.57	3.898	19.68	34,403	10.63	2.08	0.65	0.52	9.39
February	907	19.21	3.521	15.70	39,746	11.04	1.88	0.82	0.62	6.00
March	856	18.13	3.898	14.24	56,348	11.61	2.08	0.96	0.68	4.59
April	555	11.76	3.773	7.99	68,468	10.08	2.02	1.51	0.84	1.27
May	295	6.25	3.898	2.35	78,751	9.17	2.08	4.79	1	0
June	90	1.91	3.773	0	80,745	-	-	-	1	0
July	18	0.38	3.898	0	76,922	-	-	-	1	0
August	44	0.93	3.898	0	71,321	-	-	-	1	0
September	147	3.11	3.773	0	59,729	-	-	-	1	0
October	442	9.36	3.898	5.47	49,148	12.16	2.08	2.61	0.97	0.19
November	792	16.78	3.773	13.01	35,616	11.48	2.02	1.04	0.71	3.80
December	1,048	22.20	3.898	18.31	30,860	11.17	2.08	0.72	0.57	7.93
Annual	6,155			96.74						33.16

ANNUAL SHF = 0.66

SECTION 7

THE DOVE PUBLICATIONS BUILDING

Figure 7-1. The Dove Publications Building at the Benedictine Abbey, Pecos, New Mexico

BUILDER: Mike Hansen
DESIGNER: Mike Hansen
OWNER: Benedictine Monastery
TYPE: Warehouse and office building
AREA: 7,700 square feet
GENERIC TYPE: Waterwall and direct gain
LOCATION: Pecos, New Mexico
LATITUDE: 36°N.
ELEVATION: 7,000 feet
CLIMATE DATA: Heating dd: 6,600
Design temp: 27°F (65°F inside)
Horiz. insolation (Jan. day): 1100 Btu/ft^2

Figure 7-2. An Office within the Dove Publications Building

Figure 7-3. The Warehouse Space in the Building

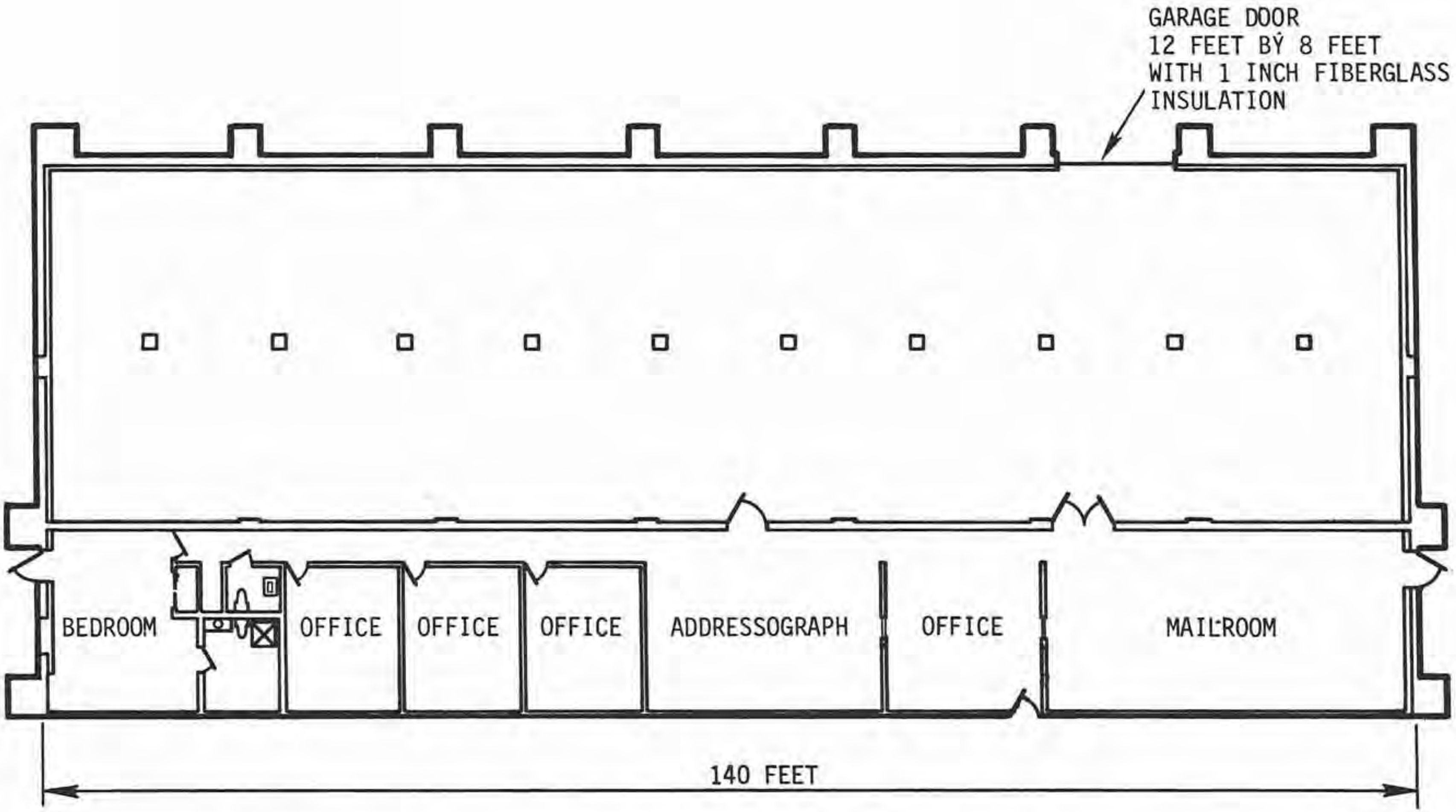


Figure 7-4. Floor Plan for the Dove Publications Building

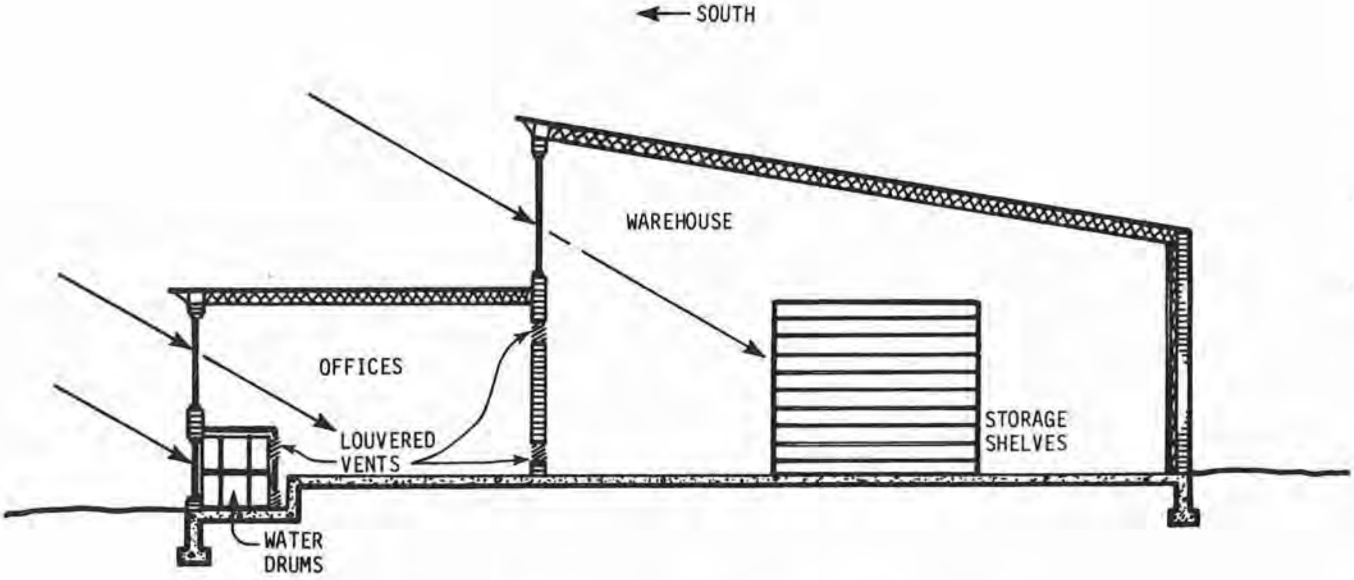


Figure 7-5. Thermal Flow Diagram

Collectors -- Three rows of windows running the length of the south wall are the collectors for this building. The bottom row admits sunlight to the drum storage system. The middle row provides direct gain to the office spaces. The top row provides direct gain to the warehouse area.

Storage -- 138 water drums (55-gallon capacity each) provide the primary thermal storage. An internal sand-filled concrete block wall supplements the primary thermal storage.

Distribution -- Heat from the water drum storage is delivered to the office space by convection. Vents between the warehouse area and the office spaces allow heat to be transferred to the warehouse area if required.

Auxiliary Heat -- Electric radiant panels mounted on the office walls provide backup heat in the office space. There is no backup system for the warehouse area.

Domestic Hot Water -- A flat-plate collector supplies the hot water for the apartment included in the building.

Controls -- Manually operated vents control the flow of heat from the water drum area into the office space. Other manual vents control the flow of heat from the office space into the warehouse area.

Description

The Pecos Benedictine Monastery lies in the narrow valley of the Pecos River 25 miles east of Santa Fe, New Mexico. A subordinate organization called Dove Publications edits, stores, and distributes printed religious literature. The growth of this operation required the construction of an expanded facility. In addition to offices, a warehouse was needed to store printed material prior to its distribution. The building concept selected was a combined office and warehouse structure. Because of rising fuel costs, it was decided to incorporate passive solar heating into the design. The building was designed by architect Mike Hansen in conjunction with Steve Baer and his Zomeworks firm.

The building is a rectangle 140 feet long by 55 feet wide, with the long axis running east-west. The offices, a mailroom, and an apartment (for a full-time occupant) are arranged along the south wall. Two rows of windows run the entire length of this wall and occupy its entire area (with the exception of an entryway). The ground-level row of windows admits sun to the inside of an insulated cabinet containing 55-gallon drums filled with a mixture of water and propylene glycol, with a little 10-weight oil added as a rust inhibitor. The floor of the cabinet is countersunk below the office floor. The top of the cabinet is at a convenient working height and serves as a wide shelf and counter. Each window is fitted with an aluminum cover hinged along its lower edge so that it can be laid flat on the ground as a reflector or raised at night as a cover. On the inside, two sets of louvered grilles allow air to circulate into the cabinet, around the drums, and back to the office space. The grilles are manually opened or shut. There are 33 double-glazed windows in the row, each measuring 41 by 44 inches. There are 138 drums in the cabinet.

A second row of 33 windows runs parallel to, and directly above, this ground-level row. These windows open directly into the office space. There are 33 double-glazed windows in the second row also, but they measure 41 by 42 inches.

The entire north side of the building, 36 feet wide and 140 feet long, is open warehouse space. A sand-filled cement block wall separates the warehouse space from the offices. Above this wall is a row of clearstory windows which admit sun into the warehouse space. There are 34 of these windows, each measuring 41 by 53 inches.

The north, east, and west walls are 8-inch cement block, insulated on the inside surface with a 2-inch layer of styrofoam. The floor is a concrete slab. The foundation perimeter is insulated with 1-inch styrofoam to a depth of 2 feet below grade.

The roof is supported on 10-inch-diameter vigas (poles). The vigas are covered with a layer of 1-inch rough-sawn boards, on top of which is erected a grid of 2 by 6's. The space between the 2 by 6's is filled with fiberglass insulation, and the whole array is covered with corrugated galvanized iron and sealed with felt and asphalt.

The apartment is supplied with hot water by a flat-plate solar collector.

Backup heat is supplied by nine 1,440-watt electric radiant heating panels mounted on the office walls. The panels are controlled by manually operated switches. There is no auxiliary heating system for the warehouse area. The north wall of the warehouse is penetrated by a 12- by 8-foot garage door insulated with 1 inch of fiberglass.

Operation

Solar insolation through the lower row of windows is collected by the stacked water drums, which are painted black. The water in the drums is warmed, but the insulated cabinet prevents the heat from being transferred to the office space unless the ventilating louvers are opened. If the louvres are opened, air moves by natural convection through the floor vents into the cabinet space, where it is warmed by the water drums. The warm air rises, passes through the vents along the upper edge of the cabinet wall, and flows into the office space. Normally the louvres are closed during the day and opened during the night. The upper-row windows provide direct-gain heating for the offices during the day. The clearstory windows provide direct-gain heating into the warehouse area.

The water drums are the major thermal storage component. The concrete floor slab and internal, sand-filled cement block wall supplement the water drums. Vents in the cement block wall can be opened to transfer warm air by natural convection from the office space into the warehouse. The east and west end walls are provided with vents in case the warehouse overheats.

Performance

Instrumentation provided by LASL has been used to monitor the temperature performance of the drumwall. Figure 7-6 illustrates representative data collected during the period February 18-22, 1977. Notice that the office temperatures range from 62° to 78°F and the warehouse temperatures average above 50°F during this period, even though the outside temperature often drops below 20°F.

A predictable 12°F temperature variation in the warehouse from the winter to the summer has been observed. Although the warehouse was designed to maintain a minimum temperature of 45°F, the average minimum temperature experienced thus far has been 50°F, and the lowest temperature in the warehouse has been 48°F, which was seen on only two or three occasions during the winter. The solar heating system has usually maintained a temperature of 62° to 65°F in the offices when the doors are closed, and the lowest temperature seen in the offices (55°F) occurred only during nonworking hours.

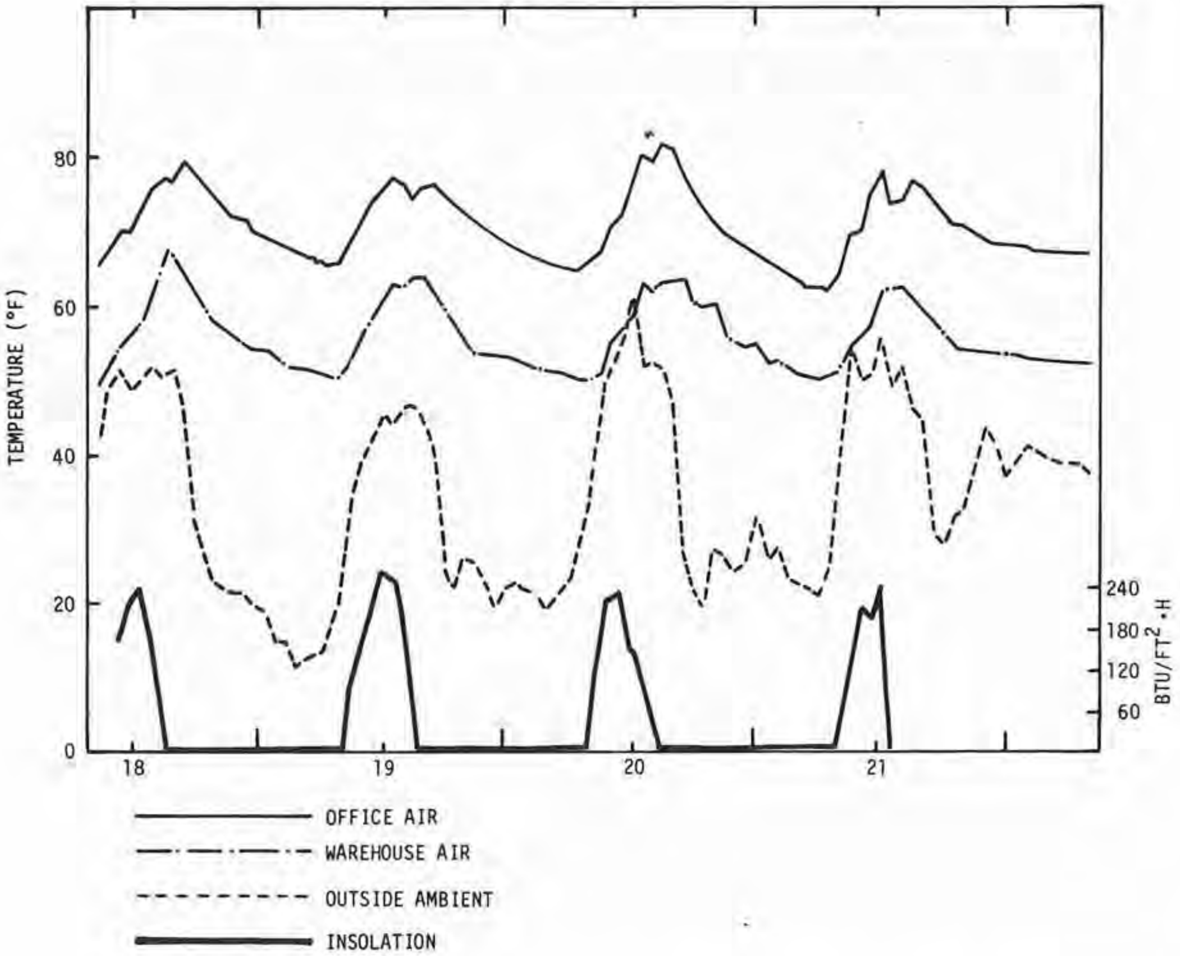


Figure 7-6. Representative Data Traces from the Dove Publications Warehouse

Vents on the east and west walls of the building have never been used, as no overheating problems have been experienced. The vents between the office area and the warehouse are normally kept closed, but on occasions when they have been opened, warehouse temperatures have increased by as much as 10°F.

Fuel costs for this building have been minimal since the backup heating system has rarely been needed. In fact, the one full-time occupant who resided in the building during an entire winter did not find it necessary to use the electric backup heating at all. Only during March and April, when several sunless days occurred, was it necessary to employ the backup heating system during working hours. The total cost of heating electricity for this building from August 1977 through June 1978 (nearly 11 months) has amounted to only $80.63.

Designer/Builder Comments

The design of this building was started in late 1972. Construction began in mid-1973 and continued into 1975. The major portion of the construction was accomplished by only three people, one of whom was the designer, Mike Hansen.

The occupants of the building have noted that it is comfortable, quiet, and without drafts. It has been described as a "very gentle" building, an appropriate characteristic for a monastery. The building is the best-heated structure in the whole monastery complex, but it should be noted that the monastic life is not devoted to high building temperatures. On spring mornings, before the sun heats the offices through the direct gain windows, it is quite cool. The vents to the water storage cabinet are kept closed during the day to store heat. At night they are opened to keep the offices warmed and prepared for the start of the next day.

In the design of the building, the two sections--the front office section and the rear warehouse section--were treated separately according to their individual functions. The office space needs higher and more uniform temperatures, while the warehouse space temperature can vary a considerable amount without discomfort to people engaged in active work.

The key features are the drumwall and the direct gain into the warehouse. The extensively glazed south wall required special design attention to assure it would be able to carry the roof and snow loads. Construction of the south-facing walls had to be very precise because the glass lites cannot accommodate to any errors or variations in dimensions.

There is not enough thermal mass in the office section (the drum storage is thermally isolated), and the offices tend to overheat in the fall. Cloudiness in the spring prevents overheating in that season. The curtains on the windows block direct sunlight but do not screen out the sun's heat.

Cost

The total construction cost of approximately $130,000 corresponds to a unitary cost of only $13 per square foot. Of that total, approximately $8,500 is attributable to the solar portion of the building, and this amount is expected to have a 2-year payback. Three people worked full-time during the construction and required 1-1/2 years to complete the building for operation.

Performance Estimate

The performance estimate for the Dove Publications building considers the office area only. Heat flowing from the office area to the warehouse area through the masonry wall separating them was treated as part of the heat load on the office area. The modified building loss coefficient for the office area is 24,650 Btu/dd using an infiltration rate of one air change per hour. The data are summarized in Table 7-I.

TABLE 7-I

Performance Estimate for the Dove Publications Building

Month	Degree-Days	Gross Load (MBtu)	Warehouse Load (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface ($Btu/ft^2 \cdot mo$)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	1,113	27.44	3.13	1.94	28.62	34,403	37.89	1.32	0.71	8.33
February	907	22.36	2.83	1.75	23.43	39,746	35.16	1.50	0.76	5.58
March	856	21.10	3.13	1.94	22.29	56,348	34.30	1.54	0.77	5.08
April	555	13.68	3.02	1.88	14.83	68,468	24.94	1.68	0.81	2.86
May	295	7.27	3.13	1.94	8.46	78,751	19.11	2.26	0.90	0.82
June	90	2.22	3.02	1.88	3.36	80,745		-	1	0
July	18	0.44	3.13	1.94	1.63	76,922		-	1	0
August	44	1.08	3.13	1.94	2.27	71,321		-	1	0
September	147	3.62	3.02	1.88	4.77	59,729		-	1	0
October	442	10.90	3.13	1.94	12.08	49,148	38.85	3.22	0.98	0.30
November	792	19.52	3.02	1.88	20.67	35,616	37.20	1.80	0.83	3.49
December	1,048	25.83	3.13	1.94	27.02	30,860	35.93	1.33	0.71	7.81
Annual					162.17					34.27

ANNUAL SHF = 0.79

SECTION 8

THE CHAVEZ HOUSE

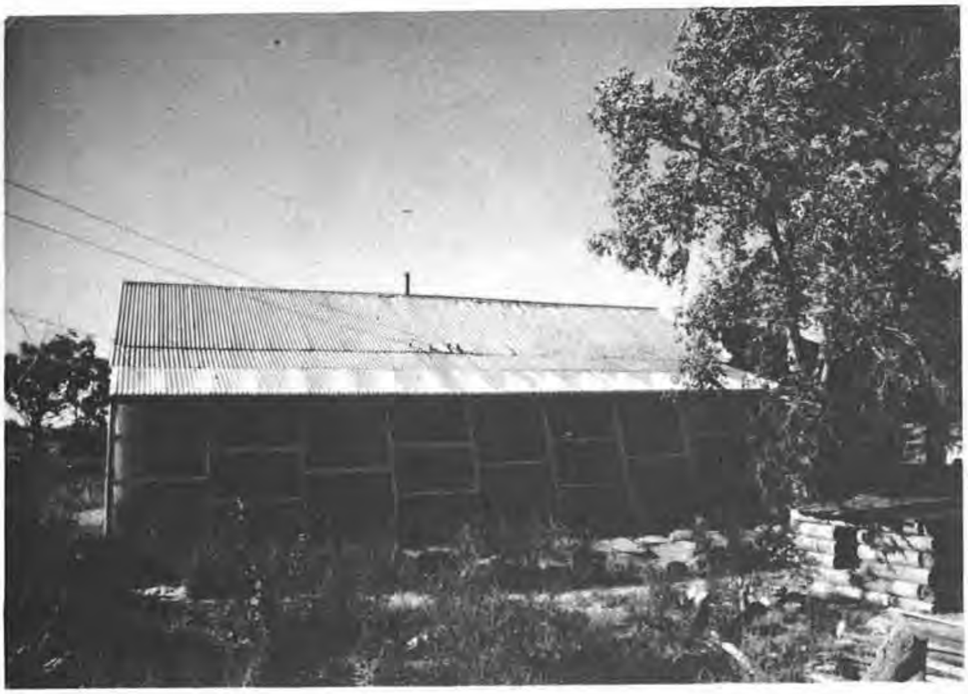


Figure 8-1. The Chavez House and Attached Solar Greenhouse

BUILDER: Bill Yanda and Solar Sustenance Crew
DESIGNER: Traditional design
OWNER: Bernardo Chavez
TYPE: Single family dwelling
AREA: 896 square feet
GENERIC TYPE: Greenhouse
LOCATION: Anton Chico, New Mexico
LATITUDE: 35°N.
ELEVATION: 5,000 feet
CLIMATE DATA: Heating dd: 3,795
Design temp: Unknown
Horiz. insolation (Jan. day): 1,200 Btu/ft^2

Figure 8-2. Interior of Greenhouse Showing Flower Bed

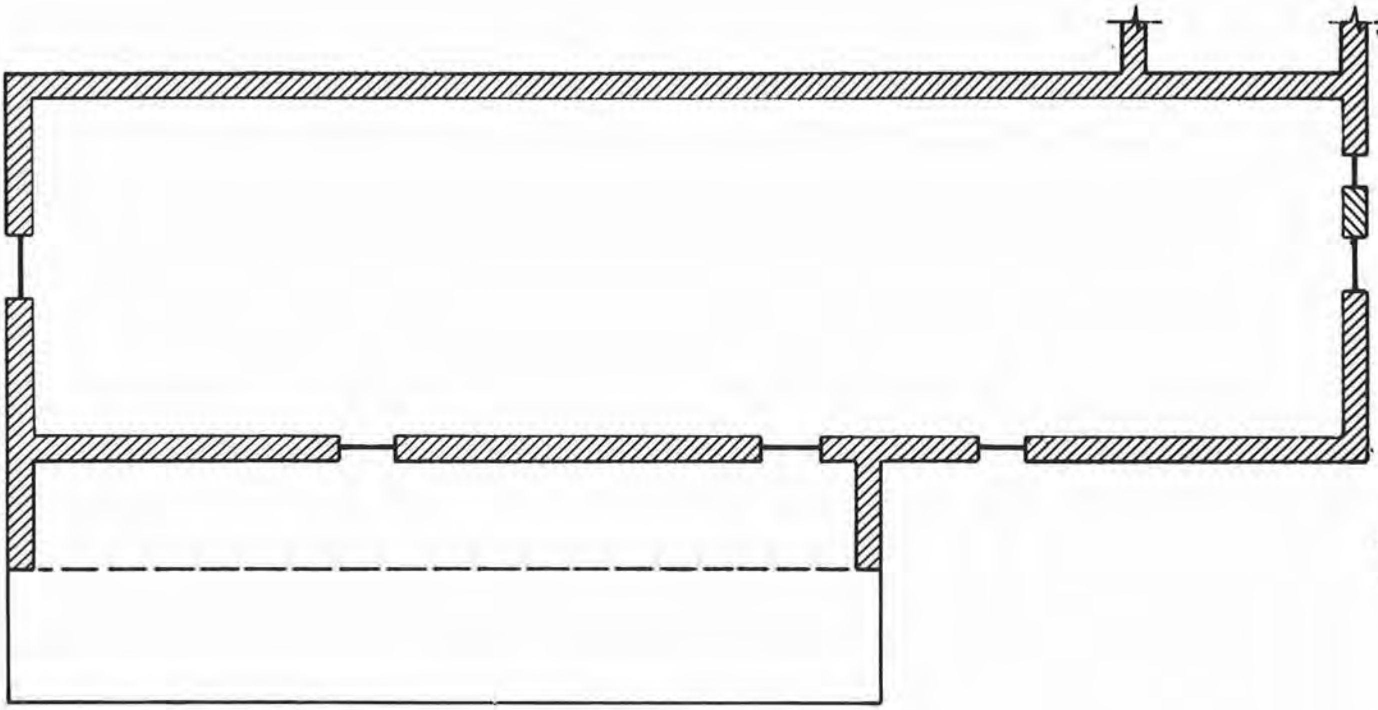


Figure 8-3. Plan of Chavez House and Greenhouse

Figure 8-4. Interior of Greenhouse Showing Water Drums

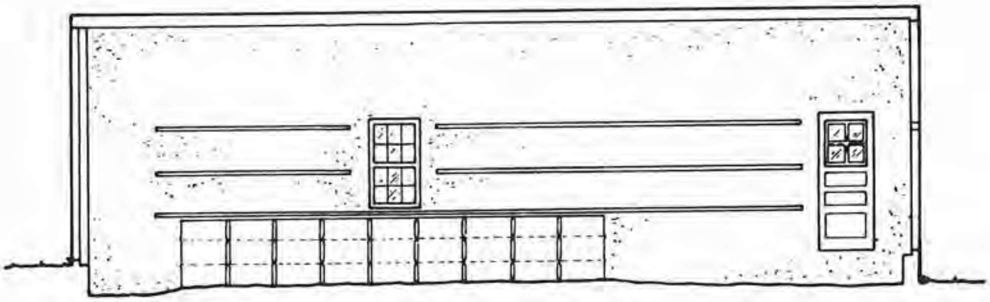


Figure 8-5. Elevation Drawing of North Wall of Greenhouse (South Wall of House)

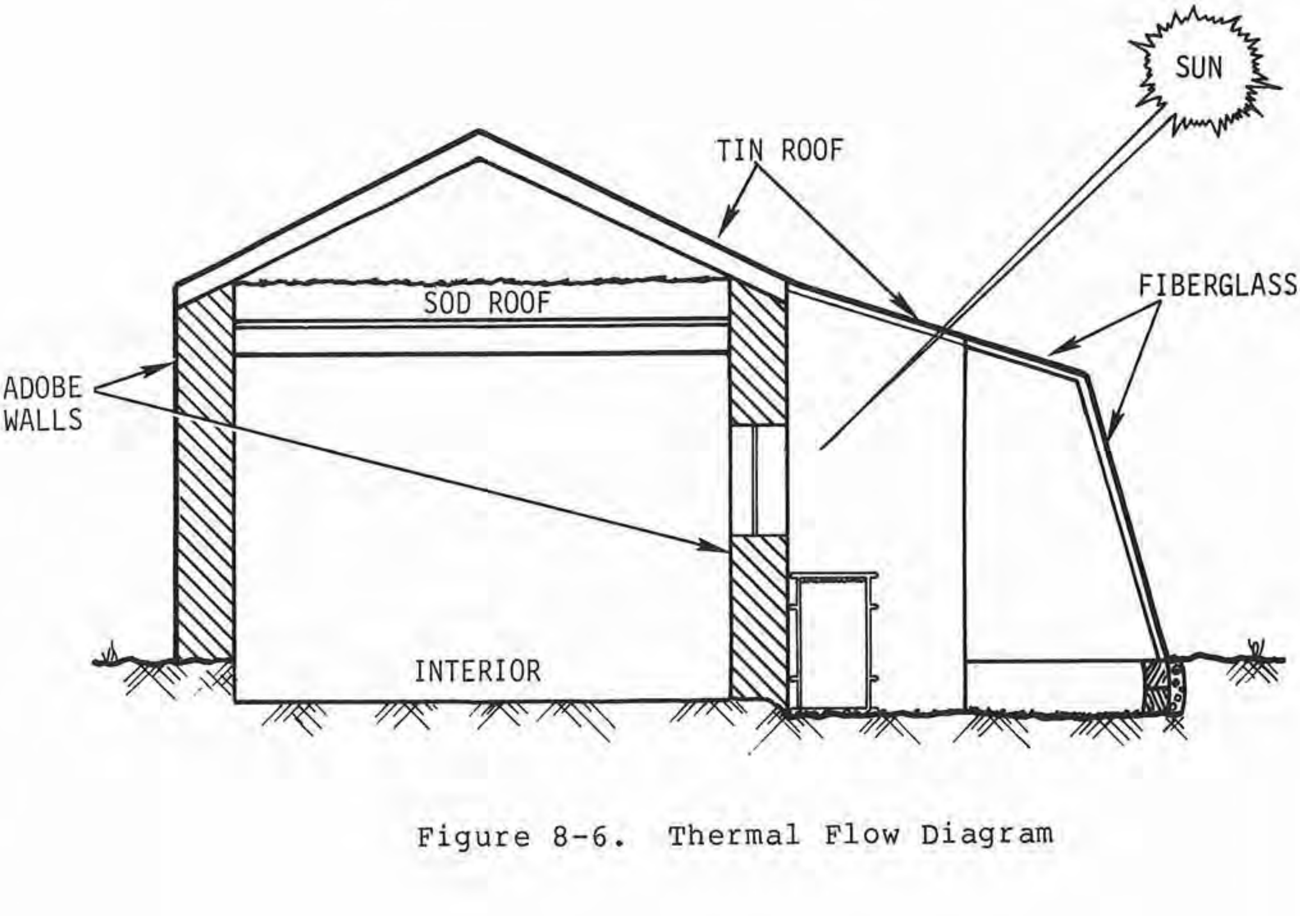


Figure 8-6. Thermal Flow Diagram

Collectors -- The south-facing greenhouse serves as a direct-gain collector. The total glazed area of the greenhouse is approximately 420 square feet.

Storage -- The thick adobe walls of the house provide the primary thermal storage. Additional thermal storage is provided by the earth floor of the greenhouse and water drums along the wall.

Distribution -- Solar energy, absorbed by the adobe walls during the day, is conducted to the inner surface and delivered to the living space by radiation and convection. Warm air from the greenhouse is delivered to the living room through the door and window which open into the greenhouse. Conversely, during cold spells heat is provided to the greenhouse from the living room.

Auxiliary Heat -- A wood-burning stove in the house provides auxiliary heat.

Domestic Hot Water -- The domestic hot water system is not connected to the solar heating system.

Controls -- Opening and closing the door and window into the greenhouse controls the flow of heat between the living space and greenhouse.

Description

Approximately 15 miles northwest of Santa Rosa, New Mexico, lies the small rural village of Anton Chico. An attached solar greenhouse was constructed in this community as part of the Solar Sustenance Project sponsored by the Energy Resources Board of the State of New Mexico. This project, directed by William F. Yanda, was responsible for the construction of many similar demonstration greenhouse units through New Mexico. The house selected at Anton Chico for the addition of the attached solar greenhouse is owned by Bernardo Chavez. It is a fine example of the traditional adobe construction methods still found in the southwest regions of the United States. Parts of the Chavez house were constructed over 100 years ago.

The basic house plan is a rectangle 16 feet wide by 56 feet long. The south wall faces 15 degrees east of south. The walls are adobe 18 inches thick. The roof is supported by 10-inch-diameter vigas. The vigas are covered with rough-sawn lumber which supports a 1-foot-thick earth roof. In recent years, a corrugated sheet-metal pitched roof was erected over the earth roof. The floor of the house is set slightly below grade so that the ceiling height in the interior measures 9 feet, 3 inches. There are no windows on the north wall.

A 36-foot-long greenhouse was constructed along the south wall, as shown in Figure 8-1. The general design for this greenhouse was developed by William Yanda. The roof slopes at an angle of 15 degrees to the horizontal. The upper half of the roof is corrugated sheet metal insulated on the underside with 6-inch fiberglass batting. This section of the roof shades the adobe wall and prevents overheating during summer months. The lower half of the roof is corrugated fiberglass paneling. The south wall is flat fiberglass paneling sloped at an angle of about 75 degrees. The end walls are also flat fiberglass paneling. The frame-supporting structure is built of 2- by 4-inch lumber. The entire inside of the greenhouse is sheathed with 6-mil polyethylene plastic sheeting, and a removable panel in each end wall provides cross ventilation through the greenhouse to vent excess heat when necessary. A door in the east wall of the greenhouse provides an entryway and can also be opened for increased ventilation. The greenhouse wall foundation consists of two courses of concrete block insulated on the outside with 1 inch of beaded polystyrene covered with chicken wire and plaster. The floor of the greenhouse, like the floor of the house itself, is set below grade.

The section of wall against which the greenhouse rests contains a door and a window. These may be opened and shut to control the exchange of air between the house and greenhouse. Nine 55-gallon drums filled with water are set inside the greenhouse along the adobe wall.

Operation

The greenhouse design fostered by William Yanda is intended to provide a suitable space for growing vegetables as well as a solar heating system. The sun entering through the glazed portion of the roof and the sloping south wall heats the adobe wall and floor of the greenhouse. These surfaces warm the air in the greenhouse, and this heat can then be transferred to the house by opening the door and window of the house that look into the greenhouse space. Part of the energy delivered to the adobe wall will conduct slowly through the wall to the interior where it will transfer by radiation and convection to heat the interior of the house. It is also possible to transfer heat from the house into the greenhouse during periods of cloudy weather with cold nights to keep plants from freezing.

The insulated portion of the greenhouse roof (actually an extension of the house roof) shades the adobe wall in summer and aids in preventing overheating of both the house and the greenhouse. The steep slope of the greenhouse wall (75 degrees from the horizontal) provides a very shallow angle of incidence to the sun's rays in summer, so a large fraction of the solar energy is reflected off and not transmitted into the greenhouse space. Conversely, in the winter, the angle of incidence is much nearer a right angle, and most of the solar energy is admitted to the greenhouse and not reflected.

The vents are located at floor level on the west side and near the eave on the east side. In summer, the prevailing winds are out of the west, so this scheme enhances the displacement of heated greenhouse air with fresh outside air. The fresh air entering the low vent provides beneficial circulation for plants in the greenhouse beds. The door on the east wall is in the best position for protection against cold northwest winds in the winter.

The thick adobe walls and earth roof provide the Chavez house with an extraordinary amount of thermal mass which strongly modulates daily temperature swings in the interior. The nine water drums perform the same temperature-modulating function within the greenhouse space.

Performance

Data recorded at the Chavez house for the period January 20-24, 1977, is shown in Figure 8-7. The weather is partly cloudy during these days, and the ambient temperature drops to freezing or below during the nights and climbs to the 40°-50°F range during the day. The solar insolation and ambient temperature traces in Figure 8-7 show this pattern.

Temperatures within the adobe wall are also shown in Figure 8-7. One trace shows the temperature at a depth of 6 inches from the outer surface, and a second trace shows the temperature at a depth of 15 inches from the outer surface. The traces show the characteristic pattern of a mass wall: at greater depths within the wall, temperatures peak at lower amplitudes and at later times. The greenhouse air temperature, also shown in Figure 8-7, is maintained about 15°F above ambient during the night but peaks to 85° or 90°F on sunny days. It must be noted that, for the period of this record, the nine water barrels had not been installed in the greenhouse. After the water barrels were set in place, the greenhouse air temperature moderated.

In this particular application, the effect of the water barrels in the greenhouse is worth consideration. Even without the water barrels the greenhouse has a very large thermal mass contained in the adobe wall and greenhouse floor. Placing the barrels along the adobe wall increases this thermal mass, but it also shades a large fraction of the wall from the sunshine. As a result, this part of the wall does not receive a daily pulse of energy to be conducted through the wall to the interior of the house; instead, the energy is stored in the water barrels and slowly reemitted to the greenhouse during the night. This would appear to improve the environment of the greenhouse at the expense of the energy contribution to the interior of the house. This may be a desirable result if food production in the greenhouse is improved.

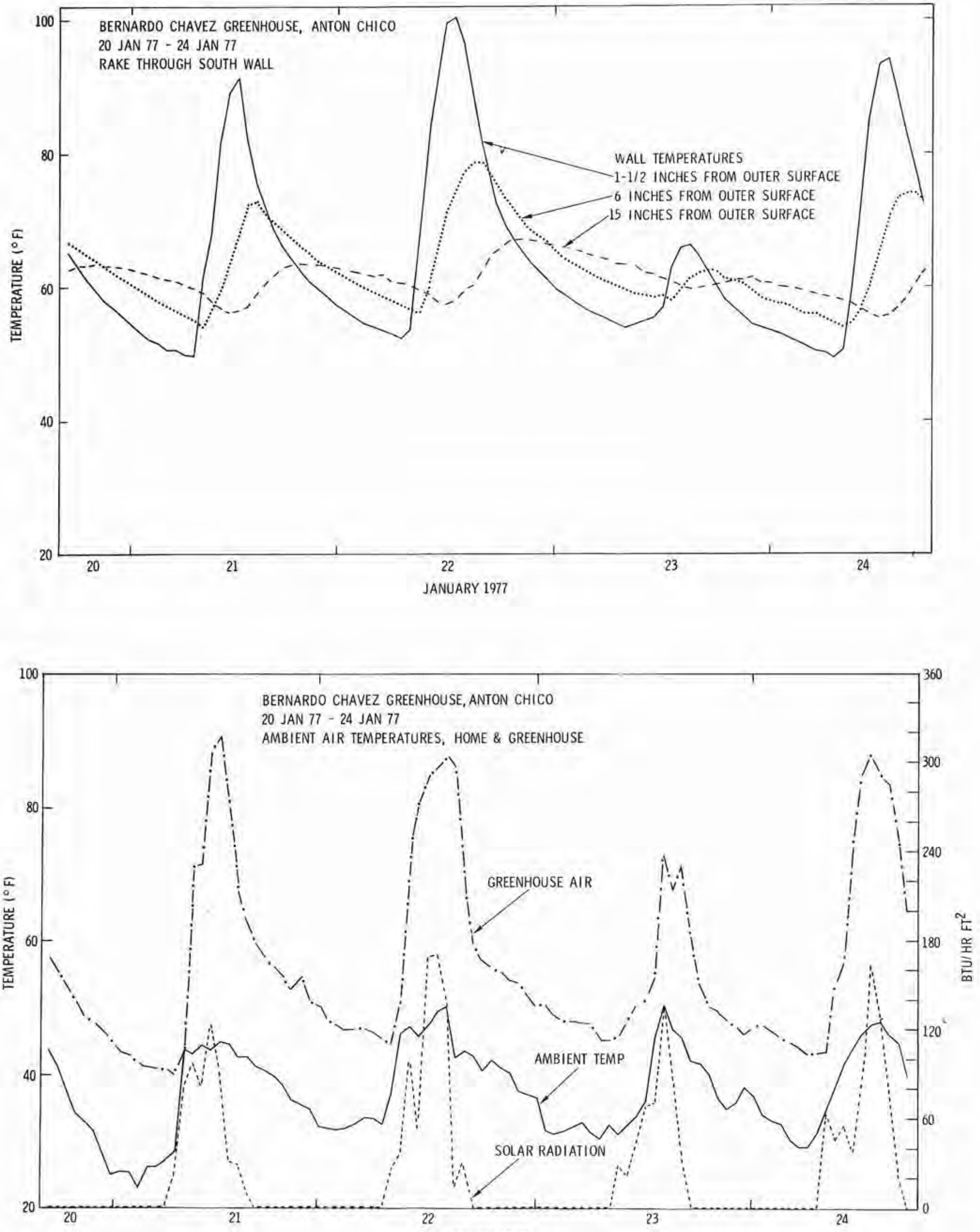


Figure 8-7. Recorded Data for the Chavez House

Owner Comments

Mrs. Chavez indicates that their house has the capability, even without the added greenhouse, of maintaining its interior temperature above freezing during the winter for indefinite periods of time, while unoccupied, and with no internal sources of heat. The massive walls and roof and minimum window area are, no doubt, the keys to this characteristic. The complementary characteristic is the ability of the house to maintain comfortable interior temperatures during hot summer days.

The greenhouse has been a very satisfactory addition to the Chavez's house. It is an efficient solar collector and reaches a temperature of at least 65°F on even the coldest winter days, provided the sun is out. When the sun sets, the temperature drops rapidly. On cloudy days, the greenhouse can become quite cold, but it never gets below freezing.

The garden area within the greenhouse has been a source of pleasure and benefit to the Chavez family. Vegetables have been grown in the garden beds, and shelves along the adobe wall hold numerous potted plants. However, the runoff from watering the potted plants created too much humidity. The humidity was absorbed by the adobe walls within the house and caused some of the finish painting to lift off. This problem has been corrected by reducing the number of potted plants and exercising more care in the watering.

Mr. Chavez believes that the extraordinarily large mass of the house--the sod roof and the thick adobe walls, particularly the south wall--are what make the greenhouse work so well. A frame or cinderblock house might have difficulties achieving similar results. The lack of any windows in the north wall helps keep the house warm in winter. In summer the greenhouse is well ventilated by the prevailing westerly breeze. Also, the greenhouse has more height than the ordinary design, and this may be helping to cool the space during summer.

If it were to be done over again, Mr. Chavez says he would enlarge the door and window that open into the greenhouse to incorporate the greenhouse space more closely with the living space.

Costs

The type of greenhouse erected by Bernardo Chavez is designed for the do-it-yourself homeowner. It was erected as a community educational project under the auspices of the New Mexico Solar Sustenance Project, directed by William Yanda. The costs and benefits associated with a greenhouse have been estimated at the New Mexico Highlands University by Mr. Michael Coca. Material costs are estimated at $2.50 per square foot of greenhouse floor area. Construction of the greenhouse should require about 1 hour of labor per square foot of greenhouse area. The total costs can vary widely depending on the locality and the talents of the builder. The estimated benefits accruing from a 160-square-foot greenhouse are $98-per-year fuel savings and the annual production of about $250 of fresh food. Assuming a $4-per-hour construction labor rate, the greenhouse should cost $1,040, and the breakeven point on the accumulated returns from the greenhouse should be less than 3 years.

Performance Estimate

The summarized results of the performance estimate for the Chavez house are shown in Table 8-I. The skin conductance of this building is about 420 Btu/h·°F. Infiltration was estimated at one-and-one-half air changes per hour. This resulted in a modified building loss coefficient of 13,541 Btu/dd. Over half of this loss is through the adobe walls and earth roof, which illustrates the poor insulating abilities of these materials ($U = 0.21$). On the other hand, the high thermal mass of the roof and walls contributes significantly to the overall performance of the house. The heat loss rate from the living space through the separating wall (with its door and window) into the greenhouse space and thence to the outside was calculated on a steady-state basis. The calculation shows that the addition of the greenhouse reduces heat loss through this part of the wall by 22 percent.

The total glazed surface of the greenhouse is about 420 square feet. Over the 212-day heating season (October through April) this glazing collects an average of 1,010 Btu/ft^2•day.

The final result of the performance estimate is a solar heating fraction of nearly 73 percent.

TABLE 8-I

Performance Estimate for the Chavez House

Month	Degree-Days	Gross Load (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface $(Btu/ft^2 \cdot mo)$	Solar Radiation Absorbed (MBtu)	SLF	SHF	Aux. Energy (MBtu)
January	812	10.99	1.99	9.00	34,410	12.77	1.42	0.631	3.32
February	633	8.57	1.80	6.77	39,732	12.22	1.80	0.722	1.88
March	555	7.52	1.99	5.53	56,358	13.43	2.43	0.826	0.96
April	261	3.53	1.93	1.61	68,460	12.85	7.97	1	-
May	(52)	-	-	-	78,740	-	-	-	-
June	-	-	-	-	80,760	-	-	-	-
July	-	-	-	-	72,819	-	-	-	-
August	-	-	-	-	71,331	-	-	-	-
September	(22)	-	-	-	59,730	-	-	-	-
October	227	3.00	1.99	1.02	49,135	14.02	13.80	1	-
November	540	7.31	1.93	5.39	35,610	12.61	2.34	0.814	1.00
December	772	10.45	1.99	8.46	30,845	12.05	1.42	0.633	3.11
Annual	3,795	51.39	13.61	37.78		89.95		0.728	10.27

ANNUAL SHF = 0.73

SECTION 9

MOBILE/MODULAR HOME II

Figure 9-1. Mobile/Modular Home II

BUILDER: Navajo Nation
DESIGNER: The Architects Taos
OWNER: U.S. Government
TYPE: Single family mobile home
AREA: 1,090 square feet
GENERIC TYPE: Modified roof pond
LOCATION: Los Alamos, New Mexico
LATITUDE: 36°N.
ELEVATION: 7,600 feet
CLIMATE DATA: Heating dd: 6,000
Design temp: 0°F
Horiz. insolation (Jan. day):
1,090 Btu/ft^2

Figure 9-2. Interior View of Mobile/Modular Home II

Figure 9-3. Roof Aperture on Mobile Modular Home II

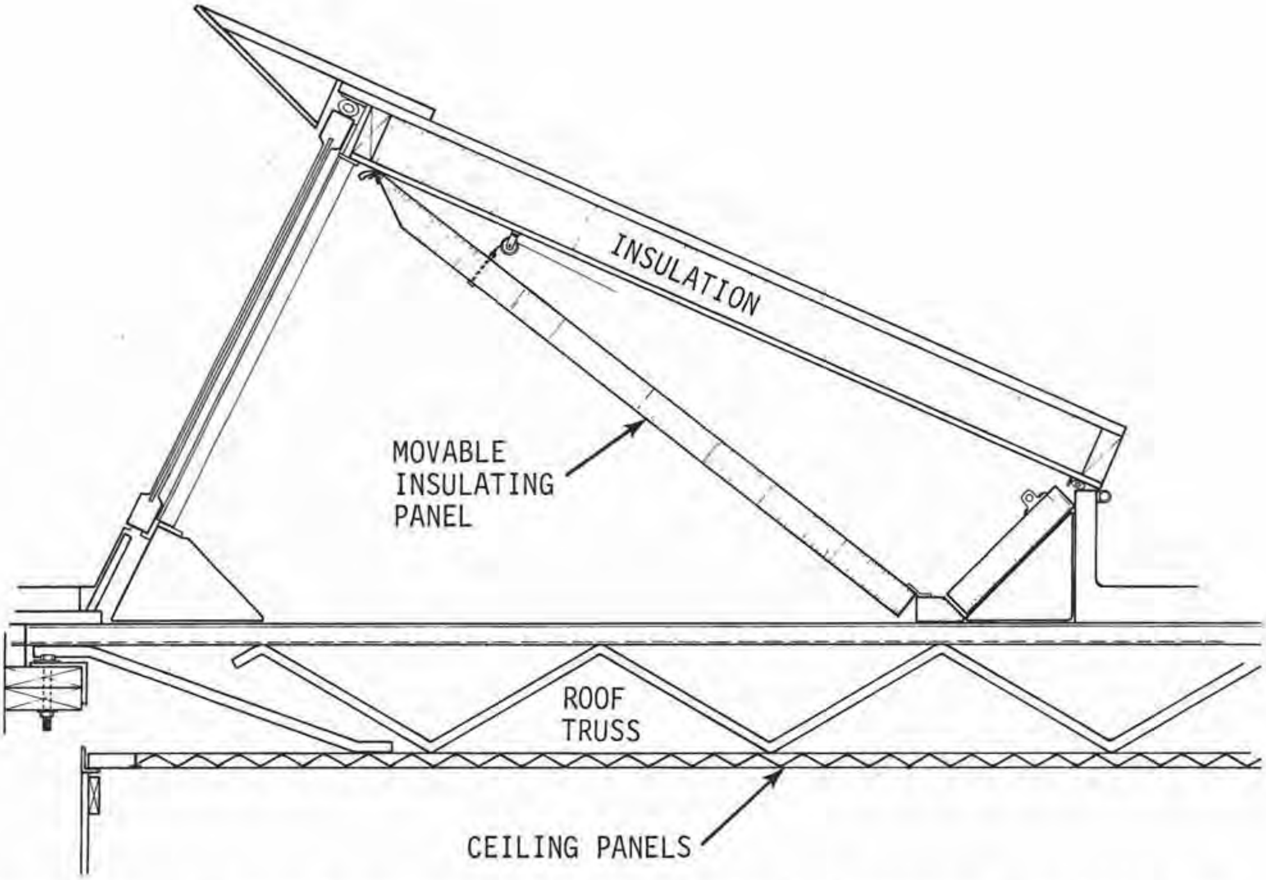


Figure 9-4. Cross-Sectional Drawing of Roof Aperture Construction

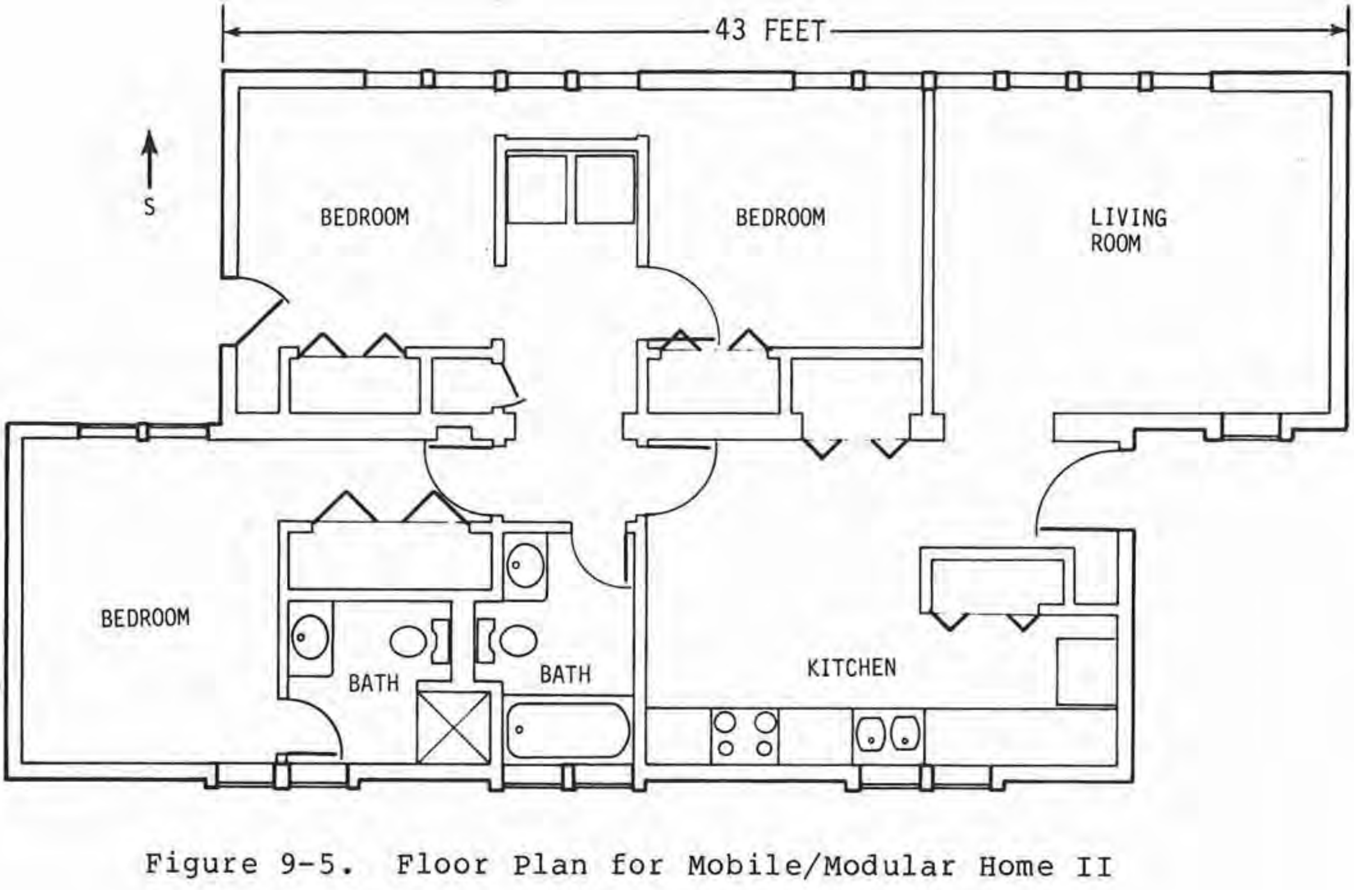


Figure 9-5. Floor Plan for Mobile/Modular Home II

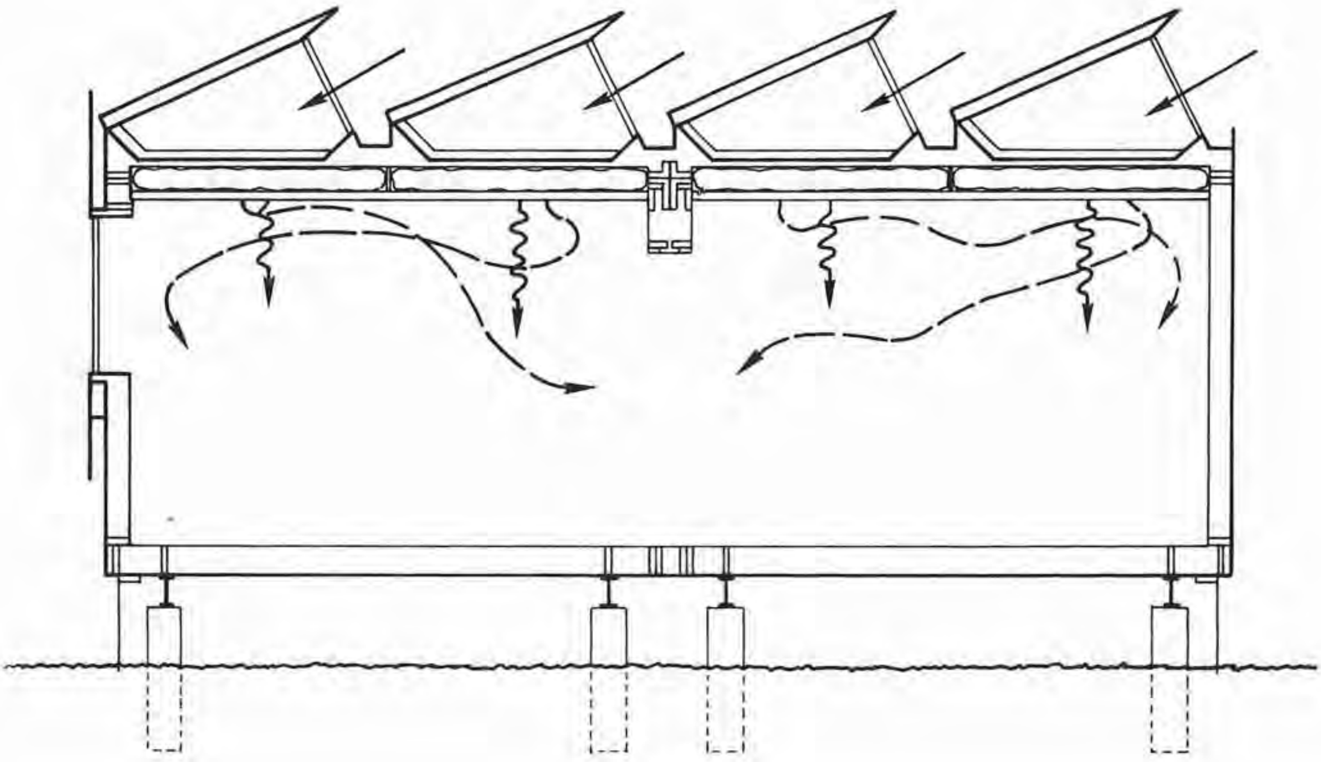


Figure 9-6. Thermal Flow Diagram for Mobile/Modular Home II

Collectors -- Four rows of south-facing roof apertures are the primary collectors. Large windows on the south wall provide supplementary direct gain.

Storage -- Waterbags resting on the ceiling panels absorb the solar radiation collected through the aperture.

Distribution -- Heat from the waterbags is conducted through the aluminum ceiling panel and radiated directly to the house interior. Direct-gain energy admitted through the south windows is first absorbed by the house furnishings and then distributed by convection.

Auxiliary Heat -- An electric furnace with forced hot air distribution provides auxiliary heat.

Domestic Hot Water -- The hot water system is not integrated into the solar heating system.

Controls -- Movable insulation panels over the waterbags can block the gain of solar energy when required. The auxiliary heat is thermostatically controlled.

Description

This home is the result of a project funded by the United States Energy Research and Development Agency through LASL. The object of the project was to (1) investigate passive solar heating systems for their applicability to the mobile/modular home industry, (2) select a single system, (3) design and build a house, and (4) measure its performance. Of the many concepts studied and analyzed, the roof-mounted system offered the most freedom from possible site restrictions: the roof apertures are relatively clear of shading from neighboring homes, trees, etc.; the design can be altered to face the apertures in any direction with respect to the house orientation; the house does not require any site preparation other than that normally required for a modular home; and the water for thermal storage can be loaded into the plastic bags after the house is established on its permanent site, reducing the over-the-highway shipping weight.

In order to meet the width limitations of highway transportation, the house is constructed in two units, each measuring 13 by 43 feet. The two units are bolted together onsite to form a single house. One unit contains a living room, two bedrooms, and a small utility center for a washer-dryer combination; the second unit contains the kitchen, master bedroom, and two baths.

The walls are standard frame construction using 2 by 6's for studs. The inside is finished with drywall material, and the outside, with wood paneling. The voids between the studs are filled with cellulosic fiber insulation.

The floor joists are 2 by 3's which are sheathed, top and bottom, with plywood. Again, the voids are filled with cellulosic fiber. When emplaced on concrete block piers at its permanent site, a fiberboard skirting is attached around the perimeter to seal off the space between the floor and the ground. This skirting can be insulated on the inner side to further reduce heat losses through the floor to the outside.

The roof is supported by open-web metal trusses. Corrugated aluminum ceiling panels rest on the lower flanges of the trusses and on top of these panels lie the water-filled thermal storage bags. An angle-iron framework on top of the trusses supports the sawtooth roof structure. The south-facing surfaces are double glazed; standard patio doors were used in this model. The north-facing surfaces are sheathed with plywood and covered with polished aluminum sheeting, which acts as a reflector. A 3-1/2-inch layer of urethane foam insulates the underside of the plywood sheathing. Within each of the sawtooth apertures, an insulating panel rests on the top flange of the roof trusses, insulating the water storage bags that lie beneath. These panels are hinged along their north edge and can be lifted by a cable-and-pulley mechanism to expose the waterbags to sunlight admitted through the glazed, south-facing surfaces of the sawtooth roof. These panels are made of plywood bonded to 2-inch-thick rigid urethane foam. The bottom side of each panel is covered with polished aluminum sheeting which, when the panel is raised, reflects incident sunlight onto the waterbags lying below. In this model, the panels are raised and lowered by an electrically powered automatic system keyed to photoelectric sensors in the apertures.

Operation

This solar system is totally passive in operation except for the action of the movable insulation over the waterbags. When the sun is shining, the insulating panels are raised, allowing the solar energy to fall on, and be absorbed by, the water-filled bags. The reflecting surfaces on the north slopes of the sawtooth roof and on the underside of the insulating panels direct additional sunlight onto the waterbags, increasing the overall gain of the apertures. At night, or on cloudy days, the insulating panel is closed, and thermal radiation from the waterbag is returned to it by reflection. A flexible rubber seal around the perimeter of the insulating panel prevents warm air around the waterbags from seeping into the aperture space, where the heat would be lost to the outside through the glazing.

The waterbags rest on the aluminum ceiling panels. Heat is conducted from the waterbag through the panel and transferred by radiation and convection to the living space. Convective heat transfer from the warm ceiling to the air below is rather inefficient, hence the radiative mode accounts for most of the heat transfer.

The geometry of the sawtooth roof was optimized by computer simulation methods. Optimum dimensions were selected based upon minimum annual auxiliary energy requirements as determined from the computer simulation analysis. There are two critical design parameters: the angle of tilt of the glazing and the length of the roof overhang. The transmittance of the glazing (the fraction of sunlight which actually passes through both panes of glass) varies with the angle of incidence of the sunlight on the glass surface. The more obliquely the sunlight strikes the glass surface, the less of it is transmitted through the glass and the more of it is reflected away. The overhang shades the glass beneath it--the longer the overhang, the more glass is placed in the shade. In summer, the overhang provides more shade than in winter. The effects of this combination of reflecting and shading characteristics was explored by the computer simulation, and the optimum geometry for full-year performance was chosen. The glass tilt angle is 65 degrees from the horizontal. The overhang extends about 1 foot beyond the front plane of the glass. These parameters would be different for different latitudes and for localities with different annual insolation patterns. The width of the glazing in the apertures is about 26 inches, and each of the four apertures extends the full length of the house.

The waterbags can be filled to a maximum depth of 8 inches. At this maximum capacity, the thermal storage mass is 40,000 pounds of water (about 4,800 gallons). This works out to a thermal storage capacity of about 40 Btu/°F for every square foot of floorspace in the house. The design of the house includes additional structural support for this added mass.

The 12 south-facing windows admit direct-gain solar energy to the house interior to supplement the roof-pond aperture system.

Performance

This house was completed and transported to its site at Los Alamos in September 1977. Installation of instrumentation for monitoring the performance of the house was completed in January 1978. Performance data has been recorded continuously over a period of at least 1 year.

A series of typical data records covering the period March 23-25, 1978, are shown in Figures 9-7(a) through 9-7(c). The first two days are cloudy, while the third day is clear and sunny, as is shown by the insolation curves. Outdoor ambient temperatures are about the same for each of the three days and are relatively moderate, so these records do not illustrate a severe test of the solar heating system.

The responsiveness of room temperature to the sun is clearly illustrated on March 23. An early morning burst of sunshine is followed by more than an hour of cloudiness with the sun obscured. The room temperature climbs rapidly in response to the direct gain coming through the large south windows. During the cloudy period, the room temperature initially drops rapidly and then levels out as thermal equilibrium is established. In general, whenever the insolation curve shows sharp variations due to cloudiness, the room temperature curve is correspondingly ragged.

On the sunny day, March 25, the movable insulation panels in the apertures open at about 8:40 in the morning, when the insolation level was already up to about 180 $Btu/ft^2 \cdot h$. The waterbag temperature begins to climb immediately, as shown by the sharp change in the slope of that curve. The waterbag temperature peaks just before 1600 hours (4 p.m.), when the insolation curve is on a decreasing slope, and has

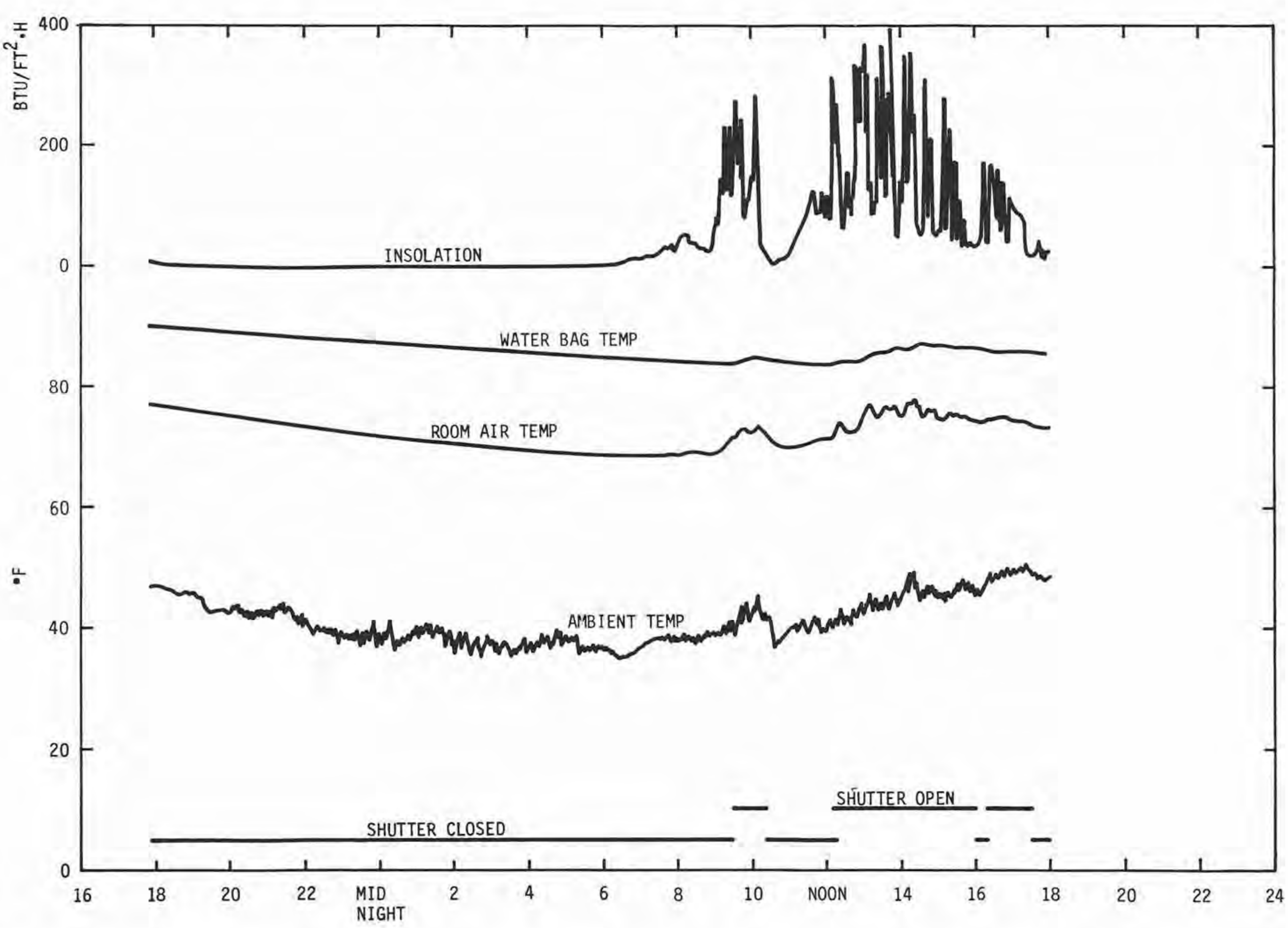


Figure 9-7(a). Recorded Data from Mobile/Modular Home II for March 23, 1978

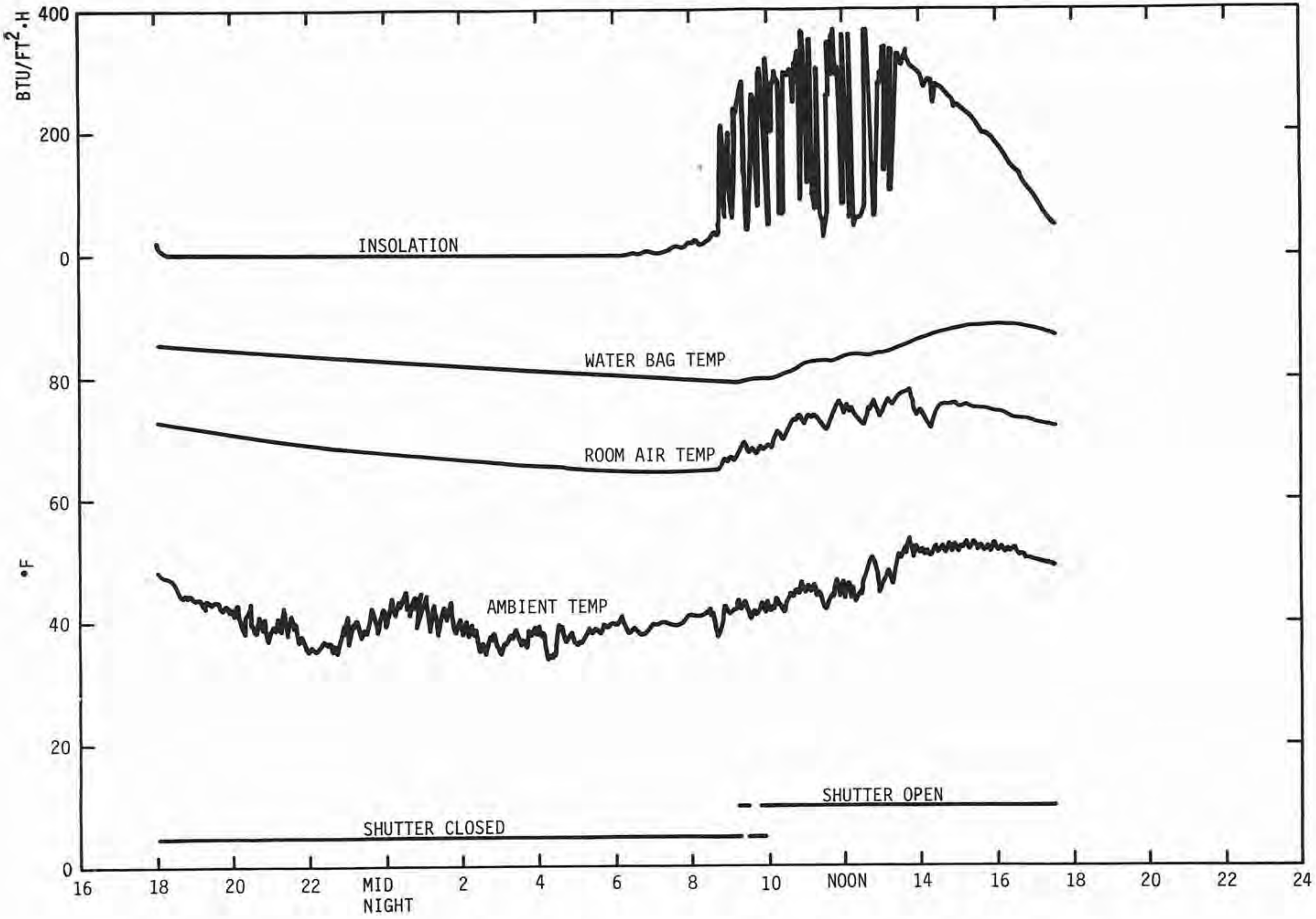


Figure 9-7(b). Recorded Data from Mobile/Modular Home II for March 24, 1978

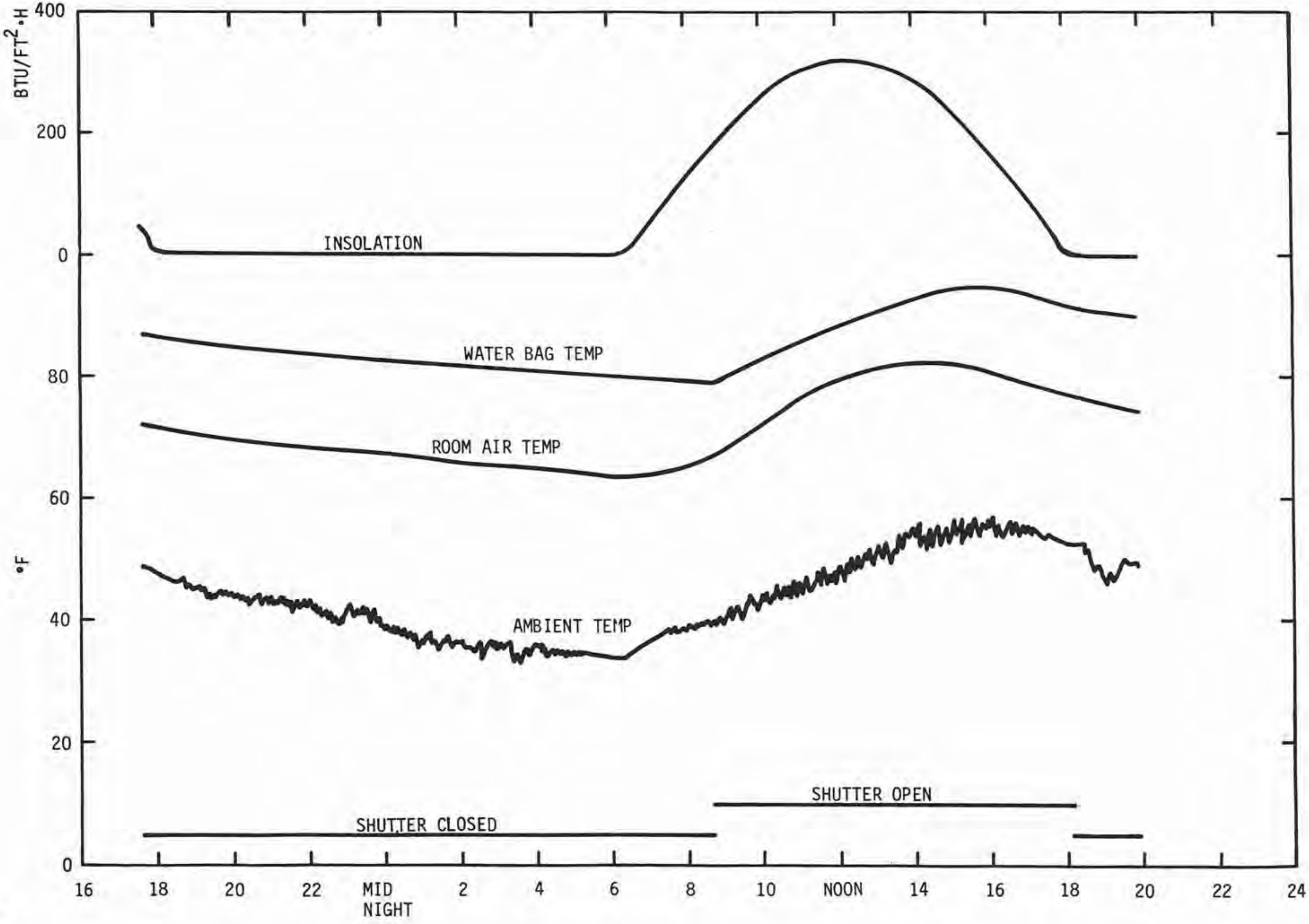


Figure 9-7(c). Recorded Data from Mobile/Modular Home for March 25, 1978 reached about 195 Btu/ft^2·h. The insulating panel does not close as the sun's insolation drops below the 180 Btu/ft^2·h mark; instead, it remains open until the sun has apparently set at 1800 hours (6 p.m.). During these last 2 hours that the panel is open, the thermal storage mass is cooling, not warming. The rate at which the waterbags are cooling is promptly slowed when the insulating panel finally closes. (Determining these operating characteristics is one of the objectives of the LASL monitoring program.)

The high interior temperatures shown should not be taken as typical. During the period that the data were taken, the house was unoccupied and kept tightly closed so that heat flow parameters could be accurately determined. House temperatures can easily be reduced to desired levels by venting excess heat to the outside.

Cost

The construction of this mobile home was accomplished by Navajo Indian students at the Fort Wingate School near Gallup, New Mexico. The work was supervised by the instructors at the school in a program designed by the XYZYX Information Corporation.

The construction cost for this model building was about $40,000, which is not a competitive figure for the modular home industry. However, estimates for construction on a mass-production basis indicate the cost could be reduced to about $25,000. The solar features, mainly the extensive glazing and complicated roof structure, represent $4,000 to $5,000 of this cost.

Performance Estimate

The modified building loss coefficient for this modular home is 14,675 Btu/dd, or 13.46 Btu/ft^2·dd. Slightly more than half of the heat loss from this house is through the south-facing glass in the walls and roof. An infiltration rate of one air change per hour was used in this estimate. The data are summarized in Table 9-I.

TABLE 9-I

Performance Estimate for Mobile/Modular Home II

Month	Degree-Days	Gross (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. (Btu/ft^2·mo)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	1,113	16.33	2.48	13.85	34,403	18.18	1.31	0.83	2.42
February	907	13.31	2.24	11.07	39,746	16.34	1.48	0.87	1.46
March	856	12.56	2.48	10.08	56,348	16.08	1.60	0.89	1.09
April	555	8.15	2.40	5.74	68,468	12.60	2.20	0.96	0.21
May	295	4.33	2.48	1.85	78,751	10.56	5.72	1	0
June	90	1.32	2.40	0	80,745	9.69	–	1	0
July	18	0.26	2.48	0	76,922	9.66	–	1	0
August	44	0.65	2.48	0	71,321	11.36	–	1	0
September	147	2.16	2.40	0	59,729	14.37	–	1	0
October	442	6.49	2.48	4.00	49,148	18.06	4.51	1	0
November	792	11.62	2.40	9.22	35,616	17.70	1.92	0.94	0.57
December	1,048	15.38	2.48	12.90	30,860	17.38	1.35	0.84	2.12
Annual				68.70					7.87

ANNUAL SHF = 0.89

SECTION 10

THE HUNN HOUSE

Figure 10-1. The Bruce Hunn House

BUILDER: Jose Herrera and Sons
DESIGNER: Bruce and Joyce Hunn with Manock Comprehensive design and Theodore R. Cole
OWNER: Bruce and Joyce Hunn
TYPE: Single family, 1 unit
AREA: 1,955 square feet
GENERIC TYPE: Trombe wall, direct gain, hybrid passive/active
LOCATION: Los Alamos, New Mexico
LATITUDE: 35.8°N.
ALTITUDE: 6,370 feet
CLIMATE DATA: Heating dd: 6,300
Cooling degree-hours: 1,000
Design temp: 0°F
Horiz. insolation (Jan. day): 1,090 Btu/ft^2

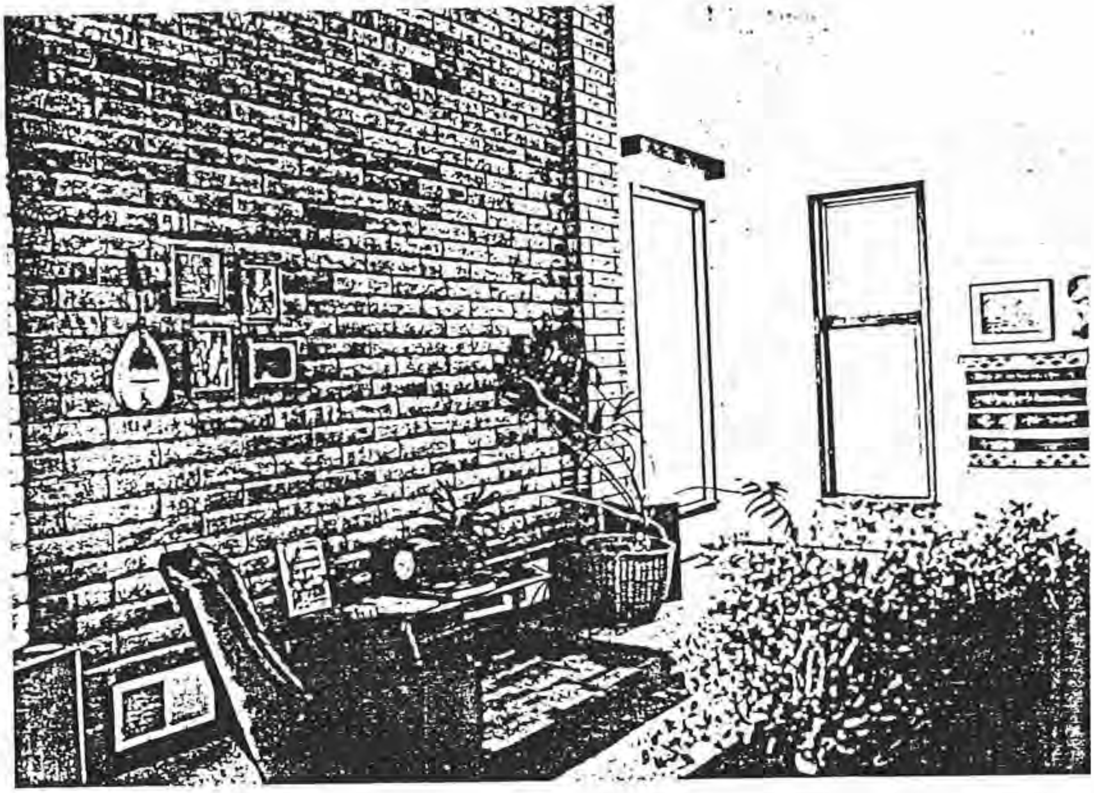


Figure 10-2. Interior of Trombe Wall, Upstairs Living Room

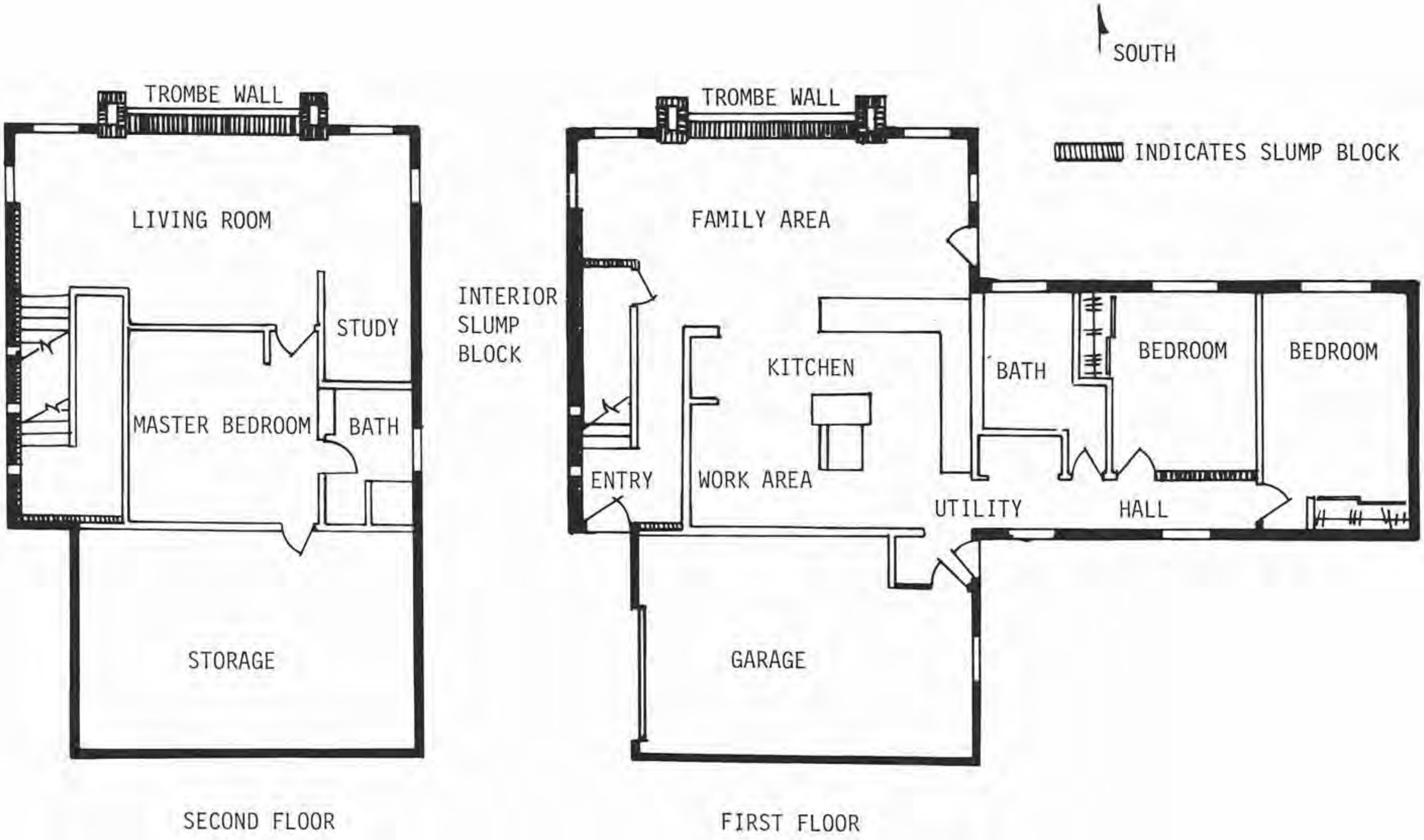


Figure 16-3. Hunn House Floor Plan

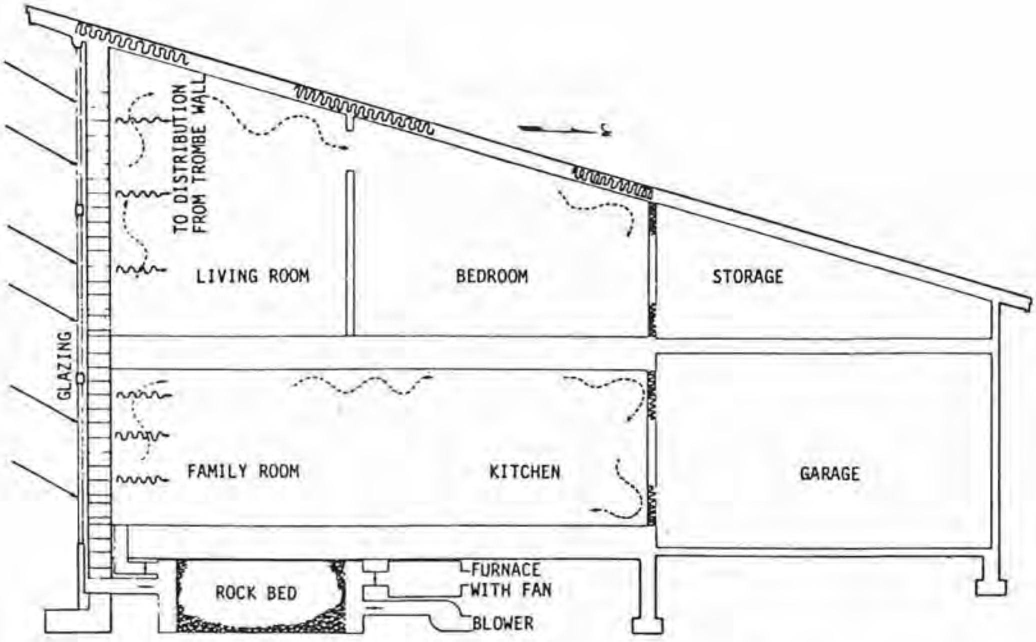


Figure 10-4. Schematic of Thermal Flow Diagram

Collectors -- A south-facing, two-story, 250-square-foot Trombe wall and 140 square feet of direct-gain windows are the collectors.

Storage -- Primary storage is the thermal mass of the Trombe wall, which is made of slump rock. Secondary storage is provided by a rock bed charged by hot air drawn from the Trombe wall system. Additional thermal mass is provided by slump rock walls in the interior of the house.

Distribution -- The Trombe wall heats the living space by radiation and convection from its inner surface. A forced-air system draws heat from the rock bed for distribution to the house.

Auxiliary Heat -- A gas-fired furnace provides auxiliary heat.

Domestic Hot Water -- A flat-plate liquid collector provides preheat for the hot water supply.

Controls -- A differential thermostat controls the fan which charges the rock bed. A standard thermostat in each of three thermal zones controls the separate forced-air distribution within the house.

Description

The house, owned by Bruce and Joyce Hunn, is located in Los Alamos, New Mexico. This community is a residential area supporting LASL and is set on top of a mesa just west of the Rio Grande Gorge. The altitude of 6,370 feet, combined with the arid southwest climate, ensures brilliantly clear skies and warm sun nearly every day of the year, but winter can be very cold.

The main section of the house is two story, with the kitchen, family, and dining spaces on the first floor, and the living room, study, master bedroom, and bath on the second floor. A single-story wing on the west side contains two bedrooms and a bath. The garage is on the north side of the two-story section, where it partially protects the house from the northerly winds characteristic of this region in the winter.

The south side of the two-story section incorporates a Trombe wall with an effective area of 250 square feet. The wall is made of 12-inch-thick open slump rock filled with cement and reinforced with No. 2 rebar. The wall is double glazed with 3/16-inch plate glass, with 1 inch separating the glass plates and a 2-inch space between the inner glass plate and the slump rock wall. The outer surface of the wall is stained a dark brown to increase its solar absorptivity to a value of 0.91. The interior side of the Trombe wall is untreated and provides a pleasing architectural motif to the family area on the first floor and the living room on the second floor. The first floor is a single open space which allows free circulation of air (and heat) from the Trombe wall to the north side. On the second floor there is a 3-foot gap between the ceiling and the top of the partition separating the living room and the bedroom so that air can circulate freely throughout the second floor also.

With the exception of the Trombe wall, the exterior walls are frame construction using 2 by 6's on 16-inch centers with fiberglass batts (R = 19) between studs for insulation. The outside is surfaced with stucco, and the inside is standard drywall finish. The masonry architectural motif of the Trombe wall is extended through the interior of the house by adding a 4-inch-thick inside layer of slump rock around the entryway, and by using 8-inch-thick slump rock for the rear wall of one bedroom in the west wing. These interior masonry walls increase the thermal mass of the house and contribute to the architectural unity.

The roof slopes from a height of 27 feet at the south wall to 12 feet at the north wall of the garage. The rafters are 2 by 6's, and fiberglass batts (R = 19) insulate the roof. A 3-foot overhang on the south side shades the Trombe wall during the summer. The roofed space over the garage helps to buffer the north wall from heat losses. It is used as an unheated storage room. The roof is sheathed with white asphalt shingles. The light color was chosen to reduce the summer heat gain.

The foundation of the house is insulated to a depth of 2 feet with a 2-inch layer of rigid expanded polystyrene. The wooden floor is built over a crawlspace where the rock bed storage is located. The rock bed is 3 feet deep, 6 feet long in the airflow direction (horizontal), and 12 feet wide. The rock bed rests on a concrete base, is framed with 2 by 4's sheathed with 3/4-inch plywood, and is insulated with 2-inch-thick extruded polystyrene ($R \cong 9$).

The house has 140 square feet of effective direct-gain area. All windows are wood framed and double glazed. Most of the window area is concentrated on the south walls for direct solar gain. Two double-glazed skylights, each measuring 2 by 4 feet, are mounted on the roof of the west wing and provide additional solar heating to the two bedrooms in that wing.

Between the two skylights on the west wing is mounted a 40-square-foot flat-plate collector for domestic hot water preheating.

The auxiliary heating unit is a 75,000 Btu/h (input rating) gas-fired furnace.

Operation

The solar heating system for the Hunn house has been operated in two distinct modes: as a purely passive thermal storage wall system and as a hybrid passive/active system. In the passive mode, all vents between the Trombe wall air space and the heated space are closed. Solar radiation, direct and diffuse, passes through the glazing, falls upon the wall surface, and is absorbed by the masonry, warming it. The masonry wall then transfers this thermal energy by several concurrent processes. Part of the energy is reradiated as infrared radiation back to the glazing and is lost. Part of the energy is transferred by convection to the air trapped in the space between the glazing and the wall. The air, now warmer than the glazing, loses heat through the glazing until an equilibrium temperature is reached. Since warm air rises, heat tends to be transferred upward, and vertical temperature gradients are established in the air space and in the Trombe wall. The last method of energy transferral is by conduction through the masonry to the inside surface, where the energy is transmitted to the interior space by radiation and convection. During the time that it takes for the thermal pulse to transit the wall, the energy is stored in the wall.

In the active mode, a fan pulls air from the top of the space between the Trombe wall and the glazing and delivers it through insulated ducts beside the Trombe wall to the rock bed, where its heat is transferred to the rocks. The cooled air is returned to the bottom of the Trombe wall to be reheated and recirculated. In the Hunn house, the rock bed is thermally isolated (i.e., insulated) from the rest of the house. When the house requires heat, a separate fan (the furnace fan)-and-ducting system pulls air backward through the rock bed, heating it, and delivers it to the house through the distribution system.

A thermostat monitors the temperature of the air coming out of the rock bed; when this temperature is too low to effectively heat the house, the furnace is turned on to supply auxiliary heat.

In the summer, vents between the Trombe wall air space and the living space are opened to allow air to be discharged outdoors through roof vents to prevent overheating of the wall.

Performance

Figure 10-5 is a compilation of data collected at the Hunn house during the period December 26, 1978 through January 8, 1979. This is the same time period as is shown for other houses in the Los Alamos-Santa Fe area. Some very cloudy weather is interrupted by sunny days, and the ambient temperature drops below 10°F on several nights. This is shown by the ambient temperature and insolation graphs in the figure.

Also, from December 16, 1978 until 9 p.m., January 1, 1979, the Hunns were away from home, the house was closed, and the thermostat was set at its lowest level. The week of December 20-27, which precedes the week shown in Figure 10-5, was one of monotonously sunny days and moderate ambient temperatures. The house, with no one around to disturb it, responded in an equally monotonous manner. The downstairs family room air temperature rose each day to a peak of 58°F, the peak occurring right at sunset. During the night, the temperature dropped at a uniform rate to a low of 50°F, the low occurring at sunrise. The average peak ambient temperature and the average minimum ambient temperature were 40° and 15°F, respectively, for this week. There is no indication that the auxiliary furnace turned on during this period.

On December 28 the good weather falters (see Figure 10-5) and without the sun, the family room temperature begins to drop. In the early morning of January 1, 1979, after 4 cloudy days, the minimum of 47°F occurs. New Year's Day is sunny, and the family room air temperature increases to 53°F. That evening, at about 8:30 p.m., the Hunns

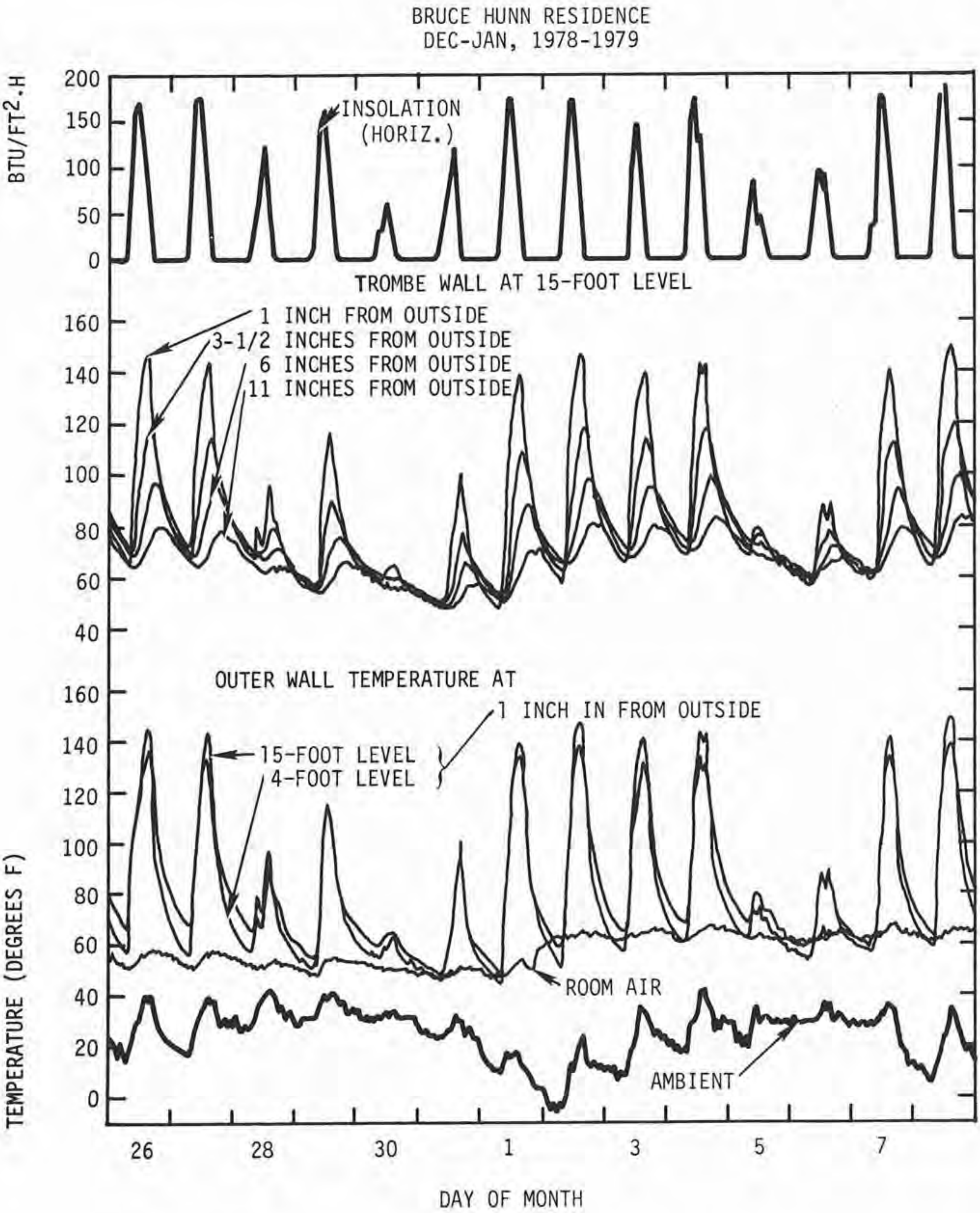


Figure 10-5. Recorded Data for the Hunn House

return home and turn up the thermostat. The living room air temperature rises sharply as a result. For the remaining record shown in Figure 16-5, internal sources and solar gains are sufficient to keep the family room minimum temperature above the 60°F thermostat setting.

A set of thermocouples was buried in the wall at the 15-foot level, at various depths from the surface. Measured from the outer surface, the depths were 1, 3-1/2, 6, and 11 inches. The temperatures recorded by these thermocouples are shown in Figure 10-5. On each sunny day, the wall receives a high temperature pulse on its outer surface. As the pulse travels through the wall, its amplitude is reduced. It takes about 5-1/2 hours for the temperature peak to travel the 10 inches from the outer thermocouple to the inner thermocouple, or about 1.8 inches per hour. Since the wall is 12 inches thick, it should take over 6-1/2 hours for the pulse to travel the full thickness of the wall. At 2:30 p.m. on January 2, 1979, the outer thermocouple reaches a peak temperature of 147°F. At this same time the thermocouple at 3-1/2-inch depth records a temperature of 112°F. The average temperature gradient between these two thermocouples (spaced 2-1/2 inches apart) is 14°F per inch. Extrapolating this gradient back to the outer surface indicates the temperature at the outer surface was about 161°F. This estimate is probably low because the temperature gradient at this time of day is higher at points nearer the surface than it is at the deeper depths in the wall.

Measurements of the wall temperature at the 1-inch depth were also taken at the 4- and 15-foot levels. These are shown as a separate pair of traces in Figure 10-5. A modest temperature stratification is indicated.

During November and December 1977, the differential controller for the rock bed was activated, and the bed was placed in the charging mode. Inlet air temperatures to the rock bed from the Trombe wall were too low to charge the bed adequately, so the blower was turned off at the end of December and has not been used since. The suspected reasons for this poor performance are (1) cold air leakage into the system, (2) duct losses, and (3) too high an air flow rate. It was discovered that the facia-board at the top of the wall is poorly sealed and leakage at the vents is evident. Also, the design air flow rate of 2 cubic feet per minute per square foot (2 $ft^3/min \cdot ft^2$) of collecting surface is too high. This value is about optimal for active collectors. However, since the wall absorbs one-half to two-thirds of the energy incident at the surface, a value of about 1 $ft^3/min \cdot ft^2$ is appropriate.

Owner Observations and Comments

Because the thermostats were normally set at 60°F, the two-story section very rarely required auxiliary heat during clear weather. This section of the house would cool to 60° to 62°F in the early morning and warm to 65° to 70°F by the afternoon. With the wall charged, these temperatures created comfortable conditions in the room. However, when the wall was not charged, the room was uncomfortable unless the temperature was 65°F or greater. Thus the thermostat was set at 65°F during a cloudy day following 1 or more cloudy days.

The single-story wing, which does not communicate directly with the Trombe wall, required intermittent auxiliary heating from about 8 p.m. to 8 a.m. No data were taken in this wing.

Future steps to improve the performance of the system when in the active mode will be to (1) slow the blower speed to achieve 200 to 250 cubic feet per minute, (2) seal the system air leaks as far as possible, and (3) reverse the flow pattern over the wall to reduce the length of the warm air duct-runs into the rock bed.

Operation in the rock-bed charging (active) mode has not yet been successful because the bed inlet temperatures are not sufficiently high. Considerable care must be taken to design for a charging air flow rate of less than 1 $ft^3/min \cdot ft^2$ of collecting surface when using this hybrid configuration. System air leaks and duct losses must be avoided unless an under-floor, low-temperature rock bed is used.

Bruce Hunn also recommends increased roof insulation for future designs, and he proposes to add a greenhouse to the west wing in the future.

Construction and Cost

The construction firm of Jose Herrera and Sons, Fairview, New Mexico, which had no previous experience with solar houses, was the builder. A conventional mortgage, obtained from a local savings and loan company, financed the project. No difficulty was encountered in obtaining the building permit.

Material costs for the space-heating and domestic hot water systems are listed in Table 10-I. A breakdown of installation costs is also given in the table, but these represent estimates, since most of these costs were simply part of the overall contract. The total (net) space-heating system cost (installed) was $5,436, including allowance for the exterior wall that was replaced by the Trombe wall. The domestic hot water system cost (installed) was $1,260. This $6,700 incremental initial cost attributable to the solar heating system represents about 10 percent of the total construction cost of the house. This does not include the cost of the interior slump block in the entryway.

However, New Mexico allows an income tax credit of 25 percent of the equipment cost (excluding labor) for a solar heating/cooling system. This resulted in a $1,000 refund, the maximum allowable.

Performance Estimate

A performance estimate using the methods described in the appendix has been made for this house. The modified building loss coefficient used is 19,554 Btu/dd, which disagrees with one calculated by Bruce Hunn, largely because the two calculations were based on different estimates of the infiltration rate. Bruce Hunn used 1/2 air change per hour, while LASL used 1.37 air changes per hour. The results of the performance estimate are shown in Table 10-II.

TABLE 10-I

Solar Heating System Cost Estimate

	Materials		Installation Labor	
Space-Heating System				
Trombe Wall				
1. 300 square feet of 1-foot-thick slump block	$ 825		$1262	
2. Masonry cement, sand, and mortar coloring	233			
3. Concrete block fill	280			
4. Concrete footings	219			
5. Rebar and Durowall reinforcing	231			
6. Wood framing for glazing	62		208	
7. Glazing	846		300	
8. Stain	25		80	
9. Ductwork	325		96	
Subtotal	$3046	+	$1946 =	$4992
Less allowance for the 6-inch frame wall that was replaced; 300 square feet at $5.25/per square foot				-1575
Rock Bed Storage				
1. 12 tons washed gravel	$ 51		$ 50	
2. Framing	150		200	
3. Insulation	134			
4. Miscellaneous hardware	54			
5. Angle-iron	77		50	
Subtotal	$ 466	+	$ 300 =	766
Extra Ductwork (including motor-operated dampers and backdraft dampers)	$ 525		$ 240	
Rock-bed Charging Blower, 500 ft^3/m New York blower	208		20	
Controls (including one Rho Sigma Model 106 controller and furnace burner thermostat)	200		60	
Subtotal	$ 933	+	$ 320 =	1253
Total Space-Heating				$5436
Domestic Hot Water System				
Two Miromit Model 200 flat-plate collectors (single-glazed, water-white crystal glass, 20 square feet each)	$ 400		$ 100	
Differential controller, Rho Sigma Model 106	$ 90		$ 30	
Circulating pump, Grundfos Model VPS 20-42	85		30	
50-gallon preheat/storage tank with finned-tube heat-exchanger coil	350		45	
Associated plumbing (including solenoid vent valves)	80		50	
Total Domestic Hot Water Heating	$1005	+	$ 255 =	$1260
Grand Total, Space Heating and Domestic Hot Water Heating				$6696

The annual net load computed in the performance estimate is 93.25 MBtu's. This results in an annual auxiliary energy prediction of 40.17 MBtu's. The actual fuel consumption records for the house indicate that this estimate is too high. The high infiltration rate used may account for this discrepancy.

TABLE 10-II

Performance Estimate for the Hunn House

Month	Degree-Days	Gross Load (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface (Btu/ft^2·mo)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	1,113	21.76	3.09	18.67	35,452	15.20	0.814	0.464	10.01
February	907	17.74	2.79	14.94	43,890	14.64	0.979	0.541	6.86
March	856	16.74	3.09	13.65	58,075	13.45	0.985	0.544	6.22
April	555	10.85	2.99	7.86	70,566	10.55	1.342	0.673	2.57
May	295	5.77	3.09	2.68	81,164	8.83	3.297	0.952	0.13
June	-	-	2.99	-	83,220	-	-	1.0	0
July	-	-	3.09	-	79,279	-	-	1.0	0
August	-	-	3.09	-	73,507	-	-	1.0	0
September	147	2.87	2.99	-	61,560	-	-	1.0	0
October	442	8.64	3.09	5.55	50,654	15.10	2.719	0.912	0.49
November	792	15.59	2.99	12.50	36,708	14.80	1.185	0.621	4.74
December	1,048	20.49	3.09	17.40	31,806	14.53	0.835	0.474	9.15
Annual				93.25				0.569	40.17

ANNUAL SHF = 0.569

SECTION 11

THE HINESBERG GREENHOUSE

Figure 11-1. Exterior View of the Hinesberg Greenhouse

BUILDER: Doug Taff and Robert Holdridge
DESIGNER: Robert Holdridge and Doug Taff
OWNER: Robert Holdridge and Doug Taff
TYPE: Add-on greenhouse (retrofit)
AREA: 98 square feet
GENERIC TYPE: Passive greenhouse
LOCATION: Hinesberg, Vermont
LATITUDE: 44.4°N.
ELEVATION: 150 feet
CLIMATE DATA: Heating dd: 8,100
Design temp: -20°F
Horiz. insolation (Jan. day): 552 Btu/ft^2
(Dec. day): 369 Btu/ft^2
(Feb. day): 785 Btu/ft^2

Figure 11-2. Interior View of the Hinesberg Greenhouse

Figure 11-3. Water Drum Thermal Storage for the Hinesberg Greenhouse

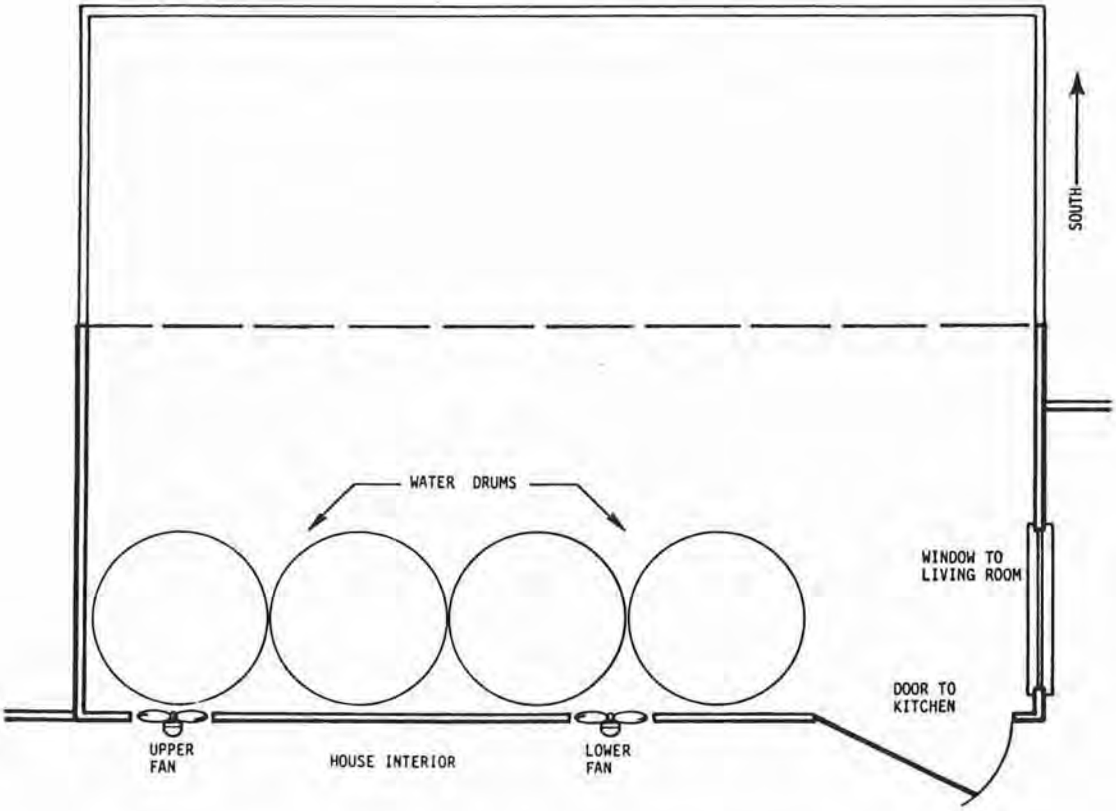


Figure 11-4. Plan for the Hinesberg Greenhouse

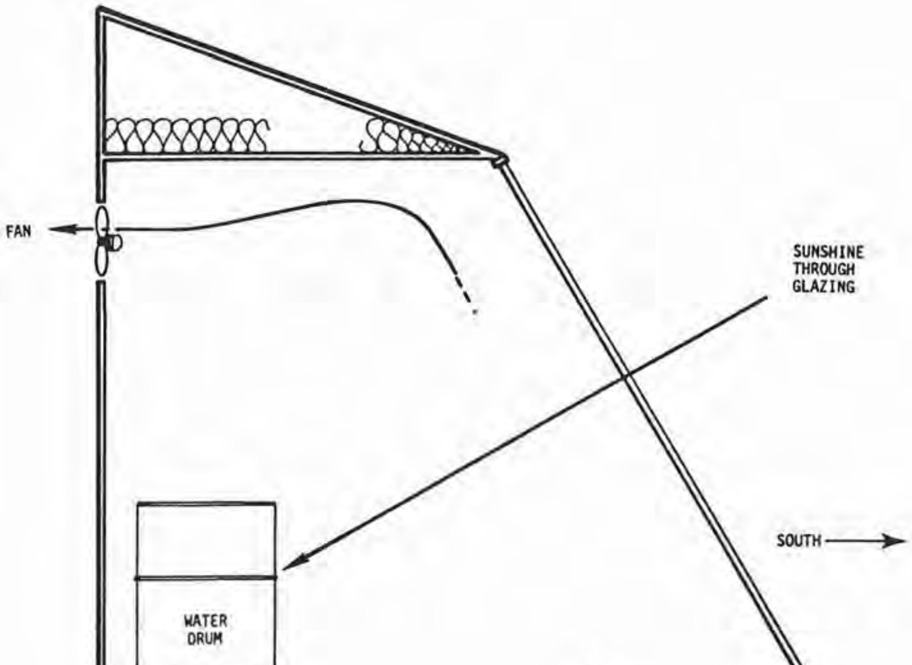


Figure 11-5. Thermal Flow Diagram of the Hinesberg Greenhouse

Collector -- The south-facing wall of the greenhouse is glazed with Sunwall® translucent fiberglass paneling units tilted 60 degrees from the horizontal. Three 4- by 8-foot units are used for a total of 96 square feet of collector area.

Storage -- A row of four 55-gallon drums painted black and filled with water provide the thermal storage mass.

Distribution -- Natural and forced convection distribute the solar heat collected within the greenhouse.

Auxiliary Heat -- Additional heat can be admitted to the greenhouse from the house to which it is attached if this is desired. Normally, excess heat generated by the greenhouse supplements the heating system of the house.

Domestic Hot Water -- Not applicable.

Controls -- A differential thermostat controls two small fans built into the wall between the house and greenhouse. The door and window into the greenhouse can be opened or closed to control natural convection.

Description

The Hinesberg greenhouse is attached to an older home of about 1,800 square feet of floor area. It is a lean-to design, with the south-facing glazed area tilted at 60 degrees to the horizontal. The glazing is two layers of fiberglass-reinforced plastic sheeting bonded to a rigid aluminum frame. An air space of 1-1/4 inches separates the two fiberglass sheets.

The floor joists are 2 by 10's supported on cinderblock piers. Plywood (3/8-inch thick) has been laid over the joists and the upper surface is finished with quarry tile. The voids between floor joists have been filled with fiberglass batting and sheathed with 1/4-inch plywood nailed to the bottom of the joists.

The walls are 2-by-4 stud construction. Fiberglass batts are pressed between the studs. Rigid styrofoam, 2 inches thick, is laid over the studs and the inside is finished with hardboard. The outside is sheathed with 3/8-inch plywood and finished with 1/2-inch redwood clapboard. A small portion of each of the end walls is double glazed with fiberglass sheeting. The ceiling of the greenhouse is insulated with 12 inches of fiberglass.

A row of four 55-gallon drums filled with water is placed along the wall which separates the greenhouse from the main house. These drums are set on cinderblocks, with their hollow cores oriented to allow air to flow horizontally underneath the drums from the wall side toward the greenhouse space. Two fans are set in the wall: one near the floor and one near the ceiling. The one near the floor blows air from the house into the greenhouse, where it is warmed. The upper fan then pulls this warmed air from the greenhouse and delivers it to the main house. The hollow cores of the cinderblock provide the passage for this flow of air beneath the water storage drums.

An insulating shade has recently been installed and can be seen in its raised position at the top of the glazing in Figure 11-2. In the down position, the edge guides hold the curtain close to the glazing and reduce the loss of heat through the glazing.

Operation

The Hinesberg greenhouse is designed to optimize collection of solar energy during the winter while minimizing heat losses to the outside. The main glazed surface of 96 square feet (sloped 60 degrees from the horizontal) faces due south. For this latitude, the sun's altitude angle at noon on the winter solstice is 22.1 degrees, so the midday sun's rays are nearly normal (perpendicular) to the glazing surface during the winter months. This feature maximizes the transmittance of solar energy through the glazed surface into the greenhouse, where it is absorbed and converted to thermal energy. Since the walls, ceiling, and floor of the greenhouse are heavily insulated, the heat losses are small; more energy is being collected than is being lost. As a result, the greenhouse interior temperature rises and can become excessively hot. Transfer of this excess heat to the main house not only helps to heat the main house, but also moderates the greenhouse temperature.

Two fans are mounted in the wall between the greenhouse and the main house and circulate air between the two. A differential thermostat turns the fans on when the temperature difference reaches 4°F. This heat-exchange process takes place only during daytime, when the house heat demand is the least and it is possible that the heat will be wasted. This situation is alleviated by storing some of the collected heat for use at a later time--the four water drums perform this function. Sunlight falling on the drums is transferred to the water within the drum instead of heating the air in the greenhouse. Because of the large amount of water in the drum and its high heat capacity, the temperature of the water rises very slowly. At the end of the day, when the sun goes down, the greenhouse temperature drops below the water drum temperature and the stored heat is released, lengthening the period when heat can be transferred to the main house and moderating the temperature extremes (both high and low) experienced within the greenhouse. It appears that the overall effect of the drums is to allow more usable heat to be delivered to the house, even though the total amount of heat delivered may be reduced.

During the summer, the altitude angle (69 degrees at noon, summer solstice) of the sun creates a sharp angle of incidence for the sun's rays on the greenhouse glazing, causing much of the incident solar energy to be reflected off. Furthermore, the amount of solar energy intercepted by the glazing surface is proportional to the cosine of the angle of incidence. The combination of these two effects sharply reduces the amount of solar energy admitted to the greenhouse, so that overheating is not a problem in the summer.

It is estimated that the insulating curtains will reduce the heat loss through the glazing by a factor of 3 (from 0.56 $\mathrm{Btu/ft^2 \cdot h}$ to 0.18 $\mathrm{Btu/ft^2 \cdot h}$).

Performance

This greenhouse has been monitored continuously since November 1976. Daily maximum and minimum temperatures have been recorded for both the interior of the greenhouse and the outside ambient air. The daily average temperature of the water storage has also been recorded. These data for the period February and March 1977 are shown in Figure 11-6. During this period, the greenhouse is isolated and insulated from the house, except for the operation of the dual fan system described previously. Heat can flow only from the greenhouse to the house under these conditions. At night, the greenhouse must survive by itself without drawing supplemental heat from the house. Despite frigid nighttime ambient temperatures, the greenhouse temperature rarely drops below 50°F and generally maintains itself above 55°F.

Insolation data has not been recorded for this period, but the days on which precipitation occurred are marked. Also, the hours per day of fan operation are shown. The amount of heat delivered to the house from the greenhouse should be roughly proportional to the number of hours of fan operation. In February, there are periods when the fan operates nearly continuously. In March, the hours of fan operation drop off, even though the greenhouse temperatures are high and there must be at least as much heat available for transfer as there is during February. The controlling factor may be the much higher outside ambient temperature in March compared to February (approximately 40°F versus 15°F). Apparently, as the house heat load is decreased, the amount of heat drawn from the greenhouse decreases also, and the house furnace continues to operate.

During February the greenhouse stays about 45°F above the outside ambient temperature, and the temperature fluctuations within the greenhouse are less than those of the ambient temperature. In March, the greenhouse is only about 30°F warmer than the outside, and the fluctuations in temperature within the greenhouse are greater than the ambient temperatures. Doug Taff has made a regression analysis of the maximum and minimum ambient temperatures and the greenhouse temperatures. The results are plotted in Figure 11-6 and clearly show these tendencies.

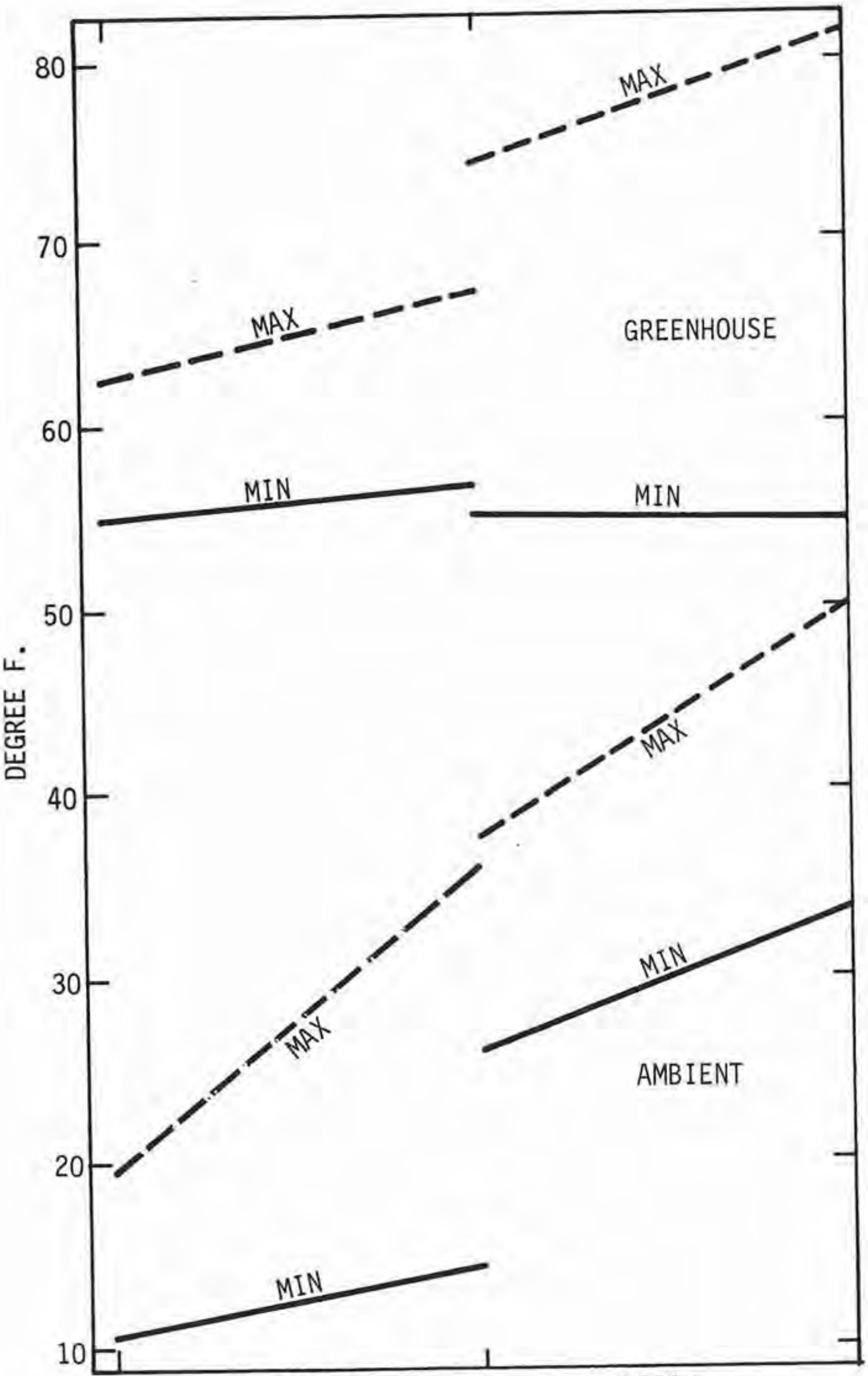


Figure 11-6. Greenhouse and Ambient Temperature Trends

In Figure 11-7, the average temperature of the water storage is shown. The plot also shows more of a temperature fluctuation in March than in February.

Records for January (not shown in Figure 11-7) show a 60°F difference between the average greenhouse temperature and the outside ambient temperature.

Builder/Designer Comments

In undertaking the design and construction of this add-on greenhouse, Doug Taff and Bob Holdridge had three goals in mind: (1) gather data on the performance of a passive greenhouse in the New England climate, (2) determine costs, and (3) develop plans for a standardized retrofit greenhouse system. All the goals have been achieved. The plans that were developed can be acquired through Garden Way Publishing, Charlotte, Vermont. No special materials or construction skills are required. The key feature of the design is the sloped window. Kalwall® panels are used in this instance, but the design is adaptable to other glazing materials. One change recommended by Doug Taff is to use 2 by 6's for the wall framing so that the insulation thickness can be increased.

Insolation data for the Burlington, Vermont, airport from 1964 to 1974 were used in the analysis for this project. The data were developed by the State University of New York, Atmospheric Sciences Center, Albany, New York. These data show that the sunshine percentages for the months of November and December are 20 and 24 percents, respectively. Although very cloudy, the ambient temperature is not severely cold. About the middle of January, the daytime weather clears up, the temperature drops, and it usually snows at night. The high percentage of cloudy weather implies that a high percentage of the solar radiation will be diffuse rather than direct or beam radiation. Under these conditions, an unfocused, low-temperature collector is the most cost-effective solution for spare heat. The add-on greenhouse fits these characteristics.

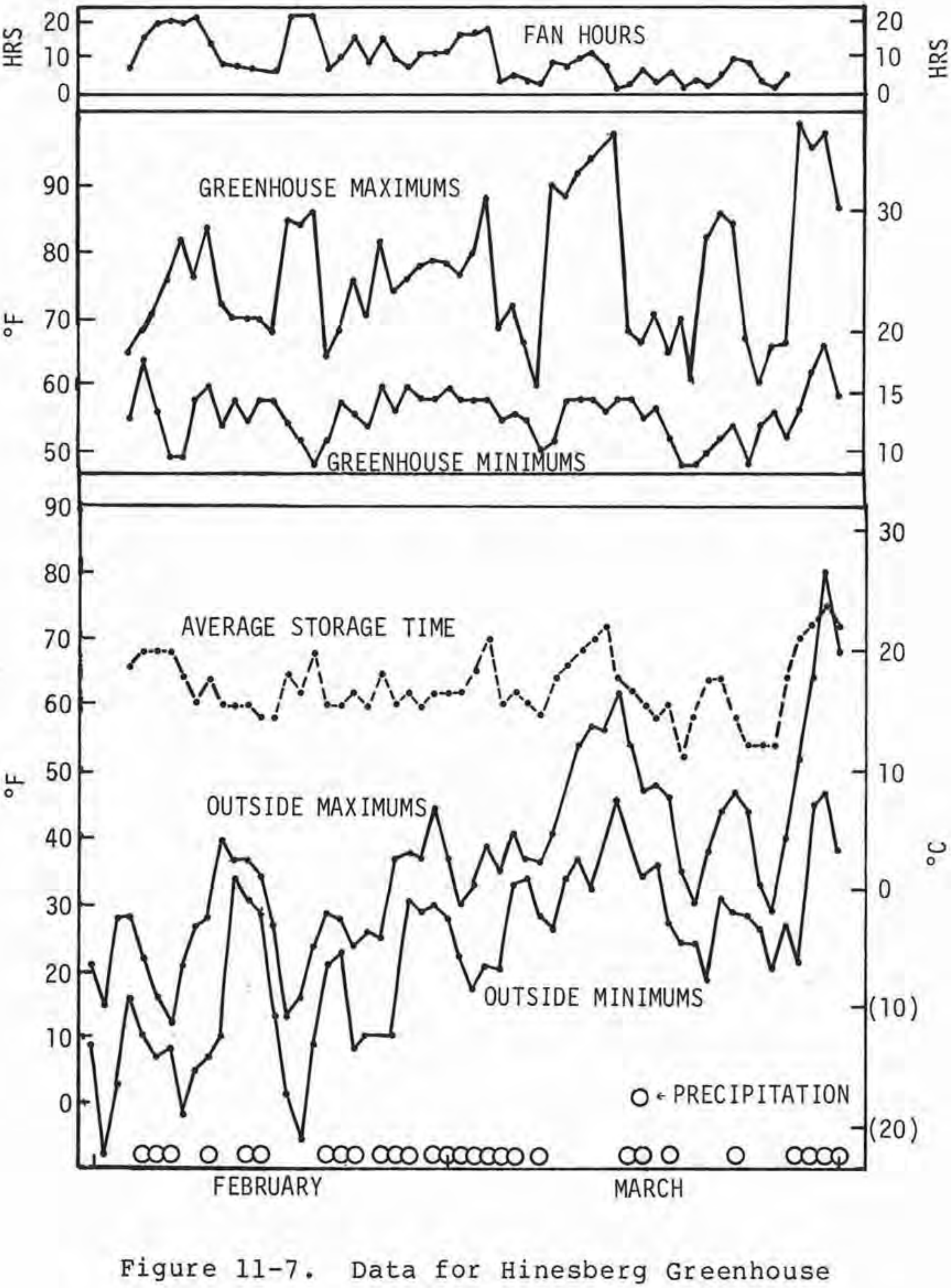


Figure 11-7. Data for Hinesberg Greenhouse

Performance Estimate

The modified building loss coefficient for this greenhouse is 1,500 Btu/dd. The kitchen adjoining the greenhouse was treated as a heat load on the greenhouse at a rate of 3,240 Btu/dd. The combination of these two losses gives the gross load shown in Table 11-I. There were no internal heat sources for the greenhouse. The computed solar heating fraction indicates that nearly one-fourth of the heat required by the kitchen is being drawn from the greenhouse.

TABLE 11-I

Performance Estimate for the Hinesberg Greenhouse

Month	Degree-Days	Gross Load, Other Sources (optional) (MBtu)	Solar Radiation on Horiz. Surface (Btu/ft^2·h)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	1,513	7.17	17,145	2.03	0.28	0.16	6.01
February	1,333	6.32	21,989	2.07	0.328	0.19	5.12
March	1,187	5.62	33,489	2.26	0.40	0.23	4.32
April	714	3.38	41,700	1.85	0.55	0.31	2.34
May	353	1.67	47,890	1.50	0.90	0.46	0.90
June	90	0.43	52,872	1.42	3.30	0.92	0.03
July	28	0.13	53,034	1.52	11.69	1	0
August	65	0.31	42,518	1.62	5.23	1	0
September	207	0.98	33,294	1.92	1.95	0.75	0.24
October	539	2.55	24,802	2.11	0.83	0.43	1.45
November	891	4.22	11,946	1.34	0.32	0.18	3.45
December	1,349	6.39	11,201	1.41	0.22	0.12	5.60
Annual		38.31					29.47

ANNUAL SHF = 0.23

SECTION 12

THE STAR TANNERY HOUSE

Figure 12-1. Exterior of Star Tannery House

BUILDER: Holt Bros. Construction
DESIGNER: Tim Maloney
OWNER: One Design, Inc.
TYPE: Single family dwelling
AREA: 1,250 square feet
GENERIC TYPE: Waterwall and direct gain
LOCATION: Star Tannery, Virginia
LATITUDE: 39.05°N.
ELEVATION: 450 feet
CLIMATE DATA:
  Heating dd: 5,500
  Design temp: 0°F
  Horiz. insolation (Jan. day): 1,188 Btu/ft^2

Figure 12-2. Living Room of Star Tannery House

Figure 12-3. Roof Configuration of Star Tannery House

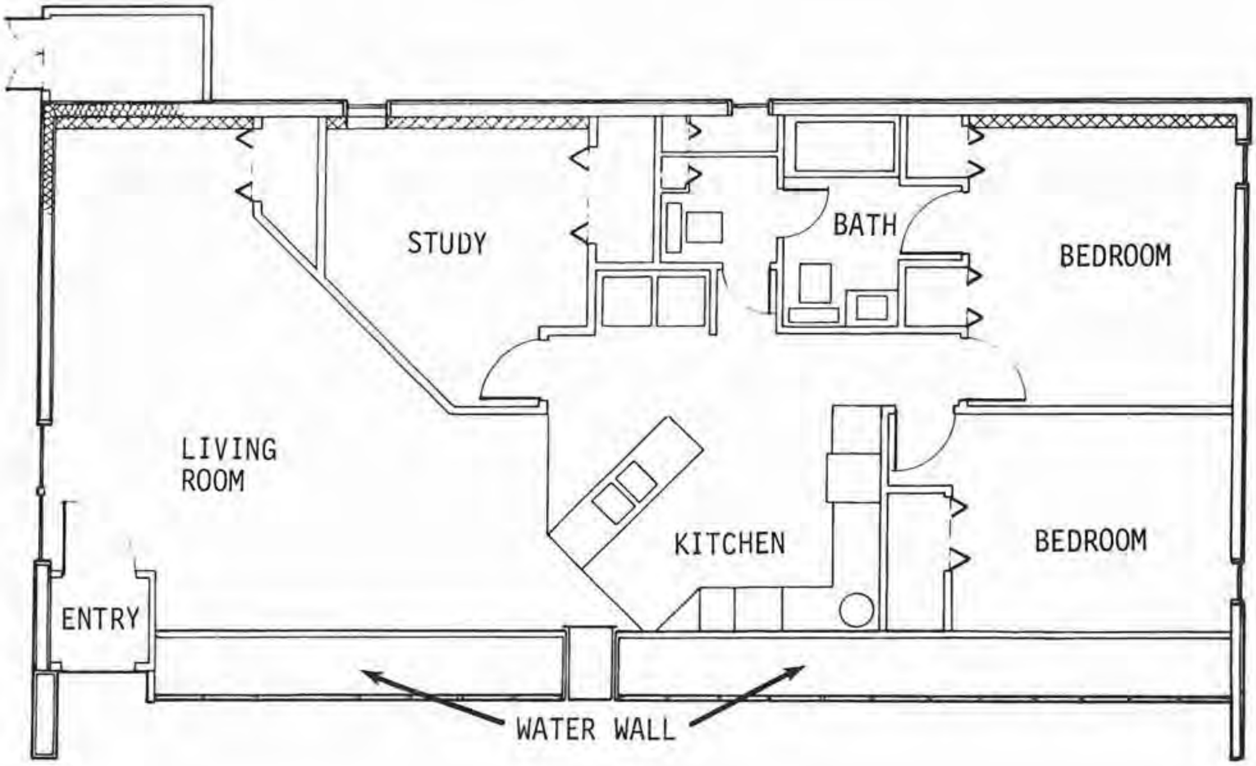


Figure 12-4. Floor Plan

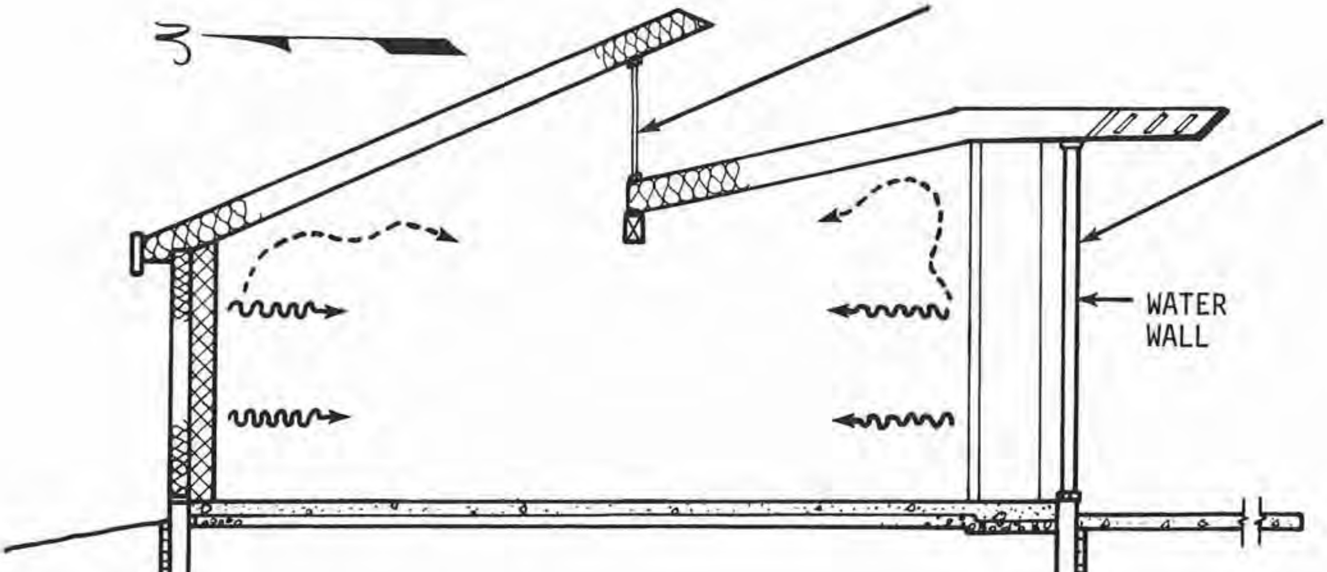


Figure 12-5. Thermal Flow Diagram

Collectors -- A triple-glazed waterwall with 400 square feet of vertical south-facing area is the primary collector. Clearstory windows admit additional solar energy to the north wall of the house.

Storage -- The waterwall holds approximately 4,000 gallons of water for thermal storage. The interior of the north wall is solid masonry for storage of energy transmitted through the clearstory windows. The concrete floor slab provides additional storage.

Distribution -- Distribution is by radiation and convection from the surfaces of the thermal storage volumes.

Auxiliary Heat -- A propane-fueled, forced hot air furnace provides backup heating.

Domestic Hot Water -- A 90-gallon electric hot water heater supplies domestic hot water needs. Heat exchanger coils in the waterwall preheat the supply water to about 80°F.

Controls -- The waterwall has manually operated dampers to allow venting of excess heat to the outdoors. Louvres in the overhang can shade the waterwall. The backup furnace is thermostatically controlled.

Description

The Star Tannery house is a single-story dwelling situated atop a knoll in the hilly country east of the Allegheny Mountains, near Winchester, Virginia. The house is a modest two-bedroom residence. The living/dining room and entryway are located at the west end of the building, and this space flows freely into the kitchen area in the central portion of the house. The two bedrooms are set against the east wall. A study and one-and-one-half baths are along the north wall. Almost the entire length of the south wall is taken up by the waterwall solar heating system. The glazing for the waterwall consists of one cover of 1/8-inch, low-iron glass and one cover of

Tuffak®, which is the Rohm and Haas brand name for double-walled, extruded polycarbonate plastic sheeting. In effect, the waterwall is triple glazed. Behind the glazing is a 2-by-4 framework lined with corrugated aluminum. This framework supports water-filled vinyl plastic bags which provide the thermal storage for the house. The living-space side of the waterwall is screened off with a standard 2-by-4 partition finished with drywall material.

The exterior walls are formed on 2- by 6-inch studs finished on the inside with 1/2-inch gypsum board. The outside is sheathed with 1/2-inch celotex (or plywood at the corners for rigidity) and finished with 3/4-inch hardboard siding. The cavities between studs are filled with cellulosic fiber which was blown into the cavity while wet.

The rafters are 2 by 10's on 24-inch centers. The ceiling is finished with 5/8-inch interior drywall sheeting. The exterior is sheathed with 1/2-inch plywood covered with felt and shingled with asphalt shingles. The cavities between rafters are filled with cellulosic fiber blown in dry. The roof is a sawtooth configuration forming a clearstory window down the center for the full length of the building. This clearstory is glazed with two layers of Tuffak®. The endwalls of the house conceal the sawtooth shape of the roofline, making it appear as a simple pitched roof.

The house is erected on a concrete floor slab. The foundation is insulated with 2-inch-thick styrofoam to a depth of 3 feet.

The windows are wood framed and double glazed. There are 17 square feet of window area on the north wall and 24 on the east wall. One 20-square-foot window penetrates the waterwall on the south. A metal-framed, double-glazed, sliding glass door is on the west wall. The clearstory window has 147 square feet of glazing which provides abundant and pleasant lighting to the interior.

The inside of the north walls of the living room, study, and north bedroom have been covered with masonry 8 inches thick. This masonry is painted a dark rust-red and acts both as a collector for sunlight entering the clearstory and as a pleasing architectural feature.

The domestic hot water is provided by a standard 90-gallon electric water heater. The water supply is preheated by a heat exchanger in the waterwall. Auxiliary heat is generated by a propane-fueled furnace and delivered through a forced-air distribution system.

Operation

The operation of the waterwall in the One Design house differs from that in the usual waterwall system. In the usual design, the solar energy collected is transferred through the waterwall to the interior wall of the house where, by radiation and convection, it is transferred to the living space. In the One Design construction, this thermal flow path is interrupted by the air space (about 4 inches wide) between the waterbag thermal storage structure and the interior wall of the house. In effect, this waterwall consists of a freestanding water container within a long thin closet which has a glazed south wall. Solar energy incident on the south wall passes through the glazing and is absorbed on the corrugated aluminum sheeting where it is conducted immediately to the mass of water in the bag. Convection currents cause the warmed water to rise such that the water at the top is warmer than at the bottom. The surfaces of the water container heat the air in the enclosed space and radiate energy to the walls. Heat is therefore transferred through the partition to the interior of the house. Heat is also lost through the glazing to the outdoors. There are vents at the top and bottom of the partition to increase the circulation of warm air to the living space but these have not been used.

An overhang above the glazed south wall is fitted with movable louvers to provide shade for the waterwall when desired.

The waterwall system is supplemented by the large array of clearstory windows. Sunlight entering these windows falls, for the most part, on the masonry along the north wall, where it is stored until the house requires heat. Roof overhangs shade the clearstory windows in the summer when the house does not need heat.

The preheat system for the domestic hot water draws its heat directly from the waterwall storage via the heat exchanger. This is an effective and economical system. Its drawback is that the waterwall is essentially unheated during the summer, so little solar energy is contributed to the domestic hot water system over the summer months. The electric booster features an automatic nighttime setback on the thermostat temperature control.

Another energy-conserving feature is incorporated in the electric clothes dryer: the filtered hot air from the exhaust can be delivered into the house in the winter months or to the outside in the summer.

The front entry of the house, on the west end of the south wall, is an airlock. Both doors of the airlock are insulated metal with magnetic weatherstripping.

Performance

The performance of this house has been monitored by several stripchart temperature recording gauges. Composites of these recordings for the weeks of December 19-25, 1977, and January 2-8, 1978, are presented in Figure 12-6. The insolation curve is derived from a homemade pyranometer, which is uncalibrated and gives an indication of relative insolation only.

The week of December 19 starts with 3 sunless days followed by 4 days of partial sun, and the ambient temperature oscillates around the freezing point. (The auxiliary heating system was turned off during this period.) This is a very severe test for the solar heating system. At the start of the week, the average waterwall temperature is about 67°F, and during the 3 sunless days this drops to about 58°F. The top-to-bottom stratification of the waterwall is about 10°F during the entire time. The next 4 days have varying degrees of sunshine.

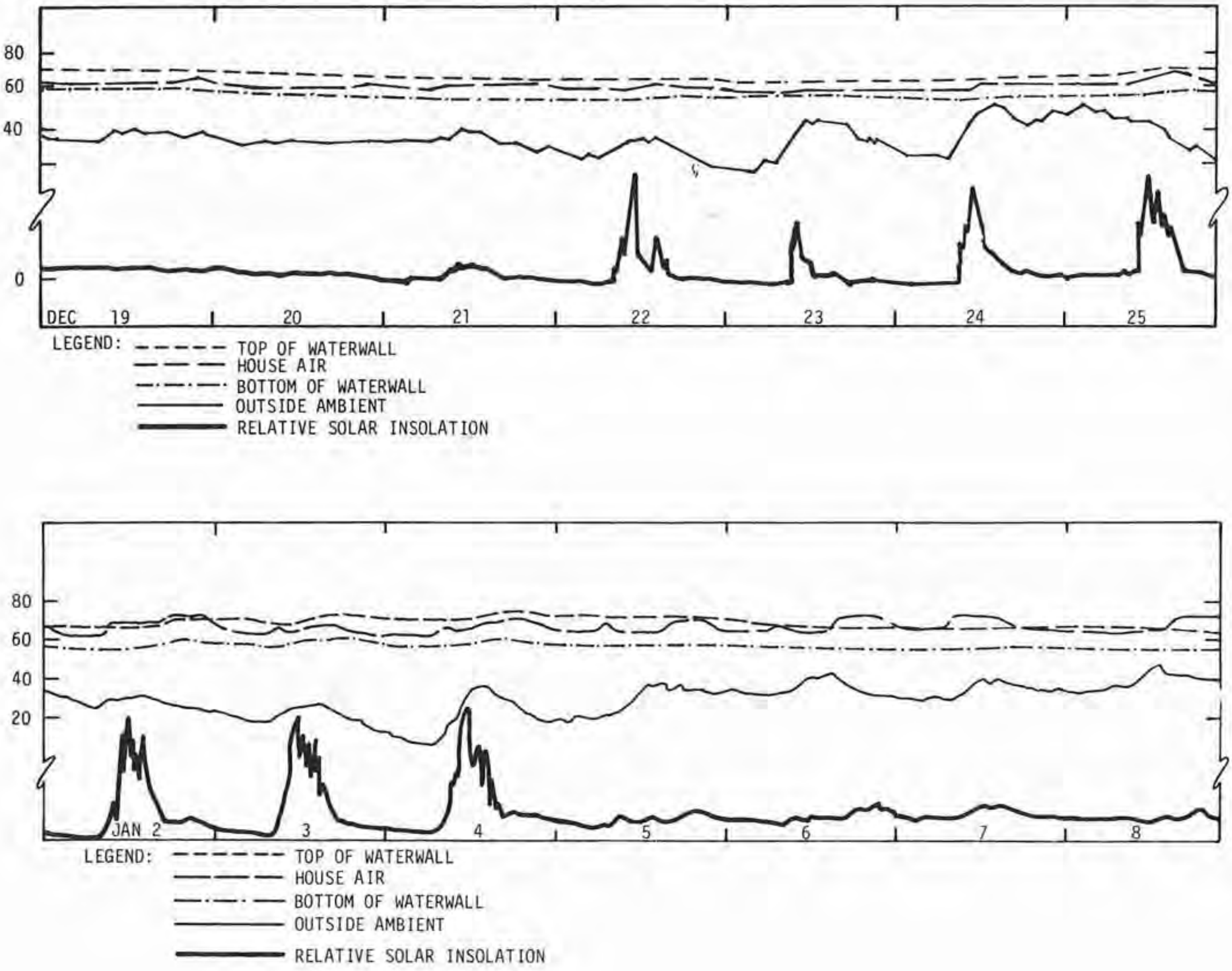


Figure 12-6. Temperature Recordings from the Star Tannery House

The broken nature of the insolation curve indicates that the days are partly cloudy. The average waterwall temperature slowly rises to about 64°F, maintaining the same stratification pattern. The indoor temperature generally coincides with the average waterwall temperature, with the significant difference that during periods of sunshine there is an immediate boost, apparently from the direct-gain energy received through the clearstory windows. The minimum indoor temperature is 56°F on the night of December 22-23, while the outdoor ambient temperature drops to 17°F.

The January 2-8 period starts with 3 days of fairly good sunshine, although it is still partly cloudy. The response of the waterwall is clearly shown by its rise in temperature for each day of sun, even though the outdoor ambient falls to a very cold 5°F. The succeeding 4 sunless days show a pattern similar to the sunless December period, except that the indoor temperature receives strong boosts from the auxiliary heating system.

A total of 330 cubic feet of propane gas was consumed during this week; over the period August 1977 to mid-April 1978, the auxiliary heating system used 6,280 cubic feet of propane gas.

Temperature measurements within the living space show a temperature difference of about 2°F between the north and south sides of the house and also between floor and ceiling temperatures. Special fans have been installed to break up temperature stratification in the living space, but they have never been used.

Designer Comments

In undertaking the design of this house, the basic philosophy was to achieve a completely passive solar system with a simplicity of operation that could be easily understood by the owner. In order to offer complete control of the living space temperature, the waterwall was designed for storage temperatures just below the comfort range. Thermostatically controlled auxiliary heaters are therefore in a position to hold the temperature at an occupant-set level.

The key feature of the design is the waterwall, and its construction posed an unusual problem for the builder. The bags used for water storage are off-the-shelf fuel storage containers. They sometimes have small leaks which are difficult to locate. The Tuffak® glazing has not been entirely satisfactory. It is not rigid enough, and in the Virginia climate, water condenses between the two layers and it becomes moldy. The wet-blown cellulosic wall insulation takes too long to dry out, and while it is wet, the insulation values are considerably reduced.

For the 1978-79 heating season, One Design replaced the galvanized sheet metal and vinyl bladders in the waterwall with modular rigid containers of various types and sizes. Twenty modules of 3 different types were installed: 5 fiberglass modules providing 53 pounds of water per square foot of glazing, 5 heavier fiberglass modules providing 93 pounds of water per square foot of glazing, and 10 galvanized metal tanks providing 68 pounds of water per square foot of glazing. Altogether the waterwall contains 26,166 pounds of water. The waterwall glazing was replaced with double-skinned acrylic sheet with a Teflon film inner glazing. Temperatures at 32 points in the waterwall and within the house are being monitored to assess the effects of varying waterwall thermal mass and absorptive surface treatment (black vs. green vs. black chrome).

The lighter versions of the fiberglass waterwall modules designed by One Design are 96 inches long, 24-1/2 inches tall, and 16-1/2 inches wide. They hold 94 gallons (784 pounds) of water. The modules can be stacked five high to make a 10-foot-high waterwall. For shipment (without the water), the modules nest together to save space.

Cost

This 1,250-square-foot residential home was constructed in rural Virginia with a completion date of February 1977. The construction cost of $34,000 was financed locally. This cost does not include the cost of the land.

Performance Estimate

The performance estimate for the Star Tannery house is summarized in Table 12-I. The estimate predicts an auxiliary energy consumption of 6.12 MBtu's for the heating season. Actual use was 6,280 cubic feet of propane gas.

At a furnace efficiency of 66 percent and a fuel rating of 2400 Btu's per cubic foot, this amounts to an auxiliary energy consumption of 9.95 MBtu's for the heating season. This is 62 percent higher than what was calculated in the performance estimate. The difference is most probably attributable to the fact that the degree-day data for the estimate is from records of the Washington D.C. area, whereas the weather at Star Tannery is considerably colder.

One Design has calculated a performance estimate using the solar load ratio method but modified to account for differences in the basic reference system. The modifications were for (1) a thermal mass greater than 45 pounds per square foot of collector area, (2) glazing transmittance better than standard insulated glass, (3) additional solar gain from the clearstory windows, and (4) additional thermal mass on the north wall. They recalculated the modified building loss coefficient as 9,200 Btu's per degree-day (as opposed to 12,050 Btu/dd used for the calculations supporting Table 12-I). Their weather data listed 5,459 degree-days (as opposed to 4,224 dd). The annual solar radiation on a horizontal surface totaled 461,680 Btu's per square foot (as opposed to 478,882 Btu/ft^2) with most of the difference coming during the winter months. Under these more severe weather conditions but with the improved modified building loss coefficient, the One Design calculation shows a solar heating fraction of 0.832 and an auxiliary heat consumption of 4.83 MBtu's.

TABLE 12-1

Performance Estimate for the Star Tannery House

Month	Degree-Days	Gross Load (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface ($Btu/ft^2 \cdot mo$)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	871	10.50	2.70	7.80	21,945	11.36	1.46	0.75	1.95
February	762	9.18	2.44	6.74	26,325	10.70	1.59	0.78	1.46
March	626	7.55	2.70	4.84	39,090	11.16	2.30	0.91	0.45
April	288	3.47	2.62	0.85	46,346	8.58	10.02	1	0
May	74	0.89	2.70	0	57,034	-	-	1	0
June	0	0	-	0	59,398	-	-	1	0
July	0	0	-	0	59,092	-	-	1	0
August	0	0	-	0	54,291	-	-	1	0
September	33	0.40	2.62	0	42,364	-	-	1	0
October	217	2.62	2.70	0	33,603	-	-	1	0
November	519	6.26	2.62	3.64	21,458	10.47	2.88	0.96	0.16
December	834	10.00	2.70	7.35	17,936	9.81	1.33	0.71	2.11
Annual	4,224			31.23					6.12

ANNUAL SHF = 0.80

SECTION 13

THE KELLER WAREHOUSE

Figure 13-1. Retrofitted Trombe Wall on Warehouse

BUILDER: Kalwall Corporation
DESIGNER: Kalwall Corporation
OWNER: Keller Products
TYPE: Commercial brick building
AREA: 1,800 square feet
GENERIC TYPE: Trombe
LOCATION: Manchester, New Hampshire
LATITUDE: 43°N.
ELEVATION: 175 feet
CLIMATE DATA:
  Heating dd: 7,800
  Design temp: Unknown
  Horiz. insolation (Jan. day):
    435 Btu/ft^2

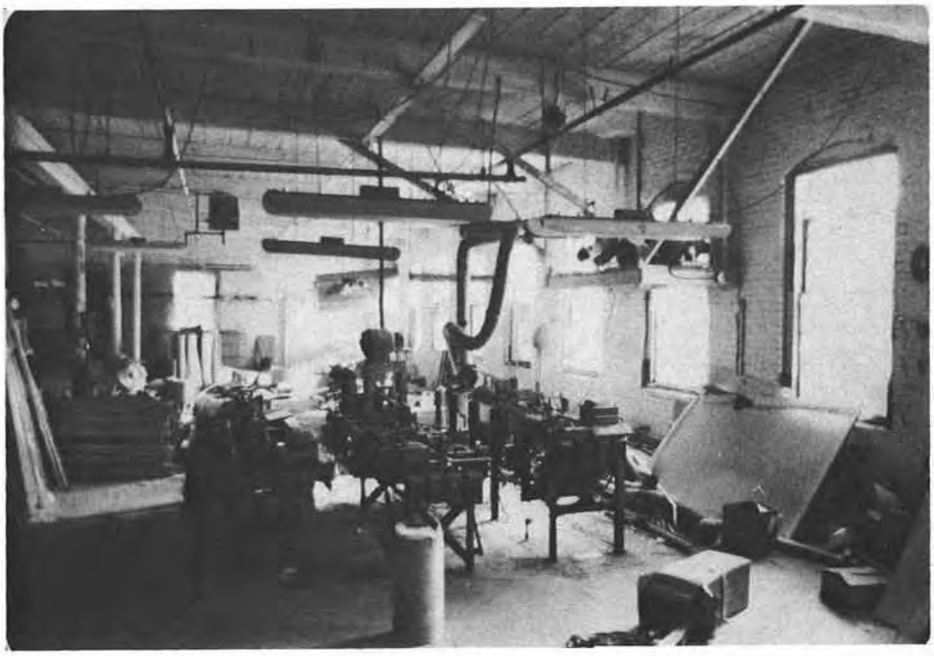


Figure 13-2. Interior of Warehouse

Figure 13-3. North Wall of Warehouse Showing Original Construction

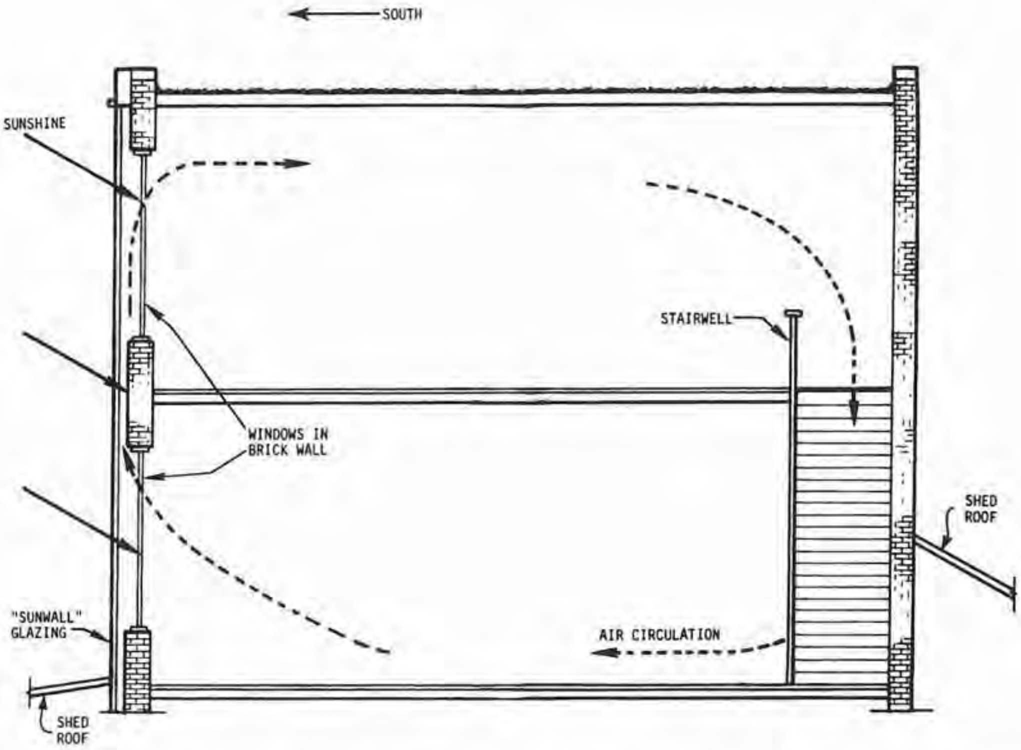


Figure 13-4. Thermal Flow Diagram for Keller Warehouse Trombe Wall System

Collector -- The south wall of the upper two stories of an old manufacturing building acts as both a direct-gain collector and as a Trombe wall. Total collector area is 1,970 square feet.

Storage -- Primary thermal storage is the 12-inch-thick brick which forms the south wall. Additional thermal storage is provided by materials within the building, which is used partly as a warehouse.

Distribution -- Distribution of heat is by radiation from the inside surface of the brick wall and by natural air convection.

Auxiliary Heat -- A central heating plant provides auxiliary heat.

Domestic Hot Water -- Not applicable.

Controls -- Rows of sash-type windows on the second and third floor levels can be opened to control thermocirculation of the Trombe wall. Loading dock doors on the north wall can be opened to vent excess heat. The auxiliary heat is thermostatically controlled.

Description

An old (1920's) factory in Manchester, New Hampshire, occupied by Keller Products, Inc., was retrofitted with a hybrid mass-wall/direct-gain passive solar heating system. The building is three stories tall and constructed of brick and mortar. The walls are 12 inches thick, and the south wall is pierced with 24 sash-type windows--a row of 12 on both the second and third floors. The south wall corresponding to the second and third floors was painted black and then covered with translucent wall panel sections. The panels covered both the brick wall and the windows in the wall. The panels used are a commercial product of Kalwall Corporation called Sunwall® Solar Window Panels. The panels are 2-3/4 inches thick and are made of two sheets of fiberglass-reinforced plastic bonded to an aluminum grid structure. The panels were mounted so that there was a 3-inch space between the brick wall surface and the inner surface of the panel. A total surface area of 1,970 square feet was glazed in this manner. The 24 windows, each measuring 3.8 by 7 feet, occupy 630 square feet of this area. The retrofitted wall is, therefore, approximately one-third passive direct gain and two-thirds passive mass wall.

The north wall of the building is similar to the south wall before the retrofit. The grade level has been built up to the second floor on the north side and one of the windows on the second floor replaced with a loading dock door measuring approximately 8 by 10 feet. Four of the windows on the second floor have been blocked up with masonry. Many of the remaining windows have been roughly boarded up. Because of the age of the building, all the window sashes are loose and warped and appear to allow heavy air infiltration into the building interior. The east and west walls are a solid brick and mortar 12 inches thick and have no windows. There is a fire escape doorway on the east wall for both the second and third stories.

The floors are wooden, and there are no partitions on either the second or third stories to block air circulation. Two stairwells connect the second and third floors. There is an elevator in the building, but the shaft is closed to air circulation by automatic sliding doors at each level. The roof is wooden with a built-up asphalt sealer.

Operation

In operation, direct and indirect solar radiation is transmitted through the double-walled fiberglass panels and absorbed by the black-painted brick wall or is admitted through one of the windows as direct gain to the warehouse space. That radiation which is absorbed onto the brick surface is converted to thermal energy which in turn is either reradiated back through the fiberglass cover or is conducted into the 12-inch-thick wall. The thermal conductivity of brick is low, and the conduction of energy through the wall is therefore a slow process. The warmed outer surface of the brick wall will also warm the air in the space between the brick and the fiberglass cover. By opening the windows on both the second and third stories, this warm air can circulate into the third story, down the stairwells into the second story, and complete the circuit by passing out through the second story windows to reenter the space between the brick and fiberglass cover. This flow of air cools the brick wall by transferring some of its heat into the warehouse space. If the windows are kept closed, shutting off this air flow, the brick wall surface temperature is significantly increased. This stores more heat in the brick wall but also increases radiation losses through the fiberglass cover.

Performance

Temperatures of the inside and outside surfaces of the brick wall, wall interior, air gap, outside air, and room air were measured. A vertically mounted pyranometer on a nearby building measured insolation. Thermosiphoning flow rates were measured by attaching a rectangular duct to the inside of the second window from the east on the third floor and surveying the flow at the duct outlet with a thermoanemometer. Temperatures of the outlet air flow and the inlet air flow at the second story window directly beneath were measured with shielded thermocouples. Temperatures inside the brick wall were measured at two depths at each location, 4 inches and 8 inches from the exterior surface.

The system is operated in the unvented mode during the day of January 3, 1978. On that day the total insolation is 1,780 Btu/ft^2 with a peak rate of 315 Btu/ft^2·h. The average ambient temperature is 22°F. Figure 13-5 plots some of the data taken on this day. The closed vents and the high peak insolation rate combine to produce a peak wall surface temperature of 153°F at 1 p.m. After this time, the outer brick surface temperature declines. This does not mean that the brick wall has ceased to increase its store of thermal energy. As long as the temperature gradient, measured from the outer surface into the brick wall, is negative (i.e., in the region near the surface of the brick the temperature decreases with depth), the wall will be storing solar energy. Figure 13-6 shows a series of temperature profiles through the brick wall at various times of the day. The curves indicate that the temperature gradient at the outer surface remains positive until shortly after 1700 hours (5 p.m.).

The inside air temperature curve in Figure 13-5 indicates a very rapid heating of the warehouse space by the direct solar gain through the sash windows. By approximately 0900 hours (9 a.m.), the inside air is warmer than the inside surface of the brick wall, and it remains warmer until about 1500 hours (3 p.m.). During this period heat is being transferred from the air into the wall for storage. After 1500 hours, this heat, plus heat conducted from the outer surface, is transferred back to the warehouse space.

Figures 13-7 and 13-8 are similar curves for the period February 4-6, 1978. During this period the system is operated with the windows open, venting the air space into the warehouse. The windows are opened at 0800 hours (8 a.m.) and closed at 1700 hours (5 p.m.). The

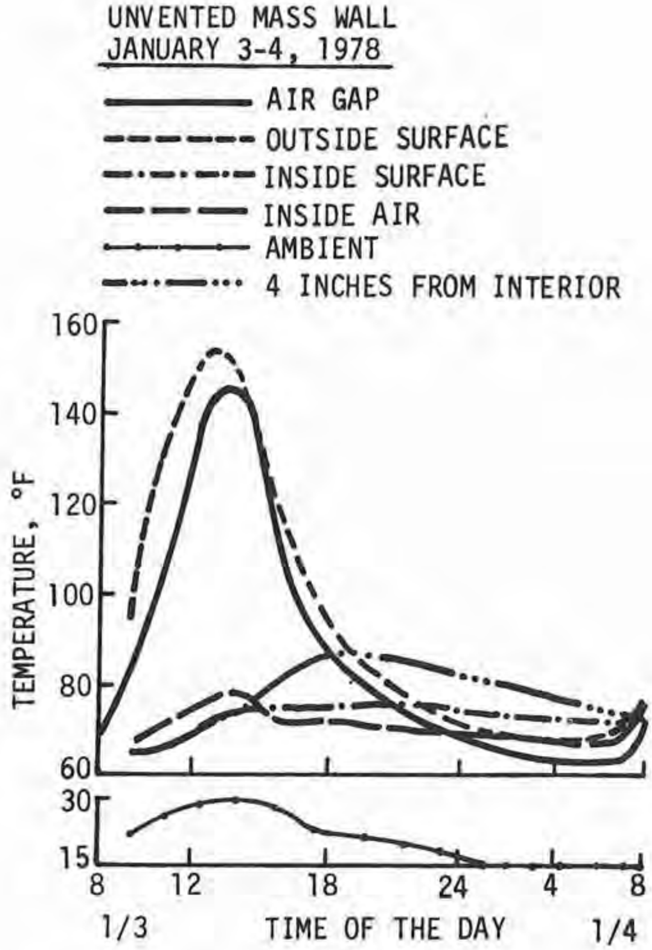


Figure 13-5. Temperature Recorded for Keller Warehouse, Unvented Case

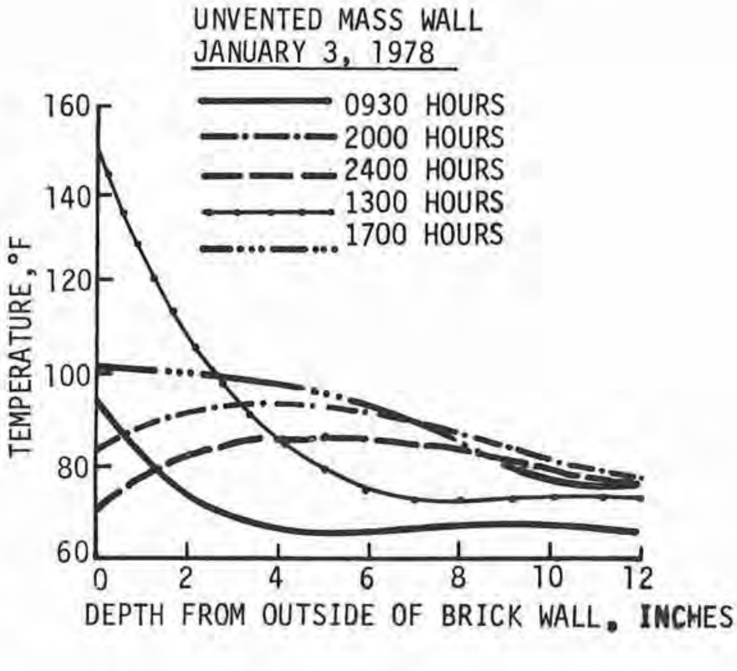


Figure 13-6. Temperature Profile in Brick Wall, Unvented

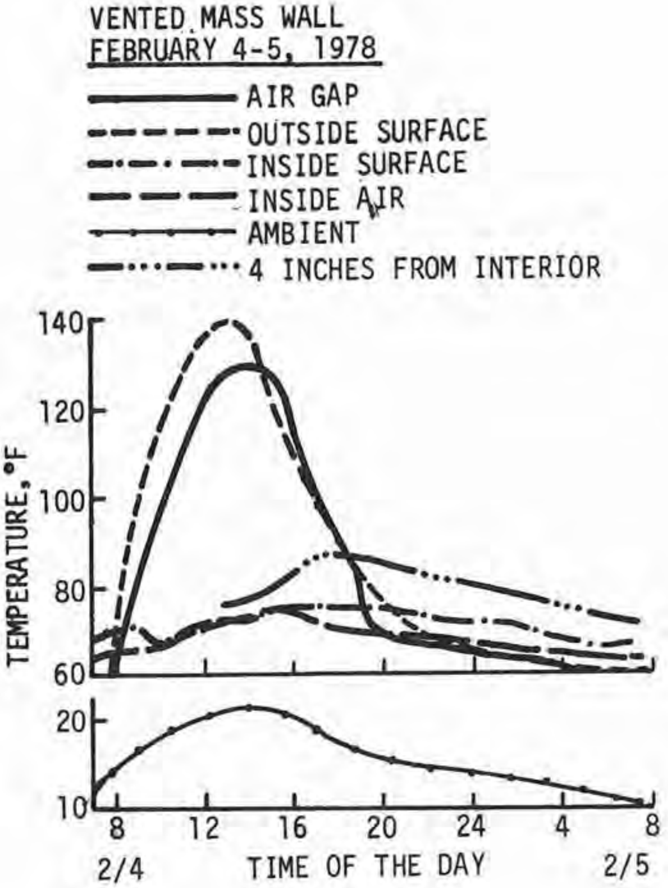


Figure 13-7. Temperatures Recorded for Keller Warehouse, Vented Case

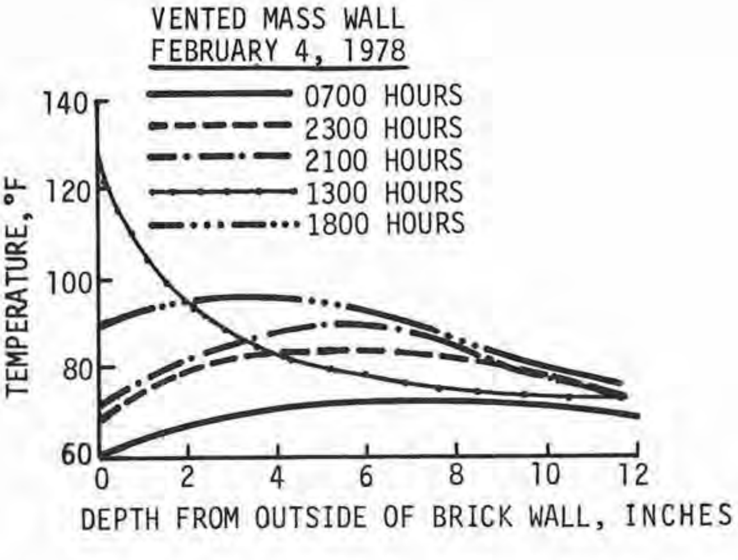


Figure 13-8. Temperature Profile in Brick Wall, Vented Case

total insolation for the day is 1,940 Btu/ft^2, with a peak rate of 287 Btu/ft^2·h. The average ambient temperature is 13°F.

The combined effects of a lower peak insolation rate, lower ambient temperature, and the venting reduce the peak wall outer surface temperature to 139°F. The heat conduction and temperature profiles within the brick wall are essentially the same as for the unvented case. The only significant difference is that the interior air temperature never exceeds the inner wall surface temperature as occurred in the unvented case. This may be the result of more rapid movement of cool air from the north wall to the south wall on the second story because of the thermosiphoning effect.

The velocity and temperature of the air flowing through one of the third story windows were measured on January 31, 1978, a day with weather similar to that on February 4. The heat flow rate into the third story from this window was calculated and plotted as a function of time. The plot is shown in Figure 13-9.

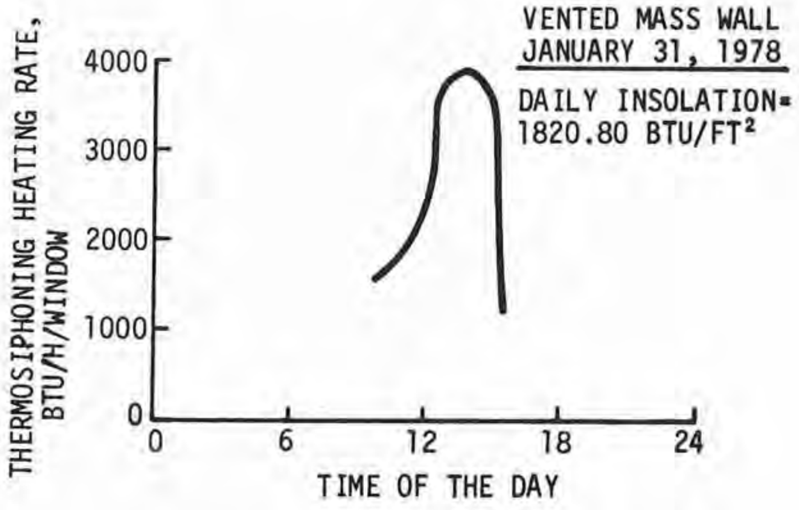


Figure 13-9. Thermosiphon Heating Rate into Keller Warehouse

Calculations made by the Kalwall Corporation indicate that the retrofitted wall provided 800,000 Btu's per day in the unvented case and 770,000 Btu's per day in the vented case. Without the retrofit "Sunwall" system, the wall would have lost about 1.36 million Btu's per day. The overall contribution of the retrofit system is, therefore, about 2.16 million Btu's per day for these weather conditions.

A major weathering effect on masonry structures is alternate freezing and thawing in the presence of moisture. The retrofit system shields the masonry from moisture and eliminates this effect. No detrimental effects have been noted due to the higher daytime outer-surface temperatures caused by the glazing system.

Owner Comments

Many old brick commercial structures exist in the United States. The walls of these buildings offer a large solar collection area and high thermal mass--two characteristics essential to a passive solar heating system. These buildings, therefore, are excellent candidates for retrofitting as a passive, mass-wall solar heating system. The objectives of the Kalwall Corporation in this particular project were

1. To provide information on the effects of retrofitting old brick and masonry structures with passive solar systems.
2. To add to the limited base of information available which evaluates brick as a thermal storage medium versus water. The Kalwall corporation has been and is involved in several projects utilizing water as the absorber/storage vehicle. Little practical information is available to building owners for evaluation of the two systems.
3. To monitor temperatures and heat gains/losses with the system operating under stagnation conditions (as a solid mass wall) or in a thermosiphoning (vented) condition similar to the Trombe wall.
4. To gain a more complete understanding of the relative costs and performance involved in retrofitting an existing structure.
5. To indicate areas for future product development.

Performance Estimate

The modified building loss coefficient for this warehouse is 137,800 Btu/dd, or 13.78 Btu/ft^2·dd. The solar system is a combination of direct gain and Trombe wall. Approximately 30 percent of the glazed south wall is window area with the remainder being brick. The SHF was calculated for each month for both types of solar systems and a weighted average of the two calculations is shown in Table 13-I.

TABLE 13-I

Performance Estimate for the Keller Warehouse

Month	Degree-Days	Gross and Net Loads (MBtu)	Solar Radiation on Horiz. Surface ($MBtu/ft^2 \cdot mo$)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	1,358	187.13	16,687	41.45	0.22	0.13	163.36
February	1,184	163.15	22,402	44.14	0.27	0.16	137.54
March	1,032	142.21	34,746	48.73	0.34	0.20	113.91
April	630	87.64	40,926	37.58	0.43	0.25	65.73
May	298	41.06	50,976	33.09	0.81	0.45	22.79
June	75	10.34	53,646	30.04	2.91	0.90	1.03
July	6	0.83	54,634	32.61	39.44	1	0
August	50	6.89	48,805	38.55	5.60	1	0
September	177	24.39	37,276	44.49	1.82	0.76	5.83
October	505	69.59	28,917	51.34	0.74	0.41	40.92
November	822	113.27	17,034	39.99	0.35	0.21	90.05
December	1,240	170.87	14,744	38.84	0.23	0.13	148.14
Annual		999.31					789.30

ANNUAL SHF = 0.21

SECTION 14

THE KALWALL DIRECT-GAIN WAREHOUSE

Figure 14-1. Direct-Gain Solar Heated Warehouse

BUILDER: Kalwall Corporation
DESIGNER: Kalwall Corporation
OWNER: Kalwall Corporation
TYPE: Warehouse
AREA: 10,000 square feet
GENERIC TYPE: Direct gain
LOCATION: Manchester, New Hampshire
LATITUDE: 43°N.
ELEVATION: 100 feet
CLIMATE DATA:
Heating dd: 7,800
Horiz. insolation (Jan. day): 435 Btu/ft^2

Figure 14-2. Interior of Direct-Gain Solar Heated Warehouse

Figure 14-3. Circulating Fans in Warehouse

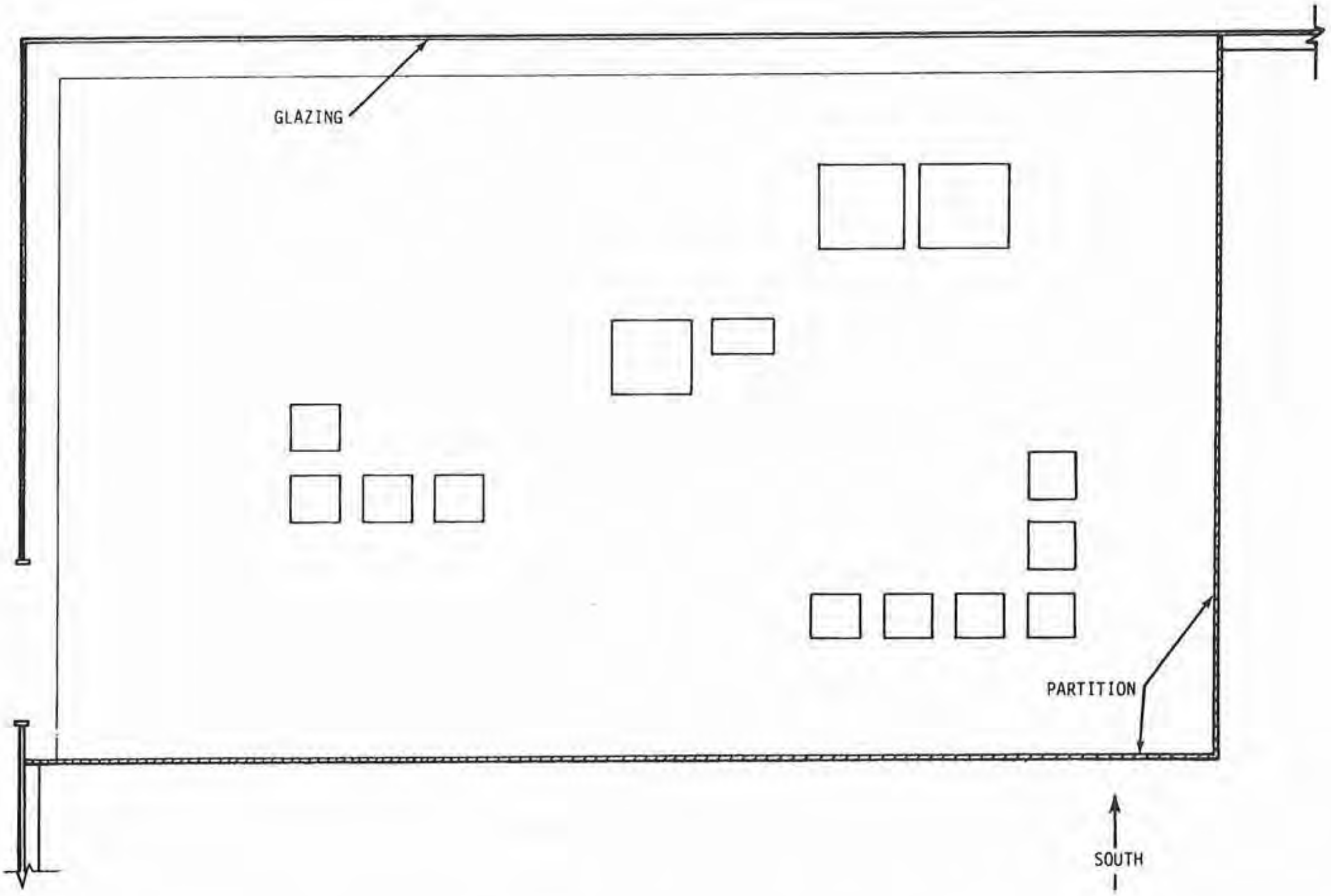


Figure 14-4. Warehouse Floor Plan

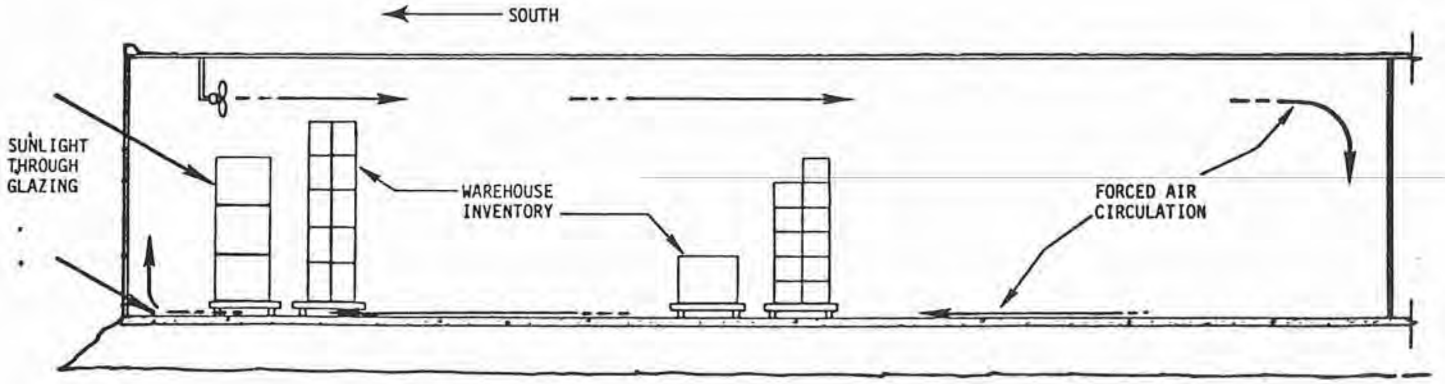


Figure 14-5. Thermal Flow Diagram

Collectors -- A section of the south wall of the warehouse has been retrofitted with translucent paneling to form a direct-gain collector. The collector area measures 125 feet long by 14 feet high for a total area of 1,750 square feet.

Storage -- The concrete slab floor and the stored materials in the warehouse provide the thermal storage mass.

Distribution -- Thermal energy is distributed by natural convection and radiation and by the forced circulation of air with electric-powered fans.

Auxiliary Heat -- Two forced-draft unit heaters fed with hot water from a central heating system supply the auxiliary heat.

Domestic Hot Water -- Not applicable.

Controls -- The unit heaters are thermostatically controlled.

Description

The Kalwall Corporation selected one of their own warehouses in Manchester, New Hampshire, to be retrofitted with a direct-gain solar wall. The building was of timber post-and-beam construction with lightly insulating building panels for the walls and roof. The southeast corner of the 40,000-square-foot warehouse was isolated with internal partitions. The isolated section measures 125 feet long (on the east-west axis) and 75 feet wide. The south wall of the isolated section, 125 feet long and 14 feet high, was replaced with "sandwich" panels faced with fiberglass-reinforced plastic sheets bonded to an aluminum grid core. The panels are 2-3/4 inches thick and transmit 77 percent of the solar radiation at normal incidence. This paneling is a commercial product of Kalwall Corporation identified as Sunwall® Solar Window Panel, a registered trademark.

The east wall of the isolated section is made of standard Kalwall® fiberglass panels, similar to the Sunwall® panels except that their transmission factor is only 40 percent.

The internal partitions are constructed of 2- by 4-inch studs sheathed on both sides with fiberglass-reinforced plastic sheeting.

The original roof was 2-3/4-inch-thick Kalwall® panels supported on wood rafters. In the fall of 1977, 2 inches of sprayed-in-place urethane foam was added to the top surface of the roof and sealed with plastic sheeting. There is a 16-inch roof overhang.

The floor of the warehouse is built up to a height of 30 inches above the surrounding grade level. The floor surface is an 8-inch-thick concrete slab. A 3-1/2-foot band of the floor along the direct-gain wall has been painted black. The 30-inch-high retaining wall around the perimeter of the warehouse floor has been insulated with a 2-inch layer of urethane foam insulation sheathed with fiberglass sheeting.

There are no windows into the partitioned-off section of the warehouse. The walls, exterior and interior, are translucent and admit light. The east wall is fitted with a 16- by 24-foot rollup door. Rigid urethane foam, 2 inches thick, has been glued to each door panel and covered with plastic sheeting. The door is tightly weather-stripped around the edges.

Five 24-inch-diameter, 1/4-horsepower fans are spaced along the south wall 4 feet below the ceiling to blow air toward the north wall. The stores in the warehouse are stacked on pallets which provide an open channel for air circulation along the slab from the north wall to the south wall.

One of the auxiliary unit heaters, located near the south wall, has a rating of 196,000 Btu's per hour (Btu/h) with a 1/3-horsepower motor and a 3,740 cubic feet per minute (ft^3/m) fan. The other unit above the loading dock (northeast corner) is rated at 209,000 Btu/h with a 1/2-horsepower motor and a 4,885 ft^3/m fan. The fans are oriented to move the air in a circular fashion around the warehouse interior.

Operation

During the day, solar radiation is admitted directly into the warehouse through the translucent south wall and falls on the black-painted floor slab or on the stacks of stored material in the warehouse. Most of this solar radiation is absorbed and warms the floor and stored materials that are near the south wall. The warehouse is 75 feet deep, and this heat must be distributed throughout the warehouse area. The fans perform this function. Each fan is individually controlled by its own pair of thermostatic switches. One thermostat is located near the ceiling above the fan, and the other is at the 5-foot level, below the fan. The upper thermostat turns on at temperatures above 85°F. The lower thermostat turns on at temperatures below 55°F. This arrangement distributes heat to the north side of the building when ceiling temperatures on the south side are high (above 85°F); this heat is absorbed by the floor and by stacks of material on the north side. The cooled air moves along the floor back to the south wall to be rewarmed and recirculated.

When the lower thermostats are on, the increased air circulation improves the heat transfer rate between surfaces so that heat can move rapidly from the floor slab storage mass into the stacks of inventory materials.

The auxiliary heating units turn on when the warehouse air temperature drops below 45°F. The circulating fans will also be on at this time so that the auxiliary heat is distributed rapidly throughout the warehouse to help maintain the minimum temperature of 45°F.

Performance

This passive solar system is a participant in the Department of Energy's Commercial Solar Heating and Cooling Demonstration Project

(Cycle 1). The data acquisition equipment used for measuring warehouse performance was supplied by NASA, and the sensor data is continuously monitored by IBM. The NASA/IBM system is designed to monitor and record surface, air, and auxiliary water heater temperatures at various locations inside and outside the warehouse every 320 seconds. Flow rates for calculations of auxiliary heat usage are recorded. Weather data such as wind speed and direction, ambient air temperature, and insolation on the vertical Sunwall® surface are also monitored. All data are recorded and then remotely interrogated and transmitted to an IBM central data processing site. A data reduction program developed by IBM assimilates and presents the performance in graphical or tabular form.

Figure 14-6 displays selected data for December 11, 1977. On this day, the insolation at noon on the south wall was 297.5 Btu/ft^2·h. This is significantly greater than the 263 Btu/ft^2·h value listed in the ASHRAE tables for a vertical south-facing wall at 42°N. latitude.

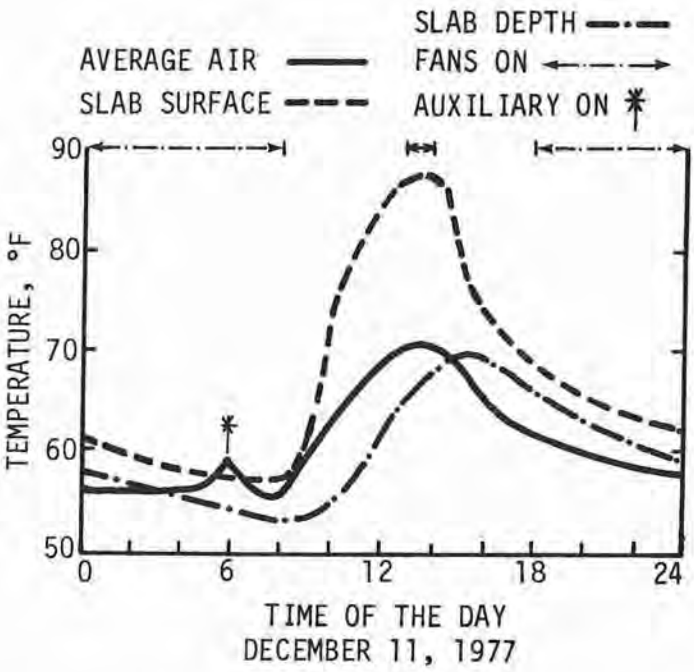


Figure 14-6. Data for December 11, 1977 from the Kalwall Warehouse Direct-Gain Solar System

The average ambient temperature on this day was 9°F, well below the average monthly ambient temperature of 33°F for this area. These conditions--high insolation with low ambient temperature--are common in many parts of the United States. Abundant solar energy is provided when the heating requirement is highest.

Concrete slab temperature shown were measured in the aisle where the slab is exposed to direct solar radiation transmitted through the south wall. The curves illustrate the familiar characteristics of a masonry thermal mass exposed to solar radiation: rapid buildup of surface temperature peaking shortly past solar noon, and a time lag and decrease in value of the peak temperature at points beneath the surface. Large fluctuations in average air temperature are allowable within a warehouse and have no effect on the inventory or the inhabitants. During the winter of 1977-78, the temperature excursions within this warehouse were in the range of 30°F. Large allowable fluctuations reduce the demand for energy from the auxiliary heating system.

Kalwall Corporation studies, based on previous heating season fuel bills, show an estimated savings of 270 million Btu's per year over two successive winter heating seasons. This indicates that the direct-gain passive solar heating system supplied approximately 55 percent of the heating requirements of the warehouse.

Figure 14-7 is a graphical summary of the NASA/IBM data for the month of December 1977.

Builder Comments

The millions of square feet of warehouse space in the United States represent a substantial fraction of the national consumption of energy for space heating. The concrete floors and the stored inventory of the warehouses can provide the thermal mass which is an essential component for a passive solar heating system. In general, wide temperature fluctuations are acceptable in a warehouse. These characteristics are ideal for incorporation into a passive solar heating

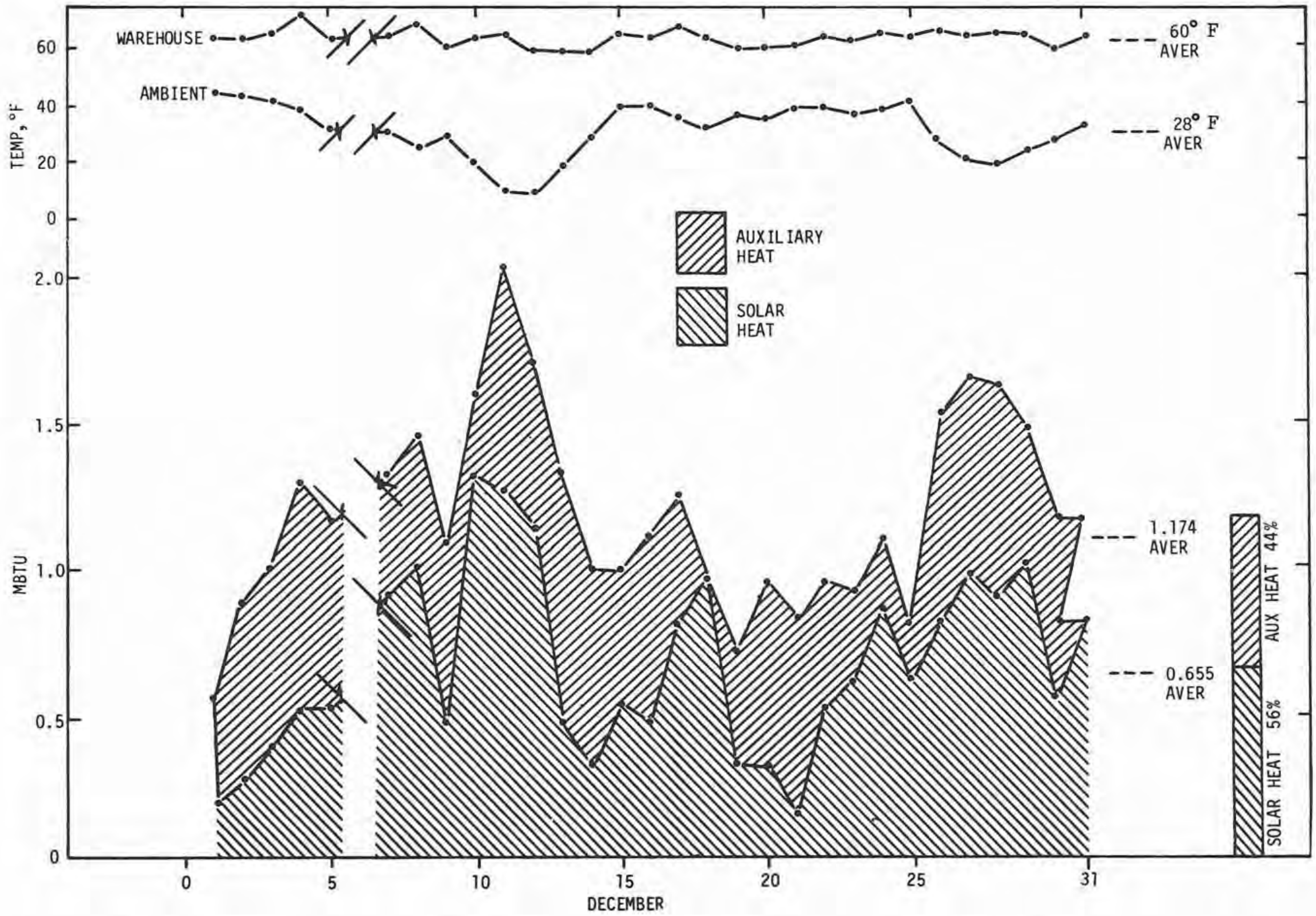


Figure 14-7. Graphical Summary of the Performance of the Kalwall Warehouse for December 1977

system. If the system employs direct gain, the admitted sunlight will reduce or eliminate the auxiliary lighting needs within the warehouse.

Very few passive solar heated warehouses exist, and very little information is available on operational and maintenance costs. The Kalwall Corporation undertook the development of a direct-gain passive solar system because such a system would be compatible with Kalwall's extensive experience in the design, manufacture, and installation of insulated, light-transmitting panels for the walls and roofs of buildings. The design philosophy for this project was to develop a simple retrofit package with low initial and life-cycle costs to conserve energy in warehouse-type buildings throughout the United States.

The use of the warehouse concrete floor slab as the thermal storage mass is a key feature of the system. The construction of a thermal storage system for a retrofit solar heating system would raise initial costs to the point that most potential projects would no longer be economically justifiable. A second key feature is the use of forced-air circulation by low-power fans to move heat from the collection zone near the south wall and distribute it more uniformly through the warehouse. The retrofit package employs the Sunwall® glazing system developed, manufactured, and distributed by the Kalwall Corporation. This glazing system requires no special construction skills to install.

In selecting a site for application of this retrofit system, it is important to provide a roof overhang to at least partially shade the direct-gain wall during the summer to prevent overheating. Large reflective areas such as snow-covered parking lots should also be taken into consideration, since such features can strongly affect system performance.

Cost

Retrofitting the south wall with the Kalwall Sunwall® panel system cost about $8,000. At a current cost for fuel oil in this area of approximately $4 per million Btu's, the yearly savings is about $1,100. This indicates about a 7-year payback time for the initial investment in the solar direct-gain system. If it is assumed that fuel prices will escalate at a rate of 15 percent per year, this payback time is reduced to about 5-1/2 years.

SECTION 15

THE KELBAUGH HOUSE

Figure 15-1. The Kelbaugh House

BUILDER: Nate Bard
DESIGNER: Doug Kelbaugh
OWNER: Doug and Meg Kelbaugh
TYPE: Single family, 1 unit
AREA: 1,850 square feet (plus 200-square-foot basement)
GENERIC TYPE: Trombe wall and greenhouse
LOCATION: Princeton, New Jersey
LATITUDE: 40°21'N.
ELEVATION: 100 feet
CLIMATE DATA: Heating dd: 5,100
Design temp: 0°F
Insolation (Jan. day): 638 Btu/ft^2

Figure 15-2. Interior of Kelbaugh House Downstairs

Figure 15-3. Interior of Kelbaugh Greenhouse

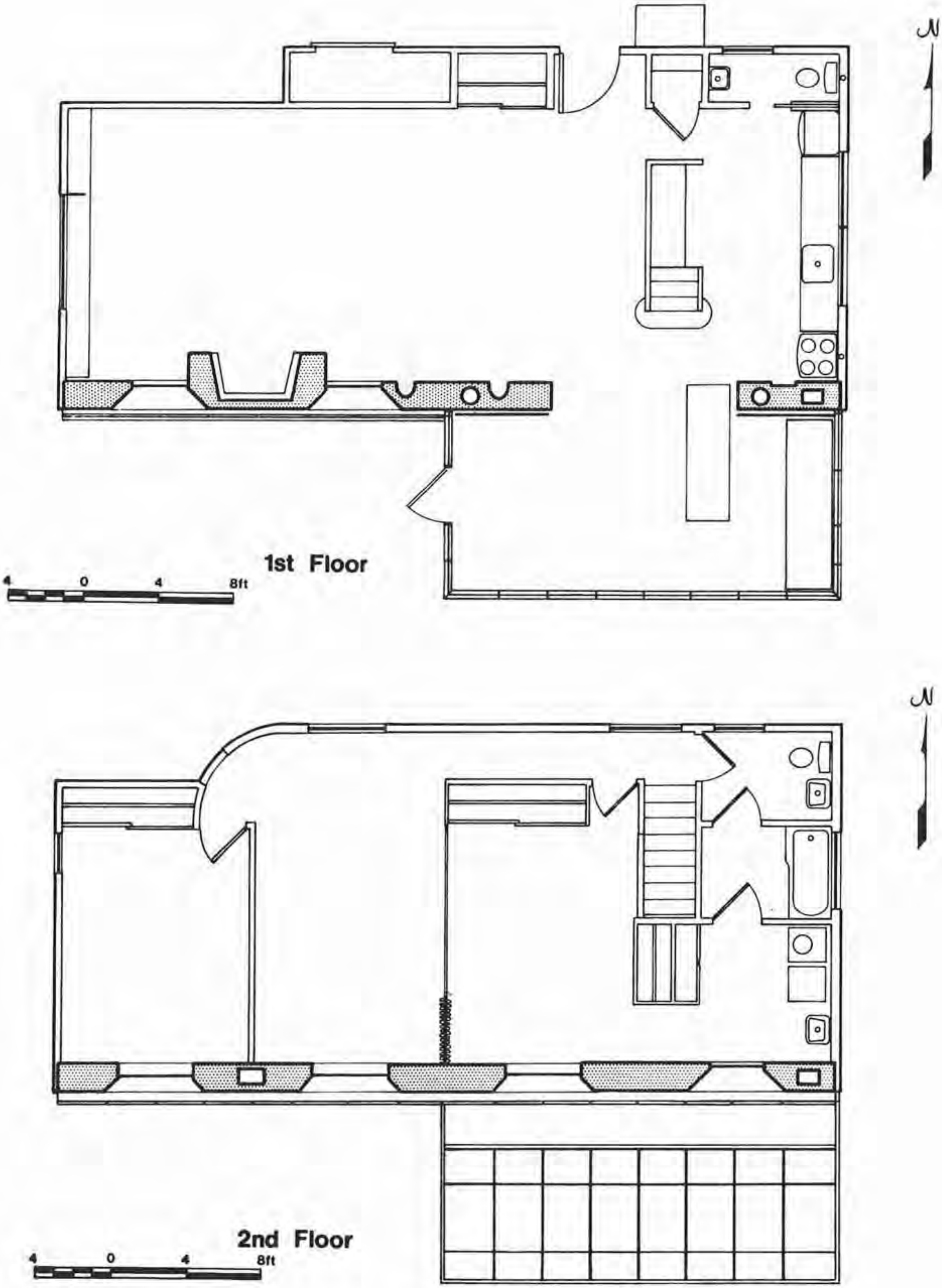


Figure 15-4. Floor Plan of the Kelbaugh House

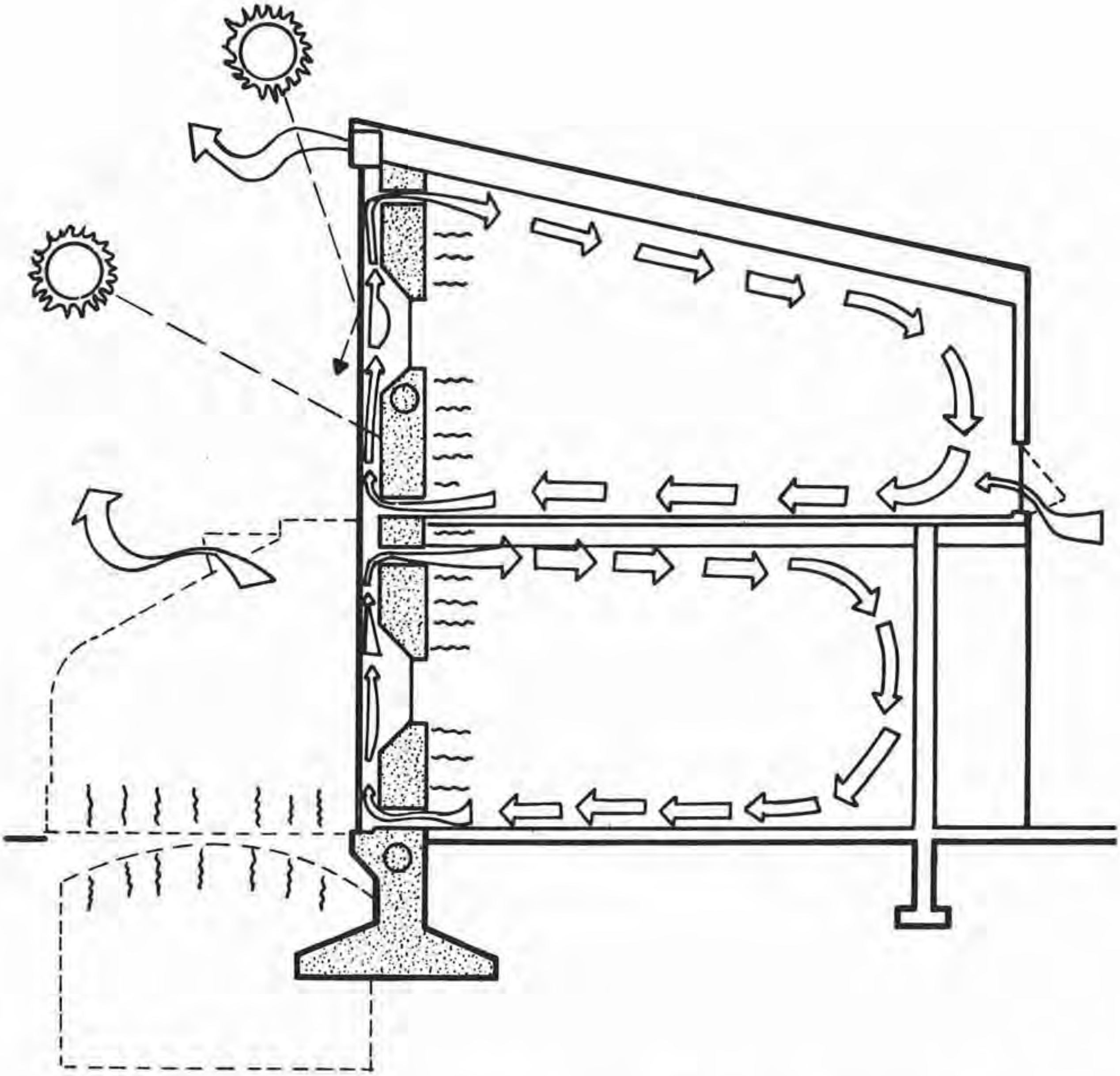


Figure 15-5. Thermal Flow Diagram of the Kelbaugh House

Collectors -- The entire south-facing wall serves as a collector. About three-quarters of the wall (615 square feet) is the vertical glazing for the Trombe wall. The remainder, the eastern half of the first floor, is a lean-to greenhouse with a total glass area, including end walls, of about 313 square feet.

Storage -- The primary storage is in the 15-inch-thick, poured-in-place concrete Trombe wall heated directly by the sun. Additional thermal storage is obtained from the concrete floor slab and greenhouse floor and from eight 55-gallon drums of water in the greenhouse.

Distribution -- The Trombe wall supplies heat to the living spaces by convection and radiation. The greenhouse, during daytime, supplies warm air to the house by convection.

Auxiliary Heat -- A gas-fired, forced hot air furnace provides auxiliary heating. A Heatilator wood fireplace also can provide auxiliary heat. Three manually operated 250-watt infrared heaters provide auxiliary heat in the bathrooms.

Domestic Hot Water -- A gas-fired heater provides domestic hot water. This system is not integrated with the solar heating system but is retrofitted with an extra jacket of insulation.

Controls -- Dampers and blower fans on the Trombe wall exhaust excess heat to the outdoors during summer. A thermostat controls the auxiliary furnace.

Description

Doug and Meg Kelbaugh became fond of the thermal and architectural virtues of massive masonry walls while living in an 18th-century New Jersey farmhouse. Doug, an architect and solar consultant, was captivated by the idea of the Trombe wall from information obtained in an article in a 1973 issue of A.D., the English architectural magazine. Upon moving to Princeton, N.J., Doug set himself the task of designing a house with a $45,000 maximum construction cost, a Trombe wall, a large interior room, one large exterior yard, a fireplace, a greenhouse, and three bedrooms.

The lot selected for the house (one of the last building lots in Princeton) was 60 by 100 feet, with the long axis running nearly east-west and with a large tree near the center. In order to save the tree and to avoid shaded areas, a zoning variance to build the house within 5 feet of the north boundary and 13 feet of the sidewalk was required. The variance was granted without opposition. This variance also provided the desired large exterior yard.

In the design, the ground floor was kept as one continuous space, with the kitchen on the east end partially separated from the living and dining area by the stair. The three bedrooms were strung along the concrete Trombe wall on the second floor. A European bathroom arrangement with separate rooms for toilet, bath/shower, and utility were set along the east wall. All the plumbing lies along the east wall of the house. A standard Lord and Burnham lean-to greenhouse is set against the east end of the Trombe wall. A wide arch through the Trombe wall connects the greenhouse space with the downstairs living space. A basement containing the auxiliary furnace and hot water heater lies beneath the greenhouse.

The north, east, and west walls are framed with 2- by 4-inch studs sheathed with 5/8-inch plywood and tarpaper. The exterior finish is rough-sawn cedar plywood. On the first floor the 2 by 4's are furred out 1 inch to provide a 4-1/2-inch cavity. The wall cavities upstairs and downstairs are blown full of cellulosic fiber. The interior finish is 1/2-inch sheetrock.

A minimum amount of window area was used, particularly on the north wall, which sees no sun during the winter. All windows are wood framed, weatherstripped, and triple glazed. The two north windows on the second floor hallway are fitted with 1-inch-thick styrofoam panels that can slide across the windows to insulate them. A wood-framed, sliding glass door in the west wall provides access to the yard.

The roof beams are 2 by 10's with 5/8-inch plywood decking surfaced with asphalt roll roofing. The inside is finished with a polyethylene vapor barrier and 1/2-inch sheetrock. The 9-1/2-inch-deep cavity between the roof beams is blown full of cellulosic fiber. A skylight is fitted into the roof over the bathroom.

Operation

The rays of the winter sun, low in the sky, hit the southern wall nearly perpendicularly, readily penetrate the two sheets of double-strength window glass, and hit the 15-inch concrete wall. The concrete is painted with a special black paint. Some of the absorbed heat is radiated back towards the glass but at a much longer wavelength than sunlight. About two-thirds of the heat radiated back is trapped inside because glass is opaque to low-frequency heat. The warm wall and glass heat up the air, which then rises up the slot. The chimney effect pulls cool air in at the bottom and supplies warm air at the top. The warm air released at the top gradually cools and falls on the northern side of the room. The cooler, heavier air is drawn over to the return hole in the concrete wall and back up the solar chimney. Thus, heat in the form of warmed air is circulated throughout the rooms of the house, all of which face onto the concrete wall. In the meantime, the sun has been slowly heating the concrete wall through. By nightfall, heat will have reached its inside surface which, because of concrete's thermal mass, radiates heat until the following day. If it has been a cloudy day, the backup system will be started by thermostat. The backup system is a conventional hot air furnace with ducts cast in the concrete wall, and with one branch that leaves the wall to supply the bathrooms, which are isolated from the concrete wall. The furnace is small because the skin of the rest of the house is heavily insulated (average $U = 0.05$). The lean-to greenhouse, which acts synergistically with the solar wall, has been added to grow plants. Its thick black concrete floor also stores heat for the cellar as well as the greenhouse.

The rays of the summer sun, high in the sky, hit the southern wall at a more oblique angle and are primary reflected off. Any heat built up is exhausted through four vents at the eaves. The chimney effect, which can be augmented by small fans, ventilates the entire house by pulling air across the rooms from windows on the north wall. By night ventilating, the concrete wall becomes cooler and absorbs heat from the room on the following day. Shades must be drawn over the greenhouse because its tilted glass transmits most of the high summer sun. Two large deciduous trees also provide protection from the summer sun.

Sometime in the future, a solar water heater for domestic hot water will be placed on the greenhouse deck or hung in the greenhouse.

Performance

The Kelbaugh house has been occupied since July 1975. During the first winter, which was comparatively mild (4,500 dd), the actual furnace fuel consumption was 33,800 cubic feet of natural gas at a cost of $108 at local rates. The indoor temperature was allowed to swing 3°-6°F during a 24-hour cycle to allow the concrete wall to collect and discharge its heat. The seasonal high and low temperatures and the estimated average temperatures for the upstairs and downstairs living areas are shown in Table 15-I.

TABLE 15-I

Seasonal and Average Temperatures for Mid-Winter

	Seasonal High (°F)	Seasonal Low (°F)	Estimated Average (°F)	
			Day	Night
Upstairs	74	62	64	60
Downstairs	70	53	62	54

The thermostat setting for the backup furnace was set between 60° and 62°F during the daytime and at 55°F at night.

The Heatilator fireplace was fired up two or three times a week. Since the fireplace combusts warm room air and pulls in cold outside air, its heat contribution to the house is mostly offset. It was, however, an esthetic asset and provided localized comfort.

The three electric infrared heaters in the bathrooms were seldom used.

Standard heat loss calculations show that the solar heating system reduced the space heating cost by 76 percent for a savings of $330.

In response to a number of problems that were discovered during the first winter of occupancy, several modifications have been made to the solar design in order to improve its effectiveness.

One problem encountered was that of reverse thermosiphoning, whereby warm air at the ceiling height would leave the room at night through the upper vents in the concrete wall, wash down along the exterior glass wall, and reenter the room through the lower vents at a lower temperature than it left the room. This problem was solved simply and effectively by installing a passive damper consisting of a screen (on the inside of the concrete wall) covered by a 1/2-mil plastic film which permits air circulation in one direction (inward) only.

Another problem encountered was that of heat migration to the second floor. Because there is an open stairwell and the backup system seldom cycles air, the warmer air has a longer time to rise and collect upstairs. The average winter room temperature upstairs was about 5°F higher than downstairs. This problem has been helped somewhat by putting a door at the top of the open stairwell. Doug feels that the only way to completely overcome heat stratification in a multistory passive solar building is by mechanical means, such as a small duct with blower.

Heat loss from the single-glazed greenhouse represented a sizable fraction of the total house heat loss. A second layer of glass has been added to the greenhouse to reduce this heat loss.

The greenhouse temperature fluctuated from about 80°F on a sunny winter day to 45°F at night. The eight 55-gallon water drums were placed in the greenhouse to reduce this fluctuation. The drums are used as benches for plants and flowers.

The movable insulation for the two second-floor, northwall windows was also added after the first winter, as was triple glazing on some of the windows.

The second winter of occupancy (1976-77) was more severe than the first, having 5,556 dd versus 4,500 dd for the first winter. Despite this, and because of the modifications noted above, the gas consumption for the auxiliary heating system was reduced to 24,600 cubic feet ($75), 70 percent of the previous year's consumption. The heat loss calculations indicate the solar system reduced the space heating cost by 84 percent during the winter of 1976-77.

Instrumentation provided by LASL has been installed to monitor the performance of the Kelbaugh house. Two graphs of this data are included as Figures 15-6 and 15-7. Figure 15-7 shows that for the period December 4-10, 1977, the temperature stratification between upstairs and downstairs has not been alleviated by the door installed at the top of the stairway. The 35°F temperature fluctuation in the greenhouse has been somewhat moderated by the addition of the water drums.

Owner/Designer Observations and Comments

The swing in air temperature in the living spaces was permitted to achieve high fuel savings and did not prove to be uncomfortable. In terms of comfort, the radiant heat from the Trombe wall seems to compensate for at least a couple of degrees reduction in air temperature. Nevertheless, the Kelbaughs feel they have learned to live in a cooler house, probably as a result of fuel costs as much as beause of the influence of the solar design. The family is also more aware of the climate than they were previously.

Doug Kelbaugh recommends several minor revisions to the house design. First, a direct fresh air vent should be provided for the fireplace. Second, the eaves vents should be enlarged and/or operable windows should be installed in the south wall to increase cross ventilation. The perimeter styrofoam insulation should be 2 inches rather

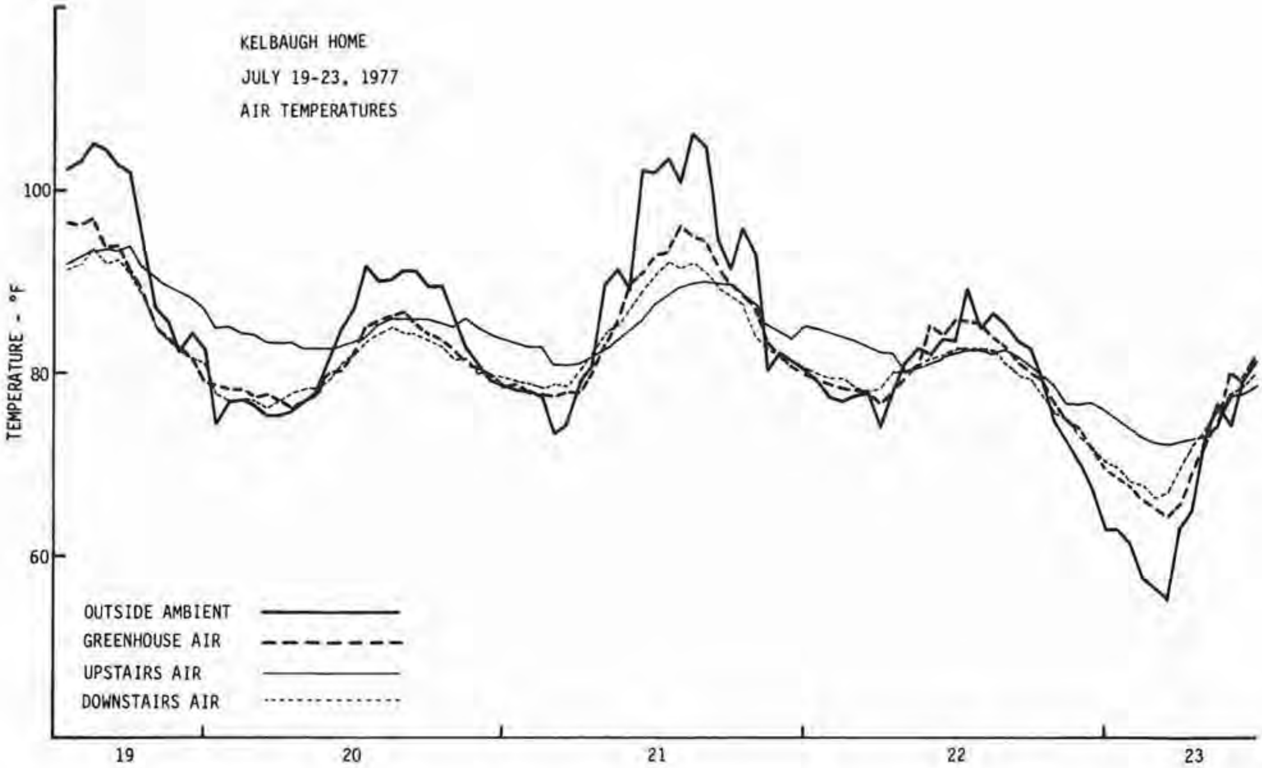


Figure 15-6. Recorded Data for July 19-23, 1977

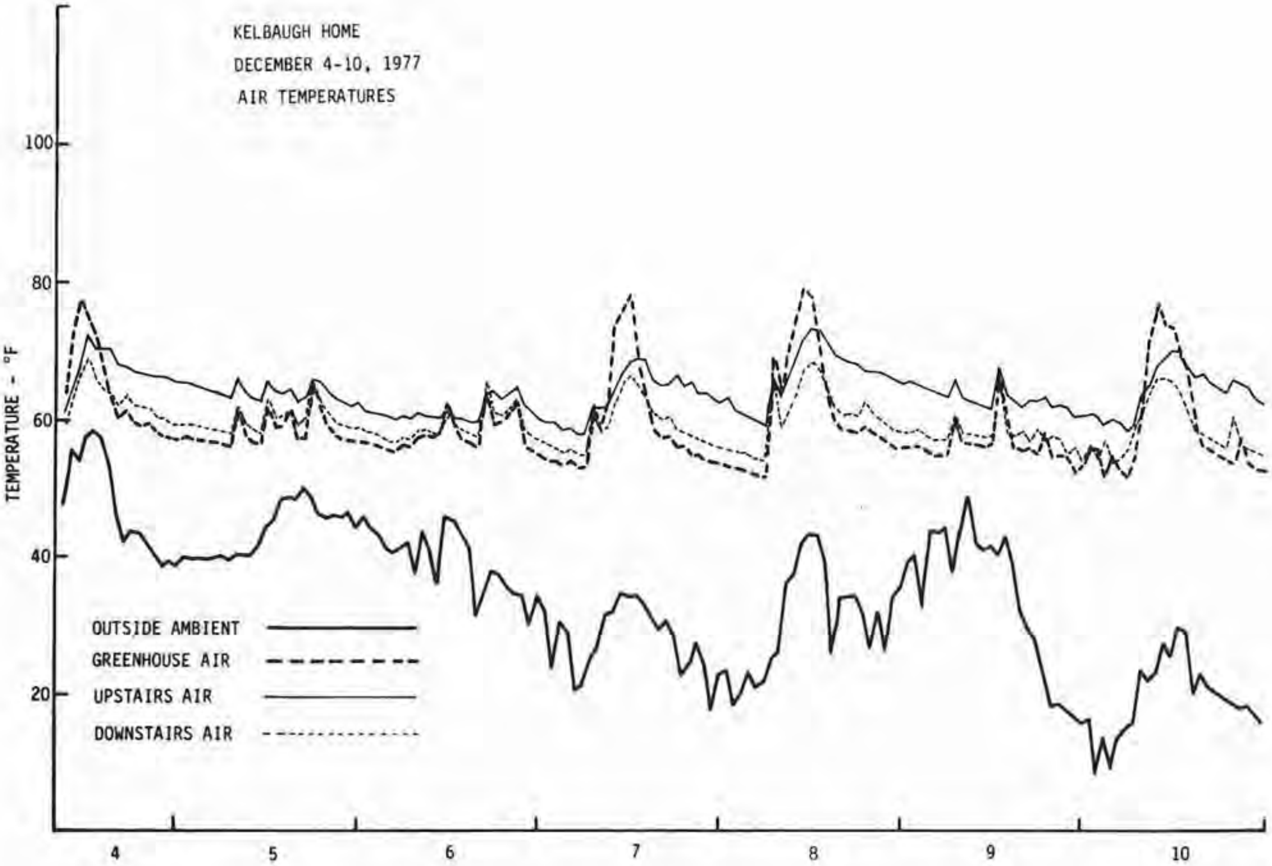


Figure 15-7. Recorded Data for December 4-10, 1977

than 1 in thickness; in fact, 2 or 3 inches of urethane would be preferable. The upper and lower vents in the concrete wall should be larger and more frequent--a total area at least one-half the cross-sectional area of the solar chamber between the glazing and the concrete. Lastly, a means should be provided for insulating the greenhouse from the living space during cold nights. The Kelbaughs have recently hung an insulated curtain which keeps the downstairs warmer at night and lets the greenhouse temperature drop into the 40's and occasionally the 30's. Hoarding heat in the living space makes more sense than keeping the greenhouse warmer than the plants require.

Construction and Cost

Design of the house took about 1 year from conception to groundbreaking, although the actual design stage was much shorter since considerable preliminary effort was expended in researching thermodynamics and getting municipal approvals. The basic construction required about 1 year to complete, but the owners moved in during July 1975, approximately 9 months after construction had commenced.

The entire cost of the house was $55,000, plus the owner's labor. The additional initial cost of the house directly attributable to the solar heating and cooling system is approximately $8,000 to $10,000. This figure includes a modest allowance for the cost of the wall which the Trombe wall replaces. In addition, several thousand dollars could have been saved if solid concrete block were used instead of poured-in concrete. It is difficult to estimate construction cost since the system is so closely integrated into the design of the house.

Based on varying assumptions regarding general inflation and the escalation of natural gas prices, the owner estimates that the payback period for the system is from 10 to 17 years. Considering the declining availability of fossil fuels and the long life of the system, he expects the Trombe wall to pay for itself many times over in the long run.

Performance Estimate

The modified building loss coefficient computed for the Kelbaugh house is 13,093 Btu/dd, or 6.89 Btu/ft^2·dd. In the analysis scheme, solar radiation absorbed by the Trombe wall and the greenhouse was considered separately from that received by direct gain through the windows. The energy received by direct gain amounted to less than 9 percent of the total solar energy absorbed by the house. The solar heating fraction was adjusted to account for these different sources of solar energy.

The results of the performance estimate for the Kelbaugh house are summarized in Table 15-II. The degree-days for the climatic data used in the estimate total 4,980, which is greater than the 4,500 experienced in the winter of 1975-76 but less than the 5,400 experienced in the winter of 1976-77. Solar data is from the 20-year records of Rutgers University, 15 miles from Princeton.

The final result of the estimate--83 percent SHF--is in close agreement with the results of Doug Kelbaugh's analyses discussed above.

TABLE 15-II

Performance Estimate for the Kelbaugh House

Month	Degree-Days	Gross Load (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface (Btu/ft^2·mo)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	989	12.95	3.17	9.77	19,785	17.84	1.83	0.74	2.541
February	885	11.59	2.87	8.72	25,613	18.15	2.08	0.78	1.918
March	753	9.86	3.17	6.68	39,787	19.87	2.97	0.89	0.735
April	399	5.22	3.07	2.15	46,069	14.94	6.94	1	0
May	121	1.58	3.17	–	56,703	–	–	1	0
June	12	–	3.07	–	59,796	–	–	1	0
July	0	–	3.17	–	59,012	–	–	1	0
August	0	–	3.17	–	52,417	–	–	1	0
September	57	–	3.07	–	43,813	–	–	1	0
October	264	3.46	3.17	0.28	34,632	22.04	7.8+	1.00	0
November	576	7.54	3.07	4.47	22,155	18.82	4.21	0.96	0.179
December	924	12.10	3.17	8.92	18,162	17.37	1.95	0.76	2.143
Annual				44.01				0.83	7.516

ANNUAL SHF = 0.83

SECTION 16

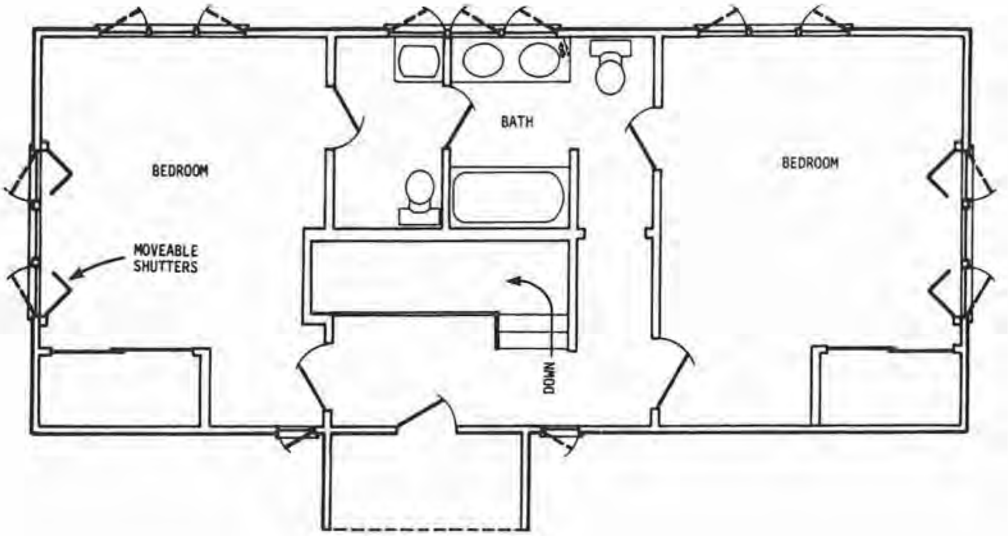
GREEN MOUNTAIN HOME

Figure 16-1. The Green Mountain Home

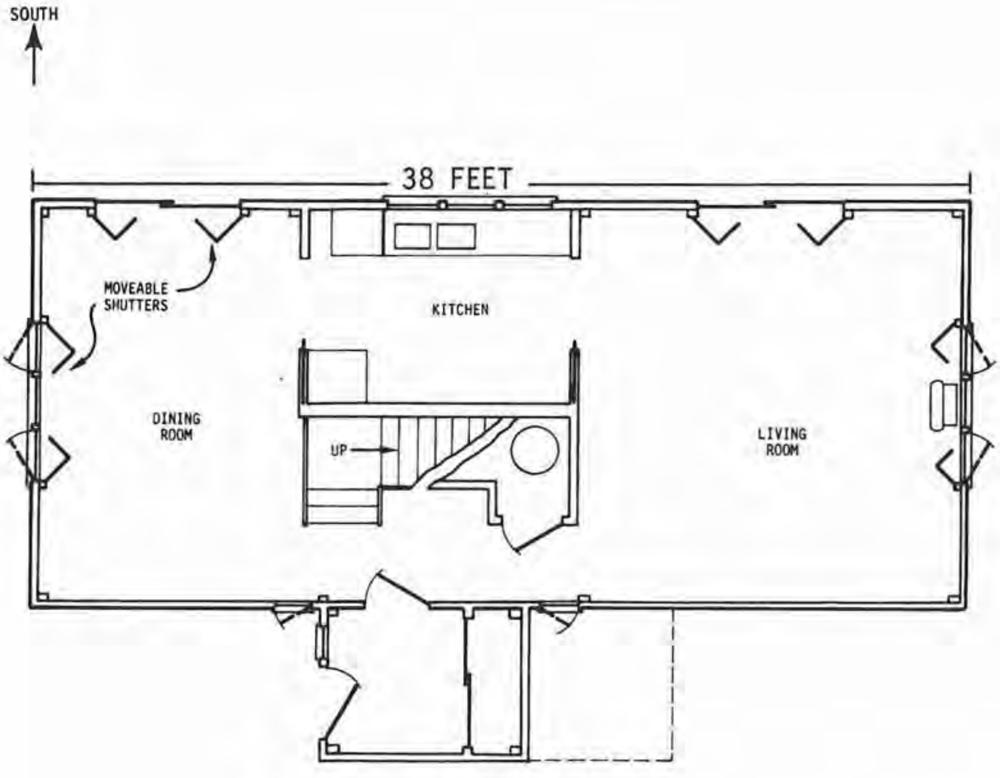
BUILDER: Green Mountain Homes
DESIGNER: James Kachadorian
OWNER: Green Mountain Homes
TYPE: Single family dwelling
AREA: 1,264 square feet (inside dimensions)
GENERIC TYPE: Direct gain, Active storage
LOCATION: Royalton,Vermont
LATITUDE: 44°N.
ELEVATION: 1,500 feet (estimate)
CLIMATE DATA: (Heating dd at Burlington): 8,269
Design temp: 72°F inside, -15°F outside, 20 mph wind
Horiz. insolation (Jan. day): 553 $\text{Btu/ft}^2\cdot\text{day}$

Figure 16-2. Interior of the Green Mountain Home

Figure 16-3. Upstairs in the Home



SECOND FLOOR



FIRST FLOOR

Figure 16-4. Floor Plan of the Green Mountain Home

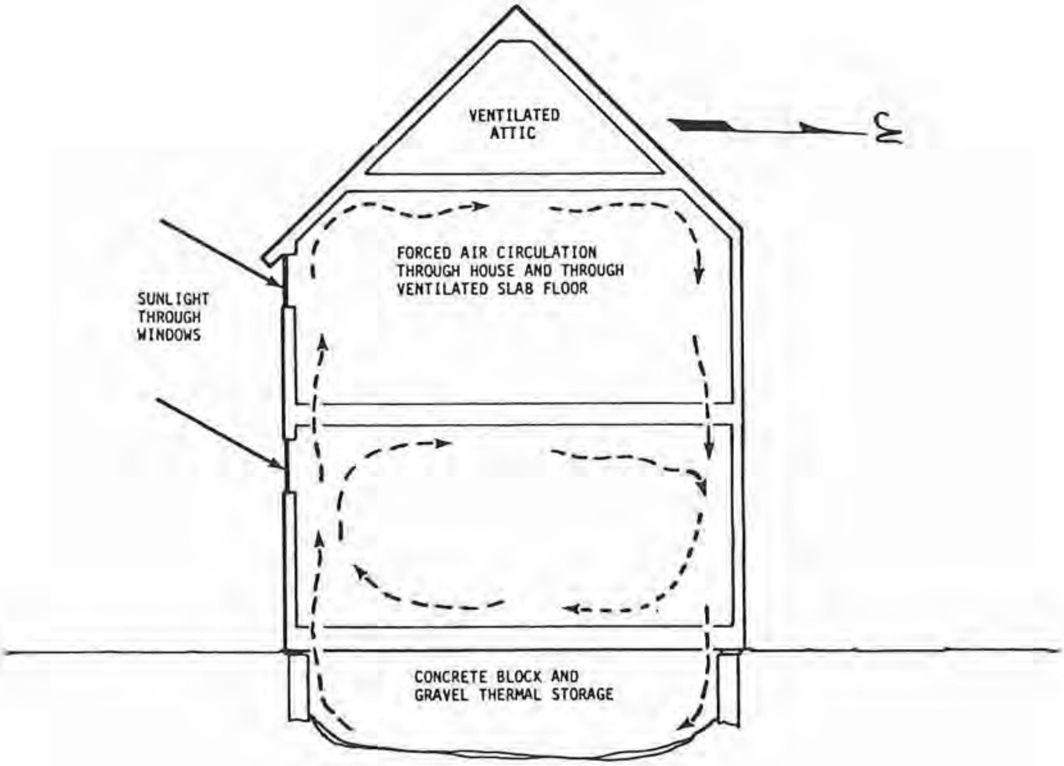


Figure 16-5. Thermal Flow Diagram of the Green Mountain Home

Collectors -- The windows of this house serve as direct-gain collectors. The house has 219 square feet of window area, of which 120 square feet is south facing.

Storage -- The thermal storage consists of the concrete floor slab and the concrete blocks and gravel under the floor slab.

Distribution -- The direct-gain heat received through the windows is initially distributed by natural convection and radiation. Heat is then transferred from the air to storage (or vice versa) by pumping the air through the thermal storage system beneath the floor slab.

Auxiliary Heat -- Auxiliary heat is supplied by an oil-burning furnace and a wood-burning stove.

Domestic Hot Water -- Coils embedded in the concrete floor slab preheat the water supplied to the domestic hot water system.

Controls -- The fans for circulating air are controlled by a thermostat which senses house air temperature.

Description

This house, located in east-central Vermont in the town of Royalton, is one of a series of post-and-beam panelized models marketed by Green Mountain Homes, Inc. The house is two story. The dining room occupies the east end of the first floor, and the living room is on the west end. A galley kitchen and the stairwell are in-between. Upstairs are two bedrooms and one-and-one-half baths. The post-and-beam construction allows adaptation of different room arrangements within the same external shell, since there are no internal load-bearing walls.

The wall panel sections are formed with 2 by 4's, with fiberglass batting filling the voids. On the exterior, the 2 by 4's are covered with 1/2-inch plywood, insulated with 3/4-inch styrofoam (Dow Chemical Total Wall System) and finished with 3/4-inch wood siding. On the inside, there is a polyethylene vapor barrier and 1/2-inch fiberboard.

On the second floor, the ceiling of 1/2-inch hardboard is laid over a polyethlene vapor barrier. The voids between the 2-by-6 ceiling joists are filled with fiberglass batts. On top of this is a layer of 3-1/2-inch fiberglass batts laid perpendicular to the joists. The peaked roof is uninsulated, and the attic (a convenient storage area) is thoroughly ventilated to the outside air.

The house is constructed on a combined foundation and thermal storage system which Green Mountain Homes calls the "Solar Slab®." The specific construction details for this floor system are proprietary and patented. It consists of a combination of concrete, concrete blocks, and gravel arranged so that air can be drawn from the house down through the thermal storage and back to the house. For this house, there are 536 cubic feet of concrete (slab and blocks) and 1,072 cubic feet of gravel. Preheat coils for the domestic hot water system are built into this Solar Slab®. A finished wood floor is laid over the concrete slab.

The entry to the house is an airlock on the north side. There are 219 square feet of glass door and window area: 120 square feet on the south, 58 square feet on the east, 32 square feet on the west, and only 9 square feet on the north. All the windows are wood frame and double glazed. The glass door is metal framed but has an insulating barrier between the outside and inside metal frames to reduce the heat loss. Large windows and sliding glass doors have a movable, 2-inch-thick shutter for night insulation.

A fan on the second floor can either circulate air between the first and second floors or exhaust air to the outside. A second fan on the first floor can circulate house air (or outside air) through the ventilated thermal storage system.

Auxiliary heat is supplied by an oil-fired, forced hot air system.

Operation

Sun shining through the windows of the house falls on the wood floor and furnishings, warming these surfaces and heating the air in the house. The warm air tends to rise through the stairwell and gather in the second story. When the second floor temperature rises above 72°F, a thermostat turns on the upstairs fan to circulate air between the upstairs and downstairs. As the day goes on, more solar energy is collected, and the temperature, upstairs and downstairs, rises. When the downstairs temperature rises above 72°F, the main fan is turned on, circulating air through the thermal storage. The permeable arrangement of concrete block and gravel beneath the floor slab acts as a heat exchanger, extracting heat from the flow of air and storing it for later use.

When the first floor temperature falls below 70°F, the main fan is again turned on, forcing air through the ventilated slab and then through the furnace and back into the living space. If the temperature of the air coming from the ventilated slab is greater than 68°F, the furnace does not fire up; when it is less than 68°F, the furnace is activated, and auxiliary heat is delivered to the living space.

In summer, the upper fan can vent excess heat from the second floor directly to the outside. At night, the main fan can circulate outside air through the thermal storage to keep temperatures cool.

In summary, the collected solar energy in excess of that required to heat the house to 72°F is stored in the thermal storage. At night, when the thermostat is set back to 55°F, this energy is used to heat the house. In summer, the thermal storage is cooled with night air and then used as a heat sink for house air during the day.

Performance

The performance of this house has been well monitored. Separate cumulative readings of the electrical consumption were taken for the main circulating fan, the upstairs circulating fan, and the fuel pump for the oil furnace. The total electrical consumption for the house was also recorded. The following temperature measurements were recorded: (1) inside downstairs, (2) the difference between inside and outside of the house, (3) the difference across the furnace, (4) the difference in air entering and exiting the ventilated slab, and (5) the slab itself.

The insolation incident on the south wall was measured. (The south wall actually faces 20 degrees west of true south.) Based on this measured value, the solar energy transmitted through each of the glazings on the east, west, and south sides of the house was calculated. To check these calculations, insolation meters were installed behind the south door and the east windows. The value of extinction coefficient of the glass was then adjusted so the calculated values of the transmitted insolation agreed as closely as possible with the measured value. This procedure was accomplished in February 1977, and the indoor insolation meters were then removed. The glass properties finally selected for use in the transmittance calculation are shown in Table 16-I. Using these values, the ratio of insolation transmitted through each window (and the door) to the insolation incident on the south wall was computed for each month of the year. The results are shown in Table 16-II.

TABLE 16-I

Glass Properties

Properties	Door	Window
Glass thickness, cm	0.3175	0.3175
Extinction coefficient, cm^{-1}	0.2	0.1
Index of refraction	1.526	1.526
Number of panes	2	2
Plate absorptivity	1	1

TABLE 16-II

Computed Distribution of Insolation

Day of	Fraction of Insolation on South Meter through:			
Year	S. Door	S. Window	E. Window	W. Window
21	0.612	0.853	0.377	0.148
51	0.588	0.846	0.447	0.227
81	0.558	0.887	0.562	0.366
111	0.516	0.862	0.713	0.549
141	0.458	0.78	0.885	0.772
171	0.436	0.754	0.948	0.877
201	0.456	0.781	0.885	0.778
231	0.507	0.822	0.726	0.552
261	0.55	0.812	0.552	0.334
291	0.582	0.798	0.427	0.191
321	0.608	0.796	0.356	0.114
351	0.619	0.821	0.34	0.106

Table 16-III is a summary of the performance data collected for the Green Mountain Home. Column 2 shows the degree-days based upon the actual inside house temperature instead of the usual constant 65°F base. Column 8 shows the contribution to house heat from the electricity used in the two circulating fans and the furnace oil pumps. The electrical energy consumed for household uses (e.g., lighting) was not considered as a contribution to house heating.

The wood stove was not installed until the fall of 1977. The heating contribution credited to the stove is an estimate only. A complicating factor in judging the performance of the house is that the insulated shutters for the windows and doors were also not installed until the fall of 1977.

The average daily maximum temperature of the house in winter was approximately 72°F, with a standard deviation of 3.5°F. In the spring (April, May), the average daily maximum was 74°F, with a standard deviation of 4.4°F. In winter, night temperature minimums in the house were 50°-52°F. In the spring, the night minimum rose to 61.5°F.

The monitoring of the Green Mountain Home was extended through May 27, 1978, and the results are reported in Monitoring Studies of Green Mountain Homes Hybrid Systems (Dartmouth College, Thayer School of Engineering; Hanover, New Hampshire; December 8, 1978) by A. O. Converse and J. Kachadorian. In this report the authors conclude that "the purchased energy requirments were quite low, and the percent solar is well above 40 percent."

Owner/Builder Comments

The philosophy behind the development of this house was to produce a design, the basic structural components, and a complete set of plans which could be sold as a kit on the commercial market. Good ideas don't automatically result in a good house--the design must be foolproof so that the construction team can't go wrong in the construction operation. This means that the design must be kept simple and be presented as a detailed set of plans with a detailed description.

TABLE 16-III

The Green Mountain Home Performance Data*

(1) Period	(2) Degree-Days (°F·day)	(3) Average Insolation on External Meter (Btu/ft^2·day)	(4) Percent of Maximum Possible Insolation	(5) Heating Energy (MBtu)	(6) Solar Component of Heating Energy (MBtu)	(7) Solar Component of Heating Energy (Percent)	(8) Electrical Component of Heating Energy (MBtu)	(9) Auxiliary Energy (Oil) (MBtu)	(10) Auxiliary Energy (Wood) (MBtu))	(11) Heat Loss (kBtu/ °F·day)
1/11 - 2/8/77	1445	916	46.8	11.4	2.94	25.7	0.52	7.94	-	7.9
2/8 - 3/10/77	1010	782	36.1	7.75	2.63	33.9	0.32	4.80	-	7.6
3/10 - 4/11/77	949	960	47.4	7.12	4.08	57.3	0.38	2.66	-	7.4
4/11 - 5/11/77	560	870	56.8	4.82	2.80	78.9	0.59	1.43	-	8.6
May 11 through Sept 13					OMITTED					
7/13 - 10/14/77	560	450	24.3	2.15	1.75	81.4	0.27	0.13	-	3.8
10/14 - 11/8/77	567	771	41.5	3.06	2.29	74.7	0.36	0.41	-	5.4
11/8 - 12/14/77	1209	505	28.9	7.88	2.03	25.8	0.47	4.34	1.04	6.5
12/16/77 - 1/12/78	702	652	37.7	5.93	1.27	21.4	0.43	3.19	1.04	8.4
Totals	7002			50.11	19.79	39.5	3.34	24.9	2.08	7.2

***Extracted from Green Mountain Homes Hybrid System by J. Kachadorian and A.O. Converse**

The thermal mass in the Solar Slab® is the key feature of the design. Collection area is also important. However, the amount of glass in the house is not in excess of that specified for normal architectural requirements; it is simply redistributed to enhance solar utilization.

No special materials are needed. No special construction skills are required either. The house can be erected from the plans and materials of the kit by the do-it-yourself individual. The major site consideration is the south orientation, although even this is somewhat flexible, as illustrated by the orientation of this house.

The major climatic consideration in the design was the number of degree-days per year. The original goal was to cut the heating season from 6 months to 3 months--the design came out somewhat better than that.

The contribution of the thermal storage to the performance of the house has not been firmly established. The daily change in slab energy content has been calculated from measurements made of the slab temperature at 7 a.m. and 4 p.m. each day. Also, the temperature and flow rate of the forced air stream through the slab was measured and the energy exchange computed. The change in slab energy content is much greater than the energy to or from the slab by forced convection. More detailed studies are needed of this aspect of the design. It should be noted that the air circulation and the thermal slab are improvements upon the tendency of wood stoves to overheat one area while failing to heat other areas. The air circulation distributes the heat spatially, while the slab distributes the heat over time.

Costs

The construction cost for this house is estimated as $32,000 if owner-built, or $40,000 if contractor-built. This does not include the cost of land. The Solar Slab® has an incremental cost of $1,350 over a conventional concrete slab floor.

Since the amount of glass is consistent with normal architectural requirements, its cost is not considered to be a specific solar heating feature. The incremental cost of additional glass (based on an 18-square-foot casement window) is $16.70 per square foot. For a sliding glass door, this cost is reduced to $10 per square foot. The low cost per square foot for the sliding glass doors may be deceptive as far as its value as a solar collector is concerned, because the glass often has a poor transmittance coefficient.

Performance Estimate

The modified building loss coefficient for the Green Mountain Home is 9,246 Btu/dd, or 7.31 Btu/dd·ft^2. The estimate computed by Professor A. O. Converse of the Thayer School of Engineering, Dartmouth University, using different methods, was 10,212 Btu/dd. The performance estimate is summarized in Table 16-IV.

In comparing the results of Table 16-IV with Table 16-III it should be noted that, while both tables cover a complete year, the calculation of solar entering the house is different in the two tables and the number of degree-days in the year is also different. The energy contributed by internal sources is not accounted for in the method used to compile Table 16-III, except for electrical energy consumed by the heating system.

TABLE 16-IV

Performance Estimate for the Green Mountain Home

Month	Degree-Days	Gross (MBtu)	Internal Sources (MBtu)	Net Load (MBtu)	Solar Radiation on Horiz. Surface (Btu/ft$^2\cdot$mo)	Solar Radiation Absorbed (MBtu)	SLR	SHF	Aux. Energy (MBtu)
January	1,513	13.99	2.69	11.30	17,145	3.21	0.28	0.25	8.44
February	1,333	12.33	2.43	9.89	21,989	3.27	0.33	0.30	6.98
March	1,187	10.98	2.69	8.28	33,489	3.56	0.43	0.38	5.17
April	714	6.60	2.61	3.99	41,700	2.91	0.73	0.57	1.72
May	353	3.26	2.69	0.57	47,890	2.36	4.14	1	0
June	90	0.83	2.61	0	-	-	-	1	0
July	28	0.26	2.69	0	-	-	-	1	0
August	65	0.60	2.69	0	-	-	-	1	0
September	207	1.91	2.61	0	-	-	-	1	0
October	539	4.98	2.69	2.29	24,802	3.33	1.45	0.83	0.39
November	891	8.24	2.61	5.63	11,946	2.12	0.38	0.33	3.76
December	1,349	12.47	2.69	9.78	11,201	2.22	0.23	0.20	7.84
Annual				51.73					34.30

ANNUAL SHF = 0.34

SECTION 17

ECONOMIC FACTORS

There exists in the minds of many the misconception that a passive solar home is significantly more expensive to build than a conventional home.

The objective of this section is to present some facts about the cost of construction of the passive solar homes and to compare the cost to that of conventional homes of similar quality.

The Green Mountain home and the Star Tannery home were both designed to meet mass or tract housing needs and are reproducible today for approximately $40,000 not including the land. This is comparable to current conventional construction costs.

In order to make an unbiased and factual comparison, The following four adobe homes in the Santa Fe and Los Alamos, New Mexico area were considered: Unit One, the Mark Jones house, the Williamson house, and the Gunderson house. These homes were chosen because they are all in one geographic area and economic level. All four of these homes are luxury, custom built adobe homes ranging in cost from $80,000 to $130,000. The cost data and other pertinent information for these and the other homes are shown in Table 17-I. The cost of construction of similar luxury, custom adobe homes, using conventional heating, was $35* to $45 per square foot in 1975; $38* to $49 in 1976; $43* to $55 in 1977; $48* to $60 in 1978. Based on these figures,

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*Number provided by F. A. Wolak, cost analyst, Federal Housing Administration.

TABLE 17-I

Economic Facts on Solar Projects

TITLE	CONSTRUCTION PERIOD	HEATED AREA	COST OF CONSTRUCTION	COST PER SQ FT	SOLAR COST
Unit One First Village	Completed January 1976	2,300	80,000	34.78	12,000
Mark Jones House	Oct 76 June 77	2,650 Living 230 Usable Greenhouse	137,000	47.57	6,500
The Williamson House	1978	1,265	85,000	62.27	
The Gunderson House	Completed Nov 78	2,200	96,000	43.64	5,700
The Shankland House	July 77	2,000	65,000	32.50	4,000
The Dove Publications Building	1973-1975	10,000	130,000*	13.0	8,500
The Chavez House	Oct 1976	896 Add-on	1,040*	1.16	
Mobile/Modular Home II	Oct 1977	1,090 each	25,000	22.94	
The Hunn Residence	Completed Dec 77	1,955	67,000	34.27	6,700
The Hinesberg Greenhouse	1976	98*			
Star Tannery House	1977	1,250	34,000	27.20	
Keller Warehouse	N.D.				
Kalwall Warehouse	1977	10,000	8,000* Retrofit	0.80	
Kelbaugh House	1975	1,900	55,000	28.95	10,000
Green Mountain Home		2,364	35,250	14.91	

*Cost of materials only, no labor figures included.

Unit One and the Gunderson house all fall below the cost of conventional construction, and the Jones home is within the cost range. Only the Williamson home exceeds the conventional construction cost range. This is not because of the simple passive solar heat system but is due to other construction amenities.

One advantage of the passive solar investment is that the material currently in use on most passive systems, i.e., trombe walls, rock beds, and concrete slabs will last for the life of the home, whereas some active solar systems home parts wear out or must be replaced at a substantial cost to the homeowner.

The question of today's and the future market value must be considered when investing in a home. Today's home buyers determine their purchasing power by the total cash outlay per month. This outlay is comprised of the mortgage payment, taxes, insurance, maintenance, and utilities. In an efficient passive solar home, 50% to 90% of the heating cost is eliminated, thus allowing more money to be applied to the mortgage payment. Therefore, the market value of the passive home is equal to or greater than that of a conventional home. The trend of increasing utilities costs increases the appreciation of solar homes.

In conclusion, investment in a well designed solar home (compared to an equivalent investment in a conventional home) can bring a return to the owner of lower heating cost and equal or greater property appreciation, without loss of quality, size or comfort.

APPENDIX

Related Papers

A DESIGN AND SIZING PROCEDURE
FOR PASSIVE SOLAR HEATED BUILDINGS

By

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A DESIGN AND SIZING PROCEDURE FOR PASSIVE SOLAR HEATED BUILDINGS

INTRODUCTION

Passive solar heating systems are integral to the architecture of a building, or, to put it another way, the building or some element of it is the system. Whereas conventional or active solar heating systems can be somewhat independent of the conceptual organization of the building, it is extremely difficult to add a passive system to a building once it has been designed.

To date, relatively few architects, builders and owner-builders have made use of the information available concerning passive systems because it is too technical, cumbersome and time consuming in application. To be useful, information must lead to the necessary degree of accuracy at each stage of a building's design. The degree of accuracy increases as the design moves from the schematic stage through detailed drawings and models and finally to construction documents. In the early stages, it makes no sense to perform extensive heat loss and heat gain calculations since the design will change many times before the process is complete.

All acts of building, no matter how large or small, are based on rules-of-thumb. Architects, contractors, mechanical engineers and owner-builders, design and build buildings based on the rules-of-thumb they have developed through the years of their own or other people's experience. For example, a rule-of-thumb to determine the depth of 2-inch floor joists is given as 1/2 the span of the joists (feet) in inches, plus two, or to span a 20 foot space one would need roughly 2 x 12 inch joists. Calculations are used to verify and modify these rules-of-thumb after the building has been designed.

To be useful in a design process, rules-of-thumb must be specific, yet not too specific. For example, if you are required to know the heat loss of a space before applying a rule-of-thumb to size south-facing glass areas, then the rule-of-thumb is to specific and of little use since a building has not yet been defined. If, on the other hand, the rule-of-thumb recommends a rough size of glass needed for each square foot of building floor area, then the glass can be incorporated into the building's design. After a preliminary design is completed, then space heat loss can be calculated and the glazing areas adjusted accordingly.

The purpose of the design process outlined below is to facilitate the integration of technical information into the earliest phases of the project. The various architectural elements that make up a passively heated building are treated separately and ordered in a sequence that makes them easy to apply to a building's design. The intent is to lead the designer through a process that allows him to choose and size a system suited to a particular set of functional requirements and climatic conditions.

THE PROCESS

Passive systems demand a skillful and total integration of all the architectural elements within each space - glazing, walls, floor, roof and in some cases, even interior surface colors. In general, the way in which the glazing and thermal mass are designed determines the efficiency and level of thermal comfort provided by the system.

Two concepts are critical to understanding the thermal performance of a passively heated space. They are:

1. That the quantity of south glazing, insulating properties of the space, and outdoor climatic conditions will determine the average temperature in a space over the day, and
2. That the size, distribution, material, and in some cases (Direct Gain systems) surface color of thermal mass in the space will determine the daily fluctuation above and below the average indoor temperature.

Calculating heat gain and loss is a relatively straight forward procedure, however, the storage and control of heat in a passively heated space is the major problem confronting most designers. In the process of storing and releasing heat, thermal mass in a space will fluctuate in temperature, yet the object of the heating system is to maintain a relatively constant interior temperature. For each system, the integration of thermal mass in a space will determine the fluctuation of indoor temperature over the day. For example, in a Direct Gain system, with masonry thermal mass, the major determinant of indoor air temperature fluctuations is both the amount of exposed surface area of masonry in the space and the distribution of sunlight over the masonry surface; in a Thermal Storage Wall system, it is the thickness of the material used to construct the wall; and, in a Roof Pond system, it is the quantity of water in the ponds. The following is a procedure for sizing both a Direct Gain and Thermal Storage Wall system.

1. Direct Gain

Direct Gain systems are characterized by daily fluctuations of indoor temperatures which range from only 10°F to as much as 30°F. The heating system cannot be turned on or off since there is little control of natural heat flows in the space. To prevent overheating, shading devices are used to reduce solar heat gain, or excess heat is vented by opening windows or activating an exhaust fan.

The major glass areas (collector) of each space must be oriented to the south for maximum solar heat gain in winter. However, these windows can serve other functions as well, such as openings for light and views.

Each space must also contain enough thermal mass for the storage of solar heat gain. This implies a heavy masonry building, however, the masonry can be as thin as four inches. If an interior water wall is used for heat storage, then light weight construction (wood frame) can be used.

a. South-Glazing:

Our criterion for a well designed space is that it gain enough solar energy, on an average sunny day in winter, to maintain an average space temperature of $68^{\circ}F\underline{+}$ over that 24 hour period. By establishing this criterion, it is possible to develop ratios for the preliminary sizing of south-glazing. The following table lists ratios for various climates and locations that apply to a well-insulated residence:

TABLE 1

Average Winter (Clear-day) Outdoor Temperature[1]	Glazing/Floor Area[2]			
	36°NL	40°NL	44°NL	48°NL
Cold Climates				
20°F	.24	.25	.29	.31 (w/night insul.)
25°F	.22	.23	.25	.28 (w/night insul.)
30°F	.19	.20	.22	.24
Temperate Climates				
35°F	.16	.17	.19	.21
40°F	.13	.14	.16	.17
45°F	.10	.11	.12	.13

Notes: [1] Temperatures listed are for December and January, usually the coldest months.

[2] These ratios apply to a well insulated space with a heat loss of 8 BTU/day/sq. Ft.$_{fl.}$/°F. If space heat loss is more or less than this figure, adjust the ratios accordingly.

For example, in Denver, Colorado at 40°NL, with an average January temperature of 30°F, a well insulated space would need approximately 0.20 square feet of south-glazing for each one square foot of space floor area (i.e., a 200 square foot space needs 40 square feet of south-glazing).

In a Direct Gain System, sunlight can also be admitted into a space through clerestories and skylights, as well as through vertical south-facing windows. This approach may be taken because of: 1) a desire for privacy, 2) shading of the south facade, 3) spaces located along facades other than south or, 4) a desire to avoid direct sunlight on people and furniture. Use the following guidelines when designing clerestories and skylights:

Clerestory - locate the clerestory at a distance in front of an interior thermal storage wall of roughly 1 to 1.5 times the height of the thermal wall. Make the ceiling of the clerestory a light color to reflect and diffuse sunlight down into the space.

Sawtooth Clerestories - make the angle of each clerestory roof (as measured from horizontal) equal to, or less than the altitude of the sun at noon, on December 21, the winter solstice. Make the underside of the clerestories a light color.

Skylight - use a reflector with horizontal skylights to increase solar gain in winter and shade both horizontal and south-facing skylights in summer to prevent excessive solar gain.

b. Thermal Storage Mass:

To minimize temperature fluctuations within acceptable levels, enough mass must be properly located to absorb and store daytime solar heat gain for use during the evening. The two most common materials used for storing heat are masonry and water.

Masonry materials transfer heat from their surface to interior at a slow rate. If direct sunlight is applied to the surface of a dark colored masonry material it will become uncomfortably hot, giving much of its heat to the air in the space rather than conducting it away from the surface for storage. This results in daytime overheating and large daily temperature fluctuations in the space. To reduce fluctuations, direct sunlight must be spread over a large surface area of masonry so that roughly 60% of the solar energy admitted into the space is stored as heat in the walls and/or floor and/or ceiling at sunset. To accomplish this:

Construct interior walls and floors of masonry at least 4 inches in thickness.

Diffuse direct sunlight over the surface area of the masonry by using either a translucent glazing material by placing a number of small windows so that they admit sunlight in patches, or by reflecting direct sunlight off a light colored interior surface first.

Use the following guidelines for selecting interior surface colors and finishes:

- masonry floors a dark color
- masonry walls any color
- lightweight construction (little thermal mass) a light color to reflect sunlight to masonry surfaces
- avoid direct sunlight on dark colored masonry surfaces for long periods of time
- do not use wall-to-wall carpeting over masonry floors

By following these recommendations, temperature fluctuations in the space on clear-winter days will be approximately 10°F to 15°F.

Masonry may need sunlight diffused over a large surface area, but water in containers can absorb and store direct sunlight effectively even when it is concentrated by a reflector. First, water is a more efficient heat storage medium than masonry, storing more than twice as many BTU's for each 1°F temperature rise for the same volume of material. In addition, water heats up somewhat uniformly, transfering heat rapidly from the collecting surface to the entire volume of water. Heated water in contact with the inside surface of the container rises and produces a convection current which distributes the heat throughout the container. The volume of water in direct sunlight and the surface color of the container (thin metal or plastic) will determine the temperature fluctuation in the space over the day (See Table 2). When using a water wall for heat storage:

Locate the wall so it receives direct sunlight between the hours of 10 a.m. and 2 p.m.

Make the surface of the container exposed to direct sunlight a dark color (at least 75% solar absorption).

Use roughly one cubic foot (7.48 gallons) of water for each one square foot of south glazing.*

Note that when using an interior water wall there are few restrictions regarding other wall and floor materials and surface colors in the space. The water can be stored within an interior wall of in free standing containers, as long as the surface of the water wall is a thin material exposed to direct sunlight.

TABLE 2

DAILY SPACE AIR TEMPERATURE FLUCTUATIONS[1] FOR DIRECT GAIN WATER STORAGE WALL SYSTEMS[2]

Solar Absorption (Surface Color)	Volume[3] of Water Wall for Each One Square Foot South-Facing Glass			
	1 cu.ft.	1.5 cu.ft.	2 cu.ft.	3 cu.ft.
75% (dark color)	17°F	15°F	13°F	12°F
90% (black)	15°F	12°F	10°F	9°F

Notes: [1] Temperature fluctuations are for a clear winter day with approximately 3 square feet of exposed wall area for each one square foot of glass. If less wall area is exposed to the space, temperature fluctuations will be slightly higher. If additional mass is located in the space (such as masonry walls and/or floor) then fluctuations will be less than those listed and therefore less water can be used.

[2] Assumes 75% of the sunlight entering the space strikes the mass wall.

[3] One cubic foot of water = 62.4 lbs. or 7.48 gallons.

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*Adjust the volume of water according to the temperature fluctuation desired in the space.

2. Thermal Storage Wall

The predominant architectural expression of the building is south facing glass. The glass functions as a collecting surface only, and admits no natural light into the space. However, windows can be included in the wall to admit natural light, direct heat, and also to permit a view.

Either water or masonry can be used for a thermal storage wall. Since the mass is concentrated along the south face of the building, there is no limit to the choice of construction materials and interior finishes in the remainder of the space.

a. South-Glazing:

Our criterion for a double glazed Thermal Storage Wall is the same as for a Direct Gain system, that it transmit enough heat on an average sunny winter day to supply a space with all its heating needs for that day. To accomplish this use the following tables* as a guide for sizing the glazing of masonry or water wall:

TABLE 3

Average Winter (Clear-day) Outdoor Temperature	Masonry Wall/Space Floor Area[1]			
	36°NL	40°NL	44°NL	48°NL
Cold Climates				
20°F	.71	.75	.85	.95
25°F	.59	.63	.75	.84
30°F	.50	.53	.60	.70
Temperate Climates				
35°F	.40	.43	.50	.55
40°F	.32	.35	.40	.44
45°F	.25	.26	.30	.33

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*These tables apply to a well insulated space with a heat loss of 8 BTU/day/sq.ft.$_{fl.}$/°F. If space heat loss is more or less than this figure, adjust the ratios accordingly. The surface area of the wall is assumed to be the same size as the glazing.

Average Winter (Clear-day) Outdoor Temperature	Water Wall/Space Floor Area[1] 36°NL	40°NL	44°NL	48°NL
Cold Climates				
20°F	.52	.55	.65	.80
25°F	.45	.47	.55	.64
30°F	.36	.39	.45	.55
Temperate Climates				
35°	.28	.31	.35	.40
40°	.23	.25	.29	.32
45°	.17	.18	.20	.24

Note: [1] For thermal walls with a horizontal specular reflector equal to the height of the wall in length, use 67% of the recommended ratios. For thermal walls with night insulation (R-8), use 85% of the recommended ratios. With both night insulation and reflectors, use 57% of the recommended ratios.

For example, in Boston, Massachusetts, at 42°NL, with an average January temperature of 31.4°, a well insulated space will need approximately 0.41 square feet of double glazed water wall for each one square foot of building floor area, (i.e., a 200 square foot space will need about 82 square feet of glazing).

b. Wall Details:

While the above procedure gives guidelines for the overall size (surface area) of a Thermal Storage Wall, the efficiency of the wall as a heating system depends mainly on its thickness, material and surface color. If the wall is made too thin, the space will overheat during the day and be too cool in the evening; if it is too thick, it becomes inefficient as a heating source since little energy is transmitted through it.

Material	Recommended Thickness
Adobe	8 - 12 inches
Brick (common)	10 - 14 inches
Concrete (dense)	12 - 18 inches
Brick[1] (magnesium oxide additive)	16 - 24 inches
Water[2]	6 inches or more

Notes: [1] Magnesium oxide is commonly used as an additive to brick to darken its color. It also greatly increases the thermal conductivity of the material.

[2] When using water in tubes, cylinders, or other types of circular containers, use at least a 9½ inch diameter container or 1/2 cubic foot (31 lbs., 3.7 gallons) of water for each one square foot of glazing.

The choice of a wall thickness, within the range given for each material, will determine the air temperature fluctuation in the space over the day. As a general rule the greater the wall thickness the less the indoor temperature fluctuation. Use the following table for selecting a wall thickness:

APPROXIMATE SPACE TEMPERATURE FLUCTUATIONS[1] AS A FUNCTION OF THERMAL STORAGE WALL MATERIAL AND THICKNESS

	Wall Thickness in Inches					
Material	4	8	12	16	20	24
Adobe	-	18	7	7	8	-
Brick (common)	-	24	11	7	-	-
Concrete (dense)	-	28	16	10	6	5
Brick (magnesium oxide additive)	-	35	24	17	12	9
Water	31°F	18	13	11	10	9

Note: [1] Assumes a double glazed thermal wall. If additional mass is located in the space, such as masonry walls and/or floors, then temperature fluctuations will be less than those listed. Values are given for clear winter days.

The greater the absorption of solar energy at the exterior face of a thermal wall, the greater the quantity of incident energy transfered through the wall into the building. Therefore:

> Make the outside face of the wall a dark color (preferably black) with a solar absorption of at least 85%.

In cold climates, the addition of thermocirculation vents in a masonry wall will significantly increase the performance of the wall. In mild climates, however, the vents are unnecessary since winter daytime temperatures are comfortable and heating is usually not needed at that time. To size the vents:

> Make the total area of each row of vents equal to approximately one square foot for each 100 square feet of wall surface area.

Prevent reverse air flow at night by placing an operable damper over the inside face of the upper row of vents.

CONCLUSION

Since a building, or some element of it, is the passive system, the use of passive solar energy must be included in every step of a building's design. The format outlined here provides a method for including technical information in a way that can be applied by architects, builders and owner-builders.

Author's Note: Information for this paper is excepted and condensed from Edward Mazria's book, The Passive Solar Energy Book, published by Rodale Press, Emmaus, Pennsylvania. Some of the work has been performed for the Department of Energy under a contract from Lawrence Berkeley Laboratory, Berkeley, California.

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TITLE: TROMBE WALL vs DIRECT GAIN: A COMPARATIVE ANALYSIS OF PASSIVE SOLAR HEATING SYSTEMS

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TROMBE WALL vs DIRECT GAIN:

A COMPARATIVE ANALYSIS OF PASSIVE SOLAR HEATING SYSTEMS*

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ABSTRACT

Until recently only the thermal storage wall passive solar heating system had been characterized by thermal network calculators using hour-by-hour historical weather data. The greater popularity and market acceptability of direct gain systems has led to a lively, but inconclusive debate concerning the relative effectiveness of the two configurations. The recent development and validation of PASOLE/SUNSPOT, a thermal network code for direct gain enclosures, has provided the tool necessary for a quantitative comparison.

The results of performance analysis calculations for both Trombe wall and direct gain systems in Albuquerque, New Mexico, and Madison, Wisconsin, are reported in this paper. The comparative analysis includes parametric variation of fundamental design parameters including building load, glazing area, total mass, mass thickness, number of glazings, night insulation value and allowable temperature swing. Thermal comfort within the two generic types of buildings is considered as well as energy efficient performance.

1. INTRODUCTION

The thermal performance calculations presented herein for thermal storage wall and direct gain passive solar heating systems were performed with the PASOLE and SUNSPOT thermal network codes respectively. PASOLE was developed and validated a couple of years ago at Los Alamos Scientific Laboratory and has recently been documented.[1,2] SUNSPOT is a recent development.[3] It is a modified version of PASOLE capable of simulating the thermal performance of direct gain buildings on two distinct levels of detail. Level I, on which this report is based, is a fairly coarse model that considers only the gross characteristics of direct gain buildings. Nevertheless, the Level I model accurately reproduces passive test cell data at Los Alamos indicating that the dominant physical phenomena occurring in direct gain enclosures have been correctly identified and modeled. The Level II model, which is currently under development, is very detailed and, therefore, suitable for studying second order effects, which arise due to internal distribution of energy and variations in geometry and configuration.

Albuquerque, New Mexico, and Madison, Wisconsin, were selected as sites for the comparative parametric evaluation of direct gain and Trombe wall buildings because they represent environmental extremes, which, therefore, yield an appreciation of the effect of climate on appropriate passive solar design procedures. Albuquerque has a moderately high heating load, 4253 annual degree days, and is blessed with enough solar radiation, 680,000 Btu/ft^2 annually, to meet most space heating requirements fairly easily. This is an ideal climate for passive solar applications. Madison, on the other hand, has a very high heating load, 7350 annual degree days, and receives only about 518,000 Btu/ft^2 of solar radiation each year. The high heating load combined with low solar input makes passive solar design in Madison a challenging proposition.

The significance of variations in solar aperture area, number of glazings, resistance of night insulation, allowable indoor temperature swing, and building loss coefficient with respect to thermal performance of passive solar buildings is investigated on the basis of a series of SUNSPOT and PASOLE calculations. The relationship between performance and available thermal storage mass is also considered. For Trombe walls the mass wall surface area is assumed equal to the glazing area so that the storage mass is directly proportional to wall thickness. For direct gain buildings an additional degree of freedom exists because the storage mass surface area is variable as well as the thickness.

Thermal performance results are expressed in terms of the annual solar fraction. Minimum indoor air temperatures are maintained by auxiliary heaters and ventilation cooling is employed to limit the maximum air temperature to

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*Work performed under the auspices of the U.S. Department of Energy, R&D Branch for Heating and Cooling, Office of the Assistant Secretary for Conservation and Solar Energy.

a specified level. The reference indoor temperature is set at 68°F in all calculations and variations, ΔT, of $\pm 2°F$, $\pm 5°F$ and $\pm 10°F$ about the reference value are considered. Thus, in all cases the indoor air temperature is allowed to fluctuate within prescribed bounds. However, the mean radiant temperature, which is determined by the temperatures of all surfaces bounding the living space, is constrained only by the characteristics of a specific passive design and the local weather. The thermal comfort of building occupants depends on both the mean radiant and the air temperatures in a manner which will be explained in a later section. Passive solar heated buildings, therefore, have different comfort characteristics even though the air temperature variations within the structure may be carefully bounded. In an effort to reveal general thermal comfort characteristics of different passive solar designs, monthly air, mass surface and mean radiant temperature histograms were calculated during the thermal network simulations. Appropriate weighting of the air and mean radiant temperatures yields a single thermal index, which can be directly related to occupant comfort, thereby facilitating comparative analysis.

The economic consequences of the thermal performance characteristics of passive solar heating designs considered in this paper have been evaluated by Scott Noll of Group S-2 at Los Alamos Scientific Laboratory and are reported in a separate paper in these proceedings.[4]

2. DIRECT GAIN PERFORMANCE

Since the performance characteristics of thermal storage walls have been reported extensively in the literature, some simulation results for direct gain buildings in Albuquerque are included here before proceeding to a comparative analysis of the two generic types of passive solar buildings.

2.1. Effect of Design Option Combinations

The percent solar yielded by various combinations of design options for direct gain buildings in Albuquerque is presented in Fig. 1. In each case, the thermal storage mass consists of a 6 in. thick layer of high density concrete (150 lb/ft^3) with a surface area equal to three times the glazing area. Thus, the total thermal storage mass, M/A_g, is 225 lbs per square foot of glazing. Additionally, the glazing area to building load ratio, A_g/L, is 1.0 $ft^2/(Btu/hr°F)$ for each case represented in Fig. 1. The variable design options are the number of glazings, NGL, the resistance of movable night insulation, R_n, and the allowable indoor temperature swing, ΔT, about the 68°F reference value.

One of the more striking features of the bar graph in Fig. 1 is the lack of significant performance variations among configurations No. 4 through No. 7. All four cases have a temperature swing of $\pm 5°F$. The performance appears to be dominated by the fact that each of these configurations has night insulation with a resistance of at least R5. Increasing the night insulation to R9 has little effect. Also, the effect of varying the number of glazings from one to three is largely masked by the presence of night insulation. A comparison of configurations No. 1 and No. 3 shows that, in the absence of night insulation, the number of glazings has a significant effect on performance. The allowable indoor temperature swing has a large effect on performance, even with night insulation, as indicated by a comparison of configurations No. 2, No. 6, and No. 10 for which ΔT is $\pm 2°F$, $\pm 5°F$ and $\pm 10°F$ respectively.

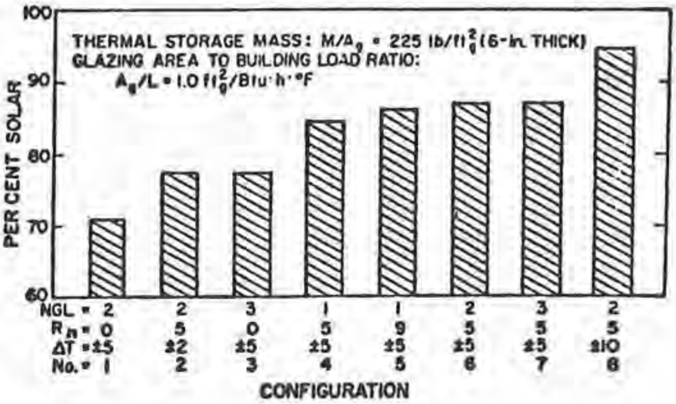

Fig. 1. The effect of design option combinations on direct gain performance in Albuquerque.

The effect of varying the glazing area to building load ratio is depicted in Fig. 2, where the behavior of four separate design option combinations is included. Cutting the glazing area in half (or doubling the thermal load) such that A_g/L is decreased from 1.0 to 0.5 causes a 20 to 25 per cent reduction in solar fraction. The rate at which solar fraction increases with the area/load ratio diminishes rapidly at high solar fractions.

3. Comparison of Direct Gain and Trombe Wall Performance in Albuquerque, New Mexico.

For the comparisons presented in this section, the number of glazings is fixed at 2, the temperature swing at $\pm 5°F$ and the area/load ratio at 1.0 $ft^2/(Btu/hr°F)$. The performance of Trombe wall and Direct Gain buildings having no night insulation is plotted as a function of thermal storage mass per unit glazing area, M/A_g, in Fig. 3. The thermal storage mass is high density (150 lbs/ft^3) concrete. For the Trombe wall case, the mass surface area is equal to the glazing area so that M/A_g is directly proportional to thickness of the wall. In direct gain buildings the mass surface area is variable, providing an additional degree of freedom. We have chosen to present the direct gain results in the form of three curves, each representing a different mass thickness, for which the mass per unit glazing area is then directly proportional to mass surface area. The thicknesses selected are 4 in., 6 in. and 8 in., and in each case the surface area is varied from twice the glazing area to five times the glazing area.

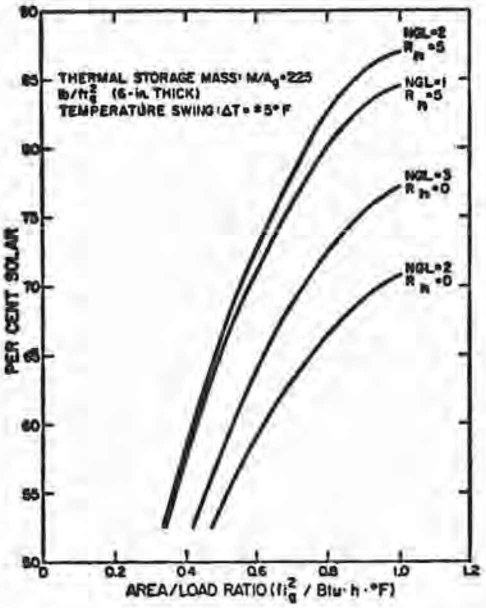

Fig. 2. Dependence of direct gain performance on the area/load ratio.

Inspection of Fig. 3 reveals a performance maximum for Trombe walls at $M/A_g = 175$ lbs/ft$_g^2$, which corresponds to a thickness of 14 inches. For direct gain buildings performance maxima do not appear. Regardless of the mass thickness selected, the solar fraction continues to increase as the mass surface area is extended up to five times the glazing area. It is apparent from the curves in Fig. 3 that the best way to distribute a given amount of thermal storage mass in a direct gain building is in a thin layer (down to a minimum of 4 in.) having the largest possible surface area. When compared with a Trombe wall, the 4 in. direct gain system is capable of achieving higher solar fractions for thermal storage masses greater than 190 lbs/ft$_g^2$. For masses less than 190 lbs/ft$_g^2$ the Trombe wall is a superior performer. Thus, Trombe walls up to 15 in. thick yield higher solar fractions than direct gain buildings employing comparable amounts of thermal storage mass in a 4 in. thick layer.

In Fig. 4 we show the effect of adding R5 night insulation to the same passive solar designs represented in Fig. 3. Energy efficient performance is uniformly improved, and there is little or no change in the relative advantages of Trombe wall and direct gain buildings.

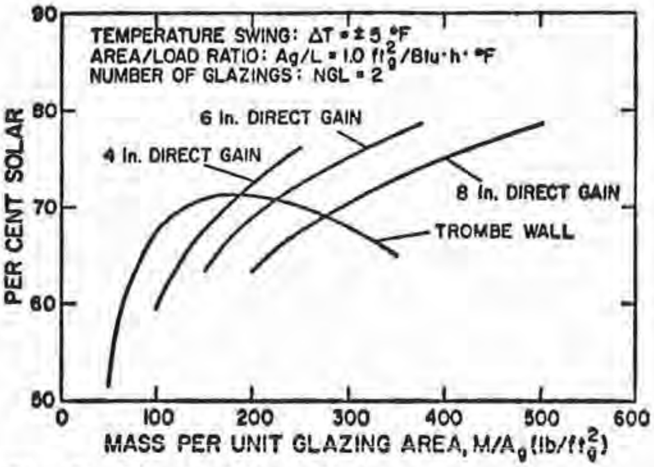

Fig. 3. Effect of thermal storage mass on passive solar building performance in Albuquerque without night insulation.

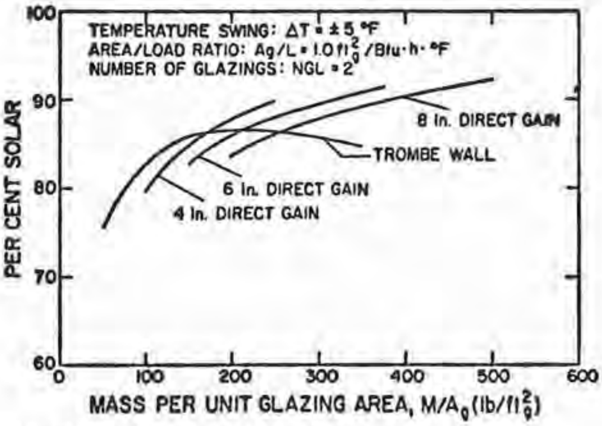

Fig. 4. Effect of thermal storage mass on passive solar building performance in Albuquerque with R5 night insulation.

4. Comparison of Direct Gain and Trombe Wall Performance in Madison, Wisconsin.

Now suppose we take the passive solar designs considered in the previous section and move them from Albuquerque, New Mexico, to the less forgiving climate of Madison, Wisconsin. The results for buildings with no night insulation are presented in Fig. 5. Note the marked deterioration of direct gain performance relative to the Trombe wall. In the harsh Madison climate a direct gain structure loses too much thermal energy through the glazing aperture to remain competitive with a Trombe wall in the absence of night insulation. However, as illustrated in Fig. 6, when R5 night insulation is added to both generic types, we obtain roughly the same relative performance previously observed in Albuquerque.

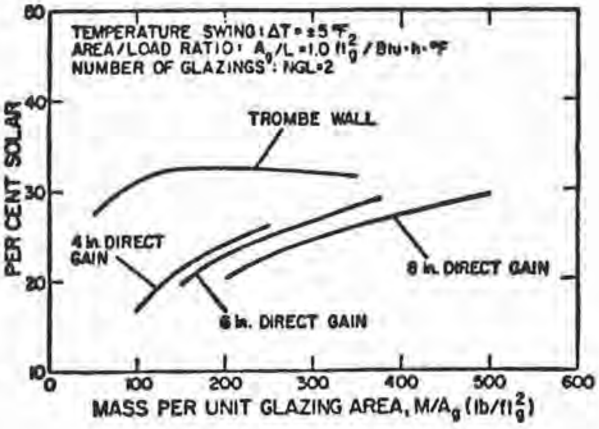

Fig. 5. Effect of thermal storage mass on passive solar building performance in Madison without night insulation.

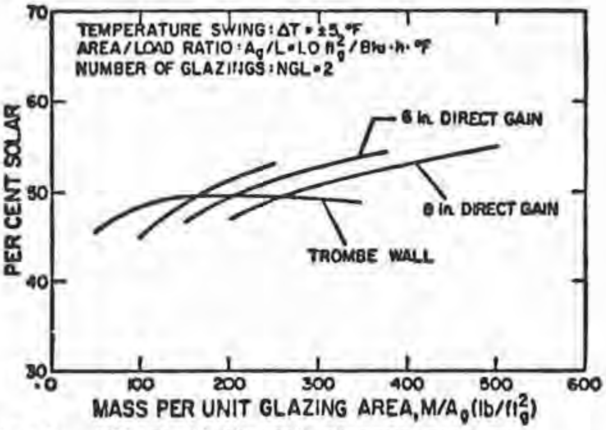

Fig. 6. Effect of thermal storage mass on passive solar building performance in Madison with R5 night insulation.

5. Mixed Systems.

Almost all buildings must have windows, for reasons of aesthetics, natural daylighting, and to serve as emergency exits. Typical window areas are in the range of 10% to 20% of the building floor area. Ten percent is a normal minimum specified by code, and architects frequently employ 20% or even more. Thus it is appropriate to use these windows as direct gain solar collection elements as much as possible, locating them on the south side of the building.

An effective design strategy is to mix direct gain and Trombe wall in the same building. A normal procedure in a cold climate is to size the window area based on the non-solar considerations mentioned above but locate them on the south side and in clerestories as much as possible. Additional solar gain is then added using Trombe walls between the south windows or by piercing the Trombe wall with a window. This approach has superior comfort and performance characteristics to the use of a pure direct gain or Trombe wall approach. It is better than the pure Trombe wall because energy-losing windows would then have to be located in the non-south walls. It is better than a pure direct gain building because the timing of energy delivery is more uniform, there is much less of a sudden drop in mean radiant temperature at nightfall, and the large temperature swing associated with a large-area direct gain building is avoided.

Simulatons of mixed systems will be made in the future to explore their performance and comfort characteristics in detail.

6. Thermal Comfort in Passive Solar Heated Buildings.

6.1. Theoretical Considerations

Most buildings of conventional construction are light weight and have limited glazing areas. As a general rule the thermal environment in such buildings is very nearly uniform. In this context the term "uniform" refers to an environment in which the air and mean radiant temperature are equal. In passive solar heated buildings the presence of massive thermal storage elements and/or large glazed areas, which communicate directly with the living space produces thermal environments which are characteristically non-uniform. The thermal storage mass surfaces facing the living space may be either warmer or colder than the room air, depending on whether current space heating requirements are being met by heat transfer from the storage mass or from the auxiliary heater. Since the mean radiant temperature is affected by radiation exchanges with all surfaces bounding an enclosure, the presence of thermal storage mass with surface temperatures different from the air temperature induces thermal non-uniformity. Large glazed areas, which communicate directly with the living space, as in direct gain buildings, can affect the mean radiant temperature in two ways. First, during daylight hours sunlight transmitted through the glazing can directly induce significant increases in the mean radiant temperature. Secondly, at night glazed areas not covered with movable insulation become much colder than the room air and tend to force the mean radiant temperature downward.

The problem of assessing thermal comfort in both uniform and non-uniform environments has been extensively researched by P. O. Fanger. On the basis of Fanger's work, it is possible to derive an expression for the "equivalent uniform temperature," T_{eu}, which is defined as "the uniform temperature of an imaginary enclosure in which a person will experience the same degree of thermal comfort as in the actual non-uniform environment."[6] The details of the derivation are presented in Reference 6, which is currently under review for publication as a Los Alamos required. The effect of employing ventilation cooling wherever the air temperature gets up to 73°F is evident in that both buildings have the next largest T_{eu} time fraction in the 72°F to 74°F range. Due to radiation from the inner wall surface, the Trombe wall building reaches a maximum T_{eu} interval of 74°F to 76°F. Due to the combined effect of radiation from the thermal storage mass and direct irradiation by the solar source, the direct gain building reaches a maximum T_{eu} interval of 76°F to 78°F. The monthly solar fractions in October were 73% for the Trombe wall and 72% for the direct gain building. Increases in monthly solar fractions are always accompanied by T_{eu} histograms, which shift from the low end of the scale near the minimum air temperature toward the high end near the maximum air temperature. The mean radiant temperature range is usually much larger than the air temperature range which leads to T_{eu} histograms, which extend beyond the air temperature boundaries at both ends. Trombe walls always yield smaller T_{eu} swings than direct gain buildings, which generate comparable solar fractions.

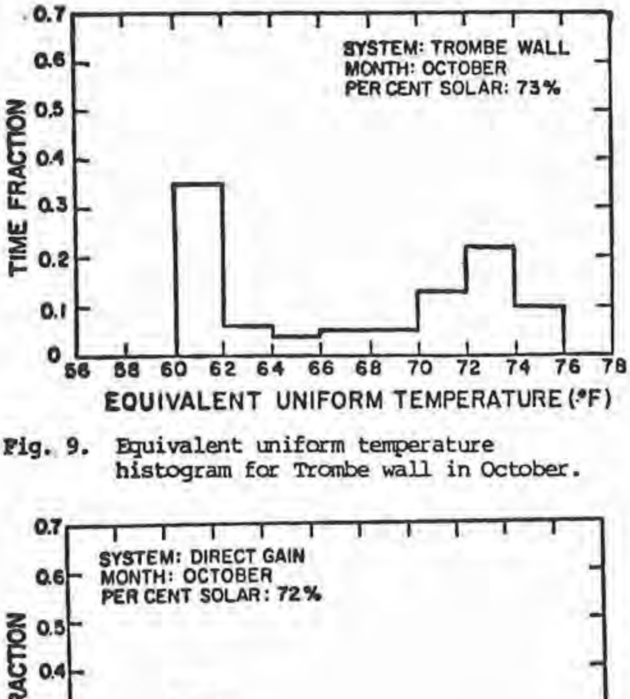

Fig. 9. Equivalent uniform temperature histogram for Trombe wall in October.

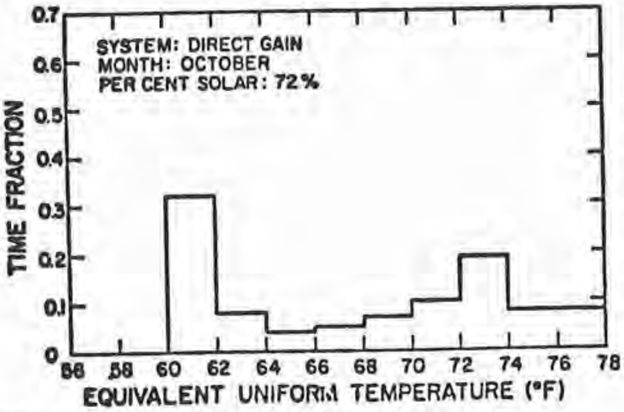

Fig. 10. Equivalent uniform temperature histogram for direct gain building in October.

As the above observations indicate, the problem of assessing comfort levels in passive solar heated buildings can be quite complex. Each particular building design in a given location will exhibit diurnal fluctuations in the equivalent uniform temperature, which are characteristic of that particular structure's response to the local climate. Each month there is a significant change in the character of the diurnal fluctuations as the structure responds to seasonal variations in heating load, total insolation and solar declination. Using thermal network codes, one can easily generate more data on thermal comfort indices than he has time to interpret. It is desirable to define an overall thermal quality index, which could serve as a basis for rating the comfort characteristics of different types of passive solar buildings on a comparative basis. Future work on thermal comfort at LASL will consider appropriate definitions for such an index.

7. CONCLUSIONS

Trombe wall and direct gain buildings each have certain advantages with respect to energy efficient performance. As a general rule, Trombe walls are able to achieve higher solar fractions on a limited amount of thermal storage mass. For thermal storage masses up to about 175 lbs per square foot of glazing Trombe walls consistently out perform direct gain buildings. However, if one is allowed to include more than about 175 lbs/ft$_g^2$ of thermal storage mass, the direct gain building begins to surpass the Trombe wall. This transition occurs because a Trombe wall reaches a performance peak between 150 lbs/ft$_g^2$ and 200 lbs/ft$_g^2$ (or 12 in. to 16 in. of 150 lb/ft^3 high density concrete) while performance of the direct gain building continues to rise as the surface area of the thermal storage mass is increased with the thickness held constant. Mixed systems offer potential advantages over either pure direct gain or Trombe wall approaches.

With respect to thermal comfort, the Trombe wall appears to be superior to direct gain buildings yieldling comparable solar fractions. Although both types of structures undergo equivalent uniform temperature swings, which exceed the thermostatically imposed air temperature boundaries at the upper and lower limits, the T_{eu} range in Trombe wall systems is consistently smaller than in direct gain buildings.

ACKNOWLEDGMENT

The authors would like to express their appreciation to Mark Beckett of Group Q-11 at Los Alamos, who performed the matrix of thermal network calculations on which this paper is based.

Scientific Laboratory Report. The relationship between the equivalent uniform temperature, the air temperature, T_a, and the mean radiant temperature, T_{mr}, has the following functional form:

$$T_{eu} = f\,T_a + (1-f)\,T_{mr} \qquad (1)$$

$$f = f(A,C,H,V)$$

where A is the activity level (metabolic rate), C is the clothing insulation value, H is the relative humidity, and V is the relative wind velocity. Thus, the relative importance of air and mean radiant temperature depends on a set of environmental and physiological parameters. It is demonstrated in Reference 6 that for extreme, but still realistic combinations of these parameters, the function f can vary from 0.48 to 0.68. On the basis of assumptions concerning conditions likely to exist in a passive solar heated dwelling, the following expression for the equivalent uniform temperature is obtained.

$$T_{eu} = 0.55\,T_a + 0.45\,T_{mr} \qquad (2)$$

Eq. 2 represents a subject dressed in medium-weight clothing and performing light activity in an environment with a relative humidity of 50% and low relative wind velocities dominated by free convection processes.

The concept of an equivalent uniform temperature is quite useful because it enables one to assess thermal comfort levels in non-uniform environments in terms of a single thermal index, which can be directly related to subjective personal experience. Unlike the "operative temperature" defined in the ASHRAE handbook,[7] the equivalent uniform temperature is explicitly related to human thermal comfort and includes the effect of all latent heat loss phenomena on which that comfort depends.

6.2. Equivalent Uniform Temperatures in Passive Solar Heated Buildings.

In this section we present monthly histograms of the equivalent uniform temperature in two passive solar heated buildings located in Madison, Wisconsin. The histograms were calculated by PASOLE and SUNSPOT, the thermal network simulation codes. Double glazing with R5 night insulation is employed in both designs considered in this section, and the area/load ratio is held constant at 1.0 $ft_g^2/(Btu/hr^oF)$. The allowable air temperature swing is from 63°F to 73°F. The Trombe wall design employs a 16 in. thick wall of high density concrete yielding 200 lbs of thermal storage mass per square foot of glazing. The direct gain system has 6 inches of concrete with a surface area equal to three times the glazing area, which yields 225 lbs/ft_g^2. Both configurations obtain an annual solar fraction of 50% in Madison. Equivalent uniform temperature histograms for the Trombe wall and direct gain buildings during the month of January are presented in Figs. 7 and 8 respectively.

Both buildings had a solar fraction of 35% for the month. The low solar fraction results from the high heating load in January. Since 65% of the heating load is met by the auxiliary heater, which is controlled by a thermostat set at 63°F, the air temperature is held at 63°F most of the time. The mean radiant temperature drops below the air temperature far enough to induce an equivalent uniform temperature which is between 60°F and 62°F over half the time. The Trombe wall building never falls any lower than the 60°F level. However, the direct gain building has a T_{eu}, which spends 10% of the time at the minimum level of 58°F to 60°F. Both buildings reach a maximum T_{eu} interval of 74°F to 76°F, although the time fractions at this level are quite small.

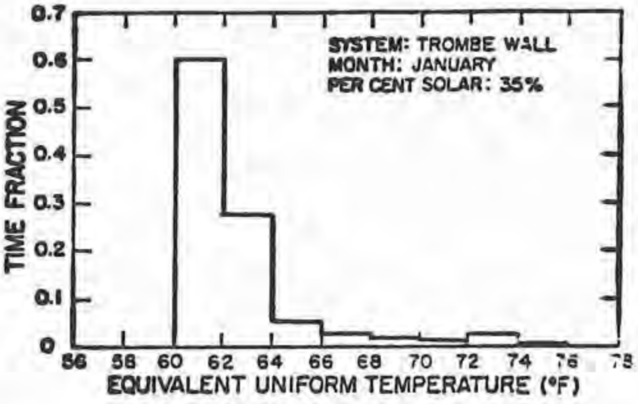

Fig. 7. Equivalent uniform temperature histogram for Trombe wall in January.

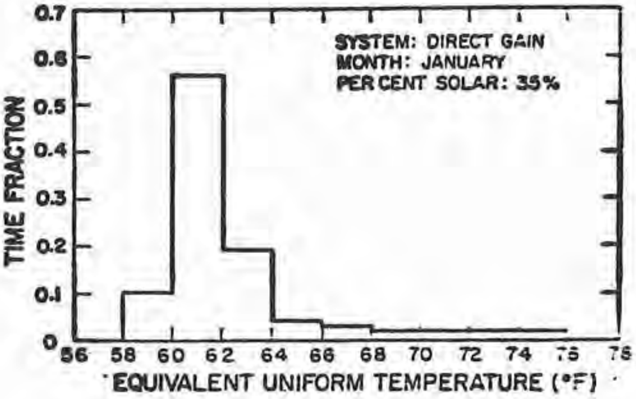

Fig. 8. Equivalent uniform temperature histogram for direct gain building in January.

In October the equivalent uniform temperature histograms have quite a different character as shown in Figs. 9 and 10. The largest time fraction is again in the 60°F to 62°F for both buildings due to the combined effect of the air temperature being thermostatically held to a minimum of 63°F and the thermal storage mass being cooler than the air when auxiliary heat is

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TITLE: A SEMI-EMPIRICAL METHOD FOR ESTIMATING THE PERFORMANCE OF DIRECT GAIN PASSIVE SOLAR HEATED BUILDINGS

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A SEMI-EMPIRICAL METHOD FOR ESTIMATING THE PERFORMANCE OF DIRECT GAIN PASSIVE SOLAR HEATED BUILDINGS

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ABSTRACT

The SUNSPOT code for performance analysis of direct gain passive solar heated buildings is used to calculate the annual solar fraction for two representative designs in ten American cities. The two representative designs involve a single thermal storage mass configuration which is evaluated with and without night insulation. In both cases the solar aperture is double glazed. The results of the detailed thermal network calculations are then correlated using the monthly solar load ratio method which has already been successfully applied to the analysis of both active solar heated buildings and passive thermal storage wall systems. The method is based on a correlation between the monthly solar heating fraction and the monthly solar load ratio. The monthly solar load ratio is defined as the ratio of the monthly solar energy transmitted through the glazing aperture to the building's monthly thermal load.

The procedure using the monthly method for any location is discussed in detail. In addition, a table of annual performance results for 84 cities is presented, enabling the designer to bypass the monthly method for these locations.

1. Introduction

The solar load ratio method for estimating the performance of solar heated buildings was originally developed as a design tool for active systems.(1) Later the technique was modified slightly by Balcomb and McFarland(2) and applied to passive solar heated buildings of the thermal storage wall type. In this paper, the technique of Balcomb and McFarland, as described in Ref. 2, is extended to include direct gain passive solar heated buildings.

The solar load ratio method involves the use of a correlation between monthly solar heating fraction and monthly solar load ratio. The monthly solar load ratio is defined as the ratio of the solar radiation transmitted through the glazing of the solar aperture during a one month period to the total building heating load during the same one month period. Simulation results on which to base the correlation for direct gain buildings were obtained from a series of calculations performed with the PASOLE/SUNSPOT(3) thermal network code. SUNSPOT has been validated on the basis of experimental data from the direct gain test cell at the Los Alamos Solar Laboratory and although it is quite a simple model it is considered a reasonably accurate representation of actual direct gain buildings.

In the following sections we describe the procedure used to correlate the monthly solar heating fraction for direct gain buildings with the monthly solar load ratio. Limitations and accuracy of the resulting correlation are discussed. Finally a step-by-step procedure for estimating the annual performance of an arbitrarily located direct gain building on the basis of the solar load ratio correlation is presented.

2. The Reference Direct Gain Design

A single reference design is used in this study. It is, of course, desirable to have several reference designs available for analysis by the solar load ratio method and studies involving other configurations are therefore planned for the near future. At present, however, the performance of direct gain systems other than the reference design must be estimated by scaling the results based on parametric studies as will be discussed later.

The characteristics of the direct gain reference design are matched to corresponding characteristics of the previously reported solar load ratio analysis of thermal storage wall systems(4) wherever possible. For example, the direct gain design has a six inch thick layer of high density concrete distributed on the floor and north, east and west walls of the enclosure. The mass surface area is three times the glazing area. Thus the total volume of concrete thermal storage mass is equal to that available in an 18

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inch Trombe wall whose surface area equals the glazing area. The remaining characteristics of the reference direct gain design are:

Thermal Storage: 45 Btu/°F-ft^2 of glazing
Mass Distribution: 6 in. thick layer of concrete on floor and north, east or west walls. Mass surface area is three times the glazing area.
Other Building Mass: Negligible
Double Glazing: Normal solar transmittance = 0.747
Air Temperature Range in Building: 65°F to 75°F
Night Insulation: R9 when used. Insulation in place from 5 p.m. to 7 a.m.
Mass-surface-to-room air conductance: 1.0 Btu/hr ft^2 °F
Storage Mass Properties:
  thermal conductivity = 1.0 Btu/hr ft °F
  heat capacity =30 Btu/ft^3 °F
Glazing Orientation: Vertical and south facing
Mass Surface Solar Absorptance: 0.8
Ground Reflectance: 0.3
Overhang: None

The above design is not as constrained as first appearances might indicate. Although the thickness and surface area of the thermal storage mass are fixed, the distribution of the mass along the interior surfaces of the enclosure is arbitrary except that the ceiling is excluded. During the course of validating the SUNSPOT model it was determined that the performance of direct gain enclosures is not very sensitive to variations of mass or solar radiation distribution within the enclosure. However, all non-massive surfaces are modeled as perfect reflectors representing the use of light colors on all light weight elements of the building shell. In order to account for the presence of furniture, rugs and other low thermal capacity objects in the direct gain enclosure, it is assumed that 20% of the transmitted solar flux was absorbed directly into the room air. This procedure synthesizes the absorption of solar radiation by objects which heat up rapidly due to their low heat capacity and subsequently lose thermal energy to the room air with very little lag time.

3. The Solar Load Ratio Correlation

A data base for the solar load ratio correlation was generated by performing a one year SUNSPOT calculation for the reference direct gain design (with and without night insulation) in each of ten American cities. The ten cities were selected on the basis of obtaining a variety of different types of climates. A list of the ten cities is presented in Table I as are the latitude, longitude, annual heating degree days and annual insolation at each site. The beginning date of the "typical year" historical weather file used for each city is also listed. The typical years were determined for each city on the basis of past work on active system simulation as the year which gives an annual performance closest to the average annual performance over a ten year period. Calculations in each city were run with and without night insulation for four different glazing area to building load ratios. Thus a total of 10 x 2 x 4 = 80 annual calculations were performed. The monthly data points obtained with and without night insulation are plotted in Figs. 1 and 2 respectively. In each figure, the monthly solar heating fraction is plotted as a function of the monthly solar load ratio. The grouping of the data points indicates that a correlation does exist and, as shown in Figs. 1 and 2, we have fit analytic curves to both sets of data. The functional relationship is given by:

$$\mathrm{SHF} = a_1(\mathrm{SLR}), \qquad \mathrm{SLR} \quad R$$

$$\mathrm{SHF} = a_2 - a_3 \,\mathrm{EXP} \left|-a_4(\mathrm{SLR})\right| \quad , \mathrm{SLR} \quad R$$

The coefficients selected are those which yield a least squares fit to annual solar heating fraction for the whole data set. The coefficients are given in Table II along with the standard deviation, , of the annual data.

The correspondence between annual solar heating fraction by the monthly solar load ratio method as compared with the hour-by-hour results is given in Figs.3 and 4.

Table I

American Cities used in Solar Load Ratio Correlation

City	Latitude	Longitude	Annual Heating Degree Days	Annual Insolation (10^3Btu/ft^2)	Typical Year Start Date
Albuquerque	35.0	1.6	4253	688	7/1/62
Los Alamos	35.8	1.3	7350	518	9/1/72
Madison	43.0	-0.7	7838	513	7/1/61
Medford	42.3	2.9	5275	527	7/1/61
Boston	42.3	6.7	5535	444	7/1/57
Santa Maria	34.8	0.4	3065	649	7/1/56
Nashville	36.1	-3.3	3786	513	7/1/55
Charleston	32.8	5.0	2255	554	7/1/63
Bismark	46.8	10.8	8234	484	7/1/54
Lake Charles	30.1	3.2	1694	546	7/1/57

Table II

Coefficients for Solar Heating Fraction Correlation Function

	Direct Gain (DG)	Direct Gain with Night Insulation (DGNI)
R	0.100	0.600
a_1	0.6182	0.8865
a_2	1.0097	1.0028
a_3	1.0710	1.2646
a_4	1.2208	1.6467
	.025	.030

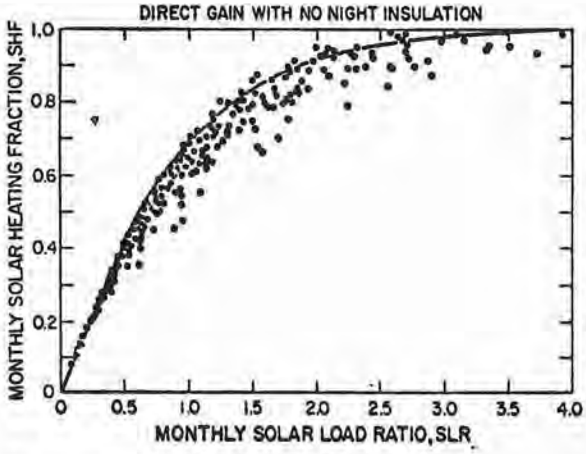

Fig. 1. Monthly Solar Heating Fraction vs Monthly Solar Load Ratio for reference direct gain design with no night insulation.

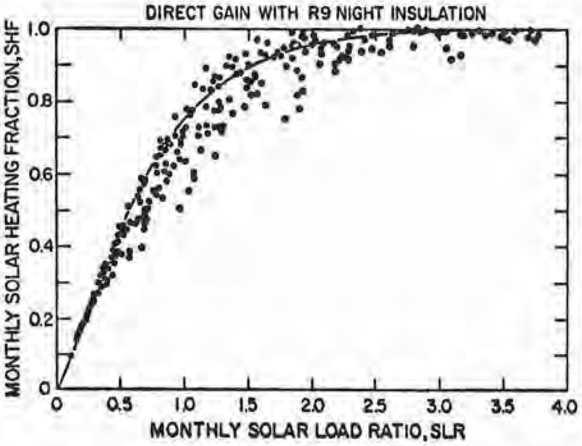

Fig. Monthly solar heating fraction vs monthly solar load ratio for reference direct gain design with R9 night insulation.

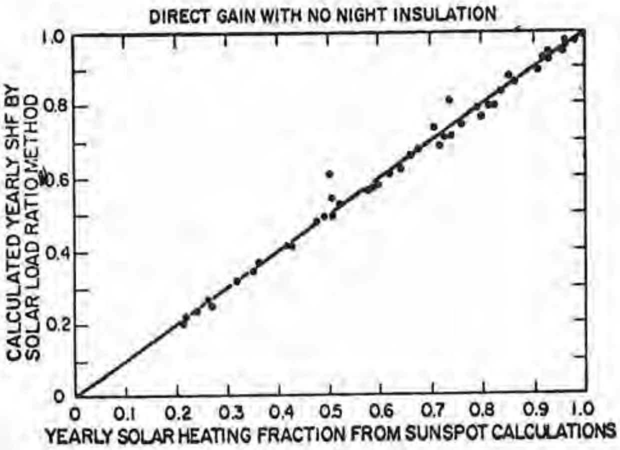

Fig. 3. Comparison of Annual Solar Heating fractions obtained from SUNSPOT calculations and by the solar load ratio method for the Reference Direct gain design with no night insulation.

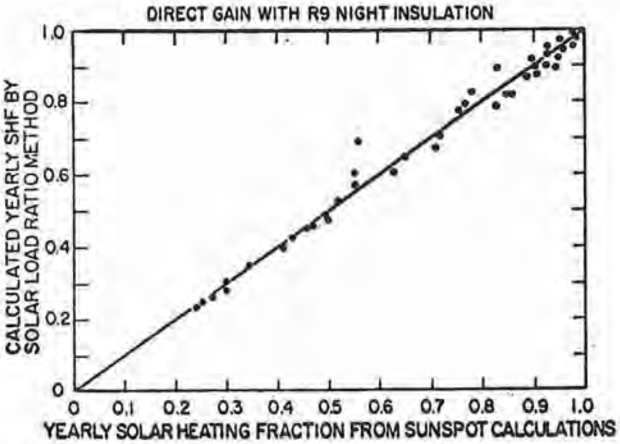

Fig. 4. Comparison of Annual Solar Heating Fraction obtained from SUNSPOT calculations and by the solar load ratio method for the reference direct gain design with R9 night insulation.

4. Estimating the Performance of Direct Gain Buildings

In this section we present a method for estimating the annual performance of direct gain solar buildings of the reference type at arbitrary locations. The only weather data required are total monthly insolation on a horizontal surface and monthly heating degree days. Extention of the results to non-reference designs is discussed in the following section.

Monthly Transmitted Solar Radiation

Step 1: Obtain the total monthly solar radiation on a horizontal surface, Q_H(Btu/ft^2), from weather data at the location of interest. Repeat for all 12 months.

Step 2: Calculate (L -δ) for each month where
L = latitude (deg)
$= 23.3^\circ \cos(30^\circ M - 187^\circ)$, solar declination at mid-month (M = month number, i.e. M = 1 for January)

Step 3: From Fig. 5, determine a value of Q_T/Q_H for each of the monthly values of (L-δ).
Then calculate

$$Q_T = \left(\frac{Q_T}{Q_H}\right) \cdot Q_H \qquad (1)$$

where Q_T is the monthly solar radiation transmitted through each square foot of vertical double glazing facing due south. (The data presented in Fig. 5 is the result of hour by hour simulations in 21 U.S. cities. The Boes correlation$^{(5)}$ was used to determine hourly direct normal and diffuse solar radiation from hourly total horizontal radiation). The analytic form of the function presented in Fig. 5 is:

$$\frac{Q_T}{Q_H} = .226 - .00251\ (L-\delta) + .000308(L-\delta)^2 \qquad (2)$$

The standard deviation is 0.060.

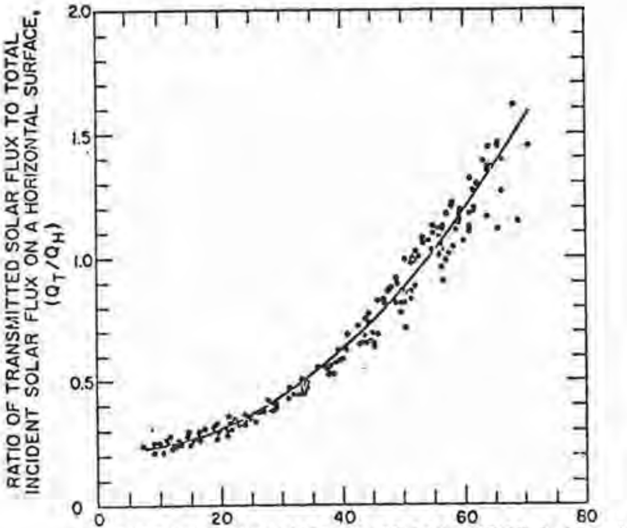

Fig. 5 Ratio of solar flux transmitted through double glazing to solar flux incident on horizontal surface vs latitude minus mid-month solar declination.

Step 4: The relationship represented in Equation (2) is based on an assumed ground reflectance of 0.3. In some cases a designer may wish to use a horizontal specular reflector on the ground in front of the solar aperture. If the reflector is equal in area to the glazing aperture and has a reflectance of 0.8, the monthly transmitted solar radiation is enhanced as illustrated in Fig. 6. The enhanced monthly transmitted solar radiation is given by

$$Q'_T = Q_T \cdot EF$$

where EF is the enhancement factor and Q_T is the transmitted solar radiation obtained in Step 3 above. The correlation in Fig. 6 was obtained from hour by hour simulations in ten American cities. The standard deviation is 0.0197. The analytic form of the function in Fig. 6 is:

$$\begin{aligned} EF = {} & 1.008 - 0.179(L-\delta) + .00192\ (L-\delta)^2 \\ & - 4.03 \times 10^{-5}(L-\delta)^3 \\ & + 2.47 \times 10^{-7}(L-\delta)^4 \end{aligned} \qquad (3)$$

Q'_T is the desired monthly transmitted solar radiation.

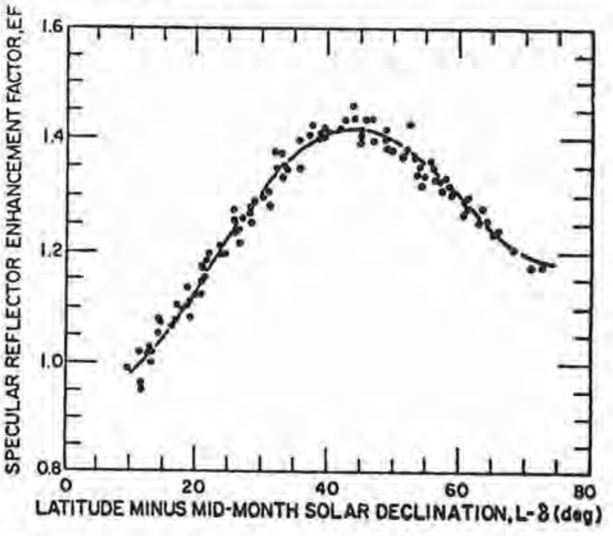

Fig. 6. Specular reflector enhancement factor vs latitude minus mid-month solar declination.

Monthly Thermal Load

Step 1: Calculate the building loss coefficient (BLC) in Btu/degree-day. The BLC is the sum of the building skin conductance (including the south facing glazing) and the infiltration.

Step 2: Determine the monthly heating degree days, DD, from weather data at the site of interest.

Step 3: Determine the monthly thermal load, MTL, by taking the product of the building loss coefficient and the monthly heating degree day values.

$$MTL = BLC \cdot DD$$

Monthly Solar Load Ratio

The monthly solar load ratio is

$$SLR = Q_T/MTL$$

Monthly Solar Heating Fraction

Each previously calculated monthly solar load ratio corresponds to a unique monthly solar heating fraction, SHF, which can be obtained from the solid lines graphed in Figs. 1 and 2 for designs without and with night insulation, respectively.

Monthly Auxiliary Energy Required

The auxiliary heating energy, AUX, required each month is calculated as follows:

$$AUX = (1-SHF) \cdot BLC \cdot DD$$

Annual Auxiliary Energy Required

Simply sum the monthly AUX's to get the annual total.

$$\text{ANNUAL AUX} = \sum_{i=1}^{12} AUX_i$$

Annual Solar Heating Fraction

Sum monthly heating degree days to get ANNUAL DD and evaluate the annual solar fraction as follows:

$$\text{ANNUAL SHF} = 1 - \frac{\text{ANNUAL AUX}}{\text{BLC} \cdot \text{ANNUAL DD}}$$

5. Variations from the Reference Designs

In the near future solar load ratio curves will be generated for several additional direct gain configurations in order to extend the applicability of the solar load ratio method. In the meantime, the performance of non-reference configurations must be approximated by scaling annual solar fractions obtained for the reference design on the basis of detailed sensitivity study results. The variation of annual solar heating fraction as a function of number of glazings, resistance of night insulation, thickness of thermal storage mass, surface area of thermal storage mass, and allowable room air temperature swing has been determined by performing an extensive matrix of SUNSPOT calculations. The results are reported in another paper in these proceedings.(6) From the calculated results presented in Reference 6 it is possible to determine the fractional change in annual solar heating fraction which results from a selected design departure from the reference system. The annual solar heating fraction obtained by the solar load ratio method can be multiplied by the appropriate fractional change in order to determine the performance of the configuration of interest to the designer. Application of this approximation involves the implicit assumption that fractional variations of the annual solar heating fraction due to changes in a single design parameter are insensitive to the values of the remaining design parameters. This implicit assumption is of course not rigorously correct but use of the suggested scaling correction is better than using no correction at all for off-reference configurations.

6. Tabular Solution for Annual Solar Heating Fraction in 84 U.S. and Canadian Cities

A variation of the solar load ratio method described in Section 4 has been used to calculate annual solar heating fractions for the reference direct gain designs in 84 U.S. and Canadian cities and the results are presented in Table III. A designer interested in a building site located in one of the cities included in Table III need not perform the month by month calculations required by the solar load ratio method. Instead, the following much simpler procedure may be followed:

Step 1: Calculate the building loss coefficient (BLC) in Btu/degree-day. This is the sum of the building skin conductance (excluding the south facing glazing) and the infiltration load. Internal heat sources may be subtracted from the building loss coefficient. IMPORTANT: Remember that when using Table III the calculated building loss coefficient should not include the south facing glazing of the solar aperture.

Step 2: Calculate the building load collector ratio (LCR) defined as follows:

$$LCR = \frac{BLC}{\text{Solar Collection Area } (ft_g^2)}$$

Step 3: Locate the city and reference design of interest in Table III. The symbol DG refers to the direct gain design and DGNI is the direct gain design with night insulation. The load collector ratios required to achieve the indicated solar heating fractions, which range from 0.1 to 0.9, appear beneath the solar heating fractions. It will usually be necessary to interpolate in the table in order to determine the correct solar heating fraction.

Step 4: The annual auxiliary energy required by the building is given by:

$$\text{ANNUAL AUX} = (1-SHF) \cdot (\text{ANNUAL DD}) \cdot (BLC)$$

where, again, the building loss coefficient does not include the solar aperture.

TABLE III: Heating-LOAD/COLLECTOR-AREA RATIO FOR GIVEN SOLAR FRACTIONS
Heating-Load in Btu/DD; Area in Sq. Ft.

Page, AZ 6632 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	217.0	110.5	64.6	39.1	22.4	0.0	0.0	0.0	0.0
LCR(DGNI)	339.0	156.1	97.6	68.6	51.3	38.9	28.7	19.9	11.6

Phoenix, AZ 1765 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	724.5	396.7	256.0	177.7	127.6	92.5	66.0	44.7	26.0
LCR(DGNI)	959.8	452.8	289.2	209.3	158.9	123.7	95.8	71.2	48.1

Tucson, AZ (State Univ.) 1800 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	724.7	394.6	253.8	175.9	126.3	91.6	65.6	44.6	26.3
LCR(DGNI)	974.3	451.0	286.0	206.3	157.0	123.1	95.4	71.2	48.4

Little Rock, AR 3219 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	269.4	140.0	84.0	53.1	33.3	19.3	0.0	0.0	0.0
LCR(DGNI)	405.1	188.6	116.2	82.1	61.2	46.7	34.8	24.6	15.0

Davis, CA 2502 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	486.2	249.5	154.6	102.2	69.3	46.4	29.4	15.5	0.0
LCR(DGNI)	664.7	307.2	190.7	133.8	98.3	73.5	55.2	39.3	24.5

El Centro, CA 1458 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	1211.3	662.5	428.2	298.2	215.8	158.7	116.1	82.2	52.5
LCR(DGNI)	1578.6	742.0	464.8	331.4	251.3	197.1	153.3	115.3	79.7

Fresno, CA 2492 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	476.9	242.9	149.4	97.9	65.5	43.3	26.7	13.0	0.0
LCR(DGNI)	642.3	303.1	186.2	129.5	94.6	70.2	52.5	37.1	22.9

Inyokern, CA (China Lake) 3528 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	528.6	280.1	176.0	118.5	82.2	57.0	38.3	23.5	0.0
LCR(DGNI)	727.4	338.6	210.7	147.8	110.6	84.9	64.7	47.2	31.0

Los Angeles, CA 2061 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	892.7	489.1	314.2	216.8	155.1	112.4	80.9	56.0	34.6
LCR(DGNI)	1177.7	563.1	350.1	247.0	186.1	145.6	112.7	84.4	58.1

Riverside, CA 1803 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	895.5	488.1	314.8	218.7	157.6	115.1	83.4	58.0	35.7
LCR(DGNI)	1182.8	551.7	348.2	249.4	190.2	149.0	115.7	86.8	59.5

Boise, ID 5809 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	205.2	98.6	53.5	27.4	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	328.2	151.1	91.9	61.7	43.6	31.0	21.7	13.6	0.0

Argonne Nat. Lab., Lemont, IL 6155 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	124.3	54.2	21.2	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	231.0	103.9	62.6	42.7	30.8	22.3	15.3	9.2	0.0

Indianapolis, IN 5699 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	142.6	64.7	30.2	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	254.7	114.6	68.7	46.8	33.8	24.5	17.0	10.6	0.0

Ames, IA (State Univ.) 6588 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	119.0	51.3	16.7	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	223.7	101.1	61.0	41.6	29.9	21.5	14.7	8.7	0.0

Dodge City, KS 4986 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	245.0	127.7	76.8	48.4	30.0	16.5	0.0	0.0	0.0
LCR(DGNI)	368.1	174.0	109.1	77.0	57.8	44.3	32.9	23.2	14.1

Manhattan, KS 5182 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	177.6	87.4	48.2	25.8	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	290.9	134.7	82.8	57.5	42.4	31.7	22.8	15.3	8.2

Lexington, KY 4683 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	150.7	70.8	35.7	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	260.8	119.4	72.4	49.7	36.2	26.6	18.8	12.1	0.0

Lake Charles, LA 1459 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	601.4	325.1	207.7	142.9	101.6	72.8	51.1	33.7	18.3
LCR(DGNI)	817.4	377.3	239.2	172.9	131.5	102.3	79.0	58.5	39.2

Shreveport, LA 2184 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	405.6	218.0	136.9	92.0	63.6	43.8	28.9	16.7	0.0
LCR(DGNI)	573.3	266.3	167.4	120.3	91.2	71.2	54.4	39.8	26.2

Caribou, ME 9767 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	76.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	175.4	78.1	46.9	31.1	21.2	14.2	8.3	0.0	0.0

Santa Maria, CA 2967 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	660.7	372.7	243.7	170.2	122.4	88.7	63.2	42.7	24.7
LCR(DGNI)	853.2	426.6	278.5	200.4	152.7	119.8	92.5	68.9	46.6

Boulder, CO 5509 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	211.8	109.4	64.8	39.9	23.5	0.0	0.0	0.0	0.0
LCR(DGNI)	327.2	152.8	96.8	69.0	52.0	39.8	29.5	20.7	12.3

Granby, CO 10802 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	90.2	39.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	169.6	84.6	54.6	38.8	28.5	20.8	14.3	8.6	0.0

Grand Junction, CO 5641 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	222.1	114.0	67.3	41.0	23.8	0.0	0.0	0.0	0.0
LCR(DGNI)	341.4	160.6	100.6	70.7	52.6	39.7	29.2	20.2	11.8

Washington, DC, Silver Hill, MD 4224 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	225.5	114.6	66.8	40.2.	22.9	0.0	0.0	0.0	0.0
LCR(DNGI)	351.5	162.3	100.4	70.1	51.8	39.1	28.7	19.8	11.5

Apalachicola, FL 1308 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	818.2	446.4	287.3	199.4	143.5	104.5	75.3	52.0	31.4
LCR(DGNI)	1093.5	505.9	321.2	229.9	175.0	137.4	106.5	79.7	54.5

Gainsville, FL 1239 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	857.7	466.8	301.1	209.8	151.6	111.0	80.5	56.0	34.3
LCR(DGNI)	1146.3	524.3	334.5	240.5	183.9	144.6	112.5	84.4	57.8

Tallahassee, FL (State Univ.) 1485 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	701.7	382.9	245.1	169.0	121.0	87.6	62.6	42.5	25.0
LCR(DGNI)	952.4	439.3	276.4	198.7	151.1	118.8	92.0	68.7	46.8

Tampa, FL 683 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	1403.0	802.6	533.8	380.6	281.0	210.4	156.9	113.6	75.1
LCR(DGNI)	1742.7	871.4	570.1	415.6	321.8	255.7	200.7	152.7	107.1

Atlanta, GA 2961 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	342.3	179.5	110.0	71.8	47.7	30.8	18.1	0.0	0.0
LCR(DGNI)	500.5	230.0	142.3	100.2	75.0	57.7	43.4	31.2	19.8

Portland, ME 7511 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	132.2	60.0	27.4	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	238.5	108.0	66.1	45.4	32.9	24.0	16.7	10.3	0.0

Boston, MA 5634 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	141.4	65.2	32.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	250.2	113.2	69.0	47.8	34.8	25.6	18.0	11.4	0.0

East Lansing, MI 6909 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	111.0	44.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	218.5	96.8	57.6	38.8	27.6	19.5	13.0	7.2	0.0

Sault Ste. Marie, MI 9048 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	90.0	25.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	194.6	85.9	50.8	33.4	22.6	15.1	8.9	0.0	0.0

Saint Cloud, MN 8879 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	93.6	31.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	198.1	87.5	52.2	34.7	24.0	16.4	10.3	0.0	0.0

Columbia, MO 5046 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	188.9	92.5	51.1	27.7	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	309.0	141.2	86.0	59.4	43.5	32.4	23.3	15.6	8.3

Glasgow, MT 8996 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	179.0	87.1	47.0	23.3	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	295.0	136.5	83.6	57.2	41.2	29.9	21.1	13.6	0.0

Great Falls, MT 7750 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	146.2	67.5	32.1	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	255.7	117.6	71.9	48.6	34.3	24.3	16.5	9.7	0.0

Lincoln, NB 5864 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	189.9	93.0	51.4	28.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	310.6	141.8	86.3	59.4	43.7	32.5	23.5	15.8	8.5

Ely, NV 7733 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	191.1	97.6	56.9	33.9	18.1	0.0	0.0	0.0	0.0
LCR(DGNI)	299.6	141.4	89.6	63.6	47.8	36.3	26.7	18.4	10.6

Las Vegas, NV 2709 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	513.9	278.1	175.8	119.1	83.0	58.1	39.5	24.6	0.0
LCR(DGNI)	708.4	333.4	208.4	148.4	111.7	86.2	66.0	48.4	31.9

Reno, NV 6332 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	207.8	105.7	61.1	35.9	18.9	0.0	0.0	0.0	0.0
LCR(DGNI)	325.2	152.4	95.4	66.8	49.1	36.5	26.6	18.0	9.8

Seabrook, NJ 4812 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	170.2	82.4	44.5	22.3	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	283.9	130.1	79.5	55.2	40.4	30.1	21.5	14.2	0.0

Albuquerque, NM 4348 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	321.9	173.5	108.2	71.6	48.1	31.6	19.0	0.0	0.0
LCR(DGNI)	457.4	220.4	139.8	99.5	75.5	58.4	44.2	31.9	20.4

Ithaca, NY 6914 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	81.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	189.2	80.9	47.0	31.0	21.3	14.3	8.5	0.0	0.0

New York, NY (Central Park) 4871 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	158.6	76.0	39.9	17.9	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	269.4	123.4	75.5	52.4	38.3	28.4	20.2	13.2	0.0

Sayville, NY 4811 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	182.3	90.8	51.0	28.3	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	294.5	137.3	84.9	59.5	43.9	33.0	23.9	16.1	8.8

Schenectady, NY 6650 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	78.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	177.9	79.0	47.1	31.6	22.0	15.1	9.3	0.0	0.0

Greensboro, NC 3805 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	264.0	136.6	81.9	51.7	32.5	18.6	0.0	0.0	0.0
LCR(DGNI)	398.9	184.1	114.4	80.5	60.2	46.0	34.3	24.2	14.8

Hatteras, NC 2612 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	463.4	249.1	156.3	105.1	72.7	50.2	33.5	20.0	0.0
LCR(DGNI)	651.9	301.5	189.9	133.7	100.5	77.9	59.4	43.4	28.4

Newport, RI (Eppley Lab.) 5804 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	157.2	75.6	40.1	18.9	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	267.2	121.9	75.0	52.3	38.7	28.9	20.8	13.8	0.0

Charleston, SC 2033 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	507.2	275.5	174.2	118.2	82.8	58.2	40.0	25.4	0.0
LCR(DGNI)	703.2	329.0	205.1	146.5	111.0	86.7	66.6	49.2	32.9

Rapid City, SD 7345 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	159.8	77.3	40.9	18.7	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	269.5	124.5	76.8	53.0	38.8	28.6	20.3	13.2	0.0

Nashville, TN 3578 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	244.0	122.0	70.6	42.5	24.5	0.0	0.0	0.0	0.0
LCR(DGNI)	384.1	172.4	104.2	72.3	53.2	40.2	29.5	20.4	11.9

Oak Ridge TN 3817 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	221.8	110.9	63.6	37.5	20.4	0.0	0.0	0.0	0.0
LCR(DGNI)	351.8	159.8	97.4	67.5	49.9	37.6	27.5	18.9	10.8

Brownsville, TX 600 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	1308.7	740.8	492.6	350.8	258.3	192.4	142.2	101.4	65.0
LCR(DGNI)	1607.2	803.6	533.0	390.2	299.8	234.6	183.2	137.7	94.7

El Paso TX 2700 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	506.2	278.1	177.4	120.9	84.9	59.7	41.0	25.9	0.0
LCR(DGNI)	688.3	331.4	209.3	149.9	113.7	88.0	67.6	49.8	33.0

Fort Worth, TX 2405 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	424.1	230.6	145.7	98.4	68.2	47.2	31.4	18.5	0.0
LCR(DGNI)	590.3	279.9	177.0	127.1	96.1	74.6	57.1	41.8	27.4

Midland, TX (Sloan Field) 2591 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	449.4	246.2	156.3	105.9	73.8	51.3	34.6	21.1	0.0
LCR(DGNI)	616.0	297.5	187.6	134.4	101.8	79.1	60.6	44.5	29.4

San Antonio, TX 1546 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	644.3	350.8	224.4	154.5	110.2	79.3	56.2	37.6	21.3
LCR(DGNI)	872.9	405.5	255.7	184.4	140.1	109.5	84.7	63.1	42.6

Raleigh, NC 3393 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	290.7	151.7	92.1	59.3	38.4	23.6	11.9	0.0	0.0
LCR(DGNI)	431.8	200.0	124.2	87.4	65.7	50.6	37.9	27.1	17.0

Bismark, ND 8851 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	110.3	43.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	219.2	97.1	57.6	38.1	26.5	18.4	11.8	5.9	0.0

Cleveland, OH 6351 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	94.3	30.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	203.7	87.8	51.3	34.0	23.7	16.4	10.3	0.0	0.0

Columbus, OH (State Univ.) 5211 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	121.7	52.5	17.4	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	228.0	102.8	61.9	42.2	30.0	21.4	14.5	8.4	0.0

Put-In-Bay, OH (Stone Lab.) 5796 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	95.5	28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	207.6	88.8	51.6	34.1	22.8	15.1	8.8	0.0	0.0

Oklahoma City, OK 3725 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	276.2	144.2	87.2	55.7	35.6	21.3	0.0	0.0	0.0
LCR(DGNI)	411.7	191.7	119.4	84.3	63.1	48.4	36.2	25.7	15.9

Astoria, OR 5186 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	236.9	117.3	67.3	38.5	17.8	0.0	0.0	0.0	0.0
LCR(DGNI)	349.7	169.6	105.4	72.1	51.0	36.2	25.0	15.7	0.0

Corvallis, OR (State College) 4726 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	252.5	118.7	66.5	37.5	17.3	0.0	0.0	0.0	0.0
LCR(DGNI)	389.7	172.4	104.6	70.8	50.1	35.8	25.1	16.0	0.0

Medford, OR 5008 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	201.9	94.5	50.6	24.8	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	324.0	146.7	89.6	60.4	42.4	29.8	20.4	12.4	0.0

State College, PA 5934 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	120.5	52.1	17.8	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	225.9	102.2	61.6	41.9	30.1	21.6	14.7	8.7	0.0

Flaming Gorge, UT 6929 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	189.7	96.6	55.6	32.4	16.1	0.0	0.0	0.0	0.0
LCR(DGNI)	299.7	141.3	89.0	62.7	46.7	35.2	25.7	17.6	9.9

Salt Lake City, UT 6052 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	212.4	106.5	60.7	34.9	17.2	0.0	0.0	0.0	0.0
LCR(DGNI)	336.8	155.5	96.0	66.3	48.3	35.6	25.7	17.2	9.2

Burlington, VT 8269 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	64.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	169.1	72.4	42.4	27.9	19.2	12.7	7.1	0.0	0.0

Pullman, WA 5542 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	194.0	89.3	45.8	18.2	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	316.3	143.3	86.3	57.1	39.5	27.4	18.5	10.9	0.0

Richland, WA 5941 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	195.0	87.2	42.9	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	320.5	143.5	85.3	55.3	37.5	25.6	17.0	9.6	0.0

Seattle, WA (Univ. of Wash.) 4424 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	243.7	109.0	57.4	28.1	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	380.2	167.0	98.8	64.9	44.3	30.4	20.4	12.0	0.0

Spokane, WA 6655 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	156.6	67.2	27.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	276.5	123.0	72.6	47.0	31.7	21.3	13.6	6.8	0.0

Madison, WI 7863 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	104.5	40.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	212.2	93.3	55.3	37.1	26.2	18.4	12.0	6.4	0.0

Lander, WY 7870 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	182.8	92.8	53.1	30.2	13.3	0.0	0.0	0.0	0.0
LCR(DGNI)	289.5	137.8	87.0	61.2	45.3	33.9	24.6	16.6	9.1

Laramie, WY (State Univ.) 7381 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	171.9	86.1	48.8	27.4	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	277.7	130.1	81.8	57.9	43.6	32.9	24.1	16.5	9.3

Edmonton, Alberta, Canada 10268 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	79.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	192.9	83.6	46.1	26.8	15.2	6.6	0.0	0.0	0.0

Ottawa, ONT., Canada 8735 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	77.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	184.8	78.9	46.2	30.1	20.4	13.5	7.7	0.0	0.0

Toronto, Canada 6827 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	102.5	39.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	207.7	92.1	55.1	37.0	26.1	18.3	11.9	6.2	0.0

Winnipeg, MAN., Canada 10679 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	56.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	163.5	70.9	40.6	25.0	15.5	8.6	0.0	0.0	0.0

7. Conclusion

The information and techniques presented in this paper, when combined with the results of the sensitivity study reported in Reference 6, are sufficient to provide an estimate of the annual performance of most direct gain designs at any building site in the United States or Canada. Solar load ratio correlations for additional direct gain designs will be developed in the near future in order to minimize the amount of scaling (based on sensitivity calculations) required to estimate building performance.

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THE EFFECT OF DESIGN PARAMETER CHANGES ON THE PERFORMANCE OF THERMAL STORAGE WALL PASSIVE SYSTEMS*

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ABSTRACT

Hour-by-hour computer simulations based on one year of solar radiation and temperature data are used to analyze annual energy savings in thermal storage wall passive designs - both Trombe wall and water wall cases. The calculations are rerun many times changing various parameters one at a time to assess the effect on performance. Parameters analyzed are: night insulation R-value, number of glazings, wall absorptance and emittance, thermal storage capacity, Trombe wall properties and vent area size, additional building mass, and temperature control set points. Calculations are done for eight cities.

INTRODUCTION

In the course of building design, many important decisions must be made regarding selection of design parameters. Often the most important considerations are cost and energy savings although availability of materials, thermal comfort, aesthetics, and expected lifetime are also determinants. The purpose of this paper is to present the results of a large number of simulation analyses which show the effect on annual energy savings resulting from changes in design parameters. The buildings analyzed are all of the thermal storage wall type of passive solar heated structures, that is, Trombe walls and water walls.

A reasonable design procedure is the following. The annual thermal performance is estimated for the particular location based on monthly solar and temperature data using a reference design. The Monthly Solar Load Ratio method has been developed for this purpose and correlation curves, based on a large variety of solar/weather data sets, have been published.(1) Then curves showing the effect of variations in design parameters, compared to the reference design, are used to estimate the performance of the actual building. To do this it is desirable to use curves for a climate similar to the one where the building is to be located.

One must be careful in using annual energy savings as the sole performance determinant. For example, the cost-optimum thickness of a concrete Trombe wall, considering only the tradeoff between initial cost and performance, is usually in the range between 6 and 8 in. Increases in thickness beyond this result in only a small increase in annual energy saved but greatly increase the cost of the wall. However the inside surface temperature of a 6 in. wall will swing 40 to 50°F during the course of a clear winter day. Such a swing may be acceptable in some situations but generally would be unacceptable. Therefore one must consider thermal comfort and its value in making this design selection and would probably opt for a thicker wall.

Both analysts and designers should be skeptical of simplified design correlations which presume to incorporate a variety of design variables into one equation. Effects which are thought to be second order and are ignored often turn out to be major when analyzed with a simulation of the actual physical situation on an hour-by-hour basis.

ANALYSIS PROCEDURE

Thermal network models of thermal storage wall passive solar heated buildings are used to mathematically simulate solar heating performance for several U.S. solar/weather data sets. An hour-by-hour calculation is made over a one year period and total auxiliary heating needed to maintain a 65°F room temperature is calculated. The annual solar heating fraction, F, based on energy saved by solar, is then calculated as follows:

$$F = 1 - \frac{\text{auxiliary heating required}}{\text{heating which would be required without solar}}$$

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The heating which would be required without solar is simply the product of the annual degree-hours below 65°F times the building loss coefficient, exclusive of the solar wall.

In the analysis, the building room temperature is allowed to float between 65°F and 75°F. If it tends above 75°F, energy is removed to maintain 75°F.

The thermal network model used has been validated by comparison of predictions against measured data for unheated test rooms in Los Alamos. The test rooms are quite predictable. This does not prove, of course, that all sensitivities are accurately represented in the model, but most of the mathematical representations used are based on well-proved principles and thus should accurately represent the actual situation.

Reference Case

Reference building design parameters used are the following:

- No shading
- Ground reflectance = 0.3, isotropic
- Vertical, south-facing glass
- Glass spacing = 1/4"
- Double glazing, normal transmittance = 0.747
- Wall absorptance = 1.0
- Thermal storage = 45 Btu/°F-ft^2 of glazing
- Building mass is negligible
- Room temperature range: 65°F to 75°F
- Wall-to-room heat transfer coefficient = 1.0 Btu/ft hr °F
- Trombe wall properties:
  - k = 1.0 Btu/ft hr °F
  - c = 30 Btu/ft^3°F
- Night insulation (when used) is R9; 5:00 p.m. to 8:00 a.m.

The variations in each parameter are made assuming that the other parameters remain constant. The solid point plotted on each curve represents the reference value.

Effect of Night Insulation R-value

The effect of using R9 night insulation shows up in the tables and solar load ratio curves in Reference 1. The effect is pronounced, especially in cold climates. For other than R9 night insulation, the results from several cities can be well correlated by a single curve (Fig. 1).

In the analysis, the night insulation was controlled strictly by time of day, being put in place at 5 p.m. each day and removed at 7 a.m. each morning. A number of calculations done with a "smart" controller showed that improvements possible by control strategy are very small.

Effect of Number of Glazings

Effects of different number of glazings for water walls is shown in Figs. 2-7 for several values of load collector ratio (LCR), defined as follows:

$$\mathrm{LCR} = \frac{\text{building load} \begin{pmatrix}\text{exclusive of}\\ \text{solar wall}\end{pmatrix}\text{, Btu/DD}}{\text{collector wall area, sq. ft.}}$$

The curves for a selective surface on the wall assume solar absorptance = 0.95 and infrared emittance = 0.08. The effect of glass absorptance and spacing is given in the following table:

Number of Glazings	DD	LCR	Increase in F: Clear Glass 2	Increase in F: Clear Glass 4	Increase in F: 3/4" spacing 2	Increase in F: 3/4" spacing 4
Albuquerque	4253	48.0	.03	.06	.03	.04
Los Alamos	7350	16.8	.06	.09	.06	.07
Madison	7840	8.0	.07	.07	.10	.09
Medford	5275	19.0	.04	.06	.05	.06
Boston	5535	18.2	.05	.08	.06	.07
Santa Maria	3065	72.0	.04	.07	.03	.03
Nashville	3805	25.4	.04	.07	.05	.05

These effects are all much reduced if night insulation is used, and performance decreases with added glazings in most cases.

Either multiple glazings, up to four, or a selective surface on the wall, but not both combined, are seen to be attractive alternatives to the use of night insulation. Performance may not be quite as good but cost, and especially complexity, are reduced.

The situation for Trombe walls is similar, but differs some in detail. The improvement due to added glazings is slightly less in Madison, Medford and Boston, but about equal in Albuquerque, Nashville, and Santa Maria.

Effect of Wall Absorptance and Emittance

Fig. 8 is a composite plot showing these effects for Los Alamos for various numbers of glazings and for LCR = 16.8.

Effect of Thermal Storage Heat Capacity

For water walls, performance generally increases with increasing thermal storage heat capacity, whereas with Trombe walls there is generally an optimum thickness. These effects are shown in Figs. 9-11 for Boston, Albuquerque, and Madison. If the Trombe wall is unvented, the optimum is at a lower value, for example at M=30 Btu/°F ft^2 (12" thickness) rather than at M=45 Btu/°F ft^2 (18" thickness) with vents. By far, the most important function of storage is to carry over the day's heat into the night rather than multi-day heat storage. Note, however, that the effect of variations in thermal storage is more important for higher values of F (corresponding to smaller values of LCR) for which multi-day storage becomes more important, and is relatively insensitive at low values of F.

Effect of Trombe Wall Properties

Because of the structure of the diffusion equation, the effect of changes in heat capacity, density, thermal conductivity, and wall thickness can be combined into just two groupings of these properties, as follows:

$M = \rho c L$ and $\rho c k$

where

M = the thermal heat storage capacity, per unit area

L = wall thickness, ft. and

ρ = density, lb/ft^3

c = heat capacity, Btu/lb^oF

k = thermal conductivity, $Btu/ft\ hr\ ^oF$

The reference value of M is 45 and $\rho c k$ is 30. The effect of changing M has been given in the preceding section. The effect of changing $\rho c k$ is shown on Figs. 12-14, for the same cities for different values of M and LCR.

Effect of Vent Area

Thermocircutation enhances the performance of a Trombe wall somewhat, especially if daytime temperatures are low requiring daytime heating. (The same effect could be obtained, however, by direct gain). The optimum vent size depends on the solar heating fraction, as follows:

SHF	Vent Area	Comment
25%	3%	Performance levels off above 3%
50%	1%	Performance levels off above 1/%
75%	1/2%	Performance decreases above 1%

The "vent area" is the area of the lower vents (which is the same as the upper vents) measured as a percentage of the total Trombe wall area.

If vents are to be used, they should have some means to prevent backflow at night, such as passive backdraft dampers or performance will be severely impaired at values of LCR less than 24 unless night insulation is used.

Effect of Additional Building Mass

Additional building mass enhances performance by adding heat storage. The following values of F (in percent) are for a water wall.

The added mass is in square feet of mass surface area, internal to the building thermal insulation, per unit of heating load ($ft^2/[Btu/hr\ ^oF]$). The wall is one foot thick.

City	LCR	Added Building Mass 0	1.0	2.5
Albuquerque	24	76	83	87
	48	50	56	58
	108	26	31	33
Madison	4.8	61	66	71
	8	53	57	60
	32	23	25	27
Los Alamos	7.2	78	84	90
	16.8	56	60	63
	43.2	28	34	35

Effect of Temperature Control Set Points

Raising the upper temperature limit above 75°F has less than a 2% effect on annual solar heating fraction. Reducing the limit has a larger effect, especially at higher values of F, reducing the value by as much as 5% (from 85% to 80% for LCR = 0.73 in Albuquerque) if the allowable swing is reduced to zero.

Lowering the minimum temperature limit below 65°F, of course, has a much larger effect as shown on Figs. 15 and 16.

REFERENCE

1. J. D. Balcomb, and R. D. McFarland, "A Simple Empirical Method for Estimating the Performance of Passive Solar Heating Systems," Proceedings of the 2nd National Passive Solar Conference, Philadelphia, March 1978.

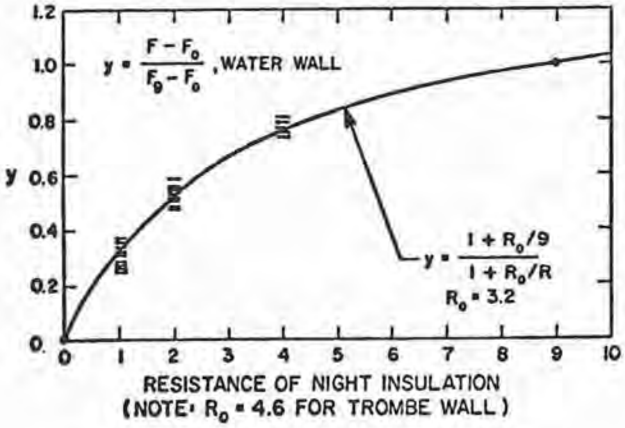

Fig. 1. Effect of Night Insulation Resistance

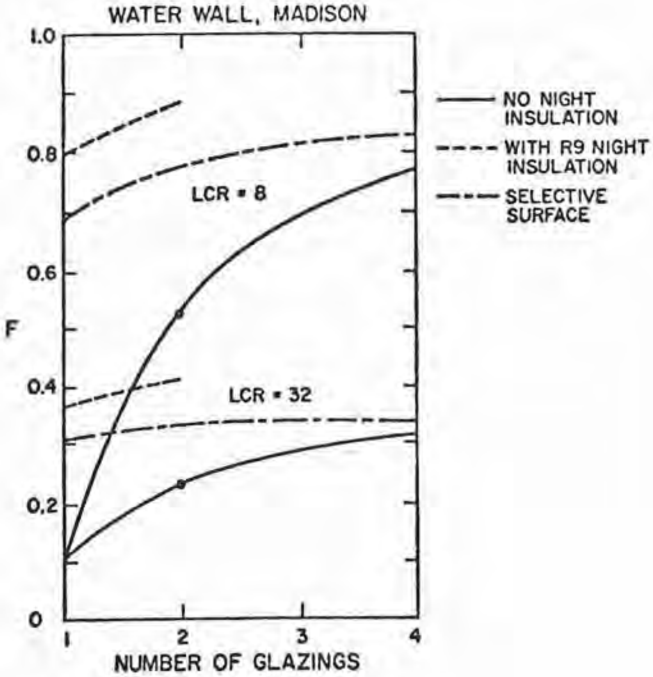

Fig. 3. Effect of Glazings Madison

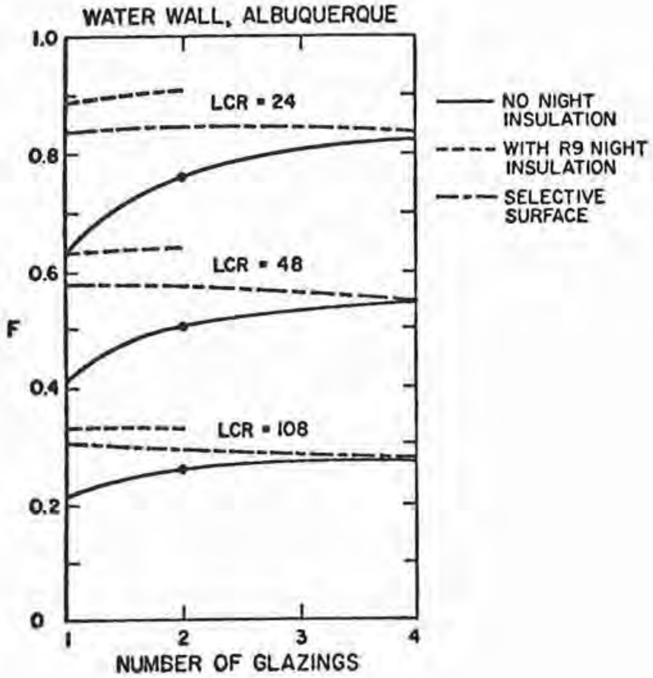

Fig. 2. Effect of Glazings Albuquerque

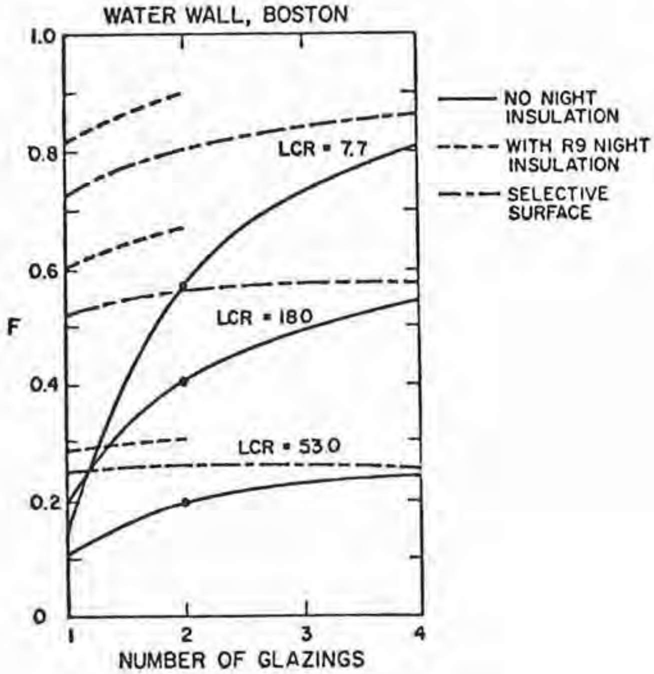

Fig. 4. Effect of Glazings Boston

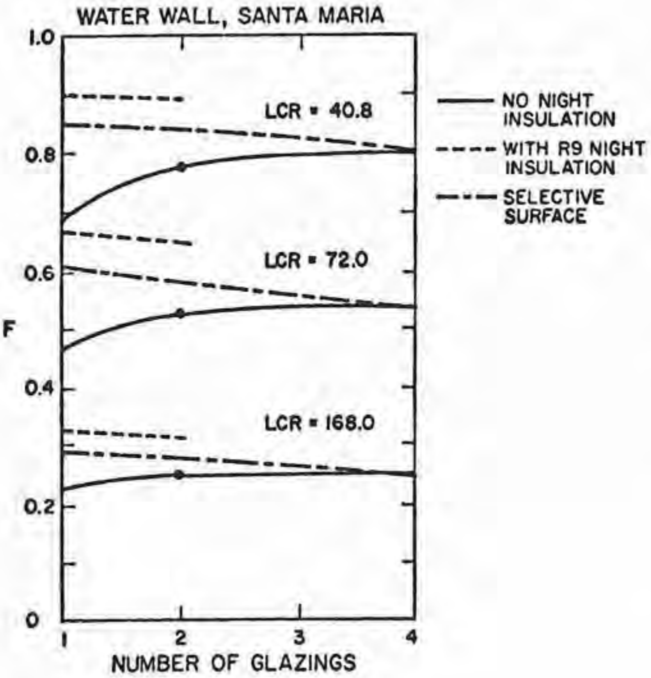

Fig. 5. Effect of Glazings
Santa Maria

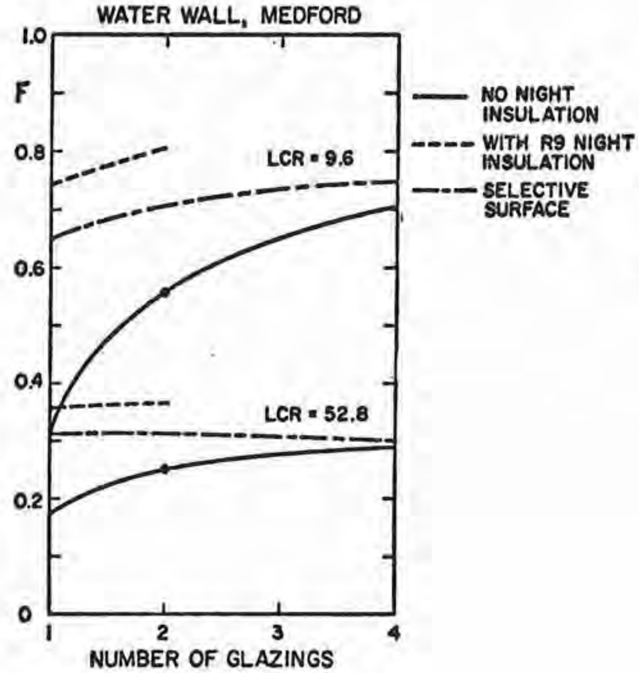

Fig. 7. Effect of Glazings
Medford

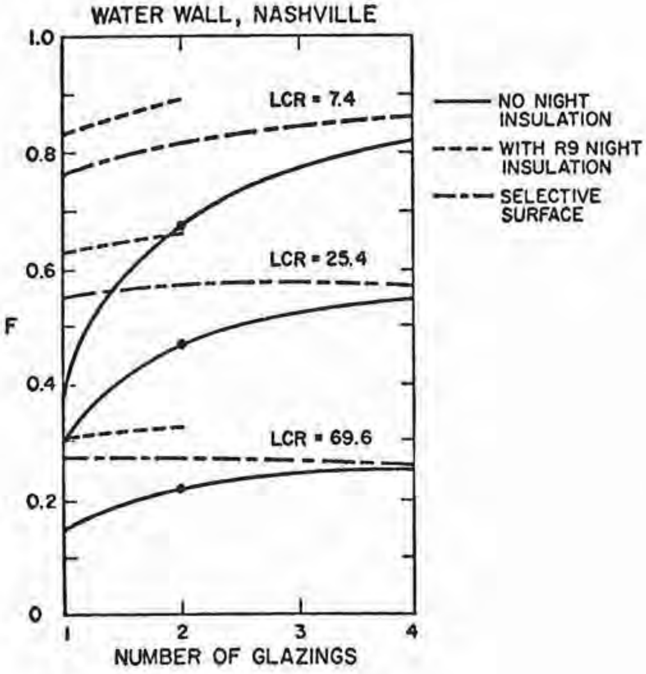

Fig. 6. Effect of Glazings
Nashville

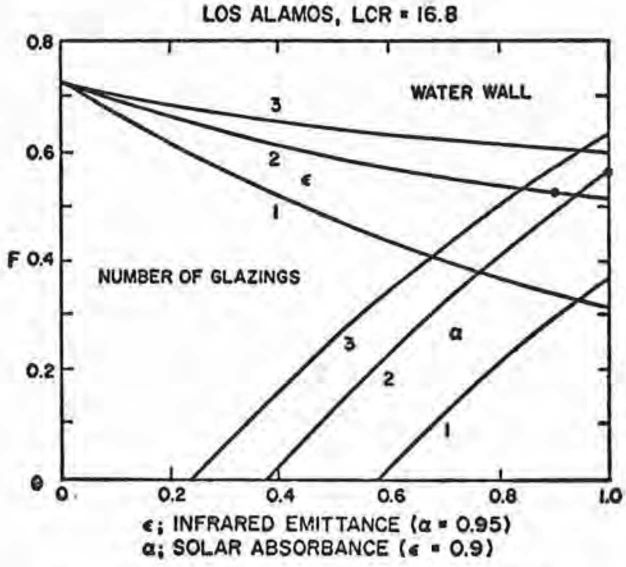

Fig. 8. Wall Infrared Emittance and Solar Absorptance

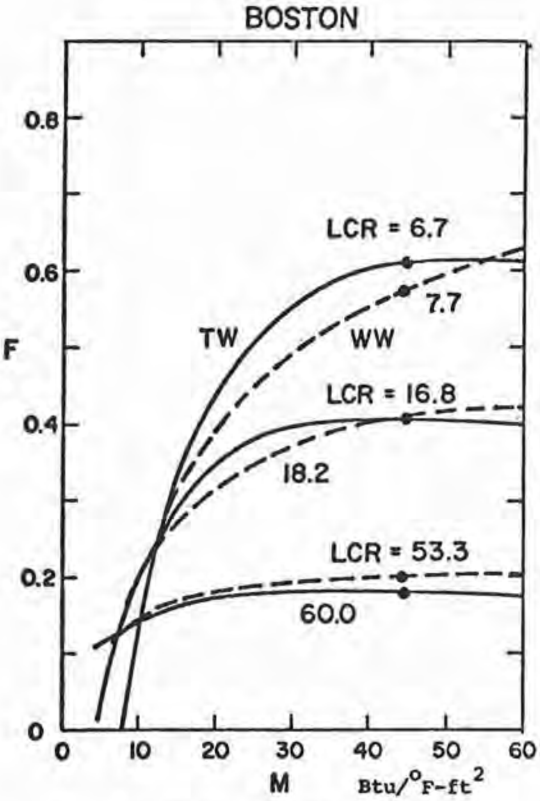

Fig. 9. Effect of Wall Thermal Mass
Boston

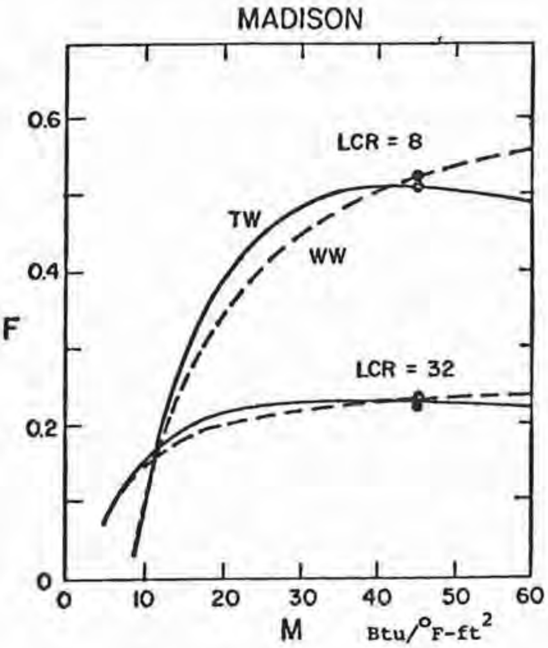

Fig. 11. Effect of Wall Thermal Mass
Madison

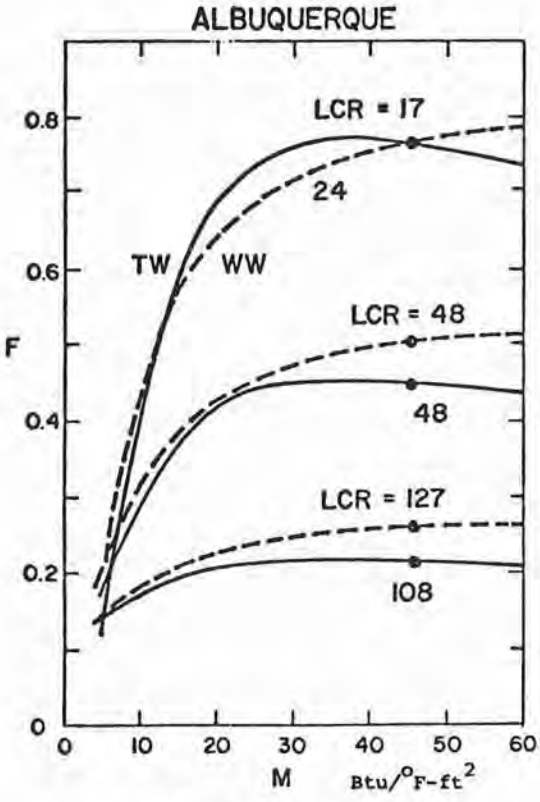

Fig. 10. Effect of Wall Thermal Mass
Albuquerque

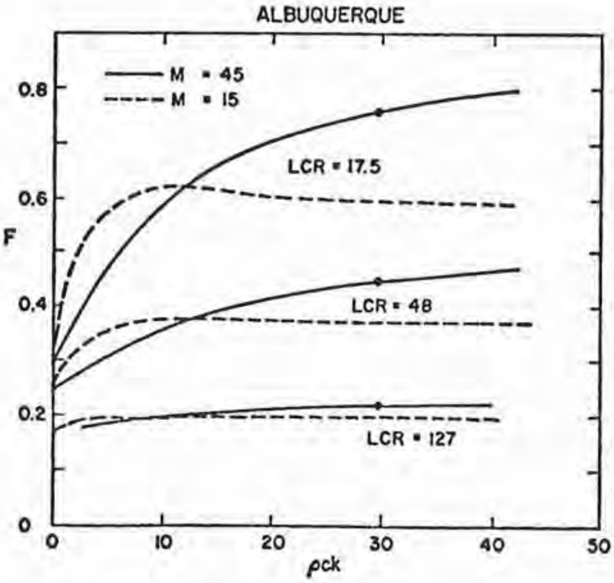

Fig. 12. Effect of Wall Properties
Albuquerque

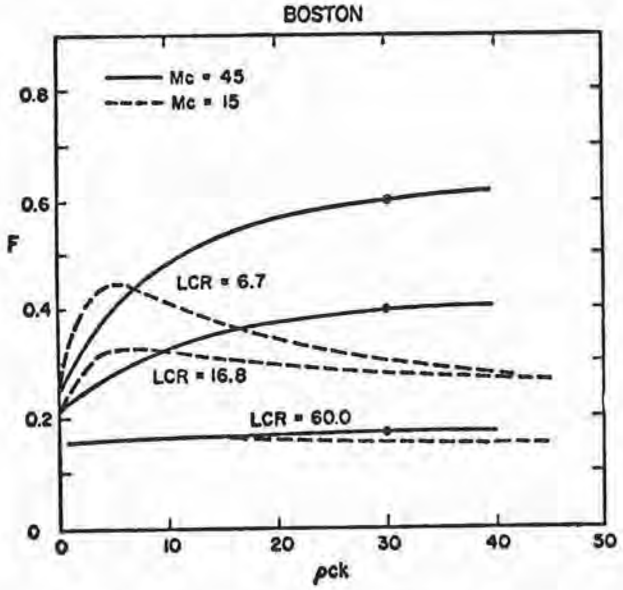

Fig. 13. Effect of Wall Properties Boston

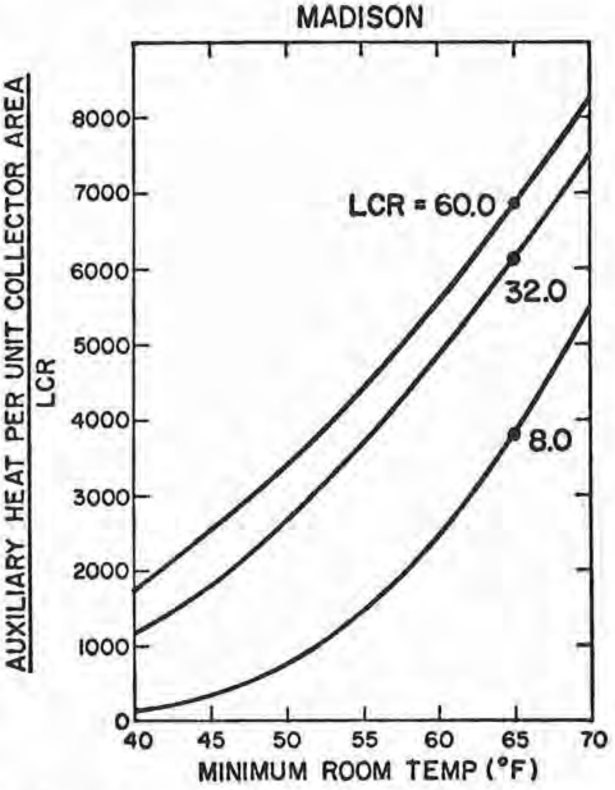

Fig. 15. Auxiliary Heat as a Function of Minimum Room Temperature - Madison

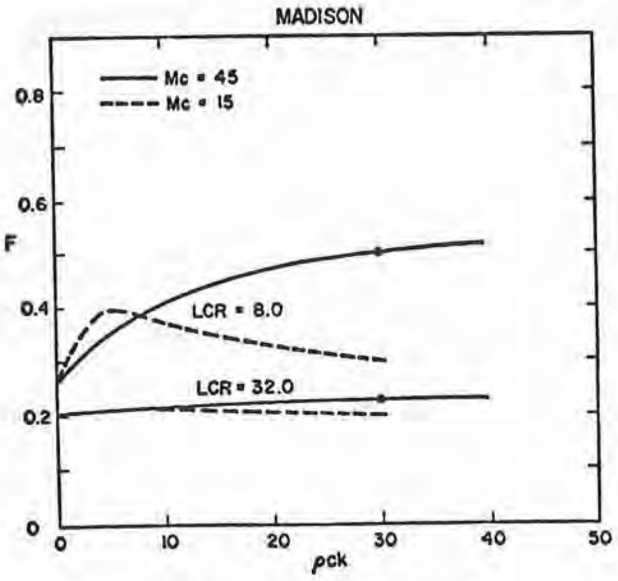

Fig. 14. Effect of Wall Properties Madison

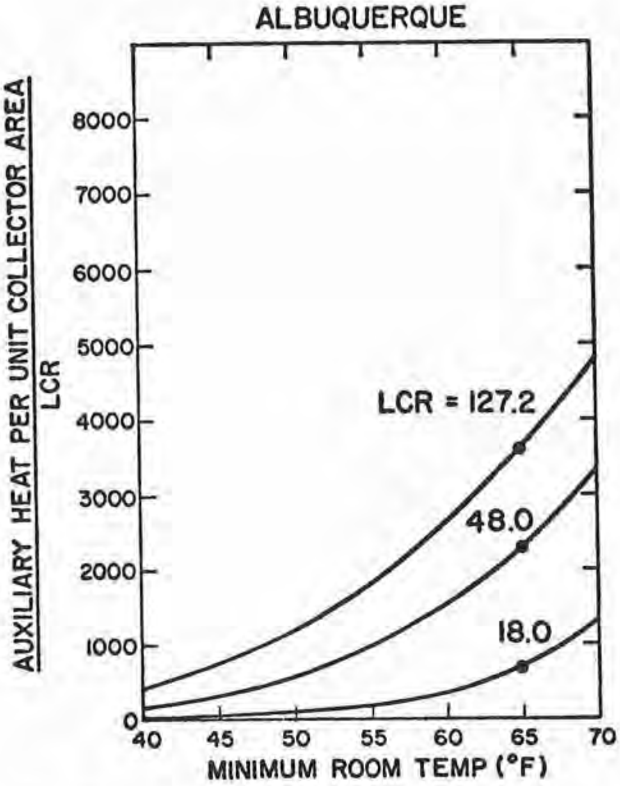

Fig. 16. Auxiliary Heat as a Function of Minimum Room Temperature - Albuquerque

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TITLE: A SIMPLE EMPIRICAL METHOD FOR ESTIMATING THE PERFORMANCE OF A PASSIVE SOLAR HEATED BUILDING OF THE THERMAL STORAGE WALL TYPE

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A SIMPLE EMPIRICAL METHOD FOR ESTIMATING THE PERFORMANCE OF A PASSIVE SOLAR HEATED BUILDING OF THE THERMAL STORAGE WALL TYPE*

by

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ABSTRACT

Two methods are presented for estimating the annual solar heating performance of a building utilizing a passive thermal storage wall of the Trombe wall or water wall type with or without night insulation and with or without a reflector. The method is accurate to ± 3% as compared with hour-by-hour computer simulations.

INTRODUCTION

A simple procedure has been devised for predicting the performance of solar heated structures. It has been determined that reasonable estimates (± 3%) can be made based on monthly values of solar radiation, heating degree days, and the thermal loss and solar gain characteristics of the building. The method was originally developed for studying active systems[1] but proves to be even more accurate for the analysis of passive systems. The correlations are based on a very comprehensive set of calculations which have been made using the hour-by-hour computer simulation analysis techniques developed at Los Alamos for passive systems. Several hundred year-long calculations were made for 29 different cities and for 6 different building loads in each city. The simplified method relies on the use of an appropriate correlating parameter (the Solar Load Ratio) and an empirical fit to this large ensemble of results.

The method is presented in two options. Method A, which is the simplest to use, is described first. Temperature and solar radiation are compacted into a single coefficient called the Load Collector Ratio given for 84 cities. These tabulated values have been derived from the more general Method B, which is the Monthly Solar Load Ratio technique.

The designer may wish to use Method B for any of the following reasons.

1. The location of interest is not in Table 1.
2. The building load is more complex than a simple conductance. For example, accounting for internal heat generation in the building would require using Method B.
3. The user wishes to obtain an estimate of month-by-month distribution of heating load and solar heating contribution.

Both methods are quite constraining. They only apply to the specific systems which were studied: a Trombe wall and a water wall with and without night insulation. An extension of the technique to apply to cases utilizing a horizontal reflector, located in front of the collector wall, is presented in the last section.

Although the data sets which were used to generate the correlations are from the United States, Southern Canada, and three other cities, it is believed that the method can be used for most climates throughout the world. In order to obtain the best estimates possible, however, it is desirable to use the best technique available for calculating the solar radiation transmitted through the glazing. For latitudes outside the

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*Work performed under the auspices of the U. S. Department of Energy, R&D Branch for Heating and Cooling, Assistant Secretary for Conservation and Solar Energy Projects.

U. S. range, it is recommended that the correlations developed for calculating the ratio of vertical radiation transmitted to horizontal not be used. The monthly solar load ratio curves, however, should be usable at any location.

The definition of load is confusing and the user should be alert to handle this correctly. The auxiliary energy required is unambiguous and is accurately estimated by both methods.

METHOD A

This method can be used to estimate the performance of passive solar buildings with a south-facing, vertical double glazed Trombe wall or water wall with or without night insulation. In order to obtain an estimate of the solar heating fraction and auxiliary energy required for any location listed in Table 1, perform the following steps.

Step 1

Estimate the Building Loss Coefficient (BLC) in BTU/degree-day. This is the sum of the building skin conductance plus infiltration. It is the extra energy required (BTU) per day for each additional 1°F increase in temperature difference between the building interior and outside. It can be calculated from the sum of the UxA values for the exterior areas of the building plus infiltration. IMPORTANT--in calculating the Building Loss Coefficient, the passive thermal storage wall should not be included in the load.

Step 2

Calculate the building Load Collector Ratio (LCR) defined as follows:

$$\text{Load Collector Ratio} = \frac{\text{Building Loss Coefficient (BTU/DD)}}{\text{Solar Collection Area (ft}^2\text{)}}$$

In calculating the Load Collector Ratio the solar collection area used should be the net glazed area (the actual solar collection aperture) and not the gross area of the solar wall.

Step 3

Go to Table 1 and locate the city of interest and the wall type of interest. If the Load Collector Ratio determined in Step 2 corresponds exactly to one of the values listed in the table, then this is the desired answer. If not, one needs to interpolate in the table. The meaning of a Solar Heating Fraction is ambiguous when applied to a passive solar building. What is the building being compared with? As used herein, the SHF is the fraction of the degree-day load (the product of the degree-days times the Building Loss Coefficient) which is supplied by the solar wall. The wall is not credited with the heat used to supply its own steady-state load since a "normal" south wall would presumably have a much lower loss coefficient and would inevitably benefit from solar gains, even if they are unintentional.

The auxiliary used is a less ambiguous peg point, leaving the basis of comparison up to the user.

Step 4

The annual auxiliary energy required to maintain the building at a minimum temperature of 65°F can be estimated from the following equation:

$$\text{Auxiliary Energy BTU/yr} = (1-\text{SHF})\begin{pmatrix}\text{Annual}\\ \text{Heating}\\ \text{Degree-}\\ \text{Days}\end{pmatrix}\begin{pmatrix}\text{Building Loss}\\ \text{Coefficient,}\\ \text{BTU/Degree-}\\ \text{Day}\end{pmatrix}$$

Example

A 72' x 24' building in Dodge City, Kansas is to be constructed with a 309 sq ft water wall on the south side. The water wall will contain 45 lbs of water per sq ft of south glazing for a total of 13,500 lbs of water or 1618 gallons. The wall is double glazed with normal sealed glass units which have a net transmittance of 0.74 for sunlight striking the glass perpendicularly. Other than the thermal storage wall, the building is of light frame construction with little additional mass. It is desired to estimate the annual solar heating contribution.

(Step 1) The Building Loss Coefficient is estimated as follows:

Skin Conduction:

Surface Type	Area ft^2	U-Value BTU/ft^2°F hr	UxA BTU/°F hr
Water Wall	309	(not included in BLC)	
Opaque Walls	1107	0.07	77.5
Windows (E,W,N)	120	0.55	66.0
Roof	1728	0.05	86.4
Floor	1728	0.05	86.4

Building Skin Conductance = 316.3

Infiltration:

$(12320\ ft^3)(1/2\ ACH)(0.018)$ = 110.9

Total: Building Loss Coefficient = 427.2 BTU/hr°F

= 10250 BTU/DD

The building is tightly sealed and equipped with an air-lock entry and thus the infiltration can probably be held to the minimum recommended level of 1/2 air change per hour.

(Step 2) The building south wall is glazed with 18 standard patio door size sealed double glass units each with a net effective exposed area of 75 x 33 in. for a total of 309 sq ft of collection area. Thus the Load Collector Ratio is 10250/309 = 33.2 BTU/degree-day-sq ft.

(Step 3) In the table for Dodge City, Kansas we find the following entries for the case of a water wall without night insulation:

SHF	0.30	0.40	0.50	0.60
LCR	61	43	31	23

Our Load Collector Ratio of 33.2 lies between the two values of 0.40 and 0.50 Solar Heating Fraction. By interpolation we obtain:

$$SHF = 0.48$$

The energy saved by the installation of the solar wall is estimated as (0.48)(10250)(4986) = 24.5 MBTU/yr. The energy actually supplied by the solar wall will be greater than this as discussed in the last section of the paper.

(Step 4) The auxiliary energy can be estimated as:

$$\begin{matrix}\text{Auxiliary}\\ \text{Energy}\end{matrix} = (1-0.48)(10250)\ (4986) = 26.6\ \text{MBTU/yr.}$$

METHOD B

The values listed in Table 1 for use in Method A were derived using the Monthly Solar Load Ratio Method. This method provides an empirical means of estimating the monthly solar auxiliary energy requirements based on the Monthly Solar Load Ratio (SLR). The Monthly Solar Load Ratio is a dimensionless correlation parameter defined as follows:

$$SLR \equiv \frac{\begin{matrix}\text{monthly solar energy absorbed on}\\ \text{the thermal storage wall surface}\end{matrix}}{\begin{matrix}\text{monthly building load (including}\\ \text{the wall steady-state losses in}\\ \text{the absence of solar gains)}\end{matrix}}$$

The numerator is equal to the product of the total solar collection wall area times the monthly solar energy transmitted through one square foot of south glazing times the wall absorptance. The denominator is equal to the building loss coefficient (including the steady state conduction through the south solar collection wall) times the monthly heating degree days.

The SLR can be expressed as follows:

$$SLR = \frac{\begin{pmatrix}\text{Collector}\\ \text{Wall Area}\end{pmatrix} (\text{Absorptance}) \begin{pmatrix}\text{Monthly Solar Energy}\\ \text{Transmitted through}\\ \text{the Glazing}\end{pmatrix}}{\begin{pmatrix}\text{Modified Building}\\ \text{Loss Coefficient}\end{pmatrix} (\text{Monthly Degree Days})}$$

$$SLR = \frac{\begin{pmatrix}\text{Monthly Solar Energy}\\ \text{Transmitted}\end{pmatrix} \Big/ (\text{Monthly Degree Days})}{\begin{pmatrix}\text{Modified Building}\\ \text{Loss Coefficient}\end{pmatrix} \Big/ \begin{pmatrix}\text{Wall area}\\ \text{x Absorptance}\end{pmatrix}}$$

$$SLR = \frac{\text{Solar Capability Index}}{\text{Modified Load Collector Ratio}}$$

The SLR is given by the ratio of two different terms, the Solar Capability Index, which depends only on the weather for the locality and a Modified Load Collector Ratio (MLCR) which depends only on the building construction.

Step 1

Determine the Building Loss Coefficient in the same manner as in Step 1 of Method A. Compute a Modified Building Loss Coefficient by adding the term 24 x (Solar Wall Area)x U_W where U_W is taken from the following table:

BTU/hr°F ft^2	Plain Double Glazed	With R9 Insulation added from 5:00 p.m. to 8:00 a.m.
Water Wall	0.33	0.18
18" Trombe Wall	0.22	0.12

The value of U_W is the steady-state conduction coefficient of the combined wall, glazing, and insulation, averaged over the day.

Step 2

Determine the SLR for each month of the year. Solar radiation values generally available in tables are measured on a horizontal surface, whereas the values required in order to determine the SLR are the actual solar radiation transmitted through the vertical south facing surface. The values of solar radiation in the ASHRAE tables for clear-day conditions are not applicable. The use of a cloudiness factor, which is an approach sometimes used, is not accurate enough. Thus it is necessary to provide a simple method of making a transformation.

Hour-by-hour calculations were made for one month periods for the 29 locations for each month of the year. The hourly transformation from the horizontal to the vertical was made using the correlation technique developed by Boes,[2] for separating diffuse from direct beam radiation. A ground reflectance of 0.3 was assumed. The fraction of the incident energy which is actually transmitted through the glazing was then calculated using the Fresnel relationship for the hourly angles of incidence and the absorption coefficient of ordinary double strength glass. The hourly values were summed in order to determine monthly integrals. It was found that the results could be correlated quite well using the following parameter

L-D = Latitude - Solar Declination at Mid-Month

The solar declination at mid-month should be estimated from the following equation:

$$D = 23.3° \cos(30°M - 187°)$$

M = month (i.e., June = 6)

This plotting parameter, L - D, is equal to the noon-time angle between the vertical and the sun. A plot of the results is shown in Fig. 1. The solid line plotted on Fig. 1 is a least-squares fit through the data given by the following equation:

$$\frac{\text{Monthly Solar Energy Transmitted through South Double Glazing}}{\text{Monthly Solar Energy Incident on Horizontal Surface}} = 0.2260 - .002512(L-D) + .0003075(L-D)^2$$

The errors which would be incurred by using the least-squares fit rather than the actual values of solar radiation transmitted do not significantly increase the error in Monthly Solar Heating Fraction indicating that the two errors are uncorrelated.

If the building does not face due south, then this equation cannot be used as is. It will be necessary to make another correction for building orientation. LASL has not yet devised a separate series of correlations for different tilts and orientations. It is felt, however, that a correction factor based on the ASHRAE clear-day tables would probably be a reasonable estimate. Those tables provide values for the clear day conditions for southwest and southeast orientations as well as due south, as a function of latitude. For the time being, a straight proportional correction factor based on these tables is recommended. Note that a separate correction factor will be required for each month.

Step 3

Determine the Monthly Solar Heating Fraction for each month of the year based on the values of SLR computed in Step 2. Plots of the function for the four different cases of Trombe wall and water wall with and without night insulation are given in Fig. 2.

Step 4

Compute the auxiliary energy required each month from the following equation:

$$\text{Auxiliary Energy} = (1\text{-SHF})(\text{Degree Days})(\text{Modified Building Loss Coefficient})$$

Step 5

Compute the sum of the monthly auxiliary energy requirements. This is the annual auxiliary energy. The annual solar heating fraction can then be determined from the following equation:

$$\text{Annual SHF} = 1 - \frac{\text{Annual Auxiliary Energy}}{\begin{pmatrix}\text{Annual}\\ \text{Degree}\\ \text{Days}\end{pmatrix} \times \begin{pmatrix}\text{Building Loss}\\ \text{Coefficient}\\ \text{(Unmodified)}\end{pmatrix}}$$

Example

The same building in Dodge City, Kansas will now be used as an example for Method B. The Building Loss Coefficient has already been determined as 10250 BTU/degree-day. The latitude of Dodge City is 38°. Following through these steps, one by one, results in the table on the next page.

The small error observed between the auxiliary energy calculated by Method A and that by Method B in this example is attributed to the slight error in interpolating in the table and the round-off of the numbers listed in Table I.

If the user desires to calculate values of the collector load ratio similar to those listed in Table I, but for a different locality or a different set of values of solar radiation or heating degree-days, he can easily do so by carrying through the five steps of Method B for various values of the Load Collector Ratio. In this manner as many points as are desired can be filled in to the table for various values of Solar Heating Fraction. It will be necessary to iterate in order to determine an exact value of Solar Heating Fraction.

The values of heating degree-days and solar radiation incident on a horizontal surface which were used to compute Table I are the standard values

Dodge City	DD	Modified Monthly Load, MBTU/Mo.	Horizontal Solar Radiation BTU/Mo. ft^2	L-D	Solar Radiation Absorbed MBTU/Mo.	SLR	SHF	Auxiliary MBTU/Mo.
Oct.	251	3.19	41180	47.1	10.05	3.15	.972	.09
Nov.	666	8.46	28560	56.6	9.43	1.11	.631	3.12
Dec.	939	11.92	25050	61.1	9.45	.79	.474	6.77
Jan.	1051	13.35	27910	59.4	10.02	.75	.450	7.34
Feb.	840	10.67	33270	57.0	9.53	.89	.529	5.03
Mar.	719	9.13	47590	40.8	9.34	1.02	.592	3.73
Apr.	354	4.50	58230	28.9	7.38	1.64	.797	.91
May	124	1.57	65320	19.4	5.91	3.76	.992	.01
Total	4944							27.00

The column labeled Modified Load is calculated with a Modified Building Loss Coefficient of 12700 BTU/DD. The added loss is (309 ft^2)(.33)(24) = 2450 BTU/DD to account for the steady state solar wall loss coefficient. The Solar Heating Fraction is calculated from the (unmodified) Building Loss Coefficient as follows:

$$\text{SHF} = 1 - \frac{27.0 \times 10^6}{(10250)(4944)} = 0.47$$

which have been listed in the literature. Revised values of solar radiation will probably be generated to reflect better knowledge of pyranometer calibrations and other factors. As these numbers become available, more accurate values for Table I can be generated. It should be noted however, that the accuracy of the Solar Load Ratio Method itself does not depend on the accuracy of the solar radiation data used, since there was complete consistency between the values of the hourly solar radiation used and the monthly integrals of solar radiation.

EFFECT OF INTERNAL GENERATION IN THE BUILDING

Heat generated in the building, by people, lights and equipment is effective in reducing the monthly load. This reduces both the auxiliary energy requirements and the monthly solar contribution.

The original basis for defining the degree-day base at 65°F was on the assumption that these internal energy sources would raise the building temperature from 65°F up to the accepted comfort standard of 72°F. This assumption can still be made in using the results from this section, namely, that the actual building temperature would be several degrees greater than the 65°F to 75°F band assumed in the analysis.

However, experience has been that most people now set their thermostat at lower levels. This is especially true of people who live in passive solar homes because the effect of the warm surrounding surfaces of these buildings increases the mean radiant temperature within the space so that one can be comfortable at a reduced air temperature. In any case, a 65°F thermostat setting seems more consistent with actual practice in the winter than the ASHRAE standard value of 72°F.

The hour-by-hour analysis used to determine the Monthly Solar Load Ratio curves did not provide any internal energy in the building to account for that generated by people, lights and equipment. The user of the method can correct for this by subtracting the estimated internal energy generation from the monthly loads prior to computing the monthly Solar Load Ratio. The effect of this would be to increase the Solar Load Ratio, increase the Monthly Solar Heating Fraction, and decrease the auxiliary energy requirements.

VARIATIONS FROM THE ASSUMED REFERENCE SYSTEMS

The monthly solar load ratio curves which have been determined are for very specific reference systems as defined in Table II. If it is desired to estimate the performance of the system which is different than one of these reference systems, then it is necessary to make a correction. The most reliable way of doing this is to refer to results of hour-by-hour calculations which are made for a specific system varying only the parameter of interest. Quite a few such calculations have been made by LASL and have been published.[3,4] These describe the effect of water mass in a water wall, the effect of using or not using the vents in the

Trombe wall, the effect of thickness of a Trombe wall, and the effect of different thermal conductivities of the material.

The recommended procedure is to make a calculation for the reference case and then to adjust that value up or down.

EFFECT OF A REFLECTOR

A tremendous performance advantage can be achieved through the use of a reflector to increase the total amount of solar radiation on the solar collection wall. A combination of a reflector and night insulation was demonstrated by Steve Baer in his Corrales home using water walls. He used a fold-down door hinged at the base with a reflective surface on the inner side. The door was insulated so that when it was raised it would reduce nighttime heat loss. When lowered during the day, the reflector augmentation increased performance.

LASL has calculated the performance increase to be expected from the reflector, and has determined that the estimating procedure can accurately be separated into two steps. The first step is to estimate the increase in solar radiation transmitted through the south facing glazing. The second step is to use this information in Monthly Solar Load Ratio calculation to determine monthly performance.

The reflector geometry which was studied is as follows: The size of the reflector is exactly equal to that of the solar collection wall. It is positioned horizontally in front of the solar collection wall so that the edge of the reflector is against the base of the wall (as if it were folded down from the wall, hinged at the bottom). The end effects were calculated assuming that the width of both the wall and the reflector is equal to five times the height of the wall. The reflectance of the material of the reflector was assumed to be 0.8, equivalent to that of the best commercial reflective materials available. (Reflectance of normal shop-grade aluminum is approximately 0.6.)

The method used to calculate the reflector enhancement achieved was similar to that used to calculate the ratio of vertical energy transmitted to horizontal energy as described in Step 2 of Method B. Hour-by-hour calculations were made for the 12 months of each year for 10 locations. The angular effects were calculated each hour as well as the effect of the modified incidence angle on the collection wall of the reflected beam. The energy transmitted through the glazing was decreased by the amount which would have been reflected from a diffuse foreground with a reflectance of 0.3, which is the assumption which had been made for all of the preceding calculations.

The ratio of the total monthly solar energy transmitted with the reflector to that without the reflector is plotted in Fig. 3. Again it was found that the parameter L - D was an effective correlating parameter for this ratio. A least-squares fit of these data is given by the following equation:

$$\text{Enhancement} = 1.0083 - .01787(L-D) + .001916(L-D)^2 - 4.031 \times 10^{-5}\,(L-D)^3 + 2.466 \times 10^{-7}\,(L-D)^4$$

which is the solid line shown on the figure.

If a reflector is used with a reflectance other than 0.8, the enhanced values of solar radiation can be computed from the above equation by assuming that the difference between unity and the calculated enhancement is proportional to the reflectance.

DERIVATION OF THE CORRELATIONS

The method is based on a brute-force empirical curve fitting approach using appropriate correlating parameters (the solar load ratio and monthly degree-days) based on detailed hour-by-hour computer simulation analyses from a wide variety of climates and building loads. Thus far, the method has been developed only for four types of passive solar heating buildings all of which fall in the category of thermal storage walls.

The method was first applied to active systems.[1] In an active system the load is a separable quantity unconnected to the solar heat supply. However, in most passive systems the thermal load and the solar heat supply are inter-related. It was determined, by trial and error, that if the load were calculated to include the steady-state load associated with the collector wall, then the Solar Load Ratio (SLR) is an effective correlating parameter. Consistent results were only obtained by using this approach.

The basic assumption of the method is that the monthly Solar Heating Fraction can be expressed as a unique function of the SLR, independent of either location or time of year. This is a rather brash assumption considering the variability of the weather in various locations and clearly one cannot expect exact answers from such a broad-brush approach.

In order to test the hypothesis, hour-by-hour computer simulation analyses were run for 29 different cities scattered throughout the U. S., Southern Canada, and three foreign locations. Six different values of the Load/Collector Ratio were chosen for each city so that the total of 174 year-long calculations were made altogether, representing a total of 1390 months during the heating season. A plot of all these results is shown on Fig. 4 for the case of a Trombe wall.

In order to make such a calculation the system had to be completely defined. A reference system was chosen as indicated in Table II.

The data of Fig. 3 show a relatively good correlation between Monthly Solar Heating Fraction and Monthly Solar Load Ratio. The individual plotting symbols shown on Fig. 4 identify the city for which the calculation was made. A list of these cities and their associated plotting parameters are given in Table III.

The reason for the scatter in Fig. 4 is that the assumption made is not quite correct. Two months may have the same Monthly Solar Load Ratio and yet actually have a different load, a different amount of sunshine incident on the wall and furthermore, the distribution of sunny and cloudy days within the two months may be entirely different. However, given these disparities, it is encouraging to note the total range of monthly solar heating fractions is as small as observed.

A least squares fit could have been made through the data of Fig. 4. Such a fit would give a minimum rms error in the predicted Monthly Solar Heating Fraction. However, it was desired to obtain a minimum error in the annual Solar Heating Fraction, not the monthly values. In order to do this, a functional form was chosen for the relationship between Monthly Heating Fraction and Monthly Solar Load Ratio as follows:

$$\mathrm{SHF} = a_1(\mathrm{SLR}) \qquad \mathrm{SLR} < R$$

$$\mathrm{SHF} = a_2 - a_3\, e^{-a_4(\mathrm{SLR})} \qquad \mathrm{SLR} > R$$

such that the values are equal at SLR = R. The values of the parameters in the function were chosen to give a minimum least square error in the annual solar heating fraction for the 174 sample years calculated. The resulting function for a Trombe wall is shown plotted on Fig. 4; the results on Fig. 5.

The values of the least-squares coefficients and the standard deviation of annual SHF are as follows:

Case	R	a_1	a_2	a_3	a_4	σ
WW	0.8	0.5995	1.0149	1.2600	1.0701	.028
WWNI	0.7	0.7642	1.0102	1.4027	1.5461	.026
TW	0.1	0.4520	1.0137	1.0392	0.7047	.024
TWNI	0.5	0.7197	1.0074	1.1195	1.0948	.023

Discussion of Loads

Two coefficients have been used to describe the heat loss characteristics of the building: a Building Loss Coefficient, used in Method A, and a Modified Building Loss Coefficient, used to determine the Solar Load Ratio in Method B. The difference is the steady-state or static loss coefficient of the solar wall in the absence of solar gains, $24 \times A_W \times U_W$. The Modified BLC was introduced only to facilitate the calculation of the Solar Load Ratio, as discussed above.

Monthly heating degree-day values were used in the correlation procedure because they are the only indicators of heating load that are readily available in most localities. The actual annual auxiliary heating values used in calculating the ordinant of Fig. 4 were the sum of the hour-by-hour requirements from the simulation. Thus the auxiliary will be accurately estimated provided the user is consistent in calculating loads in the same way that was used to determine the correlations.

The Modified Monthly Load, which is the product of the monthly degree-days times the Modified Building Loss Coefficient, has no accurate physical meaning. It is simply a convenient intermediate parameter used in the calculation.

It is possible to distinguish between two solar heat contributions from the solar wall: 1) the energy saved, and 2) the energy supplied. The difference is explained in the following paragraphs. In this paper the energy saved is used to define the solar heating fraction even though it gives a lower value.

Since the auxiliary energy is only required during periods when the temperature inside the room is actually at 65°F, the auxiliary energy requirements determined by the simplified method will be a good estimate.

The actual solar energy supplied by the solar collection wall will be greater than that estimated by taking the difference between the annual degree-day load and the auxiliary energy. The extra solar heat is the amount used to maintain the building above 65°F during a significant portion of the year. Since it is the actual auxiliary energy required which is the most important number to be estimated, it was felt that the approach used was best.

In reality, the solar heated building will generally be warmer than the non-solar heated building, assuming that the thermostat is set at 65°F in both cases. The non-solar heated building will frequently rise above that value and occasionally to 75°F, at which time it is assumed that any additional energy is dumped (presumably by opening a window).

REFERENCES:

1. J. D. Balcomb and J. C. Hedstrom, "A Simplified Method for Calculating Required Solar Collector Array Size for Space Heating," Proceedings, 1976 ISES Annual Meeting, Vol. 4, Winnipeg, Canada, Aug. 15-20, 1976. See also: ERDA's Pacific Regional Solar Heating Handbook, Nov. 1976.

2. E. C. Boes, et al., "Distribution of Direct and Total Solar Radiation Availabilities for the USA." Proceedings of the 1976 ISES Annual Meeting, Vol. 1, Winnipeg, Canada, Aug. 15-20, 1976.

3. J. D. Balcomb, et al., "Simulation Analysis of Passive Solar Heated Buildings--Preliminary Results," Solar Energy, Vol. 19, pp 277-282 (1977).

4. J. D. Balcomb, J. C. Hedstrom, and R. D. McFarland, "Passive Solar Heating of Buildings." Printed in SAND-77-1204 and also Solar Architecture, Ann Arbor Science (1977).

TABLE III

WEATHER DATA USED FOR CORRELATIONS

City	Symbol (Figs. 3-4)
Los Alamos, NM	1
El Paso, TX	2
Fort Worth, TX	3
Madison, WI	4
Albuquerque, NM	5
Phoenix, AZ	6
Lake Charles, LA	7
Fresno, CA	8
Medford, OR	9
Bismarck, ND	0
New York, NY	A
Tallahassee, FL	B
Dodge City, KS	C
Nashville, TN	D
Santa Maria, CA	E
Boston, MA	F
Charleston, SC	G
Los Angeles, CA	H
Seattle, WA	I
Lincoln, NE	J
Boulder, CO	K
Vancouver, BC	L
Edmonton, ALB	M
Winnipeg, MAN	N
Ottawa, ONT	P
Frederickton, NB	Q
Hamburg	R
Denmark	S
Tokyo	T

TABLE II

REFERENCE PASSIVE SOLAR SYSTEMS USED FOR CORRELATIONS

Assumptions for both Method A and Method B:

Thermal Storage = 45 BTU/°F ft^2 of glazing
Trombe wall has vents with backdraft dampers
Double Glazing (normal transmittance = 0.747)
Temperature Range in Building: 65°F to 75°F
Building Mass is Negligible
Night Insulation (when used) is R9;
5:00 p.m. to 8:00 a.m.
Wall to room conductance = 1.0 BTU/hr °F ft^2
Trombe wall properties $k = 1.0$ BTU/ft hr °F
$\rho c = 30$ BTU/ft^3 °F

Additional Assumptions for Method A:

Vertical, south-facing glass
Wall absorptance = 1.0
Ground reflectance = 0.3
No Shadings

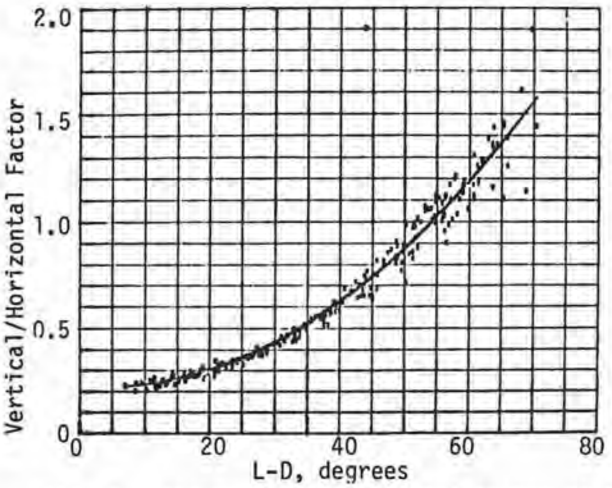


Fig. 1. The vertical/horizontal factor is the ratio of the monthly solar radiation transmitted through vertical south-facing double glazing to the monthly total horizontal solar radiation. L-D is the latitude minus the solar declination at mid-month. Ground reflectance is 0.3 and is diffuse. No shading is used.

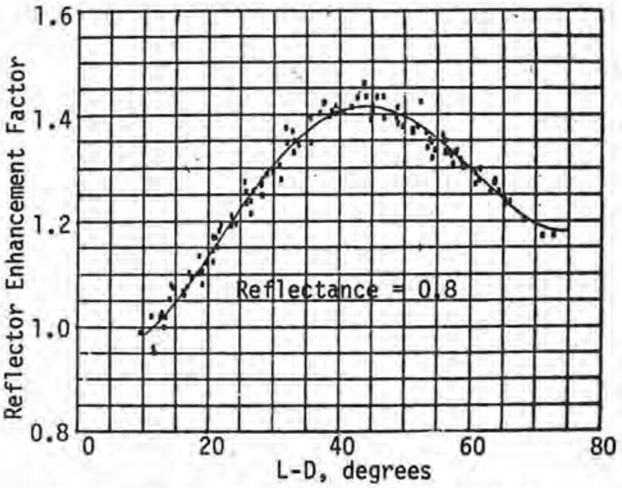


Fig. 3. The reflector enhancement factor is the ratio of the monthly solar radiation transmitted through vertical south facing double glazing with a reflector to that without a reflector. The reflector size is equal to the window size and is horizontal in front of the window. Reflectance is 0.8 and is specular.

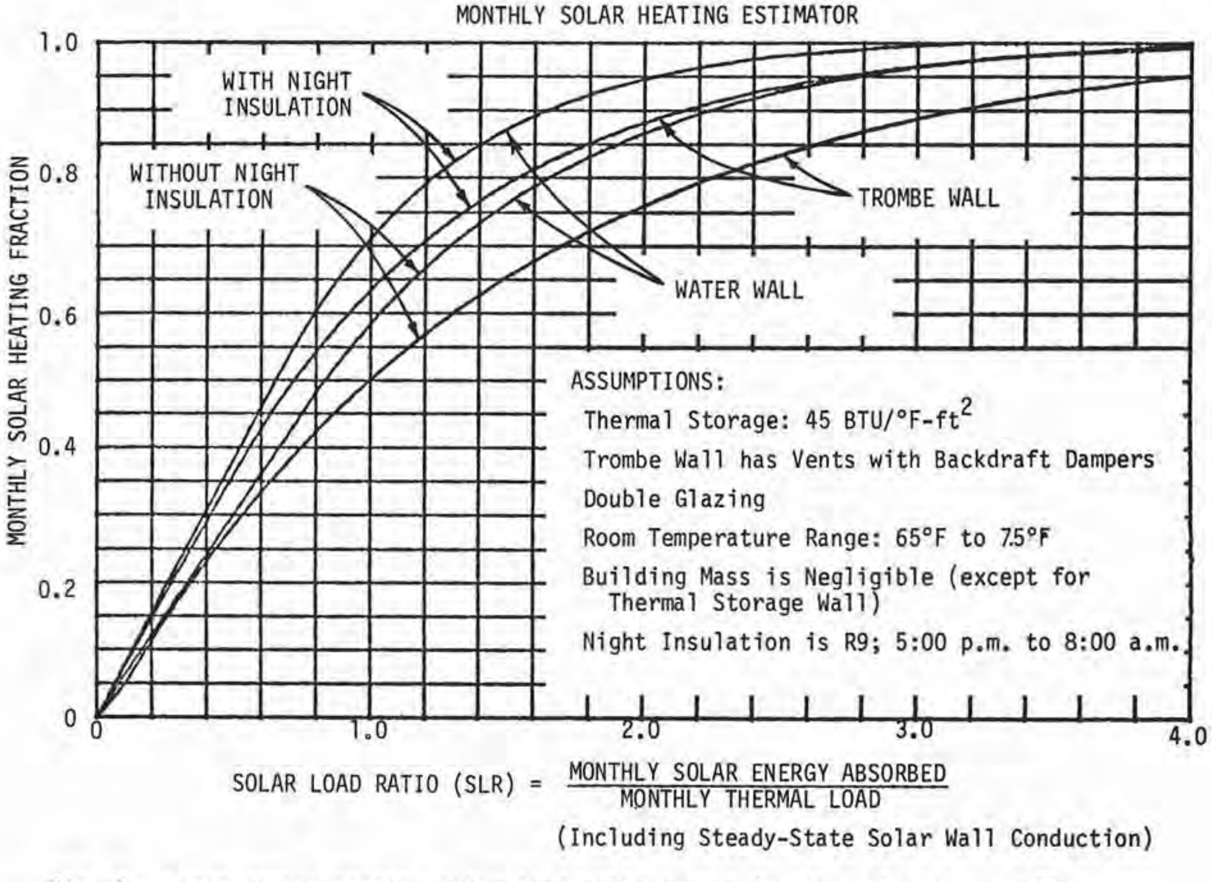


Fig. 2. Least-square monthly solar load ratio curves for thermal storage walls.

Fig. 4

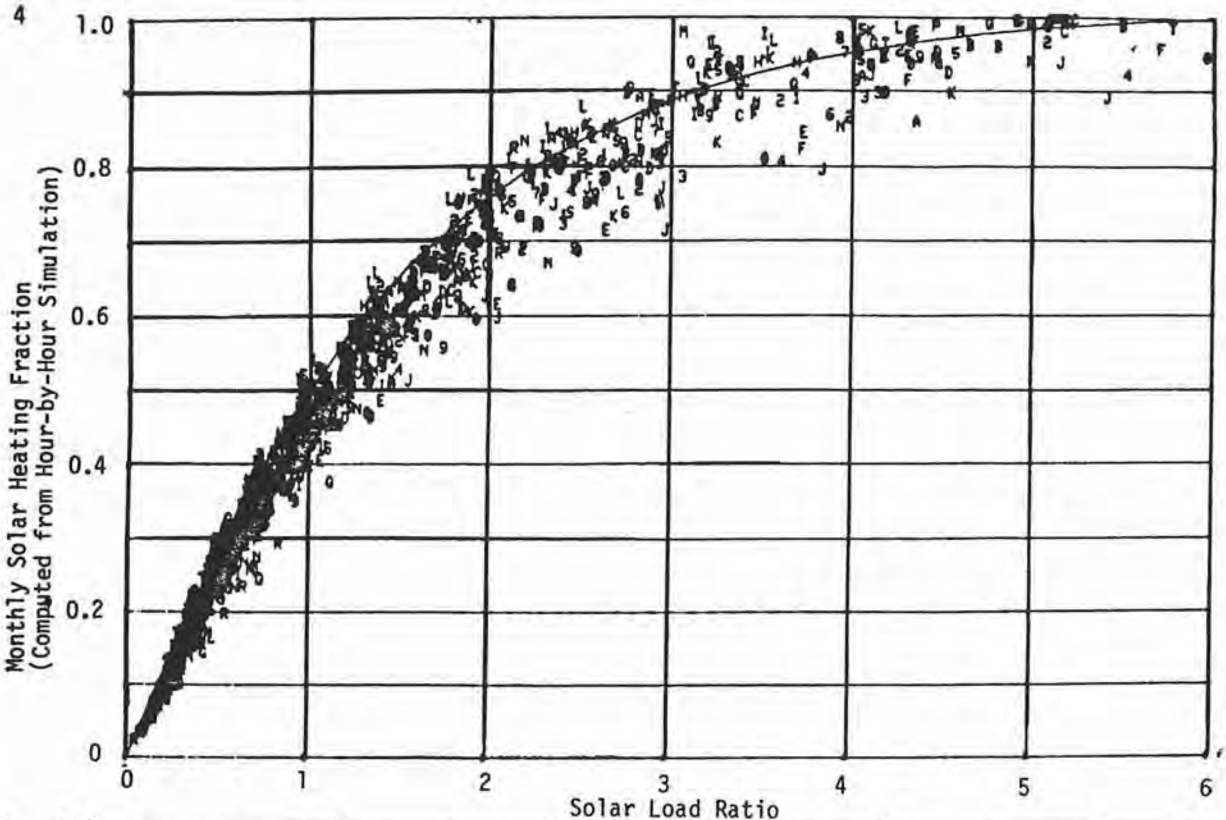
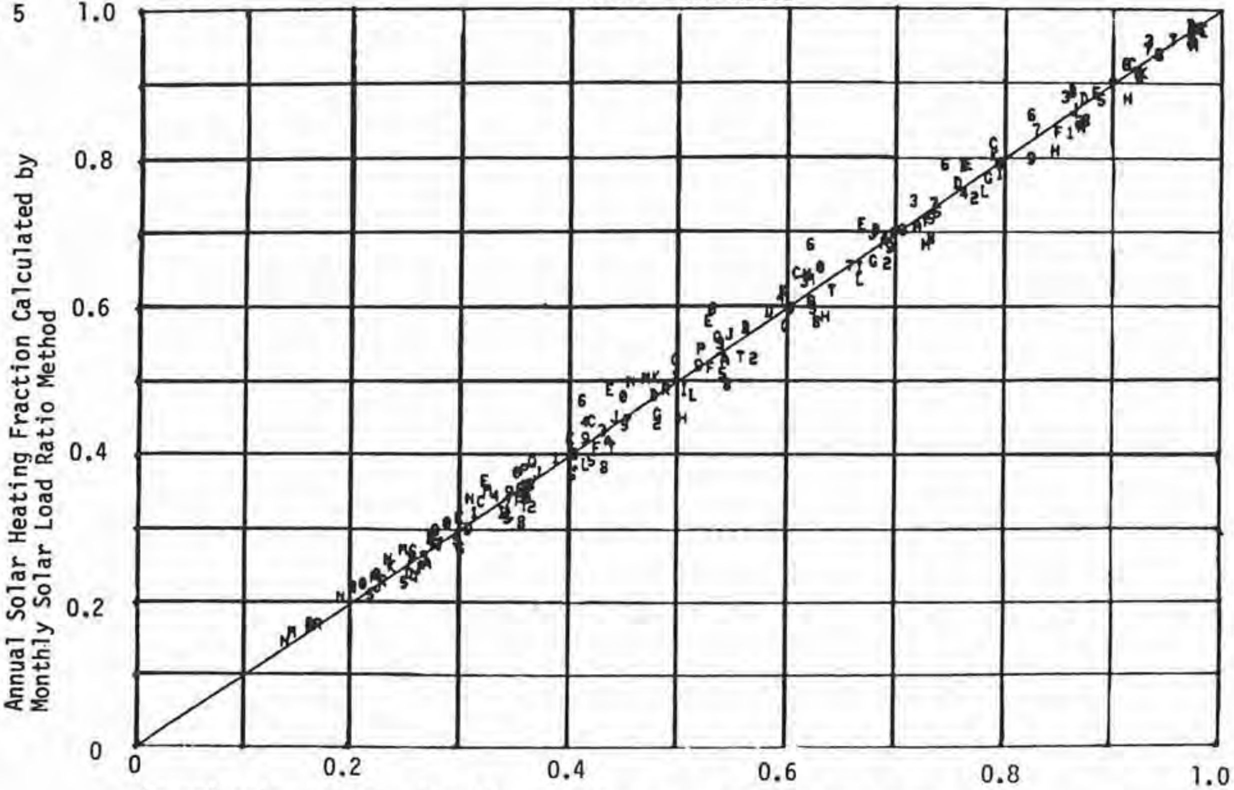


Fig. 5



Annual solar heating fraction calculated by hour-by-hour simulation.

See Table III to identify plotting symbols on Figs. 4 and 5.

TABLE I: PERFORMANCE PARAMETERS FOR PASSIVE SOLAR HEATING SYSTEMS USING THERMAL STORAGE WALLS
Load Collector Ratio (BTU/DD-ft^2) for particular values of Solar Heating Fraction (SHF)

Page, Arizona	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	196	88	54	37	27	19	13	7	
6632 DD	WWNI	312	145	91	65	49	38	29	22	15
	TW	195	94	56	37	25	17	11	6	
37°N	TWNI	304	141	89	63	46	35	26	18	12

Phoenix, Arizona	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	626	294	188	135	102	78	60	44	29
1765 DD	WWNI	863	407	261	189	145	114	90	69	49
	TW	577	287	179	123	88	64	47	33	21
33°N	TWNI	819	386	247	176	132	101	76	56	38

Tucson, Arizona	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	631	291	184	132	100	77	59	43	29
1800 DD	WWNI	871	403	256	185	142	112	89	68	49
	TW	578	284	176	121	87	63	46	33	21
32°N	TWNI	825	383	243	173	130	99	75	56	38

Little Rock, Arkansas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	239	108	66	46	33	24	17	11	
3219 DD	WWNI	365	172	107	76	57	44	35	26	18
	TW	232	112	67	44	30	21	14	9	
35°N	TWNI	356	165	103	73	54	40	30	22	14

Davis, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	409	187	115	79	57	42	30	21	11
2502 DD	WWNI	585	272	170	120	89	68	52	39	26
	TW	376	183	111	74	51	36	25	16	9
39°N	TWNI	556	259	161	112	82	61	45	32	21

El Centro, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	1028	482	301	214	161	125	97	72	50
1458 DD	WWNI	1375	649	407	290	221	175	139	107	77
	TW	916	458	284	194	140	103	75	54	36
33°N	TWNI	1294	608	382	270	202	154	117	87	60

Fresno, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	405	186	113	77	55	40	29	19	10
2492 DD	WWNI	577	271	168	117	87	66	50	37	25
	TW	370	181	109	72	49	34	24	15	8
37°N	TWNI	550	257	159	110	79	59	43	31	20

Inyokern, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	453	209	129	90	66	50	37	26	16
3528 DD	WWNI	641	300	188	132	100	77	60	46	32
	TW	419	204	124	84	59	42	30	20	12
36°N	TWNI	613	284	177	124	92	69	52	38	25

Los Angeles, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	763	362	225	158	118	91	70	52	35
2061 DD	WWNI	1032	498	310	219	165	131	103	80	57
	TW	687	344	213	145	103	75	55	39	26
34°N	TWNI	979	464	291	205	153	116	88	65	45

Riverside, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	767	356	224	160	121	94	72	53	36
1803 DD	WWNI	1039	488	308	221	169	134	106	82	58
	TW	692	344	214	146	105	77	56	40	26
34°N	TWNI	984	459	290	207	155	118	90	67	46

Santa Maria, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	544	272	176	126	96	74	56	41	27
2967 DD	WWNI	752	376	247	179	137	108	86	66	45
	TW	514	264	167	115	83	61	44	31	20
35°N	TWNI	720	358	231	166	126	96	73	54	36

Granby, Colorado	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	196	90	56	39	28	20	14	8	
5524 DD	WWNI	313	146	94	67	51	40	31	23	15
	TW	197	96	58	38	26	18	12	7	
40°N	TWNI	303	143	91	65	48	36	27	19	13

Grand Junction, Colorado	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	199	92	56	39	28	20	13		
5641 DD	WWNI	317	150	95	67	51	39	30	22	15
	TW	201	97	58	38	26	17	11	6	
39°N	TWNI	310	145	91	64	48	36	26	19	12

Washington, D. C.	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	179	79	47	32	22	15	9		
4224 DD	WWNI	292	135	83	58	44	33	25	18	12
	TW	180	85	50	32	21	13	8		
39°N	TWNI	285	131	81	57	41	31	22	16	10

Apalachicola, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	700	322	204	145	110	85	65	48	32
1308 DD	WWNI	956	444	281	203	155	123	97	75	53
	TW	635	313	194	133	95	70	51	36	24
30°N	TWNI	906	240	266	189	142	108	82	61	42

Gainesville, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	731	333	212	152	116	90	69	51	35
1239 DD	WWNI	1000	457	292	211	162	129	102	79	56
	TW	662	326	202	139	100	73	54	39	25
30°N	TWNI	943	435	276	197	148	113	86	64	44

Tallahassee, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	621	285	179	128	97	75	57	42	28
1485 DD	WWNI	857	397	249	180	138	109	87	67	48
	TW	563	279	172	117	84	61	45	32	21
30°N	TWNI	809	376	237	169	127	97	73	54	37

Tampa, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	1147	573	374	272	210	166	129	98	69
683 DD	WWNI	1520	760	500	365	283	227	182	141	102
	TW	1059	548	351	245	179	134	100	73	49
28°N	TWNI	1443	717	467	339	258	199	152	114	80

Atlanta, Georgia	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	301	136	83	58	43	31	23	15	8
2961 DD	WWNI	448	207	129	91	69	54	42	32	22
	TW	286	138	83	55	38	27	18	12	7
34°N	TWNI	431	198	123	87	64	48	36	26	17

Boise, Idaho	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	185	83	48	31	20	12	6		
5809 DD	WWNI	299	139	86	59	43	31	23	16	10
	TW	182	86	50	31	20	12	6		
44°N	TWNI	290	135	83	56	40	29	21	14	8

Lemont (ANL) Illinois	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	120	51	29	18	11				
6155 DD	WWNI	219	100	61	42	31	24	18	13	8
	TW	129	59	33	20	12	7			
42°N	TWNI	216	99	61	42	30	22	16	11	7

Indianapolis, Indiana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	136	58	33	21	14	7			
5699 DD	WWNI	239	109	67	46	34	26	19	14	9
	TW	142	65	37	23	14	8			
40°N	TWNI	235	107	66	45	33	24	17	12	7

Ames, Iowa	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	117	50	29	18	11				
6588 DD	WWNI	215	99	61	42	31	23	18	12	8
	TW	127	58	33	20	12	6			
42°N	TWNI	213	98	60	41	30	22	16	11	7

Dodge City, Kansas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	214	99	61	43	31	23	16	10	
4986 DD	WWNI	335	160	101	72	54	42	33	25	17
	TW	214	104	63	41	28	20	13	8	
38°N	TWNI	327	154	97	69	51	38	29	21	14

Manhattan, Kansas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	165	74	44	30	21	14	8		
5182 DD	WWNI	274	128	80	56	42	32	25	18	12
	TW	169	80	47	30	20	13	8		
39°N	TWNI	269	125	78	54	40	30	22	15	10

Lexington, Kentucky	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	143	63	36	24	16	10			
4683 DD	WWNI	246	114	70	49	36	28	21	15	10
	TW	148	70	40	25	16	10	5		
38°N	TWNI	242	112	69	48	35	26	19	13	8

Lake Charles, Louisiana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	522	239	152	109	82	63	48	35	23
1459 DD	WWNI	730	338	214	155	119	94	74	57	40
	TW	481	237	146	100	71	52	38	26	17
30°N	TWNI	695	322	204	146	109	83	63	46	32

Shreveport, Louisiana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	361	166	104	74	65	42	31	22	14
2184 DD	WWNI	524	245	154	111	85	67	53	40	28
	TW	340	167	103	69	49	35	25	17	10
32°N	TWNI	500	234	148	105	79	60	45	33	22

TABLE I: PERFORMANCE PARAMETERS FOR PASSIVE SOLAR HEATING SYSTEMS USING THERMAL STORAGE WALLS (Cont.)
Load Collector Ratio (BTU/DD-ft^2) for particular values of Solar Heating Fraction (SHF)

Caribou, Maine	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	83	34	17	8					
9769 DD	WWNI	172	78	48	33	24	17	13	8	
	TW	97	43	23	12	5				
47°N	TWNI	172	79	48	33	23	17	12	8	4

Portland, Maine	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	125	54	31	20	13	7			
7511 DD	WWNI	223	103	64	45	33	25	19	14	8
	TW	133	62	35	22	14	8			
44°N	TWNI	221	102	63	44	32	23	17	12	7

Boston, Massachusetts	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	137	60	35	23	15	9			
5634 DD	WWNI	241	110	68	48	36	27	21	15	9
	TW	145	67	39	24	15	9	5		
42°N	TWNI	238	108	67	47	34	25	18	13	8

East Lansing, Michigan	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	111	46	25	15	8				
6909 DD	WWNI	208	94	57	39	29	22	16	11	7
	TW	120	54	30	18	10	4			
43°N	TWNI	206	93	57	39	28	20	15	10	6

Sault St. Marie, Michigan	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	100	40	21	11					
9048 DD	WWNI	193	87	53	36	26	19	13	9	5
	TW	110	49	26	15	7				
46°N	TWNI	192	87	53	36	25	18	13	8	4

St. Cloud, Minnesota	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	96	39	21	11					
8879 DD	WWNI	189	85	52	36	26	19	14	9	5
	TW	108	48	26	15	7				
46°N	TWNI	189	86	52	36	25	18	13	8	5

Columbia, Missouri	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	175	77	46	31	21	14	8		
5046 DD	WWNI	287	133	82	57	43	33	25	18	12
	TW	177	83	49	31	20	13	8		
39°N	TWNI	281	129	80	55	41	30	22	15	10

Glasgow, Montana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	168	75	44	29	19	12	6		
8996 DD	WWNI	277	130	81	56	41	31	23	17	10
	TW	171	80	47	30	19	12	7		
48°N	TWNI	272	126	78	54	39	29	21	14	9

Great Falls, Montana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	143	63	37	23	14	8			
7750 DD	WWNI	246	115	71	49	36	27	20	14	8
	TW	149	69	40	25	15	9			
47°N	TWNI	243	112	69	48	34	25	18	12	7

Lincoln, Nebraska	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	175	77	45	30	21	14	8		
5864 DD	WWNI	288	133	82	57	42	33	25	18	12
	TW	176	83	48	31	20	13	8		
41°N	TWNI	280	129	79	55	40	30	22	16	10

Ely, Nevada	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	172	80	50	35	25	18	12	6	
7733 DD	WWNI	282	134	85	61	47	36	28	21	14
	TW	178	86	52	34	23	16	10	6	
39°N	TWNI	277	131	83	59	44	33	25	18	11

Las Vegas, Nevada	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	448	209	130	92	68	52	39	28	17
2709 DD	WWNI	632	300	188	134	102	80	63	48	33
	TW	414	205	126	85	60	43	31	21	13
36°N	TWNI	603	284	179	126	94	71	53	39	26

Reno, Nevada	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	192	88	54	37	26	18	12	6	
6332 DD	WWNI	307	145	91	65	49	37	28	21	13
	TW	192	93	55	36	24	16	10	5	
39°N	TWNI	298	141	89	62	46	34	25	18	11

Seabrook, New Jersey	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	163	72	43	29	20	13	8		
4812 DD	WWNI	271	126	78	55	41	31	24	17	11
	TW	167	78	46	29	19	12	7		
39°N	TWNI	267	123	76	53	39	29	21	15	9

Albuquerque, New Mexico	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	278	133	83	59	44	33	24	16	9
4348 DD	WWNI	414	201	128	92	70	55	43	33	23
	TW	271	135	83	56	39	28	19	13	7
35°N	TWNI	402	193	123	87	65	49	37	27	18

Los Alamos, New Mexico	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	179	84	52	36	26	18	12	7	
6604 DD	WWNI	288	139	89	64	48	37	29	21	14
	TW	183	89	54	36	24	16	11	6	
36°N	TWNI	283	136	86	61	45	34	25	18	12

Ithaca, New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	93	36	18	9					
6914 DD	WWNI	189	83	50	34	24	18	13	9	5
	TW	106	46	24	13	6				
42°N	TWNI	188	83	50	34	24	17	12	8	4

New York City, New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	147	64	38	25	17	11	5		
4871 DD	WWNI	250	117	72	51	38	29	22	16	10
	TW	152	71	42	26	17	11	6		
41°N	TWNI	247	114	71	49	36	27	20	14	9

Sayville, L.I. New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	165	74	45	30	21	14	9		
4811 DD	WWNI	272	129	80	57	43	33	25	18	12
	TW	169	81	48	31	20	13	8	4	
41°N	TWNI	268	125	78	55	40	30	22	16	10

Schenectady, New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	84	34	18	9					
6650 DD	WWNI	174	79	48	33	24	18	13	9	5
	TW	98	43	23	13	6				
43°N	TWNI	175	79	49	33	24	17	12	8	5

Greensboro, North Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	237	107	66	46	33	24	17	11	
3805 DD	WWNI	367	170	107	75	57	44	35	26	18
	TW	231	112	67	44	30	21	14	9	
36°N	TWNI	354	165	103	72	54	40	30	22	14

Hatteras, North Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	412	189	118	82	61	46	34	24	15
2612 DD	WWNI	588	274	173	123	93	73	57	43	30
	TW	381	187	115	77	54	39	28	19	11
35°N	TWNI	560	261	164	115	86	65	49	36	24

Raleigh, North Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	256	117	71	50	37	27	19	12	7
3393 DD	WWNI	391	182	114	80	61	48	37	28	19
	TW	249	120	72	48	33	23	16	10	5
36°N	TWNI	378	175	109	77	57	43	32	23	15

Bismarck, North Dakota	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	111	46	25	14	6				
8851 DD	WWNI	208	94	57	39	28	21	15	10	6
	TW	120	54	30	17	9				
47°N	TWNI	207	94	57	39	27	20	14	9	5

Cleveland, Ohio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	103	41	22	12					
6351 DD	WWNI	202	89	53	36	26	20	14	10	6
	TW	114	50	27	15	8				
41°N	TWNI	200	89	53	36	26	19	13	9	5

Columbus, Ohio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	120	51	29	18	11				
5211 DD	WWNI	218	100	61	42	31	23	17	12	7
	TW	128	59	33	20	12	6			
40°N	TWNI	216	99	61	42	30	22	16	11	6

Put-in-Bay, Ohio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	102	39	20	9					
5796 DD	WWNI	199	88	52	35	25	18	13	8	
	TW	112	48	26	14	6				
42°N	TWNI	199	87	52	35	25	18	12	8	4

Oklahoma City, Oklahoma	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	250	115	70	49	36	26	19	12	6
3725 DD	WWNI	382	179	112	80	60	47	37	28	19
	TW	243	118	71	47	32	23	15	10	5
35°N	TWNI	370	172	108	76	57	43	32	23	15

TABLE I: PERFORMANCE PARAMETERS FOR PASSIVE SOLAR HEATING SYSTEMS USING THERMAL STORAGE WALLS (Cont.)
Load Collector Ratio (BTU/DD-ft^2) for particular values of Solar Heating Fraction (SHF)

Astoria, Oregon	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	207	98	59	39	26	17	9		
5186 DD	WWNI	322	158	99	69	50	37	27	19	11
	TW	205	99	59	38	25	16	9		
46°N	TWNI	315	152	95	65	47	34	24	16	9

Corvallis, Oregon	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	224	96	57	37	24	16	9		
4726 DD	WWNI	352	158	97	67	48	36	26	18	11
	TW	217	100	58	36	24	15	9		
45°N	TWNI	341	153	93	63	45	33	23	16	9

Medford, Oregon	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	188	83	49	31	20	12			
5008 DD	WWNI	306	139	86	60	43	32	23	16	9
	TW	186	87	50	31	20	12	6		
42°N	TWNI	296	136	83	57	40	29	21	14	8

State College, Pennsylvania	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	117	50	28	18	11				
5934 DD	WWNI	214	98	61	42	31	23	17	12	7
	TW	126	58	33	20	12	6			
41°N	TWNI	213	97	60	41	30	22	16	11	6

Newport, Rhode Island	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	150	66	40	27	19	12	7		
5804 DD	WWNI	256	118	74	52	39	30	23	17	11
	TW	156	74	43	27	18	11	7		
41°N	TWNI	251	116	72	51	37	28	20	14	9

Charleston, South Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	442	204	127	90	67	52	39	28	18
2033 DD	WWNI	624	295	184	132	100	79	63	48	34
	TW	407	202	124	84	59	43	31	21	13
33°N	TWNI	594	279	176	124	93	71	53	39	27

Rapid City, South Dakota	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	149	67	40	26	18	11	6		
7345 DD	WWNI	253	118	74	52	39	30	22	16	10
	TW	155	73	43	27	17	11	6		
44°N	TWNI	249	116	72	50	37	27	20	14	9

Flaming Gorge, Utah	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	170	79	48	33	23	16	10	5	
6929 DD	WWNI	277	132	84	60	45	35	27	20	13
	TW	173	84	50	33	22	15	9	5	
41°N	TWNI	272	129	82	58	43	32	24	17	11

Salt Lake City, Utah	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	192	86	52	35	24	16	10		
6052 DD	WWNI	308	143	90	63	46	35	27	19	12
	TW	190	91	54	34	23	15	9	4	
41°N	TWNI	299	140	87	60	44	32	24	17	10

Burlington, Vermont	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	80	30	15						
8269 DD	WWNI	171	75	46	31	23	17	12	8	4
	TW	94	41	21	11					
44°N	TWNI	172	77	46	31	22	16	11	7	4

Pullman, Washington	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	178	78	44	27	17	9			
5542 DD	WWNI	291	134	82	56	40	29	21	14	8
	TW	175	81	46	28	18	10			
47°N	TWNI	282	130	79	53	37	27	19	13	7

Richland, Washington	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	179	77	43	25	15	7			
5941 DD	WWNI	293	133	81	54	38	27	19	13	7
	TW	176	80	45	27	16	9			
47°N	TWNI	285	130	78	52	36	26	18	12	7

Seattle, Washington	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	219	93	52	32	20	11			
4424 DD	WWNI	346	154	93	62	44	31	22	15	9
	TW	211	95	54	33	20	12	6		
48°N	TWNI	333	149	89	59	41	29	20	13	8

Spokane, Washington	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	149	63	34	20	10				
6655 DD	WWNI	255	116	70	47	33	23	17	11	6
	TW	151	68	38	22	13	6			
48°N	TWNI	251	114	68	45	32	22	16	10	5

Nashville, Tennessee	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	227	99	59	40	28	20	13	8	
3578 DD	WWNI	355	161	98	68	51	39	30	23	15
	TW	219	103	61	39	26	18	11	7	
36°N	TWNI	343	155	95	66	48	36	27	19	12

Oak Ridge, Tennessee	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	204	90	54	36	26	18	12	6	
3817 DD	WWNI	325	149	92	64	48	37	29	21	14
	TW	201	95	56	36	24	16	6		
36°N	TWNI	315	145	89	62	46	34	25	18	11

Brownsville, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	1052	526	348	254	194	151	117	88	60
600 DD	WWNI	1399	700	465	342	265	209	165	127	90
	TW	976	506	324	226	165	123	91	66	44
26°N	TWNI	1330	664	435	315	238	183	140	104	71

El Paso, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	431	205	129	92	69	52	39	28	18
2700 DD	WWNI	608	295	187	134	103	80	63	48	34
	TW	402	202	125	85	60	44	31	22	13
32°N	TWNI	582	279	178	126	94	72	54	40	27

Fort Worth, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	364	171	108	76	57	43	32	23	14
2405 DD	WWNI	526	251	159	115	87	69	54	41	29
	TW	344	171	106	71	50	36	26	18	10
33°N	TWNI	503	239	152	108	81	61	46	34	23

Midland, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	385	184	115	82	61	47	35	25	16
2591 DD	WWNI	548	267	169	121	93	73	57	44	31
	TW	362	182	113	76	54	39	28	19	12
32°N	TWNI	527	253	161	115	86	65	49	36	24

San Antonio, Texas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	547	253	159	114	86	66	50	37	24
1546 DD	WWNI	762	355	224	162	124	98	78	60	42
	TW	501	248	154	104	75	54	40	28	18
30°N	TWNI	722	337	213	152	114	87	66	49	33

Madison, Wisconsin	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	108	44	24	14	7				
7863 DD	WWNI	206	92	56	38	28	21	16	11	6
	TW	119	53	29	17	10				
43°N	TWNI	204	92	56	38	27	20	14	10	6

Lander, Wyoming	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	163	76	47	32	22	15	9		
7870 DD	WWNI	267	129	82	58	44	34	26	19	12
	TW	168	81	49	32	21	14	9	4	
43°N	TWNI	264	126	80	56	41	31	23	16	10

Laramie, Wyoming	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	157	72	44	31	22	15	10		
7381 DD	WWNI	263	124	79	56	43	33	26	19	13
	TW	164	79	47	31	21	14	9	4	
41°N	TWNI	259	122	77	55	41	30	23	16	10

Edmonton, Alberta	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	93	34							
10268 DD	WWNI	184	83	48	31	20	13	8	4	
	TW	102	42	20						
54°N	TWNI	184	83	48	31	20	14	9	5	

Ottawa, Ontario	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	91	35	17	7					
8735 DD	WWNI	185	81	49	33	24	17	12	8	4
	TW	103	45	23	13					
45°N	TWNI	184	82	49	33	24	17	12	8	4

Toronto, Ontorio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	103	42	23	14	6				
6827 DD	WWNI	198	89	55	38	27	21	15	10	6
	TW	114	51	28	16	9				
44°N	TWNI	197	89	55	37	27	19	14	9	5

Winnipeg, Manatoba	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	74	27							
10679 DD	WWNI	162	73	44	29	20	14	9	5	
	TW	88	37	18	7					
50°N	TWNI	164	74	44	29	20	14	9	5	

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