Sol-Clad-Siding and Trans-Lucent-Insulation: Curtain Wall Components for Conserving Dwelling Heat by Passive-Solar Means

by
Doru Iliesiu
Bachelor in Architecture, University of Toronto,
Toronto, Canada
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Signature of author ______________________
Doru Iliesiu, Department of Architecture,
May 13, 1983

Certified by ______________________
Timothy E. Johnson, Principal Research
Associate, Thesis Supervisor

Accepted by ______________________
N. John Habraken, Chairman, Departmental
Committee for Graduate Students

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ABSTRACT

A prototype for a dwelling heat loss compensator is introduced in this thesis, along with its measured thermal performance and suggestions for its future development. As a heat loss compensator, the Sol-Clad-Siding collects, stores, and releases solar heat at room temperatures thereby maintaining a neutral skin for structures, which conserves energy, rather than attempting to supply heat into the interior as most solar systems do. Inhabitants' conventional objections to passive-solar systems utilized in housing are presented as a contrasting background.

The potential of the outer component, a Trans-Lucent-Insulation as a sunlight diffuser and transmitter (65 to 52% of heating season insolation) and as a good insulator [0.62 W/(sq m)($^{\circ}$K)[0.11 Btu/(hr)(sq ft)($^{\circ}$F)]] are described. The performance of the inner component, a container of phase-change materials as an efficient vertical thermal storage is discussed, and areas for future research are addressed. A very brief application of this passive-solar curtain wall system for dwellings is also given.

Thesis Supervisor: Timothy E. Johnson
Title: Principal Research Associate

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PREFACE

This research is based on the belief that the conventional life-style of residents and the utilization of passive-solar heating are compatible. A union of the two would be possible only if the inhabitants did not have to noticeably change their established pattern of living.

The Sol-Clad-Siding innovation was an outgrowth of one of my earlier studies, namely, "Passive Solar Energy and Housing Prototypes: An Application of the Principles of Passive Solar Energy to Urban Housing," (submitted to Canada Mortgage and Housing Corporation, Ottawa, May 1980). This study proposed the utilization of solar spaces, or enclosed balconies of multiple housing, as sun-powered buffer zones to insulate the units' living quarters. These solar spaces were furnished with the thermal storage tiles encasing a phase-change material core, an architectural finishing material developed at M.I.T.

In order to function efficiently, these solar spaces imposed on dwellers some unconventional restrictions such as a lack of curtains, carpets, and standard furniture. My proposal to resolve this condition was to compact these 'sun-powered buffer zones' into the skin of housing units, and therefore allow the continuation of established living pattern for the occupants without imposing any modifications on it. The only change to be accepted then, would be the large areas of glass-finished facades of dwellings, but that should most likely be more acceptable than changes in life-style.

Part 1

CONVENTIONAL OBJECTIONS TO PASSIVE-SOLAR SYSTEMS UTILIZED IN HOUSING

The notion of considering the heat generated by sunlight when defining the thermal comfort within buildings has always existed in architecture. During some periods builders have attempted to redefine and renew the potential of this notion. Innumerable generations of dwelling inhabitants have protected themselves from and/or have utilized to their advantage the condition of living under solar exposure. For the majority of people, these modes developed and maintained over time have become indistinguishable from the pattern of living conventionally in houses. Modes of relating to the sun have been perpetuated along with the enduring expectation of an improved performance of building, particularly from a thermal standpoint.

The thermal performance of dwellings and their relationship with the sun are determined to a great extent by their building skin that simultaneously fulfills a multitude of other tasks. The proportion between the building skin's translucent and the opaque parts influences their images along with their properties of daylight transmission and/or thermal insulation. To attain optimum levels the sunlight that illuminates and heats interiors has to be modulated by means of the size and selective properties of translucent materials, and conventionally by other discernible agents such as curtains, louvers, venetian blinds. large reflecting and/or shading elements. These agents are also used in varying degrees for thermal insulation and for preventing uncomfortable drafts.

The curtain and the screen are the most conventional mode of tempering the sunlight to the desired level for the dwelling inhabitants. There are many distinct types of curtains and screens, each of them offering different qualities of light, privacy and thermal comfort; but, most of these types have similar attributes. Peter Pragnell reveals these attributes by eloquently rendering what it means

> ...to draw a calico curtain over a window. The curtain transforms the sun and changes the quality of its light. The light takes on the quality of a paper lantern; its luminous glow replaces a single-minded direction (the single-minded direction so necessary to sun-dials). Light is put into corners that would otherwise be dark. It is a poetic transformation and we have made it by simply drawing a piece of cloth along a rail with our hands. ...drawing a curtain illuminates the sun and we can see, if we want to, our relation to it.
>
> --Peter Prangnell, "La 'Maison de Verre" <<Spazio e Societa>>, No. 12, Sansoni Editore Nuova S.p.A., Firenze (December 1980), p. 122.

Yet, the direct-gain, the simplest and most affordable passive-solar system, banishes any curtain or screen as a prerequisite for its performance during the day. Inhabitants are required to live with glare through oversize windows, on exposed cementitous or ceramic floors, and also to endure the consequential overheating caused by the poor heat absorbance of these materials. Contrasting glare is bearable only by few; such exposeod floors are conventionally not considered as comfortable or appropriate to all or any south-facing rooms; and overheating is generally not tolerated. Likewise, inhabitants are requested to favor the undesirable ultraviolet degradation of furniture and fabrics. Additionally, inhabitants are required to live without the feeling of security provided by curtains and screens which obstruct visual intrusion. Living without this feeling is not considered acceptable in most urban or suburban settings. And, above all these, the temperature fluctuation and thermal confort of common direct-gain systems are difficult to control by conventional means. The control is easier only if the sunlight enters rooms in a diffused mode, therfore, allowing for a facile absorption.

However, by sidestepping some or all of these conventional objections, there are some dwellings that successfully utilize the passive-solar direct-gain to provide meaningful amounts of their heating needs. Most commonly they are located in rural or secluded settings. These unconventional dwellers may slightly influence the life-styles in urban or suburban dwellings where the majority of people live.

A real breakthrough in the circle of direct-gain inadequacies is demonstrated in the experimental buildings at the Massachusetts Institute of Technology, the Solar Building No. 5 and its Crystal Pavilion addition. The main element that caused this breakthrough is the horizontal thermal storage tile, an architectural finishing that incorporates a core of two thin layers of a phase-change material within a polymer concrete casing of minimum thickness. This tile circumvents the overheating and storage capacity insufficiencies because of the phase-changing material's capacity in this makeup to absorb, store, and release many times more heat than the cementitious or ceramic components of common direct-gain systems.

The Solar Building No. 5 includes the thermal storage tiles on its ceiling in a dark color. The sunlight arrives there from below via mirror-finish louvers placed within the south windows. Although this complex arrangement performs very well, its applicability to conventional dwellings is problematic: the louvers' upward reflection generates a glare condition near them, therefore reducing the inhabitable space of rooms and the traditional way of approaching windows. The dark ceiling also limits the character of the room, and the illumination at night.

The Crystal Pavilion uses similar tiles on its floor in an uncommon solarium-greenhouse setting. This location of tiles is very house-like. Such spaces may become very conventional through redefined extensions of living areas such as sunrooms, and enclosed porches or terraces.

The indirect-gain, the other major passive-solar system, does not cause most of the inconveniences associated with direct solar heating. The interposition of an opaque body as a heat-sink between a large vertical area of exterior glass and a dwelling interior facilitates the management of glare and ultraviolet degradation. The performance of this system is quite controlable but only at the cost of an unconventional system of vents to regulate the movement of warmed air from and toward the generating space in between the exterior glass and the heat sink.

The prevailing objections to this system concern its efficiency vis a vis the unconventional size, weight, and construction cost of the appropriate heat-sink. Masonry is the most common opaque body utilized, although it absorbs the sun's heat very poorly. The depth of the wall has to be large enough to store more heat than it loses to the outside during the night. Because the height of buildings below walk-up type is limited, such thick walls are not used anymore in a conventional manner in the construction of dwellings, particularly of multiple dwellings. Also, thick walls easily become cold-sinks which absorb interior heat during the heating season of colder climates, and this is one of the reasons why they are not used.

Because of their light weight and compact nature, the phase-change materials have been intended (for a long time) to function as the vertical heat sink for indirect-gain systems. These materials absorb solar heat more quickly, store it longer, and release it at more uniform temperatures. These qualities are fulfilled only under specific conditions: phase-change materials cannot be in bulk form, particularly in their common states; and, their packaging must have at least one dimension of a few millimeters (few one-sixteenth inches) beginning with the vertical direction. This small dimension permits the maximum heat absorption, for any bulky mass takes much more time to be penetrated by heat, even if by this process it changes its phase to liquid. The imperative horizontal condition is also necessary to avoid the chemical breakdown caused by the gravitational pull in certain phase-change materials such as Glauber's salts. The efficiency of such an horizontal state merges successfully and appropriately with the thermal storage tile discussed earlier, but it is in prime confilict with the vertical utilization for the heat-sink of indirect-gain systems.

The above conventional technical objections can be unquestionably extended with another set of fundamental problems. First, the inorganic salts as the preferred phase-change materials have to be contained in such a way that they do not lose their water component as such loss would cause them to breakdown; second, to resist the crystals of the solid phase, very expensive puncture-proof containers and packaging must be used. However, a new product appears to solve some of the discussed problems, and it is presented in Part 4.

Noticeable progress has been made in the last century in the scientific understanding of the bases of passive-solar utilization, and in the technical means by which to advance it. Yet, the general public still appears slow in adopting this progress. This attitude may well represent the natural process of inertia by which life-styles change in time, and by which these are embodied in architectural forms. If we disregard the style and size of all past buildings, we may conclude that architecture has maintained the same very basic principles of constructing. A way of expressing these principles in their relation to passive-solar approaches is formulated by Timothy E. Johnson as following: "Structures are built not to save energy, but to tastefully provide shelter, security, and comfort." [Timothy E. Johnson, <<Solar Architecture/The Direct Gain Approach>> (New York: McGraw-Hill Book Co., 1981) p. 3].

How can a wide acceptance of passive-solar systems be accelerated? Probably the answer is by merging with and enhancing, rather than by interfering with and complicating people's life-style trends and the corresponding architectural forms. It is difficult to imagine the inertial development of the majority of people bending noticeably its course during a few generations' life span although we may wish it does. Likewise, it is difficult to envision the disappearance of such amenities as the eyelid-like screens, the bed-like wall to wall carpet, or the comforting wood floors. Moreover, it is not easy to conceive the obsolescence of lightweight construction tendencies, or of updated walk-up housing. After all, if man has invested millenaries to improve his lot, why not build upon those achievements?

Part 2

SOL-CLAD-SIDING: A MODIFIED INDIRECT GAIN APPROACH INCLUDING A TRANS-LUCENT-INSULATION

The conventional objections to passive-solar systems as presented in Part 1 may be resolved by using the Sol-Clad-Siding in housing because it does not impose any changes in the inhabitants life style. The Sol-Clad-Siding can conserve dwelling heat by collecting, storing, and releasing solar heat at room temperatures, thereby maintaining a neutral skin for structures, which conserves energy by compensating for heat losses from the interior to the colder outdoor ambient.

As a component of a conventional-type curtain wall system, the Sol-Clad-Siding panel consists of a Trans-Lucent-Insulation as the outer element, and a container of phase-change materials as the inner elements (Fig. 2.1 shows these 2 elements before assembly in the Sol-Clad-Siding prototype; Fig. 2.2 presents an outside view of about 1/4 of this prototype). A substantial amount of solar heat is transmitted by the Trans-Lucent-Insulation to the container of phase-change materials which stores this heat through a solid to liquid change of state cycle. Due to their physical properties, the phase-change materials slowly release the stored heat at comfortable indoor temperatures. Some of this stored heat is lost to the outdoors, thereby replacing the heat which would otherwise have been lost from the interior through the building skin; the remainder of the stored heat is radiated to the interior whenever the room is at a lower temperature than the phase-change materials. (The room is considered to be heated by a conventional heating system, by electrical lights, and by occupants' body heat).

The slightly elevated indoor wall temperature of the Sol-Clad-Siding increases the mean radiant temperature of the interior and permits the healthy intake of more colder fresh air for ventilation. The following quote by J.M. Fitch explains eloquently the characteristic of radiant heating:

> Using a plane surface (ceiling, walls and/or floor) as the actual heating element, the radiant panels offer an almost ideal method of manipulating the thermal environment. If installed in all six surfaces of the room, as the Romans often managed to do, they surround the body of the occupant with a balanced thermal perimeter. That is to say, the rate of heat exchange between the body and its surrounding surfaces will be equal in all directions (excepting, of course, the soles of the feet, where the heat exchange is conductive) and constant in time. This exchange is independent of the temperature, humididty and movement of the surrounding air. For example, a convective system would surround a normally clothed man at rest with 71°F air in order to maintain comfort. But with radiant surfaces at 85°F, the air temperature could drop to 59°F and the same man would be comfortable.
>
> --Fitch, James Marston, <<American Building 2: The Environmental Forces That Shape It (New York: Shocken Books, 1972), p. 52

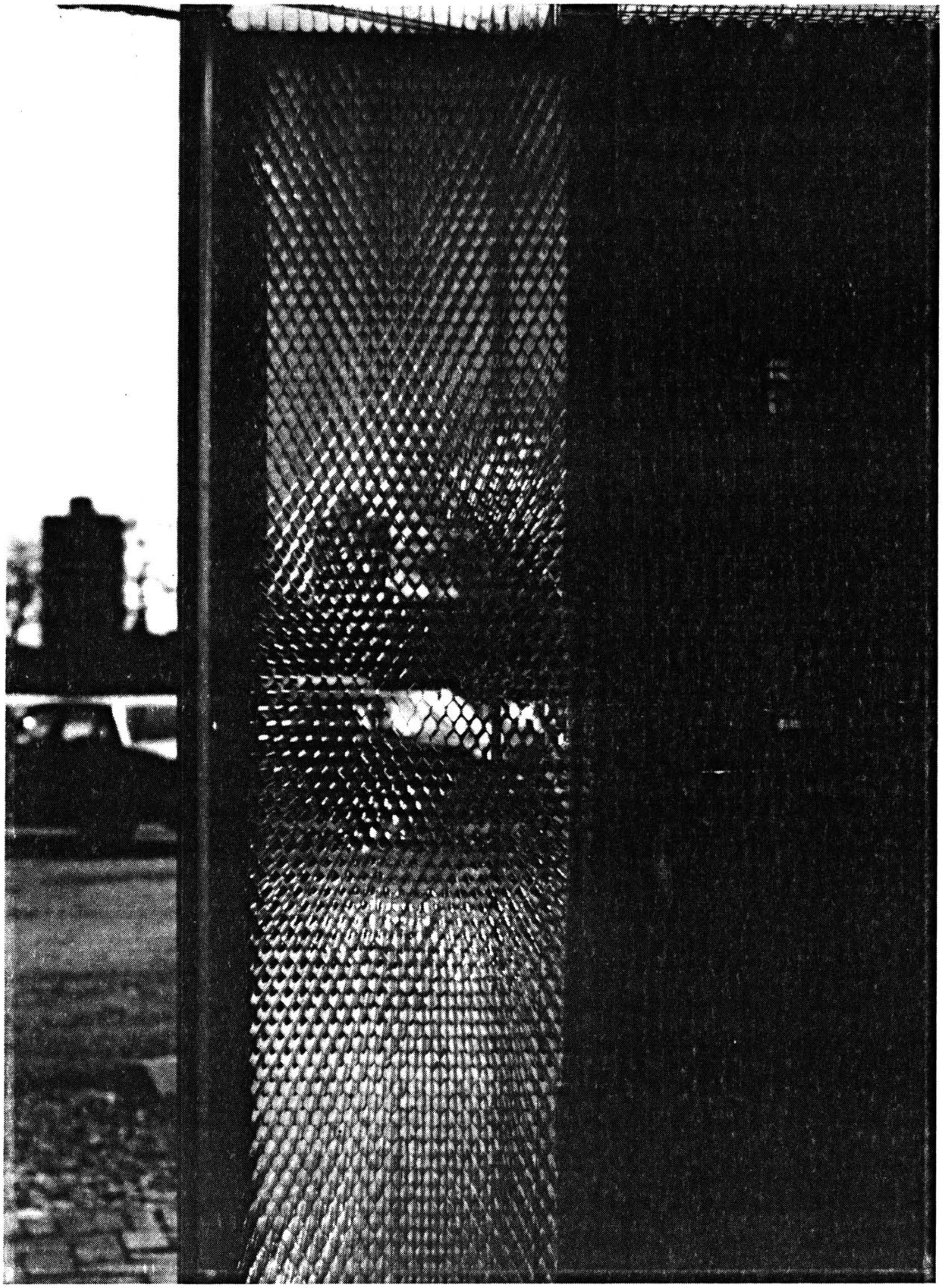


Figure 2.1. Partial views of the Trans-Lucent-Insulation (center) and the container of encapsulated phase-change materials (right), before assembly against the glass plate of window (left). Scale: 38% of real size.

The Sol-Clad-Siding would not surround the inhabitants with radiant heat panels on all facades, but it could provide them around the windows on at least the south facade. (Part 4 elaborates about the conditions under which the Sol-Clad-Siding could be utilized on the east and west facades. On the north facade it could be utilized only if the Trans-Lucent-Insulation were to transmit more of the lower intensity diffused light, and also, improve its insulating properties). The ratio between the window area and the Sol-Clad-Siding area on these facades would depend on the availability of sunshine and on the climate of the site, assuming that enough phase-change materials were supplied in order to prevent overheating.

The prototype presented in Part 4 showed that the Sol-Clad-Siding could work satisfactorily for mild heating climates such as that in Boston. However, because a large quantity of phase-change materials is necessary to avoid overheating under-average solar exposure, the amount of stored heat makes the Sol-Clad-Siding more applicable to colder climates with larger heat losses and amounts of available sunshine that were greater than or equal to those in Boston. North central United States, and central Canada would provide the most suitable applications for the Sol-Clad-Siding.

A point which must be considered is that the Sol-Clad-Siding should be shaded during the summer months when a high ambient temperature together with a high level of solar radiation would tend to overheat the phase-change materials. Such overheating would have a negative impact on the cooling load of the building. Glazings with switchable solar transmission, when their development is complete, will provide an ideal answer to this issue by screening at appropritate times the undesirable solar radiation.

The Sol-Clad-Siding can be considered as an indirect gain approach because the heat of solar radiaton is not brought directly into the building, but rather it is captured at, and utilized from the perimeter of the building. Some theoretical similarity exists between the Sol-Clad-Siding and the thermal storage walls which do not employ vents to regulate the movement of warmed air from and toward the generating space between the exterior glass and the wall itself. One major difference is the

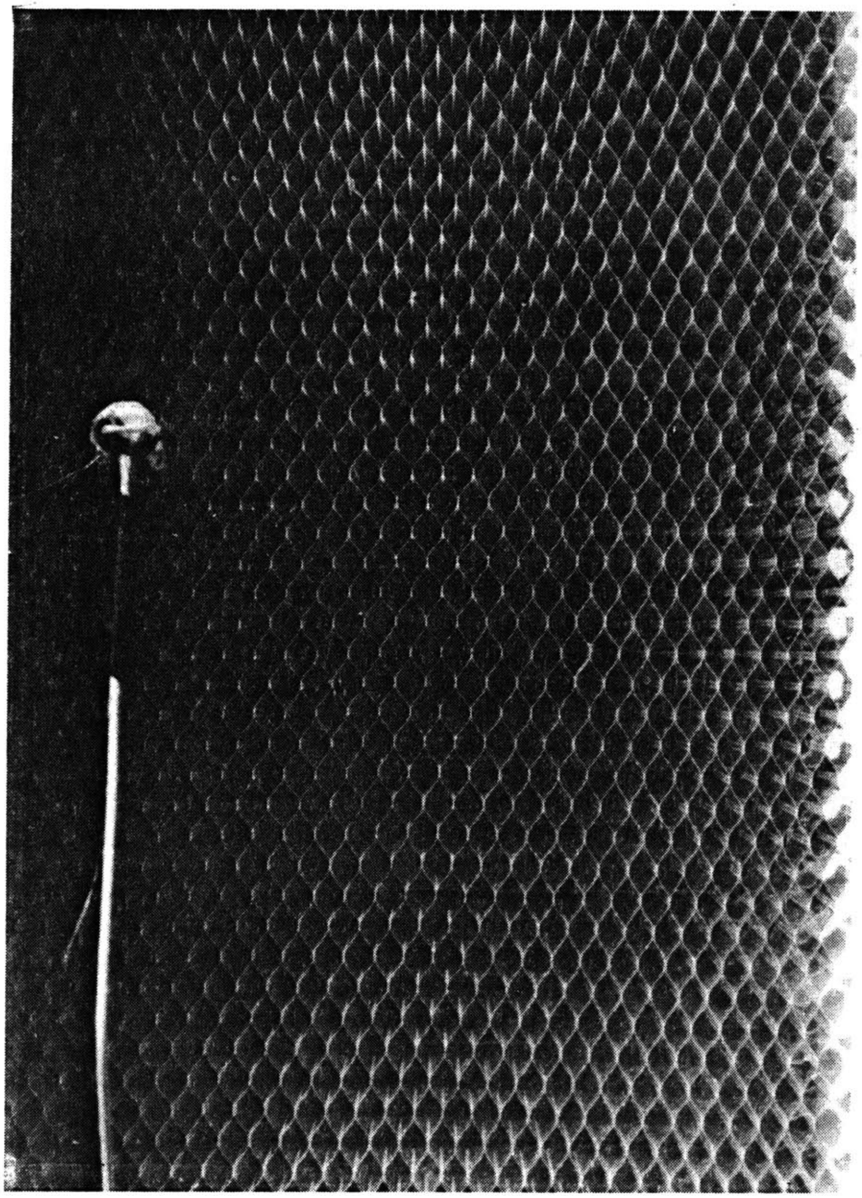


Figure 2.2. View from outside of about 1/4 of the Sol-Clad-Siding prototype. Thermistor(a) is within the cap on top of wire; thermistor (b) is hidden behind. Scale: 60% of real size.

Trans-Lucent-Insulation which replaces this intersticial space, and the other paramount difference is the utilization of phase-change materials instead of heavy masonry. The phase-change materials are not only lighter, but also have a larger storage capacity to volume ratio, than useful masonry materials; they also have an higher efficiency in absorbing solar heat radiation.

As mentioned in Part 1, the development of phase-change materials suitable for passive-solar utilization is an ongoing process to improve their heat storage capacity, and resistance to chemical separation. If both these aspects, but particularly the latter one were improved upon, phase-change materials could be applied successfully to vertical thermal storage. As the experiments of Part 4 show, a great potential exists in this direction. However, due to the necessarily vertical position of the phase-change materials, some problems must be overcome in order to realize this great potential. Part 4 addresses these issues in more detail.

The first Sol-Clad-Siding prototype has proved many issues through the experimetns described in Part 4. But above all, the most reassuring outcome was that, even during freezing outdoor temperatures, the room surface of the Sol-Clad-Siding was pleasant to the touch; as pleasant in fact as any interior surface. Inhabitants of dwellings incorporating the Sol-Clad-Siding would certainly share this reassuring feeling.

Part 3

FIRST EMBODIMENT OF THE TRANS-LUCENT INSULATION

The outer major component of the idea presented in Part 2 has been implemented as a prototype for testing its solar radiation transmitting and thermally insulating properties as part of the first embodiment of the Sol-Clad-Siding sample (presented in Part 4). The Trans-Lucent-Insulation innovation was founded on the principle of minimizing the conductive movement of air (and the transmission of heat thereby) between 2 glass plates which were part of the building skin, while maintaining high solar transmission.

The Trans-Lucent-Insulation prototype (a part of which is shown in Fig. 2.1) is composed of the following: a vertical weather surface of float glass plate [I]; a 7.6 cm (3 in) deep Teflon honeycomb [II]; a vertical inside surface of float glass plate [III]; and a frame of Plexiglass [IV]:

[I] 3 mm (1/8 in) thick, 34.3 cm (13.5 in) wide, 62.5 cm (24.63 in) high; this plate is thick enough to withstand wind loads;

[II] Teflon FEP 0.05 mm (2 mil) Fluorocarbon Film (95% solar transmission, see Appendix Alpha) separating 5050 hexagonal horizotal alveioli [each alveolus of 6.4 mm (0.25 in) horizontal apperture and 11.6 mm (0.46 in) maximum inside vertical dimension;

[III 2 mm (1/16 in) thick, 31.8 cm (12.5 in) wide 62.5 cm (24.63 in) high; the thickness of this plate is minimized so solar radiation transmission is maximized, and also it forms one of the impermeable sides of the container of encapsualtd phase-change materials;

[IV] 6.4 mm (0.25 in) thick, 7.6 cm (3 in) deep; spanning from the weather plate to the inside plate and holding the honeycomb within a rectangular shape of 32.4 cm (12.75 in) width by 60 cm (23.63 in) high.

The effective solar radiation transmission coefficients of the honeycomb were determined as 78% for the 24° angle of incidence (Dec. 21, 12h00, Boston latitude), and 67% for the 47.5 angle of incidence (Mar. 21 and Sep. 21, 12h00, Boston latitude) using a radiant flux meter. Each of these coefficients was determined as an average value of 12 ratios of 12 sets of 2 measurements.

For each angle of incidence, each separate transmission coefficient was determined as a ratio between the radiation through the honeycomb (on a surface normal to the alveoli and very close to their edges) and the radiation directly on the radiant flux meter sensor (on the same surface as above after removing the honeycomb). An easel-like device held the honeycomb frame, and a socket on a tripod held the meter sensor at the desired angle of incidence.

Therefore, the total effective transmission of the Trans-Lucent-Insulation is 65% [= (0.88) (0.78) (0.94)] for a 24° angle of incidnence, and 55% [=(0.88) (0.67) (0.94)] for a 47.5° angle of incidence [where (0.88) and (0.94) are the transmission coefficients of 3 mm (1/8 in) and 2mm (1/16 in) glass plates, respectively]. If the inside glass plate were also 3 mm (1.8 in) thick, the corresponding total effective transmission coefficient would be 60% and 52% for the 24° and 47.5 angles of incidence, respectively.

The heat transfer coefficient of the Trans-Lucent-Insulation was calculated as 0.62 W/(sq m) (^{o}k) [0.11 Btu/(hr) (sq ft) (^{o}F)] by using an algebraic expression of one unknown generated by the monitored results of an experiment described below. This calculation used as a reference the known heat transfer coefficient (for a given average temperature) of 2.54 cm (1 in) of Dow Styrofoam, SM. The experiment was carried out with the Trans-Lucent-Insulation already incorporated into the Sol-Clad-Siding sample.

This Dow Styrofoam panel was applied over the Trans-Lucent-Insulation [with an overlap of 5.1 cm (2 in) all around it]. Thermistor (a) in Fig. 4.1 was affixed to the outside surface of the Styrofoam panel, and thermistors (c), (b), and (a) formed a linear pattern following the path of heat flow through the Trans-Lucent-Insulation and the Styrofoam panel. Therefore, it was assumed that the heat transfer between thermistors (c) and (a) was equal to the heat transfer between thermistors (b) and (a). Since the heat transfer coefficient between thermistors (b) and (a) was known, by the law of proportionality it therefore became possible to calculate the heat transfer coefficient of the Trans-Lucent-Insulation between thermistors (c) and (b) by using the following formula:

$[(T_c)-(T_a)](U_x) = [(T_b)-(T_a)](U_s)$

where [(U_x) = unknown heat transfer coefficient of the Trans-Lucent-Insulation], [(U_s) = known heat transfer coefficient of 2.54 cm (1 in) Styrofoam panel (for given average temperature], [(T_a), (T_b), and (T_c) equal the monitored temperatures of thermistors (a), (b), and (c) respectively]. Solving the above formula for U_x gives the following:

$$U_x = \frac{[(T_b)-(Ta)]\ (U_s)}{[(T_c)-(T_a)]}$$

The U value of the Trans-Lucent-Insulation (U_x) was generated by an average of 10 hourly readings [of (T_a), (T_b), and (T_c)] and their associated (U_x) taken on the night of 1983 March 22. These readings were all taken during the night to eliminate the variable of daytime solar heat gain.

The Trans-Lucent-Insulation diffuses the sunlight as it passes through and reflects around the various layers of Teflon films (see Fig. 2.1). When incorporated in the Sol-Clad-Siding, this diffused light penetrates well in between the encapsulated phase-change materials, and favors a good absorption of solar heat.

The qualities of the Trans-Lucent-Insulation to insulate thermally (5-6 times better than double glazing) and to transmit substantial amounts of diffused sunlight (65 to 52% of incident radiation) could also be very well utilized in direct gain systems (dry wall, plaster, and other conventional interior finishings absorb well diffused sunlight in comparison with the direct sunbeam radiation which overwhelms and causes overheating). Panels or glass blocks filled with Teflon film honeycomb could be utilized in similar ways as glass blocks were during the beginning of this century, by framing operable windows. During those times glass blocks had a thermal resistance value 2 times greater than the popular single glazed windows. This time Trans-Lucent-Insulation glass blocks could have a thermal resistance 5-6 times greater than the conventional double glazing, and about 2 times greater than the double glazing filled wiht argon and incorporating a heat mirror. And, additionally, it offers an interesting and pleasant image.

Part 4

FIRST EMBODIMENT OF SOL-CLAD-SIDING

The idea presented in Part 2 has been realized as a prototype for testing its thermal and mechanical properties. This sample is comprised of the following: on the outside stands the Trans-Lucent-Insulation [i]; on the inside stands a hermetically sealed glass plate container [ii], which encloses encapsulated phase-change materials [iii]. The explicit characteristics of the sample shown in Fig. 4.1 are the following:

> [i] 0.194 sq m (2.092 sq ft) with height of 60.0 cm (23.63 in) inside dimensions. Components: 3mm (1/8 in) glass sheet as weather surface, and a 7.6 cm (3 in) deep honeycomb of Teflon FEP 0.05 mm (2 mil) film, as described in Part 3.
>
> [ii] 0.167 sq m (1.805 sq ft) with height of 60.0 cm (23.63 in) inside dimensions. Volume 10 714 cu cm (650 cu in) inside dimensions; defined by glass sheets of 2mm (1/16 in) against honeycomb, 5mm (3/16 in) other vertical, and 6mm (1/4 in) horizontal. (Glass plates were needed to encloe volume in order to observe the settling of capsules, and to check relative humidity levels through the occurrence of condensation from inside;

also glass plates formed an impermeable container.) Inside the container a Relative Humidity of 80% is generated by sealing 20 ml of water in a space 6 881 cu cm (0.243 cu ft) volume of dry air between capsules. (This Relative Humidity matches the water content of the encapsulated phase-change materials in order to maintain their transition temperature at 21° C (70°F).) [iii] inorganic salts (sodium sulfate decahydrate) encapsulated in latex coating. Transition Temperature: 21°C (70°F). Weight: 5.78 kg (12.75 lb). Heat storage capacity: 771 Wh/(sq m) [244 Btu/(sq ft)], or 123 Wh (421 Btu) per sample; based on calorimeter tests (both by Massachusetts Institute of Technology and Brookhaven National Laboratories) which show salts release 21 Wh/kg (33 Btu/lb) over a 2.8° C (5° F) swing. Form: 1 cu cm (0.061 cu in) capsules of 1.4 cm(0.55 in) radius packed (at 50% void fraction) within 21 stacked trays of hardware cloth, each tray 2.8 cm (1.1 in) high (the spacing of capsules is necessary to avoid having them crushed under their own weight when their core is in the liquid phase). South-facing Stack Area: 0.160 sq m (1.722 sq ft). Stack Volume: 8 617 cu cm (526 cu in). These encapsulated phase-change materials (developed by Penwalt Corporation, King of Prussia, Pennsylvania) were chosen for the following reasons: first, because they favored a good heat transfer via warmed air movement through the gaps between capsules from the sun-facing side to the opposite side of an appropriate pack; and second because they appeared to be more resistant to chemical separation due to their small separated quantities.

The Sol-Clad-Siding sample stands on the sill of a Plexiglass window (Fig. 4.2) which has a portion cut away in order to let the sun fall directly on the glass of the Trans-Lucent-Insulation. This window is part of a recessed wall that joins the south facades of Solar Building No. 5 and the Crystal Pavilion addition (Fig. 4.3) on the campus of the Massachusetts Institute of Technology in Cambridge, Massachusetts. This recessed wall is facing 14° east of true south, and its Sol-Clad-Siding sample receives direct insolation between 8h30 and 13h00 at the March equinox. The sample has been monitored since 1983 March 16 by recording hourly temperatures on a data logger. The temperature

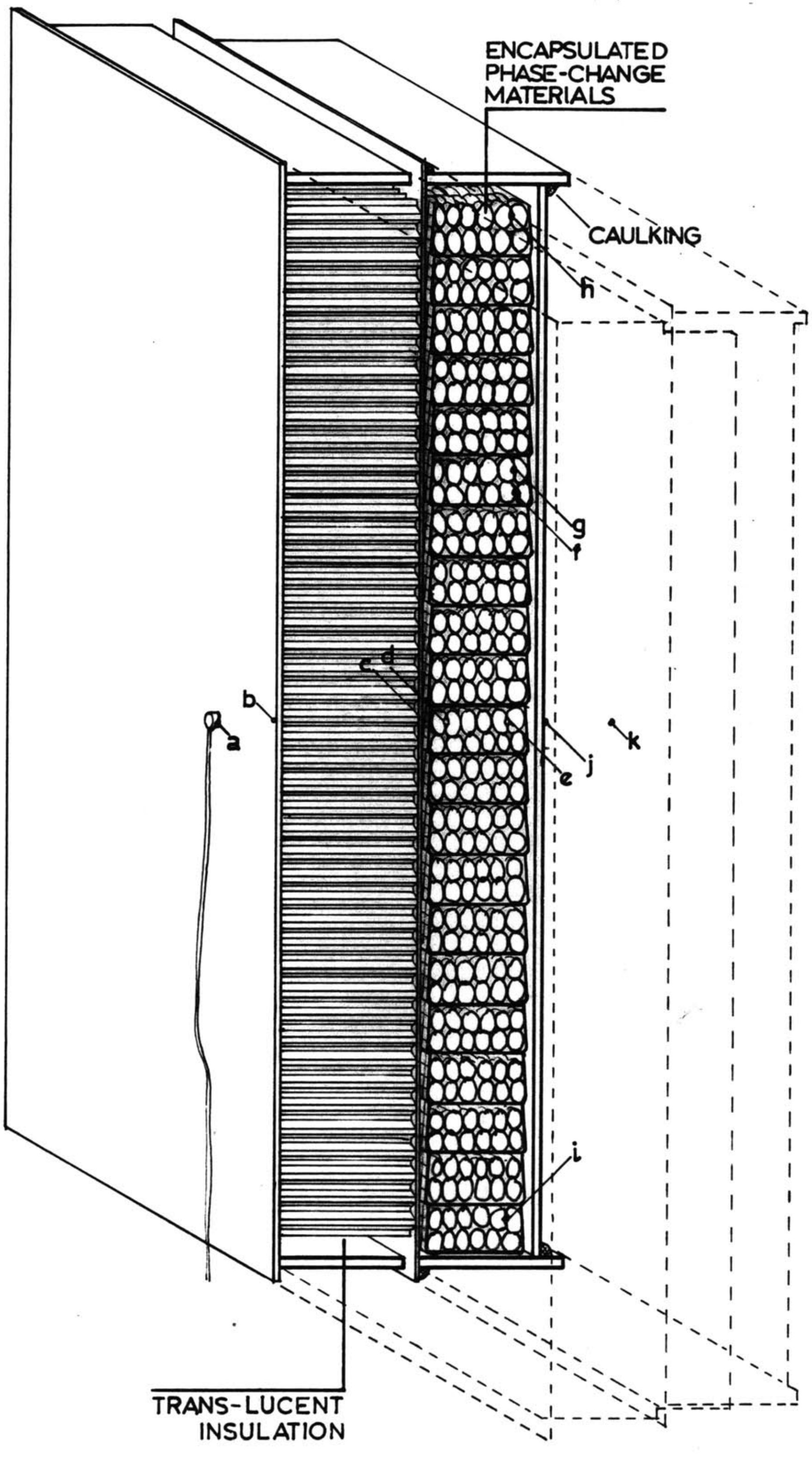


Figure 4.1. Transversal section through and axonometric projection of the Sol-Clad-Siding prototype. Letters indicate the locations of thermistors. Scale: 1/4

sensors are 11 YSI Thermilinear Thermistors set in the places indicated in Fig. 4.1(7 on the central horizontal axis, and 5 on the vertical inward axis; each of the thermisters marked (d) to (i) is placed between 2 capsules of phase-change materials taped around together).

Several days were chosen to be analyzed as typical winter conditions. Although the outdoor temperatures were mostly

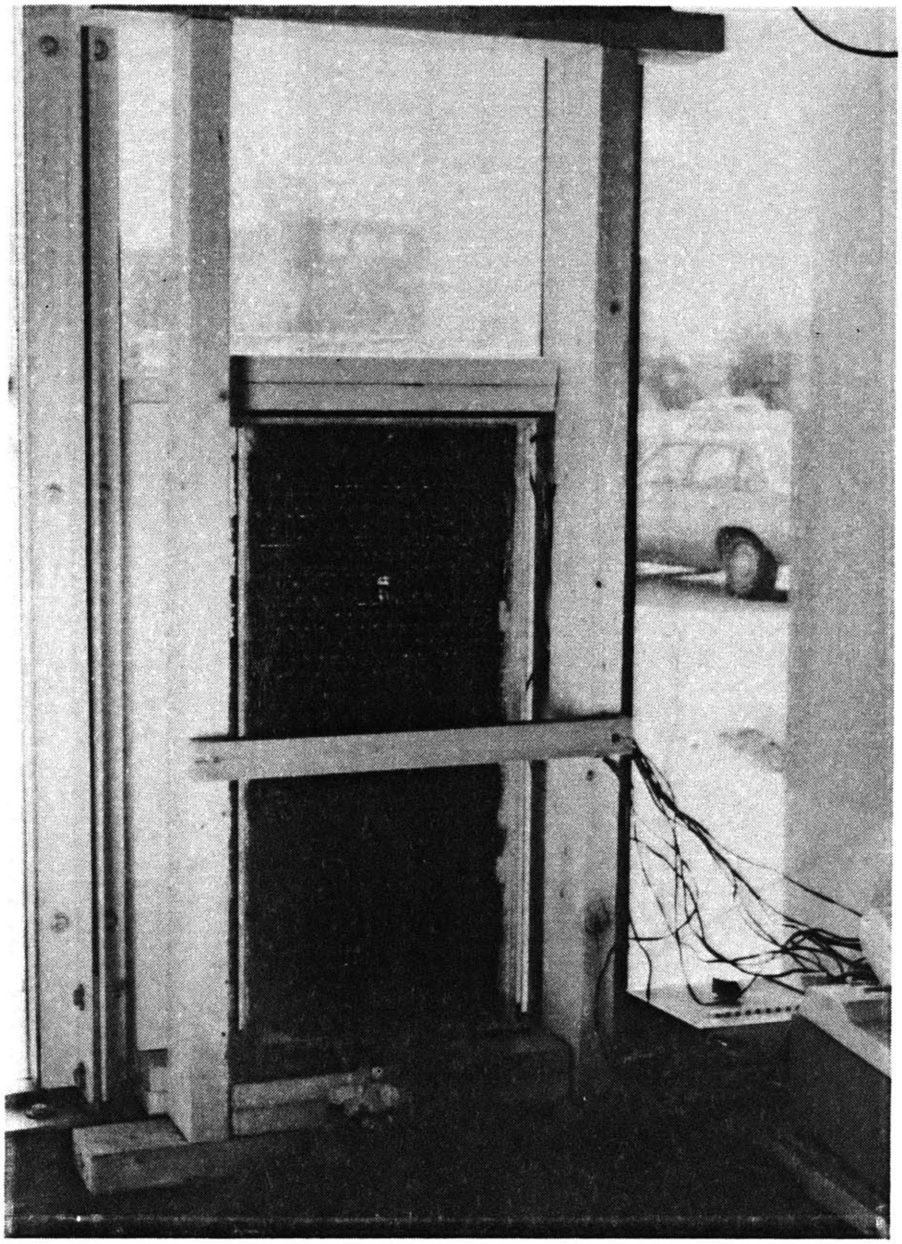


Figure 4.2. Sol-Clad-Siding prototype and the monitoring equipment viewed from inside the Crystal Pavilion.

not below the freezing point of water, conclusions could be inferred about the Sol-Clad-Siding's behavior during colder weather, and suggestions could be induced for further improvement. The analyzed conditions include the following: (A) partial Days of solar exposure preceeded by partly sunny and cloudy days; (B) full day of solar exposure preceeded by partly sunny day; (C) overcast day following the above sunny day.

(A) **Partial Days of Solar Exposure** (1983 March 24, 23, 20 and 17) preceeded by partly sunny day and cloudy days. Partial days refer to the fact that the Sol-Clad-Siding sample received direct insolation only between 8h30 and 13h00 as compared with the full day useful exposure considered to be between 9hoo and 15h00.

The hypotheses about the thermal behavior of this sample were the following: the encapsulated phase-change materials

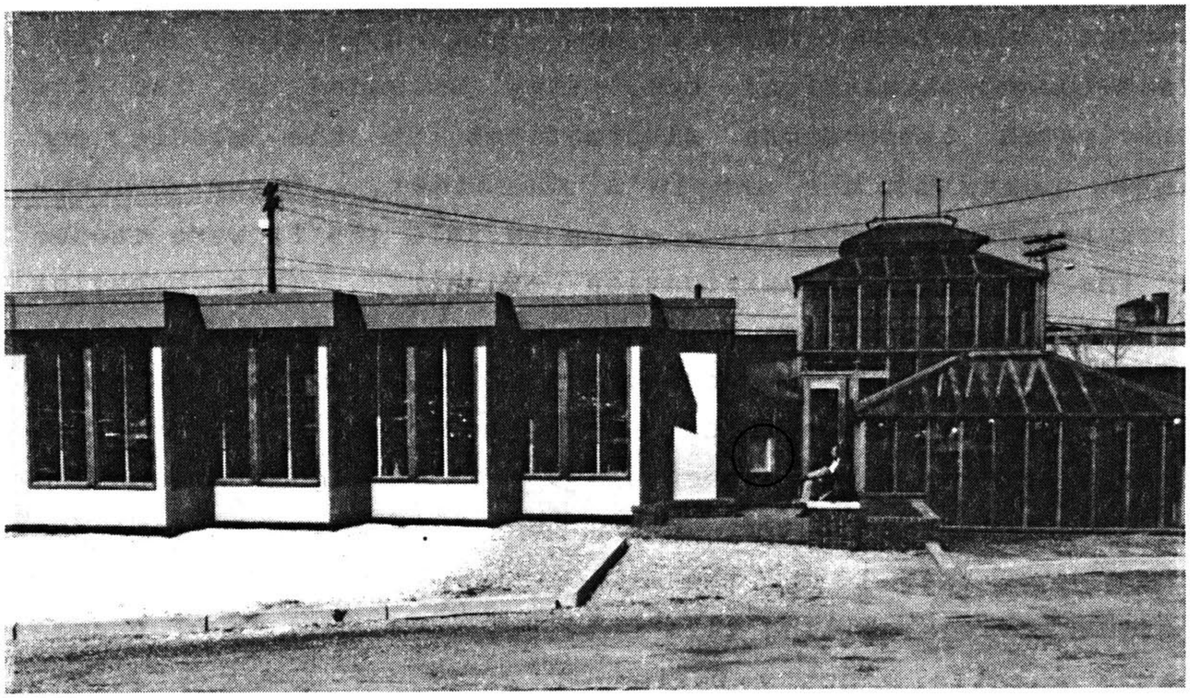


Figure 4.3. The Solar Building No. 5 (left) and the Crystal Pavilion (right). The location of the Sol-Clad-Siding is circled in. The light shade surrounding it is Styrofoam insulation.

should melt in 2-3 hours because of the 55% solar radiation transmittance coefficient (at equinox of Boston latitude) of the Trans-Lucent-Insulation; these materials to remain in the melted phase at least over the nights following a solar exposure because of the low thermal transmittance value of [0.63 W/(sq m) (^{O}C) [0.11 Btu/(hr) (sq ft) (^{O}F]] of the Trans-Lucent-Insulation; a noticeable temperature stratification of about 3-6^{O} (5-10^{O}F) to occur within the height of 60.0 cm (23.63 in) of sample's container of phase-change materials. [For the initial experiments that had led to these hypotheses, see Appendix Beta].

The monitored results of the first day considered to represent a clear winter day were graphed on Fig. 4.4. This day (1983 march 24) had an insolation of 76% of the possible sunshine (Source: Blue Hill Observatory, National Weather Service, Climatological Station, Milton, Massachusetts). These results confirmed the melting time of the phase-change materials in 2-3 hours of solar exposure for days with an average clearness factor, and the qualities of the Trans-Lucent-Insulation; but, they exceeded by far the anticipated temperature fluctuations in the middle and higher parts of the sample's container. These extreme fluctuations of temperature of up to 36^{O}C (65^{O}F) were caused by the thermal stratification of air. This behavior supported by results of similar days, precipitated a comparison between the behavior of phase-change material within the Sol-Clad-Siding sample and the M.I.T. thermal storage ceiling tile respectively.

The conclusion of this comparison (presented in Appendix Gamma) was that both, the Sol-Clad-Siding sample and the thermal storage ceiling tile hold the same amounts of phase-change material, but experienced different thermal loads. This last difference was included in the comparison process by changing the time constant of the tile cooling curve to match the more rapid loss of heat experienced by the

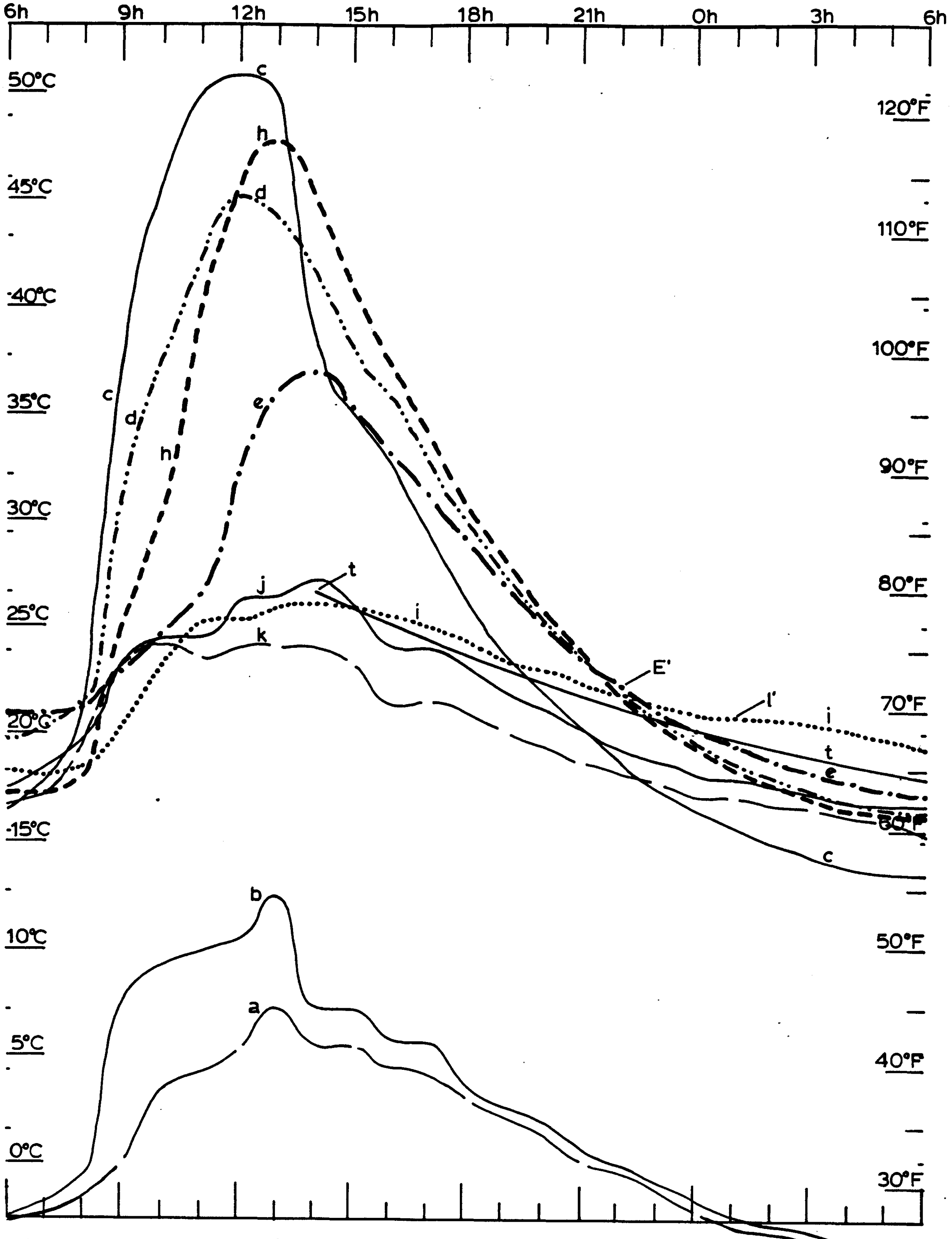


Figure 4.4. Partial day of solar exposure (1983 March 24); 76% of possible sunshine; 0.55 ratio between 'the heat storage capacity of the encapsulated phase-change materials' and 'the transmitted Solar Heat Gain Factor;' following partly sunny day.

encapsulated material of the Sol-Clad-Siding. In the process of this comparison, the resultant tile cooling curve [curve (t) in Fig. 4.4] indicated by inference the reason for the temperature excursions of the encapsulated materials at the middle and higher levels of the sample's container.

The exponentially reduced cooling curve of the tile core was almost identical to the downgrading course of the encapsulated materials situated at the lower level of the sample's container (curve 'i' in Fig. 4.4). This fact made sense because the phase-change material of the tile core was in continuous contact with its polymer concrete casing; and similarly, the encapsulated phase-change materials at the lower level were in close contact with the bottom piece of the glass container, via conduction of the capsules' surfaces and the hardware cloth trays.

The meaningful inference of this comparison was the fact that the encapsulated materials at the middle and higher levels experienced higher temperature fluctuations because of the cumulative temperature stratification of air rising by means of the heat gained by the absorption of light and energy reflected from the capsule surfaces. The thermal sensor (h) of the upper layer of capsules showed that they had the highest temperatures although they were always in the shade (see Fig. 4.1). In observing the curves (i), (e), (d), and (h) of Fig. 4.4, it became obvious that there was a clear transition from the latent heat mode of storing heat of the lower level capsules [curve (i)] to the sensible mode dominating the higher levels .`

The cooling curves of Fig. 4.4 indicated the essential difference between the encapsulated phase-change materials at the 3 distinctive levels. Not unexpectedly, curves (h), (d), and (e) plunged from their respective peaks on slopes close to each other. The higher level encapsulated materials [curve (h)] continued their descent on a smoothly leveling curve with no trace of encountering their transition temperature at $21^{\circ}C$ ($70^{\circ}F$). But, the middle level encapsulated materials [curve (e)] indicated the transition temperature by a very slight swell [marked (E') just before crossing curve (i) together with curves (d) and (h)]. In contrast with these, the lower level encapsulated materials [curve (i)] maintained a definite platform [marked (I')] just above their transition temperature on a gently descending slope. The fact that curves (d), (e), and (h) crossed the curve (i) so abruptly just before its transition temperature plateau indicated that the phase-change materials at the middle and higher levels had separated chemically.

The transition of heat on the central horizontal axis from the outside to the inside glass sheets of the sample's container could also be seen in Fig. 4.4 in the sequence (c), (d), (e), (j). (See Fig 4.1 for the exact locations of the thermistors originating these curves). The temperatures of the glass sheet between the Trans-Lucent-Insulation and the container of phase-change materials [curve (c)] showed a direct and sensible response to sunshine: it started at 6h00 from the lowest temperature of the sample's container, and climbed to the highest value at noon, [usually corresponding to the daily solar radiation peak]. At the time when the sample was shaded, the sharpest and earliest plunge from this crest completed a typical regime of thermal behavior under solar exposure. The temperatures of the outward face of the encapsulated materials [curve (d)] showed an early absorption of solar heat starting from the diffused skylight light at 6h00. Also, curve (d) showed the amount of time necessary for the heat to be transferred from the outside to the inside faces of the encapsulated materials' traystacks; this time corresponds to the time difference between the peaks of curves (d) and (e) on the horizontal coordinate. The similarity between the temperature fluctuations of the encapsulated materials at the middle and higher levels [curves (e), (d), and (h), particularly the latter two] and of the glass sheet covering them [curve (c)] was further proof of their sensible behavior and ultimately for their chemical separation.

The completing of the transition of heat could be seen in the shape of curve (j) representing the temperature excursions of the inward glass surface of the sample's container, and the proof of performance of the Sol-Clad-Siding as heat loss compensator. The fact that this curve was above the indoor temperatures [varying between 18°C (65°F) and 20°C (68°F)] exceeded the expected performance and showed the potential of the sample as a moderate source of heat for rooms with such indoor temperatures. For warmer dwelling interiors it could compensate for heat losses during winter days similar to this one by reaching through solar gains the same temperature as these interiors.

Although the conclusions were encouraging after the analysis of the first day considered to represent a clear winter day, the immediate and specific question was how could the Sol-Clad-Siding performance be improved, and through that how would the problems inherent to vertical thermal storage of phase-change materials be solved. Primarily, the question was how could the chemical separation of the encapsulated phase-change materials be avoided. The obvious conclusions were that the height of the container of encapsulated phase-change materials had to be reduced to a size that would not generate the temperature fluctuations which favored the chemical separation of these materials. Another conclusion was that the depth and the quantity of encapsulated materials had to be increased to provide a larger heat sink that would decrease the temperature fluctuations. More analysis was needed to find the appropriate height and depth of these smaller compartments for these encapsulated materials. But, first an investigation was needed to observe the stages and characteristics of the separation that occurred during the first week of experiments.

The investigation was started by graphing in Fig. 4.5 the monitored results of the previous day (1983 March 23) which had slightly less insolation: 73% (same source as 1983 March 24). The resulting curves had some similar and some dissimilar characteristics. The ascending curves of the encapsulated materials held the same positions in relation to each other, and their peak temperatures were lower. The cooling curves descended as follows (in relation to the following day): curves (e) and (d) held steadily their plateau of transition temperatures (a much better performance for both than the rapid temperature decay curve); curve (i) had a very slight swell when crossing gently below curve (d) at its plateau (a poorer performance); and curve (h) crossed all these curves in a rapid temperature decay (a similar performance).

Although the insolation was about the same, the peak of the curve (e) was much lower than in 1983 March 24: this indicated that the chemical separation grew worse with time as shown by these peaks differences. Curve (d) showed a curious behavior in changing from a rapid temperature decay (which originated at a high peak) to a transition temperature plateau just below curve (e). Since the following day curve (e) descended from a lower peak on a rapid temperature decay curve, the only explanation for the change in course of curve (d) to a plateau could be that the encapsulated materials facing the outside [curve (d)] received "help" from the heat of proximate capsules facing the inside [curve (e)] which were more stable at the transition temperature because of their location. However, the following day both curves (d) and (e) followed rapid temperature decay curves.

It became too evident that the heat storage capacity of the encapsulated materials' container was much below the amount of insolation received. An incident clear day Solar Heat Gain Factor (SHGF) for March 21 of 3 379 w/(sq m) [1 072 Btu/(hr) (sq ft)] was obtained first by interpolation from the ASHRAE tables for the Boston latitude, second by dividing the product by o.88 to cancel the transmission of DSA Glass included in this data, and third by multiplying by 0.8 to reduce the results for Boston's industrial atmosphere and exceptionally humid location. By multiplying this incident SGHF with the 0.55 equinox transmission coefficient of the Trans-Lucent-Insulation, it was found that 1 859 W/(sq m) [590 Btu/(sq ft)] could reach the container of phase-change materials. Consequently, the March 21 ratio between the heat storage capacity of the encapsulated materials and the above transmitted SHGF was the following:

$$\frac{771\ \text{W/(sq m)}}{1\ 859\ \text{W/(sq m)}} = \frac{244\ \text{Btu/(sq ft)}}{590\ \text{Btu/(sq ft)}} = 0.41$$

Therefore, on a March day with 100% of possible sunshine (at Boston latitude), the heat which could reach the encapsulated materials would be more than twice greater than the amount which they could store. Because the 100% condition was not available, this ratio was greater than 0.41. Respectively, on 1983 March 24 (Fig. 4.4) this ratio was 0.55 [the 76% of possible sunshine resulted in a SHGF denominator of 1 413 W/(sq m) [448 Btu/(hr)(sq ft)], and on 1983 March 23 (Fig. 4.5) this ratio was 0.57 [the 73% of

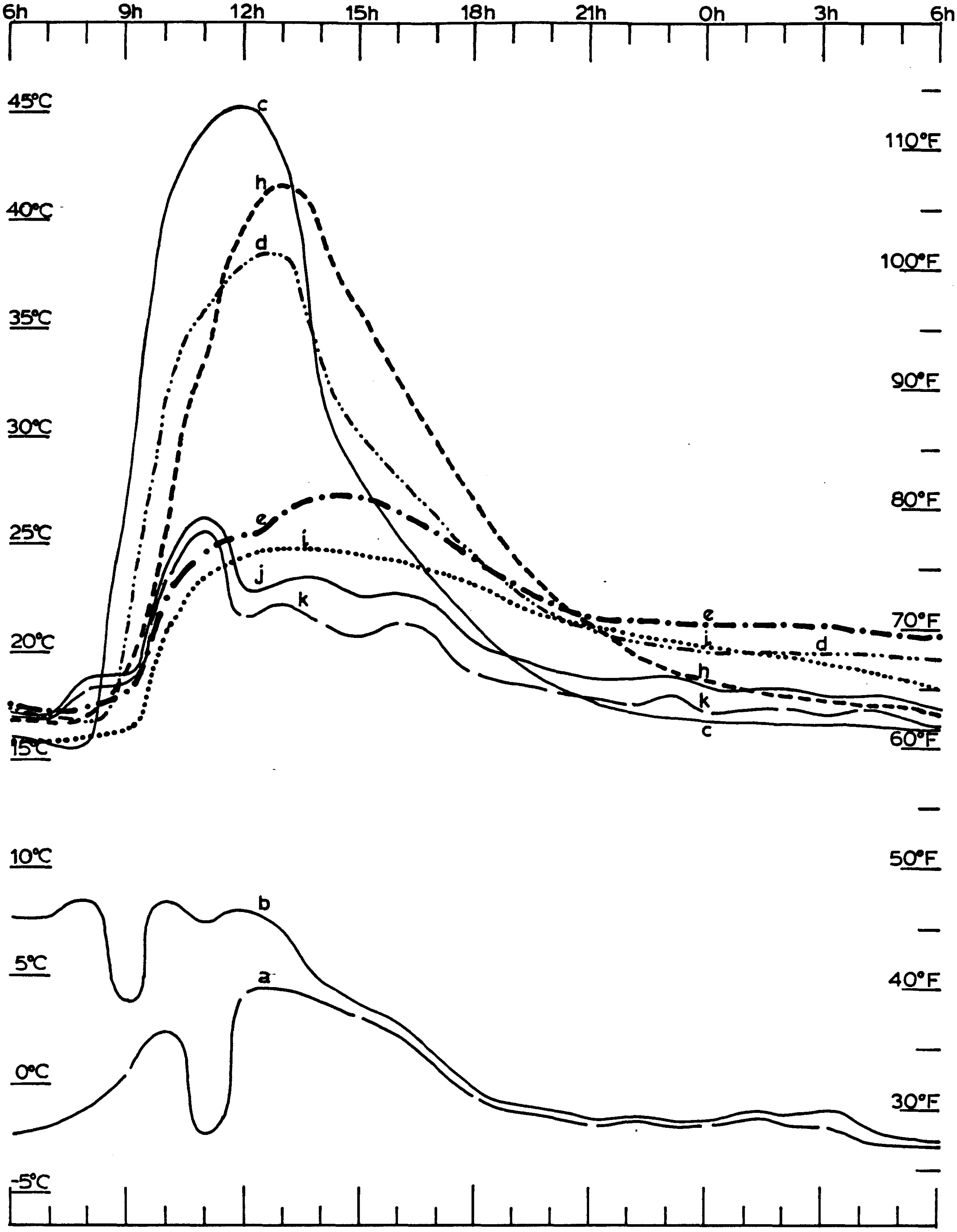


Figure 4.5. Partial day of solar exposure (1983 March 25): 73% of possible sunshine; 0.57 ratio between 'the heat storage capacity of the encapsulated materials' and 'the transmitted Solar Heat Gain Factor;' following partly sunny day.

possible sunshine resulting in a SHGF denominator of 1 357 W/(sq m) [430 Btu/(hr) (sq ft)]]. If a March day (at Boston latitude) had 41% of possible sunshine then this ratio would be 1.00 and represent the maximum and optimum storage utilization of the Sol-Clad-Siding sample. Before 1983 march 23 (Fig. 4.5), two days which had 22% and 21% of possible sunshine were analyzed for their behavior under the optimum thermal load. The percentage of possible sunshine was obtained as a ratio between the reduced incident SHGF and the indicent SHGF explained earlier. The reduced incident SHGF resulted from the sum of hourly incident SHGF data (between 7h00 and 13h00) multiplied by the percentage of sunlight of that hour (source: same as 1983 march 24; their percentage of possible sunshine was restricted by their sunshine recorder to insolation values above 230 W/sq m) [73 Btu/(sq ft)]; but this limitation was normalized by estimating the variable diffused insolation in these days by comparing the sensible regimes of these day's curves (c) to the typical sensible regime of curve (c) of 1983 March 24; and also, by comparing the differences between the sensbile regimes of these days' curves (b) in relation to their respective outdoor temperatures shown by curves (a): the greater the difference between curves (a) and (b) at a specific time, the greater the insolation).

The partly sunny day with an estimated 22% of possible sunshine (between 7h00 and 13h00) was 1983 March 20; its monitored results were graphed on Fig. 4.6. The ratio between the heat storage capacity of the encapsulated materials and this day's transmitted SHGF was 1.89 because of the low denominator of 409 W/(sq m) [130 Btu/(sq ft)]. All curves of the encapsulated phase-change materials had temperature fluctuations 2-3 times smaller than those shown in Fig. 4.5.

The graph curves illustrate the build up of heat in the encapsualted materials' container when the sun broke through the clouds. As expected, curve (d) was the first one to ascend being followed closely by curve (h). During the full sunny mornings shown in Fig. 4.4 and Fig. 4.5, curve (h) crossed above curve (d) just before 12h00. This pattern was not followed in Fig. 4.6: the reason for it was indicated by the almost vertical ascent of curve (d) evidently caused by a strong and brief dose of the sun through the clouds; curve (h) did not follow because there was not enough

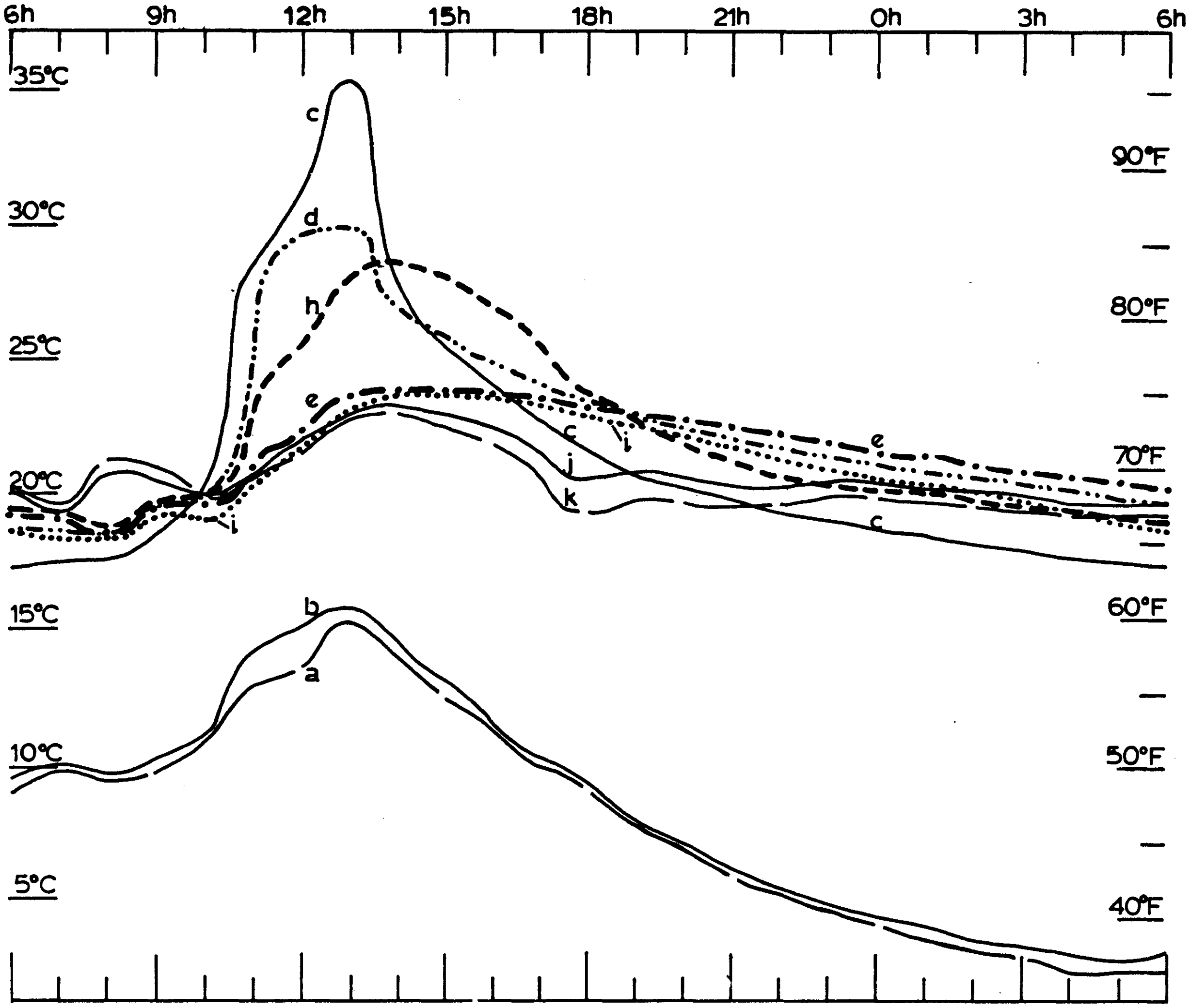


Figure 4.6. Partial day of solar exposure (1983 March 20): 22% of possible sunshine; 1.89 ratio between 'the heat storage capacity of the encapsulated phase-change materials' and 'the transmitted Solar Heat Gain Factor;' following cloudy day.

gradually accumulated stratification of warm air at the higher level of the container. However, curve (h) ascended on an angled slope, but did not get enough heat from below before 13h00 when the sample became shaded, and when the descent of curve (d) began.

The layout of these curves pointed to a problem inherent to the utilization of phase-change materials for vertical thermal storage: the sunlit surface was under heavy thermal load which could not be absorbed fast enough even by these materials. Either the sunlight reaching the outside surface of the encapsulated materials would have to be reduced by some heat diverter device, and/or the heat absorbed by this device would have to be transferred to the mass of encapsulated materials up to the inside surface. Such a device would prevent temperature fluctuations favoring chemical separation, would permit larger depths of the encapsulated materials, and a faster heat distribution. But this device would not have to be in contact with the sunlit capsules because it would increase their temperature fluctuations by the conduction of more heat. Therefore, such heat diverters of hardware cloth or fly screen would have to be a few millimeters (few 1/32 in) in front of the hardware cloth trays and connected only with the bottom of these trays for the conduction of heat through to the inside face of the encapsulated materials' stack.

The cooling curves of the encapsualted materials held well together on a gentle slope (in the expected formation) against a much steeper slope of a large and steady drop in the outdoor temperatures. This drop might be the cause for the presence of slight swells only on these curves in the vicinity of the transition temperatures, around 0h. The parallel formation of the cooling curves had the expected hierarchy: the encapsulated materials of the curve (e) had the highest temperatures because of their central position; and, the materials of curves (h) and (i) had their lowest temperatures because of their larger heat losses.

The other partly sunny day was 1983 March 17 which had an estimated 21% of possible sunshine; its monitored results were graphed on Fig. 4.7. The ratio between the heat storage capacity of the encapsualted materials and this day's transmitted SHGF was 2.07 caused by the lowest denominator of 390 W/(sq m) [124Btu/(hr) (sq ft)]. The temperature fluctuations shown by the encapsulated materials' curves were about the same when compared with those presented in Fig. 4.4 and Fig. 4.5. But, in comparing

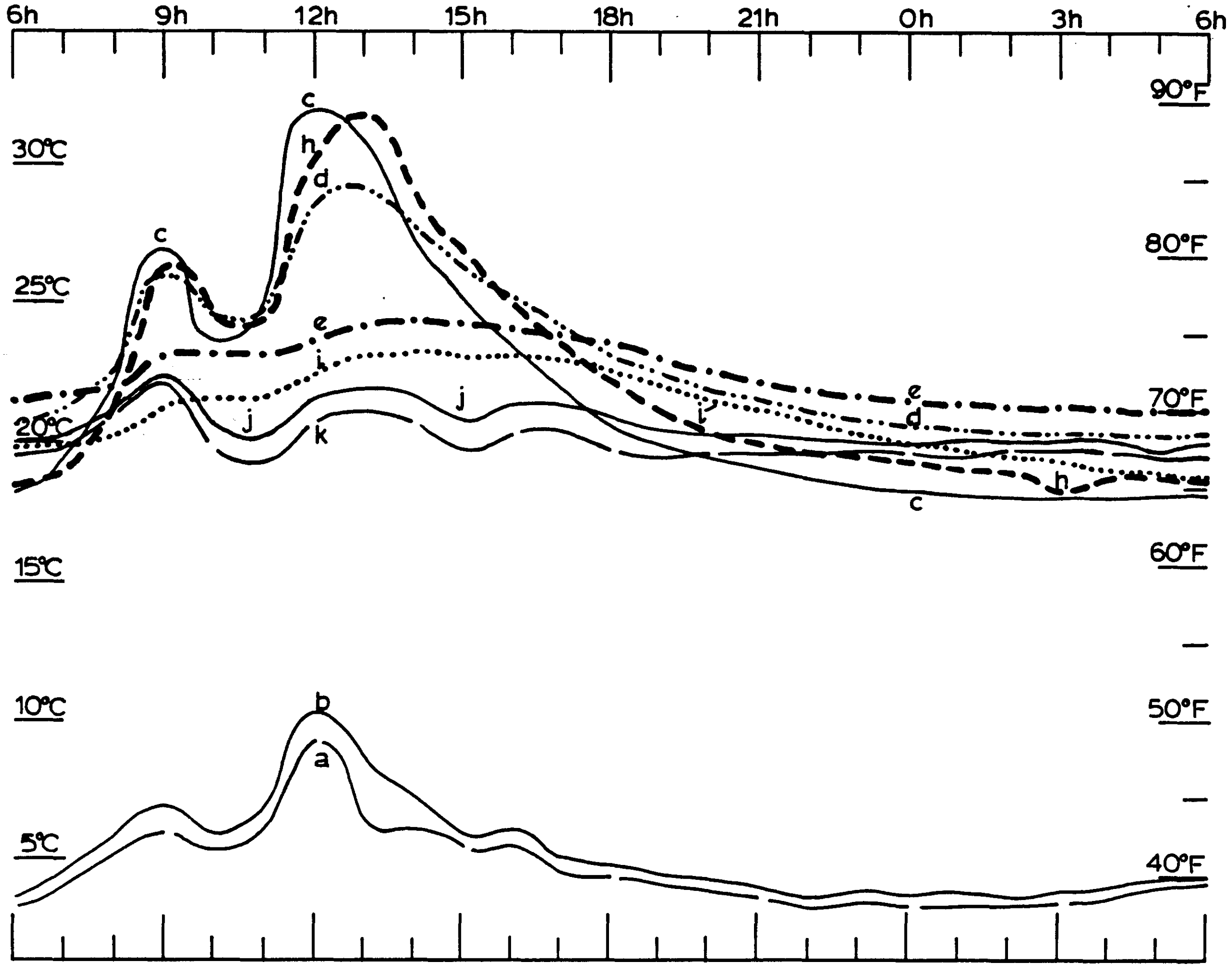


Figure 4.7. Partial day of solar exposure (1983 March 17): 21% of possible sunshine; 2.07 ratio between 'the heat sorage capacity of the encapsulated phase-change materials' and 'the transmitted Solar Heat Gain Factor;' following partly sunny day.

Fig. 4.7 with Fig. 4.6, differences could be seen in the timing of insolation through breaks in the clouds, and in the temperature fluctuations of the outside air. There were two insolation periods shown in Fig. 4.7 of which only the first one was strong enough to cast shadows (Source: same as 1983 March 24); and the outdoor temperatures were more constant at a colder level.

Both these partly sunny days had a common characteristic: the latent thermal behavior of the encapsualted phase-change materials at the middle and lower levels on the room side of the container. There were no rapid increases in the temperature shown by curves (i) of Fig. 4.7 and (c) because there was almost no vertical rise of curve (d) of the sunlit surface of the encapsulated materials' stack. The cooling curves of Fig. 4.7 started about one hour later than in Fig. 4.8, and they also held together but in a less tight formation with the same hierarchy. This difference might have been caused by the 1% extra insolation received in Fig. 4.6.

The latent regime of thermal behavior of curves (e) in both Fig. 4.7 and Fig. 4.6 suggested that the 30 cm (11.8 in) height which they represent might be appropriate for the container of these encapsualted materials. But, to be efficient and un-wasteful, such a height would have to be accompanined by a device to ease the heat load of the sunlit encapsualted materials; and, by a conductive system which would have to transfer the substracted heat from the outside face to a quantity of phase-change materials deep enough to be able to store sufficient amounts of heat to prevent large temperature fluctuations and the resultant chemical separation. However, more investigations and experiments would be necessary to establish a more specific relationship between the temperature fluctuations and the respective heights of compartments of encapsualted materials' containers: full days of solar exposure with high percentages of possible sunshine could still generate large temperature fluctuation unless the height would be smaller.

(B) **FULL DAY OF SOLAR EXPOSURE** (1983. March 26) preceeded by partly cloudy day. The hypotheses for this exposure were the following: higher temperature peaks; more solar heat stored, and the resultant longer carry-over period. To observe the behavior of the Sol-Clad-Siding sample during conventional hours of open southerly exposure (9h00 to 15h00), two mirrors of 10% absorption were applied to reflect the sunbeam from below. The experimental procedure presented in Appendix Delta arrived at the conclusion that the sample received 84% of the possible sunshine of that day. Consequently, the registered peak temperature exursions of the sample had to be multiplied by 1.19 to estimate the maximum value of insolation receivable if that day (or any other March day) were perfectly clear.

The results monitored by the data logger were graphed on Figure 4.8. They exceeded by far the expected temperature peaks, and they confirmed the storage of more heat. A longer carry-over period was observed.

In comparing this day (Fig. 4.8) with the other bright sunshine days (Fig. 4.4, and Fig. 4.5) we could observe the same very general configuration, but with quite different specific characteristics. At the first glance, the general configuration of Fig. 4.4 particularly appeared as if having been blown up to the 'scale' of Fig. 4.8. This amplified configuration of Fig. 4.8 was generated first by the higher insolation factor of 84% of the possible sunshine, second by the extended 2 hours of solar exposure, and third by the higher outdoor temperatures.

> The 13h00 peak value of curve (h) of Fig. 4.4 was reached by 12hoo in Fig. 4.5, and similarly the 14h00 peak (e) was attained by 11h30. The increased radiation minimized the latent ascent shown by curve (e), and accelerated the heat

> absorption shown by curve (i). The adjusted temperature peaks were rectified by multiplying with the 1.19 factor mentioned above. The adjusted temperature peaks were very high, but this would probably correspond to sharper plunges.

The obvious result of the extended insolation was the appearance of 'hill tops' on curves (e) and (h) and of a more pronounced curve (i). But, the declining slopes of all these curves were correspondingly sharper. Although it was not possible to draw the curves with adjusted peaks, we could assume that by the late hours they would overlap or be slightly above the monitored ones. The stored heat would basically be the same, the right amount.

Curve (j) pointed to the inconvenience that especially this type of Sol-Clad-Siding may generate if not utilized and/or sized properly, particularly around the equinox times. The temperatures of the sample surface facing the room held for more than 4 hours above 27°C (80°F). If a substantial amount of the exterior walls would incorporate this type of Sol-Clad-Siding, such situations may well urge inhabitants to open the windows. But, if nobody were home to open the windows at that time it would generate hot and stuffy interiors, conventionally unpleasant environments that would take time to ventilate when inhabitants came home.

The warmth reached by the room surface of the siding suggested that this type of Siding could be utilized in less extreme climates like "exterior wall stoves," truly-radiating elements integrated [in limited and specific areas] with the conventional interiors, that often include radiators. During cold weather this type of Siding would be very welcome. Curves of Fig. 4.4, Fig. 4.5, and Fig. 4.8 showed that when the outdoor temperatures were below or around the freezing point of water (during night or early hours) the inward suface of the Siding was within the conventional comfort range. During very cold and sunny

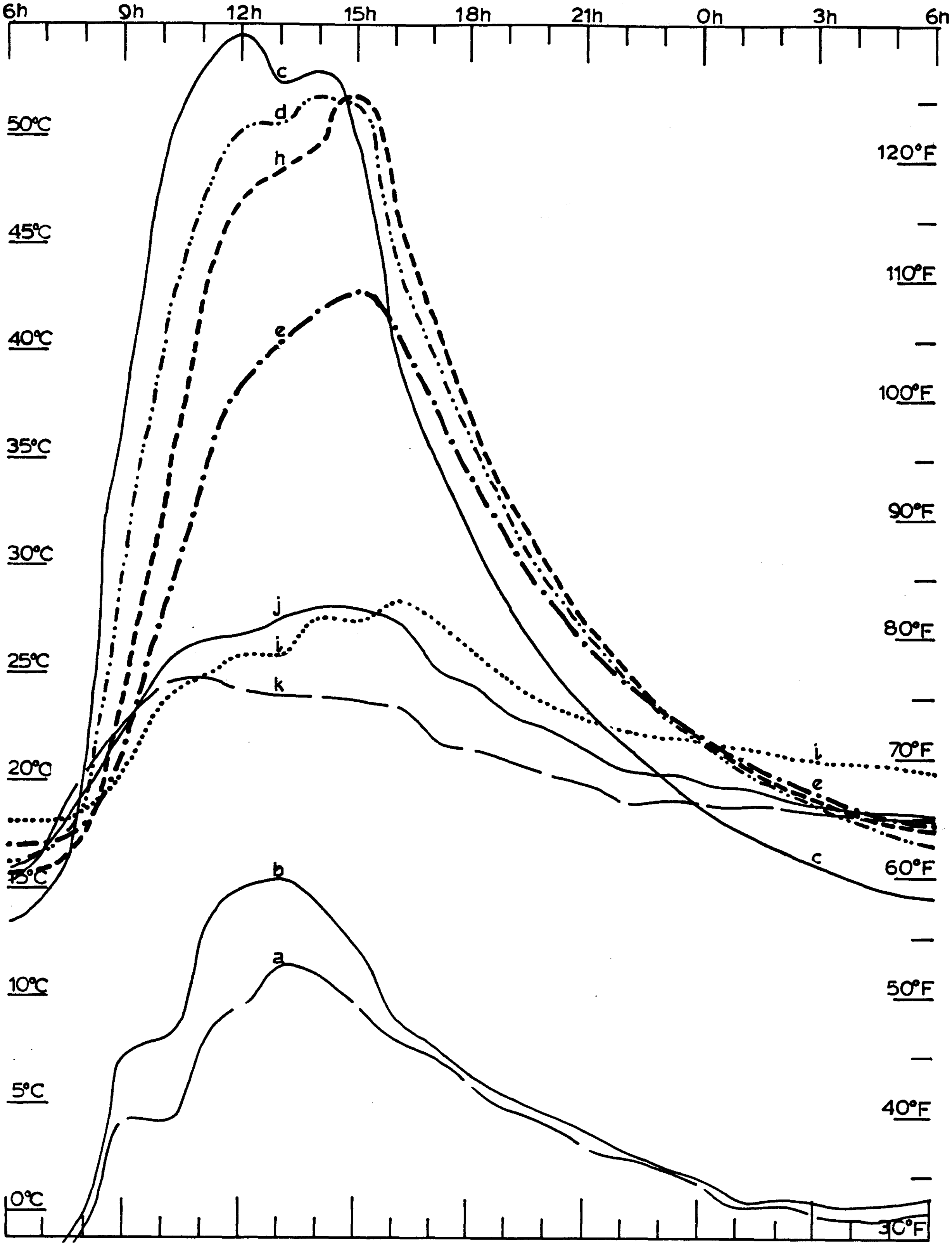


Figure 4.8. Full day of solar exposure (1983 March 26): 84% of partial sunshine; 0.49 ratio between 'the heat storage capacity of the encapsulated phase-change materials' and 'the transmitted Solar Heat Gain Factor;' following partly sunny day.

days, this Siding could probably give its best performance because during sunlight exposure all peaks would be reduced by a greater heat loss.

(c) Overcast Day following the above sunny day. This day was not an ideal overcast day (with absolutely no sunshine and no rain) but there were no better ones since the sample monitoring began. The bonus of choosing this day was to observe the carry-over period after a full day of solar exposure.

This day could be classified as a cloudy day with a slight drizzle, some dim sunshine, and 6 min. of sunshine around 12h00. The graphed temperature fluctuation curves were similar to those of Fig. 4.6 and Fig. 4.7, but with the peaks of curves (c), (d) and (h) very close to the other curves which were slightly less pronounced. This indicated the undoubted presence of a dominant diffuse radiation through clouds of different thickness (a decrease leading to the 6 min sun break). The outdoor temperatures were similar to those in Fig. 4.7 (of 1983 March 17).

The carry-over period was observed to be very satisfactory because the next morning (1983 March 28, 6h00) all the curves of the encapsulated phase-change materials were in the vicinity of 19°C (66°F). The tight configuration of these curves also occured in very 'flat' and even shapes around the same temperature during cloudy days with rain. It should be noted that in all the examples presented above (Fig. 4.4 through Fig. 4.8) the temperatures of the encapsulated materials and the room surface of the siding were between 16°C and 21°C (60°F and 70°F) and usually above 18°C (65°F).

As in several previous observations, the conduction of heat by the hardware cloth trays was observed through the temperatures indicated by thermistors (f) and (g). As was shown in Fig. 4.1, thermistor (f) was placed between 2 capsules of phase-change materials in contact with both the horizontal and the vertical component of the tray; thermistor (g) was placed similarly but above the (f) couple in contact only with the vertical component of the tray. During the daytime of this overcast weather the temperatures indicated by thermistor (f) were higher than those of thermistor (g) by 0.11 - 0.17°C (0.2-0.3°F), and during the nighttime by 0.06-0.11°C (0.1-0.2°F). This demonstrated a higher conduction of this day's diffused radiation (from the exterior to the interior sides of the tray's stack) than the conduction of heat loss during the night (from the interior to the exterior sides of tray's stack). Throughout the course of sunny or partly sunny days the same phenomenon occured but with larger differences [0.11-0.33°C (0.2-0.6°F); 0.06-0.22°C (0.1-0.4°F)].

Latex-Encapsulated Phase-Change Materials could be considered as a new product of promise for applications such as this type of Sol-Clad-Siding, but only if it were improved. An important improvement would be achieved if the latex coating was thickened to resist crystal punctures. Protuberances which foreshadow punctures caused by the sharp crystals inside the capsules could be seen, as shown in Fig. 4.9 after 2 weeks of testing. This time period represents a very few freeze-thaw cycles. For the capsules under direct sunlight the thickening of latex might be beneficial by reducing the thermal impact through the insulating property of latex. Also, stronger capsules might improve the resistance of capsules to crush under their own weight. Another required improvement of these encapsulated materials would be to increase their heat storage capacity so they caused less temperature stratification by taking longer to saturate.

An answer to the increase in heat storage capacity could be Steve Marks' work on crystal habit modifiers which minimize the individual Glauber's salt crystal sizes (U.S. Patent No. 4 349 446). This approach gives 50% higher heat capacity.

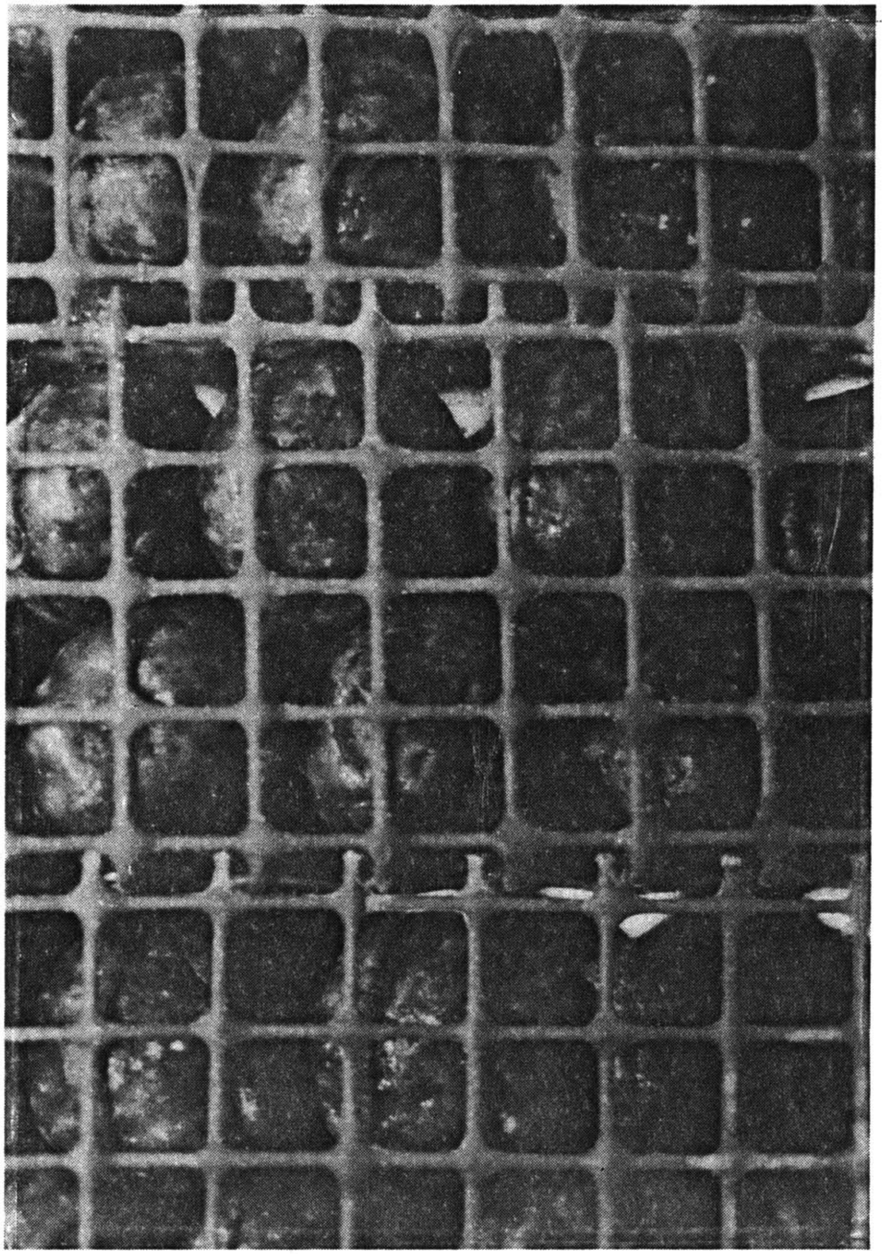


Figure 4.9. Detail of phase-change material after 2 weeks of testing. The white spots on capsules are deposits of salts which have leaked through punctures caused by crystals in the latex coating.
Scale: 2.6 times larger than real size.

Calor a new product by the Calor Group Limited (Windsor Road, Slough SL1 AEQ) England is another phase-change materal that could have been tried ot for its applicability to Sol-Clad-Siding (but a sample quantity was not available in time for testing). This material is composed of a network of open-cell latex membranes which form an aggregation of small cells of Glauber's salts (sodium sulphate decahydrate). These cells could be a viable solution to the problem of chemical separation because their size restricts the separation of the hydrated salt. As a bonus, Calor was estimated to release 27 Wh/kg (45Btu/lb) over a 2.8°C (5°F) temperature swing. Experiments would be necessary to determine the behavior of Calor under the thermal load of direct solar radiation as experienced by the encapsulated phase-change materials on the sunlit side of the container of Sol-Clad-Siding sample.

A review of the conclusions from the above experiments inferred that the Sol-Clad-Siding had a considerable potential to perform as a heat loss compensator for dwellings. The problem encountered during the above experiments were considered surmountable. Regardless of which phase-change materials are most suited for this Siding, their quantity has to be sufficient to store the solar heat radiation that is transmitted through the Trans-Lucent-Insulation. But, in order to store this radiation efficiently, the heat has to be distributed very evenly from the sunlit surface of the phase-change materials throughout its whole mass without generating more than a few degrees of temperature stratification. For this reason the vertical movement of air has to be brought to a minimum. Although air does not necessarily have to be part of a container of phase-change materials, its property of distributing the heat is too great to be ignored: it simply has to be utilized properly.

For the Sol-Clad-Siding incorporating encapsulated phase-change materials, it was already discussed that the temperature stratification was caused by the warming of air by the sunlit surface of capsules incapable of absorbing all the available solar radiation. Initially, it was expected that the phase-change materials would absorb solar energy at a faster rate than cementitious or ceramic materials. Curves (d) of Fig. 4.4 through Fig. 4.8 showed a sensible regime of behavior which occured because the sunlit encapsulated materials were overwhelmed with energy. This sensible regime was in sharp contrast with the latent regime shown by curve (i).

The temperature fluctuations shown by the curves of Fig. 4.4, Fig. 4.5, and Fig. 4.8 were in excess by far of those experienced by the core of the M.I.T. thermal storage ceiling tile that was determined to contain the same phase-change material as the capsules. The figure in Appendix Gamma showed that over a typical day in the heating season the temperature excursion of the tile core was 7.2^{o}C (13^{o}F). The curves of the 2 partly sunny days (Fig. 4.6 and Fig. 4.7) presented temperature excursions ofcurves (d) comparable with the tile core excursion. Particularly Fig. 4.7 showed a temperature excursion of 8.9^{o}C (16^{o}F) that meant the very beginning of an acceptable temperature fluctuation because it exceeded by only 1.7^{o} (3^{o}F) the tile core excursion. This day received only 21% of the possible sunshine.

It could be estimated that if a March day had no more than 21% of the possible sunshine, and if the sample's container were divided at mid-height [where the thermistor (d) was located] by an airtight partition, the temperature fluctuations inside this 30 cm (11.8 in) tall compartment would remain within the same acceptable levels as above. If the 30 cm (11.8 in) container were further subdivided in 2 by an airtight partition, the resultant 15 cm (5.9 in) tall compartments would be able to withstand exposures up to 42% of the possible sunshine. This exposure was just above the 41% value of possible sunshine which represented the maximum and optimum heat storage capacity of the sample.

To be able to withstand higher percentages of possible sunshine, the heat storage capacity of the container's encapsulated materials would have to be increased. For the same type of latex coated capsule form, an increase of the heat storage capacity could be achieved by encapsulating phase-change materials with crystal habit modifiers which as discussed earlier had 50% more heat capacity.

If the 15 cm (5.9 in) tall compartments incorporated crystal habit modifiers' encapsulated materials, the exposure would be increased by 50% to a value of 63% of possible sunshine, and still keep the temperature fluctuatios within the discussed acceptable levels. Of course, the depth and mass of these modifiers' encapsulated materials could be enlarged to augment the percentage of possible sunshine, but there would be a limit caused by the ratio between their improved heat storage capacity and their coating absorptance. Therefore, it would be more beneficial to lower the height of the container's compartments by 50% to 10 cm (3.9 in) and enlarge the depth by 50% to withstand the occasional insolation's close to 100% of possible sunshine.

Another important conclusion of all these experiments was the realization that the Sol-Clad-Siding could also be utilized for the east and west orientations for latitudes that allow positive insolation from 8hoo to 10h00 and 14h00 to 16h00. Between 10h00 and 12h00 for the east facade and 12h00 and 14h00 for the west facade, the angles of incidence of sun's rays would be too sharp to permit useful transmission by the weather surface of glass to the container of phase-change materials. Most of the graphs indicated that by 10h00 the inward surface of the sample reached the comfort temperature of dwelling rooms and did not fall below it until late in the day. But, in such a situation, the carry-over period would probably not last until the insolation time of the following day, unless a larger quantity of phase-change materials would be incorporated to store more heat, coupled with a more efficient system of absorption of solar radiation. Such ameliorations would certainly increase the applicability of this siding to the common east and west orientations.

Areas For Future Research include the following:

(F.1) Experiments for the optimum utilization of Calor for Sol-Clad Siding: These experiments may include the following: testing, monitoring, and comparing of 4 types of phase-change materials' containers. These side by side containers have to be at least 10.2 cm (4 in) deep, and they are listed below:

(F.1.1) a pan-like container (a control container) of thin steel-sheet to stand against the 2 mm (1/16 in) glass plate of the Trans-Lucent-Insulation; to check the Calor efficiency under direct solar exposure; to have a small window of glass to observe if any separation occurs;

(F.1.2) an identical pan-like container like the above but including heat diverters of fly screen against the 2 mm (1/16 in) glass plate to reduce the impact of direct sunlight and to conduct the absorbed heat to the Calor mass towards the room side via hardware cloth folded like metal deck;

(F.1.3) an identical sized container all of thin steel-sheet (almost touching the 2mm (1/16 in) glass plate and painted on the other sides; hardware cloth folded like metal deck to distribute heat from the inside face of the sunlit sheet to which it has to be welded;

(F.1.4) a container having a metal-deck-like shape (with horizontal flutes) almost touching the 2 mm (1/16 in) glass plate; with the same frontal area as the above containers.

(F2) If the encapsulated phase-change materials (developed by Pennwalt Corp.) are going to be improved by correcting the shortcomings mentioned above (particularly if they contained crystal habit modifiers which gave them 50% more heat capacity), then experiments may be conducted to find the optimum size of compartments for these materials. Testing may include 12.7 cm (5 in) deep trays in a container of thin steel-sheet divided into 2 compartments of different heights: 15 cm (5.9 in), and 10 cm (3.9 in). To reduce the impact of direct sunlight, to absorb solar heat and to distribute it, all these containers may include heat diverters of fly screen in the front of, and connected with the horizontal side of trays made of denser hardware cloth.

Part 5

SOL-CLAD-SIDING AND TRANS-LUCENT INSULATION AS CURTAIN WALL COMPONENTS FOR HOUSING

The outer surface of the Sol-Clad-Siding panel will be 3 mm (1/8 in) glass plate; the sides and the inner surfaces will be of thin steel-sheet; the glass and the steel-sheet which have very similar thermal expansion coefficients will be attached to each other by polybutyl. The thin steel-sheet will have to be of a gauge necessary to hold the weight of the contained phase-change material and to prevent easy puncture. As shown in Fig. 5.1, the Sol-Clad-Siding will have 2 separate parts, preferably connected through a thermal break. A slightly larger frame will hold the Trans-Lucent-Insulation, and the pan-like container with 2 mm (1/16 in) glass cover on the Trans-Lucent-Insulation side will hold the phase-change material. The thermal breaks would prevent conduction heat losses through the steel-sheet from the container to the outer glass plate.

As mentioned in Part 2 and Part 4, panels of Sol-Clad-Siding will be incorporated into a curtain wall system of conventional type for dwellings (particularly for multiple family housing). This system will utilize heavy duty studs [40.6 cm (16 in) on center] to secure the weight of the phase-change material containers [estimated at 75-100 kg/(sq m)[15-20 lb/(sq ft)]] between them, to withstand the wind loads on the outer membrane, and to support the weight of the interior finishes. The actual load of the storage container will depend upon the ratio of the weight to the thermal storage capacity of the phase-change material.

The studs of the curtain wall will be attached to the structure by typical fastener systems. The panels will be secured to the studs by bolts through an adaptation of existing attachment systems. These attachment systems must by strong, adjustable in 3 dimensions to allow for alignment of the wall assemblers, and easily accessible for erection and disassembly.

Gypsum board finishing placed on the inside face of the studs will proved a conventional dwelling interior finish, and also will enclose air spaces between the studs. Although the thermal resistance of these spaces will be low, they will provide a buffer zone to moderate the eventuality of slight overheating in the phase-change material container.

Trans-Lucent-Insulation glass blocks introduced in Part 3 may be placed above the view height windows to introduce diffused sunlight in rooms and to insulate where most heat losses through windows occur. Entering rooms from the most favorable angle near the ceiling, the diffused light would be easily absorbed by the conventional gypsum finishes. Window frames may incorporate and integrate these glass blocks not only on their upper parts, but also on one or both sides of their viewing and/or operable panes.

The section of Fig. 5.1 illustrates how the summer shading could be achieved with an overhang (for solar angles of Boston latitude). The most appropriate shading element

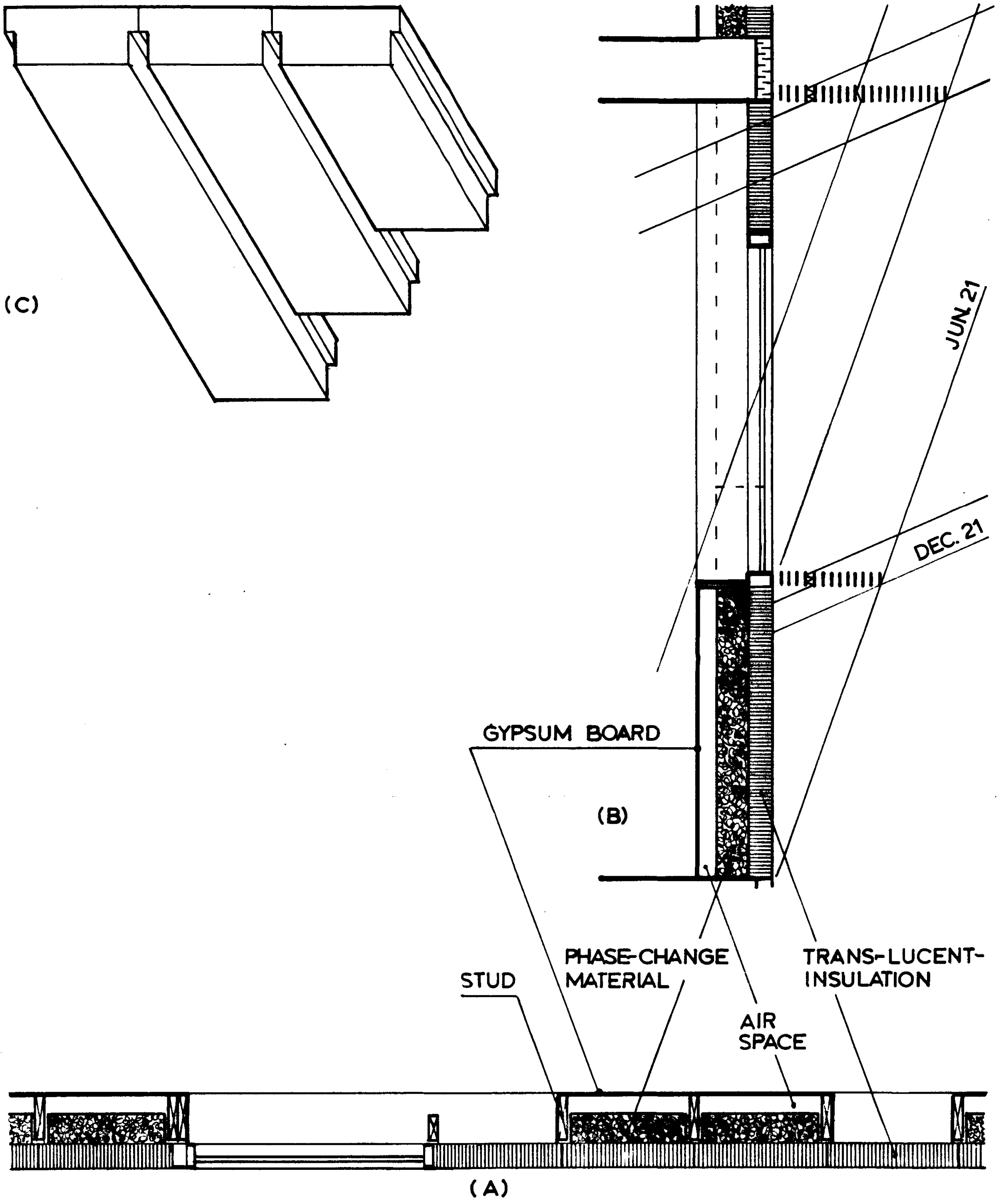


Figure 5.1. Proposal for utilizing the prototyped Sol-Clad-Siding panels and Trans-Lucent-Insulation glass blocks as a curtain wall system: [(A) = plan], [(B) = section], [(C). = axonometric projection of Sol-Clad-Siding panel]. Scale: 1/20.

would be of thin fins because of their diffusing quality through multiple reflections between the faces of these fins.

It should be mentioned that the Sol-Clad-Siding has the potential of being utilized for the retrofitting of dwellings. This could be achieved primarily if a building already has a curtain wall system, or if a structure could easily accept one. Otherwise, specific areas of facades could be covered with Sol-Clad-Siding panels to save energy through heat loss compensation.

It is possible to foresee that Sol-Clad-Siding panels and Trans-Lucent-Insulation glass blocks could one day be mass produced for affordable prices with a fast return on the initial investment. The Teflon FEP film of the honeycombe adds only about \$22-32/(sq m) [\$2-3/(sq ft)] to the double glass plates inbetween which it is placed, if manufactured by machines out of the thinnest film [0.001 mm (0.5 mil)]. This investment is attractive for the service and insulation provided. The phase-change materials already have affordable prices; the expensive part is their container and the hermetic packaging. However, progress is continously made in this field, and hopefully this research is part of that advancement.

APPENDIX ALPHA

OPTICAL PROPERTIES OF TEFLON FEP FLUORCARBON FILM

Light Transmission

"Teflon" (Reg. U.S. Pat. Off.) FEP fluorocarbon film transmits more ultraviolet, visible light and infrared radiation than does ordinary window glass. Figures 1 and 2 show the light transmission and absorbance of 0.03 and 0.13 mm (1 and 5 mil) "Teflon" FEP vs. ordinary window glass. It will be noted that "Teflon" FEP is much more transparent to the infrared spectrum than is glass and also transmits more of the ultraviolet range. Since transmittance and absorbance are reciprocal functions, they are both plotted as ordinates in Figures 1 and 2 (below).

--DU PONT/TEFLON FEP/FLUOROCARBON FILM, "BULLETIN T-5A/OPTICAL," [pamphlet: E.I. DU PONT DE NEMOURS & CO. (INC.), Wilmington, Del.]

Figure 1

ABSORPTION SPECTRUM FOR "TEFLON" FEP FILM

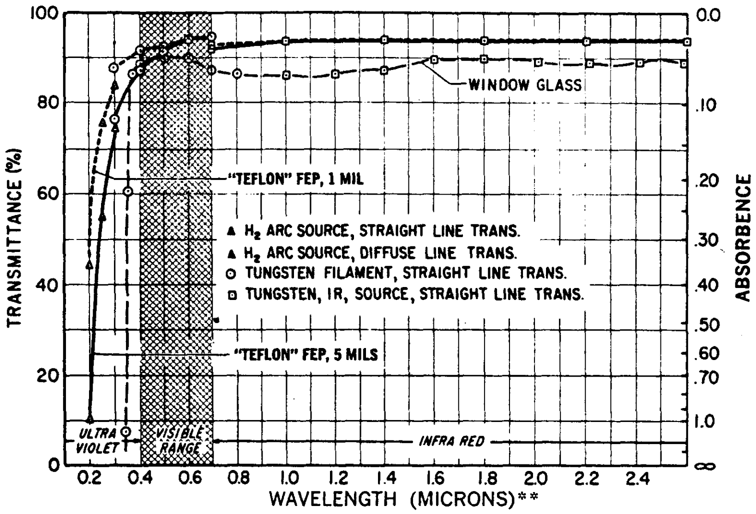
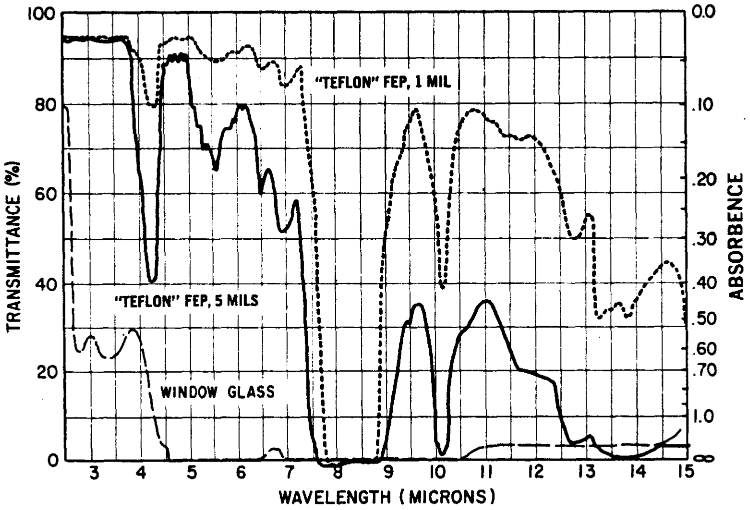


Figure 2

ABSORPTION SPECTRUM FOR "TEFLON" FEP FILM



REFRACTIVE INDEX

The refractive index of "Teflon" FEP film is between 1.341 and 1.347.

*Reg. U.S. Pat. Off.

**1 Micron = 10,000 Angstroms = 0.001 mm

APPENDIX BETA
INITIAL EXPERIMENTS WITH ENCAPSULATED PHASE-CHANGE MATERIALS

These experiments used about 0.454 kg (lb) of the first sample of encapsulated phase-change materials received from their developer (Pennwalt Corporation, King of Prussia, Pennsylvania). In the initial experiments the capsules were packed within 3 trays of a 5.4 cm (2.13 in) depth identical with the latter sample. The small tray stack was hermetically enclosed in a 6 mm (1.4 in) thick glass jar.

The jar was installed in a device (similar to air-conditioning units) on a south-facing window sill. The device was insulated all around, except for the inside and outside vertical surfaces of the jar to face the outdoor and the interior air temperatures.

The preliminary conclusions of these experiments indicated a rapid and uniform melting of these encapsulated materials in about 2 hrs. and a good distribution of heat transfer from the capsules' surfaces and the hardware cloth trays), and via air convection between capsules.

APPENDIX GAMMA

COMAPRISON BETWEEN THE BEHAVIOR OF PHASE-CHANGE MATERIALS WITHIN THE SOL-CLAD-SIDING SAMPLE AND THE M.I.T. THERMAL STORAGE CEILING TILE.

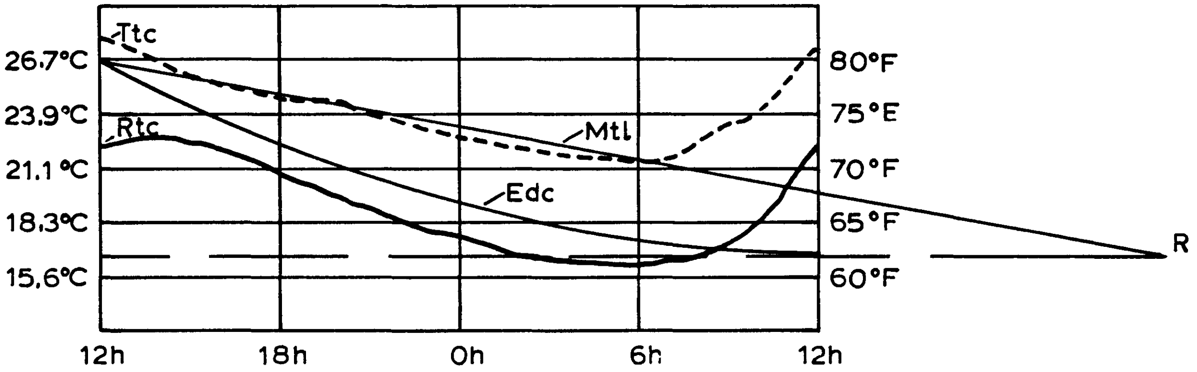
The hypothesis of this exercise was that if these materials had the same chemical composition , the slope of their cooling curves would be similar. During 1983 March 24, the container of encapsulated phase-change materials had a total average heat loss which was 1.4 times higher than the total average heat loss of the M.I.T. ceiling tile core over a typical heating season day.

[The heat loss of the encapsulated materials per 0.09 sq m (1 sq ft) was to outside through the Trans-Lucent-Insulation, and to the inside through the 5 mm (3/16 in) glass plate. And, the heat loss of the title core per 0.09 sq m (1 sq ft) was to the outside through the fiberglass insulation of the roof, and to the inside through the 0.62 cm (0.25 in) polymer concrete casing.]

In order to do a meaningful comparison, the heat loss rate of the encapsulated materials would have to match that of the tile core. This could be done by decaying the exponential curve that controlled the cooling behavior of the tile core at a 1.4 times faster rate (corresponding to the ratio between their total average heat losses).

As shown in the figure below, the graph of typical degradation temperatures of the tile core were reduced exponentially from its mean line declining toward the room temperature [point marked (R)]. This mean line corresponding to the degradation equation [y e^{-t}] was reduced to an exponential curve corresponding proportionally to the degradation equation [y $e^{-(1.4)t}$]. These equations were extrapolated from [y $e^{-(u)(t)/(c)}$], where (u) = thermal conductivity, (t) = time, and (c) = capacitance.

The resultant exponential curve was overlaid on Fig. 4.4 starting from the temperature peak time of the encapsulated materials in the lower part of the sample's container [curve (i)]. The conclusion of this exercise was that the phase-change materials of both, the Sol-Clad-Siding sample and the thermal storage tile were composed of substances with similar physical properties because they were experiencing the same latent behavior as shown by the almost identical cooling curves.



Ttc = Tile temperature curve
Mtl = Mean temperature line
Edc = Exponential degradation
Rtc = Room temperature curve

APPENDIX DELTA

EXPERIMENTAL PROCEDURE OF SIMULATED OPEN SOUTHERLY EXPOSURE DURING BRIGHT SUNSHINE DAY (1983 MARCH 26)

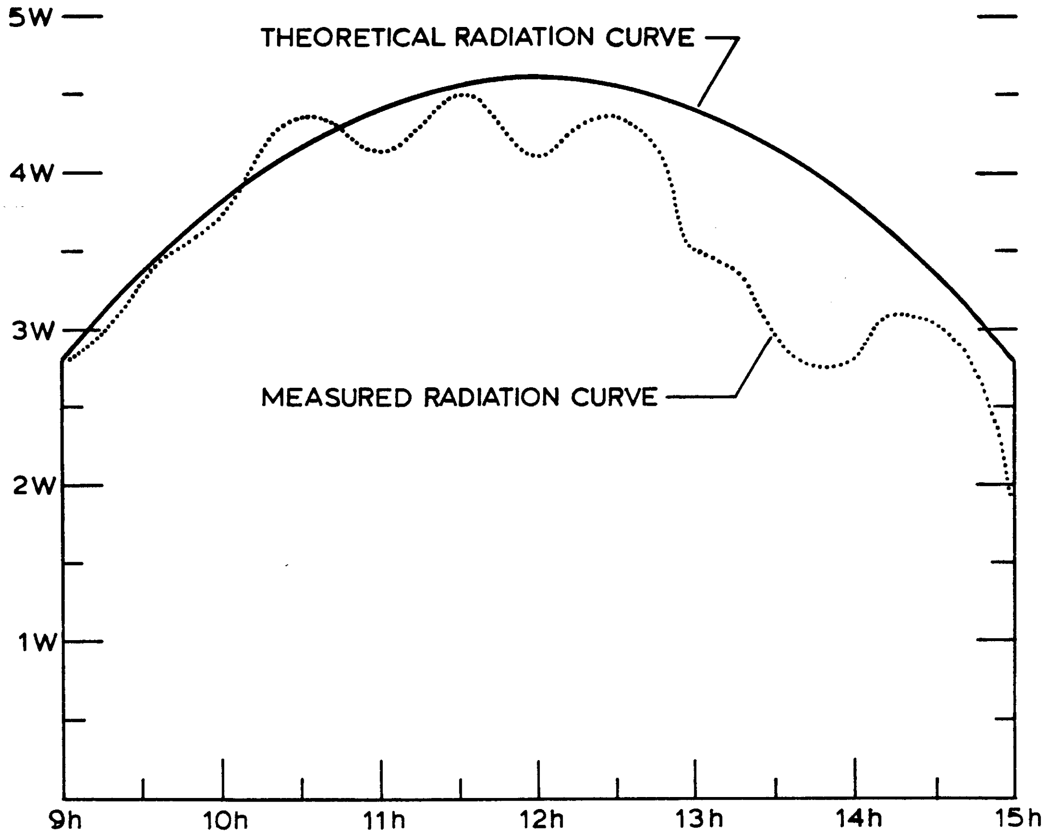
The insolation values were measured with a radiant flux meter. The sensor was placed parallel to the glazing of the window next to the sample. Measurements were taken at regular intervals (of 30 min., and occasionally 15 min.) from 11h15 until 15hoo.

At 13h15 when about 3/4 of the sample was in shade, one mirror was applied from below matching roughly a reciprocal angle of incidence. At 13h30 when all the sample was shaded, the other mirror was applied from below with a smaller angle of incidence. The mirrors were adjusted continuously except for a brief period around 14h00. At 14h30 one mirror was removed and at 15h30 the reflected exposure was ended.

The radiation measured with the flux meter was graphed below a theoretical radiation curve; the sinusoidal shape of this curve was obtained by interpolating proportionally the measured peak (of 11h30) value between the given data of Clear-Day Solar Heat Gain [source: **Edward Mazria, The Passive Solar Energy Book/Expanded Professional Edition** (Emmaus: Rodale Press, 1979) pp. 511, 517]. The figure below illustrates these curves.

The ratio between the areas below the curve of measured values, and below the theoretical sine curve, showed that from 9h00 until 15h00 the sample received 91% of the radiation of that day, which had 92% of the possible sunshine (the latter data was obtained from Blue Hill Observatory, Milton, Massachusetts).

Therefore, the sample received 84% of the possible sunshine of that typical March day. Consequently, the registered peak temperature fluctuations of the sample had to be multiplied by a factor of 1.19 to estimate their maximum values if that day were perfectly clear.



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