TOWARDS A SYNTHESIS OF ENERGY, FORM AND USE:
NEW FORMS OF SOLAR SPACE CONDITIONING MADE POSSIBLE
BY THE USE OF NEW MATERIALS

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<table>
<thead>
<tr>
<th>TABLE OF CONTENTS</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE PAGE</td>
<td></td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>3</td>
</tr>
<tr>
<td>FOREWORD</td>
<td>4</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>7</td>
</tr>
<tr>
<td>CHAPTER 1: THE PROBLEMS</td>
<td>10</td>
</tr>
<tr>
<td>CHAPTER 2: ONE POTENTIAL SOLUTION: THE NEW SOLAR MATERIALS AND THEIR PROPERTIES</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>solar glazing</td>
</tr>
<tr>
<td></td>
<td>thermal storage</td>
</tr>
<tr>
<td></td>
<td>some basic heating considerations</td>
</tr>
<tr>
<td></td>
<td>some basic lighting considerations</td>
</tr>
<tr>
<td>CHAPTER 3: THE &quot;SOLAR MODULATOR&quot; SYSTEM</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>specular light patterns</td>
</tr>
<tr>
<td></td>
<td>room glare measurements and evaluations</td>
</tr>
<tr>
<td></td>
<td>form and use studies</td>
</tr>
<tr>
<td>CHAPTER 4: THE &quot;SOLAR ROOF&quot; SYSTEM</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>light control action</td>
</tr>
<tr>
<td></td>
<td>lighting measurements and evaluations</td>
</tr>
<tr>
<td></td>
<td>thermal considerations</td>
</tr>
<tr>
<td></td>
<td>form and use studies</td>
</tr>
<tr>
<td>BIBLIOGRAPHY AND REFERENCES</td>
<td>98-100</td>
</tr>
</tbody>
</table>
ABSTRACT

TOWARDS A SYNTHESIS OF ENERGY, FORM AND USE:
NEW FORMS OF SOLAR SPACE CONDITIONING MADE POSSIBLE
BY THE USE OF NEW MATERIALS

James S. Day

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Master of Architecture

New approaches to the design of "passive" solar space conditioning are presented and evaluated in this thesis. The guiding criteria behind the evaluation are two design goals: 1) to effect a simple, useful and beautiful integration of light and heat energy within a space-conditioning system, since too often these are antagonistic elements in passive solar design; 2) to achieve a level of adaptability, modular flexibility and potential for appropriate placement which would allow conflicts with use, view and access to a living space to be minimized. The net effect of realizing these criteria will be to actually broaden the available range of possibilities for space definition in domestic architecture, as well as to increase the potential for control over the living space by the user.

The technological context which make these criteria feasible is the recent development of new building materials with improved thermal and physical properties. The thesis is structured around two proposed systems using the new materials. Models of each system are analyzed for their natural lighting qualities, using photographs, observation and measurements. In addition the second system, not presented before, is analyzed for its thermal behavior. The two studies are preceded by an introduction to the problems and inherent advantages of passive solar architecture. The new building materials are introduced, along with a description of their thermal and physical properties. A brief section then defines the natural lighting criteria and analytical rationale used in the studies. Following each of the two studies, conclusions are presented, as well as a few drawings exploring some of the form and use relationships engendered by the system configuration and its lighting and thermal characteristics.

Thesis Supervisor: Timothy Johnson
Title: Assistant Professor of Architecture
FOREWORD

"I just want to build buildings and design systems that are beautiful and simple and really work. There’s nothing earth-shattering about any of my ideas, but they keep people happy. There’s so much energy all around us that we overlook. It isn’t apparent, but we can gather it so easily." Steve Baer

My thesis has been done in this spirit. There is an increasingly urgent imperative that architects and builders must learn to accept, having to do with non-destructive, simple utilization of natural systems to provide energy for living. My belief is that it is the task of the architect, in this context, to go a step further than this: beyond non-destructive utilization towards a new, positive contribution to the language of building. A synergy of energy and form needs to be allowed to grow, enabling more useful, more delightful and cheaper forms of building to emerge out of these imperatives. My instinctive, but strong, feeling is that "solar" architecture will not be really successful until this happens. Any form of space cond-
itioning utilizing the sun, but limiting form and use in ways having no inherent meaning, will not be acceptable in the long run because it will not be necessary. The same applies to technological complexity. I have talked with many people, from very old to young, who are fascinated by the idea of using solar energy, I think partly because they feel that the principles are understandable from direct experience, unlike so much of contemporary technology. Perhaps people sense that, for once, it could be a simple answer to what is really a simple problem. I think that solar energy systems have the potential for appeal on this level; that it is possible for them to be simple and logical enough to help give the homeowner back a sense that he knows how his own house works, and that at least this part of it will not fail him unpredictably and expensively.

The thesis concentrates on one aspect of the energy/form synergy I am looking for: a broadening of the scope of possibilities for natural daylighting in houses. Another aspect is briefly discussed at the end of the final chapter. The work in the thesis is no more than an example of the kind of work I wish architects could find it possible to do more often. A healthy change will occur in architecture if in the near future, building design approaches will move away from a primary concern with style and towards a greater interest in cooperating with, and enlivening, the invisible and visible landscape of energy, matter and living things surrounding all of us. This cannot happen, however, unless architects develop enough personal care,
love and curiosity about the world right in front of them to use it as a basis for design. It is a matter of attitude: if we are to use solar and other ecologically responsible aspects of design successfully, then these issues must be seen not as a limitation on design freedom but as a new set of possibilities not only for design, but for the role architecture can play in the growth of a saner society.
INTRODUCTION

It is generally recognized that limitations in presently available building materials are the major block to the full realization of the design potentials of passive solar energy systems. Several improved materials will soon be available. They are: 1) a glazing with improved insulating capability and unimpaired light transmission; 2) a lightweight, high-capacity thermal storage "tile", using phase-change material and having a constant-temperature heat output. Two passive systems applicable to domestic use have been designed with these materials, and are evaluated in this thesis. The design goals behind each system are to utilize the flexibility made possible by the new glazing and storage to effect a beneficial management of both heat and light within a living space. The first system, developed by others at M.I.T., uses a system of light-reflecting louvers in a south-facing window to direct light upward to the storage tiles, which form a ceiling veneer. The system partially separates the light needed to charge the storage from that needed to light the living space. The second system, which I designed, utilizes a sloping, glazed roof plane, and a system of free-hanging tiles and light-control louvers adjacent to the roof glazing, to control the flow of heat and diffused sunlight.
into the living space. The two systems generate (or are adaptable to) different kinds of building configurations, and are thus not competitive. Their space-conditioning abilities are equivalent, but the kinds of living spaces they help define, in both light quality and form, are very different. I evaluated each system in several ways: 1) by the kinds of light qualities generated, both at the light source and within the living space as a whole; 2) by the kinds of use conflicts generated, and the ability, in terms of the design flexibility of the systems, to circumvent these conflicts; 3) by the kinds of house forms and living spaces engendered by the physical configuration of each system combined with the first two factors. The lighting evaluations were done using models; photographs, observations and measurements were made. The use evaluations were done with diagrams and verbal analysis. The house-form explorations were done with drawings: sections and axonometric studies of regions within a possible house, rather than complete house designs. The studies are of single-family, detached houses, but this should not imply that either system is limited to this use. The basic criterion for the evaluations, at all times, was my own judgement of how positive a contribution to a living environment these systems would be. Analysis of the thermal behavior of my own design is also included, as is an introductory discussion of the new materials and their thermal and physical characteristics. The intent of these sections, aside from description, is to give the reader a sense by example of the factors governing the way the new materials work, why
these particular systems were designed as they were, and the practical things a designer should know in order to adapt them to the context of his own needs.
Heating a living space with sunlight can be done in many ways, using many possible systems adapted to different climates and use conditions. They can generally be divided into one of two basic categories, the first generally known as "active" and the second as "passive." Active systems generally conform closely to traditional concepts of space-conditioning devices; they belong to the world of pipes, ducts, pumps, fans, tanks and radiators, and bear the same kind of relationship to the living space they serve as do conventional fossil-fuel systems. Although they are active in their internal workings, their role in defining form is passive: they can adapt their configuration to serve almost any form of living space without changing their basic performance; even the solar collector itself may be placed apart from the building envelope. On the other hand, the principles of effective passive systems "actively" limit the form that the living space can assume. Since the living space itself collects and stores the solar energy, issues of orientation and choice of materials become critical, and can affect for better or worse, the basic qualities of the space.

The most usual form of passive design follows this basic diagram:
A whole cluster of basic conflicts are inherent in this arrangement:

1) The quality and direction of the sunlight required to heat the space becomes difficult to control, and as a result gives rise to problems of glare and the fading of rug and furniture fabrics in direct sunlight.  

2) Since large areas of glazing are required to admit this light, and since even double glazing is a poor insulator, large diurnal temperature swings can occur in the living space unless some form of moveable insulation covers the glass at night.

3) To "dampen," if not remove, these large temperature swings, large amounts of heavy, thermally conductive material, usually in the form of an exposed concrete interior building structure, must be placed in a position to absorb a significant portion of the solar energy entering the space.

4) Since the position of this energy absorber and storage usually includes the floor, shading and insulating of its
surface by furniture, rugs, etc., is inevitable to some degree. This reduces its effectiveness, and at the same time increases the proportion of lightweight, non-absorbing surfaces in the space. These surfaces convert sunlight entirely into immediate heat gain, aggravating the temperature swing further.

At this point, one might ask why I even bother to discuss passive design as a reasonable alternative, and the answer is simple. It is that if these problems could be solved, there would be no question about its superiority for residential space-heating applications, for these reasons:

1) The weatherskin and internal structural and finish materials, already necessary in any building, do the work of collecting and storing the sun's energy. The first cost for materials associated with the heating function is incrementally small, since these elements can be partially amortized as building structure.

2) The task of intercepting solar light energy, converting it into heat, storing it and re-radiating it into the living space as the room air temperature drops can be performed by a single building element with no moving parts.

3) The potential thermal efficiency of a passive system is higher, due to the elimination of at least two of the heat transfer stages, with their inherent losses, formed in active systems. The practical effect of this gain in efficiency is to reduce the area needed to intercept sunlight.
4) The problem of controlling winter night freezing of collector fluid in active systems is eliminated.

Active systems do have one potential ability difficult to achieve in passive designs: the storage of enough heat for a "carryover" time of four or five days. However, this feature raises the first cost of active systems still further, takes up a lot of physical space, and is used to capacity only two or three times a year, even in the New England region.

Efforts have been made to rationalize passive design. The so-called Trombe wall, developed first in France, places the main thermal storage mass directly behind the south glazing, where it intercepts sunlight before it enters the living space.¹

The storage mass is a thick concrete slab, painted black on the sun side. Due to the imperfect conductivity of the concrete, a steep temperature gradient develops across the depth of the slab. The high concrete surface temperature is used to develop a strong air convection in the "thermosiphon" space between storage and
glazing. The convected air then circulates into the living space and back, in a large loop. At night, the thermosiphon is closed off, and the heated slab radiates into the living space. The system works best in climates where the winter daytime air temperature does not stay at very low levels, as it does in New England: when the south glazing is cooled by very cold air at the same time as the slab is heated by the sun, a closed convection loop tends to form within the thermosiphon, blocking the large convective loop warming the living space, and thus reducing the efficiency of the system. The requirements of heating and southern view are in direct conflict. Some form of moveable insulation is desirable between slab and glazing to prevent the slab from radiating as much into the outside world at night as it does into the room.

Steve Baer's house in New Mexico is superficially similar, but has no convection thermosiphon and uses water-filled oil drums for storage; these have very efficient internal thermal diffusion and a low operating surface temperature compared to concrete. Although the "compulsory" blockage of southern view still exists (traditional anyway in that climate), a new quality is introduced. Although I have never visited the house, pictures I have seen of indirect sunlight filtering between the cylindrical, stacked oil drums indicate a very pleasing quality. The modular nature of the drums, with their interstitial spaces, gives rise to a sense that the storage wall is not really a wall in the usual sense, but a filter, which in fact is what it is.
The third alternative passive system comes seemingly closer than the others to solving the problems of passive design by its basic configuration. The house designed by Harold Hay in Atascadero, California, places the thermal mass, consisting of 8 inch deep PVC bags containing water, on the roof of the house:

A system of motorized, sliding insulation panels can cover or uncover the storage as needed. (This system is designed to control climatic temperature swings narrower than those found in either New Mexico or most northern regions. The water bags are outside the weatherskin, and thus would not be appropriate for
long periods of freezing weather.) The entire collector/storage system is out of conflict with both use and view, yet design conflicts with use and space still exist, now involving vertical definitions instead of horizontal ones. The house as built is designed as a simple "pavilion" structure with a single flat roof, and indeed this would appear to be the only way to build it economically. If any roof level change were to be introduced, it would multiply cost and complexity without improvement in performance, through the necessity of duplicating the complex system of bags and sliding panels for each roof level. Though flat, the roof cannot itself be used as a use surface. It can be noted that these three systems have one design strategy in common which solves many problems: the compressing of the light aperture, heat control and storage elements into a tight "sandwich," which is itself to one side of the living space.

Since the use of sunlight is the central concern of solar energy development, and since no system can possibly convert all the sunlight it intercepts into instantly stored heat, the problem remains, in passive systems, of what to do with the light which is not so converted. The first simple choice is either to bring it in, as the Baer house does to some degree, or to exclude it, as the Trombe and Hay designs do. If excluded, that is one solution. My basic idea of synergy in this thesis is to try to bring it in and use it beneficially and controllably in a balance of lighting and heating functions, while not interfering with a wide range of use and place definitions in house design.
Over the past several years, an interrelated group of materials and light-control devices have been developed in experimental form at the Solar Energy Laboratory of the Department of Architecture at M.I.T., and elsewhere.\textsuperscript{2,4,5} Their development has been based on a goal to redesign existing construction materials for better thermal properties: to replace existing building materials with new ones, so that the additional first cost of solar design is only the incremental additional cost of the new materials. It was reasoned that if glazing had higher insulating ability than it now has, much of the need for movable insulation would disappear; if a lightweight, high-capacity, high-performance thermal storage material were to be developed, great flexibility in its placement, as well as a lighter supporting structure, would become possible.

SOLAR GLAZING

A new insulating glass has been developed, not at M.I.T. but by Suntek, in California.\textsuperscript{4} More accurately, it is normal plate glass to which has been added a layer of plastic film which reflects the longer wavelengths of infrared energy:
The specular image seen through the glass is not distorted by this layer, and light transmittance for double glazing remains at around 73%. The u value for two layers of this heat-mirror-coated glazing with a one inch air space between them is .22, while normal glass in the same configuration is around .55; an improvement of 250% in the insulating ability of glass. As an aside: this glazing alone would, of course, improve the performance of any passive design. In the case of the Trombe wall, the higher inside surface temperature of the glass resulting from the lower u value would reduce the need for moveable insulation at night, and control the convection problem on a cold day. In general glazing uses, the thermal comfort of places bounded by large areas of glass would be improved. Glass would feel warmer to the touch on a cold day. The relationship between outdoor air temperature and inside surface temperature is expressed by the formula \[ T_{\text{inside surface}} = T_{\text{room}} - (\Delta T \times \frac{.69}{R}) \]
where \( \Delta T \) is the inside-outside difference, .69 is the inside air-film coefficient of resistance, and \( R \) is the total resistance of the glazing (reciprocal of the u value), which is 1.82 for conventional double glazing and 4.54 for the heat-mirror. For an inside air temperature of 67 degrees F. and an outside
one of 15 degrees F., the glass surface would be at 47.3 degrees F. for the conventional and 59.1 degrees F. for the heat-mirror. The rise in surface temperature also has the effect of allowing a higher relative humidity inside before condensation on the glass takes place.¹⁸

One more aside: the heat-mirror layer works in quite a different manner from ordinary glass, about which there still seems to be some misunderstanding concerning the so-called "greenhouse effect." Glass is opaque to heat radiation, and does not reflect it. It would appear black if it could be seen in the heat wavelengths. Glass therefore absorbs heat, but since it is a poor insulator, the heat is conducted through it to be re-emitted to the outside. A greenhouse made from heat-transparent material such as polyethylene⁶ works as well as a glass one. The only reason heat is retained as well as it is in a greenhouse is because of 1) the sheer amount of solar energy which enters during the day; and 2) the ability of the greenhouse membrane to retain a "bubble" of air which is heated from the inside surfaces by convection.

THERMAL STORAGE

The thermal storage developed at M.I.T. takes for form of polyester concrete "tiles," filled with a phase-change material which is designed to melt or solidify at a temperature of 74 degrees F.
The dimensions of the tile are critical only in thickness, as the phase-change material must be stored in layers, less than \( \frac{1}{4} \) inch thick to prevent separation of the constituent materials. This dimension must be kept in the vertical direction, meaning that the tiles must be mounted horizontally. The polyester concrete is lightweight and waterproof, with a non-porous surface capable of accepting fine surface textures when formed. The tile weighs ten pounds per square foot.\(^5\) The working principle of the phase-change material is called latent heat storage; the heat absorbed during a phase change is not measurable as heat within the material. Rather than raising the temperature of a storage mass, the heat energy is absorbed in changing the state or phase of this material from solid to liquid. The overall efficiency of this process is very high, and as can be seen from the tile dimensions, results in a very high storage density: about the equivalent capacity to a 9 inch slab of concrete under similar use conditions.

At this point I would like to go into some detail about the behavior of latent heat storage, which, as will be seen, can actually perform only a part of the task of thermally tempering a living space. I will then discuss sensible heat gain, which is closely associated in its effects with natural light levels.
and quality; this leads to a short discussion on natural lighting criteria and definitions. This section is placed here, rather than in an appendix, so that the reader who is interested in the detail can easily use it as a preparation for the next chapters.

**SOME BASIC HEATING CONSIDERATIONS**

This somewhat simplified graph shows the main thing to bear in mind about the behavior of latent storage: that during the process of phase change—of melting or freezing of the material—the internal temperature remains almost constant. Only at the very end of the process of steadily releasing heat will the temperature of the tile core begin to fall. Room air temperature fluctuations are therefore restricted by the "clamping" effect of the nearly constant core temperature. However, although the core temperature remains constant, the actual energy flux from the core, and as a result, the time it takes for the core to freeze completely, is a variable and is dependent upon the total heat flow out of the living space to the outside.
This diagram attempts to make vivid the basic fact that heat flow from the latent storage material, through its container and into the living space is exactly equal to heat flow from the living space, through the weatherskin and into the outside, under steady-state conditions. The same diagram can be shown in more detail:

\[ T_{\text{core}} \rightarrow \left[ \frac{U_{\text{storage}}}{A_{\text{storage}}} \right] \rightarrow T_{\text{room}} \rightarrow \left[ \frac{U_{\text{weatherskin}}}{A_{\text{weatherskin}}} \right] \rightarrow T_{\text{amb}} \]

Room temperature is the resultant of the interaction of the terms on the left with the terms on the right. For a given outside temperature, the designer needs to know what combination of values will give comfort-zone conditions in the living space.\(^{19}\) Since \( T_{\text{core}} \) is fixed already at 74 degrees F., and \( U_{\text{weatherskin}} \) and \( A_{\text{weatherskin}} \) are at least roughly fixed by user needs and economy, the remaining values are \( U_{\text{storage}} \) and \( A_{\text{storage}} \). \( U_{\text{storage}} \) itself is a combination of two factors: the conductance of the \( \frac{1}{4} \) inch-thick polyester concrete tile
envelope, which is fixed at 16 BTU's/hr./ft.²/degrees F., and the skin conductance, which is in turn dependent upon three factors: room air movement, surface position—exposed surface facing up, down or both—and finally the ability of the tile to radiate directly into the living space: how much of the space it can "see".

The factors contributing to room temperature are combined in the following useful formula:

\[ T_{\text{ROOM}} = \frac{(A_{\text{ws}} U_{\text{ws}}) + (A_{\text{stor}} U_{\text{stor}}) T_{\text{core}}}{(A_{\text{ws}} U_{\text{ws}}) + (A_{\text{stor}} U_{\text{stor}})}. \]

\( T_{\text{ROOM}} \) again represents steady-state conditions, where the energy from storage is providing the only heat source. For the same conditions, the "carryover" time, or the time it takes for the storage to expend all stored heat, can be estimated. By treating the storage container and the weatherskin as series resistances, with \( R_{\text{weatherskin}} \) compensated for its greater area, an effective \( U \) value for this total effective resistance is obtained:

\[ U_{\text{storage}} + U_{\text{weatherskin}} = \frac{1}{R_{\text{stor}} + \frac{R_{\text{ws}}}{A}}. \]

where \( r \) is the number of times \( A_{\text{weatherskin}} \) exceeds \( A_{\text{storage}} \); if the ratio between the two is 5:1, \( r=5 \). Each square foot of latent storage tile is capable of storing around 300 BTU's when the core is fully melted. To find the carryover time, a corresponding square foot of material of the effective \( U \) value arrived at above is placed between the core at 74 degrees and the outside temperature:

\[ U \times I \times \Delta T = \text{BTUH} \]

where \( U \) is the value arrived at above, \( I \) is the area and \( T \) is 74 degrees - \( T_{\text{ambient}} \). 300 BTU's is then divided by the BTUH figure to arrive at the carryover time.
The thermal behavior of the tiles is influenced by the envelope in which the phase change material is contained. Polyester concrete has an unpainted surface absorptivity of around 80%; in order to improve the heat absorption the surface is painted (or the concrete is pigmented) a darker color, with the maximum practical absorptivity being around 95% with a matte black surface. Due to the effect of the envelope's U value discussed above, 50% of the total incident energy is absorbed latently, with the other 50% divided between heat and light in a proportion dependent on the surface absorptivity. This half of the energy goes towards sensible room heating. Any additional light coming into the room not intercepted by the tiles, and not finding its way out the windows again, also goes into sensible heat gain. Sensible gain can be good or terrible, depending on how well it is controlled. Two factors in the living space are responsible for this control: the absorptivity and the heat storage capacity of the walls. The best condition is for all large wall areas in south-facing spaces to have at least the amount of storage capacity provided by drywall or other masonry veneers; the floor might also have masonry tiles. The light absorptivity of these walls should be very low; white is best. The goal is to minimize instantaneous sensible heat gain which can produce intolerably hot interiors during periods of insolation, by diffusing light evenly throughout a room with surfaces having the capacity to reflect light but absorb heat. The heat absorptive masonry acts as a secondary, sensible heat storage system working in conjunction with the latent system. (White
paint, though highly reflective to light, is highly absorptive to long-wave radiation as is all paint.) The energy absorbed by this storage can be estimated by calculating its temperature rise after insolation (in contrast to latent storage), or its temperature "swing," by this formula:

\[
\frac{\text{BTU's/ft}^2}{\text{SPECIFIC HEAT \times DENSITY \times VOLUME}} = \text{SWING}
\]

As will be seen, the rules determining good management of sensible heat coincide with those for producing a low-glare interior for south-facing spaces.

SOME BASIC LIGHTING CONSIDERATIONS

The main issue for the natural lighting studies in the next chapter is that of glare: both of a very concrete and a very negative issue in natural lighting. It is a basic issue; if serious glare exists, not much else of greater subtlety can be appreciated about a space. Its very concreteness makes discussion and measurement of the conditions that lead to glare one of the relatively easier tasks of the lighting designer, although even here much controversy exists over fundamental issues such as whether or not it is even useful to attempt to measure and quantify glare phenomena. Finally, it is the main lighting issue of passive solar design, since one of the most basic forms of glare is simply the presence of direct sunlight in the eyes when it is not wanted.

There are generally considered to be several forms of glare. The first is that mentioned above, called ray glare, caused
by a simple overload of the eye with too much light. Two mechanisms appear to be at work: 1) the inability of the iris to close down enough to produce an interior light level suitable for the retina; and 2) unusually strong diffusion of the specular image within the eyeball by particles within the eye fluid.

Adaptation glare\(^1\) is a glare dependent upon contrast between more than one large area of a viewed image. If one looks at an exterior scene which is itself not "glary," but is seen framed by a room which is a) dark in its wall surfaces, and b) occupying the largest part of the visual field, the eye will be adapted more to room than view and will perceive the view as intolerably bright and harsh. The reverse can also occur, with a dark area within a bright visual field.

Framing glare\(^1\) occurs when a bright view or light source is interrupted by a pattern of much lower luminance, such as window mullions or a dark venetian blind, adding visual "noise" to the image one wants to see.

\[\text{adaptation glare}\]

\[\text{Framing glare}\]
Specular glare actually ranges from semi-diffuse to true specular reflection of a bright light source from a surface, and can be irritating over a wide range of brightness. Examples are the reflection from a road surface when one is driving into the sun, or from a shiny printed page when the light angle is wrong. The light from specular glare is polarized to some degree, and can thus be selectively removed from a scene by polarizing filters or sunglasses.

In both of the following chapters, the problem of glare will be studied from two different but related viewpoints. The first is that of the glare produced by the actual configuration of the light source itself when one looks at it, and includes the patterns of specular light and shadow in the vicinity of the source. The second is a study of the "light-space" into
which the source is set: the living space itself. Here the major concern is for the ability of that space, through its shape configuration, additional light openings, and surface reflectivities, to control the light from the source in such a way that glare is minimized. In the case of glare around the source itself, all of the forms of glare are usually present in a complex mix which only the eye can resolve and analyze, and therefore photographs are used along with observations. In the case of the "light-space," the major form of glare is usually adaptation glare, caused by the relative luminance of the source and the surrounding walls, floor and ceiling. This can be measured comparatively for different conditions and spaces, and so that is what I have done. John Meyer, in his study of glare in Norman Saunders' solar house, provides a formula for arriving at a glare index to enable one to easily compare various lighting situations from this standpoint. I did not attempt to use it, because the two designs I am evaluating are too dissimilar in the configuration of their light apertures, and in the kinds of light they admit, to allow a meaningful numerical comparison.
CHAPTER 3: THE "SOLAR MODULATOR" SYSTEM

With some of the more technical background supplied in the last chapter, the new systems can now be focused on. First is the "solar modulator" system developed at M.I.T. by Tim Johnson, Dennis Andrejko and others. This is its basic diagram:

The latent storage tiles form a ceiling veneer. Light is directed to the tiles by means of the solar modulator, which is designed to reflect sunlight, at a relatively constant angle of around 30 degrees, onto the tiles through a wide range of actual solar profile angles. (Profile angle can be defined as the angle produced by a given elevation and azimuth position of the sun, as viewed from a given direction. All sectional drawings in this paper are of south-facing structures. In this case, only at solar noon would profile and elevation angles be identical; before March 21st, profile angles move toward the horizontal on either side of noon; after, they move to the vertical.)
The louvers, due to the design of their section, need only four adjustments per heating season to maintain full insolation on the tiles. In addition to their tile-insolation function, the louvers can be adjusted by the user to control general lighting or privacy conditions within a space in a manner similar to a venetian blind. Each louver is highly reflective on the top surface; the lower surface may be any light, matte color to minimize stray specular reflection.

The diagram shows how two very different profile angles can produce an almost identical reflected angle with only a small adjustment of the louvers. The ceiling tiles are dark in shade, but not black. In lighting studies, including my own, they have been represented as being dark green in color.

The purpose of this system is to take advantage of the properties of the new solar materials to eliminate, or at the least control, the conflicts outlined in the introduction, and to provide for
user modifications to the conditions produced by the system. The concept of user adjustability is central to the design. The developers realized that any system having a large effect on living space qualities should allow such adjustability, even if maximum space-conditioning efficiency is sacrificed by some adjustments. This approach is carried over into my own design in the next chapter.

The following lighting studies will attempt to evaluate just what some of the "conditions produced by the system" mentioned above are, which are good and which bad, and what might be done about the bad ones. The study will begin with photographs, diagrams and commentary about the specular light patterns produced by a 1½"×1' model of the system. A series of design variations of the modulator and storage elements will be studied. The specular patterns are what really "identify" the system and give it its lighting character. Following this will be the results of lighting measurements within the model space, using diffuse light, and designed to identify glare problems and to study space modifications to control it.

SPECULAR LIGHT PATTERNS

The sectional diagrams accompanying each set of photographs illustrate the modulator/storage combination being discussed.
The heavy dotted lines show standard standing and seated eye heights for adults; the diagonal, fine dotted lines indicate boundaries of the light path from louvers to ceiling storage. Hatched areas indicate conflict zones: single hatching, for areas with direct ray/specular glare from the louvers, and cross hatching for use conflicts with floor storage tiles. The diagonal lines outside the south glazing represent an external sunshading device which would be desirable to prevent summer overheating in those arrangements without a full-height solar modulator; this was not included in the model. In all observations and measurements, the sun, at around a 30 degree profile angle, was used as the light source.

The first variation (shown above) is also the most basic design, with a full-height solar modulator and the maximum amount of ceiling storage for that window height. The conflict zone extends about nine feet into the space from the window for a standing adult. The photos show typical light patterns on side walls and ceiling. The effects of the model louvers were undoubtedly not exactly analogous to that which would be produced by a full-
scale, precision manufactured modulator (the model louvers were reflective strips of adhesive-backed mylar stretched across the frame. The paper backing was not removed, resulting in a white louver underside. The viscosity of the adhesive allowed the louvers to be "formed" into a gross approximation of their real curvature.) The effect of the light patterns on the space was, to my perception, very strange. The nearest common analogy would be to the effects of water: either reflections on the walls of the space from a pool outside, or looking up through water; my first impression was that I was looking up into a giant tank of water with a sunlit surface and transparent underside. The effect was not unpleasant, but was very prominent indeed, from all angles of view. I have no way to evaluate how a person living with this effect would respond to it, at full scale and over a long time span, since it has no analogue to anything in my own experience. Photo (1) shows a severe potential problem, however. The extremely bright ceiling is the result of specular glare off the ceiling, caused by my failure to use a totally matte paint to represent the tiles. Compare the apparent ceiling luminance in this picture to that in (2) to gauge its effect. Although the contrast in the picture is exaggerated, the unlit ceiling portion to the left gives a rough basis for comparison to a "normal" situation with a dark ceiling.

One other effect needs to be discussed: the quality of view to the outside through the louvers. If photo (1) is carefully studied, it will be seen that in luminance, the visible louver
undersides are midway between the darkest and lightest parts of the scene. Thus the actual contrast of the louvers to the scene is low, on the average, and what is seen is not a straightforward case of framing glare. The "striping" of the view is irritating but not harsh, and the overall effect has elements of that produced when a fine muslin curtain is in front of a window. There is a "veiling" of the view from a sense of direct access, and the window plane is emphasized, reinforcing visually the dimensions of the room (making it seem smaller) and separating inside from outside. In the conflict zone, the combination of specular and ray glare from the upper louver surfaces is intolerable. The sun reflected nearly full-strength from a point below the eyes is more irritating than the direct sun from above, I am sure because the eye/brain is used to sunlight from above and "tunes it out" automatically to some degree. The glare is further aggravated by being spread out into brilliant parallel lines or stripes by the louver curvatures: the ultimate in framing glare.

The second diagram shows what would probably be a more common use of this system, with louvers above the line of sight only, although also with greatly reduced storage area.
Unobstructed view is nearly restored, the louver reflection effects are far less noticeable and insistent, the ceiling is mostly light and the whole room seems somewhat lighter. I say "somewhat" because a new effect is working to increase contrast and glare. The sun, now entering the space through the lower part of the window, produces a line of contrast between sun and shade which seems harsher than the louver pattern on the same wall in the first variation. The same applies to the direct light on the floor.
The third diagram has no corresponding photos; it is the same arrangement as above, but with latent storage on the floor to reduce sensible heat buildup during insolation:

This of course presents a use conflict, since a large rug or
grand piano on the tiles would cancel their benefit. However, as long as the use pattern in the room permitted the furnishings on the tiles to cover or shade only a fraction of their area, it would be of greater benefit to have them. The area paved with the tiles could also be a circulation area with no furnishings, although this is an arrangement probably more appropriate in an office context than a residential one.

The next two diagrams are the reverse of the above, with louvers below and clear glazing above:

Once again we have a severe conflict zone, and the utility of this arrangement is questionable in general, since to stand at the window and look out over the louvers would mean to be within
the conflict zone. The storage tiles would be set farther back in the room, which might mean a slightly better "coverage" of the room by radiant heat, depending on use patterns and the configuration of the space. This variation does permit one new observation. The relative brightness and quality of direct and louver-reflected sunlight can be accurately seen on the side wall, where the two light patterns cross each other.

The final variation is ostensibly designed to provide a "viewing slit" in the modulator for seated people:

The band of sunlight across the floor is very noticeable and irritating, "darkening" the surrounding floor by contrast (adaptation glare). This variation, as well as the previous one, allows view quality with and without louvers to be compared.

The final pair of photos are of the room with conventional window and white ceiling. It is instructive to compare these views to the first, full-louver variation. The full view has been obtained at the expense of adaptation glare around the window. This is controlled by the louvers in the first variation, but
at the expense of view and with the addition of the louver reflection patterns. The significance of this apparent conflict will be discussed at the end of this chapter.

ROOM GLARE MEASUREMENTS AND EVALUATIONS

The measurements of light levels within the test models I constructed were designed to roughly quantify only adaption glare factors. The measurements indicate the ratio of source to surround luminance - the ratio of a window's brightness to that of its surrounding walls. As the photographs have shown, the window was as wide and high as the modeled room itself. The following diagram shows the plan proportions of the space measured, which represented a room 20 feet wide, nine feet high, and 27 feet deep. The eight standard positions for the meter cell are also shown:

The meter positions in the "A" line were designed to read progressively greater proportions of surround luminance to source luminance, and those along the "B" line read surround luminance alone. "A" is down the center of the space, facing the south window; "B" is 3 feet away from the west wall and facing it.
Both sets of readings were taken at scale eye level for a standing adult. The basic assumption I made for these measurements was this: that the closer together the readings were, regardless of absolute light levels, the less adaptation glare there was likely to be; this of course was to be checked by observations. John Meyer\textsuperscript{16} gives a rule of thumb about the surround luminance/source luminance ratio: that for best control of adaptation glare, the ratio should be 10:1 or less.

Two major modifications were made to the space, with a set of readings for each modification: 1) the ceiling color was changed from tile color (dark green) to white, and a rear skylight was added:

The ceiling color variable was chosen to isolate the effect that the necessarily dark ceiling had upon glare conditions in the space. Meyer\textsuperscript{16} reported dramatic increases in adaptation glare with increasing room surface darkness; my own results involving the ceiling alone are less clear-cut, as will be seen.

After doing some experimentation with variously located additional natural light sources, I came to a conclusion similar
to Meyer's in his Saunders study: that a skylight along the rear wall of a space, as shown in the last drawing, was about the most effective way to even out the dropoff in natural light towards the "rear" of the space. This dropoff is a major cause of adaptation glare in a light-colored room. To quote Meyer about the function of such a skylight, "The room becomes a place in itself as opposed to an open-ended box dominated by a bright view." This was also my observation prior to taking measurements, particularly after studying the following less effective alternatives:

I chose the rear skylight for another reason indicated by Meyer: that if a skylight is too close to the south glazing, a glare-producing band of apparent darkness between the two is produced (Meyer calls this framing glare, but I would call it another case of adaptation glare).
All of the glare measurements were taken with the specular light source replaced by a diffuse source corresponding to an overcast day. For the measurements, a piece of heavy vellum tracing paper was placed over the south opening and skylight opening and illuminated by the sun, to roughly approximate a diffuse sky environment with no direct sunlight. The diffuse source eliminates the complex and transitory effects of specular sunlight, which would be very difficult to translate into reliable and repeatable measurements. My sheets of vellum are a crude approximation of the carefully calculated "standard sky" developed by the Building Research Station in England. The louvers were not changed as they were for the photographs; all measurements were made with all louvers in place.

Below are the graphs of the "A" line measurements:

![Graph 1](image1)

The "W" position is a meter reading made directly adjacent to the diffuse southern light source. The other readings are expressed as a percentage of this, because I had no "real" analogue to the model to calibrate my readings to. In any event, relative
levels are more important in analysis of most glare factors than absolute levels. 16

The "A" data do not closely reflect my own observations of the difference between skylight and non-skyllight conditions. With the skylight open, the entire room, not only the rear half, seemed to lighten up and lose the "one-ended" quality that it clearly had without it. The ceiling-color variable also had more of an effect than indicated, although a less dramatic one than the skylight. Without the dark ceiling, the south window seemed to be surrounded by a halo of light creating a smooth transition along the space from light window to dark rear. With both light ceiling and skylight, the space seemed brighter but with less perceived glare. The one exception was the view of the ceiling from the very rear of the model. In this case, the specular glare from the imperfectly matte tile paint, visible in the photos, tended to cancel out the difference, and although the dark ceiling was apparently made lighter by this effect, the light quality itself was unpleasant and uneven.

On the white-ceiling graph, the wide difference in readings between positions 1 and 3 is an anomaly; a small cloud in front of the sun is the most likely explanation, although the readings were repeated several times. For both non-skyllight readings, the slope change from 3 to 4 is caused by back reflection from the white rear wall onto walls and ceiling. It will be noticed
that the change is the same for both conditions, and thus cannot be caused by the light rear ceiling in the "tile" condition. The sharp luminance change from 3 to 4 in the skylight readings is caused by the meter picking up direct light from the skylight, and again does not represent the actual observed effect of the skylight on the whole room. At first, this set of readings seems irrelevant; they become more useful when seen in conjunction with the next set.

In these graphs of side-wall luminance the effect of the skylight is immediately obvious, and closely matches my observations. It appears that it is the side and rear walls which are doing most of the work of diffusion from the rear source. This makes sense, since the white rear ceiling, which is the surface (along with the dark floor) mostly read by the meter cell in the "A" series, cannot "see" this source. Note that the non-skylight readings closely parallel the "A" readings, though lower in luminance; the same slope change from 3 to 4 can be seen, confirming the reality of that change. The higher reading at 4 in the tile/skylight graph is another anomaly, but it strangely
reflects my subjective response: that in this condition, the rear seemed brighter than the front, possibly due to the more perfectly diffused, totally indirect light from the skylight, lacking the contrast between source and surround occurring around the south window.

From this data, it is possible to arrive at a few rules of thumb for designing a "light-space" around the solar-modulator system:

1) Skylights, especially rear ones, are always good.
2) Even without a skylight, a light-colored rear wall is desirable, particularly if no north windows exist in that wall.
3) The color of any non-tiled part of the ceiling to the rear of the tiled portion is non-critical. This surface is too far back in the space to help diffuse light from the south window, and cannot help diffuse light from a rear skylight as can side and rear walls. The two exceptions to this:
   a) if the storage area is small and ends close to the south window;  b) if north windows exist whose light could be diffused by the ceiling. In both of these cases, the ceiling should be as light as possible.

I would conclude this chapter by observing that in some ways this system is a new addition to architectural vocabulary, and that the true nature of the problems I have described, and the ways to solve them must wait to be defined fully until full-scale systems are built and lived with. There are really no existing lighting standards applicable directly to the conditions
produced by this system; strong reflected light on a dark ceiling is unheard of as a normal feature of built form, as are louvers of this type. This study is an indication of areas for further study, but at this point, that is all it is. Despite this qualification, I feel I can come to some conclusions about the solar modulator system, based on the criteria I discussed in the introduction.

Like all passive space-conditioning systems, this one is a consciously designed interaction of light and heat with built form and use. In my perhaps unreasonably demanding criteria for a successful passive system for houses, I stated in effect that my idea of "success" was an integration of light, heat and built form under the banner of use. The problem in this system with the conflict zones is obvious; it is a denial of one of the essential natures of a window: an opening which one can walk up to and look out of. This problem is reinforced by the louvers themselves, although they are no worse in this respect than a light-colored normal venetian blind. It is clearly obvious that opportunity exists to circumvent the louvers and provide for view, at the expense of storage area, but I am looking, perhaps somewhat unrealistically, for the avoidance of such conflicts to begin with.

My second objection is more subtle, and will have to wait for its real validity until full-scale, refined systems are built and lived with. It is that the strong lighting effects produced
by the solar modulator/tile interaction really have no meaning. If they could be made to be beautiful and welcome any time the winter sun is out, that would make these effects acceptable to me as a "useable" element of built form. I do not really feel that they are useable in that sense in my model at least, and if the functional, room-lighting aspects of these effects are not totally unpleasant, far more pleasant effects can be achieved by good window and wall placement, and by overall room configuration. The design balance seems, again subject to further research, to favor the heating aspects over the lighting and use aspects. I think (as should anyone) that the simplicity of the system is a tremendous virtue, and I also feel that it might not be at all hard to turn the presently somewhat ambiguous lighting effects into real benefits; indeed, it may happen effortlessly as the scale (and precision) of the system increase.

The final section of this chapter comprises a few design studies, which repeat the sectional diagrams in their basic modulator/storage configurations in the context of "real" regions of a house. The basic design determinant is the relationship of solar modulator to ceiling (or floor) storage tiles, which in the context of a house, develops a flat-roofed building form. The goal in the studies was to take advantage of the requirements of the system, as well as the need to provide unrestricted view and to avoid conflict zones, to develop a range of places with relevance to domestic uses and activities.
CHAPTER 4: THE "SOLAR ROOF" SYSTEM

This system is an attempt to integrate natural, diffuse lighting and solar heating into a compact configuration which does not conflict with use or view, and which (hopefully) adds pleasing and adjustable lighting qualities to a living space. The word "compact" must be immediately and strongly qualified, since the system is dependent on a pitched roof, and if a living area is to be exposed directly to the system it must incorporate or associate in some way with the roof, whether roof and space be large or small. It is compact in the sense that all functions—light aperture, light control, storage and transfer of heat to the space—are part of that roof plane:
The roof functions as a variable membrane, controlling energy flux into the space as does the solar modulator described in the last chapter. However, the idea of using such a system as a roof has fascinated me since first becoming aware of the work on variable membranes being done by Day Chahroudi, Sean Wellesley-Miller, Tim Johnson, and others. My main and real interest is in the kind of living space such a device would make possible; I liked my own imaginings and thus wanted to test them out. Three related features separate this design from other variable membrane designs I have seen. First is the incorporation of thermal storage into the membrane functions: the energy flux over time as well as space is thus controlled. Second is the degree of "play" between heating and lighting functions during the heating season. Third is the diffuse, non-specular quality of the light admitted into the living space. This diffuse
light (along with sensible heat gain) can be admitted or excluded, without greatly affecting latent heat gain in the roof storage system. The same light-control elements which seem an optional benefit in the winter become a necessity in the summer, shading the latent storage completely while still allowing some diffuse light into the space when needed. The thermal characteristics of this design will be described following an analysis of its lighting characteristics.

The basic module of the system is shown here:

The tile in this case is more accurately a plank, suspended horizontally in free space and not replacing a ceiling veneer in exact placement although it does in function. The tile dimensions are the "standard" 1 inch thick, by 16 inches wide, and of any length consistent with tile rigidity and the structural module of the roof; in the use of my model and drawings it is 4 feet. As will be seen, an advantage of this system lies in the specialization of the two available tile surfaces. The top
surface receives direct sun and is used as the solar absorber. It can be as black as possible with no effect on room lighting quality. The lower side receives reflected light from the louvers, and is used almost entirely for diffusing sunlight into the room; it can be any light color the user wants, since the infrared emissivity of light colored paints is the same as for dark.

The light-control louver is a panel 9 inches wide and as long as the tile. As presently designed it is flat in section and probably constructed at full scale of a lightweight sandwich material such as plastic-faced "foamcore" board; it is not dependent on precision in form for efficient function. Each louver is attached to its tile by hinges, and is held in angular position by a lightweight chain or other non-stretching linkage, leading up to either a manual or motorized pulley system. The louver control system could be as elaborate and automated as the owner is willing to pay for, but automation is not necessary for good performance. The following illustration shows a two-bay-wide assemblage of louvers and tiles beneath double heat-mirror glazing. The tiles in this representation are suspended from the rafters by a simple system of "U" brackets and adjustable rods. The tiles are slid in between channel brackets and are held in place by their own weight.

LIGHT CONTROL ACTION

The function of the louvers is not analogous to the solar modu-
lator. While their primary (and necessary) function is to shade the upper tile surfaces during non-heating periods, their secondary (and optional) function is to direct light upward to a light-diffusing surface, rather than the light-absorbing surface of the solar modulator design. The following light-path studies will clarify the interactions of louvers and tile surfaces for different louver positions and for four solar profile angles.

30 Degree profile angle: this represents a good design standard for the worst heating months (January and February) in latitudes of 40 degrees -45 degrees. 1) shows maximum insolation. The louvers are out of the light path by being parallel to it, and thus the ceiling is dark as seen from the space below, or more accurately, no diffused sunlight is visible. 2) shows the louvers reflecting light horizontally on to the north ceiling slope, or anything else in the light path. A slight amount of heating insolation is sacrificed around noon. 3) shows maximum reflected insolation on the tile undersides. Some heating insolation is sacrificed. If the louvers were left in this position all day, however, the sun would cover increasingly large absorption areas on either side of noon.

20 Degree profile angle: This angle represents an early morning/late evening condition during January and February. Two new possible conditions are shown. 1) shows light entering the living space directly, through the spaces between tiles which
30 DEGREE PROFILE ANGLE

(1)

(2)

(3)
20 DEGREE PROFILE ANGLE
70 DEGREE PROFILE ANGLE
the sun "sees" at this angle. In 2), this effect is controlled by the louvers, each of which diverts the light onto the white surface of the louver underside directly above.

45 Degree profile angle: This is a spring and fall average angle. Nothing new in lighting is shown here, but what can be noticed is the partial self-shading of the absorber surfaces, which act to balance the effect of sun angle. This increases the energy density falling on a surface the closer that angle is to vertical (normal), as expressed by the formula \( Q_\theta = Q_{\text{normal}} \times \cos \theta \), where \( Q_{\text{normal}} \) is the energy flux on a surface normal to it, and \( \theta \) is the true angle of the sun to the surface.

70 Degree profile angle: This is close to the summer solstice. The main purpose of the louvers in this situation is to completely shield the tiles from the sun. 1) shows this; the roof has become a mirror, with far more efficient shading qualities than a "normal" roof of any color. As the other studies show, the louvers can still be opened quite a bit without direct insolation on the absorber surface, but at the expense of some sensible heat gain.

LIGHTING MEASUREMENTS AND EVALUATIONS

The procedure for this system was somewhat different than for the solar modulator system, for reasons that will become evident. Modifications to the building envelope, to help even out the light distribution, were not made. A comparable set of
measurements to those done with the first model were done for purposes of comparison, and these will help to explain the lack of modifications.

The model was to the same scale as that for the solar modulator system, $1\frac{1}{2}"=1'-0"$, and defined a 20-foot wide, 24' deep space with a height to the eaves of 7 feet and to the inside ridge line of 16 feet. The whole south roof place was used for the system, and some tile/louver assemblies were removable. The tile undersides were painted a bright grayish-cream color with about a 10% absorptivity, under the assumption (possibly wrong) that most people would not want a dead-white ceiling; in any event, I neglected to paint the north ceiling slope, and it remained white.

The first group of measurements I made were only indirectly concerned with room lighting quality. An important question in evaluating the real utility of this system as a controllable natural light source is how critical the louver adjustments are to obtain a particular lighting quality, and conversely, how sensitive a particular setting is to the normal hourly changes in sun angle. In short, how much fooling around a user might have to do, in the course of a day, to get satisfactory natural lighting from the roof. To gain a sense of the dynamics of the louver-adjustment effects, and to indicate directions for improvement if needed, a series of 33 light readings, of 2-degree lower adjustment increments, were made for 20 degree...
degree profile angles. The results are shown in the graph on the next page. The luminance figures are in footcandles, not necessarily useable as absolute values, and the louver positions are in degrees relative to the horizontal, with minus figures indicating a louver sloping down from its hinge, and plus sloping up. The horizontal solid and dotted lines indicate the light paths for each louver position, and this can be referred back to the light path diagrams to see what is going on. A light-level reference is provided by the 34–44 degrees lower positions on the solid line. 34 Degrees represents full insolation on the absorber surfaces, but no reflected light at all in the room. The louver position is that of 30 degrees no. (1). The readings were taken with the meter cell facing upwards from the floor of the space, in the center, and with no openings other than the roof. (The minimum readings are as high as they are in part because the model was not fully light-tight in areas other than the roof, and also because light leaked a bit between the tile ends, which would not happen in reality.) The main message the graphed data convey is that as designed, the louver adjustments are indeed sensitive and critical, particularly from -4 degrees through +14 degrees; 18 degrees out of a total 64 degrees measured adjustment range.

The following photographs give clues to the reasons for this. The pictures show a sequence of louver positions from "light on louver undersides" to "light reflected on north roof." Momentarily disregarding qualitative evaluations, it will be seen
on the second and third photographs that a sharp line divides lit from unlit portions of the tile undersides, and in the fourth and fifth, the reflected light on the roof is in the form of very brilliant and glary bars of light. One of the first subjects for further research with this system would be to test a wide range of alternative reflective louver surfaces: texturing of the silvered surface to scatter the reflected light to a controlled degree, to possibly approximate the "ideal" curve on the graph. Louver adjustment would be less critical, and lighting quality (as will be seen) would improve.

My observations are in some disagreement with the quality of the photographs. The contrast in the pictures is far higher than the reality; at no time did the tile undersides appear as dark as they do here. The contrast between lit and unlit portions of the tile undersides was the harshest aspect of the lighting, in effect a form of framing glare, but was nowhere near as terrible as it appears in the pictures. However, the last two photos of this series do accurately represent my impressions. Two louver positions seemed the most pleasing to me. The first photo, of light reflected to the louver undersides, shows to some degree the gradation of light across each row of tiles which is caused by secondary reflections from the lighted louvers. However, the ceiling was not the slate gray shade appearing in the picture. The ceiling in this mode is really quite beautiful to look at, with a mysterious quality reminiscent of light filtering through dense foliage. The fourth photo
shows the other most pleasing condition: the tile undersides are very bright in this condition — perhaps too bright for comfort. Again, a diffusing texture on the reflectors would reduce the concentration of light per unit of surface. The dappled appearance of the reflections, which is itself very unpleasant, would probably become less prominent or even disappear with an increase in scale, and might also be controlled by a textured reflector surface. In this situation, it is a strange experience to see bright light completely covering a surface and not hitting any other surface at the same time. The brain apparently needs to compare luminance on more than one type or angle of surface in order to gauge the "true" surface brightness of what is seen. I found my eyes playing strange tricks as I looked at the tiles fully illuminated. I could convince myself that the tiles themselves were the light source, as in a luminous flourescent ceiling, although the spectral quality was totally different. The moment any unlit tile surface appeared, as in the second or third pictures, this effect vanished. It was in no way unpleasant, but only slightly disorienting when I consciously looked for it. It had no relation to glare or any other problems of light balance.

Up to now, I have been looking at the roof and not the whole room. Aside from the louver positions which direct light onto other room surfaces, the general lighting effect was delightful. A very even illumination was produced, so even that in a small house, one would almost certainly want to modulate it by changes
in room surface color, or by designing deliberately shadowy places in the house as an enriching contrast. Watching the room illumination rise and fall with louver changes, or when a cloud passed in front of the sun, was an exciting experience. While this could become annoying in some weather conditions, it would always be possible to control, by louver position, the degree of connection with the "light-world" outside. There is also a seasonal variation in the amount of light admitted by the louvers. In the summer, the roof would be "shady" most of the time, as in the first photo. If more light were needed, the attendant sensible heat gain could probably be controlled by well-placed ventilation openings, possibly like those in the drawings at the end of the chapter, as long as the black absorber surfaces remained in the shade. Light-path diagrams (2) and (3) for 70 degree profile angle illustrate this.

While designing this system, I assumed that it would be possible to view through the tiles and roof glazing to the outside. As it turned out, however, I could not have designed a worse combination of specular and framing glare. The next photograph shows this glare under insolation conditions, with the louvers reflecting onto the tile undersides. The second photo shows a cloudy day simulation with tracing paper over the roof opening. The cloudy day condition is more pleasant, because the specular glare has been greatly reduced, although the framing glare in undiminished or even slightly increased. On the following page, the first diagram shows the angular zones of discomfort produced.
The mechanisms producing the specular glare are shown here:

Partly, this was caused (once again) by not having a completely matte surface on the tiles, but it is questionable whether a perfectly matte surface would survive the handling necessary to install the tiles. The following tile section shows a possible way of designing the tile surface to control specular glare.
The "virtual surface" seen by the eye would be tilted away from the line of sight at a minimum of 30 degrees on the top surface. The bottom, light-colored surface has a "softer" pattern appropriate to the need to diffuse visible light evenly into the room. The framing glare components, however, are essentially uncontrollable, since there is no way to avoid interrupting the view with contrasting and repetitive bands. This defect of the system need not rigidly determine its placement; as the next photos show, view openings can be provided by removing a few tiles.

It is still possible to create glare-producing situations with this design. To start with, the following drawings illustrate some alternatives for placing the solar roof system into a roof plane, assuming that it need not occupy the whole of that plane:
A rule of thumb is to avoid opaque surfaces in the same plane as the solar roof, particularly interrupting bands such as those in (4) and (5). The next pictures show what happens in that situation. Both the gable wall and the seemingly black band are white. The band is a board in the same plane as the tiles, as in (5). This is a classic case of adaptation glare. The gable wall, at right angles to the solar roof, acts as a "light box," creating a transition zone of a luminance between the roof and the rest of the room; the masking band cannot "see" the roof light and thus has no chance to do so. The following drawings are modifications to the first group, namely (5) and (6), and their important feature is the reveal around the solar roof sections:
I suspect, however, that as long as situations such as that in the photographs are avoided, such elaborate roof framing could remain optional, since the essential and dominant light quality in the living space would be highly even and diffuse.

Just how even and diffuse is indicated by these measurements, which were made as directly comparable to those for the solar modulator system as possible. In addition to light from the roof, a diffusing vellum sheet was placed over a full-width, full-height, south-facing window below the solar roof:
What is immediately clear is that the solar roof is only partly responsible for the even light quality in the space. In the "light on louver undersides" condition the roof is introducing little light of its own into the space, and yet the slope of this graph is identical to the others. What is doing most of the diffusing work is the white north ceiling slope, which over its whole surface is exposed to direct light from the window. In retrospect, I would have liked to darken this roof plane and take another set of readings to isolate its effect more accurately. The closeness of the readings is initially surprising, since my own impressions were quite different. However, the
south window was the dominant light source for the meter cell, and the roof played less a role for it than it did for my own eyes, observing the entire space. The first graph, of louver positions vs. luminance, which was made with the meter cell facing up into the space, corresponded more closely to my observations.

THERMAL CONSIDERATIONS

Since the function of the solar roof, as with any climate-control system, is to maintain the thermal conditions in a living space within the comfort zone, it is important to identify the contributions to sensible heat control provided by the system.

The analysis of heat flow into the living space, at night under steady-state conditions, can be structured around the two formulae provided in the first chapter, which will now be resurrected:

\[
T_{\text{ROOM}} = \frac{(A_{\text{WS}} \cdot U_{\text{WS}} \cdot T_{\text{AMBIENT}}) + (A_{\text{STOR}} \cdot U_{\text{STOR}} \cdot T_{\text{CORE}})}{(A_{\text{WS}} \cdot U_{\text{WS}}) + (A_{\text{STOR}} \cdot U_{\text{STOR}})}
\]

and

\[
\text{CARRYOVER TIME} = 300 \div \left( \frac{1}{R_{\text{STOR}} + \frac{R_{\text{WS}}}{A_{\text{WS}}} \times \Delta T} \right)
\]

Using these two formulae, I constructed the table on the next page, which shows room temperature and carryover times for nighttime on cloudy, steady-state conditions at five ambient temperatures and ten weatherskin/storage ratios. The table is an attempt to answer the very pragmatic questions that any architect actually designing with this system would have to ask: "What do I get for how much of this system, under what conditions of climate, and for how long?" The table does not include the effects of stored
<table>
<thead>
<tr>
<th>RATIO</th>
<th>TIENT 20°F</th>
<th>TIENT 25°F</th>
<th>TIENT 30°F</th>
<th>TIENT 35°F</th>
<th>TIENT 40°F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ROOM</td>
<td>CARRYOVER</td>
<td>ROOM</td>
<td>CARRYOVER</td>
<td>ROOM</td>
</tr>
<tr>
<td>1.5:1</td>
<td>70.2</td>
<td>44.4 hrs.</td>
<td>70.6</td>
<td>49.0 hrs.</td>
<td>71.0</td>
</tr>
<tr>
<td>2:1</td>
<td>69.1</td>
<td>33.3</td>
<td>69.5</td>
<td>36.7</td>
<td>70.0</td>
</tr>
<tr>
<td>2.5:1</td>
<td>68.0</td>
<td>26.7</td>
<td>68.5</td>
<td>29.4</td>
<td>69.1</td>
</tr>
<tr>
<td>3:1</td>
<td>67.0</td>
<td>23.0</td>
<td>67.6</td>
<td>25.3</td>
<td>68.2</td>
</tr>
<tr>
<td>3.5:1</td>
<td>65.9</td>
<td>20.8</td>
<td>66.7</td>
<td>23.0</td>
<td>67.4</td>
</tr>
<tr>
<td>4:1</td>
<td>64.9</td>
<td>18.5</td>
<td>65.8</td>
<td>20.4</td>
<td>66.6</td>
</tr>
<tr>
<td>4.5:1</td>
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<td>16.7</td>
<td>64.9</td>
<td>18.4</td>
<td>65.9</td>
</tr>
<tr>
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<td>63.1</td>
<td>15.5</td>
<td>64.1</td>
<td>17.1</td>
<td>65.1</td>
</tr>
<tr>
<td>5.5:1</td>
<td>62.2</td>
<td>14.8</td>
<td>63.3</td>
<td>16.3</td>
<td>64.4</td>
</tr>
<tr>
<td>6:1</td>
<td>61.4</td>
<td>13.3</td>
<td>62.6</td>
<td>14.7</td>
<td>63.8</td>
</tr>
</tbody>
</table>

![Graph 1](image1.png)

![Graph 2](image2.png)

![Graph 3](image3.png)
sensible heat in room masonry, which would increase the $T_{room}$ figures to an extent dependent on the factors outlined in Chapter 2. In other words, these figures are "worst-case" in that no help for the latent storage tiles is included. The values for $A_{weatherskin}$ and $U_{weatherskin}$ in the first formula were obtained by dimensioning a "model space" of a square plan with a gable roof, 33' by 33' by 8' to the eaves and 24' to the ridge line. Glazing area included the roof aperture, a very large 10' by 30', and 360 square feet of other glazing, for a total of 840 square feet of double heat-mirror glass with a $U$ value of .22. The rest of the weatherskin was 3135 square feet with a $U$ value of .025, for a combined $U$ value of .066 for conductive losses only. Infiltrative losses, calculated for the enclosed volume of 17,424 cubic feet at 1/2 air change per hour, raised this effective figure to .11, for a total weatherskin area of 3975 square feet, which were the values used in the formula.

One other value needs discussion: that of $U_{storage}$. The following equation defines it:

$$U_{storage} = \frac{1}{U_{concrete} + U_{skin cond.}}$$

$U_{concrete}$ is fixed; for 1/4 inch of polyester concrete, the value is 16. The variable is skin conductance, which is dependent on environmental conditions controlling the rate of conductive and radiative heat transfer to the living space. For the solar modulator design, the $U$ value for conductive transfer is .5, that for radiative transfer, 1. When this combined $U$ value of
1.5 is put into the equation, the $U_{\text{storage}}$ figure is 1.37. The value for convective transfer is dependent on the rate of air flow, through forced air movement (a fan, or simply people moving around combined with the normal air change rate and convection patterns from appliances, etc.) or natural convection, which cannot occur in the solar modulator system, since the heat source is above the entire air mass. The value for radiative transfer is dependent upon how much surface area in the living space the tile can "see" which is of a lower temperature than the tile surface itself. In the solar modulator system, there are no direct obstructions to radiative transfer over one side of the storage tiles. The case of the solar roof is quite different.

The diagram indicates that the proportions of radiative and convective transfer are not the same (for the sake of clarity, heat loss from tiles through the heat mirror to outside is not
shown). The convective transfer is higher, since the tiles are in free space and air can convect around them; the $U$ value is now around 2.0 for both surfaces, .5 for the lower surface and 1.5 for the upper surface. The radiative transfer is lower than for the modulator system, since the tiles can only "see" a lower temperature region (the living space) over less than half their surface; the rest sees either the heat mirror, another tile surface, or the non-conducting louver surfaces. The total $U$ value for radiative heat transfer is .5—half the value of the solar modulator system. The total $U$ value for the solar roof system is 2.5, which when put into the equation gives a $U_{\text{storage}}$ value of 2.16. In practice, this means a slightly higher room temperature and a slightly reduced carryover time.

Another factor useful to the designer is a rough idea of the time it would take to fully charge a tile with heat energy. For a 30 degree sun angle, and assuming that half the incident energy goes into latent storage, that figure would be around 5 hours for full sunlight, depending somewhat upon louver position.

In the second chapter, I discussed the desirability of a large amount of heat-absorptive yet light-reflective surfaces in a living space, to prevent sensible heat buildup during insolation. The solar roof system has a built-in capacity to provide this sort of diffusion for its own natural light contribution. The tile undersides are light-colored, and backed by masonry and
latent heat storage. The highly diffuse light output from the roof would lessen the need for view windows to provide the direct sunlight for room lighting purposes, while at the same time reducing the need for large areas of light-colored walls. This last, however, must be qualified by the glare-control factors discussed previously. The solar roof can control the proportion of sensible to latent heat gain in the room to a limited extent. When the louvers are parallel to the light path, all light falls on the absorber surfaces of the tiles, of which about half is converted into latent heat, as described in chapter 1:

\[ \text{LATENT} \]
\[ \text{SENSIBLE} \]

When the louvers intercept a portion of the light path, their output eventually goes almost entirely into sensible gain:

\[ \text{LATENT} \]
\[ \text{SENSIBLE} \]

As indicated, I have not modeled the effect that this sensible gain would have on day or night room temperatures.

To conclude this chapter, I would reiterate my comments at the
end of the last one about the need to build and live with full-scale versions of this design in order to evaluate it accurately. To some degree, the comments I made about the light effects from the solar modulator apply here also: that in some ways it is a new kind of light source, with no precedent available for a standard of comparison. However, I think that the kind of light produced by this system, together with its effects upon a living space, are closer to some existing situations than is true for the solar modulator system. Precedents exist for large diffuse natural light sources in the "light scoops" designed for many houses, museums, libraries, etc., or in the large frosted-glass skylights used in industrial buildings or artists' studios. The acceptability of the system in the lighting context would be largely dependent on how much a person likes the kind of light-space it produces, with its variations produced by changes in outside light conditions and seasons, always leaving in mind the greater control of light levels and quality possible with the solar roof. My drawings at the end of the chapter put the system in one possible context. They illustrate the fact that there would normally be a range of lighting conditions in a house. Rooms not exposed directly to the latent storage tiles could receive air circulated from them by natural convection or low-velocity forced air.

The real potential of solar membranes such as this one, however, seems to lie in a somewhat different context, and it is this which I mainly had in mind when developing the design. In the
"bioshelter" concepts of Day Chahroudi, the New Alchemy Institute and others, shelter design is used as a tool to allow a greater connection to grow, on many levels, between people and natural systems. It is this direction which interests me most about the future of architecture. The solar roof is really designed as a part of this context. Part of the language of bioshelter architecture seems to me to ideally consist of building skins which allow various kinds of energy—heat, light and wind—to enter where needed, in the simplest possible way. The solar roof design, with its inherent flexibility in the placement of storage tiles, would allow one basic type of south-facing construction to perform different roles in different parts of a house. In a greenhouse context, the heat-mirror roof glazing might have no storage tiles to intercept the sun; some latent or sensible heat storage, if needed, might be located in the floor, rear walls or use surfaces. In living spaces, the tiles and louvers would diffuse the light and narrow the diurnal temperature saving, while still allowing a large number of plant forms to be happy. Any in-between combination of clear roof and tiles would also be possible, as long as sensible heat gain was kept within the desired limits. This modular flexibility of the solar roof is to my mind one of its strongest points, although just how great the range of possibilities really would be practical in a use context of course remains to be seen.
BIBLIOGRAPHY AND REFERENCES

ENERGY


LIGHT


CLIMATE


HUMAN USE DIMENSIONS


SOCIAL AND DESIGN CONTEXTS


