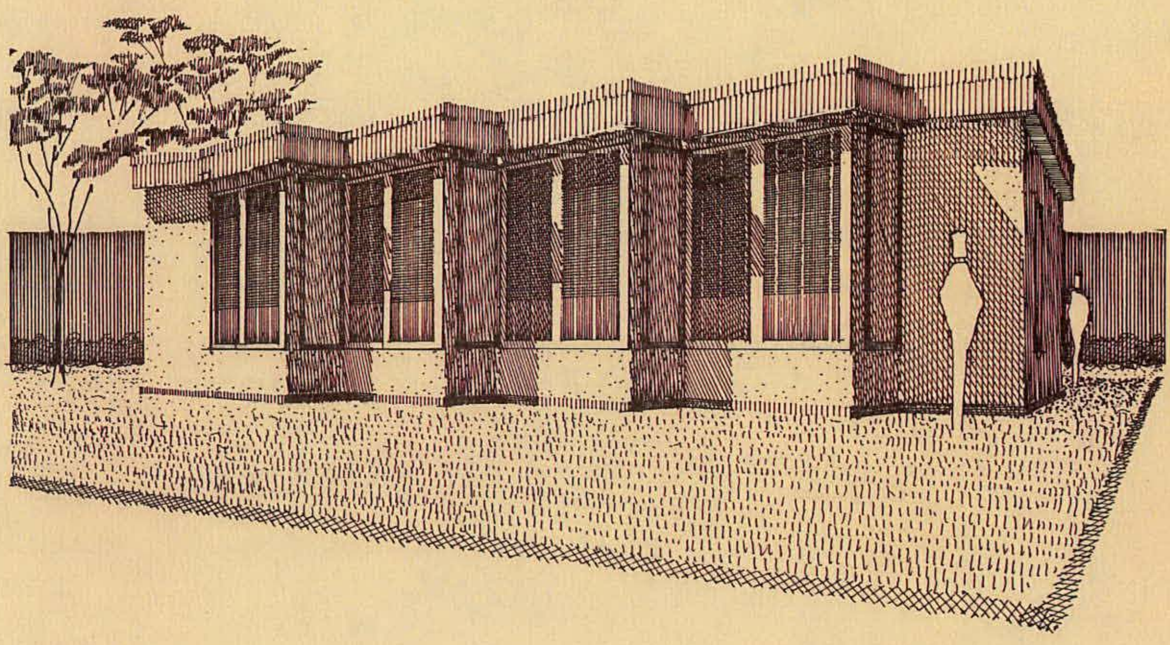
DOE/CS/34513--1

M.I.T. SOLAR BUILDING 5



THE SECOND YEAR'S PERFORMANCE

by

Timothy E. Johnson

Edward Quinlan

Department of Architecture
Massachusetts Institute of Technology
Cambridge, Massachusetts

November 1979

DISCLAIMER

DOE/CS/34513-1

M.I.T. SOLAR BUILDING 5

THE SECOND YEAR'S PERFORMANCE

by

Timothy E. Johnson

Edward Quinlan

Department of Architecture

Massachusetts Institute of Technology

Cambridge, MA

November 1979

Report for the period

October 1, 1978 to October 31, 1979

Prepared with the support of:

Department of Energy
Solar Heating and Cooling Research and Development Branch
Office of Conservation and Solar Applications

TABLE OF CONTENTS

ABSTRACT

The MIT Solar Building 5 has shown the problems associated with direct gain approaches can be overcome with new architectural finish materials that emphasize their thermophysical properties. Three new materials are demonstrated in the building: 1) a transparent window insulation, 2) a glare modulating and light directing louver and 3) a ceiling tile that stores heat latently.

Solar heating is accomplished by directing insolation to dark colored ceiling tiles containing a phase change material for thermal storage and temperature regulation. Sunlight is placed on the ceiling by exceptionally narrow, upside down reflectorized venetian blinds that are fitted between the south facing glazing. The blinds eliminate glare without sacrificing view. Heat losses through the double glazing are reduced by a factor of 3.5 by mounting a "heat mirror" between the double glazing. The "heat mirror" is so named because it reflects 75% of the room temperature infrared radiation back into the heated space while remaining transparent to visible and solar radiation (70-75% solar transmission).

1978-1979 thermal performance measurements showed the sun supplied 62% of the building's seasonal heating requirement while an additional 13% of the load was supplied by internal gains from the lights. This was done by glazing only 45% of the south wall. Economic analyses show the payback period is 4 to 5 times faster than when using the flat plate collector approach. Architectural flexibility has been increased, even to the point where new kinds of spaces can be created using these materials.

Principles & Performance

INTRODUCTION

Heating residential spaces passively with the sun has always been an attractive prospect because solar heating can be accomplished inexpensively once the solar heating elements become building elements. In passively heated buildings, most of the first costs associated with solar heating can be charged off to structure and building envelope. However, the approach has had its problems. The indirect gain approach (Fig. 1) is not attractive for multiple family construction since the roof no longer offers enough collection area, and the exterior walls must be heavily perforated to give visual and physical access. The direct gain approach (Fig. 2) suffers from sunny day overheating, short carry through, and high glare interiors.

The MIT Solar Building 5 has shown the problems associated with direct gain approaches can be overcome with new architectural finish materials that emphasize their thermophysical properties. Three new materials are demonstrated in the building: 1) a transparent window insulation, 2) a glare modulating and light directing louver, and 3) a ceiling tile that stores heat latently.

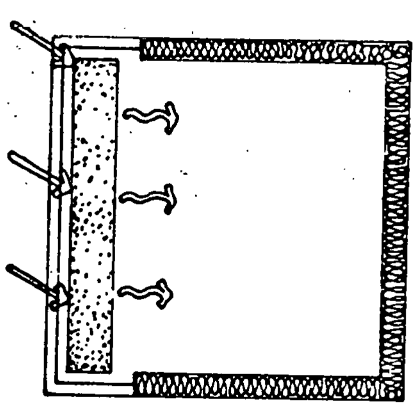


Fig. 1. INDIRECT GAIN

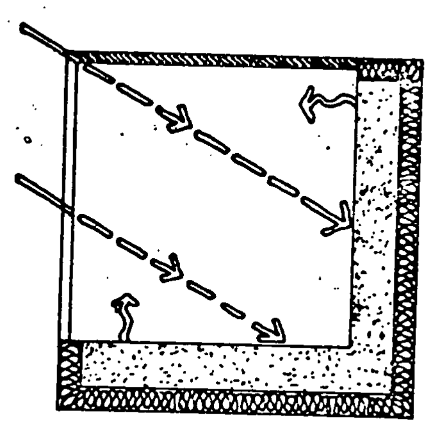


Fig.2. DIRECT GAIN

The MIT Solar Building 5* was completed for monitoring purposes on January 27, 1978. Building materials and construction labor were paid for by the MIT Godfrey Cabot Fund for Solar Research. The 866 ft^2 building (Fig. 3) is a single, one story space that is used as an experimental studio/classroom (Fig. 4) by the MIT Department of Architecture. Solar heating is

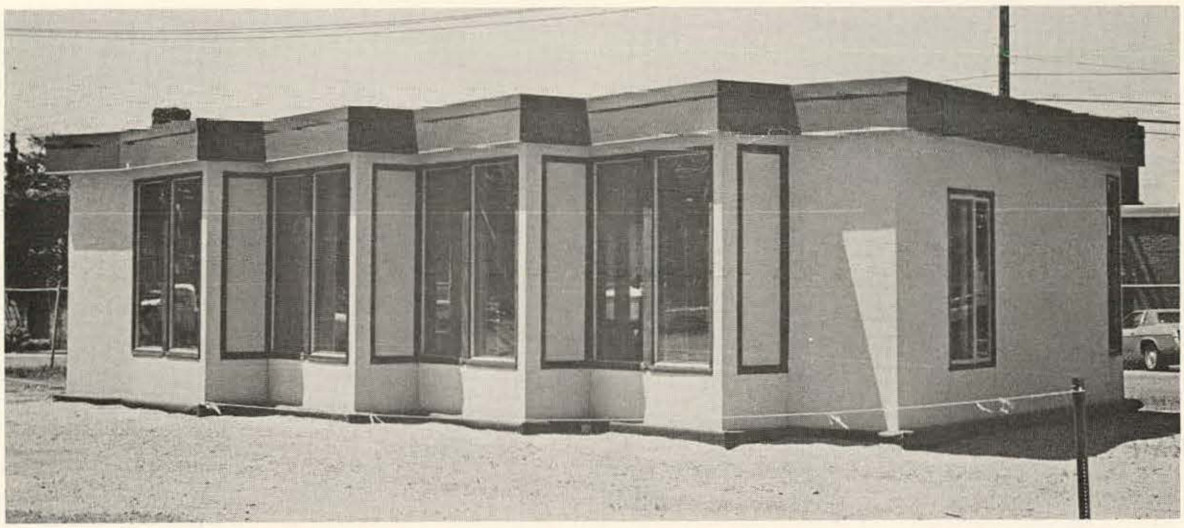


Fig. 3. Exterior South Elevation

Fig. 4. Interior

*Solar Engineer: Timothy E. Johnson; Architects: Timothy E. Johnson, Charles C. Benton, and Stephen Hale accomplished by directing insolation to dark colored ceiling tiles containing a phase change material for thermal storage and temperature regulation (Fig. 5). Sunlight is placed on the ceiling by exceptionally narrow, upside down reflectorized venetian blinds that are fitted between the South facing glazing. The blinds eliminate glare without sacrificing view. Heat losses through the double glazing are reduced by a factor of 3.5 by mounting "Heat Mirror" between the double glazing. The "Heat Mirror" is so named because it reflects 75% of the room temperature infrared radiation back into the heated space while remaining transparent to visible and solar radiation (70-75% solar transmission).

The 1978-1979 performance measurements showed the sun supplied 62% of the building's heating requirement while an additional 13% of the load was supplied by internal gains from the lights. During this period the building was heavily used 5 days and one night a week by students and public visitors.

Building Description

The flat roof, tan stuccoed building is located at 270 Vassar Street on the MIT Cambridge campus. The site, being aligned with the street, faces South-East. The windows are faced directly South by turning the building within 20° of South and finishing the turn by serrating the southern elevation of the building (Fig. 6). The resulting four window bays contain 180 ft^2 of glazing. The two West most bays contain low iron PPG Glass Lites (91% normal solar transmission) and the two East most bays contain standard production float glass (88% normal solar transmission) furnished by PPG Industries. Additional natural light and view is furnished by two 15 ft^2 double glazed casement windows in the North wall and one double glazed casement (15 ft^2) in the East wall. The classroom is entered through an unheated North facing 49 ft^2 vestibule (Fig. 7). The 817 ft^2 heated classroom has a 10 foot high ceiling.

Heat is stored latently in the southern half of the 817 ft^2 special ceiling and in the 88 ft^2 of the thermal storage tiles placed on the southern settees. The four settees provide cabinet space for storage of classroom materials and additional seating area. Heat is also stored

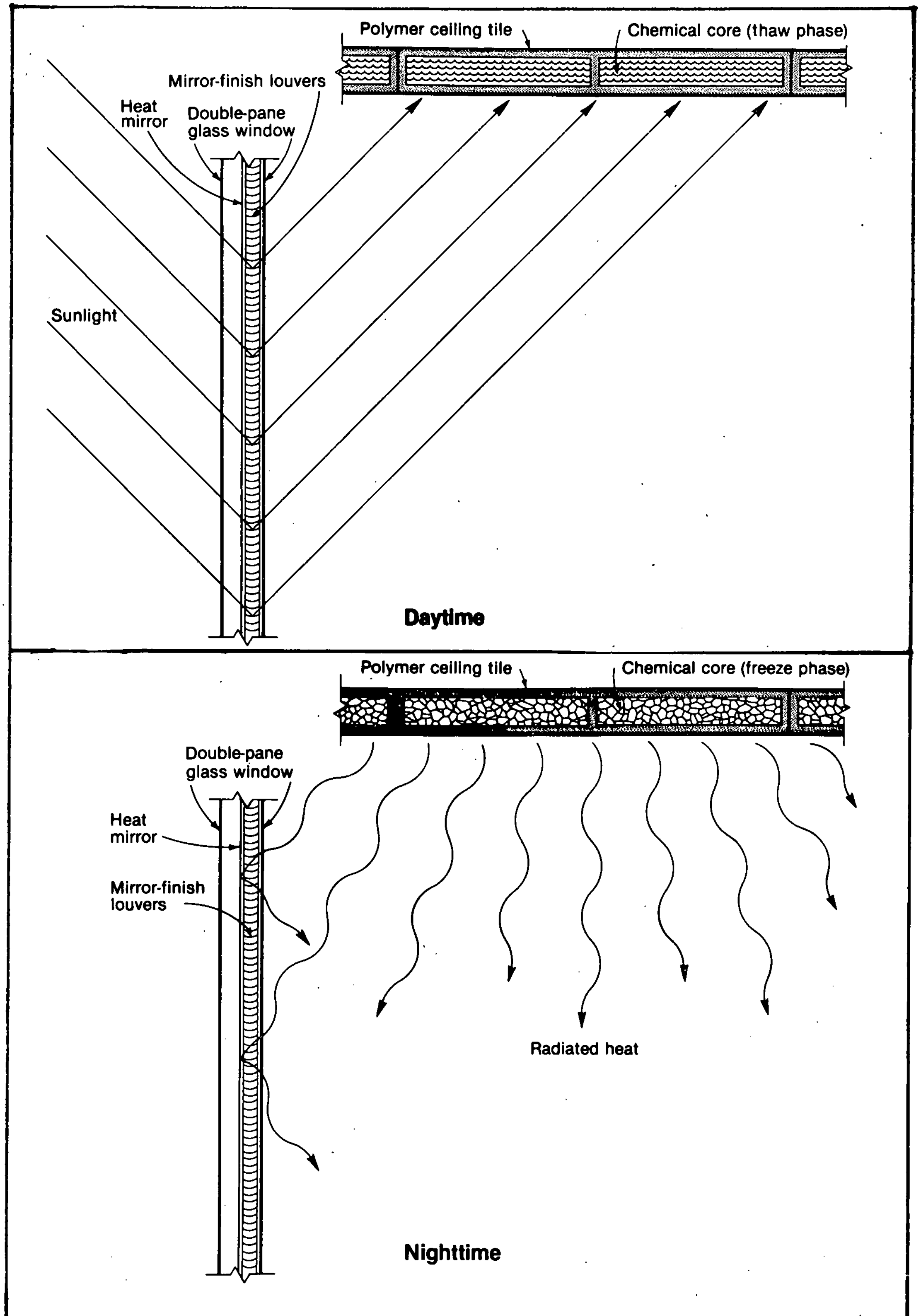


Fig. 5. Wall section/Ceiling section

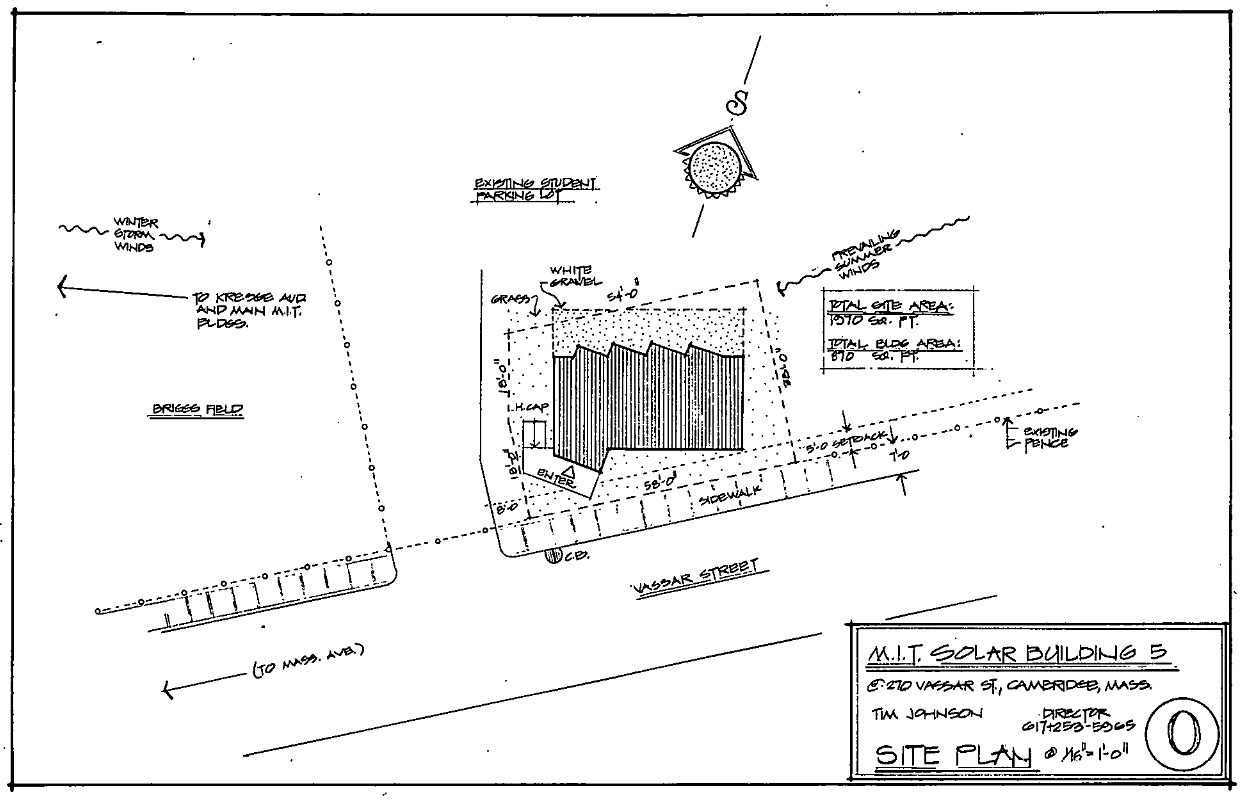


Fig. 6. Solar Building 5, site and orientation

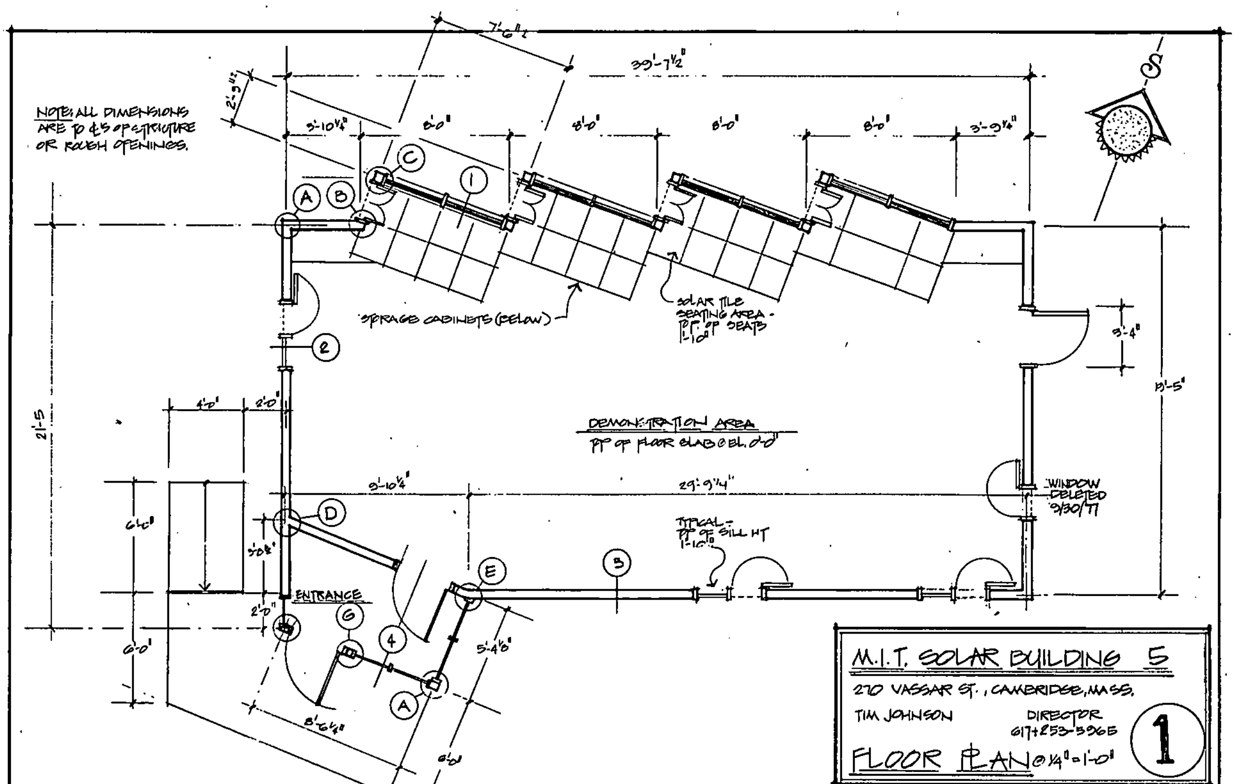


Fig. 7. Solar Building 5, floor plan

sensibly in the 5/8" thick dry wall and the 4" slab on grade. The slab is poured on 2 inches of gravel on compacted earch. Edge losses are minimized with 4" thick Styrofoam[R] SM perimeter insulation. Rather than skirt the building with 4' deep board insulation, the 4" thick insulation only goes down 18" to the depth of the perimeter 18"x18" concrete piers and then extends outward 3 feet horizontally below grade (Fig. 8). The soil heat conduction paths are just as long as the paths in the conventional full vertical sections, but excavation costs are minimized by using the 90° turn system. No frost heaving was observed during this heating season.

Because of the fire codes, the building was framed with 18 gauge Wheeling steel studding rather than wood studding. The studding was joined with sheet metal screws so future alterations could be easily accomplished. The thermal bridging in the 2"x6" steel studs and 12" sheet metal ceiling joists was brought under control with exterior board insulation. The exterior walls are made up of 1/2" exterior gypsum, 1" Styrofoam[R] and a proprietary fiberglass reinforced stucco weather skin called Dryvit. The Dryvit forms a continuous membrane that cuts down infiltration losses. The ceiling joists are covered with steel decking, 2" of Styrofoam[R] and a built-up tar and felt roof (Fig. 8). All this exterior insulation makes the steel behave thermally like wooden construction. The bulk of the insulation is accomplished with 6" of fiberglass batt in the walls and 11" in the ceiling. Vapor barriers are used throughout the building. The walls are double caulked at the foundation and the soffitt to minimize infiltration. Measured winter thermal losses due to infiltration and conduction are 270 BTU/hr°F or 6480 BTU/DD. TABLE 1 shows the computed building thermal losses from conduction.

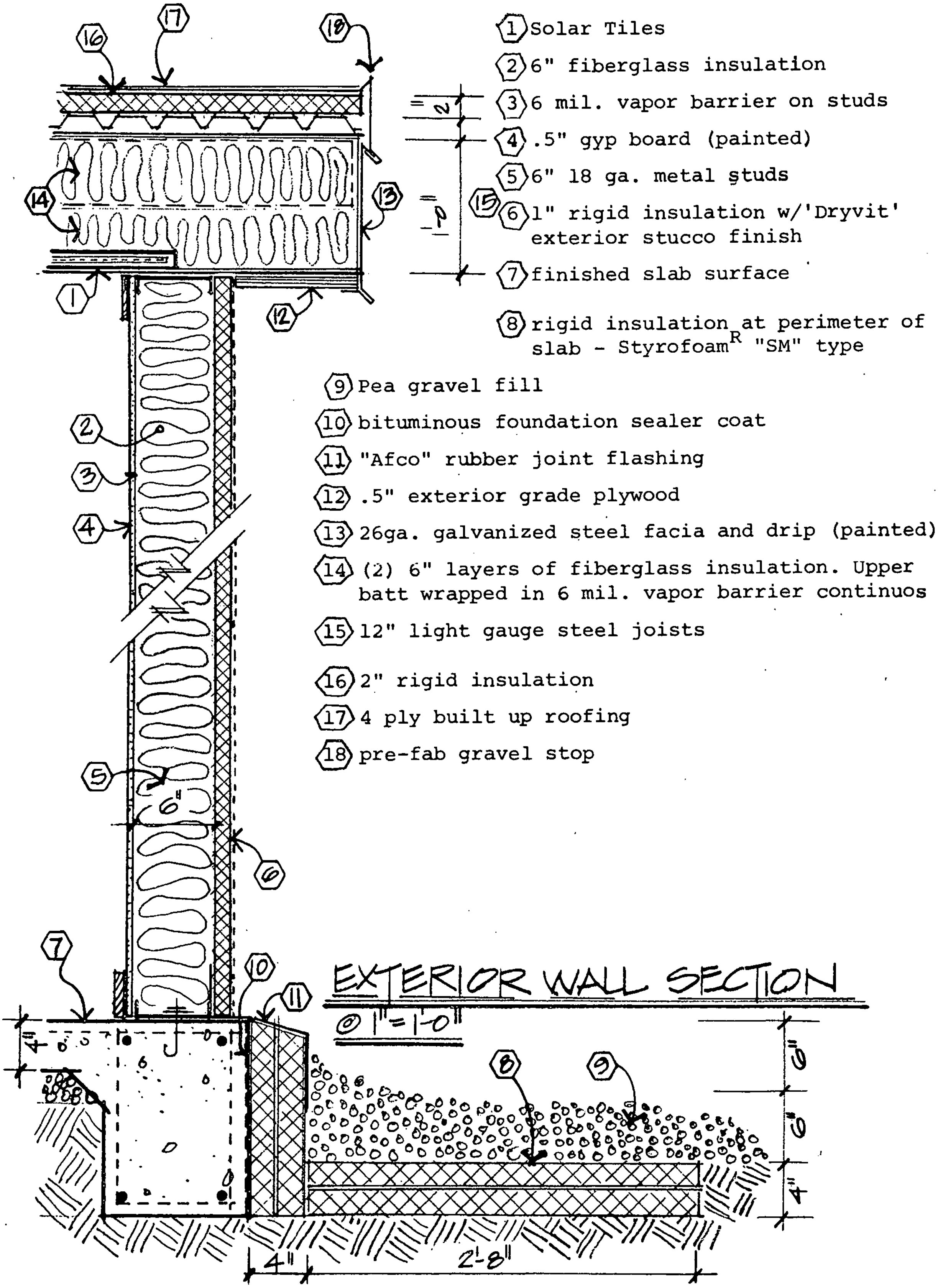


Figure 8 - Wall and Foundation Section

TABLE 1. Solar 5 Conduction Losses

Element	$U(\frac{BTU}{hrft^2 °F})$	X	$A(ft^2)$	=	UA(BTU/hr°F)
Heat Mirror Windows	0.18		180		32.40
Double Glazed Windows	0.55		45		24.80
Foundation and Edge Loss	0.05		203		10.16
Slab Loss	---		---		51.16
Walls	0.05		987		49.35
Stud Leakage	----		---		11.00
Ceiling	0.026		841		22.13
Doors	0.2		42		8.4
			TOTAL		209.45

The measured infiltration rate varied between .33 and .50 air changes per hour. The total measured heat conduction coefficient of 270 BTU/hr°F represents a thermal load that is typical of energy conserving single family detached housing for the Boston area. This can be understood by converting the above figure into a dialy load per square foot of living area (270/BTUhr°F x 24 hrs/day)/866 ft^2 = 7.48 BTU/Deg.Dayft^2).

HUD MPS minimum thermal standards state a single family detached residence in the Boston area should exhibit a load of 7.1 BTU/Deg.Dayft^2 based on an average living area of 1600 ft^2. The Solar 5 thermal load of 7.48 BTU/Deg.Dayft^2 is slightly higher due to the larger surface to volume ratio encountered in a smaller building of the Solar 5 type.

One of the goals of this experiment is to show multiple family housing can be solar heated using the three new building materials. In fact, the roof of the MIT Solar 5 building is flat and windowless to demonstrate another living unit could be placed on top of Solar 5 without affecting the solar heating fraction. HUD states the thermal load for low-rise multiple family housing sould be 6.7 BTU/Deg.Dayft^2. In order to model this situation the Solar 5 thermal load must be reduced accordingly. Once heat mirror is added to the casement windows and wall to wall carpeting is installed the heat conduction rate can be reduced to 240 BTU/hr°F or 6.68 BTU/Deg.Dayft^2. Thus, a range of housing structures can be thermally modelled with the Solar 5 building.

New Materials Description

Each of the three new materials demonstrated in the Solar 5 building emphasize various thermal-physical properties necessary to accomplish comfortable, direct gain solar heating of significant proportions.

a. Heat Mirror

The southern windows are (Fig. 9) actually a composite of several materials. The assembly, working from the outside in, is Float Glass (furnished by PPG Industries), 3/4 inch air gap, double sided Heat Mirror (developed and fabricated by Suntek Research Associates, Corte Madera, CA), modified louvers (fabricated by Rolscreen Company) in a 3/4 inch air gap, and Float Glass. The overall calculated heat conductance for the glazing assembly is 0.18 BTU/ft^2hr°F.

The major contribution to this low heat conductance is the Heat Mirror (developed by Day Chahroudi and John Brooks of Suntek); a transparent insulation composed of a Mylar substrate coated on both sides with a vacuum deposited transparent selective surface. The coating initially exhibited an emissivity of 25% to long wave thermal radiation and a 70% transparency to solar radiation. Overall solar transmission of the southern glazing was initially 59%. The view through the window assembly is clear and undistorted.

The Heat Mirror acts as a selective transmitter of radiation. The atoms in the coating are arranged in such a way that the short wave radiation (solar energy) can get through, but the returning long wave radiation (thermal radiation emitted as infra-red from the heat producing interior building surfaces) cannot pass (Fig. 10). The returning thermal energy is actually reflected into the room by the low emissivity surface. The Heat Mirror is not a perfect reflector (25% gets absorbed), so the other side of the transparent insulation is also coated with the same low emissivity material to prevent the re-radiation of any absorbed infra-red. Sixty percent of the heat loss through normal windows is due to radiation traffic (via absorption and re-emission of I.R.). The Heat Mirror stops the majority of the radiation traffic, and because the Heat Mirror tension mount employed in the Solar 5 building creates a second air gap inside the lites of glass, the overall thermal resistance of the assembly adds up to 3.5 times the thermal resistance of double glazing.

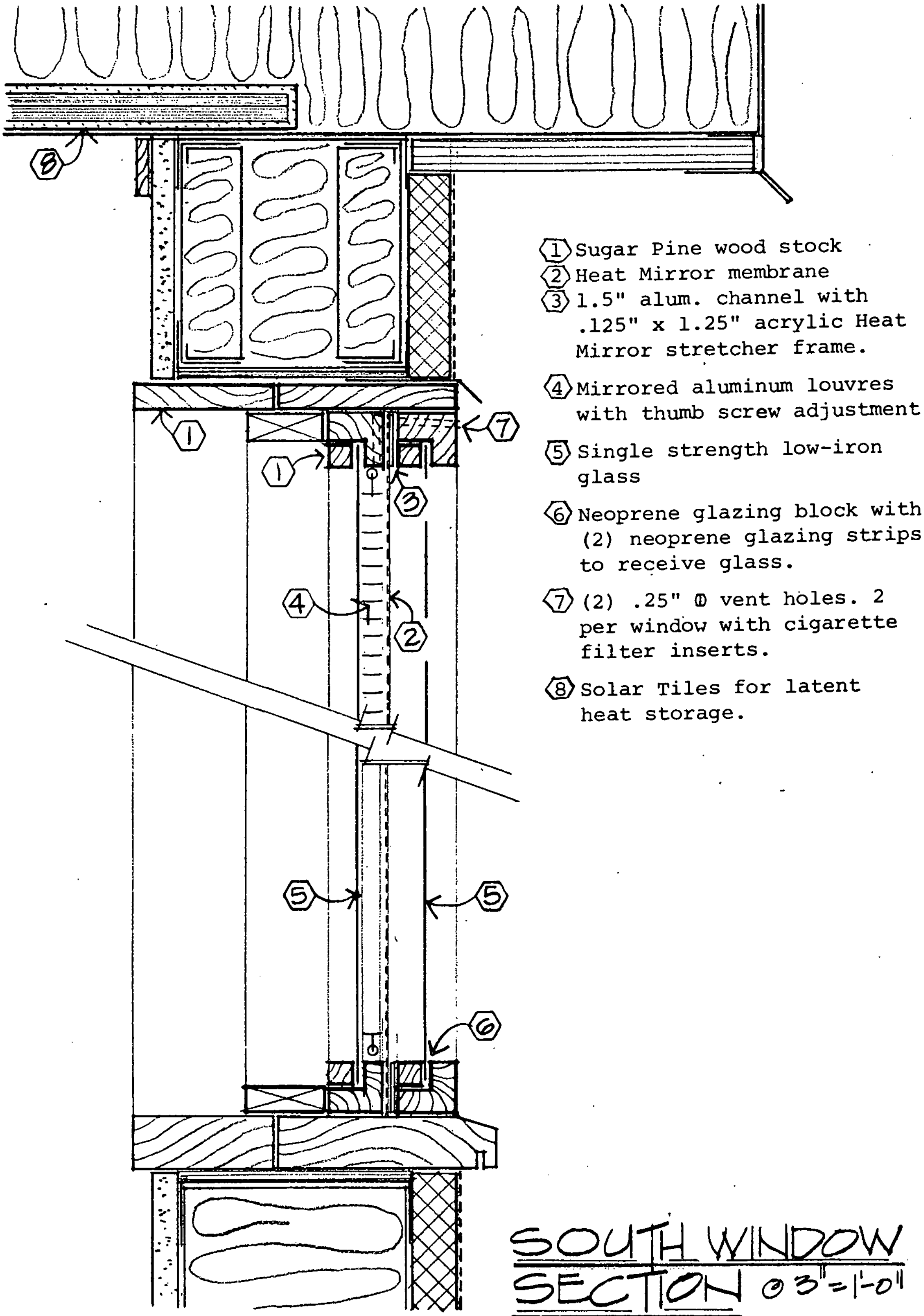


Figure 9 - Section thru solar window assembly

The quantity of electricity used by the auxiliary heaters was registered by a kwh meter and summed up at the end of the month. Heat supplied by the incandescent lighting was significant. Timers were used to cycle 1 kw of lights on for 6 hours per evening in order to simulate what would be used were the building regularly inhabited. In addition, whenever extra lighting was used, the power consumption of the fixtures and duration of its use was logged manually in a book. The results of the SHF calculations are shown in Table 2.

The gross SHF of 44% was substantially lower than what we had expected from last year's performance, which showed a gross SHF of 70%, mainly due to bad weather. A prediction based on careful analysis of historical weather data is presented below which shows how the building should perform under normal environmental conditions.

This was a bad year for solar heating in Boston. While the heating load for the area was about normal, the level of solar insolation was down more than 20%, (Nov-April). In addition, the transparent heat mirror assembly in Solar 5's South facing windows started to corrode soon after installation (summer 1978). The bulk of the corrosion occurred that summer and by the time October arrived, its overall transmissivity had degraded by an agerage of 5.5%, as measured with a radiant flux meter. Also, the north casement windows were supposed to have had a heat mirror film added to the glazing, but manufacturing problems held up installation. They are now slated to be installed in the Fall of 1979. This added an additional load of 5% to the building.

To get a normalized SHF we adjusted the measured load and solar insolation values by factors which represented the deviation from the 30 year historical norm. In addition, we adjusted for heat mirror deterioration and higher than normal UA due to the missing casement windows' heat mirror. The data used to determine the monthly temperature deviation and historical norms was obtained from the National Oceanic and Atmospheric Administration, Environmental Services. Local Climatological Data is published for Boston on a monthly basis by NOAA from information supplied by the Meteorological Observatory at Logan Airport. The method used to compare our measured insolation levels vs. the norm is documented in Appendix IV and the results are summarized in Table 2. An example of how we "normalized" each month is given in Appendix V.

The results of the analysis (Table 2) indicate that the Gross Solar Heating Fraction for a properly installed heat mirror and for normal weather conditions would be 62%. An additional 13% of the heating load will be met by the internal gains from lights and appliances. Scheduled building improvements that are discussed in the last section will bring the Gross SHF up to 73%.

TABLE 4. SEASONAL SOLAR HEATING FRACTIONS

Month	Load kwh	Aux. E. kwh	Light Used kwh	Solar Gain %	Gross SHF %	Net SHF%	Load[1] %	Solar[2] Insol.	Heat[3] Mirror %	UA[4] %	Normalized[5] Load	Normalized[5] Solar Gain	Normalized[5] Gross %	Normalized[5] Net %
Sept	142	0	0	>142	100	100	--	--	-5.5	-5	135	>135	100 (100)	100 (100)
Oct	235	0	0	>235	100	100	--	--	"	"	223	>223	100 (100)	100 (100)
Nov	1061	223	129	709	67	76	+9.7	-12	"	"	919	850 (925)	92.5 (100)	100 (100)
Dec	1613	627	216	770	48	55	-7.9	+8	"	"	1668	752 (819)	45.2 (49.3)	52 (57)
Jan	1730	1143	192	395	23	26	-10.5	-48.2	"	"	1841	802 (873)	43.7 (47.5)	49 (53)
Feb	1937	1011	201	725	37	42	+22.8	+1.5	"	"	1502	751 (818)	50 (54.5)	58 (63)
Mar	1055	418	203	434	41	51	-18.7	-32.5	"	"	1236	680 (741)	55 (60)	66 (72)
Apr	879	364	195	320	36	47	0	-30.5	"	"	837	491 (535)	59 (64)	77 (83)
May	155	0	0	>155	100	100	-	-	"	"	148	>147	100 (100)	100 (100)
Season	8807	3785	1136	3882	44	51	-.7	-18.3	-5.5	-5	8509	4831 (5215)	57 (61.5)	66 (70.7)

1. Load Deviation - % difference in experienced load vs normal load (+ greater load, - less load); 2. Solar insolation deviation - % difference in solar insolation levels; vs historical norm. See text for explanation (+ more sun, - less sun); 3. Heat mirror induced reduction in solar gain- accounts for reduced transmissivity - 5.5%, due to corrosion on heat mirror; 4. UA correction for north casement windows - accounts for increased heat loss due to delay in installation of heat mirror on north casements. 5. Normalized load, solar gains, and SHF - numbers in parentheses refer to insolation levels and SHF if the building were moved outside the Boston urban area.

INFILTRATION EXPERIMENTS

Air infiltration can represent a substantial portion of the heating load for a building, and in some older homes may actually account for 40% of the total heat load. Obviously, considerable savings in energy and money can be realized by minimizing this component of the heating load.

Infiltration is extremely difficult to quantify accurately and simply because it is a function of building configuration, orientation, windows, temperature differential and perhaps most importantly,the quality of workmanship in construction. Wind speed and temperature difference are the main environmental variables that influence infiltration. A study (1) of exposed and unexposed housing showed that wind became the predominant cause of infiltration very quickly as the velocity moved past 5 mph. In particular, it was shown that when the log of $v^2/\Delta T$ was greater than 0.3 the wind predominates. Less than 0.3 and the temperature difference is the main force driving infiltration. Another study (2) simplified their relationship as follows:

$$I = A + BW + C\Delta T$$

where

I = Infiltration rate

W = Wind velocity

ΔT = Temperature differential

A,B,C = Constants which mathematically characterize the house

This is telling us that both changes in wind speed and ΔT affect the infiltration rate in a quasi-linear fashion whose slope is dependent on the individual house characteristics as quantified by A,B,C.

Two popular methods used by designers to estimate loads due to infiltration (see ASHRAE Handbook of Fundamentals) are the crack estimation methods, and the air exchange rate method. The former is probably the more accurate one, but is quite tedious. Both are approximations at best, and were by no means accurate enough for us to gauge how tight our structure is.

1. J. Dick, D. Thomas, "Ventilation Research in Occupied Houses," J. Institute of Heating and Ventilating Eng., 19,306-326 (1951).

2. Coblentz, and Achenbach, P.R., Field Measurements of Air Infiltration in Electric Heated Houses, ASHRAE Trans., 69, 358-365 (1963).

The method employed at Solar 5 is one of the easiest (and at present most favored) methods of directly quantifying air infiltration which uses tracer gas that is released into the room in question. The initial concentration of the gas (C_o) decays as a function of the room's characteristic infiltration rate (K, air change per hour) to a lower concentration (C) after a fixed time of hours (T). The drop in concentration follows a first order decay according to the expression

$$\frac{C}{C_o} = e^{-KT}$$

where

$$K = -\frac{1}{T}(\ln\frac{C}{C_o})$$

Although there are many gases whose concentration can be observed over time, there are very few which prove suitable for use as a tracer gas in a residential infiltration experiment. Suitable tracer gases should exhibit most or all of the following properties:

1. The gas can be detected accurately in the lowest possible concentrations.
2. The method of detection has negligible cross-sensitivity for other constituents in air.
3. The tracer is inexpensive and readily available.
4. It is not adsorbed by walls and furnishings.
5. It has high chemical stability and does not decompose or react with building surfaces or constituents of air.
6. It has no adverse health effects in the concentrations used.
7. It is neither flammable or explosive.
8. It has a density comparable to air.
9. It is not normally present as a background constituent in air, and there is no source in the building under test.

To this list might be added that the analytical method is readily available, inexpensive and lends itself to automation.

A gas which does satisfy most of these requirements is sulfur hexaflouride (SF_6). Although the SF_6 is about 5 times as dense as air, it has been reported that in experiments in which hydrogen was used as a tracer gas, the measured infiltration rate stayed the same even though there was a molecular weight ratio of 1 to 36 (3). The molecular densities appear to be a significant problem only when the time span becomes much longer, e.g. days instead of hours.

SF_6 can be measured using a gas chromatograph employing an electron capture detector. Concentration of a few parts per billion can be accurately detected. We used a portable gas chromatography set-up with a built in electron capture detector manufactured by Analytical Instruments of Fowlmere, England. It is no longer available on the market. However, a company in LaJolla, California, called Systems, Science and Software, markets a similar and upgraded version of the same instrument. It lists for about $4200.

The measured infiltration rates along with the environmental conditions are listed in Table 4. We found that the infiltration rates ranged from .11 air change per hour (ΔT = 12°F) to .26 air change per hour (ΔT = 20°F). The wind velocities during all the measurements were about 5 MPH. These are conditions typical of early fall and late spring. Unfortunately, we do not have enough data with which we can accurately predict how the house will behave under average winter conditions (ambient - 40°F, winds 12 mph) or under design conditions (e.g., ambient - 0°F, winds = 20 mph). We will compile a much more extensive set of data this winter.

However, when the ΔT versus observed infiltration rate from this year's data is plotted, extrapolations from the line which is generated indicates that for:

ΔT = 25°F (average winter condition)	K = .34 ac/hr
ΔT = 30°F	K = .44 "
ΔT = 60°F	K =1.00 "

See FIG. 17

3. Tamara, G.T.,"Measurements of Air Leakage Characteristics of Home Enclosures", ASHRAE Trans., 81, 202 (1975).

TABLE 5. SOLAR 5 INFILTRATION MEASUREMENTS

Date	T_{hrs}	Average ΔT (°F)	C_o (ppm)	C (ppm)	Wind (mph)	Infiltration Rate (K) (air changes/hr)
May 11, 12	9.8	16	11	2.5	5 (E)	.15
May 6, 7	8.5	13	9	3.25	5 (NW)	.11
May 5	1	20	7.1	5.4	5 (NW)	.26
May 4	1.17	12	9.5	8.2	5-8 (NW)	.11

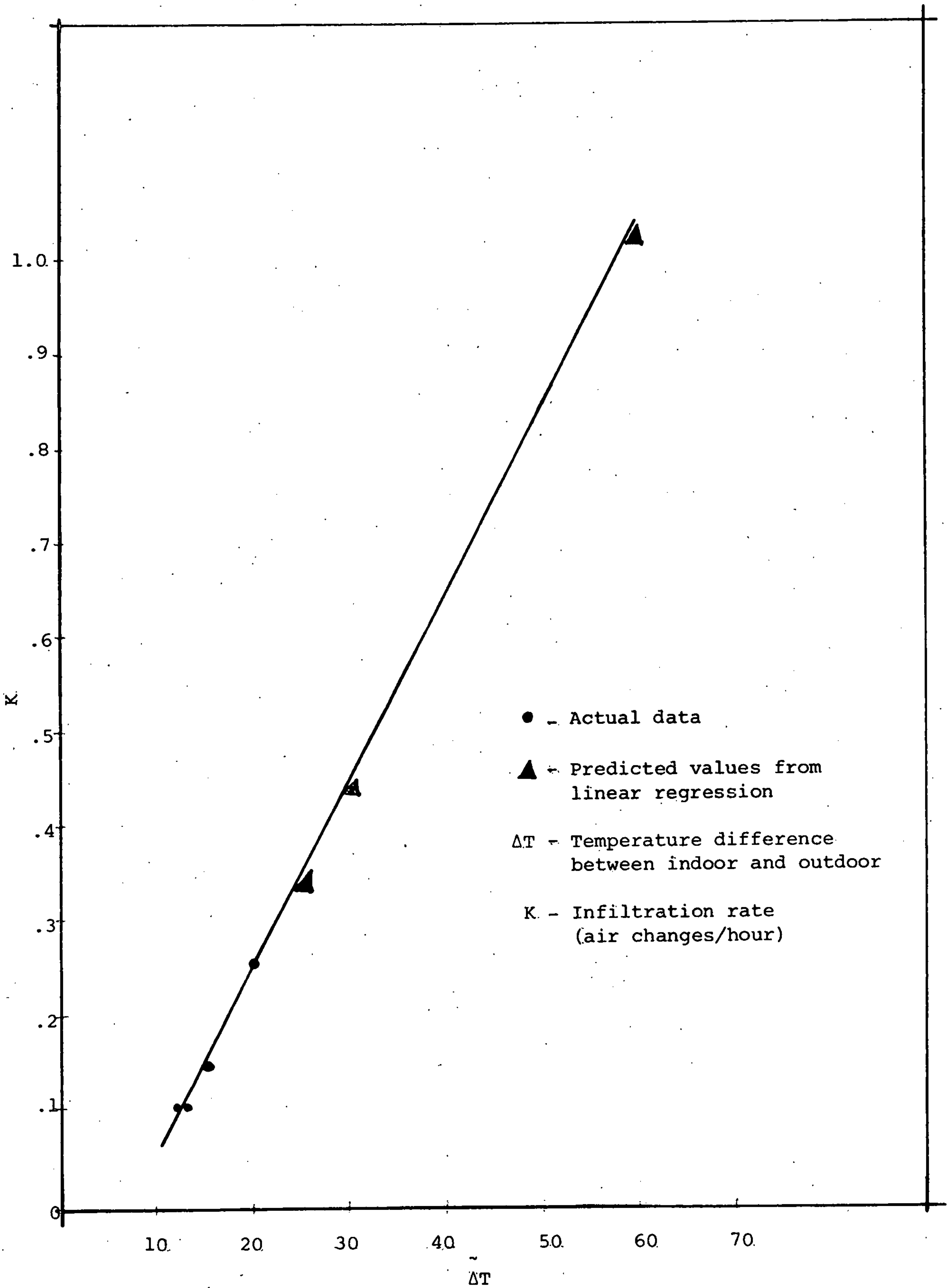


FIGURE 17. Predicted infiltration rates for various ΔT is at fixed wind velocity (~5 mph)

This assumes the winds are moving at only 5 mph which was true for our test conditions. It is obvious that the infiltration rate will increase as the winds approach their average winter velocity (12 pmh). We anticipate that the infiltration rate under average winter conditions ($\Delta T = 25°F$, winds = 12 mph) will be about .4-.45 ac per hour.

These infiltration rates are quite low compared to the typical house and indicate how much tighter houses can be made if proper constructions techniques are followed.

HEAT STORAGE PARTICIPATION BY

THE BUILDING'S THERMAL MASSES

The southern windows in the building are designed so that most of the incoming solar radiation is reflected by reflectorized louvers up to the ceiling plane. As shown in Fig. 18, the tiles containing phase-change material (PCM) convert 85% of the incident light to heat at the tile surface, the remaining 15% being reflected to the walls and floor. The

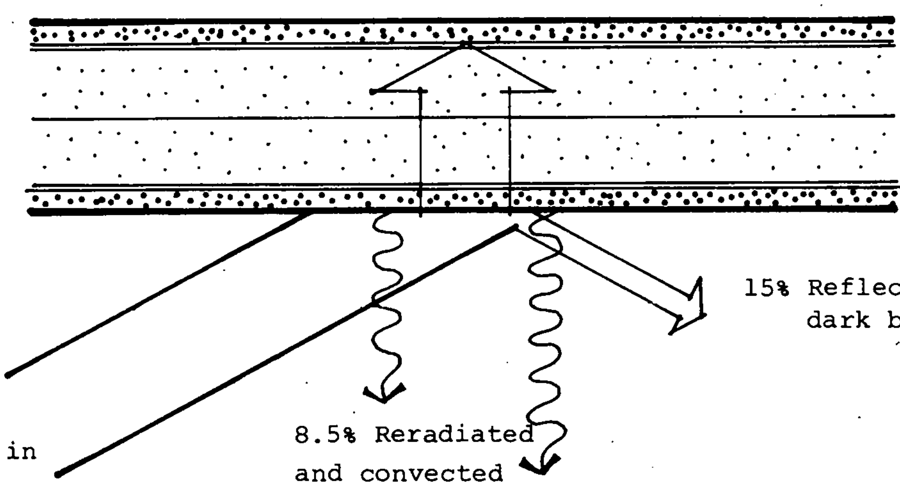


FIGURE 18. - Energy flows at ceiling tiles

white sheetrock reflects about 70% of this light again, which then strikes the slab or ceiling tiles. The slab also receives some reflected sunlight directly from the tiles. The diffuse component of the insolation primarily strikes the ceiling and walls. Little reaches the slab directly, as the slab does not "see" the sky vault due to the louvers. Some does reach the slab directly by reflection from other surfaces. Although 85% of the solar energy is converted to heat at the tile surface, 8.5% goes into heating the room instantly. The remaining 76.5% is conducted into the phase-change material. This heat flow split can be analytically determined by noting the heat flow conductance into the room by radiation and convection (for heat flow down) is 1.6 BTU/Hr°Fft^2. The conduction through the 1/4" polymer tile is 14.4 BTU/Hr°Fft^2. Therefore, 90% of the heat generated at the tile surface is conducted into the interior (.9 x .85 = 76.5% of the incident energy conducted into the tiles). 8.5% of the incident energy is lost to the room air and surface by radiation and convection.

As part of our analysis of the building performance, we wanted to determine what effect carpeting would have on the room air temperature swings. This is a real concern due to the fact that most owners of such a house would not tolerate concrete floors in living spaces. If the slab were storing and releasing a significant portion of the heat, then covering it might create an intoleably warm room due to the loss of its temperature buffering capacity. In such a case, choice of flooring would be limited to ceramic tile or linoleum type materials which would preserve thermal coupling to the slab.

We examined 5 days during this past heating season which are illustrated in Figures 19-23. The days were typically very sunny, but the weather was such that the auxiliary heat had to be called on (except for April 27) before the beginning of the next morning.

The temperature inside the building typically begins to climb soon after sunrise and sharply after about 9:30 am. By 1 pm, the temperature in the storage elements have peaked and begin to fall off. The slab, however, lags about 1 hour behind the other surfaces and typically remains at a constant temperature for about 5 hours. There are a number of interesting trends taking place through this period and are worth noting.

First, the temperature at which the solar tiles peak (giving a relative indication of how extensive the phase change is) gradually drops as we move from winter months of January and February into March and April. This is due to two things. First, the drop in beam transmission accelerate s as we enter the month of March and is quite low in the middle of April due to the angle of incidence of the beam radiation with respect to the windows. In fact, on April 1, the average angle of incidence is about 60°, causing a 10% reduction in solar gains over the previous month. (This assumes that the shape of the heat mirror transmissivity vs. angle of incidence curve is similar to that of glass). In addition, the design of the louvers is such that after the equinox some of the reflected sunlight strikes the underside of the louver immediately above it. This light is for the most part lost. This causes a substantial reduction in solar gain for April and May which is mostly offset by the reduced load. These 2 problems

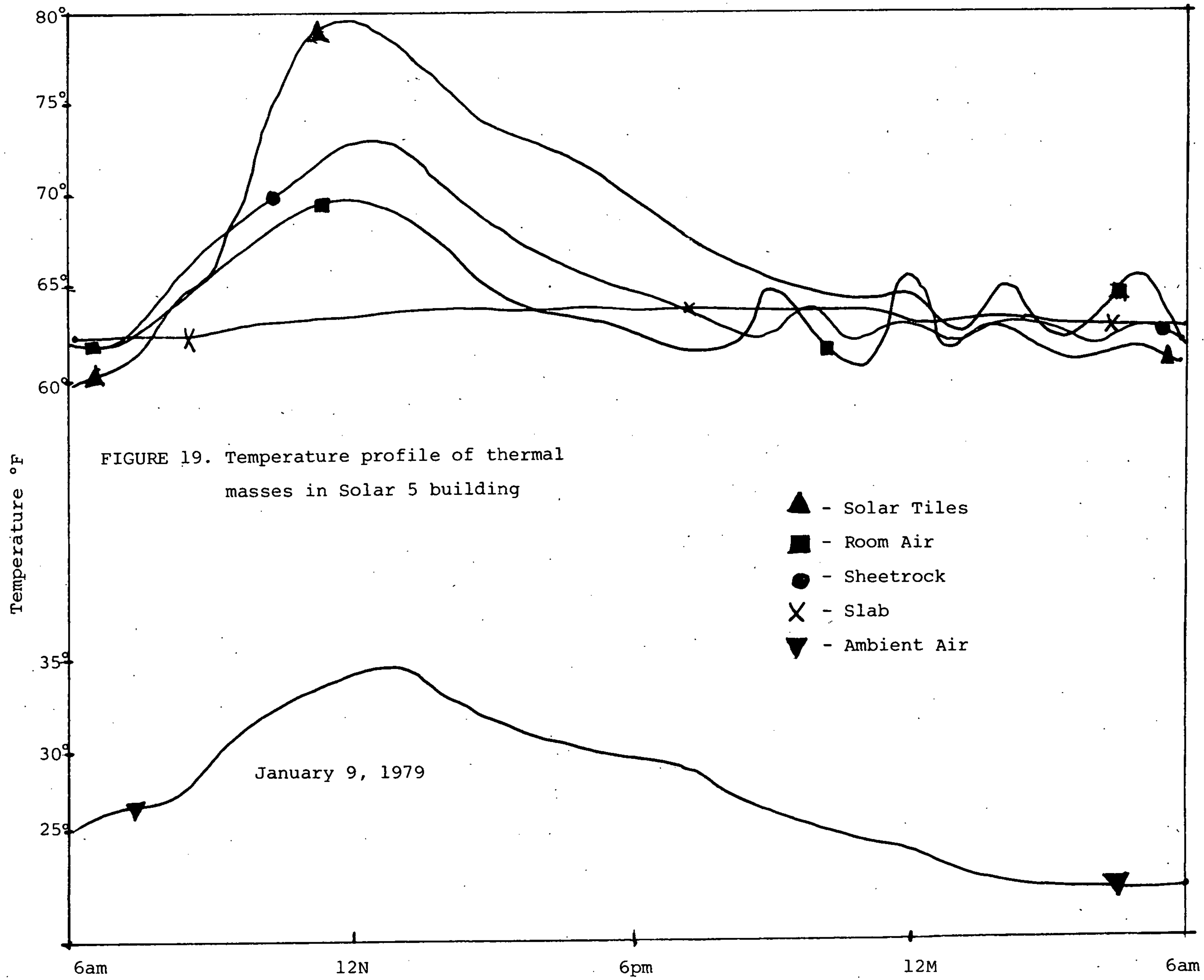


FIGURE 19. Temperature profile of thermal masses in Solar 5 building

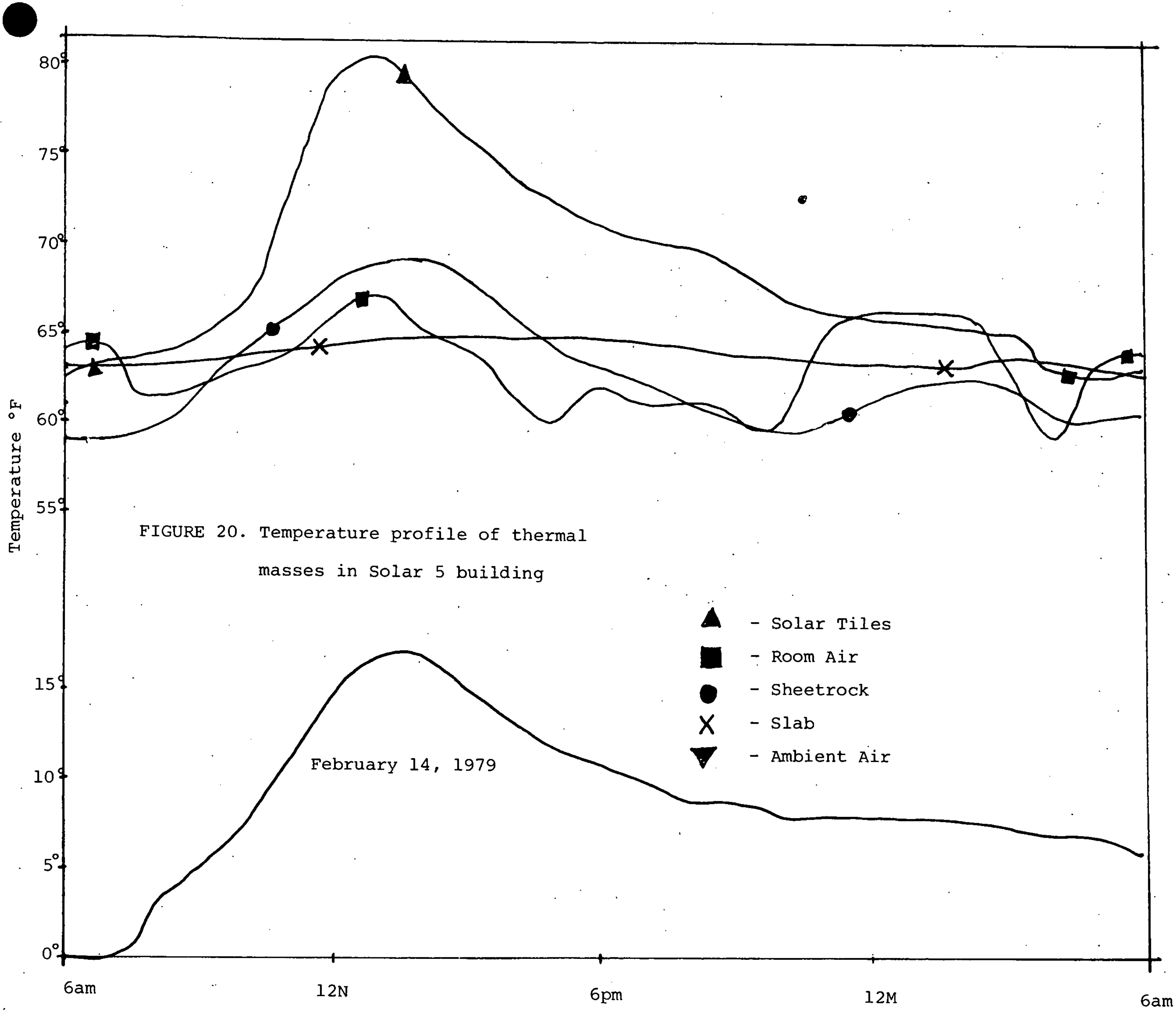


FIGURE 20. Temperature profile of thermal masses in Solar 5 building

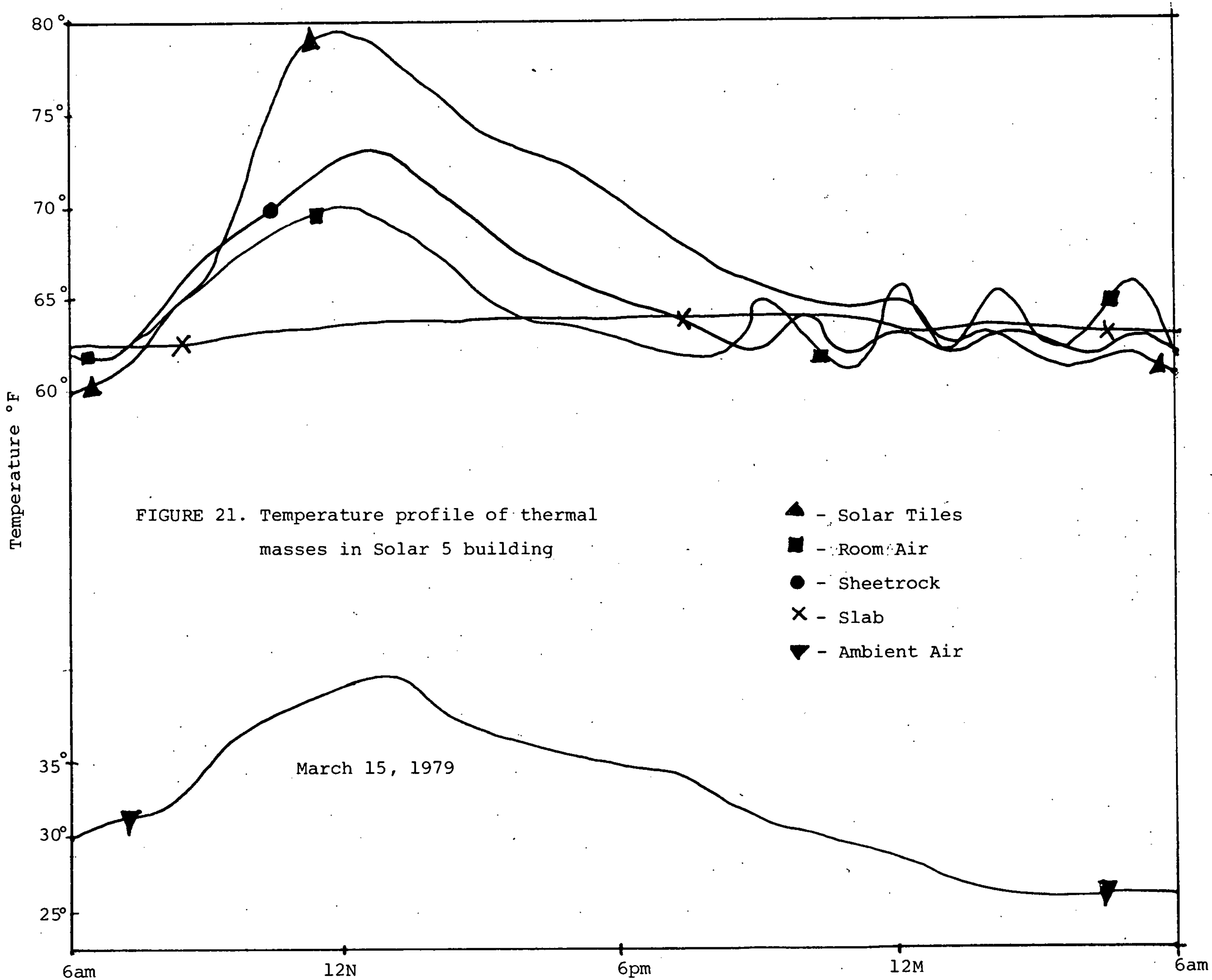


FIGURE 21. Temperature profile of thermal masses in Solar 5 building

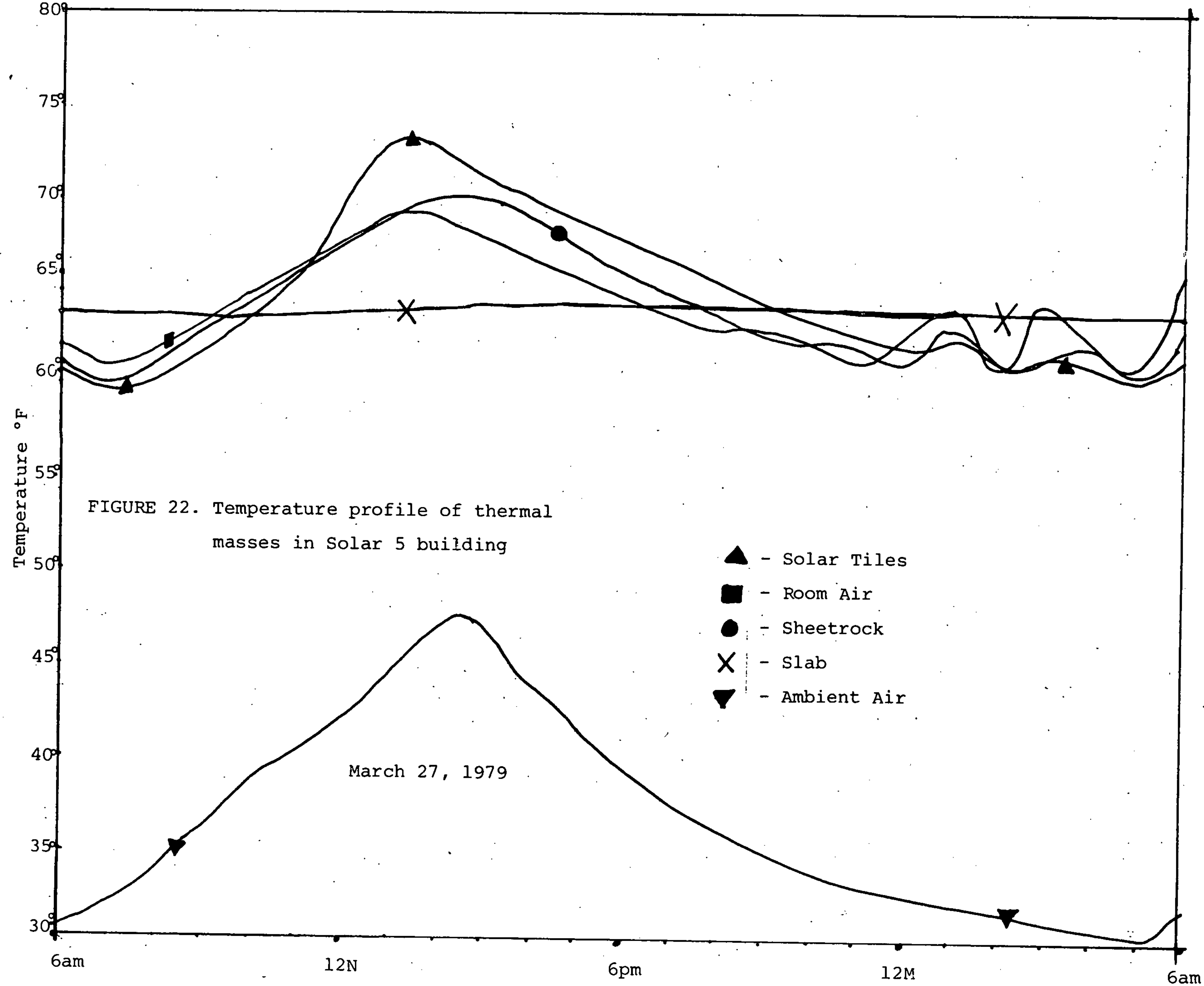


FIGURE 22. Temperature profile of thermal masses in Solar 5 building

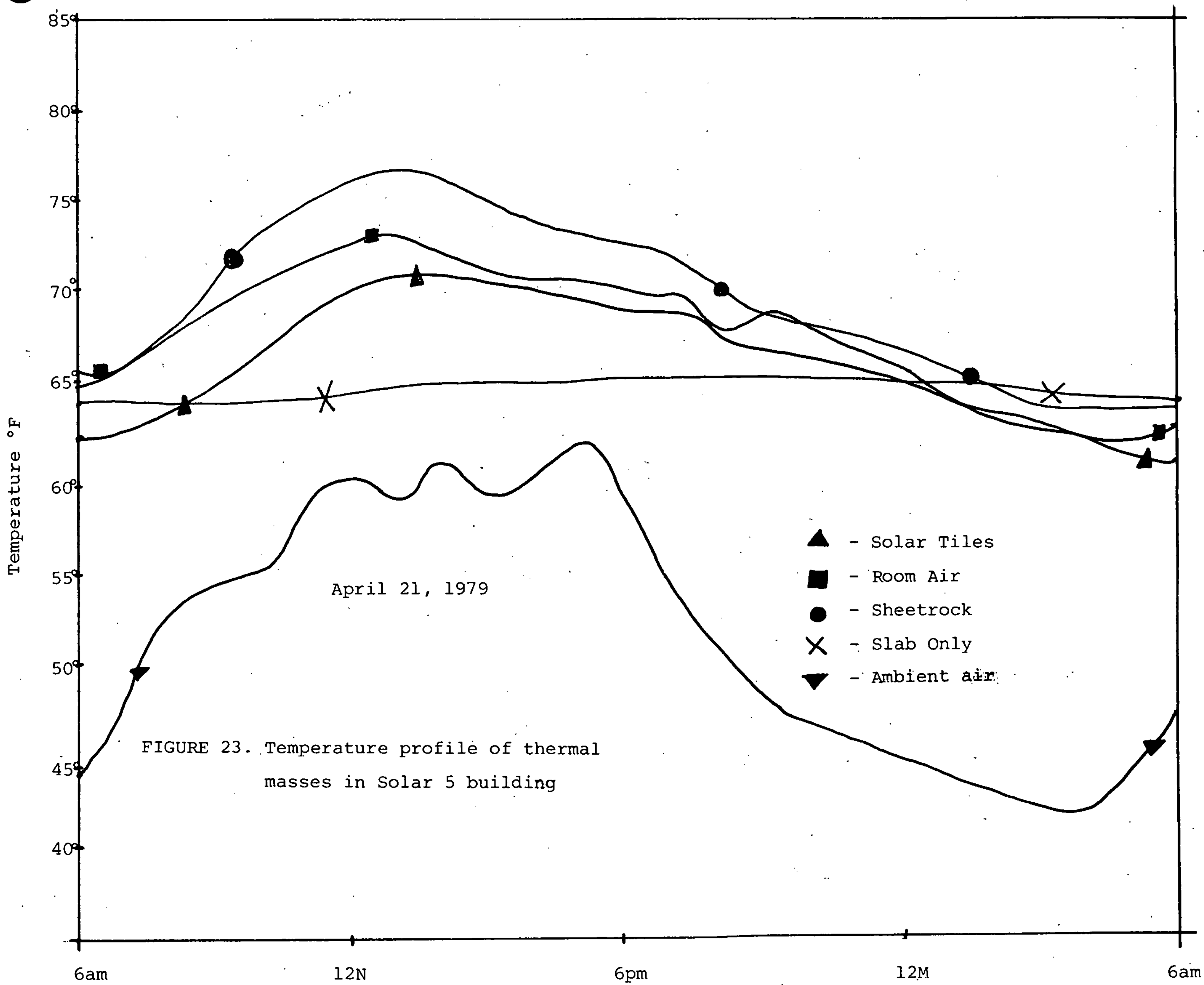


FIGURE 23. Temperature profile of thermal masses in Solar 5 building

contribute to the reduction of insolation to the tiles to the point that by the end of March it is questionable whether the tiles are actually undergoing any phase-change at all or are acting merely in a sensible manner. It should also be recognized that we are talking about only the front half of the ceilng; the tiles which occupy the back half of the room undergo only slight temperature fluctuation and apparently never change phase. The sheetrock undergoes a daily ΔT of about 10°F, peaking out at 1 pm. The sheetrock is more heavily influenced by ambient conditions than the ceiling tile due to the higher "U" of the wall. With this in mind, it appears that the wallboard is most active in January and February. On February 14, even with an average outdoor temperature of 7°F, the wallboard still undergoes a ΔT of 10°F, whereas at the end of March the wallboard only undergoes a ΔT of 10°F, while the ambient temperature is up around 43°F. Obviously, less sun is striking the sheetrock as we move further into spring. This is apparently due to the reduced levels of reflected light and IR emission from the tiles. The diffuse gain to the sheetrock should not change significantly from month to month.

The tiles, sheetrock and slab also receive energy from the windows themselves. Because of the moderate transmissivity of the heat mirror at normal incidence (.65) and its low mass, the heat mirror surface heats up considerably. The heat is syphoned off primarily by convection (due to its low emissivity) and ultimately heats the inner and outer panes of glass which then lose their heat by both convection and radiation. The temperature of the window's inner air gap is shown in Fig. 24. The temperature of the inner sheet of glass is midway between the air gap and room temperature. In January and February the air gap goes up to 115°F. The inner pane of glass must be about 90°F and is a large source of radiant and convective gains for about 4 hours. Convection from the windows is primarily to the ceiling tiles while radiation is randomly distributed. The heat gain process just described is commonly referred to as absorption heating and should be accounted for when talking about the solar gains through glazing which have this type of characteristic transmissivity.

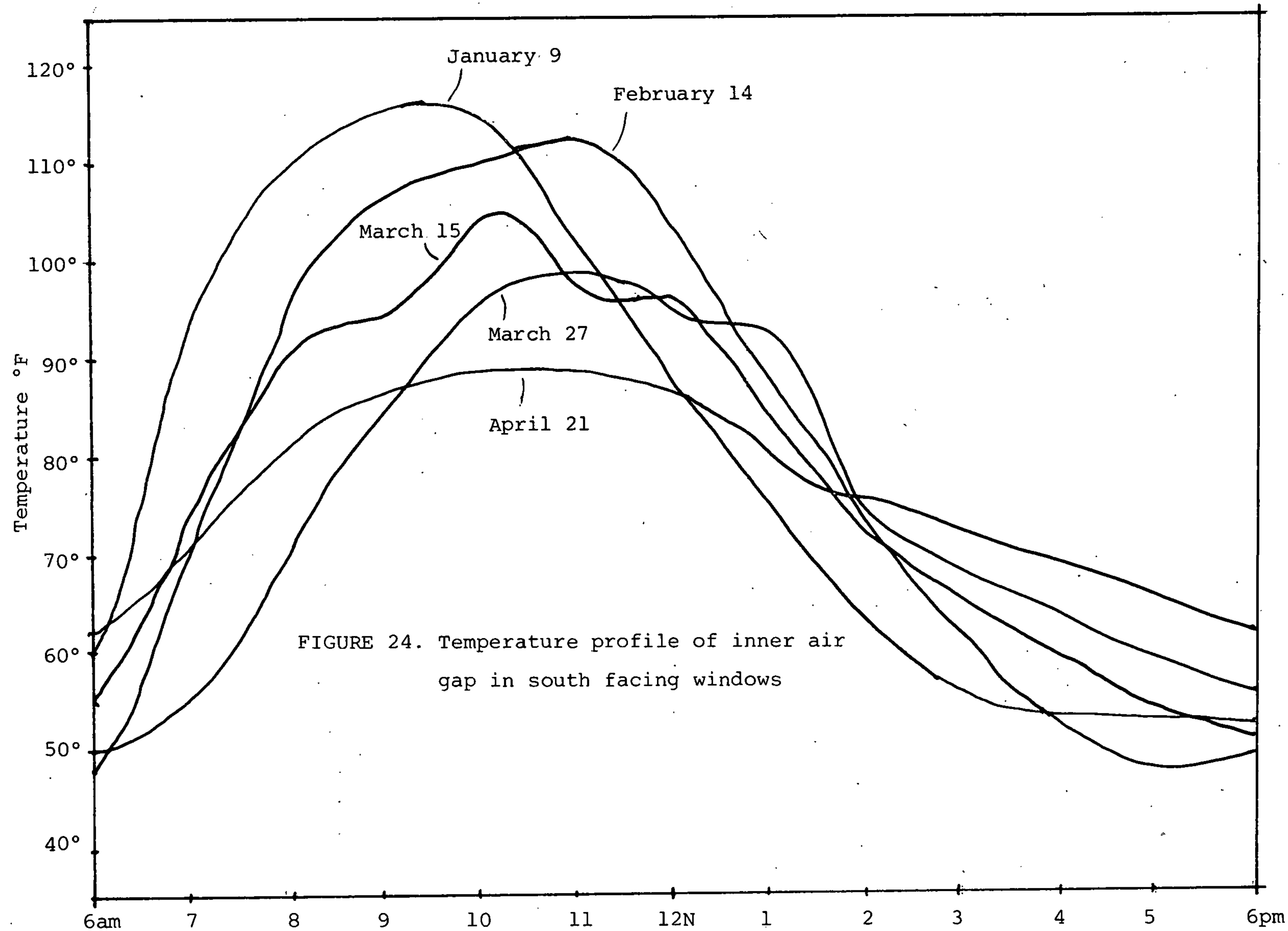


FIGURE 24. Temperature profile of inner air gap in south facing windows

It is interesting to note from Fig. 24 that the temperature of the air gap peaks out between 10-11 am and, during the cold months, falls off sharply afterwards. Two factors contribute to this. First, the solar gain to the windows in the morning is supplemented by the reflected gain off the white ventilator doors. As the sun moves past 11 am, the angle of incidence is so high that the reflected gains from the door rapidly diminish. In addition, as the sun moves past solar noon, the saw tooth shape of the south facade starts to actually shade the windows.

The amount of heat generated in the air gap drops as we move from January through April. This is evidently a manifestation of the changing angles of incidence and its effect on transmission. By the time we get to April, the inner air gap does not reach 90°F, even though this is a warm morning (about 55°F). Evidently, reflection of incident light from the window assembly is quite high by now.

While analyzing the data used to determine the percentage of participation among the ceiling, wall and floor slab, it was observed that the floor slab ran significantly cooler than anticipated. It became apparent that a great deal more heat loss was occurring straight down through the slab than had originally been calculated. When the building was first designed, only perimeter losses were thought to be significant enough to include in the heat loss calculations for the structure. This is common practice, and for most buildings, is a reasonable assumption. Accordingly, 4 inches of rigid, waterproof, polystyrene was laid around the perimeter of the slab as illustrated in Fig. 8. After a careful examination of soil survey data available for the MIT campus, it was discovered that the main water table resides about 10 feet below grade. In addition, 5 well points near the solar 5 building have shown that much of Briggs Field contains a perched water table which arises due to the presence of impervious soil layers which trap water like a pan. This raises the moisture content of the soil and thereby decreases its thermal resistance. As shown in Fig. 25 "R" sensitivity to moisture content increases with dry soil density. The moisture content and dry soil density around the Solar 5 building will be measured this fall and spring along with the deep earth temperature in order to accurately determine the slab's

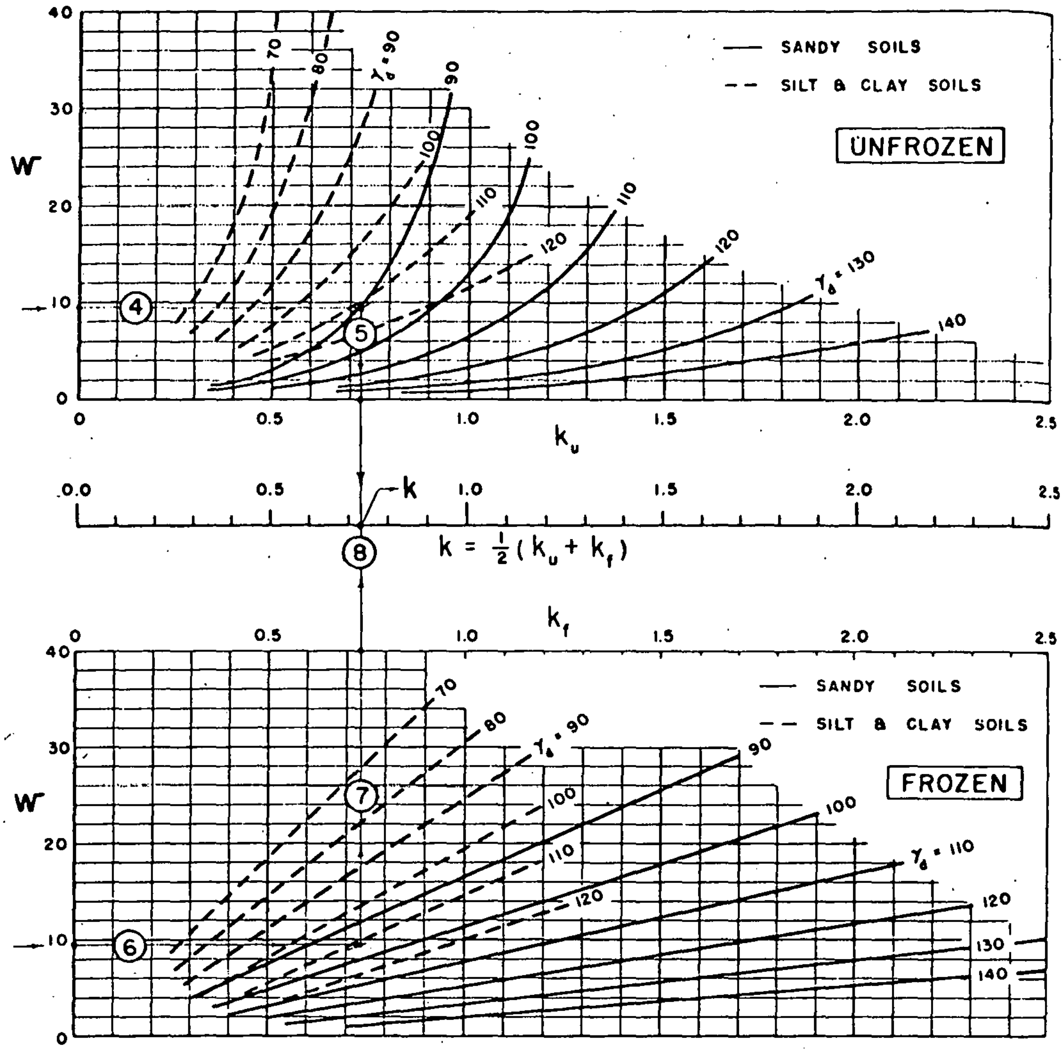


FIGURE 25. Thermal conductivity of soil vs. percentage of soil moisture and dry soil density*

w = % soil moisture

γ_d = dry soil density, lb/ft^3

k = soil conductivity, $\frac{BTU \cdot ft}{Hr \cdot ft^2 {}^\circ F}$

Aldrich, H. P.,"Thermal Properties of Soils," National Research Council, Highway Research Board, 135, pp 124-159, 1956.

heat loss. The data collected this year has indicated that the effective resistance of the perimeter and slab combined is about 12.5 $Hrft^2 °F/BTU$. This was calculated in the following manner.

Total building UA = 270 BTU/hr°F

	UA Value (BTU/hr°F)
Heat mirror windows	32.4
Casement windows	25
Walls	49
Studs	11
Ceiling	22
Doors	8.4
Subtotal	147.8 BTU/hr°F

According to infiltration studies an average ΔT of 20° and 13 mph wind gives an infiltration rate of .35 air changes per hour. This is equivalent to a UA of

$$.35 \text{ ac/hr} \times 8410 \text{ ft}^3/\text{ac} \times .018 \text{ BTU/ft}^3 °\text{F} = 53 \text{ BTU/hr°F}$$

Therefore,

$$UA_{total} = 270 = 147.8 + 53 + X_{slab\ perimeter}$$

$$270 = 200.8 + X$$

$$X = 69.2 \text{ BTU/hr°F}$$

$$= UA_{slab\ perimeter}$$

$$69.2 \text{ BTU/hr°F}/866 \text{ ft}^2 = .08 \text{ BTU/hr°Fft}^2$$

$$= U$$

$$12.5 = R$$

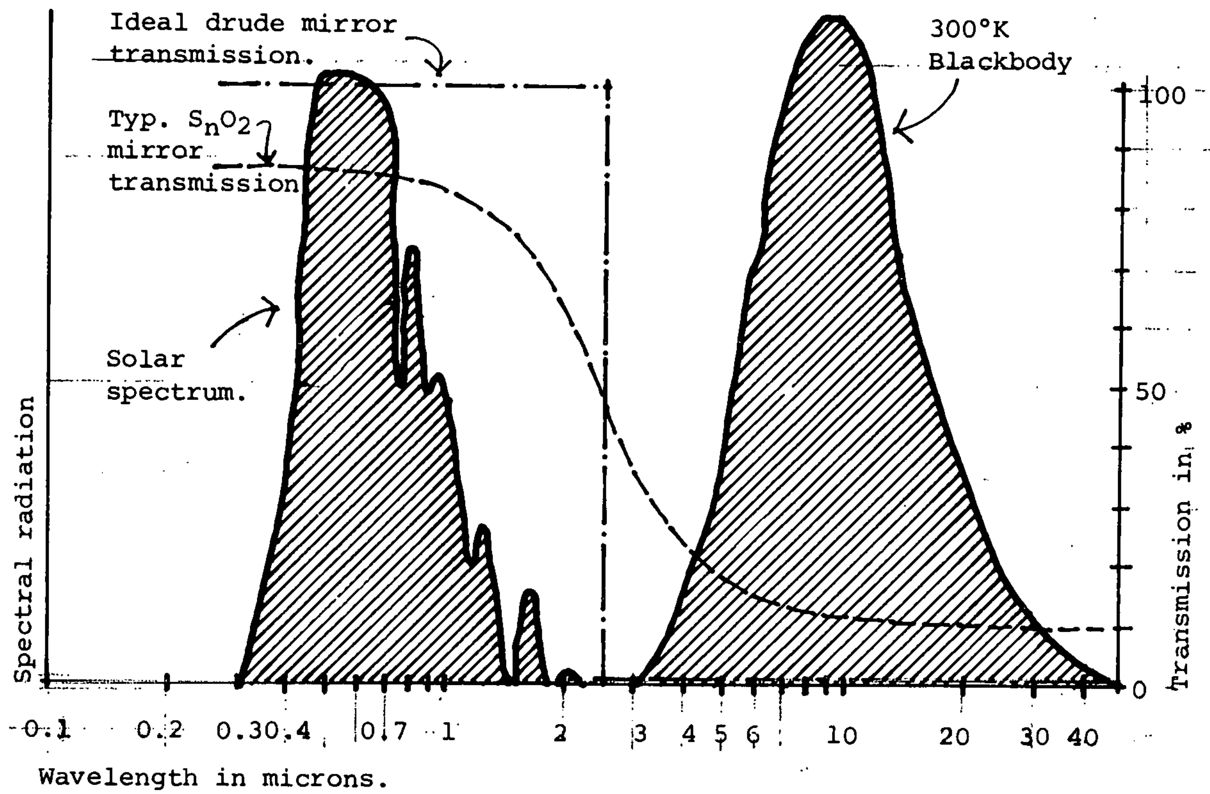


Figure 10. Heat Mirror transmission characteristics.

The tension mount is necessary to keep the heat mirror drum tight and wrinkle free as the Mylar substrate undergoes the 100°F seasonal temperature swings found in the window cavity. The heat mirror is adhered to a plexiglass frame by non-creeping Iso-tak, double sided pressure sensitive tape. The plexiglass frame has the same thermal coefficient of expansion as the Mylar so initial mounting tension is preserved as the assembly swings in temperature. The plexiglass would nevertheless deflect unacceptably under any load unless the bending forces were carried off the frame. This is done by wrapping the plexiglass grame with aluminum channels which gap at the corners (Fig. 11). The channels resist the bending moments, but still allow the plastic frame to expand and contract with temperature fluctuation. The entire assembly is held in place by the adjacent wooden window frames. Unfortunately, the rough opening for the frame is not big enough and some wrinkling does occur during cold nights.

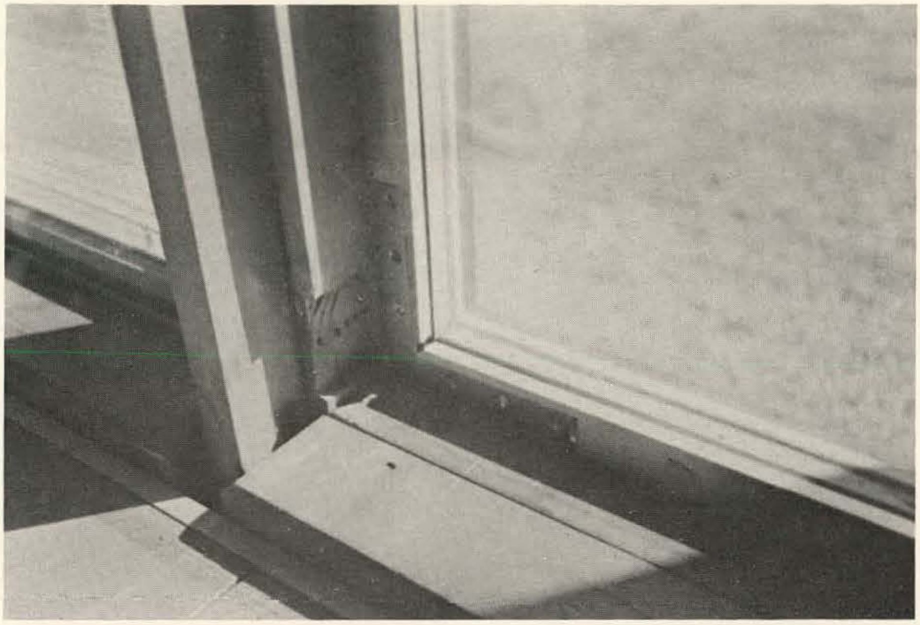


Fig. 11. Heat Mirror frame assembly (notched area receives thumb wheel)

Currently the heat mirror is only manufactured in 12 inch widths. Large areas of heat mirror were fabricated by taping the strips together with F.E.P. Iso-tack pressure sensitive tape. This fabrication method caused some puckering and rippling of the material which detracts from its architectural beauty. The current heat mirror is subject to corrosion from atmospheric pollutants and water. The window cavity is vented to the outside with a single 1/4" hole to prevent pressure build-up and condensation. During the dead of winter, it was discovered at least 4 holes were necessary to stop condensation. The vents, of course, expose the heat mirror to corrosion. The unit should ideally be hermetically sealed similar to a thremo-pane assembly. As expected the exposed heat mirror has corroded badly after nearly two years of operation. The entire window assembly has been replaced this fall (1979) with two sheets of glass coated with indium tin oxide which exhibits an overall solar transmission of 65% (including the absorption heating effect) and an emissivity of 25% (giving a U value of 0.25 $BTU/hrft^2{}^\circ F$). The coating was applied by Airco Company of Murray Hill, New Jersey. The coating is corrosion resistant, hard, and cleaned by ordinary window cleaners. Fig. 11a shows a close-up of the new selective transmitter.

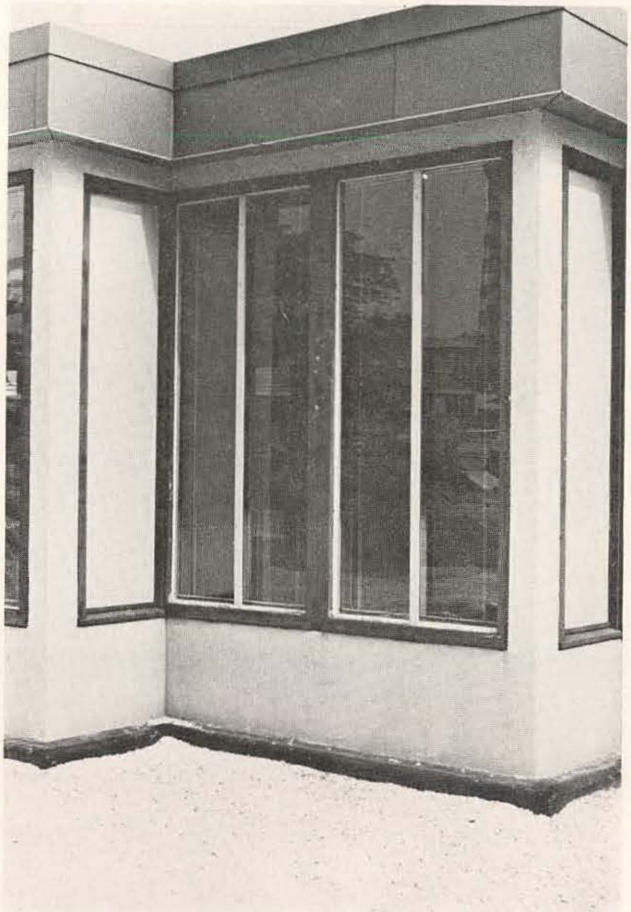


Figure 11a. South bay showing new indium-tin-oxide selective transmitter on glass. The coating is applied directly to the glass.

b. Light Directing Louvers

Insolation is directed to the dark colored ceiling by reflecting louvers (7) placed in the southern windows. The movable louvers are designed to minimize interferance with views while offering the occupant control over the visual environment. Fig. 12 shows the louver cross section for accepting a wide range of solar profile angles while remaining fixed. This particular design requires only six adjustments during the heating season to keep all reflected solar energy on the ceiling. Large area source glare and glare due to high light intensity ratios is eliminated by the louvers since sunlight is reflected harmlessly over the occupants' heads.

Fig. 13 shows the louver geometries. The slats are narrow enough (.625 inches) to give the occupant the impression of a screened view rather than a striped one. The louver spacing is closer than usual to keep sunlight from filtering through to the floor. The louver cross section is a simple arc to facilitate fabrication. Geometric optimization studies show a single arc radius will work throughout the U.S. latitudes, but at least two different slat spacings will be required.

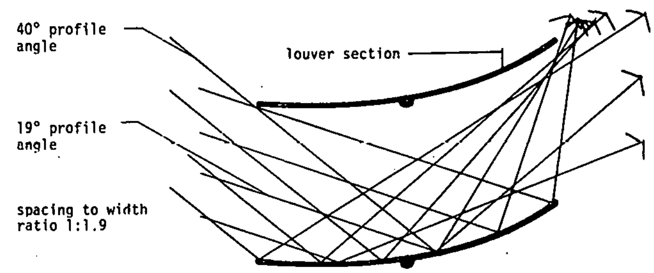


FIGURE 12. LOUVER SECTION ACCOMMODATING 19° THROUGH 40° PROFILE ANGLE RANGE

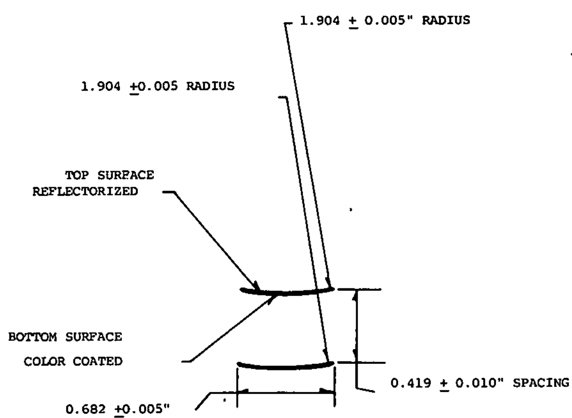


FIGURE 13 - LOUVER GEOMETRY

The top surface of the louvers are reflectorized with aluminized Mylar attached by a pressure sensitive adhesive. Rolscreen plans to market the louvers with an integral reflectorized surface to overcome possible delamination problems. Such a louver has recently been placed on the market in Sweden. Sunlight nominally leaves the louvers at a 30° angle to the horizontal, but some rays reach a maximum angle of 70°F. This causes a higher light intensity near the south side of the ceiling. The louvers are installed facing directly south so the solar profile angle variation is minimized. The louver section can readily accept a 5° to 7° variation in solar profile angle without readjustment This means the louvers need only be adjusted about once every three weeks to compensate for the seasonal movement of the sun, unless visual privacy is required at night. The rotational adjustment is simple; the blinds are rotated by a thumbwheel until sunlight disappears from the floor.

The only problem encountered with the blinds has been the polyester cord ladders that support the blades. Six of the eight ladders have stretched so that the bottom blades are no longer parallel to the top blades. This means some sun rays are beginning to hit people in the eyes. The problem is being corrected by Rolscreen by switching to a glass fiber composite which looks like nylon cord, but does not stretch.

c. Ceiling Thermal Storage Tiles

The polymer concrete ceiling tiles, two feet square and only 1 1/4 inch thick, are the storage component of the system (Fig. 14). Their chemical core-a combination of 38% sodium sulphate, 48.3% water, 3.4% Cab-O-Sil fumed silica, 2.6% borax, and 7.6% sodium chloride - stores a day's heat and then releases the retained heat as needed. Because the core stores heat latently at 73°F, it maintains nearly a constant room temperature and thus prevents overheating, which normally is wasted heat. At night, as the outside temperatures drop, the chemical core sealed within the tile parcels out enough heat to maintain room temperature near its daytime level. The core, therefore, acts as a built-in thermostat to stabilize the temperature in the room. The magnitude of this thermostat effect was readily demonstrated during the last days of construction when the building was complete, except for the ceiling tiles. Before the tiles were installed the space peaked at 86°F during sunny February days. After the tiles were installed, the space never exceeded 74°F. Fig. 15 shows typical room air

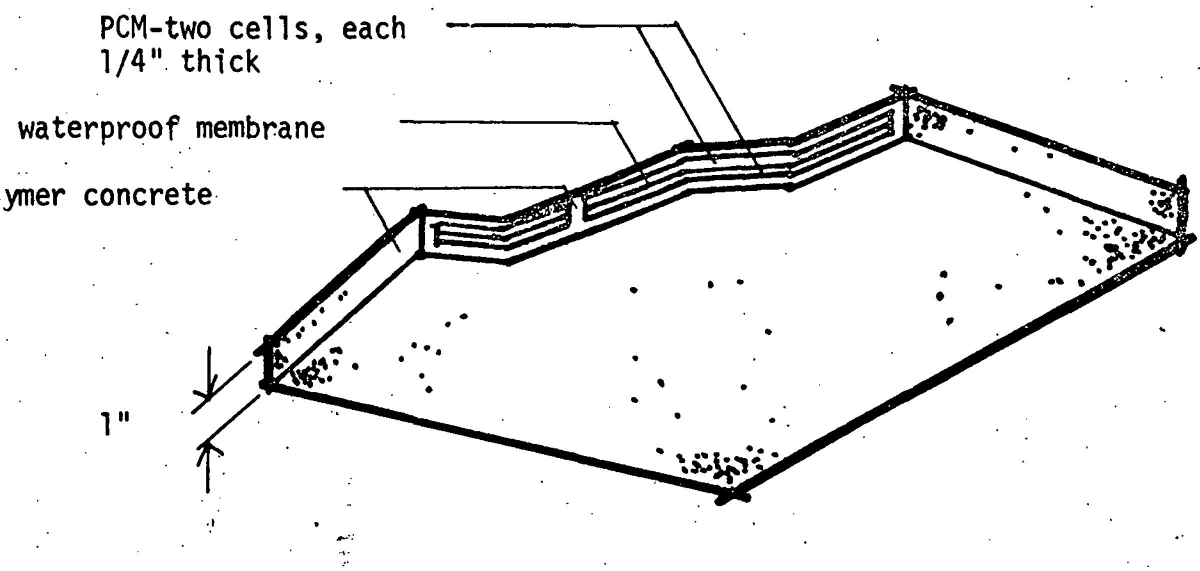


FIGURE 14. SOLAR CEILING TILE CONSTRUCTION

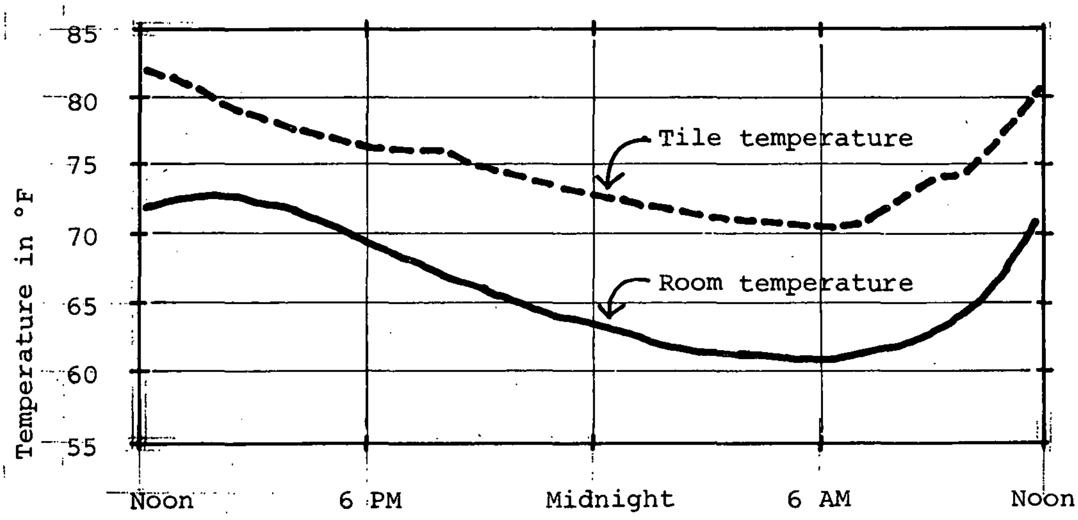


Figure 15 . Tile and room temperature for Feb. 25-26, 1978.
(90% sun. Average outdoor temp; day - 41.5°F, night - 32.2°F).

and tile core temperatures over a twenty four hour period bordered with two sunny days.

The room air temperature is measured at the 5 foot level near the thermostat mounted at the south-east corner of the building. The ceiling tile core temperature is measured with a thermistor cast in place at the lower interface between the modified Glauber's salt and the polymer concrete. The ceiling tile is located at the center of the building and 2 feet away from the south windows. The tile temperature profile does not show much of a plateau at the phase change temperature since the moving crystal front offers an increasing resistance to heat flow.

During the day, the solar heat flux is greater than the melting crystal front can accept so the tile temperature exceeds the melting point of the modified Glauber's salts. Although the tile reaches temperatures in the mid-80's, this temperature is much lower than temperatures for ordinary masonry products in similar solar exposure situations. During the night, 2/3 of the heat is transferred to the space by radiation, and 1/3 by convection. Although warm air tends to stratify at the ceiling, convection currents induced by infiltration and hot appliances remove some heat

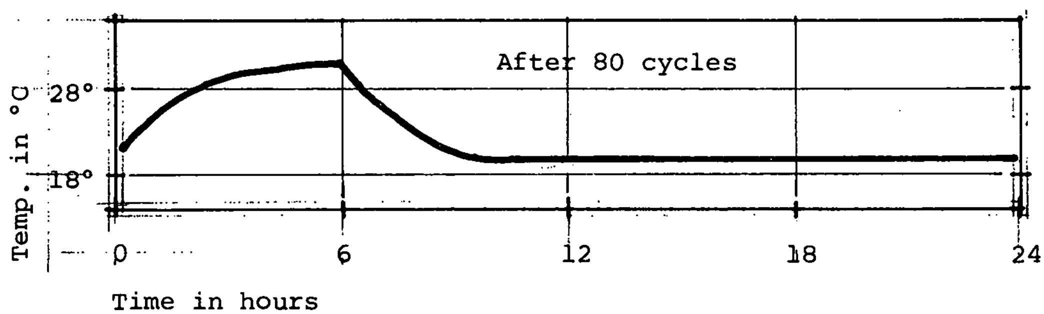


Figure 16. Solar tile core temperature vs time under a 95 BTU/SF/Hr. insolation rate. Tile absorbing surface is black and facing up in an 18°C ambient.

from the ceiling by mass transfer. Fig. 16 shows laboratory tests of a similar tile with heat flowing up (the tile is mounted on an insulated floor) and a constant load. Here the phase change plateau is much more in evidence.

The phase change temperature can be adjusted by the amount of sodium chloride added. Obviously, if the temperature is set too high, overheating will occur during the day and if set too low, underheating will occur at night. The eutectic formed by the salt is less efficient than pure Glauber's salt. The tile stores 200 BTU/ft^2 over a 10°F swing (most of the heat is released over the interior 5°F swing) and weighs 11 lb/ft^2. Out of the total, the salts contribute 6 lb/ft^2. Calorimeter tests both by MIT and Brookhaven National Laboratories show the salts release 33 BTU/# over a 5°F swing. Measurements of pure Glauber's salts thickened with Cab-O-Sil, or Min-u-Gel as Dr. Maria Telkes uses, show 44 BTU/# after 50 freeze-thaw cycles. The 11 BTU/# difference is due to the addition of NaCl. The 68 BTU/# difference between the Glauber's salt mixtures and the ideal heat of hydration is due to microscopic pools of saturated solution entrained in the solid "frozen" mixture. Even though the solid state feels dry to the touch these pools were detected by the Brookhaven differential scanning caloriometer tests.

It is felt additional research into the Cab-O-Sil surface chemistry properties will give a heat content efficiency of over 60%. Nevertheless, even though the current modified Glauber's salts only operate at 31% efficiency the heat content remains the same, regardless of the number of freeze-thaw cycles. Over 4500 freeze-thaw cycles have been accumulated in small scale laboratory tests (See Appendix I) without any signs of ageing. This is equivalent to over 23 years of operation in a residential environment. The well known ageing problem has been overcome by packaging the salts in two adjacent 5/16" layers that are thin enough to allow crystal growth by diffusion. However, some free solution would still be present unless the Cab-O-Sil were added. Conversely, thicker layers will separate even with the Cab-O-Sil added. Cab-O-Sil was used because it forms a three dimensional interlocking matrix that holds the material in suspension. The tiles can only be installed in horizontal positions (floors, ceiling, settees, etc.) since any angular mounting would introduce a hydrostatic head in the salt that would cause separation of the material.

The salts are packaged in a bag formed from 1 mil aluminum foil laminated with 2 mil polyethylene. The bag is heat sealed with an inner polyethylene divider to form the two 5/16" compartments. The aluminum is there to prevent water permeation over the years. The polyethylene protects the aluminum from corrosion. The chemical core was developed at MIT and produced for the MIT demonstration facility by the Cab-O-Sil Division of Cabot Corporation at its Billerica, MA research laboratories.

The polymer concrete tile casing forms a water-tight envelope that resists crystal puncture from the sodium sulphate material. Polymer concrete is nominally 15% polyester resin and 85% aggregate by weight. The heat transfer characteristics are only slightly lower than concrete, but when reinforced with fiberglass, polymer concrete becomes 5-6 times stronger than concrete. Thus, the tile casing can be made extremely thin (1/4") to promote high heat transfer. Less than a 1°F drop is observed through the polymer concrete tile during operation. Polymer concrete is also used because it can be colored and textured to mimic a variety of building materials (wood, masonry, etc.). For example, the ceiling tiles in Solar 5 are dark blue with a pebble texture, and the settees mimic slate. The tiles were developed at MIT with the assistance of Architectural Research Corporation of Livonia, Michigan. The 2'x2'x1 1/4" tiles are placed in the ceiling by suspending these between the flanges of 12" sheet metal joists mounted on 24" centers. The tiles can also be mounted in heavy duty suspended ceiling systems, provided the wire hanger frequencing is increased. At 11#/ft^2, the tiles are 20-30% heavier than a plaster ceiling, which means the tiles can be used as a retrofit in structures coded for plaster ceilings.

No tile warping has occurred. Three tiles out of the 257 installed in the ceiling and settees have leaked. The leaks occurred in the top surface of a ceiling tile because excessive air entrainment in the polymer concrete of those particular tiles created an open cell structure. Future fabrication techniques will be adjusted to minimize air entrainment.

After 1 1/2 years of operation a tile was broken open in the frozen state. No free solution was observed and no corrosion had occurred in the aluminum foil barrier. The foil barrier had been punctured by the sharp Na_2SO_4 crystals but the polymer concrete had successfully sealed the system.

A less expensive alternative to the tile is now on the market. A heavy duty polymer and foil bag has been developed by C.M.I., Inc. of Andover, MA for packaging the salts in a 3/4" x 2'x1' volume. The bag has the usual interior divider to keep the $Na_2SO_4 \cdot 10H_2O$ in two thin layers. The flexible container has successfully resisted crystal puncture after 50 freeze/thaw cycles, where each cycle took 24 hours to accomplish. The bags must be supported from below, usually by high density, high heat conducting drywall (called fire-rated drywall) screwed directly to the joists. When access to the ceiling is required, the polymer concrete tile system is preferred.

Building Heat Storage Period

Carry through was measured during a cloudy February period when day and night outdoor air temperatures remained at 29°F. No internal gains occurred from light or appliances during this period. The tiles lost their charge 24 hours after sunset. The expiration of heat stored in the ceiling was evidenced in two ways; 1) the thermostat (set at 60°F) turned on the auxiliary heaters, and 2) the cooling of the ceiling tiles proceed at a more rapid rate at the end of the 24 hour period. It is estimated that 30% of the heat liberated in this period came from the exposed 4 inch concrete floor slab and 5/8" thick drywall which underwent an 11°F drop in temperature. Normal internal gains from lights of 2.2 kw hr would have extended the carry through to 34 hours after sunset during an average February period. More average winter conditions, where outside temperatures hover around 40°F, would extend the carry-through to 42 hours after sunset.

In conclusion, the tiles, louvers, and heat mirror combine to give a thermally and visually comfortable direct gain environment for the first time. One of the most exciting promises of this research is the prospect of creating new kinds of spaces with windows that truly insulate and building surfaces that truly heat.

Payback Analysis

The major advantage of passive solar heating is the solar heating "plant" can be partially amortized over the building functions the heating components serve. The passive solar heating approach demonstrated in Solar 5 is no exception. The bags of phase change material are added to the dry wall ceiling. The heat mirror can convert an ordinary window to a solar collector with only a small add-on cost. The louvers can be charged off to the window shading function. Listed below are projected wholesale costs for the three components demonstrated in Solar 5. These figures are based on mass production projections performed by the four companies involved in these components:

Bagged Phase-Change-Material	$1.90 ft^2$
Heat Mirror on Glass	$1.50 ft^2$
Louvers	$3.50 ft^2$

The louvers replace drapes in some cases that run more than the louvers. Appendix II shows a payback analysis for both a 1600 ft^2 single family detached house and an 1100 ft^2 multi-family residence where 1) no deduction is taken on the louvers (i.e., additional window dressing is still used); and 2) double glazed windows are assumed to be standard. The building load is proportional to the Solar 5 thermal load and it is also assumed that fuel inflation just covers the interest payments on the borrowed capital. The analysis shows both housing types can recover the investment cost in 7.5 years of savings from oil heat. If a full deduction were taken for the louvers, the pay-back would be less than 5 years. (Similar analysis for the flat plate collector system gives a 28 year payback period assuming the collector system cost $25 ft^2$.

Real estate investors generally consider a payback period of 5 years makes economic sense in today's market. At only 50% more than that figure, the Solar 5 materials already show good economic promise.

Measurements & Experiments

INTRODUCTION

The following sections document the various thermal experiments performed in the Solar 5 building. A moderate array of sensors were used in the building. Table 0 shows the location and type of sensors used.

TABLE 2. SENSOR TYPES AND POSITION

Type	Location
1. Pyranometer	center of facia over west most southern window bay
2. Watt meter	auxiliary heater circuit
3. Watt meter	building feeder circuit
4. Thermostat	south-east corner of building, 5 foot level
5. Mercury thermometer	thermostat
6. YSI Linear 44203 thermistor (measures temperature)	outdoors, 2" below northern soffit, 6' from north-west building corner
7. "	indoors, 2" below central ceiling tile
8. "	stud side of south-west dry wall at 5 foot level
9. "	imbedded in center of concrete slab (2" below the surface)
10. "	below center of slab at the gravel/ soil interface
11. "	at the center of the south side of the building 2" below the surface
12. "	at the center of the south side of the building,at gravel/soil interface
13. "	imbedded in tile at lower polymer concrete/bag interface (tile at center,south edge of ceiling)
14. "	imbedded in tile at lower polymer concrete bag interface(tile at left center, south edge)
15. "	" (tile at center 1/3 back from south)
16. "	" (tile at center of the ceiling)

Sensor numbers 16, 7, 6, and 1 were recorded every hour for 1 minute on a strip chart recorder. The watt meters were manually recorded once a day. The remainder of the thermistors were recorded on a tape cassette by a digital multiplexer.

BUILDING LOAD DETERMINATION

Heat loss from a structure is driven by temperature and pressure differentials across its envelope. The rate of heat loss is directly proportional to the conductivity of its weather exposed surfaces and also related to the air tightness of the structure. Conduction, convection, and radiation pathways interact to produce an overall building heat loss coefficient which is the sum of all the surface areas (A) times their respective thermal conductivities (U) plus a value which represents the amount of heat loss due to infiltration.

$$\Sigma(U_1 \times A_1) + (U_2 \times A_2) + (U_n \times A_n) + UA_{infilt.} = UA_{building}$$

where

A = Area (ft^2)
U = Conductivity ($BTU/hrft^2{}^\circ F$)
UA = Heat loss rate per °F temperature difference (BTU/hr°F)

By multiplying the UA of the building times the temperature difference (ΔT) between the indoor-outdoor air, one can determine the quantity of heat lost per hour:

$$(UA) \times \Delta T = BTU/hr$$

This method is commonly used by designers and engineers for sizing heating systems and estimating fuel costs for new buildings. This method assumes that thermal conductivity characteristics of the building materials are constant and what the manufacturer specifies. This is not always the case due to quality control problems in manufacturing and variability of installation techniques. In addition, quantifying the infiltration rate of a structure without the proper equipment, is more guess work than science. Because of the large number of variables in this method, one can hope the building can, at best, be within 10% of the computed UA.

A more accurate method (which was used for this report) can be employed with existing structures that utilize electric resistance heat. The method involves recording the actual energy consumption under known steady state environmental conditions. This requires the measurement of:

1. Outdoor temperatures
2. Indoor temperatures
3. Auxiliary heat supplied
4. # hours elapsed
5. Wind velocity

Given this information, one can apply the following formula:

$$Q = U \times A \times \Delta T \times Hrs$$

Therefore,

$$U \times A = \frac{Q}{\Delta T \times Hrs}$$

where

Q = Electric energy consumed during period
ΔT = Average indoor-outdoor temperature difference for the period
Hrs = # hours elapsed during monitoring period

In the Solar 5 building, it is important that all the stored solar energy be depleted before the test begins. Otherwise an abnormally low UA will be calculated due to the fact that the value for Q would include some solar gains that were not accounted for. To avoid this problem, the measurements were made after a 2 day period of cold, cloudy weather that thoroughly depleted the store of solar energy from the thermal masses of the building. Under these conditions all the energy supplied to the building could be accurately determined. Because of the 100% efficiency of electric resistance heating, we know that for every kwh of electricity consumed we gain 3412 BTU of heat to the space. Accordingly, the previous formula can be altered to

TABLE 3. DETERMINATION OF BUILDING "UA"

Date	Time	Heating (Kwhrs)	Lighting (Kwhrs)	Total (Kwhrs)	Average ΔT°F	Average winds (mph)	Calculated UA BTU/hr°F
2/26-2/27	6am-11:40am	60	6	66	27.9	12.6 (N)	271
3/7-3/8	5:30pm-12n	14	13.7	27.7	19.2	13.2 (NW)	266
4/4-4/5	5:30pm-11:45am	16	14.6	30.6	20.7	16.2 (E)	276
4/9-4/10	6:10pm-9:10am	22	6	28	23.9	20 (NW)	267
						Average UA =	270

$$UA = \frac{(kwh_{aux.heat} + kwh_{aux.light}) \times 3412 \text{ BTU/kwh}}{hrs \times avg.\ \Delta T}$$

Hourly outdoor and indoor temperatures were recorded digitally on tape. Electric resistance heating was registered on a conventional kwh meter and logged manually at the beginning and end of the test period. The wind conditions were obtained from the weather observatory on campus. A typical monitoring period ran from late afternoon on a cold cloudy day till the following morning.

As shown in Table 1, the UA's calculated on 4 separate occasions were averaged to arrive at a UA of 270 BTU/hr°F. The days chosen satisfied the criteria of prior cold, cloudy weather. Also, the building was not in use during the test periods which eliminated any infiltration due to the use of the doors. Nevertheless, the existing vestibule acts as an air lock and any use of the doors would have had minimal impact on the measurements. The winds proved to be slightly higher than normal and there appeared to be no correlation between wind speed and UA. Further studies will be done this winter.

SOLAR HEATING FRACTION

Determination of the building's UA product enables one to easily calculate the heating load that will be experienced for a variety of outdoor temperatures. By knowing this load, along with the solar and internal gains, the building's performance can be evaluated.

Solar heated buildings are usually evaluated in terms of their Gross solar heating fraction (SHF), or Net SHF. The Gross SHF is an indication of what percentage of the Gross Heating Load is met by the solar system. The gross heating load is a measure of how much energy is needed to maintain a space at its thermostat setting. In other words, it is the sum of internal gains, auxiliary heat, and solar gains (if any).

The gross SHF can be computed as follows:

$$\text{Gross SHF} = \frac{\text{Total Solar Gain}}{\text{Gross Heating Load}}$$

Gross Heating Load = Auxiliary Energy + Internal Gains + Solar Gains

The Net SHF is an indication of what percentage of the Net Heating Load the solar system supplies that would otherwise have been met by the home's heating system. The heating load in this case has been reduced from a Gross Heating Load to a Net Heating Load by the supply of heat from internal gains such as lights, people and appliances. The net heating load is equal to the Gross Load - Internal Gains and may also be computed by multiplying the UA by the ΔT between ambient air temperature and the structure's balance point. The balance point is the ambient temperature at which point the internal gains can no longer keep the house air temperature above the thermostat setting, necessitating the supply of heat from the furnace. As structures become thermally tighter, the balance point moves lower, indicating that the internal gains are supplying an increasing percentage of the house's heating needs. (For an example of how internal gains affect the building's balance point, and load, see Appendix 3). The NET SHF can be computed as follows:

$$\text{NET SHF} = \frac{\text{Total Solar Gain}}{\text{Net Heating Load + Solar}}$$

The Net SHF is most often used by builders, salesmen, and realtors to indicate how much the use of a home heating system will be reduced by a particular solar heating system.

Another way to evaluate the thermal efficiency of a structure is to compare its seasonal heat load to the HUD minimum property standards (MPS). MPS defines an energy efficient single family detached building as one in which the load is less than 7.1 BTU/DDft^2.

Passively heated structures often fail MPS. This is primarily due to the large expanse of glass that is integral to their design. In Solar 5 the impact of the large expanse of south facing glass has been minimized by the use of the heat mirror windows. Our UA of 270 BTU/hr°F converts to

$$\frac{(270 \text{ BTU/hr°F})(24 \text{ hrs})}{866 \text{ ft}^2} = 7.48 \text{ BTU/DDft}^2$$

This is only slightly higher than the MPS and is due to Solar 5's large surface to volume ratio, typical of a small building. Thus, the solar heating fraction reported for the Solar 5 building represents a true savings in auxiliary heat since the building's load is not higher than normal.

The gross heating load for Solar 5 was calculated as

$$Q_{\text{gross load}} = UA \times \Delta T \times \text{hrs}$$

where

UA = calculated as shown in previous section

ΔT = average of the months indoor-outdoor temperature difference

hrs = number of hrs per month

The quantity of solar gain per month was equal to

$$Q_{\text{solar for month}} = \text{Gross load} - (\text{Aux.used} + \text{Int. gains})$$

The earth sink temperature can be found by calculating the heat flow between the room and the slab. Since it is a series heat flow, $Q_{room \rightarrow slab}$ must equal $Q_{room \rightarrow earth\ sink}$. In order to perform this calculation, the room's environmental temepratute must be determined. This is a combination of the room's MRT and air temperature, and is equated as

$$\text{Room env. temp.} = \frac{\left[\frac{\Sigma(\text{surface area x Avg.temp.})}{\text{surface area}}\right] + \text{Room air temp}}{2}$$

For March 15 the environmental temperature = 66°F (average 7am-5pm). As shown on the graph for 3/15/79, (Fig. 21), the slab runs at an average of 64°F (7am-5pm); this is 2°F below the room environmental temperature. The resistance between the room environment (convection, radiation) and the floor is 0.9 (ASHRAE). In addition, the thermistor is located 2 inches below the surface of the slab which adds an additional .166 R.

$$\text{Total } R_{room \rightarrow thermistor} = 1.066$$

$$U = .94 \frac{BTU}{Hr \cdot Ft^2 \cdot {}^\circ F}$$

$$Q = 729\ ft^2{}_{exp.slab} \times \frac{.94\ BTU}{hrft^2\,{}^\circ F} \times 2^\circ F \times 10\ hrs$$

$$= 13,705\ BTU$$

Solving for deep earth temperature (water table 10ft. below grade), and knowing that the $U_{room \rightarrow water\ table} = .08 \frac{BTU}{Hr \cdot Ft^2 \cdot {}^\circ F}$, we find that

$$Q = A \times U \times \Delta T \times hrs, \text{ or}$$

$$13,705\ BTU = 729\ ft^2 \times .08 \frac{BTU}{hrft^2\,{}^\circ F} \times X^\circ \times 10\ hrs,$$

giving,

$$X = 23.5°F$$

$$\text{Room environment temperature} = 65.7°F$$
$$\Delta T = 23.5°F$$
$$\text{Earth sink} = 42.4°F$$

The actual slab-perimeter UA (about 70 BTU/hr°F) is 7 times what was accounted for last year. The fact that this slab is running in the low to mid 60's is therefore not surprising. The impact of all this on building performance is three-fold:

1. The slab runs cool, causing the MRT of the room to be lower than usual, necessitating a higher dry bulb temperature in order to maintain human comfort.

2. The UA of the building is higher than it otherwise would be, causing excessive drain from the solar tiles and lowered solar heating fraction.

3. Even though the slab goes through a temperature swing during a sunny day, its bulk temperature rarely gets above 65°F and can contribute only slightly to the heating of the space.

With these conditions revealed and understood, a discussion of participation among storage elements is warranted.

We were interested in seeing how much energy remained in the 3 storage elements after the solar gains for that day fell to zero. For that reason, temperatures of the storage elements were recorded just after sunrise (7 am) and just before sunset (5 pm). By knowing the average temperature excursions for the slab and dry wall, one can calculate the heat absorbed by the materials during a sunny day. The amount of energy stored in the tiles is equal to the total quantity of solar energy stored minus the sum of energy stored in the wall and the slab. The exposed area of floor slab is 729 ft^2. The slab is 4 inch thick concrete; its sensible heat content is:

$$144 \text{ lbs/ft}^3 \times .2 \text{ BTU/lb°F} \times 4"/12" \times 729 \text{ ft}^2 = 7000 \text{ BTU/°F}$$

The slab rests on 2 inches of gravel and soil. 4 inches of this material participates; therefore the sensible heat content of the adjacent gravel and soil is:

$$100 \text{ lbs/ft}^3 \times .2 \text{ BTU/lb°F} \times 4"/12" \times 729 \text{ ft}^2 = 4860 \text{ BTU/°F}$$

The total sensible heat content equals 11,860 BTU/°F. The heat content of the 898 ft^2 of 5/8" drywall is

$$80 \text{ lbs/ft}^3 \times .3 \text{ BTU/lb°F} \times 5/8"/12" \times 898 \text{ ft}^2 = 1123 \text{ BTU/°F}$$

Quantifying the heat content of the solar tiles required a different manipulation of the data. Because the tiles go through sensible and latent heating, it is not sufficient to multiply their heat capacity times their ΔT. In addition, all the tiles do not participate uniformly. Therefore, the heat stored had to be determined by a process of elimination as follows:

1. Determine the load on the building over a 24 hour period
2. Record all auxiliary uses of energy
3. Solar gain = load - auxiliary used
4. Determine instantaneous load on building (7am - 5 pm) (solar gains satisfy this load)
5. Solar gain - instantaneous load = solar energy stored
6. ΔT of slab and sheetrock times their respective heat capacities = heat stored in these masses. (Note $\Delta T = T_{5pm} - T_{7am}$)
7. Solar stored in tiles = total solar stored - energy stored in walls and slab.

This method has been applied to the data collected at the solar building on 5 days in early 1979. All the days were clear and provided the opportunity to observe the net result of the slab, ceiling and wall interaction after solar gain for the day had ended. This data, Table 4, indicates that under average winter conditions (after sunset) 60-65% of the heat is stored in the tiles, 25%-30% in the slab, and about 10% in the sheetrock.

TABLE 6. CEILING, WALL, SLAB PARTICIPATION IN HEAT STORAGE

	Jan. 9	Feb. 14	March 15	March 27	April 21
Average 24 hr ambient temp. (°F)	30	7	26	40	49
Solar Gain Period	8am-4pm	8am-4pm	7am-5pm	7am-5pm	6:30am-5:30pm
24 hr building load (10^5 BTU)	2.37	3.93	2.64	2.0	1.03
Auxiliary Used (10^5 BTU)	1.02	1.97	1.26	.853	.255
Solar Intake (10^5 BTU)	1.35	1.96	1.38	1.15	.78
Instantaneous Load (10^5 BTU)	.756	1.2	.986	.78	.386
Solar Stored (10^5 BTU)	.6	.767	.396	.37	.395
ΔT Wall (°F)	5	6	4	7	10
Q Stored (BTU) in wall (%)	5615 9	6738 9	4492 10	7861 21.3	11,230 29
ΔT Slab (°F) Gravel	1.5	1.5	1.0	.5	.88
Q stored (BTU) in Slab (%)	17,790 30	17,790 23	11,860 28	5930 16	10,400 26
Q stored (BTU) in tile (%)	36,595 61	52,122 68	23,284 59	23,200 62.7	17,870 45

*Note: Carpet installed on March 17,1979

TABLE 7. HEAT STORAGE IN BUILDING THERMAL MASSES WITHOUT CARPETING

March 15, 1979 - No carpeting

Average $T_{ambient}$ = 26°F

Building Load = (38°F)(24 hrs)(290 BTU/hr°F) = 264,480 BTU

*Note- 290 was used on this day due to winds being about 20 mph

Auxiliary Energy = 37 kwh
= 126,244 BTU

Solar Gain = 264,480 - 126,244
= 138,236 BTU

Instantaneous Load = (34°F)(10 hr-7am-5pm)(290 BTU/hr°F)
= 98,600 BTU

Solar Energy Stored = 138,236 - 98,600
= 39,639 BTU

ΔT $Slab_{7am-5pm}$ = 1.0°F

Q_{Slab} = (1.0°F)(11,860 BTU/°F)
= 11,860 BTU

ΔT Wall = 4°F

Q_{Wall} = (4°F)(1123 BTU/°F)
= 4492 BTU

$Q_{Tile} = Q_{Total\ Stored} - (Q_{Wall} + Q_{Slab})$

= 23,284

TABLE 8. HEAT STORAGE IN BUILDING THERMAL MASS WITH PARTIAL CARPETING

March 27 (Floor 50% carpeted)

Average ambient Temperature = 40°F

Building Load = (290 BTU/hr°F)(24 hrs)(28.8°F) = 200,448 BTU

Auxiliary Energy = 25 kwh =

= 85,300 BTU

$Q_{Solar\ Gain}$ = 200,448 - 85,064

= 115,384 BTU

$Q_{Instantaneous\ Load}$ = (290 BTU/hr°F)(10 hr)(27°F) = 78,300 BTU

Q_{Stored} = 37,084 BTU

ΔT Slab = .5°F

Q_{Slab} = (11,860 BTU/°F)(.5°F)

= 5930 BTU

ΔT_{Wall} = 7°F

Q_{Wall} = (1123 BTU/°F)(7°F)

= 7861 BTU

Q_{Tile} = $Q_{Total\ Stored} - (Q_{wall} + Q_{slab})$

= 23,200 BTU

EFFECT OF CARPETING

1/2" carpeting was installed in March 17 over 50% of the floor slab. To observe its effect, data collected on 3/15 and 3/27 was analyzed in such a way as to account for the variation in load and insolation levels so that any difference in storage element behavior could be attributed to the carpeting.

The participation of the thermal masses on the 2 dates was:

	No Carpeting March 15		Carpeting March 27	
Slab	11,860 BTU	- 29%	5930 BTU	- 16%
Wall	4,492	- 11%	7861	- 22%
Tiles	23,284	- 60%	22,709	- 62%
Q_{stored}	39,639	-100%	36,500	-100%
Ambient temp. (24 hr avg.)	26°F		40°F	
Room air temp.	69°F		69.5°F	

These calculations are detailed in Tables 5 and 6.

Although the behavior of the thermal masses seems quite different, some of this is attributable to external influences. To correct for these environmental influences, the total energy input to the storage elements over the course of the 10 hr day must be accounted for. It is known that total energy to storage elements = $Q_{stored} + Q_{lost\ to\ ambient}$. This accounts for the differences in load between the 2 days. Differences in solar gain to the building must also be corrected so that energy input to the building is equal on both days. With these corrections (showed in Appendix 6) we find that the wall will have retained an additional 2079 BTU over the course of the day. This is equivalent to a 1.8°F higher wall temperature at 5 pm. The ceiling will retain an extra 3812 BTU which is equivalent to approximately .5°F higher temperature at 5 pm. The total of the extra energy retained by the 2 storage elements over this 10 hour period equals 5891 BTU. This is energy that would have otherwise been transferred to the slab during the day. To check our method, the reduction in slab participation should approximately equal the energy retained by the building storage elements. As shown in Table 4 the slab's temperature swing is cut in half which is equivalent to a reduction of stored energy which equals 5930 BTU. In addition, due to the carpeting, the heat loss through the slab is reduced by 1042 BTU over the 10 hr period. The reduction of heat flow to the slab equals 5930 BTU + 1042 BTU which equals 6973 BTU. This is reasonably close to the 5891 BTU that was retained by the thermal masses and is within the margin of error inherent in these calculations.

It should be noted that after the course of a 24 hour period, the net gain in BTU's by having the carpeting installed is only 2500 BTU. The effect of the carpeting therefore, is to throttle down the radiative losses to the slab. The losses are not reduced tremendously. Rather, the heat transfer occurs at a lower rate over a longer period of time. The subtle, but significant, difference is that the room's surfaces stay warmer longer, and thereby helps maintain a comfortable room MRT further into the night.

This fall (1979), a 1" thick wall to wall carpet was installed. The heat loss from the slab will be reduced by 16% and the surface temperature of the carpet will be somewhat higher than the carpeting used this past apring. Its 'U' value will be .42 BTU/hrft^2°F. Thermal effect of this new carpeting on the room environment has been simulated and the results of this analysis are illustrated in Figure 25.

From the simulation, the average and peak temperatures of the surfaces and air for the 7-5 pm period before and after installation of the 1" carpet were found to increase as shown in Table 7. The peak room air temperature increased from 69°F to 72.5°F.

TABLE 9. ROOM TEMPERATURES	Average Temperature °F*		Peak Temperature °F	
	Carpet Condition	Bare Concrete Condition	Carpet Condition	Bare Concrete Condition
Wall Temp.**	70	68	74	71.5
Active ceiling temp.	70.5	70	77	77
Floor surface	67	61.6	71	62.2
Air temp.	68.5	66	72.5	69
MRT	69	66.5	73.6	69.75
Env. temp.	68.75	66	73	69.4

* Between hours of 7 am - 5 pm.

** Includes 400 ft^2 of tiles which are not included in phase change

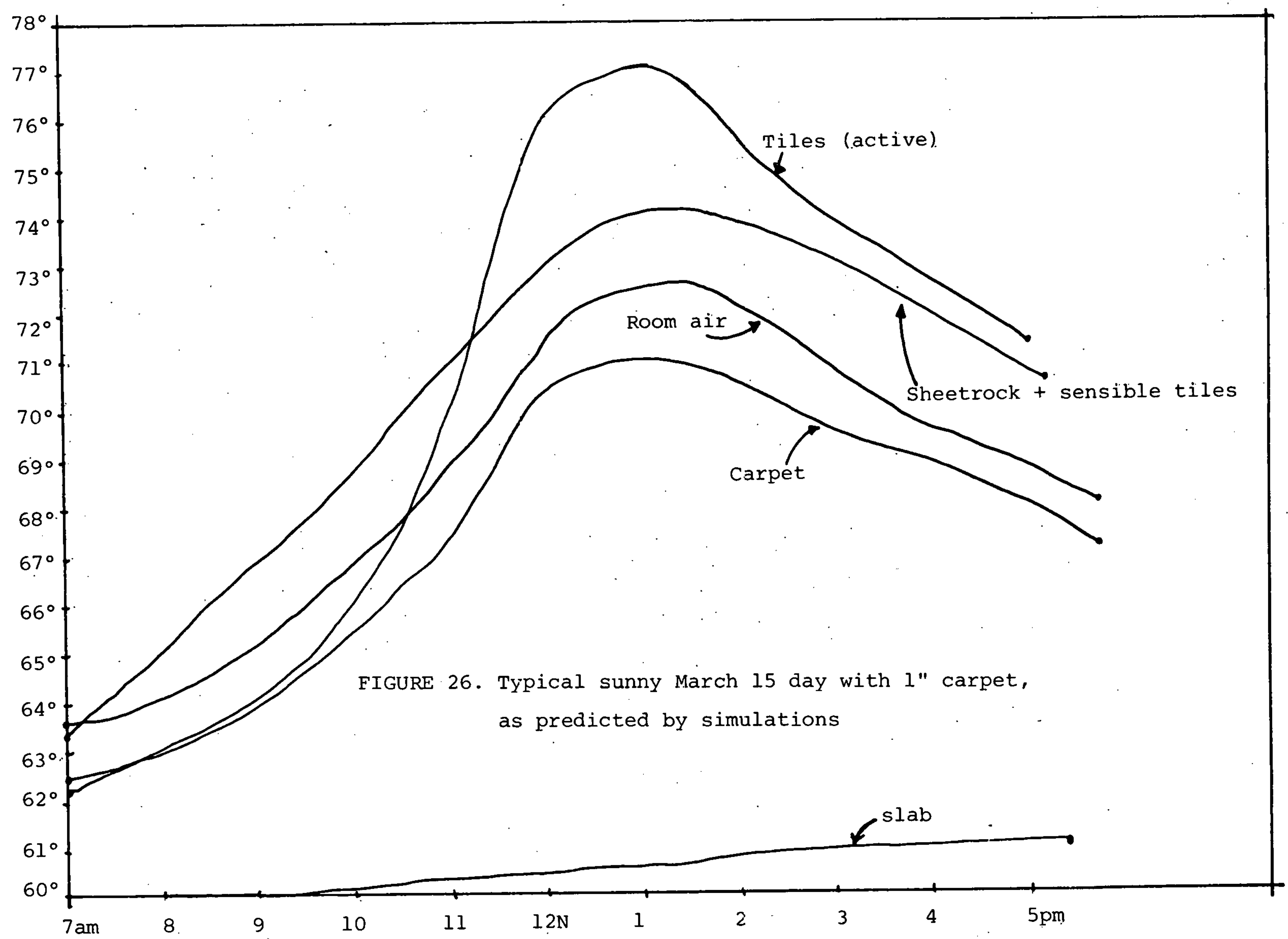


FIGURE 26. Typical sunny March 15 day with 1" carpet, as predicted by simulations

We do not anticipate any overheating problems on moderately warm (50°F), sunny March days. From an overall energy balance standpoint, the quantity of heat saved by the carpeting will amount to about 5000 BTU per day. In addition, the acoustic and aesthetic qualities of the room will be enhanced without suffering the consequences of overheating.

Infra-red Thermography

The thermal integrity of the Solar 5 building skin was checked out with far infra-red thermography. A liquid nitrogen cooled thermographer was used that was sensitive out to 40 microns, which easily encompasses IR radiation in the room temperature regime. The building was inspected on the night of April 15 when the outside temperature was 43°F and the room air temperature of the building was 64°F.

Figure 27 shows the South elevation, Figure 28 shows the West elevation. Notice here the West wall steel stud work is visible through the 1" thick exterior styrofoam. This is a testimony to the sensitivity of the thermograph and does not indicate a loss of any magnitude. The white structures behind the building are neighboring buildings of masonry construction. Notice they are losing as much heat as the double glazing in Solar 5. Figure 29 shows the North elevation. Notice no white areas show (except at the windows) which means no unexpected heat losses are occurring. Figure 30 shows the East elevation. Figure 31 shows the effect of the single Heat Mirror that was installed at the time. The Heat Mirror was only a single sided version (now, Heat Mirror is deposited directly on glass on one side only). The scale at the bottom is a quantitative temperature profile at mid-picture height. Notice the temperature of the outside lite of glass is lower (2.2°F) in the bay with Heat Mirror indicating less heat is escaping. Figure 32 shows an interior detail of the heat storing ceiling tiles (white in this picture) and the window header.

Figure 33 shows a typical ceiling wall joint showing no thermal leakage (again the steel stud work is visible behind the wall board). Figure 34 shows the first of three serious heat leaks found by the study. An air leak at the North facia/soffit is cooling the ceiling/wall joint (the blackened area) and conducting 'cold' down the studs to the window header. This leak has been corrected. Figure 35 shows the vestibule door seal leaking at the joint and the sill. Another non-reproducible shot showed an air leak at one of the ventilator windows. These have all been subsequently fixed.

All in all, the study shows the building is exceptionally tight thermally. The study showed the building also lost much less heat through the joists than expected; in fact less heat is lost than through the studs.

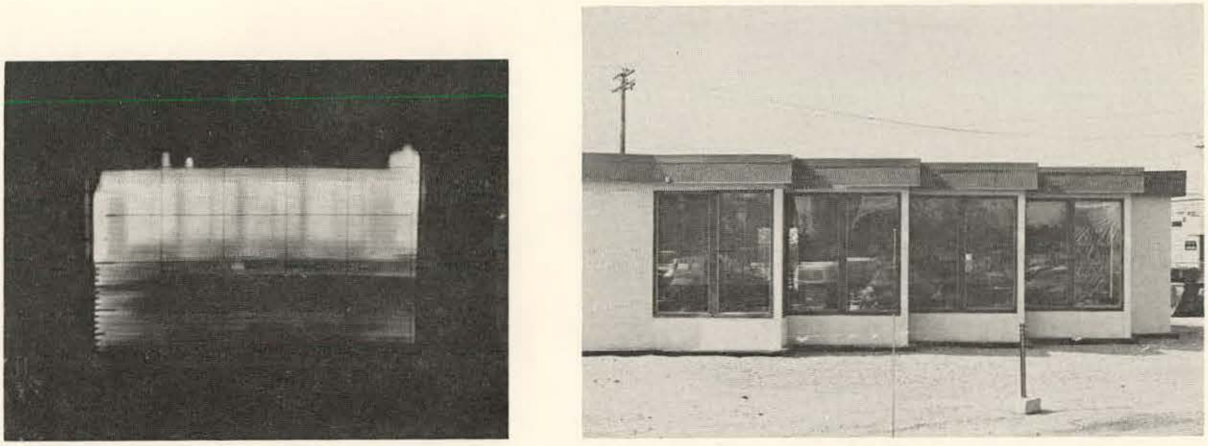


Fig. 27. South Elevation

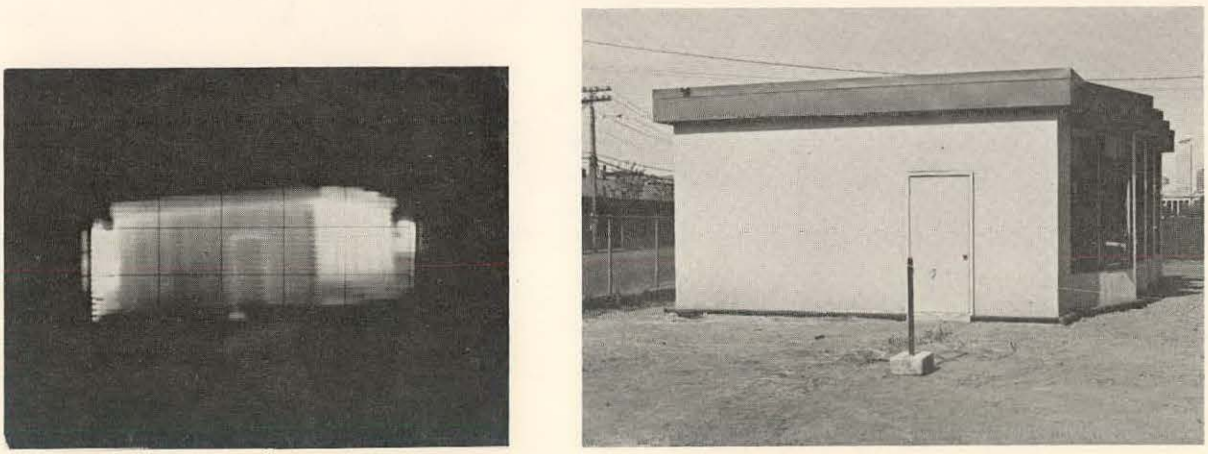


Fig. 28. West Elevation

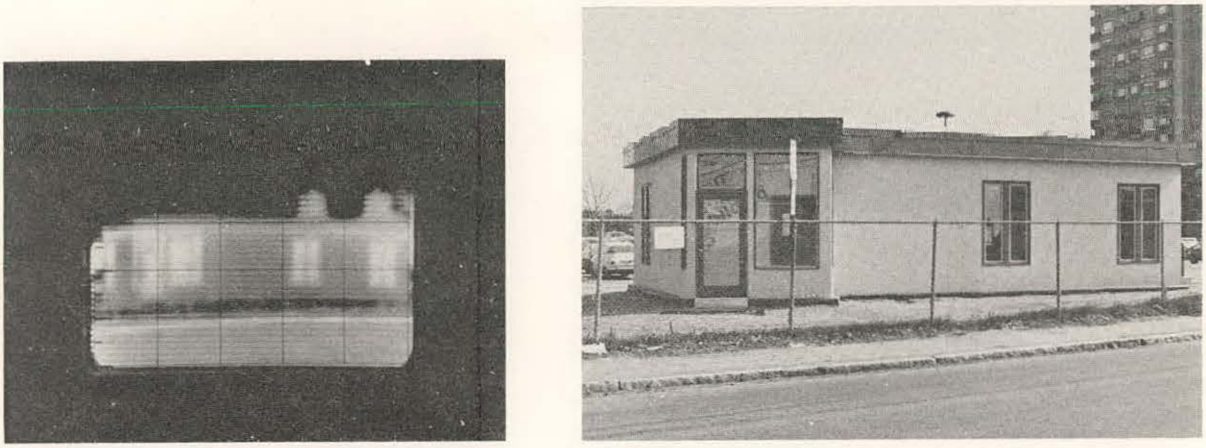


Fig. 29. North Elevation

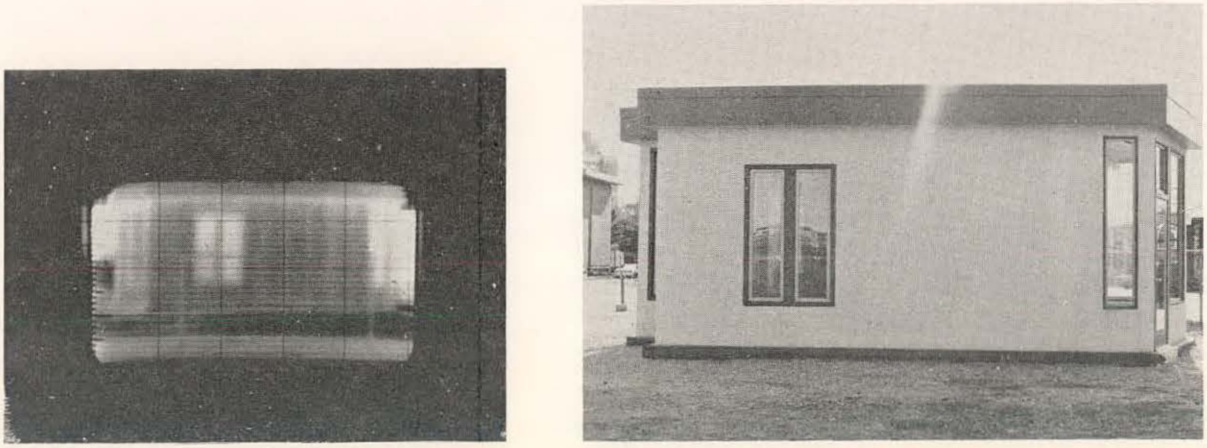


Fig. 30. East Elevation

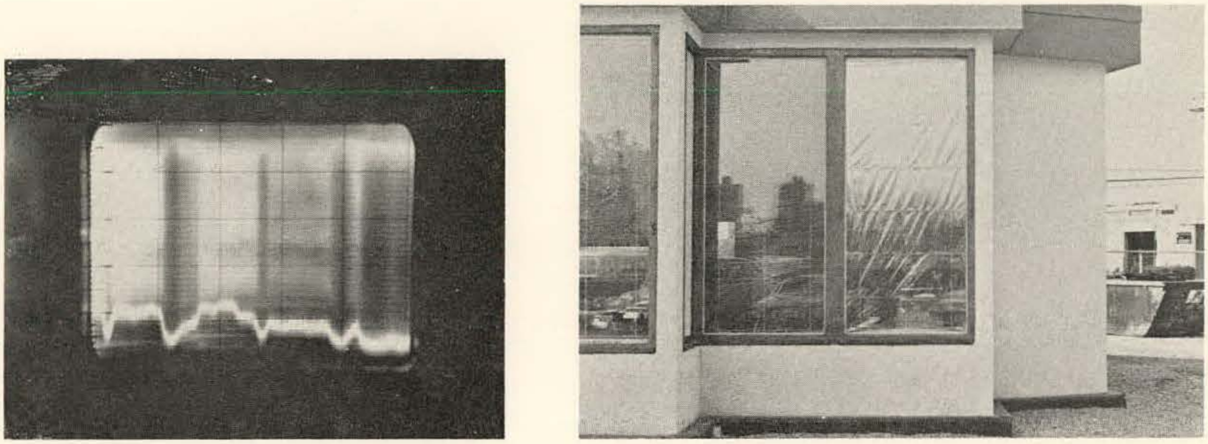


Fig. 31. South window close up; right side has Heat Mirror between double glazing; left side does not.

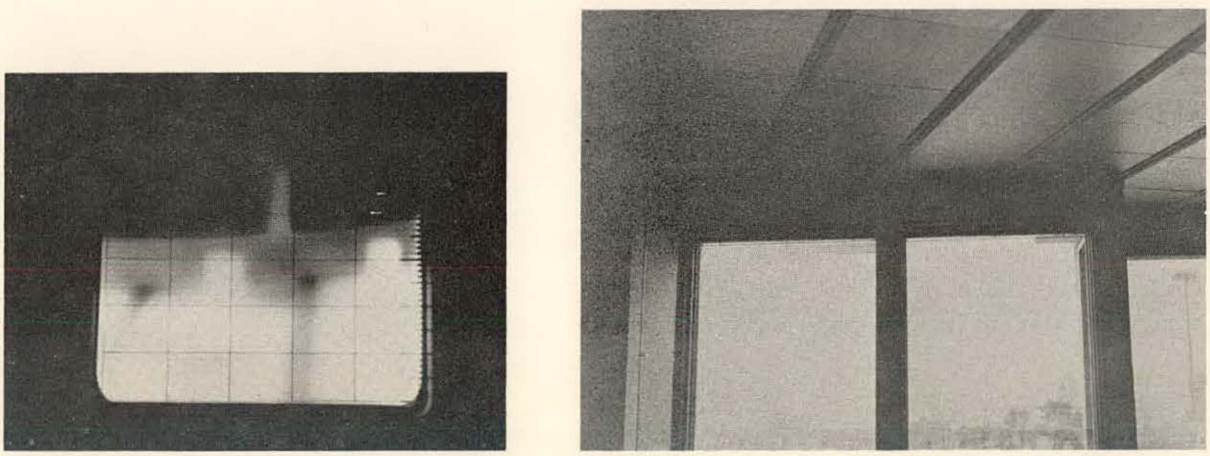


Fig. 32. Interior photo of heat storing tiles and top of South window frames.

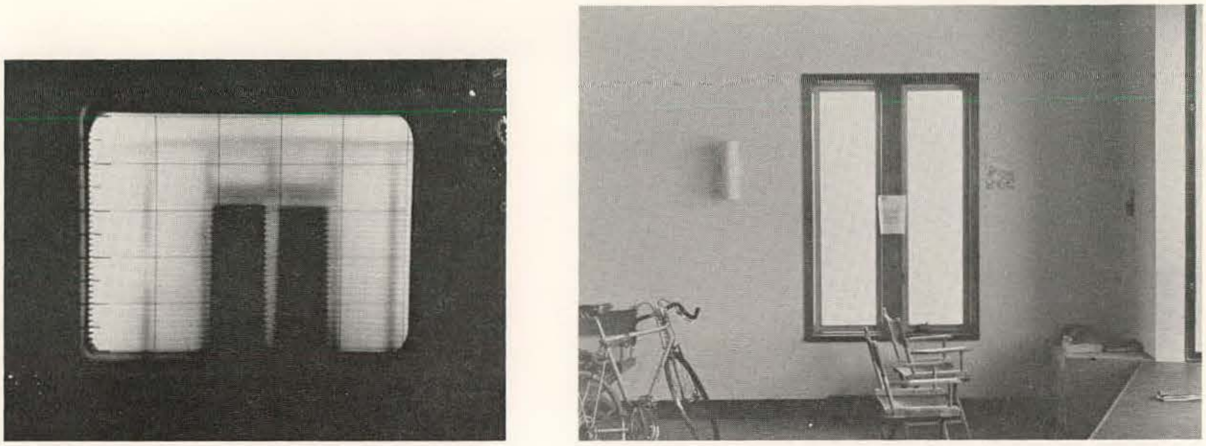


Fig. 33. Typical interior ceiling/wall intersection

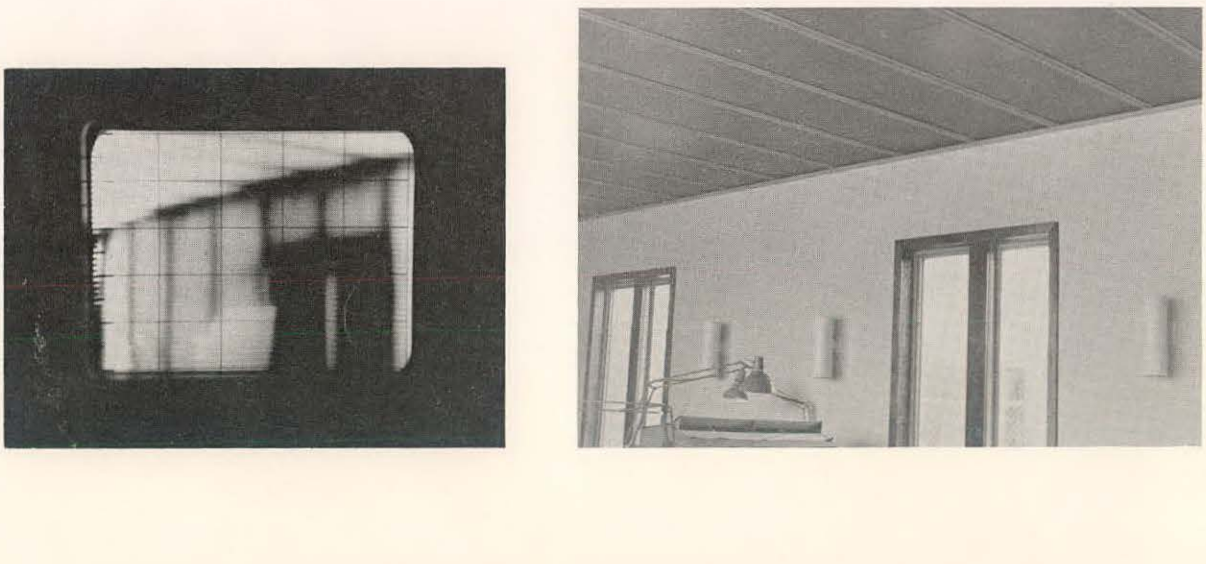


Fig. 34. Heat leak at window

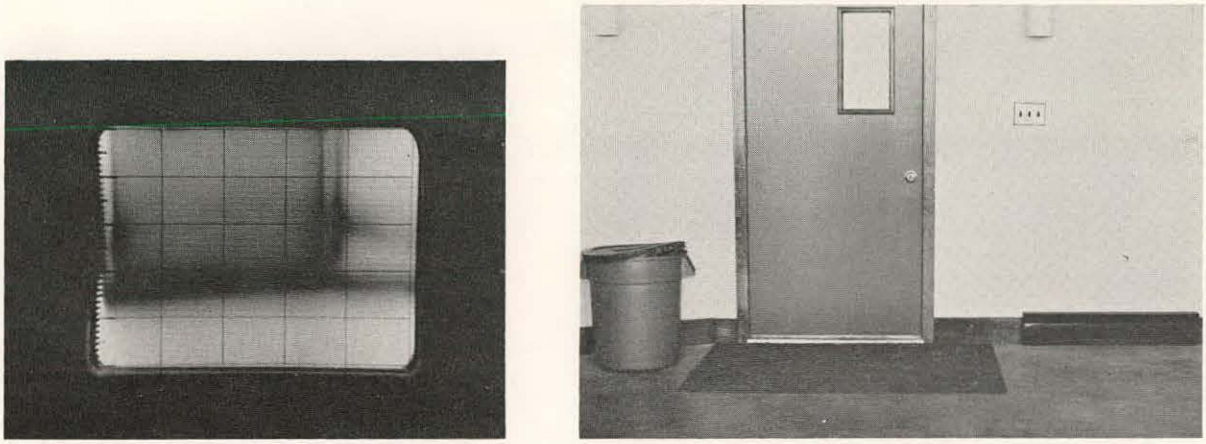


Fig. 35. Heat leak at base of door.

BUILDING IMPROVEMENTS

Each of the three new finish materials developed a minor problem during the first four months of operation.

The polyester cord ladders that support the modified louvers started stretching after the first months of operation; so the bottom slats were no longer parallel to the top slats. This meant that the insolation reflected off the blinds no longer struck the ceiling as intended, resulting in either a less intense solar flux at the ceiling or the sun glinting into people's eyes. The problem is being corrected by Rolscreen Company by switching to fiberglass filament ladders.

Two problems surfaced with the ceiling tiles. One problem was odor; the volatile agents in the polymer concrete continued to cause a faint smell of resin. The Architectural Research Corporation has overcome this by adding a special surface treatment. The second problem was infrequent leaks. Three tiles (two in the ceiling and one in a settee) out of 263 tiles leaked after 4 months of operation. An additional 2 ceiling tiles leaked over the next year. This was due to air bubbles in the polymer concrete that opened a path for the salts once the salt crystals punctured the thin barrier. The leaks occurred on the non-finish side of the tile and were not visible until some salt crystals reached the tile edge; no liquid was ever noticeable. The problem has been solved by minimizine the entrainment of air in the polymer concrete during the mixing stages through vibration of the forms.

The plastic based heat mirror started to corrode in the presence of gaseous pollutants at the tape joints (which was expected), but the corrosion continued to enlarge at some of the sites when the summer heat arrived. 35% of the heat mirror surface area has corroded, causing the transmissivity through the corroded area to be reduced from 70% to 55%. The overall transmissivity of the southern glazing has been reduced by 5.5%. The Suntek heat mirror is being replaced this fall with glass coated with Indium-tin-oxide by Airco Company. The solar transmissivity of one sheet of glass coated on one side with the indium-tin-oxide equals .81. (This includes absorption heating gain to the space). Our southern glazing will consist of 2 lites for an overall solar transmissivity of 65%. The transmissivity of the southern glazing with heat mirror on mylar between 2 lites was 54% (before corrosion). The difference in solar transmission will be .65/.54 or 1.2 which equals 20% more solar gain.

However, the heat loss through the south windows will be increased. The 'U' of the new window assembly will be .26 BTU/hrft^{2}°F. The old windows had a 'U' of .18. The increase in the building load will be $UA_{new\ window} - UA_{old\ window}$.

$$\frac{(UA_{new\ window} - UA_{old\ window}) + UA_{building\ normalized}}{UA_{building\ normalized}}$$

whereby

$$\frac{\left(.26\ \frac{BTU}{hrft^{2}{}^{\circ}F} \times 180\ ft^{2} - .18\ \frac{BTU}{hrft^{2}{}^{\circ}F} \times 180\ ft^{2}\right) + 255\ \frac{BTU}{hr^{\circ}F}}{255\ \frac{BTU}{hr^{\circ}F}}$$

= 1.056, which is equivalent to a 5.6% increase in load.

The carpeting installed will reduce our building UA by about 4%. Therefore, the net change in the building load will be 1.6%.

Referring to Table 1, the normalized building load should increase from 8492 kwh to 8628 kwh. Also, the solar gain should increase from 4831 kwh to 5797 kwh. The gross solar heating fraction should increase from 57% to 67% (urban Boston area). For outside the Boston area, the new solar insolation level will be 6258 kwh yielding a seasonal gross SHF of about 73% and a net SHF of about 84%.

Summer Cooling

The building is cooled in the summer by massive nocturnal cross ventilation. This is accomplished by opening the four ventilator doors on the South side of the building and the three North facing casement windows. Using the SF_6 gas detector, it was determined that with all the windows and ventilator doors open, and with a 5 mph breeze, the quantity of air movement through the building was equal to about 7.5 air changes per hour. This is equal to about 65,000 ft^3/hr or about 1000 cfm.

This air movement will eventually cool down the internal surfaces to the early morning air temperatures (typically 65°F). During the day, the ventilator doors are closed, and the casements are left open a crack for ventilation. The initially cool building masses then soak up the day's heat. This procedure resulted in interior peak room air temperatures that ran 8° below peak outdoor temperatures. This is not regarded as remarkable performance. Some of the heat added to the room comes from heat absorbed in the heat mirror which radiates into the room. Also, there are no shade trees over the roof which would be helpful in any situation. Given normal landscaping, it is felt the building would perform acceptably.

User Reaction

The building was used by two distinct groups, students and the general public. Eight students occupied the building for 2 hours, two afternoons a week and 5 hours one night a week for one semester. Between 15 and 20 people per hour visited the building during the four weekly hours the building was open to the public.

The only thermal complaints were registered on two different cold winter nights by most of the students. The students felt cold in certain areas of the of the space when the air temperatures were 62-61°F. Normally the radiantly heated ceiling would compensate for these low temperatures. About half the people felt the space was stuffy (due to the low infiltration rates and relatively small volume), but most of these complaints were occasioned by the ever present smell of polyester resin coming from the ceiling tiles.

The natural daylighting was deemed very pleasant during sunny hours. Task lighting was necessary for the students at their drawing boards on most overcast days. The lighting proved to be even and shadowless. Visitors were pleasantly surprized by the view afforded by the narrow louvers and remarked their opinion of venetian blinds had been altered by the visit. Although glare was greatly reduced, some public visitors complained of the remaining glare. Subsequent questioning showed most of the complaints were due to glare produced by the cars in the adjoining parking lot.

The dark colored ceiling received many complaints when viewed during the day; surprizing, not because of its tone, but because of its color. Most of the complainers did not approve of blue, but would have accepted an equally dark green or terra cotta. A very small percentage of the visitors would not accept any dark ceiling.

The visitor group was not very representative of the buying American public since anyone who visited the building was obviously interested in solar energy and therefore less conservative. Nevertheless, opinions on decor were freely offered and one suspects these opinions were as frank as any one could call for.

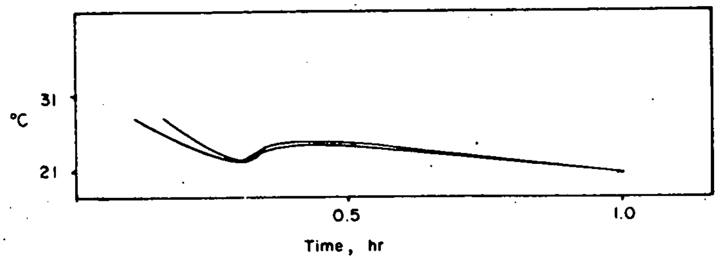
The nighttime lighting scheme was a failure; a subject of nearly universal complaint. The room was lit by ten wall washers (a wall fixture that throws light up and down the white wall) and by 8 down lights over the South windows, using a total of 2200 watts. The ceiling absorbed enough light to make the room feel dark (slightly less than 3 foot candles). One possible solution to this problem is using one or two central ceiling fixtures instead of the wall washers. A central fixture would not interfer with solar collection since only the front half of the ceiling participates.

The overall public impression is nicely summed up in the September 1978 issue of Solar Age: "... A pleasant little demonstration building."

SUMMARY

MIT Solar 5 has shown thermal and visually comfortable spaces can be heated with direct gain methods when new architectural finish materials are used. The heat mirror, louvers and ceiling tiles help trap and moderate enough solar energy to supply 62-70% of the building's seasonal heating requirement (internal gains supplied another 13%). This was done by glazing only 45% of the South wall. Economic analyses show payback period is 3 to 4 times faster than when using the flat plate collector approach. Architectural flexibility has been increased, even to the point where new kinds of spaces can be created using these materials.

APPENDIX I



Cooling behavior of modified Glauber salts in a 15°C ambient when packaged in small diameter vials. Top curve shows behavior after 266 freeze/thaw cycles, bottom curve shows behavior after 500 cycles.

FIGURE 36.

Accelerated thermal aging tests are being conducted on small samples of the modified Glauber salts, containing the NaCl and the thickenre addition. 56g of H_2O, 44g of Na_2SO_4, 3g of Borax and 9g of NaCl, 4g of properly dispersed thickener are sealed in a screwtop, glass vial that varies in diameter from 1.2 to 0.3 cm. Since some of the water can escape through the rigid plastic screwtop, the vial is sealed inside a transparent Mason jar to prevent the further escape of water. The jar is heated with an IR lamp for 2 hrs, and allowed to cool in a 15°F (62°F) atmosphere for 4 hrs. So far 4300 freeze-thaw cycles have shown no water pooling, a typical sing of aging. Some small deposits of anhydrous sodium sulphate have formed in the large diameter sections of the vial, but no deletorious deposits have appeared in the vial sections less than 0.63 cm in diameter. Figure I shows the freezing behavior of the mixture at the 266th cycle and the 500th cycle as measured by a thermistor burried in the center of the material.

Appendices

APPENDIX II

MIT SOLAR BUILDING 5

ECONOMIC ANALYSIS

October 1979

I. New Building Component Costs (based on mass produced quantities)

A. Ceiling

Bag and chemical core cost: $1.90 ft^2$

B. Transparent Insulation

1. Heat mirror cost: $1.50 ft^2$
2. Cost of materials being replaced: assume double glazed windows already exist
3. Net costs: $1.50-0.00 = $1.50 ft^2$

C. Modified Louvers

1. Mirrored venetian blinds: $3.50 ft^2$
2. Assume additional window dressing is still used
3. Net Costs: $3.50-0.00 = $3.50 ft^2$

II. Typical square footage involved (where 80% of the heating load is met by passive gains). The following material percentages are based on the MIT Solar Building 5 performance

A. Two story single family detached residence (1600 ft^2)

1. Ceiling area 52% of ceiling is in sunshine: 833 ft^2
2. Window area: 480 ft^2 (effective collection area = 460 ft^2)

B. Multiple family construction (1100 ft^2)

1. Ceiling area (40% of ceiling is in sunshine): 440 ft^2
2. Window area: 255 ft^2 (effective collection area = 242 ft^2)

III. Incremental Building Cost

A. Single family

1. Ceiling ($1.90 ft^2)	$1582
2. Window ($1.50 + $3.50 = $5.00 ft^2)	$2400
3. Total ($1.50+$3.50)	$3982

III. (Continued)

B. Multiple family

1. Ceiling $ 836
2. Window $1275
3. Total $2111

IV. Seasonal energy balance (Boston climate); when operating with internal heat gains, the ceiling and window area can be reduced.

A. Single family: Building losses (with Heat Mirror) is 9600 BTU/degree day.

Month	Deg. Days	Heat Loss	$x10^6$ BTU Window heat gain	Solar used	% Heated
OCT	316	3.034	6.001	3.034	100
NOV	603	5.789	7.152	5.789	100
DEC	983	9.437	7.078	7.078	75
JAN	1088	10.445	6.267	6.267	60
FEB	972	9.331	5.600	5.600	60
MAR	846	8.121	7.309	7.309	90
APR	513	4.925	5.109	4.925	100
MAY	208	1.997	3.502	1.997	100
	5627	53.079		41.999	79

B. Multiple family (4900 BTU/degree day)

OCT	1.538	3.123	1.538	100
NOV	2.934	3.721	2.934	100
DEC	4.783	3.587	3.587	75
JAN	5.294	3.176	3.176	60
FEB	4.729	2.837	2.837	60
MAR	4.117	3.705	3.705	90
APR	2.496	2.501	2.496	100
MAY	1.012	1.822	1.012	100
	26.903		21.285	79

V. Payback period (if 98,000 BTU can be delivered from each gallon of oil at \$.91 per gallon, then 10^6 BTU cost \$9.29)

The payback period is conservatively computed by dividing the first cost by the annual savings. This is based on the assumption that fuel inflation covers the interest payment on the borrowed capital.

Annual savings are the sum of captured solar energy fuel equivalent and the savings developed by placing heat mirror on the windows. Conventional energy loss through double glazed windows is proportional to the heat conductance (.55 BTU/hr°Fft^2) times the degree days. Energy loss with heat mirror is one half the conventional loss.

A. Single family: $\text{Payback} = \dfrac{\text{capital cost (\$)}}{\text{annual savings (\$/yr)}}$

$$= \frac{\$3982}{\$9.29/10^6\text{BTU}((.55-.55/2)\text{BTU/hr°Fft}^2\text{x}460\text{ft}^2\text{x}24\text{hrs/dayx}5627\text{°f days})+41.999\text{x}10^6\text{BTU})}$$

= 7.3 years

B. Multiple Family

$$\frac{\$2111}{(((.55-.55/2)\text{x}242\text{x}24\text{x}5627) + 21.285)\text{x}\$9.29} = 7.5 \text{ years}$$

APPENDIX III

Balance Point

A building's balance point is the ambient temperature at which point the home's heating plant must supply energy to the space in order to keep it at the thermostat setting. Internal gains keep the house air temperature above the thermostat setting until the ambient temperature reaches the balance point. The balance point equals

$$BP = \text{thermostat setting} - \frac{\text{Internal gains (BTU/hr)}}{UA_{\text{building}}\ (\text{BTU/hr°F})}$$

A 2000 ft^2 energy efficient single family dwelling as defined by the Building Energy Performance Standards, would have a balance point of

Thermostat	= 65°F
$UA_{building}$	= 600 BTU/hr°F
Internal gains	= 3333 BTU/hr

$$\text{Balance point} = 65°F - \frac{3333\ \text{BTU/hr}}{600\ \text{BTU/hr°F}} = 59.4°F$$

This home's net heating load is equal to 4290 degree days (Boston) rather than the usual 5527 degree days published for a 65°F balance point. This difference is equivalent to a reduction of 22% in the load of the building. Heating plant sizing as described in ASHRAE always assumed a balance point of 65°F for residential structures. While this generalization may have been adequate in the past, it is no longer sufficient in light of today's move toward more energy efficient buildings. In the past people who designed energy efficient, solar heated dwellings were usually pleasantly surprised when they found that their houses performed better than expected. More often than not, it was for the reason that they overestimated their load by assuming an incorrect balance point.

APPENDIX IV

Method Used to Calculate Insolation Deviations

The MIT Solar 5 building is equipped with a thermopile pyranometer mounted vertically behind one of the South facing windows in the room. The voltage generated in the thermopile is amplified and fed to a strip chart recorder. The strip chart is run through a planimeter to compute the total transmitted solar radiation. Unfortunately, it was not possible to calibrate the pyranometer with a known source due to the fact that the 2 pyranometer installations in the Boston area (Blue Hill and Boston University) were out of service throughout the winter and spring of 1978-79. For this reason, the strip charts had to be calibrated by using available data and computer programs.

The method began with first determining the "clear day" total radiation on a vertical, South surface for mid-March in Boston. ASHRAE data did not prove satisfactory since what is listed in the book assumes an atmospheric transmissivity (clear day) for non-urban areas. In addition, the table did not take into account the variability of ground reflectance. The solar building has white stone spread out in front of the South windows to help increase our ground reflectance from a typical value of .2 (grassy field) to .35.

We examined the SOLMET Data that was available for Boston. SOLMET Data is reworking of solar data that had been collected at the Boston US Customs House and later the Post Office. The data has been upgraded in order to fill in missing sections and account for degradation of equipment. In the SOLMET Volume II report are listed standard year, clear day, solar noon irradiation values on a horizontal surface for each day of the year. The data is plotted on Fig. 37. The trouble with this data is that it is an average of data collected from 1941-1970 and obviously comes under question as to whether or not it truly represents the quality and transmissivity of the atmosphere over Boston today. The only other station in Boston that has been collecting data continuously for a number of years is the one located at Boston University across the Charles River from MIT. Up until May of 1978, the BU station was collecting data with an EPPLY 180° "Black and White" pyranometer. Their

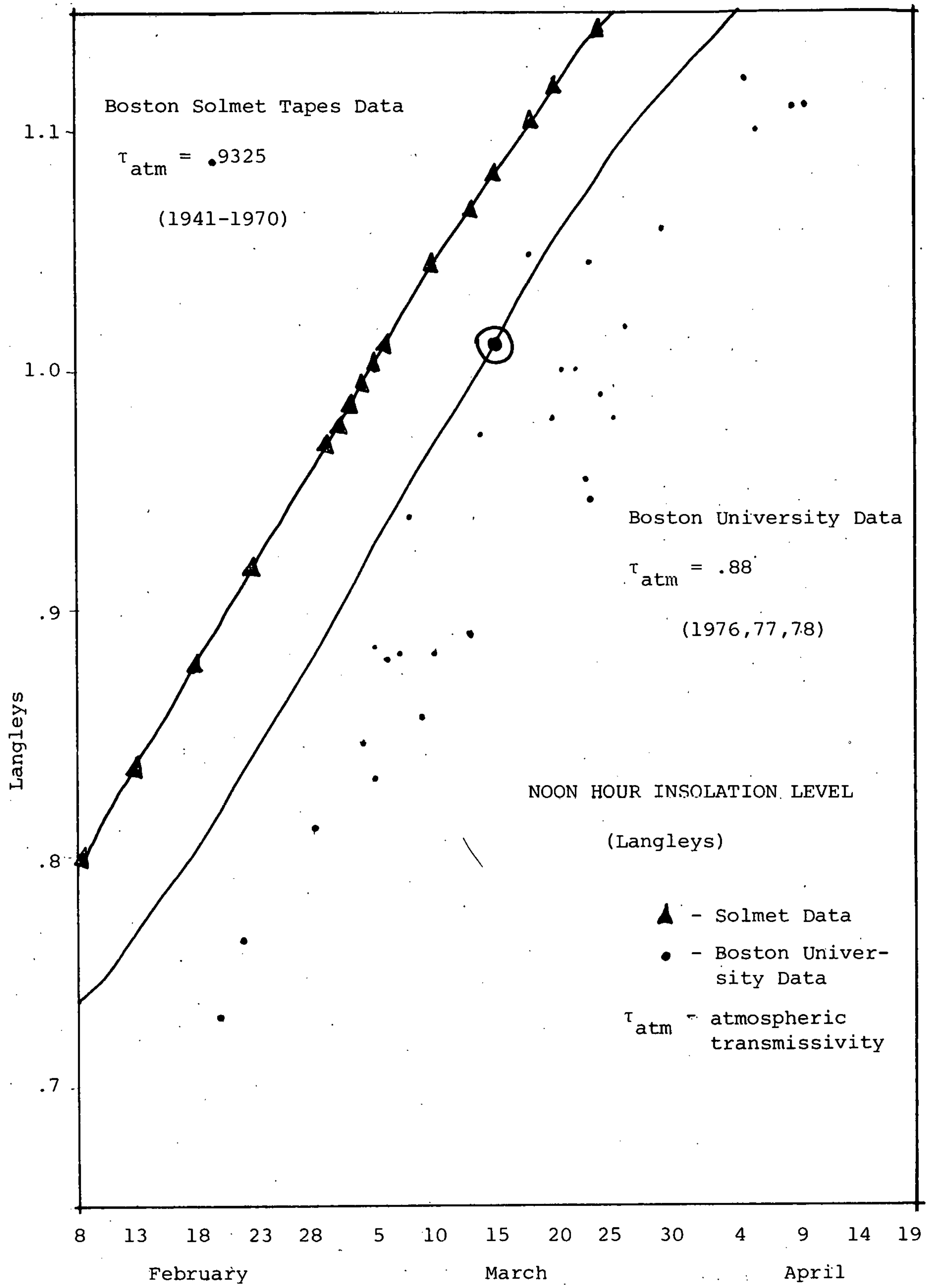


FIGURE 37. CLEAR DAY SOLAR INSOLATION DATA

March records from 1976-78 were searched and the noon hour insolation levels plotted on Fig. 37 adjacent to the SOLMET data. As can be seen, the data was not subjected to a linear regression to construct the line. This can be understood if one recognizes the fact that all the points from the BU data do not necessarily represent the real "clear sky at noon" value. Only those points to the left of main bulk of points represent a clear sky with no haze and low humidity. It was decided to take the average of the top two points and then draw a line from that point such that it is parallel to the SOLMET line. Because of the lack of any other recent data from the Boston area, it was assumed that the BU data was more representative of the solar transmissivity of the atmosphere here today. If this is in fact the case, it represents a reduction in clear day atmospheric transmissivity of 6.5% over about 22 years (1955-1977) - midpoints in the collection period for the SOLMET and BU data. It will be interesting to see further research conducted on this point.

From Fig. 37 we see that on a clear March 15th during the noon hour one can expect to receive about 1.01 Langleys per hour on a horizontal surface. This is equivalent to 223.4 BTU/hrft^2. From this we must determine what the clear day insolation levels are for a vertical surface since the Solar 5 building collects sunlight with vertical windows. A computer program written by Cris Benton at MIT for use with the TI-59 can calculate the clear day hourly insolation on any surface for any month of the year based on the ASHRAE method. The program takes into account extra terrestrial radiation (ETR), atmospheric clearance, longitude, latitude, surface tilt, azimuth and ground reflectance. (In addition, it will calculate solar transmission through glazing materials if the transmissivity properties of the glazing is known.)

In our case, the only significant unknown among all these variables was the atmospheric clearance. As used by ASHRAE, this is a dimensionless number and is used to adjust the amount of ETR that actually penetrates the atmosphere. An atmospheric clearance value of 1.0 is defined by ASHRAE as being representative of an average non-urban atmosphere. The 1.0 does not have anything to do with the ratio between solar intensity at sea level and ETR, that ratio is about .5. By substituting various atmospheric clearance values into the program, we eventually found one which generated a noon hour insolation value that matched our data for a horizontal surface.

The atmospheric clearance value was .88. Knowing this, the computed clear day incident gain for the vertical South glass was 1618 BTU/ft^2day (1253 BTU beam, 365 BTU diffuse and reflect.) March 15, 1979 was the clearest day of the month as indicated by strip chart recorder. By running the curve for that day through the planimeter we could find the area under the curve which would be equivalent to the total radiation for a clear March day. To accurately tabulate the area under the curve we had to estimate what the shape of the curve would be during those periods when clouds passed in front of the sun. We filled in these "holes" by looking at previous clear days and by simply following the trend of the curve for that day thereby constructing the ideal March 15 clear day. With 3 runs through the planimeter the average clear day area was .402 area units; thus, .402 area units equals 1618 $BTU/dayft^2$. When the whole month of March was run through the planimeter the total equals 5.442 area units (See Fig. 38). Thus, the average daily area units equal 5.442/31 days equals .1755 area units. Because the area is directly proportional to incident energy then the following equality is true:

$$\frac{.402 \text{ area units}}{1618 \text{ BTU/ft}^2\text{day}} = \frac{.1755 \text{ area units}}{X}$$

where

$$X = 706.6 \text{ BTU/ft}^2\text{day}$$

This is equal to the average daily insolation on the vertical south facing glass during March 1979.

To determine what fraction of "normal" this 706 BTU/ft^2day represents, we need to compute what the "norm", in fact, is. S. A. Klein[1] has proposed a method for determining average daily radiation on a surface of given orientation. Jim Rosen from MIT has successfully written a computer program using Klein's method for use on a TI-59. The data base for the program includes surface orientation and tilt, ground reflectance, latitude, declination, and average monthly solar insolation on a horizontal surface as observed by recording stations.

1. S. A. Klein, "Calculations of Monthly Insolation on Tilted Surfaces," Solar Energy, Vol. 19, p. 325-329.

FIGURE 38.

PLANIMETER READINGS (Area Units)

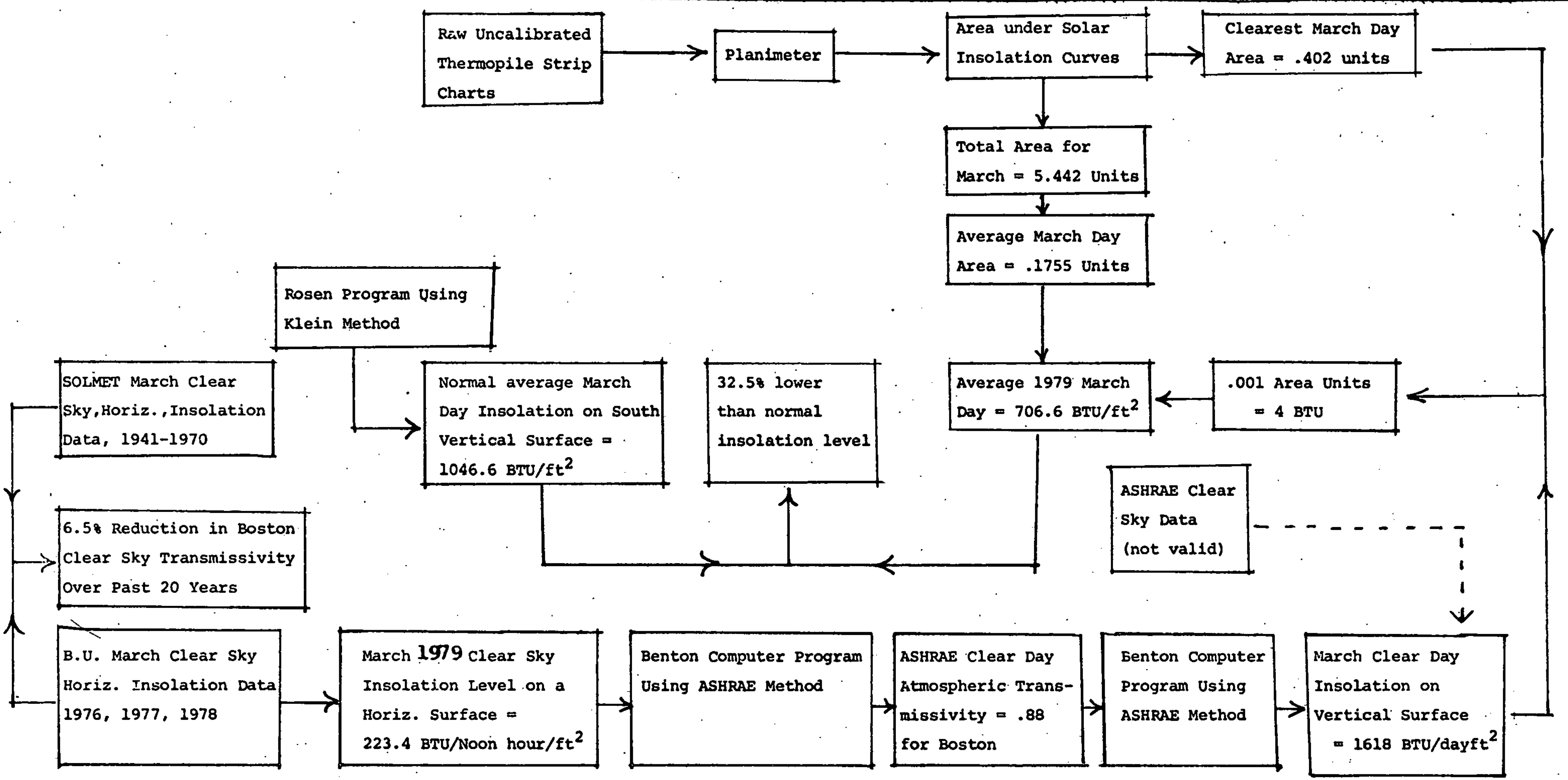
	PLANIMETER RUNS			
MARCH	1	2	3	Average
1	.218	.23	.225	.224
2	.02	.02		.020
3	.10	.10		.100
4	.10	.095		.097
5	.134	.136		.135
6	.022	.023		.023
7	.02	.03		.025
8	.06	.062		.061
9	.26	.266		.263
10	.023	.021		.022
11		.032	.032	.032
12	.28	.30		.290
13		.19	.183	.187
14	.063	.053		.058
15	.375	.38		.378
16	.38	.375		.378
17	.275	.295	.3	.290
18	.2	.21		.205
19	.132	.11		.121
20	.263	.271		.267
21	.252	.25		.251
22	.35	.36		.355
23	.325	.338		.331
24	.27	.27		.270
25	.03	.032		.031
26	.24	.225		.233
27		.315	.3	.308
28	.33	.34		.355
29	.06	.073		.067
30	.03	.045	.03	.035
31	.05	.05		.050
				5.442

5.442/31 = .175 average day

This program indicates that we should have received 1046.6 BTU/ft^2 day on our South facing glass. The ratio between the 2 numbers $\frac{I\ actual}{I\ normal} = .675$. In other words, the insolation levels on our windows for March 1979 were 32.5% below normal. This, finally, is the number we used to correct our March solar gain so as to arrive at a "normalized" figure for the month. The flow chart in Fig. 39 shows the progression involved in this method.

In addition, using the Rosen program we found that if Solar 5 were located outside of Boston (using Blue Hill data from previous years) then the solar gain for an average day in March would increase by about 8%. This accounts for Boston's decreased atmospheric transmissivity as a factor of increased water vapor and pollution. (This correction is also included in Table 1). In the course of this investigation we received information that Aerospace Corporation of Burlington, MA (about 10 miles NW of Boston) had solar insolation data for the months of February, March, and April. We used this data to check against our method just explained. We had to re-run Rosen's program due to the fact that their pyranometer was oriented 20° east of South and tilted at 45°. (Same angle and orientation as their collector array). In addition we used Blue Hill solar data rather than Boston data to take account of Burlington's cleaner air. Rosen's program incidates that they should have received 1368 BTU/ft^2day. According to the preliminary analysis received from DOE in Huntsville, Alabama, the actual solar intensities measured 27,900 BTU/ft^2 for the month of March which averages out to be 900 BTU/ft^2day. This is a reduction of 34% which correlated closely with our 32.5% (difference of +4.5%). Deviations for all the other months were handled in a similar manner.

Figure 39. Method of Determining March 1979 Insolation Level on Vertical Surface with Respect to the Norm



APPENDIX V

Example of the procedure used to "normalize" the SOLAR HEATING FRACTION for March 1979.

Actual March 1979 Solar Heating Fraction

$Q_{gross\ load} = A \times U \times \Delta T_{average\ month} \times hrs$

$= 270\ BTU/hr°F \times 19.19°F \times 696\ hrs$

$= 3.6\ BTU^6$

$= 1055.1\ kwh$

$Q_{aux.\ heat} = 418$ kwh (recorded on kwh meter)

$Q_{lites} = 203.3$ kwh (6 kwh/day + extra lite use logged)

Solar gain = gross load - (aux. heat + lites)

= 1055.1 kwh - (418 kwh + 203.3 kwh)

= 433.8 kwh

$$\text{Net SHF} = \frac{\text{Total Solar Gains}}{\text{Aux. Used + Solar Gains}}$$

$$= \frac{433.8\ \text{kwh}}{851.8\ \text{kwh}}$$

= 50.9%

$$\text{Gross SHF} = \frac{\text{Total Solar Gains}}{\text{Load}}$$

$$= \frac{433.8\ \text{kwh}}{1055.1\ \text{kwh}}$$

= 41.1%

Load Normalization

Weather Bureau records show that average ambient temperature was 4.4°F warmer than usual, therefore,

$$\Delta T_{\text{March 1979}} = 19.17°F$$

$$\Delta T_{\text{normalized March}} = 19.17°F + 4.4°F = 23.57°F$$

$$\text{Load (temperature) deviation} = \frac{19.17°F}{23.57°F} = -18.7\%$$

warmer than usual

$$Q_{\text{load}} = \frac{1055.1}{.813} = 1298 \text{ kwh}$$

UA will be reduced 5% when heat mirror is added to the north casement window so:

$$\frac{1298 \text{ kwh}}{1.05} = 1236 \text{ kwh - normal March load}$$

Solar Gain Normalization

As described in the text, after extensive examination of all available data, we determined that March's solar insolation was 32.5% lower than normal. Actual solar gain for March = 433.8 kwh.

$$Q_{\text{corrected for normalization}} = \frac{433.8}{.675} = 643 \text{ kwh}$$

In addition, the corroded heat mirror reduced solar gain an additional 5.5%

$$Q_{\text{solar normlized}} = \frac{643 \text{ kwh}}{.945} = 680 \text{ kwh}$$

Solar Heating Fraction Normalization

Our normalized solar heating fraction for March is

$$\text{Gross} = \frac{680\ \text{kwh}}{1236\ \text{kwh}} = 55\%$$

$$\text{Net} = \frac{680\ \text{kwh}}{680 + 353} = 66\%$$

If the solar building were moved outside the Boston urban area we could e expect an insolation increase of 8% which would raise the solar gain to 739 kwh and increase the solar heating fraction to

$$\text{Gross} = 61\%$$

$$\text{Net} = 71\%$$

We arrived at this average 8% differential by examining solar insolation data collected at urban (Boston) and rural (Blue Hill) observatories from the past thirty years.

The method for analyzing other months of the year was the same. To determine the seasonal load and gains, the monthly totals were added up and handled like the individual months.

APPENDIX VI

Load and Solar Normalization for Thermal Mass Participation on 3/15 and 3/27/79

Walls

3/15, no carpet

Solar Gain = 138,236 BTU

$\Delta T_{sheetrock-ambient}$ = 37°F (7am-5pm)

$Q_{lost\ through\ walls}$ = (.05 BTU/ft^{2}hr°F)(987 ft^2)(37°F)(10 hrs) = 18,259 BTU

$Q_{stored\ in\ walls}$ = 1123 BTU/°F × 4°F = 4492 BTU

BTU into walls = BTU_{lost} + BTU_{stored}

= 18,259 + 4492

= 22,751 BTU

3/27 - carpet over 50% of floor

Solar Gain = 115,384

$\Delta T_{sheetrock-ambient}$ = 26°F (7am-5pm)

$Q_{lost\ through\ walls}$ = (.05 BTU/ft^{2}hr°F)(987 ft^2)(26°F)(10 hrs) = 12,831 BTU

$Q_{stored\ in\ walls}$ = 1123 BTU/°F × 7°F = 7861 BTU

BTU into walls = 12,831 + 7861

= 20,692 BTU

To correct for the difference in insolation levels between 3/15 and 3/27, divide the $Q_{solar\ intake}$ 3/15 by Q_{solar} 3/27

$$\frac{138{,}236\ \text{BTU}}{115{,}148\ \text{BTU}} = 1.2\ (20\%\ \text{more insolation on 3/15})$$

BTU into walls (relative to 3/15):

$1.2 \times 20,692$ BTU = 24,830 BTU

$\Delta Q_{\text{into wall 3/15-3/27}}$ = 2097 BTU/10 hour period

Ceiling

3/15, no carpet

$Q_{\text{lost through ceiling}} = (.026\ \text{BTU/ft}^2\text{hr°F})(841\ \text{ft}^2)(10\ \text{hr})(40°\text{F})$

$= 8746$ BTU

$Q_{\text{stored}} = 23,284$ BTU

$Q_{\text{into ceiling}} = 32,030$ BTU

3/27 - Carpet

$Q_{\text{lost through ceiling}} = (.026\ \text{BTU/ft}^2\text{hr°F})(841\ \text{ft}^2)(10\ \text{hrs})(30.5°\text{F})$

$= 6669$ BTU

$Q_{\text{stored}} = 23,200$ BTU

Adjust for decreased insolation

29,869 BTU × 1.2 = 35,842 BTU

Q_{ceiling} (3/27-3/15) = 35,842 BTU - 32,030 BTU

= 3812 BTU

Total energy retained by ceiling and walls

3812 BTU + 2079 BTU

=5891 BTU

To Check

$\Delta Q_{ceiling\ and\ wall} \cong \Delta Q_{Slab}$

$Q_{into\ slab}$ 3/15 $= Q_{stored} + Q_{lost}$

$= 11{,}860 + (800\ ft^2 \times .08\ BTU/ft^2 hr°F \times 22°F \times 10\ hrs)$

$= 11{,}860 + 14{,}080$ BTU

$= 25{,}940$ BTU

$Q_{into\ slab}$ 3/27 $= 5930 + (800\ ft^2 \times .074\ BTU/ft^2 hr°F \times 22°F \times 10\ hrs)$

$= 5930 + 13{,}037$ BTU

$= 18{,}967$ BTU

ΔQ_{slab} (before and after carpeting) $= 25{,}940$ BTU $- 18{,}967$

$= 6972$ BTU

This is the quantity of heat which is no longer transferred to the slab. This should be approximately equal to the quantity of heat which remained in the walls and ceiling (5891 BTU). The difference of 18% $(\frac{5891\ BTU}{6972\ BTU})$ is within the margin of error inherent in this analysis.

REFERENCES

1. E. Speyer, Optimum storage of heat in a solar house, Solar Energy, 4, 24(1959).

2. H. R. Hay and J. I. Yellott, ASHRAE Trans., Vol. 75, Part I, 105-177 (1969).

3. S. Baer, Sunspots, Zomeworks, Albuquerque, N.M.

4. M. Telkes, Storage of solar heating/cooling, ASHRAE Trans., Vol. 80, Part II (1974).

5. Sean Wellesley-Miller and Day Chahroudi, A climatic envelope for the Aspen design conference, AIA Solar Conf., Washington (1974).

6. J. D. Balcomb and J. C. Hedstrom, Simulation Analysis of Passive Solar Heated Buildings - Preliminary Results, Los Alamos Scientific Laboratory, UCLA, Los Alamos, New Mexico, Report No. LA-UR-76-89.

7. D. A. Andrejko, The solar modulator: a novel approach to direct solar gain in architectural applications, New England Solar Energy Soc. Conf. Proc., Amherst, MA (1976).

8. D. Chahroudi, Suspension Media for Heat Storage Materials, Zomeworks Corporation, Albuquerque, NM (1972).

9. W. H. Severns, Heating, Ventilating and Air Conditioning Fundamentals, Wiley, New York (1949).

10. T. Johnson, Sean Wellesley-Miller and Day Chahroudi, Exploring Space Conditioning with Variable Membranes, NTIS, U. S. Department of Commerce, Springfield, VA 22161. Report No. PF 245137 (1975).

11. System Design Manual, Carrier Air Conditioning Company, New York, New York (1972).

12. T. Johnson, New building materials and components for passive heating of buildings, Passive Solar Heating and Cooling Conf. Proc. ERDA, Albuquerque, NM (1976).

13. T. Johnson, Lightweight thermal storage for solar heated buildings, Solar Energy, Vol. 19, 669-675 (1977).

14. D. R. Mayner, An Investigation into the Use of High Heat of Fusion Salts for the Storage of Heat in Residential Floor Slabs, B.S.M.E. Thesis, Massachusetts Institute of Technology, Cambridge, MA (1976).

15. Frank Kreith, Principles of Heat Transfer, International Textbook Co., (1960).

16. Ralph M. Lebens, Exploring various aspects of passive solar energy collection collection with particular reference to its potential use in the rehabilitation of nineteenth century row housing in England, M.Arch.A.S., Department of Architecture, MIT, 1978.

17. Timothy E. Johnson, et al., MIT Solar Building 5, Initial Performance, Department of Architecture, MIT, October 1978.