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SOLAR HOUSE

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**PERFORMANCE AND COST OF A HYBRID
PASSIVE/ACTIVE SOLAR HOUSE**

by

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ABSTRACT

The design, construction, cost, and initial operation of a hybrid passive/active solar-heated house in Los Alamos, New Mexico, is described. The system is dominated by a two-story Trombe wall, constructed of 0.3-m-thick (1-ft) slump block, that can be operated in either a passive or active mode. In the active mode, a blower circulates air through the Trombe wall air space and into a rock bed. A three-zone forced-air distribution system is connected to the rock bed. A separate flat-plate collector array heats a preheater tank for domestic hot water.

Operating results of the system, which is being monitored by the Los Alamos Scientific Laboratory (LASL), are reported for just over the first year of operation (1977 and part of 1978). In addition, system cost, occupant observations, and conclusions are presented.

Energy consumption records for 1977 indicate that approximately 60% of the net space heating load was provided by solar energy.

KEY WORDS

Solar, Space-Heating, Energy, Residential, Architecture, Monitoring.

INTRODUCTION

A passive approach to solar heating, incorporating the Trombe (thermal storage) wall concept and direct solar gain (1), offers several advantages over active systems. Such a system is simple and has thermal and architectural advantages in that the Trombe wall not only forms all or part of the south wall of the house, but also serves as collector, storage, and built-in radiant heating panel. However, unless all rooms in the house communicate directly with the Trombe wall, control of heating is difficult and separated rooms tend to be cold and must be heated by different means.

This suggests the combination of the passive and active features of solar heating to gain the advantages of both. Such an approach was implemented by the author and his family in the construction of their three-bedroom, 181.7 m^2 (1955 ft^2) house in Los Alamos, New Mexico, which was completed in December 1976. A second design consideration was to construct an architecturally pleasing home with standard building materials. The house is located at an elevation of 1950 m (6400 ft), where the winters are cold ($3500^\circ\text{C-days} = 6300^\circ\text{F-days}$), but sunshine is plentiful.

The solar system features a two-story modified Trombe wall (actually a thermal storage wall because air is not circulated into the occupied space from the wall) of 23.2 m^2 (250 ft^2) in effective collection area, covered by a double glazing. This wall can be operated in either a passive mode or an active mode wherein a rock bed in the crawl space is charged by a blower that circulates air from the Trombe wall air space to the rock bed. Additional solar collection is obtained by direct gain

through 13.0 m^2 (140 ft^2) of windows. A separate flat-plate liquid collector array heats water going to a preheater tank for domestic hot water.

This paper describes the design, cost, and just over the first year's operation of the system. Owner/occupant observations are also reported. Although operation in the active mode has not yet been fully successful, data are reported for both the passive and active modes. Finally, measured energy consumption for the year is presented, and a calculation of the actual solar contribution to space heating is discussed.

DESIGN OF HOUSE AND SOLAR HEATING SYSTEM

The House

The house has a two-story section whose south wall is formed by a 3.7-m-wide by 8.2-m-high (12-ft by 27-ft) Trombe wall in the center, with large windows on each side for direct solar gain (Fig. 1). The roof slopes from 8.2 m (27 ft) at the south wall to 3.7 m (12 ft) at the north wall of the garage. The first and second floors of this section were kept as large, continuous spaces to allow free circulation of air from the Trombe wall to the north side of the rooms.

The floor plan includes a family/dining area, children's work area, and kitchen on the first floor, separated from the entryway and stairs by a wall that is open at the top. The east and west walls have minimum window area. All windows are wood frame and double glazed. The garage is attached to the north wall of the two-story section and acts as a buffer against heat loss. A 10.2-cm (4-in.) inside layer of slump block was placed in the entryway for additional thermal storage. These blocks and those of the Trombe wall were left unpainted inside the house, providing a pleasing interior decor.

The living room and study are upstairs on the south side, with the master bedroom and bath behind them. A storage area above the garage buffers this north wall. The bedroom is separated from the living room by a 2.3-m (7.6-ft) wall, which leaves a 0.9-m (3-ft) space between its top and the sloping ceiling for air circulation.

A single-story wing attached to the west wall of the two-story section contains a bathroom and two bedrooms. Its peaked roof has a 45° south-facing slope on which are mounted the solar water heating collectors. On each side of these collectors are 0.6-m by 1.2-m (2-ft by 4-ft) double-glazed skylights that, in the winter, admit sunlight to the interior walls of the bedrooms. One bedroom has a 20.3-cm (8-in.) slump block rear wall that acts as thermal storage. Large windows on the south wall are the only windows in the wing, except for two small windows on the north wall of the hallway.

Except for the Trombe wall, all walls and the roof are 15.2-cm (6-in.) frame, filled with R-19 fiberglass batts. Five centimeters (2 in.) of beaded styrofoam were placed on the foundation walls inside the crawl space.

Additional design details are available in Ref. 2.

Solar Heating System

The solar system is built around the Trombe wall, which is constructed of 0.3-m-thick (1-ft) open slump block completely filled with cement. This thickness has been shown to be optimal for concrete, having a thermal conductivity of $0.017 \text{ W/cm-}^{\circ}\text{C}$ ($1.0 \text{ Btu/h-ft-}^{\circ}\text{F}$)(3). The outside surface of the wall is covered with a dark brown stain that has a measured solar absorptivity of 0.91. A 5.1-cm (2-in.) air space separates the wall from the double glazing. The glazings are standard plate glass 2.5 cm

(1 in.) apart, and are mounted in six sets of 117-cm by 229-cm (46-in. by 90-in.) sheets on a wood frame bolted to the wall. A 0.9-m (3-ft) overhang shades the wall in the summer, and vents at floor level and at the top of the wall may be operated manually to purge the air space to prevent overheating.

In the passive mode, heating is by radiation and convection from the inside wall surface. The outer surface is heated by absorbed solar radiation and the stagnant air column that builds up in the air space. No air flows directly from the wall air space to the heated space.

In the active mode, the rock bed is charged by a 236-liter/s (500-cfm) blower, which is controlled by a differential thermostat, and that circulates air up through the Trombe wall air space, down ducts on each side of the wall, and into a rock bed in the crawl space. (See Fig. 2.) The 10,900-kg (12-ton) rock bed is of the horizontal flow type, 1.8 m (6 ft) in the flow direction with a 0.9-m by 3.7-m (3-ft by 12-ft) face, filled with 5-10-cm-diam (2-4-in.) washed gravel.

A three-zone forced-air distribution system, with a natural gas auxiliary furnace, rated at 79,100 kJ/h (75,000 Btu/h) input, is connected to the rock bed (Fig. 2). When any zone calls for heat, return air is ducted to the cold side of the rock bed, out the warm end, and then through the furnace. A thermostat, located in the furnace inlet air stream, turns on the furnace burner if the inlet air is below a preset value, 25-27°C (77-80°F).

The system is rounded out with an active water heating system that heats a tank used to preheat domestic hot water. The collectors are two 1.9 m² (20 ft²) flat-plate modules mounted on the roof of the single-story wing. Air vents, controlled by a second differential controller

that also operates the water circulating pump, allow the collector water to drain down to the heater tank when the system is not charging.

SYSTEM COST

Material costs for the space heating and domestic hot water systems are listed in Table 1. A breakdown of installation costs is also given in the table, but because most of these were included in the overall contract, they have only been roughly estimated. The total (net) space heating system cost, installed, was \$5436, including credit for the exterior wall that was replaced by the Trombe wall. The domestic hot water system cost was \$1260, installed. This \$6700 incremental initial cost attributable to the solar system represents about 10% of the total construction cost of the house. This does not include the cost of the interior slump block in the entryway.

However, the State of New Mexico allows an income tax credit of 25% of the equipment cost (excluding labor) for a solar heating/cooling system. This resulted in a \$1000 refund, the maximum allowable.

SYSTEM PERFORMANCE

Owner Observations

The thermostats were normally set at 16°C (60°F), in which case the two-story section rarely required auxiliary heat during clear weather. This section of the house would cool to 16 or 17°C (60 or 62°F) at 6 a.m. as the ambient temperature dropped to -18°C (0°F) and below. As soon as the morning sun struck the south and east windows, an immediate warming was noted resulting in temperatures of 18 - 21°C (65 - 70°F) by the afternoon. 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.

When the Trombe wall was fully charged, which took about two days of clear weather, it attained temperatures of about 29°C (85°F) on the inner surface. When this occurred, the radiant effect of the wall was most evident and the room was comfortable, even below 18°C (65°F) air temperatures. On the other hand, when the wall was discharged after two or more cloudy days, the inner wall temperature would drop to 16 - 18°C (60 - 65°F), in which case the room was uncomfortable unless the temperature was 18°C (65°F) or greater. Thus, the thermostat was set at 18°C (65°F) during a cloudy day following one or more cloudy days.

Measured Performance

Hourly temperature profiles in the Trombe wall at four levels, 1.2, 2.4, 4.6, and 7.9 m (4, 8, 15, and 26 ft), as well as the inside ambient temperature (downstairs in the two-story section), have been recorded continuously since January 1977. Thermocouples were installed during construction at 2.5, 8.9, 15.2, and 27.9 cm (1, 3.5, 6, and 11 in.) from the outside surface of the blocks to determine the temperature gradient through the wall. The integrated horizontal insolation, ambient dry-bulb temperature, and wind speed and direction at the site were recorded hourly.

Throughout 1977, the recordings were made on a Brown 16-point recorder. Thus, only selected profiles, plus the weather data, were monitored during this period. On January 16, 1978, an Acurex Autodata 9 40-channel recorder was installed, so that all the Trombe wall and 13 rock bed thermocouples, plus the weather data, could be monitored.

The system was operated in the passive mode, except during November and December 1977 when the rock bed was being charged.

Figure 3 shows data for the period January 21-24, 1978, which included a partly cloudy day followed by a clear day, followed by two cloudy days. The wall temperatures shown were recorded at the 4.6-m (15-ft) level. Note that on a clear day the near-outer surface temperature peaks at about 60°C (140°F) slightly after midday; this is a characteristic result. Maximum peak temperatures of 63°C (145°F) were observed for the year. The peak temperature wave propagates through the wall so that the peak at the near-inner surface position occurs about 6 h later. This 6-h delay was very consistent throughout the year for both cloudy and clear weather (see Figs. 3-6). Note the recovery of the wall temperatures during the sunny day following the initial partly cloudy day and the decay during the last two cloudy days. Although the outside ambient temperature dropped to nearly -12°C (10°F) on January 25, 1978, the inside ambient was very stable through the four-day period. Except under unusual circumstances (extremely cold after more than two cloudy days), the inside ambient temperature holds to above 16°C (60°F), the normal thermostat set-point. Thus, no auxiliary energy was required at night for the two-story section during this period. However, the small spikes in the inside ambient temperature during the cold, cloudy days of January 23 and 24, 1978, indicate that the auxiliary furnace was firing during the day while the thermostat was set at 18°C (65°F).

A poor solar period, February 10-15, 1978, is depicted in Fig. 4. It consists of a clear day followed by a mixture of five cloudy and partly cloudy days. The wall temperatures are at the 4.6-m (15-ft) level. Note that peak near-outer surface temperatures are between 38 and 49°C (100 and 120°F) on partly cloudy days and between 21 and 27°C (70 and 80°F) on cloudy days. It is seen that on the night following this

series of cloudy days, the near-outer wall temperature drops to 12°C (53°F), while the near-inner wall temperature drops to 14°C (58°F). These were the coldest wall temperatures observed during the year. Generally, after a prolonged cold and cloudy period, the temperature gradient dissipates and the wall stays around 16°C (60°F) until it is charged the next day.

Note again the stability of the inside ambient temperature and the carry-through at night, without auxiliary heating. During most of the cloudy daytimes, auxiliary heating is evident. However, on the clear day (February 10), the inside ambient temperature rises to 22°C (72°F) without auxiliary heating.

The final winter period shown (Fig. 5) is represented by a series of temperatures at the 4.6-m (15-ft) level for five clear days, February 19-23, 1978. Note that the peak and average temperatures steadily rise as the wall is charged. Once the wall is charged, the near-outer wall temperature fluctuates $\approx 39^{\circ}\text{C}$ (70°F), while the near-inner wall temperature fluctuates $\approx 11^{\circ}\text{C}$ (20°F) over a day. Typically, when the wall is charged the near-inner wall varies from 18 - 29°C (65 - 85°F). Under these circumstances, the daily average outside-to-inside ambient temperature difference is 17 - 19°C (30 - 35°F).

Also shown in Fig. 5 is the decay of the inside ambient temperature when the house is unoccupied and the auxiliary is shut off (February 19). The 18th and 19th were both mostly clear, and the night between was moderately cold. Note that the inside ambient temperature bottoms out at about 11°C (51°F).

Figure 6 shows fall results; peak temperatures are about 57°C (135°F), showing the combined effect of nonoptimal solar incidence

angles and mild outside ambient temperatures. Because considerable energy is being stored in the wall when no heating is required, the house tends to overheat during this season. Inside ambient temperatures in the 27-29°C (80-85°F) range often result.

Additional performance data are given in Ref. 4.

ACTIVE MODE OPERATION

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.

Figure 7 shows typical rock bed operation during charging. The inlet air peaks at only 33°C (92°F) at about 1 p.m.; the blower shuts off at about 6 p.m. Note that the warm end of the bed attains peak temperatures of only 32°C (90°F) followed by a decay of about 3°C (5°F) overnight. Under these circumstances, the maximum discharge temperatures are only 27-29°C (80-85°F) and performance is marginal.

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 fascia board at the top of the wall is poorly sealed and leakage at the vents is evident. Also, the design air flow rate of 10 liters/s/m² (2 cfm/ft²) of collecting surface is too high. This value is about optimal for active collectors. However, because the wall absorbs one-half to two-thirds of the energy incident at the surface, a value of about 5 liters/s/m² (1 cfm/ft²) is appropriate. Future steps to correct the problem will be (1) slow the blower

speed to achieve 94-118 liters/s (200-250 cfm), (2) seal as many air leaks as possible, and (3) reverse the flow pattern over the wall to reduce the length of warm air duct runs.

ENERGY CONSUMPTION AND SOLAR FRACTION

Because the gas consumption for January 1977 was only estimated, reliable utility records for the February 1, 1977, to January 31, 1978, year have been used in this accounting. Gas and electricity consumption for this period are shown in Table 2. Figure 8 shows the annual energy balance for the house. Also shown in the table are the monthly degree days, measured at LASL and referenced to 18°C (65°F), and the heat loss computed using these degree-day values. A heat loss coefficient of $147 \text{ kJ}/^{\circ}\text{C}\cdot\text{day}\cdot\text{m}^2$ ($7.2 \text{ Btu}/\text{DD}\cdot\text{ft}^2$) of house was used in the computation.

A credit was taken against the computed heat loss for electrical consumption, nonfurnace gas consumption (for the water heating auxiliary, stove, and clothes dryer), and people, to compute the expected furnace consumption (space heating requirement) for the nonsolar reference case. This credit accounts for the heating from internal sources ("free heat") and represents the lowering of the thermal balance point below the 18°C (65°F) average inside ambient temperature. The resulting net space heating load to be supplied by the furnace is $58.1 \times 10^6 \text{ kJ}$ ($55.1 \times 10^6 \text{ Btu}$) (Table 2 and Fig. 8).

The metered annual gross gas energy consumption was $67.3 \times 10^6 \text{ kJ}$ ($63.8 \times 10^6 \text{ Btu}$). Subtracting the nonfurnace (obtained from summer records) gas consumption for each month yields the actual furnace energy consumption of $40.0 \times 10^6 \text{ kJ}$ ($37.9 \times 10^6 \text{ Btu}$). Because the furnace efficiency is unknown, furnace efficiencies of 0.5, 0.6, and 0.7 were

assumed, resulting in outputs of 20.0, 24.0 or 28.0×10^6 kJ (19.0, 22.7, or 26.5×10^6 Btu), respectively (Fig. 8). The computed solar fraction for the year is then $f_{yr} = \text{solar heating/net space heating load} = 1 - (\text{furnace output/net space heating load}) = 0.66, 0.59, \text{ and } 0.52$ for furnace efficiencies of 0.5, 0.6, and 0.7, respectively. Thus the annual space heating solar fraction is about 60%.

CONCLUSIONS

The hybrid passive/active solar heating system described herein has generally been a success throughout its first year of operation. When charged, the Trombe (thermal storage) wall affords a high level of comfort.

The measured space heating solar fraction for the year was about 60%. With the wall charged, a daily average inside-to-outside ambient temperature difference of $17\text{--}19^\circ\text{C}$ ($30\text{--}35^\circ\text{F}$) is obtained. The measured 6-h thermal lag between outside and inside Trombe wall temperatures provides heat to the house during the evening when it is most needed.

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 5 liters/s/m^2 (1 cfm/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.

Finally, the combined space and water heating system cost of \$6700 is about 10% of the initial cost of the house. Thus, this hybrid passive/active system provides an attractive, economically competitive alternative to active solar heating systems.

ACKNOWLEDGMENT

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TABLE 1
SOLAR SYSTEM COST ESTIMATE

	<u>Materials</u>		<u>Installation Labor</u>	
I. Space Heating System				
A. Trombe Wall				
1. 27.9 m ² (300 ft ²) of 0.3-m-thick (1-ft) slump block	\$ 825			
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			
7. Glazing	846			
8. Stain	25			
9. Ductwork	325			
Subtotal	\$3046	+	\$1946	= \$4992
Less credit for the 15.2-cm (6-in.) frame wall that was replaced, 27.9 m ² @ \$56.48/m ² (300 ft ² @ \$5.25/ft ²)				-1575
B. Rock Bed Storage				
1. 10,900 kg (12 tons) washed gravel	\$ 51		\$ 50	
2. Framing	150			
3. Insulation	134		200	
4. Miscellaneous hardware	54			
5. Angle iron	77		50	
Subtotal	\$ 466	+	\$ 300	= 766
C. Extra Ductwork (including motor-operated dampers and back-draft dampers)	\$ 525		\$ 240	
D. Rock Bed Charging Blower, 236 liters/s (500 cfm), New York blower	208		20	
E. Controls (including one Rho Sigma Model 106 controller and furnace burner thermostat)	200		60	
Subtotal	\$ 933	+	\$ 320	= 1253
Total Item I.				\$5436
II. Domestic Hot Water System				
A. Two Miromit Model 200 flat-plate collectors (single-glazed, water white crystal glass, 1.9 m² (20 ft²) each)	\$ 400		\$ 100	
B. Differential controller, Rho Sigma Model 106	90		30	
C. Circulating pump, Grundfos Model VPS 20-42	85		30	
D. 189-liter (50-gal) Preheater/storage tank with finned tube heat exchanger coil	350		45	
E. Associated piping (including solenoid vent valves)	80		50	
Total Item II.	\$1005	+	\$ 255	= \$1260
Grand Total, Space Heating and Domestic Hot Water Heating				\$6696

TABLE 2
ENERGY CONSUMPTION DATA
FOR FEBRUARY 1, 1977, TO JANUARY 31, 1978

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Month	Degree-Days (65°F reference)	Heat Loss ^a (10 ⁶ Btu)	Gross Gas Consumption ^b (10 ⁶ Btu)	Electricity Consumption ^c (10 ⁶ Btu)	Nonspace Heating Gas Consumption Sources ^d (10 ⁶ Btu)	Credits Toward Space Heating ^e (10 ⁶ Btu)	Net Space Heating Load to be Supplied by Furnace (10 ⁶ Btu)
F	910	12.8	10.3	1.3	1.6	3.3	9.5
M	925	13.0	11.2	1.3	1.6	3.3	9.7
A	543	7.6	4.9	1.2	1.6	3.2	4.4
M	308	4.3	2.7	1.1	1.6	3.1	1.2
J	22	0.3	1.4	0.7	0	0.3	0
J	16	0.2	2.5	1.1	0	0.2	0
A	33	0.5	2.1	1.1	0	0.5	0
S	123	1.7	2.1	1.2	0.5	1.7	0
O	404	5.7	2.1	1.1	1.6	3.1	2.6
N	737	10.4	4.5	1.6	1.6	3.6	6.8
D	930	13.1	8.8	1.9	1.6	3.9	9.2
J	<u>1099</u>	<u>15.5</u>	<u>11.2</u>	<u>1.8</u>	<u>1.6</u>	<u>3.8</u>	<u>11.7</u>
Year	6050	85.1	63.8	15.4	13.3	30.0	55.1

^aAssumes 0.5 air changes/h infiltration.

^bIncludes water heating auxiliary, stove, clothes dryer (vented to outside), gas heating value = 830 Btu/ft³ at 6600-ft altitude.

^cNinety per cent of gross consumption (10% reduction accounts for outside uses).

^dEstimated values, included only to the extent of heating loads not covered by electrical consumption.

^eColumns 5 + 6 + people at 0.4 x 10⁶ Btu/month, included only to the extent of heating loads not otherwise covered.

LIST OF FIGURES

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4	Trombe wall temperature scan at 4.6-m (15-ft) level for February 10-15, 1978.
5	Trombe wall temperature scan at 4.6-m (15-ft) level for February 18-23, 1978.
6	Trombe wall temperature scan at 4.6-m (15-ft) level for September 20-23, 1977.
7	Rock bed temperatures during charging mode, November 12-15, 1977.
8	Annual energy balance for house.

Fig. 2

Fig. 4

Trombe Wall Scan, 15-ft Level

Trombe Wall Scan, 15-ft Level

ANNUAL ENERGY BALANCE FOR HOUSE

All units in 10^6 BTU except for η_f = furnace efficiency

Fig. 8