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PASSIVE SOLAR DESIGN HANDBOOK - VOLUME ONE OF TWO VOLUMES: PASSIVE SOLAR DESIGN CONCEPTS

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Passive Solar Design Handbook

Volume One of Two Volumes:
Passive Solar Design Concepts

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PASSIVE SOLAR DESIGN CONCEPTS

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Foreword

The DOE Passive Solar Design Handbook was conceived several years ago. Writing began shortly before the March 1978 Second National Passive Conference in Philadelphia. The original five-month project expanded to two years as the solar team headed by J. Douglas Balcomb at Los Alamos Scientific Laboratories labored to ensure that the technical data would be current, accurate, and useful.

The original concept called for a single volume, the first section written by me and the second by Doug and his staff. The eventual large sizes and disparate nature of the two sections resulted in two volumes: Volume One: Passive Solar Design Concepts, and Volume Two: Passive Solar Design Analysis. Together, the two volumes comprise the DOE Passive Solar Design Handbook. As the titles imply, Concepts is an introduction to passive. For the most part, the information is qualitative and is written for the uninitiated. Analysis is quantitative and written for the architect, engineer, and researcher.

Passive solar offers an unprecedented opportunity to address the pressing energy needs of our country's energy stock. Combined with energy conservation, active solar, and other energy options, passive solar is an important ingredient in reducing building energy consumption. In some cases, it will provide the major means of reducing consumption of conventional fuels. In other cases, it will play a minor role but will act as a catalyst for incorporating other, low-energy practices. Passive Solar Design Concepts is dedicated to enriching passive's role in our energy futures.

Bruce Anderson
December 1979

CHAPTER A

BACKGROUND TO PASSIVE SOLAR BUILDING DESIGN

A. BACKGROUND TO PASSIVE SOLAR BUILDING DESIGN

A.1 DEFINITION OF PASSIVE SOLAR

A formal definition of passive solar design is the following:

> Passive solar designs are methods for heating or cooling buildings or for heating domestic water in which thermal energy flows by natural means (i.e., without pumps or fans).

Thermal energy transfer into and out of buildings, into and out of thermal energy storage, and around and through a conditioned space occurs naturally — through conduction, convection, and radiation (see section A.3).

This definition differs from a common perception of solar heating and cooling systems. It is often assumed that using solar energy requires an assemblage of components that includes an array of collectors, a thermal energy storage system, and two thermal energy transport systems — one between the collector and storage, and another between storage and the heated or cooled building. Both transport systems ordinarily use pumps or fans. Further, the components are usually attached to or installed in a building without greatly affecting the building's architectural fabric (roof, walls, floor, etc.). These systems are often termed "active" because of the moving parts and power requirements of the fans and pumps.

These narrow definitions of passive and active systems tend to exclude techniques that combine natural thermal energy flow with mechanically-powered energy flow. For example, a fan added to a passive system may improve the energy transfer or provide an additional level of control over the amount and time of such transfer. Because they fit neither definition, such systems are sometimes called "hybrid." (Some people reserve the use of the term "hybrid" for buildings that have both an active and a passive system.)

Similarly, the term passive may overlap with some energy conservation definitions. Energy conservation in buildings is usually perceived as reducing energy consumption, whether the conserved energy is renewable (e.g., solar) or nonrenewable (e.g., fossil fuel). Although solar energy systems can reduce consumption of fossil fuels, they are not generally regarded as energy conservation since they don't necessarily reduce the building's total energy use. Therefore, many simple techniques, such as combining south-facing glass and thermal mass, are usually not considered energy conservation measures. On the other hand, some passive solar designs can also be regarded as energy conservation.

Passive may also exclude other natural energy uses not usually considered energy conservation measures. For example, wood heating and natural ventilation are neither energy conservation nor passive solar design as commonly defined, although the latter two are discussed briefly in Chapter D.

Thus, although a great deal of overlap is unavoidable, a range of techniques for reducing a building's consumption of nonrenewable energy might look as follows:

Energy Conservation Techniques ● Natural Energy Features ● Passive Solar Design ● Hybrid Solar Systems ● Active Solar Systems

In general, energy conservation techniques tend to be the simplest and least costly of the five categories. Active systems tend to be the most complex and expensive.

This Handbook addresses passive solar design. Passive's cost and complexity generally fall somewhere between energy conservation techniques and active solar systems. However, the proper semantic cataloging of these techniques is unimportant compared with the concepts they try to communicate. With good cause, the above terms may not be adopted universally. But as our understanding and use of these techniques evolve, so also will our vocabulary for communicating them.

In fact, the cataloging of passive techniques is also fraught with ambiguity. The method used in this Handbook combines simplicity with comprehensiveness. Dozens of variations and permutations fall within the five basic passive heating system types described. Sometimes they fit neatly and sometimes they fit only through the use of a giant shoehorn. This great variety and diversity of passive system types, although making it diffcult to catalog them neatly, is also an advantage: there are many approaches from which to select one that is most appropriate for a particular climate, site, and building type. Although this variety gives passive versatility, wise decision-making requires more than just a passing interest in the subject. Analyzing, predicting, and evaluating passive's thermal and economic performance is a complex task. Fortunately, however, passive solar designs usually apply simple concepts and are easy to build. Also, the performance of most passive systems is stable despite many design variations.

A.2 ADVANTAGES AND DISADVANTAGES

When compared with active systems, passive solar designs (direct gain, convective loops, thermal storage walls and roofs, and attached sunspacea) have both advantages and disadvantages. Most advantages stem from the inherent simplicity of passive systems; this simplicity generally results in greater reliability, lower costs, and longer lifetimes. Most of the disadvantages are related to "market acceptability" by homebuyers and the building industry.

Since passive systems have few (or no) moving parts and usually employ conventional building materials, their performance is reliable.

Windows and walls perform their solar task effortlessly and quietly without mechanical or electrical commands or requirements. Generally, there are no wearing surfaces or need for lubrication. If any external control is required (e.g., of shutters), it is usually a simple task performed by the occupant. Using conventional building materials such as glass, concrete, and brick involves well-known construction techniques, and these materials are generally long-lasting.

Simplicity, low initial costs of conventional materials, low maintenance costs, and long lifetimes all contribute to the cost-effectiveness of well-designed passive systems. But perhaps the most significant reason for passive's cost-effectivness is the long lifetime. For the life of the building, a passive system should continually maintain, if not improve, its value in at least equal proportion to the rest of the building. It should require no more maintenance than any other wall or roof. This is particularly true when the passive system fulfills the dual role of admitting solar energy and forming an integral part of the building's surface and structure.

While simplicity lowers the capital cost (no motorized dampers, automatic valves, sophisticated control systems, or high-technology details or materials), a further consequence of this simplicity is the relative lack of legal barriers and certification requirements. Although there may be some new materials developed for passive that will require certification, certification procedures have already been established for the standard construction materials used in normal applications.

Another advantage of passive is that, since it can be applied even in small amounts, the initial involvement can be a relatively small step requiring a small risk. Thus, individuals can gain real experience with passive before making a larger commitment; if a design mistake is made, it can be recognized and corrected with minimal loss.

From the viewpoint of society as a whole, passive solar offers many benefits. The most obvious is a savings of fossil fuels, which helps the economy and preserves these resources for their optimum applications. The economy profits both by reducing the balance of payments deficit and freeing capital from fossil fuel expenditures for better uses. The decrease in fossil fuel use also has a beneficial environmental impact. After installation, solar heating and cooling requires few, if any, transmission lines, pipe lines, or strip mines; it produces no dangerous radioactive wastes and no polluted air or water. Solar systems have few negative impacts since they use materials that are renewable and can be recycled. Passive solar promises to favorably impact employment since it generally requires additional construction labor and materials.

Potential difficulties of occupant interaction with passive systems are sometimes regarded as a disadvantage. For optimum performance, some passive systems require daily moving of shutters or vents.

To some people this is an imposition; others find it not only tolerable but actually a pleasant way of growing closer to their environment.

Many feel that the radiant heating from large surfaces, characteristic of most passive systems, is more comfortable than conventional heating methods, which usually heat the air first. A frequent characterization of some passive designs is wide temperature swings; however, in well-designed systems these swings are small, generally on the order of 5 F. Nevertheless, some people enjoy excessively warm room temperatures during the cold winter and feel that wide temperature fluctuations are not undesirable.

Almost all passive systems require more occupant awareness of the environment than active systems do, but experience has shown that residents usually enjoy their passive homes.

It is difficult to incorporate passive solar design without significantly affecting the building's appearance, which, in turn, affects the willingness of builders to build it or buyers to purchase it. However, if the building has low heating or cooling loads, or if passive solar is designed to provide only a small fraction of the loads, the passive system will have a small surface area and, therefore, only a small effect on the building's appearance.

The primary disadvantage of passive design is that in most cases, but not all, it increases construction cost. To achieve a large solar fraction (i.e., a large decrease in conventional fuel bills) the cost can approach that of active systems. However, the financial risk can be limited by building only a small system (perhaps as little as 75 square feet of convective loop collector).

A.3 SOME PASSIVE DESIGN BUILDING BLOCKS

Building elements (such as glass) and thermal processes (such as conduction) are combined in various ways in passive designs. Familiarity with these "building blocks" will enable the designer to make decisions for each particular design project. In addition, the designer can vary these tools to suit the particular needs of a project. Such needs differ and are most affected by the site, the climate, and the purpose of and activities within the building. These variations in turn affect the choice of the passive design. The following brief, introductory descriptions will provide a foundation for their use throughout this Handbook.

Building Elements

Insulation

Insulation is a material with a high resistance to heat flow. It is used to reduce conductive heat loss from buildings in cold climates and to reduce heat gains in warm climates. Movable insulation retards energy flows through windows, e.g., at night when the sun isn't shining.

Glazing

Glazing is a material that is highly transparent to solar irradiation. It is used to admit and trap solar heat. Glazing, usually glass or plastic, is an essential element in most passive designs.

As windows, glazing can be both solar collectors and sources of light. Window design and orientation are extremely important. Windows facing south receive maximum winter gains and have minimal summer gains. Glazing covers such building elements as metal or masonry walls, converting them to "solar collectors." Larger spaces between the glazing and the building can be used successfully as greenhouses or other sunspaces.

Shading

Keeping the sun off the building and off the windows at appropriate times of the year is essential for keeping the building cool. Shading mechanisms include vegetation, portions of the building itself, auxiliary devices such as overhangs, and insulation in the form of drapes that shade and shutters that insulate.

Reflectors

Reflectors increase the amount of solar radiation striking a surface or entering through a window. Movable reflectors can also be positioned to shade a building during the summer.

Thermal Mass

Heavy materials within buildings, such as concrete, stone, and water, aid in the storage of thermal energy for both heating and cooling. They can temper and time delay the effects of fluctuating inputs of energy, such as solar. For example, during the cooling season, they absorb excess daytime heat to keep the building from overheating.

Heat-of-fusion (or phase-change) materials store heat when they melt and release the heat when they re-solidify. They require smaller mass and volume to store the same amount of thermal energy as the more conventional heat storage materials, such as concrete. They also store heat with little or no change in temperature.

Thermal Processes

Thermal Radiation

Thermal radiation is a major energy transfer means inside a building. This radiation is similar to light, but it has such a long wavelength that it is not visible. It is easily sensed as a "warm feeling," expecially by the back of the hand or face, and it is especially pronounced near warm objects such as a hot stove pipe or wall. Thermal radiation is absorbed at the surface of non-reflective objects; this warms the surface which then transfers energy by conduction (see below) to the interior mass. The energy is released from the thermal mass back to the heated space by radiation and convection.

People interact thermally by radiation with the surfaces of walls, ceilings, floors, and other surfaces. This radiant exchange is fully as important to a person's perception of comfort as is the air temperature, and it can be used to maintain comfort when air temperatures are at uncomfortably low levels.

Natural Convection

Natural convection is air movement resulting from differing temperatures of adjacent masses of air. It is used to transport thermal energy, without fans, from one location to another. This is most easily accomplished when the warmest location and source of heat is lower in elevation than cooler locations requiring heat.

Conduction

Conduction is the transfer of thermal energy through materials, from the warmest spot to the coolest spot. The larger the temperature difference, the faster is the energy movement.

Air Stratification

Warm air rises to high points within a building because it is lighter and more buoyant than cooler air. Air stratification is usually undesirable in the winter. However, stratified warm air can be transported to other parts of the building or to the heat storage. During the summer, the warm air can be vented, inducing natural ventilation through the building and reducing the need for air conditioning.

Evaporation

When water and air are in contact and the relative humidity of the air is less than 100 percent, water will evaporate. The energy required to evaporate the water reduces the air temperature. The added moisture raises the humidity.

This cooling process is the principle behind the evaporative coolers used primarily in the southwestern United States. There, the cooler, more humid air is more comfortable than the ambient warmer, dryer air. Evaporative cooling is not as effective in humid climates because the air is already moisture-laden. Dehumidification is usually more effective in such climates.

Thermosiphoning (Thermocirculation)

Fluids (liquids or air) become lighter and hence more buoyant as they are heated. As in a chimney when heated air rises, cool air enters to replace it; this motive force can be used to circulate heated air or liquid from a collector to storage or to the living space. When the air or liquid flows in this continuous, somewhat circular loop, it is said to thermosiphon.

The passive designer need not necessarily experiment with new combinations of the above design building blocks. Although passive solar design is in a somewhat embryonic stage, many designs were developed long ago and are used widely today.

A.4 FIVE BASIC SYSTEM TYPES

A.4.a Brief Descriptions

Passive solar designs can be categorized in diverse ways. Also, as noted earlier, overlap is inevitable. The approach used here is to describe five physically identifiable methods:

1. Direct Gain
2. Convective Loops
3. Thermal Storage Walls
4. Thermal Storage Roofs
5. Attached Sunspaces

The physical images that these five methods evoke help to simplify the task of communicating passive to millions of people. At the same time, this categorization system is sufficiently flexible to permit innovation.

A more general categorization, which is generic rather than physical, is to classify passive concepts according to the following:

a. Direct Gain

b. Indirect Gain

c. Isolated Gain

The direct gain category is the same in both classification schemes. The other four physical categories are either indirect or isolated, depending on whether the thermal storage mass is in direct thermal contact with theheated space or is thermally isolated (by either distance or insulation).

The following brief descriptions will introduce the designer to the basic components of these five system types. They are discussed in detail in Chapters C1 through C5.

A.4.a.l Direct Gain (Figure A-1)

Direct gain systems use solar radiation that enters through glass or plastic directly into the space to be heated. Nearly all of the solar radiation entering the rocm is immediately converted to heat. Thermal mass for storing excess solar heat is most effective when located with direct exposure to the sunlight (as in a concrete floor). To reduce heat loss and, therefore, to increase overall thermal performance, insulation may be applied at night to the glass, either inside or outside. During the heating season, south-facing glass takes advantage of the sun's low position in the sky; in the summer when the sun is high in the sky, the glass is shaded by overhangs, awnings, or trees.

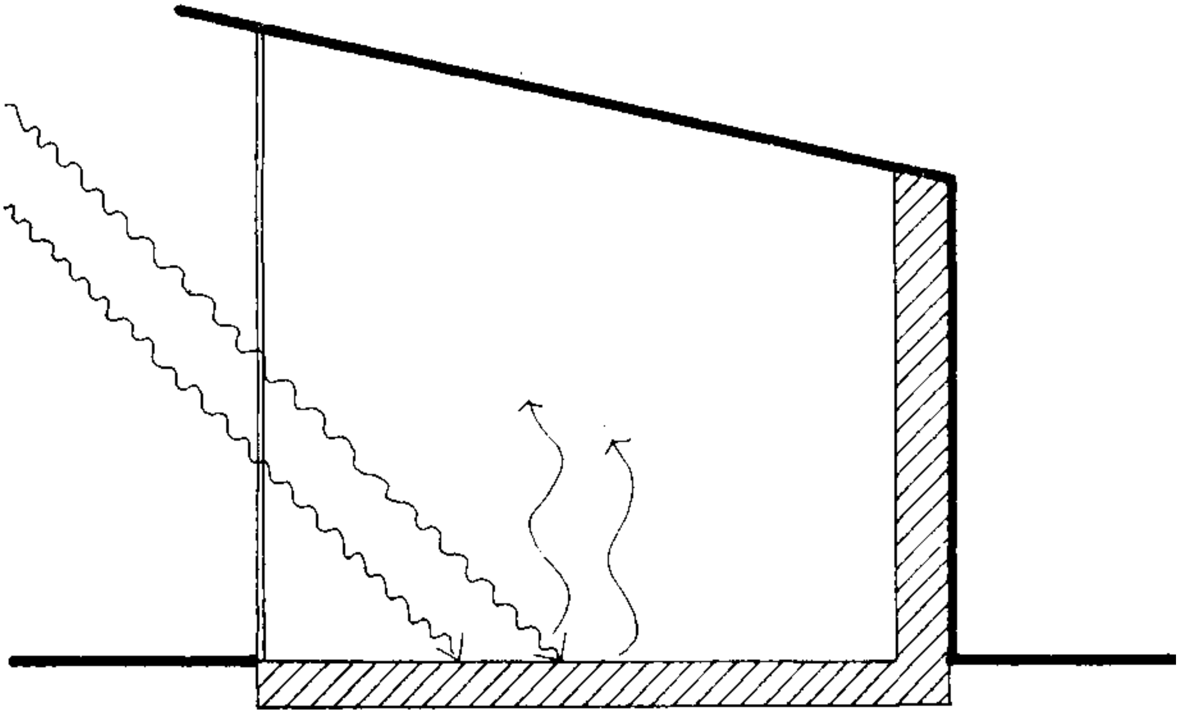


Figure A-l: Direct gain (HON).

A.4.a.2 Convective Loops (Figure A-2)

As a fluid increases in temperature, its density decreases and it becomes more buoyant than a cooler fluid. The result is that a warm fluid tends to rise as it is warmed, and a cooler fluid moves downward to take its place. Thermocirculation is a natural convective loop that permits a fluid heated by an absorbing surface to rise either directly to the space to be heated or to a thermal storage container elevated above the absorber. Cooler fluid is drawn from the room (or from thermal storage) to the collector, replacing the warm, rising fluid.

Figure A-2 illustrates the simplest form of a convective loop air collector. As the air in the space between the glass and the blackened absorber surface is heated, it expands and becomes lighter, rises through the collector, and flows into the room through a vent at the top. Cooled room air, drawn into the collector through another vent at the base of the wall, replaces the warmed air leaving the collector. It, too, is heated and subsequently expelled from the top of the collector into the room. This process continues as long as there is enough solar radiation to raise the temperature of the collector above the temperature of the room.

In these systems, reverse thermocirculation should be prevented at night. Reverse thermocirculation occurs when the blackened absorber surface, due to its close proximity to the glass, becomes cooler than the room air. The cool absorber surface cools the air

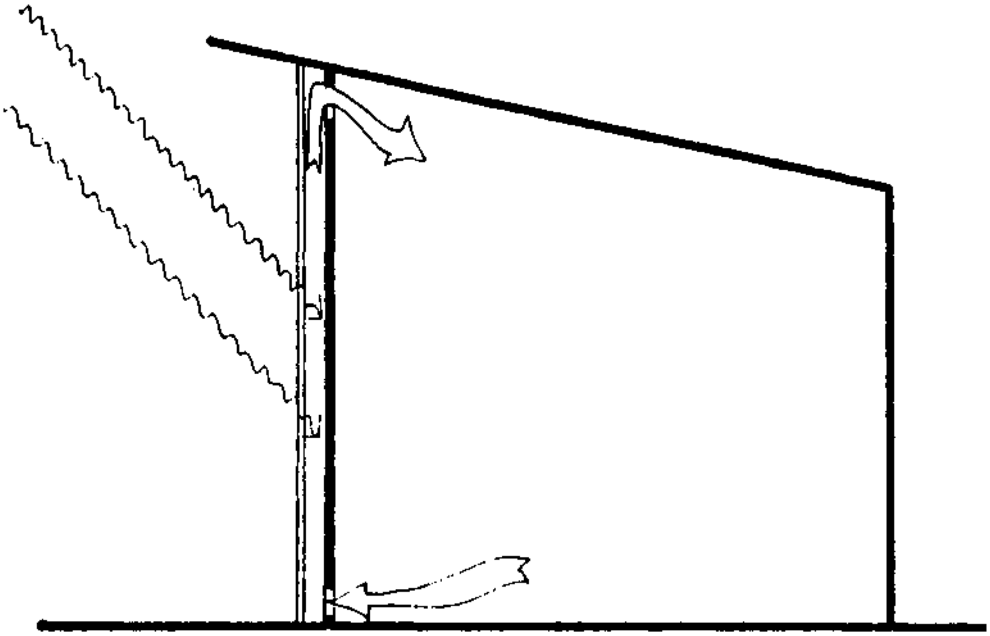


Figure A-2: A thermosiphoning air heater (HON).

in contact with it. The cool, dense air moves downward and enters the room at the lower vent. Warm air is then pulled into the upper vent, and the circulation loop continues. A simple backdraft damper (see Figure C2-7) over either vent opening will prevent this.

A.4.a.3 Thermal Storage Walls (Figure A-3)

In many applications of passive solar heating, thermal energy storage is located between a wall of glass (or plastic) and the space to be heated. To date, there are two general types of thermal storage walls. One uses heavy masonry materials 1 foot or so thick. The outside surface of the wall, painted a dark color, heats up as the sun irradiates it. The heat is conducted through the wall and is then transmitted to the interior spaces by convection and radiation several hours after the sun's energy strikes the wall.

The second general type of thermal storage wall employs water instead of masonry materials. Tubes of water, 55-gallon drums, and specially fabricated water walls are commonly used. The natural flow of air from the room to the space between the glass wall and the containers of water and then back to the room is usually not a serious design consideration. Instead, water absorbs the heat, and the heat radiates directly to the room.

To control this radiative heating (or to conceal the containers), a partition can be placed between the water wall and the room. A

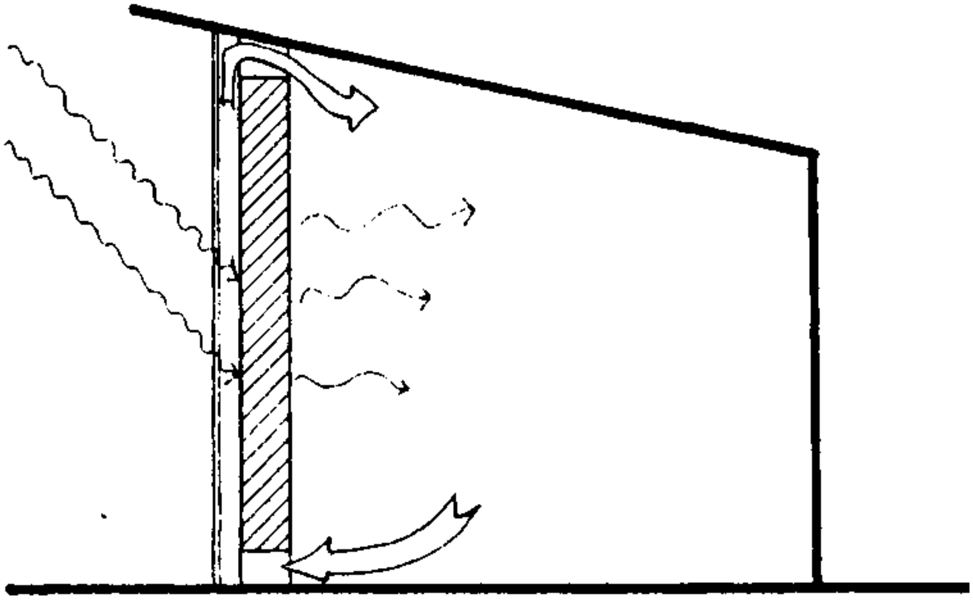


Figure A-3: Thermal storage wall with thermocirculation vents (HON).

thermostatically controlled fan could then be used to directly supply warm air from the resulting warm water wall "closet" to the space.

In masonry thermal storage walls, vent holes frequently are placed at the top and bottom to allow room air to enter, rise in the warm space between the storage wall and the glass, and re-enter the room. This combines the convective loop process with a thermal storage wall. Such systems are usually referred to as "Trombe walls" after Felix Trombe of Odeillo, France, who gave a substantial boost to their development.

Fans can be used to increase and control airflow. Even when vents are used, however, the majority of the heat is absorbed by and conducted through the masonry material. In many systems, manual or automatic dampers prevent the nighttime reverse flow of air that would cool the space. As with direct gain systems, movable insulation may be used to cover the glass at night to reduce heat loss and thereby increase overall thermal performance, especially in cold climates.

A.4.a.4 Thermal Storage Roofs (Figure A-4)

Some passive designs locate the thermal storage on the roof. The most widely known system, developed by Harold Hay, is called "Skytherm."[R] It uses roof ponds of water stored in large, clear vinyl bags that are supported on a black, waterproof liner. Solar

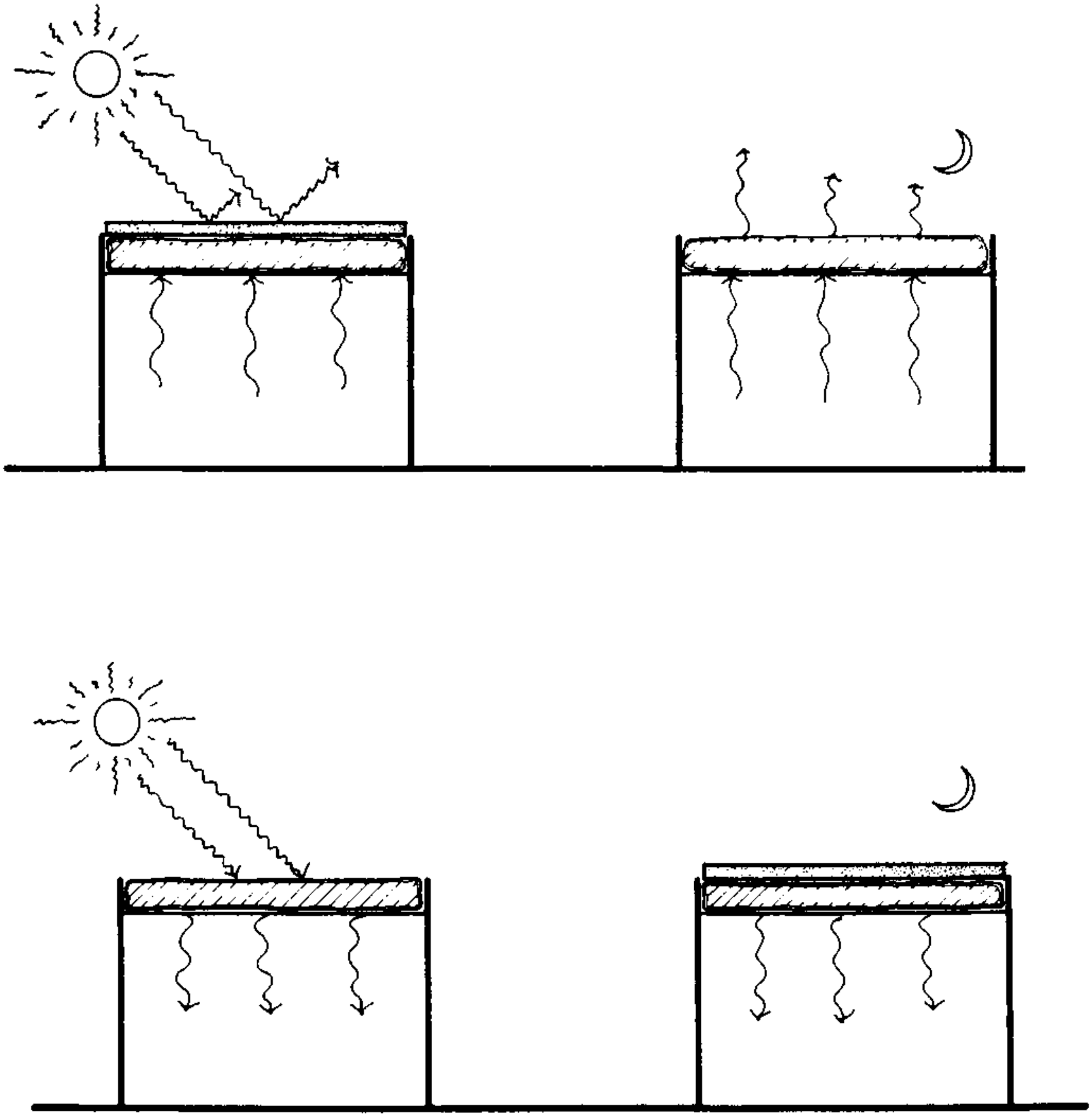


Figure A-4: "Skytherm"^{R} sthermal storage roofs — summer and winter operation (HON).

radiation is absorbed both by the water and the black liners. This heat is then conducted through the ceiling, in contact with the bags, to the space below. Insulating panels cover the roof ponds at night to minimize heat loss.

Depending on the climate, this system can be used for cooling during the summer. The water absorbs heat from the space below and radiates the heat to the cold night sky through a process called nocturnal radiative cooling. By flooding the water bags, evaporative cooling can be used effectively. The insulating panels cover and shade the roof ponds during the day and are removed at night to permit radiative and evaporative cooling as well as convective cooling when the outdoor air is cooler than the pond.

Other variations, developed for heating in colder climates, use glazing incorporated into a south-sloping roof pitch and water containers or "thermo-ponds" supported by the ceiling.

A.4.a.5 Attached Sunspaces (Figure A-5)

Greenhouses and other "solar rooms" can be attached to new or existing buildings. Overheated sunspace air is either delivered directly to the building to be heated, or the building and the sunspace can have a common thermal storage wall or rockbed. The heat

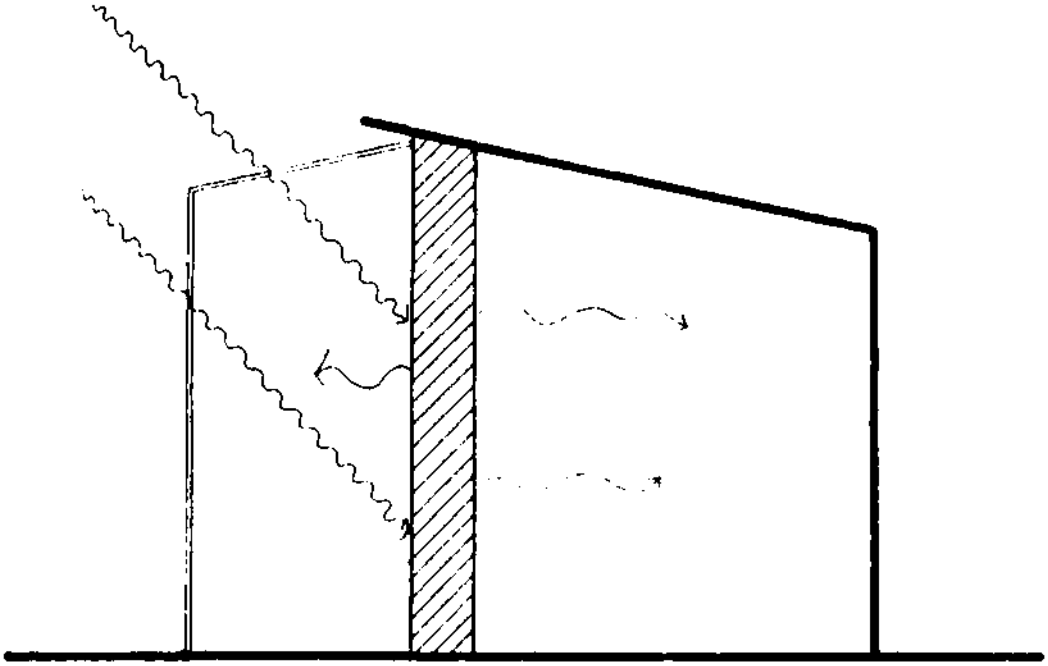


Figure A-5: Solar greenhouse (HON).

stored in the thermal storage wall will be shared by both the sunspace and the building. Some of the heat from the wall warms the greenhouse before passing to the outdoors, thereby extending the growing season. At the same time, the wall helps to keep the greenhouse from becoming overheated on clear, sunny days. Solar energy can provide all, or nearly all, of the heat required by a properly designed sunspace. The sunspace provides substantial quantities of excess energy to heat the building while simultaneously acting as a buffer zone to reduce heat loss from the building to the outdoors.

A.4.b Summary of Advantages and Disadvantages

1. Direct Gain

Advantages

- Glazing is a relatively inexpensive form of solar collector and is widely available and thoroughly tested.
- The overall system can be one of the least expensive means of solar heating.
- Direct gain is the simplest solar energy system to conceptualize and can be the easiest to build. In many instances it is achieved by simply relocating windows.
- The glazing serves multiple functions, allowing solar radiation to enter the building while also admitting natural

daylight and providing visual access to the outside.

- To provide only a small fraction of the heating needs of a building, direct gain systems do not necessarily need thermal storage.

Disadvantages

- Large expanses of glass can result in too much glare during the day and loss of privacy at night.
- Ultraviolet radiation in the sunlight will degrade fabrics and photographs.
- If the design is to achieve large energy savings, then relatively large glazing areas and concomitant large amounts of thermal mass are required to decrease temperature swings.
- Thermal mass is expensive, particularly if it serves no structural purpose.
- Interior diurnal temperature swings of 15 to 20 F are common.
- Providing for reduced heat loss at night through the glazing can be expensive and awkward.

2. Convective Loops

Advantages

- Glare and ultraviolet degradation of fabrics are not problems.

- Convective loops provide one of the least expensive ways to solar heat.
- To provide only a small fraction of the heating needs of a building, thermal storage is not necessarily needed.
- They are easily incorporated into south facades.
- They are readily adaptable to existing buildings.
- Because the collector can be thermally isolated from the building interior, night heat losses can be lower than for any other passive design.

Disadvantages

- The collector is an add-on device to the building (a possible advantage in retrofitting).
- Both careful engineering and construction are required to ensure proper airflows and adequate thermal isolation at night.
- The thermal energy is delivered as warmed air. It is difficult to then store this heat for later retrieval because air has poor heat transfer characteristics to mass compared to mass directly irradiated by the sun.
- When thermal storage is used, the system works best when the collector is located below the building and the storage. Such a configuration is difficult to achieve with conventional construction.

3. Thermal Storage Walls

Advantages

- Glare and ultraviolet degradation of fabrics are not problems.
- Temperature swings in the living space are lower than with direct gain or convective loop systems.
- The time delay between the absorption of radiant energy by the surface and the delivery of the resulting heat to the space provides warmth in the evening when most residences need it.
- The state-of-the-art in analyzing thermal storage walls is well-advanced.

Disadvantages

- Two south walls, a glazed wall and a mass wall, are needed.
- Massive walls tend to be costly and are not generally used in modern residential construction (although thermal storage walls may be the least expensive way to achieve the required thermal storage since they are compactly located behind the glass).
- The mass wall occupies valuable space within the building.
- In cold climates considerable heat is lost to the outside from the warm wall through the glazing unless the glazing is insulated at night; movable insulation tends to be expensive and awkward.

4. Thermal Storage Roofs

Advantages

- Compared with many passive systems, the heating and cooling effects are more uniformly distributed throughout the building.
- Temperature swings in the building may be small.
- Glare and ultraviolet degradation are not problems.
- This system can provide both heating and cooling.
- Backup heating and cooling systems can be eliminated in mild climates (when codes permit).

Disadvantages

- The heavy weight of thermal mass above the ceiling might be psychologically unacceptable (especially in an earthquake-prone area).
- The thermal storage roof area needs to be at least 50 percent of the total floor area to produce a significant fraction of the thermal energy needs of the building.
- Compared with other passive systems, further refinement is required in order for designers and builders to make immediate widespread use of the design.
- Structural support for the heavy mass can be costly.

5. Attached Sunspaces

Advantages

- Temperature swings in adjacent living spaces are small.
- They provide space for growing food and other plants.
- They reduce heat loss from buildings by acting as buffer zones.
- They can help bring people closer to nature.
- They are readily adaptable to existing buildings.
- Since the sunspace serves more than one function, it is a natural and integrated part of the building design.

Disadvantages

- Thermal performance varies greatly from one design to another, making the performance difficult to predict.
- Although construction costs can be kept low, commercial-quality construction is expensive.

A.2.d Glazing Configurations for South Walls

An invaluable aid for selecting the most appropriate passive design is an understanding of the dynamics of heat transfer through walls of various constructions. This understanding can help develop an intuitive feel for passive design. In winter there are two primary flows of heat. One is solar radiation into the building; the other is heat loss from the building. These two energy flows vary in amount and rate, depending on outdoor weather, time of day, and time of year. For example, the rate of solar radiation varies from very high levels when the sun is unobstructed from shining through windows to about one-tenth of this level when the sun is completely obscured in a dense fog. The amount of heat loss ranges by a factor of 30 between well-insulated walls and single glass.

Standard construction methods and materials can be used to reduce heat loss, but properly-used glazing can permit heat gains. The diagrams in Figure A-6 simplistically show that transparent glazing can be added to the exterior of a building in a number of ways. The primary effect of adding glazing to existing glazing (Diagram A) is to reduce heat loss. However, it reduces admitted solar energy only slightly. Adding glazing to the prepared wall surface of a building (Diagram B) transforms the wall into a solar collector, greatly increasing the flow of solar energy through it but having little effect on heat loss. Adding a layer of glazing to an uninsulated masonry wall (Diagram C) greatly reduces heat loss and greatly increases solar heat gain. When the space between the glazing and the wall is enlarged (Diagram D), the resulting sunspace tempers and delays the effects of outdoor weather extremes on the building's interior while also providing solar heat.

To elaborate further, Diagram A represents direct gain systems. Heat transfer rates and amounts are high for both solar radiation and heat loss through a single layer of glass. A second layer of glass reduces solar heat gain by about 10 to 20 percent, but it reduces heat loss

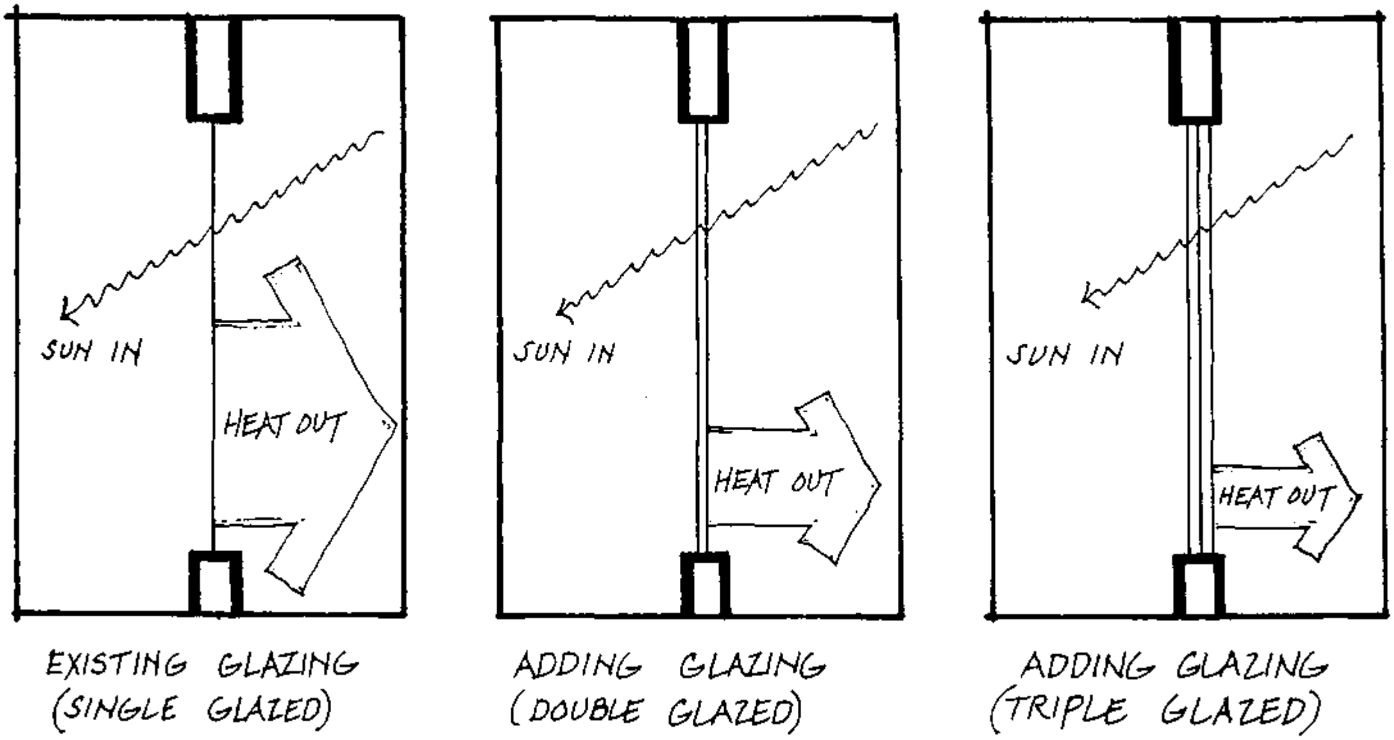


Diagram A, Direct Gain Systems

Figure A-6: Glazing configurations for south walls on new or existing buildings (PUT).

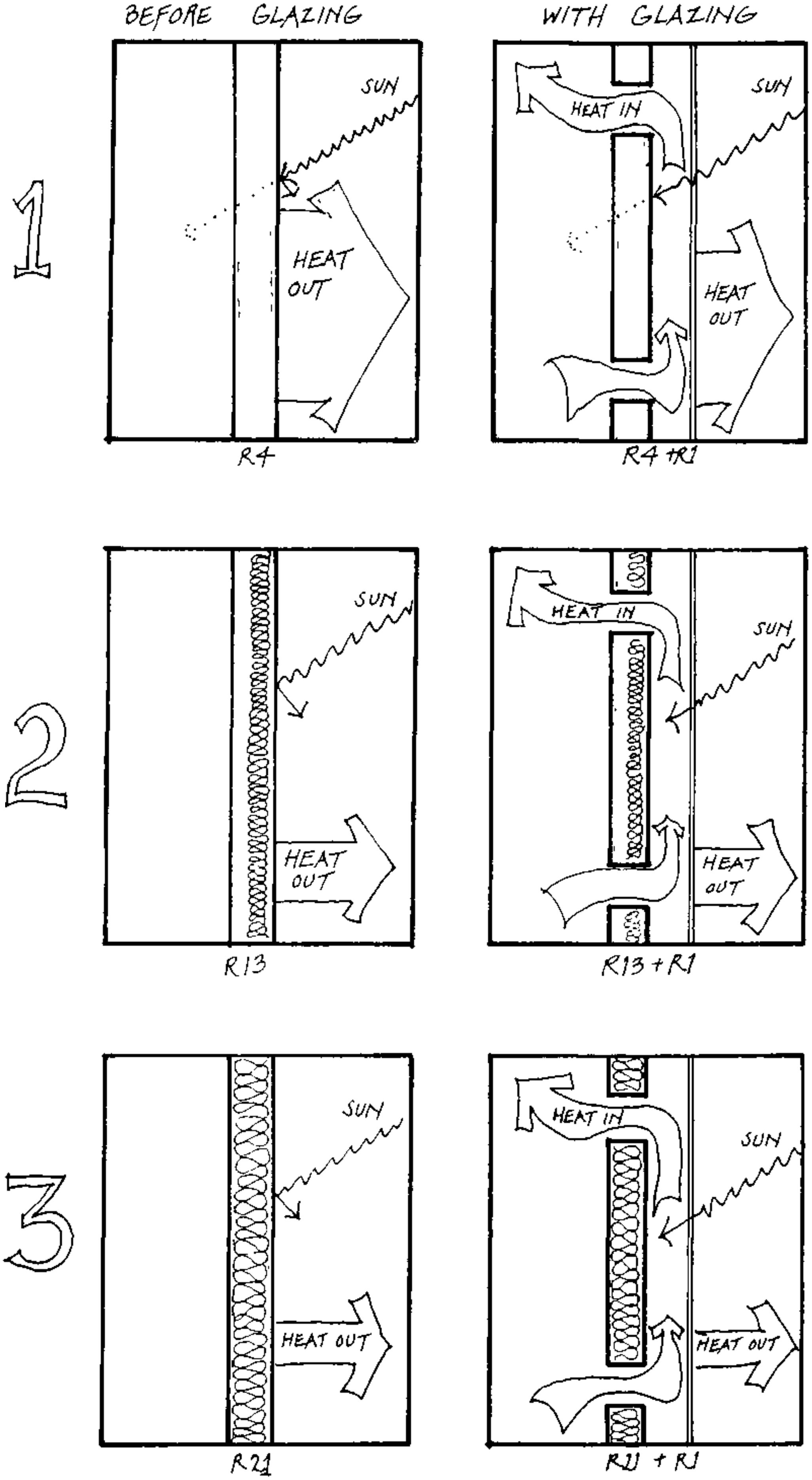
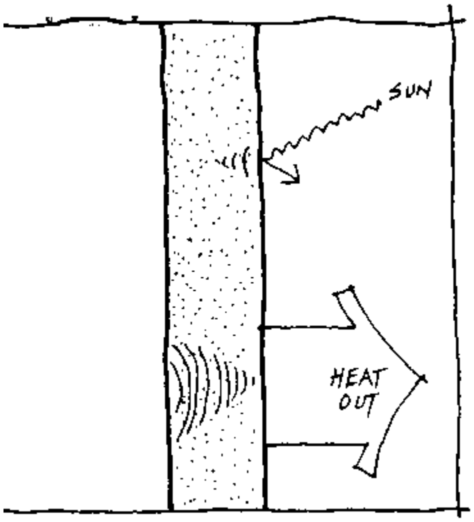
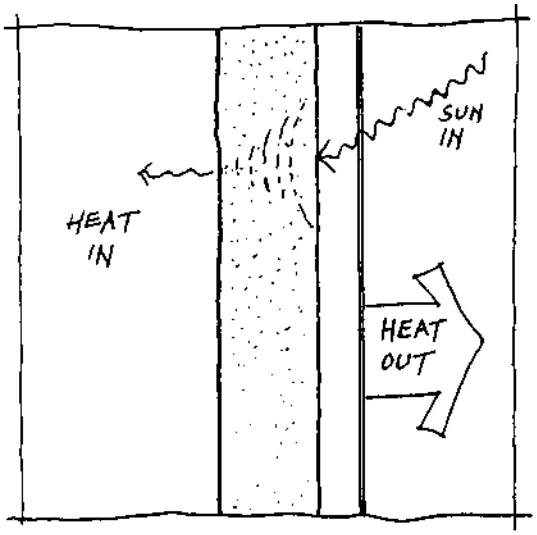


Diagram B, Convective Loop Systems
Figure A-6 (cont'd.): Glazing configurations for south walls on new or existing buildings (PUT).





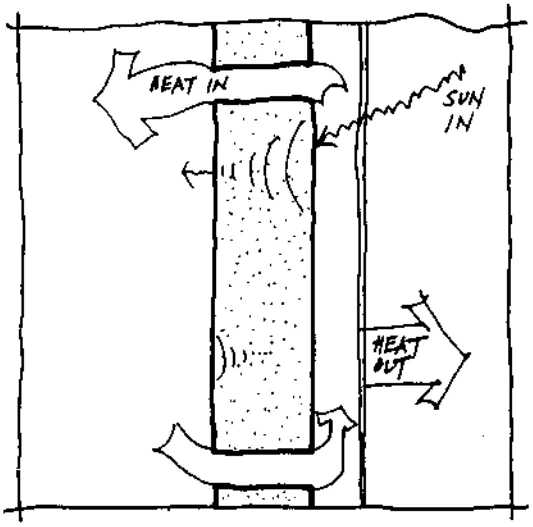


Diagram C, Thermal Storage Walls

Figure A-6 (cont'd.): Glazing configurations for south walls on new or existing buildings (PUT).

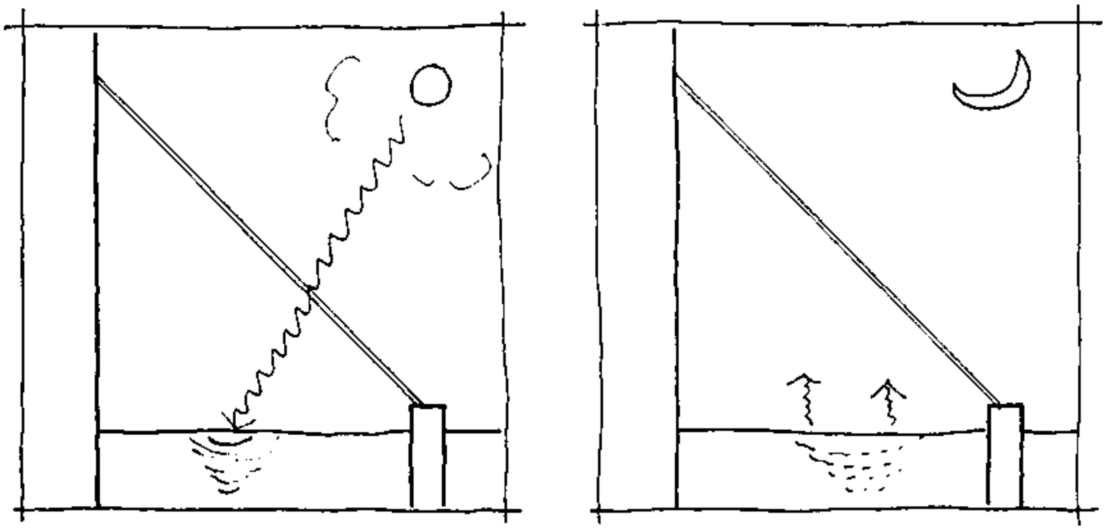


Diagram D, Sunspaces

Figure A-6 (cont'd.): Glazing configurations for south walls on new or existing buildings (PUT).

by about 50 percent. Adding a third layer of glass reduces solar heat gain by another 10 to 20 percent but heat loss is reduced by an additional one-third. For all three window configurations, admitted solar energy, as well as heat loss, tracks outdoor weather almost immediately. That is, when the sun is shining, the building experiences heat gain instantly and in direct proportion to the level of solar radiation. Heat loss increases with almost no delay as the indoor temperature increases or the outdoor temperature drops.

Diagram B represents convective loop systems. A layer of glass or plastic is added to an uninsulated wall (R-4) and to two insulated walls (R-13 and R-28). Vents are introduced at the bottom and top to permit thermocirculation of solar heated air into the building.

Prior to being glazed, the uninsulated wall has small but measurable amounts of admitted solar energy. The insulated walls yield little or no solar energy. The uninsulated wall has high heat losses, the insulated walls have very little.

With the addition of the glazing and the resulting convective loop, solar gain is increased in all three cases. In fact, daytime solar gains through the uninsulated wall is the best of the three; it has not only natural convection but also increased conduction gains. In contrast to the immediate response by windows to sunlight, these walls are relatively sluggish and have somewhat less total solar gain.

For the uninsulated wall, heat loss is noticeably reduced due to the addition of the air space between the glazing and the wall; the total heat flow resistance is increased from R-4 to approximately R-5, a 25 percent increase. Heat loss will still be significant compared to that of insulated walls, especially at night and during cloudy weather.

For the insulated walls, solar heat gain is significantly increased by the new layer of glazing, but heat loss at night is affected only negligibly. Daytime heat loss is reduced because of the warm air between the glass and the wall. This has a minor effect on the net energy contribution of the wall to the building.

Diagram C represents thermal storage walls. A layer of glass or plastic is added to the exterior surface of a solid masonry wall. The heat is delivered to the building by conduction through the mass, and heat delivery to the room is delayed by several hours. In many applications, vents are cut through the top and bottom of the wall to provide a convective loop effect. As with the convective loop walls, there is a slight delay compared to windows from the time the sun shines on the wall until the heat actually enters the space. Similar also to convective loops, the solar gain is not as great as with windows since some heat is lost from the hot wall through the glass to the outside. Also, much of the heat is absorbed by the masonry, which further slows the responsiveness of the wall to supply solar heat to the building. The absorption of heat by the masonry, in fact, greatly delays the time when the conducted solar heat finally enters the building. The solar gain, therefore, is distributed at lower rates over a longer period of time, which makes control of excessive solar gain a lesser problem than with direct gain systems.

When the masonry is warm from the sun, there is no heat loss from the building through the wall to the outside. After long periods of cold, cloudy weather, however, the wall temperature can fall below room temperature, and then heat loss is high since concrete is a poor insulator. This problem can be solved in a number of ways and is discussed in Chapter C3, Thermal Storage Walls. In any case, the heat lost from the living space through a glazed mass wall is less than that through a comparable direct gain glazing system.

The vertical glazing described in the example above forms a small, dead air space over what was the exterior wall surface. If the glazing is instead installed in a lean-to fashion, as in Diagram D, the small air space becomes a larger area that can be called an attached sunspace. The heat loss through the wall is no longer to the outside; instead it is to this larger air space which, depending on the added thermal mass, is more or less useful as a living/working space.

The glazing can beat slopes other than a lean-to shape to better use the inside space. If the wall in common with the building is wood-framed, a sunspace is likely to experience wide temperature fluctuations.

It will be hot on sunny days and mild on cloudy days. Some sunshine will penetrate directly into the living space through any windows in the wall between the house and sunspace. Some solar heat will be conducted through the wall, but unless the wall is solid masonry, this contribution will be relatively small. Vents can be introduced at the bottom and top of the wall to permit additional heat to enter the building through the thermocirculation of warm air. Alternatively, a fan can be used to mechanically move the warm air, although this is seldom necessary. The warm air can also be circulated through a gravel bed to store the heat, in which case a fan is required.

At night the temperature of this sunspace design will drop fairly quickly. However, due to the thermal mass of the floor, the temperature levels off warmer than the outside air and then drops slowly compared to the temperature of the air space in a convective loop collector. During severely cold weather, the above-freezing temperatures of the floor will moderate the sunspace temperature, maintaining it above that of the outdoors. The building loses heat to this sunspace rather than to the outdoors. The mass of the sunspace floor helps to modulate the effects on the building of extremes of sunshine and cold weather. Like a thermal storage wall, the solar gains to the building are stretched out over a time longer than while the sun is actually shining. Also like a thermal storage wall, heat loss from the building is reduced at night due to the heat storage capacity of the system. An additional advantage of the sunspaces is that even during periods of cold, cloudy weather (when direct gain systems, thermal storage roof systems, and thermal storage walls are normally experiencing large amounts of heat loss), the heat transfer from the ground to the sunspace enables it to act as a buffer zone, thereby continuing to reduce heat loss from the building.

A.2.f A General Approach to Evaluating Costs

Given these five, basic passive solar energy system types, not to mention the dozens of variations and permutations, how can the designer select the most appropriate system or combinations of systems based on costs? Although the answer is difficult, a few basic observations can help sort through the seeming maze of complexity.

A direct gain system can be either the least costly or the most costly selection. For example, it may be the least costly choice 1) if a building's south-facing glass area can be increased simply by decreasing planned glazing on the east, west, and north facades, 2) if added mass is not needed (because the building is to be built of massive materials regardless of whether it is a direct gain system or not, or if it can be permitted to fluctuate widely in temperature, or if the glazing area is small enough that the normal building mass is sufficient), and 3) if it is in a mild climate so that movable insulation over the windows to reduce heat loss at night is not necessary.

On the other hand, direct gain systems are expensive 1) if additional south-facing glass results in significantly greater cost than the wall that would have been there, 2) if great expense is required to add sufficient thermal mass to keep temperature fluctuations within comfort limits, and 3) if great expense is required to reduce heat loss through the glass at night and to shade it during the summer.

If a south-facing wall can be easily converted to a convective loop wall collector through a simple application of a single layer of glazing, the cost will be much less than if a special support structure must be built. If the convective loop collectors are sized to provide only daytime heating requirements, no additional thermal mass is needed. The cost of the convective loop, then, will be primarily the collectors. Often, however, thermal mass must be added to accommodate the heat from the convective loop collectors. Since the mass is not directly irradiated by the sun, the exposed surface area, and therefore the cost, of the required mass can be high. Unlike direct gain systems, however, no additional cost is involved in reducing heat loss from the collector when the sun is not shining since the existing insulated wall does that anyway.

The cost of changing a masonry wall into a thermal storage wall can vary greatly. In mild climates, only single glazing may be necessary, while in cold climates (greater than 6,000 degree days) even triple glazing may be both necessary and cost-effective. Movable insulation is usually difficult to justify through conventional economic analysis and may be difficult to integrate into the design. Additional structural costs, including larger foundations, are often overlooked. Although perhaps negligible, or even nonexistent in construction that would have incorporated a heavy wall anyway (such as adobe construction), these costs can be high when incorporated into light-frame construction. Multi-story storage walls can also have these higher hidden costs.

Often, too, the floor area that must be built to accommodate the thermal storage wall can vary greatly. For example, an 8- or 12-inch-thick concrete wall may have no additional cost associated with it, particularly if the wall would have been there anyway, which is usually the case if it is supporting the roof. On the other hand, for free-standing water walls such as fiberglass tubes or 55-gallon drums, the attributable cost due to the lost usable floor area can be several dollars per square foot of glazing.

Since not nearly as much information exists about thermal storage roofs as about other passive system types, cost evaluations are even more elusive. At the extreme low end, if Harold Hay's "Skytherm"^{R} house in Atascadero, California, were built in large numbers, it would cost no more than conventional housing since it requires no backup heating or cooling systems in that climate. According to Mr. Hay, the resultant cost savings completely pay for the passive system.

On the other hand, thermal storage roofs can also be expensive. Significant additional structural work may be required to support thermal mass. Movable insulation may need careful detailing to ensure tight fits. If the building requires conventional heating and cooling equipment, the cost associated with the thermal storage roof will be an additional, rather than substitute, cost.

A single-glazed attached sunspace may cost only a few dollars if the frame is built of used lumber and if the glazing is thin sheets of plastic. On the other hand, commercially available greenhouses for integration into buildings are usually costly. However, sunspaces can be integrated into buildings in ways that may reduce costs of other building components. For example, if the sunspace is protecting walls that would otherwise be exposed to the weather, the walls can be simplified and the costs reduced.

CHAPTER B

BASICS OF SOLAR BUILDING DESIGN

B.1 PASSIVE DESIGN AND ENERGY CONSERVATION

B.2 SOLAR POSITION

B.3 SITING

B.4 LENGTH/WIDTH/HEIGHT RATIOS

B.5 DAYLIGHTING

B.1 PASSIVE DESIGN AND ENERGY CONSERVATION BASICS

Passive solar heating and cooling methods extend our understanding of energy conservation and of designing with, rather than against, nature. Countless pages have been written on both the philosophy and the applications of energy conservation and of climate-responsive and site-sensitive design. Although this subject is not discussed in detail here, a few observations on the relationship between passive design and conservation are in order.

Energy conservation is the best first step in the thermal design of buildings. This makes sense from both an economic and a practical engineering standpoint. The procedure for determining the optimum amount of energy conservation is no different for a passive or active solar house than for any other building. Insulation is added until a point of diminishing returns is reached — that is, until the cost of additional insulation begins to exceed the life-cycle cost of the fuel that the added insulation will save. The same procedure is used for determining the optimum size of the solar energy system — its size is increased until the cost of additional collection area (including all of the associated system costs) begins to exceed the life-cycle cost of the fuel to be saved from the additional collector. The optimum mix occurs when there is a three-way equality: the added cost of energy conservation equals the added cost of solar collection equals the life-cycle cost of the fuel to be saved by either.

Given normal architectural and geometrical constraints, it is difficult to match the appropriate solar collection glazing to the building without energy conservation. Depending on climate, a glazing area equal to 20 to 50 percent of the floor area is required to reduce a well-insulated (ASHRAE Standards 90-75 or equivalent) building's heating bill 50 to 80 percent with passive (or active) solar energy. Thus, the collection glazing covers much of the available south facade of the building. Achieving a high solar heating fraction on a poorly insulated building would not be feasible except in a very mild climate.

Additionally, by reducing energy demands through energy conservation, conventional energy systems can be reduced in size and complexity. For example,, the traditionally elaborate heat distribution system may be eliminated. Instead, a central space heater (through-the-wall type, beneath-the-floor type, or even a wood stove) can heat a full-sized house.

Energy conservation can significantly affect passive system design. As a result of conservation measures, a building is able to be warmed by low temperature heat. Most passive systems are low temperature systems. The sun's energy is usually used at low temperatures rather than high. In general, the lower the temperatures that a solar energy system provides, the less heat is lost to the outdoors and the greater the percentage of the sun's heat that can be fully utilized to provide comfort.

Many designers are finding, in fact, that when energy conservation and solar energy systems (whether active or passive) are analyzed with the same economic criteria, climate determines the appropriate mix. In cold, cloudy climates, energy conservation measures are usually more cost-effective than solar until building heating loads are reduced to a very small fraction of conventional loads. On the other hand, in mild, sunny climates, solar heating and cooling may be more cost-effective than energy conservation for reducing both fuel bills and fossil fuel use.

Regardless of how fuel bills are reduced, the primary purpose of fuel consumption for heating and cooling is to keep occupants comfortable, not to condition a space. This can have important design implications. For example, the better a wall is insulated, the higher will be its interior surface temperature during cold weather. This warmer surface temperature allows interior air temperatures to remain lower and still provide comfort; in turn, heat loss is reduced to the outside due to the smaller difference between the indoor and outdoor air temperatures. This lower heat loss reduces the size of the heating systems and reduces the need to deliver heat to the building's perimeter.

The human body uses three basic mechanisms to maintain comfort: convection, evaporation/respiration, and radiation. Air temperature, humidity, air speed, and mean radiant temperature (MRT) are parameters affected by energy conservation techniques, and they influence how the body uses its comfort control mechanisms. These parameters and mechanisms cannot be discussed at length here, but due to the dearth of information about mean radiant temperature and since it is particularly important to passive design, a brief discussion of it is in order.

Mean radiant temperature (MRT) refers to the average surface temperatures of all the surfaces of a space: interior walls, windows, ceilings, floors and furniture. Different combinations of mean radiant temperature and air temperature can produce the same comfort sensation. The following pairs of combined numbers produce the equivalent sensation of 70 F (HAG-2).

Air Temperature	49	56	63	70	77	84	91
Mean Radiant Temperature	85	80	75	70	65	60	55

The first pair of numbers, for example, indicate that if the air temperature is 49 F and the surfaces of the walls and other surrounding surfaces average 85 F, then the sensation will be 70 F. The last pair of numbers reveals that if the air temperature is 91 F and the MRT of the surrounding surfaces is 55 F, the comfort sensation will be similar to that experienced by most lightly-clad occupants at 70 F air and surface temperature.

MRT is crucial for providing comfort in passive solar design since many passive systems rely on warm (or cool) surfaces to exchange energy with the air. For heating, the often-higher MRT's provide comfort at lower air temperatures, hence saving energy through lower infiltration and conduction.

B.2 SOLAR POSITION

The sun's position is designated by two angles (see Figure B-1). Solar altitude, β , is the angle measured upward from the horizontal to the sun. It equals 0° when the sun is on the horizon and 90° when the sun is directly overhead. Solar azimuth, Φ, is the angle measured in a horizontal plane from south to the projection of the sun on the horizon. It equals 0° at south, 90° at east and west, and 180° at north (ASH-1). (Note that some references instead measure the azimuth from the north.)

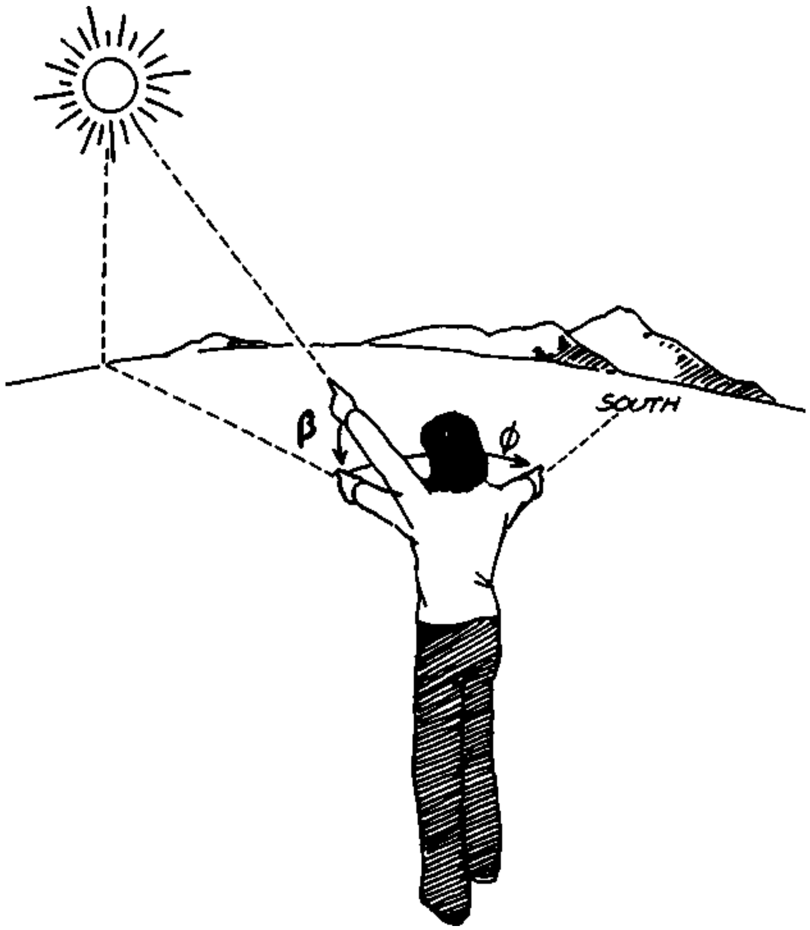


Figure B-1: Measuring the sun's position — the solar altitudeβ is the angle between the sun and the horizon; the azimuth Φ is measured from true south (AND-1).

The sun's path across the sky varies with the time of year, but it always follows a circular arc across the sky dome. Figure B-2 shows three diurnal paths: the summer solstice (21 June), the vernal equinox (21 March), and the winter solstice (21 December). The numbers in circles represent times of day.

Solar altitutde and azimuth can be determined for the 21st day of each month and for any hour of the day by using sun path diagrams. A different diagram is required for each latitude, although interpolation between graphs is reasonably accurate. Reprinted in Figure B-3 is a representative diagram for 40° N latitude. Other diagrams are in Appendix 5 and in references (RAM), (BEN), and (MAZ-2). By using this diagram, for example, one can determine the solar altitude and azimuth at 4:00 p.m. solar time on April 21 in New York City (40°N). Locate the April line, the dark line running left-to-right numbered "IV" (April is the 4th month). Next locate the 4:00 p.m. line, the dark up-and-down line numbered "4." The intersection of these lines indicates the solar position. Solar altitude is read from the concentric circles; in this case it is 30 . The solar azimuth is read from the radial lines, 80°W in this case.

A primary application of solar angle information is to determine shading angles for windows and collector surfaces. Shading should protect a surface from excessive sun but not from useful solar energy. The above references are excellent guides for designing shading devices.

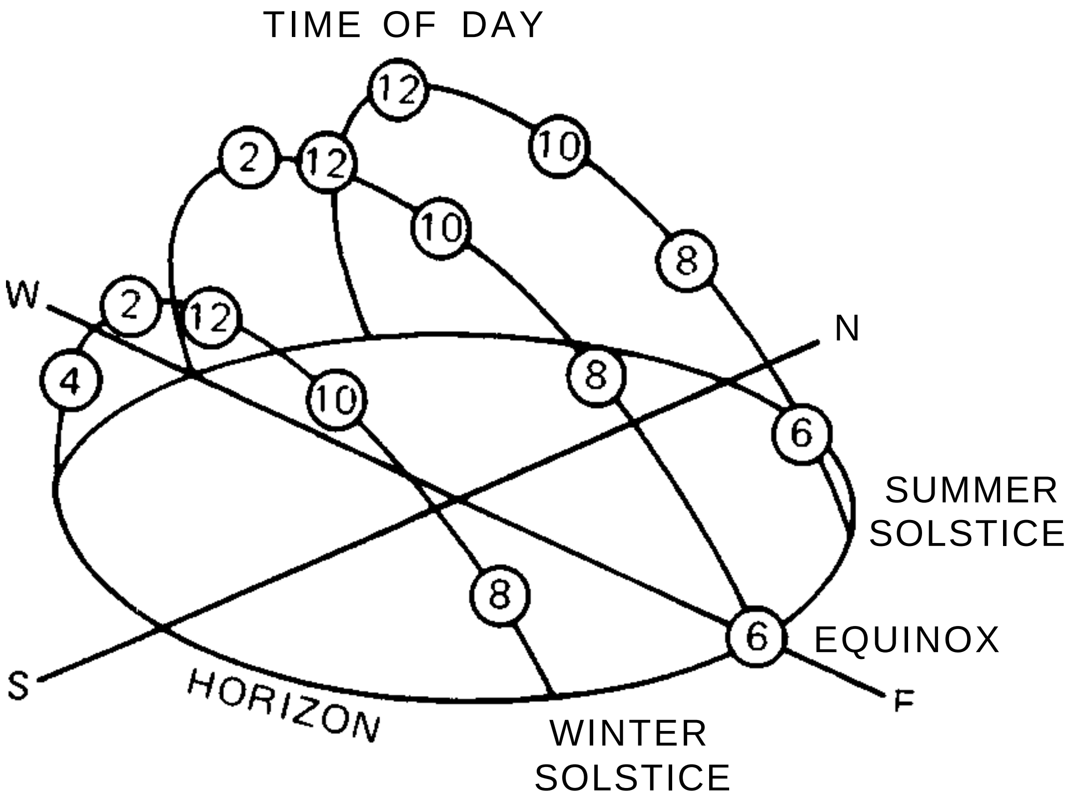


Figure B-2: The sun's daily path across the sky — the sun is higher in the sky in summer than in winter due to the tilt of the earth's axis (AND-1).

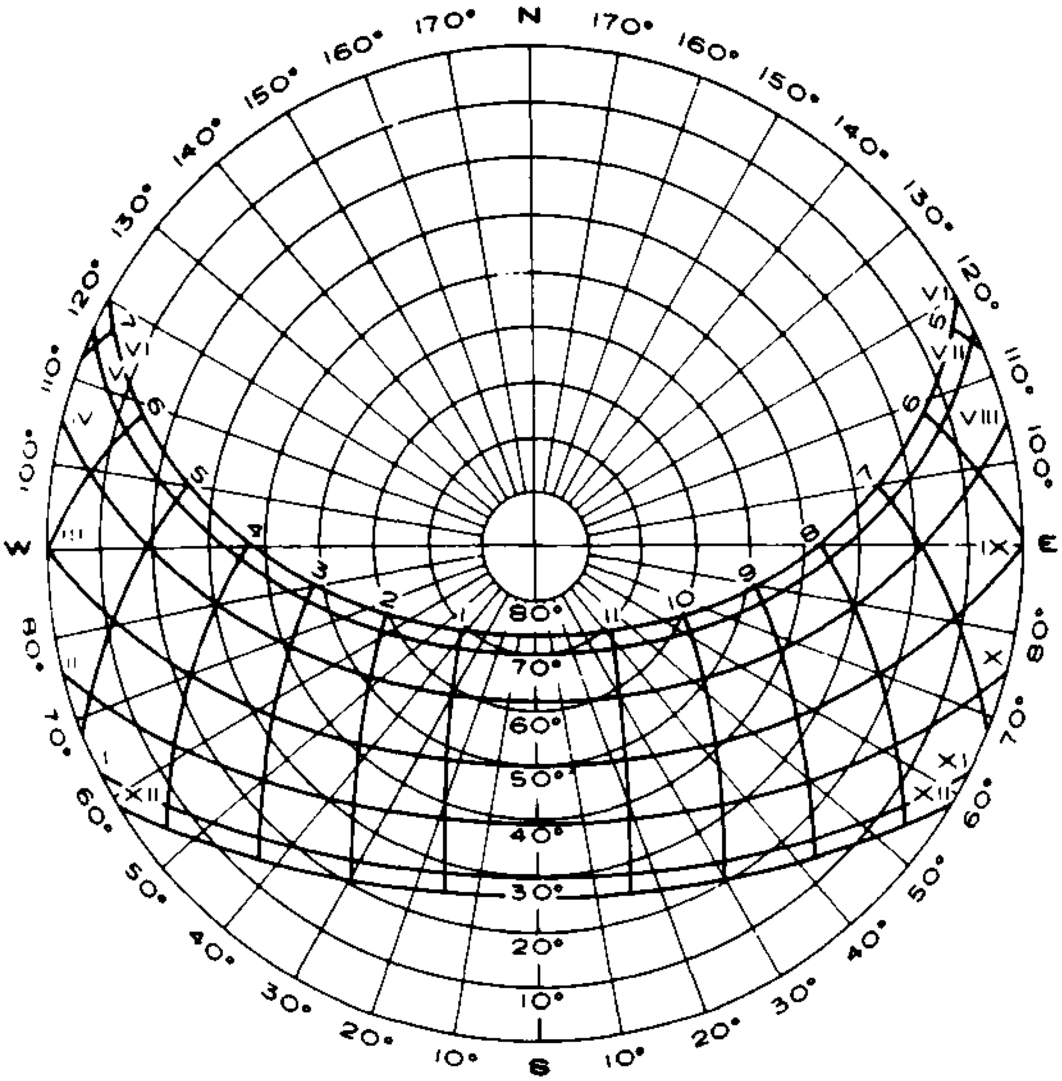


Figure B-3: Sun path diagram, 40 degrees N latitude (RAM).

Most, but not all, passive solar heating methods use vertical south-facing surfaces. Fortunately, more solar radiation strikes a vertical surface during the heating season than during the summer. In contrast, vertical surfaces of other orientations have greater solar gain during the summer than during the winter. Figure B-4 is a plot of the average solar radiation values on vertical walls of various orientations in New York City (AND-2).

The quantity of solar radiation that penetrates a south-facing window on an average sunny day in the winter is greater than that through the same window on an average sunny day in the summer. There are a number of reasons for this:

1. Although more daylight hours occur during the summer than during the winter, there are more hours of possible sunshine on a south-facing window in winter than in summer. For example, at 35 north latitude, there are 14 hours of sunshine on June 21. But since the sun remains north of east until after 8:30 a.m. and moves to north of west before 3:30 p.m., direct sunshine occurs for only seven hours on the south-facing wall. On December 21, however, the sun is on the south wall for the full 10 hours that it is above the horizon.

2. The intensity of solar radiation on a surface perpendicular to the sun's rays is greater in the win-

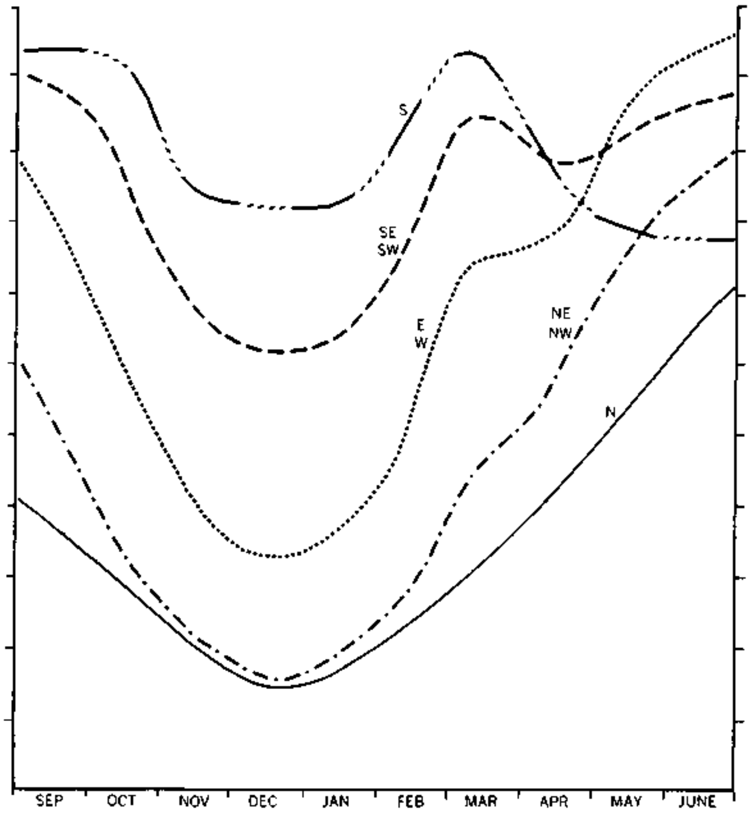


Figure B-4: Relative average solar radiation on vertical walls in New York City (AND-2).

ter than in the summer. The earth is slightly closer to the sun during the winter, and the moisture content of the air is not as great.

3. Since the sun is closer to the horizon during the winter, the rays strike the windows at more nearly right angles than they do in the summer when the sun is at a higher altitude. At 35° north, 150 units of energy may strike a square foot of window during an average winter hour; during the summer this number would be 100 units.

4. The closer the sun's rays hit the windows at right angles, the greater the transmittance of the glazing.

5. A small roof overhang, usually to be found above a window, will shield it from most direct summer irradiation.

In fact, about twice as much solar radiation is transmitted through unshaded south-facing windows in winter as in summer. If the windows are shaded in the summer, the difference is significantly greater.

Vertical surfaces are more adaptable to passive systems than tilted surfaces such as roofs. The amount of solar energy striking a south-facing vertical surface in northern latitudes during the winter is almost identical to that striking a steeply tilted surface. With reflective surfaces, such as snow, on the ground, a south-facing vertical surface may actually receive more incident energy during the middle of the winter than a south-facing tilted one. Figure B-5 compares incident energy on south-facing surfaces of various tilts ranging from vertical to horizontal. The curves are for 40° N latitude. Note that during the primary heating months, from October 1 to March 15, tilted surfaces gain very little more than vertical surfaces. In fact, the difference is less significant in more northern latitudes (AND-2). Keep in mind also that tilted surfaces receive more solar irradiation in the summer and are more difficult to shade than vertical surfaces.

Figure B-6 compares the daily total sky radiation on clear days, both on earth and outside the atmosphere, at 42°N latitude on south-facing vertical surfaces. Note that the amount of solar radiation on earth from October 1 to March 15 fluctuates very little, enabling south-facing vertical surfaces to perform well throughout the heating season. In the same figure there is recorded daily radiation incident upon a south-facing vertical surface; included are weekly means and the minimum and maximum records. This data, recorded at Blue Hill, Massachusetts, is representative of other localities at about 42°N latitude that have reasonably dust-free atmospheres and about 50 percent possible sunshine during December and January. Until recently, Blue Hill Observatory, which began collecting data in 1945, was the only weather station in the country that had recorded data for radiation received on south-facing vertical surfaces.

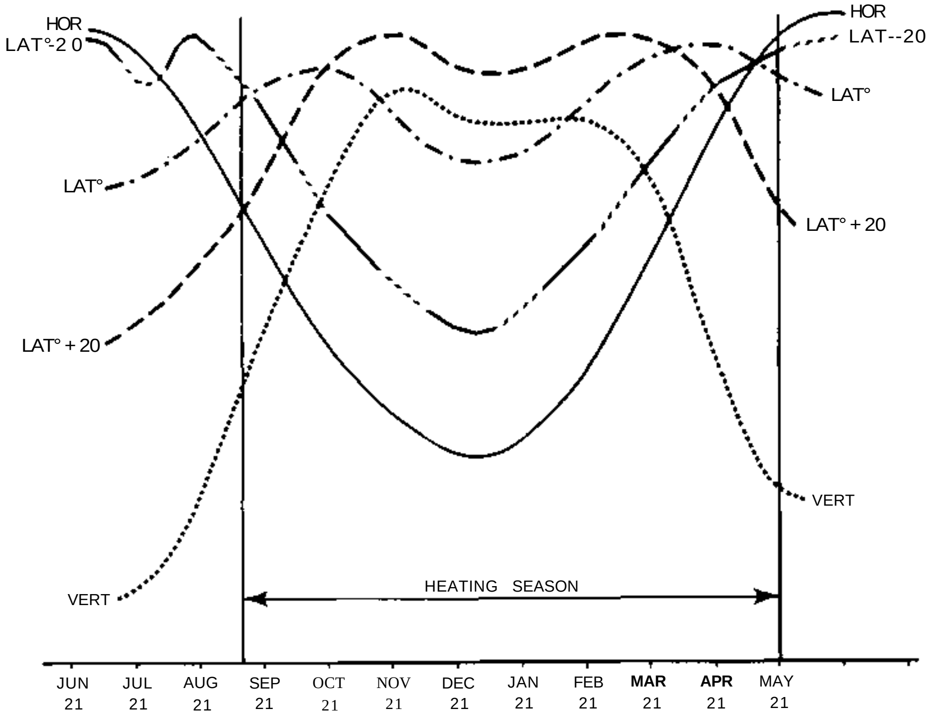


Figure B-5: South-facing surfaces: effect of tilt on direct radiation for 40° N latitude (JOR).

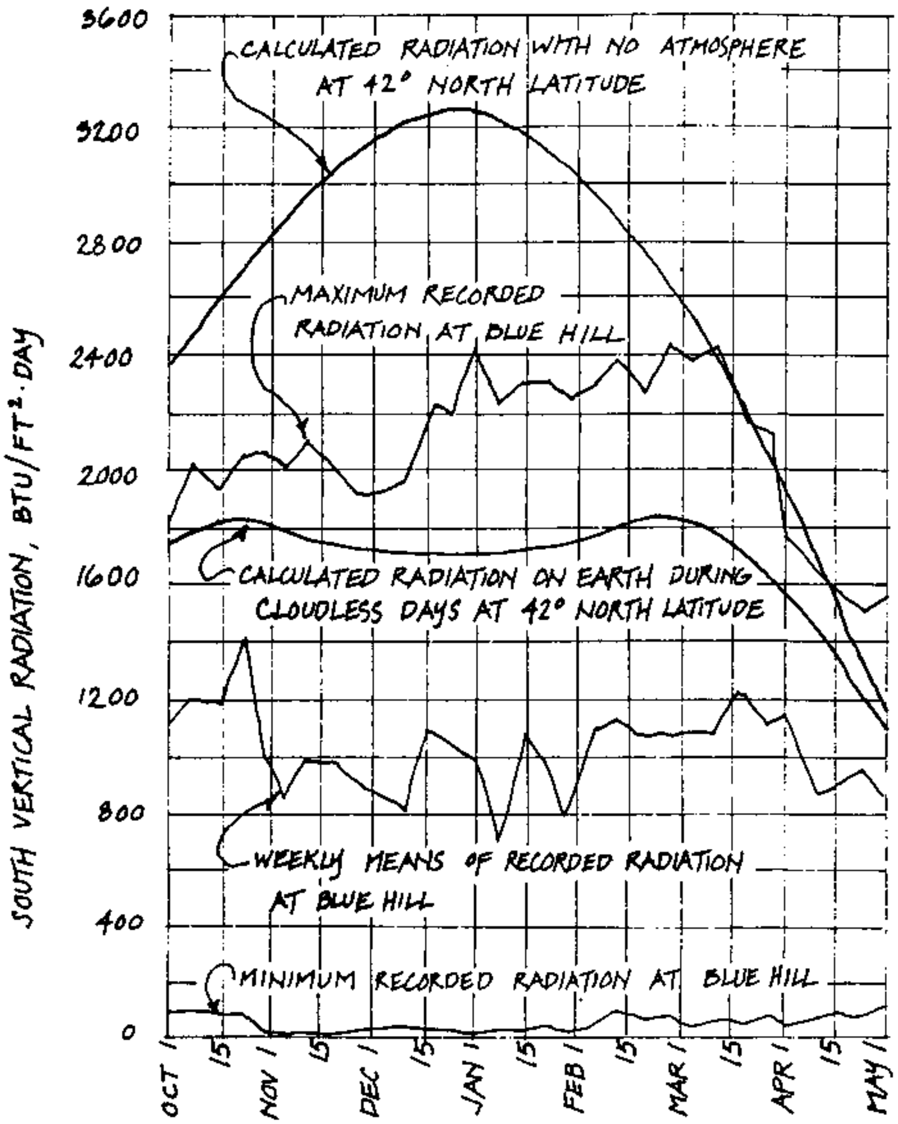


Figure B-6: Calculated and recorded daily radiation incident upon a south-facing vertical surface at Blue Hill (near Boston), Massachusetts (JOR).

Figures B-7 and B-8 show the estimated average daily solar and sky radiation incident upon south-facing vertical surfaces in the United States during December and January. Significant ground reflection off snow is not considered.

Observe from these figures that a relatively small amount of radiation is available in winter on south-facing vertical surfaces in the regions southeast of the Great Lakes and the Pacific Northwest. At any given latitude, the available radiation is greatest in those states west of the Mississippi River, and it reaches a maximum in the Rocky Mountains. In both December and January, the maximum radiation is found in Colorado and New Mexico.

Passive designs usually use glazings in a vertical rather than tilted position. Designing with tilted glazing is more difficult since it tends to be more costly to construct and harder to shade. It is also less easily insulated at night. On the other hand, roofs are less likely than walls to be shaded by trees and other buildings, and they have large surfaces for collecting solar energy. Norman Saunders, in recognizing both the opportunities and problems of roofs, developed the Solar Staircase™ (see Figure B-9). The Staircase consists of horizontal treads that are faced on both sides with a reflective surface. The vertical risers are transparent. This Staircase, which extends the length of the roof, is located directly below a sloping sheet of glass or other glazing material. During the winter, sun-

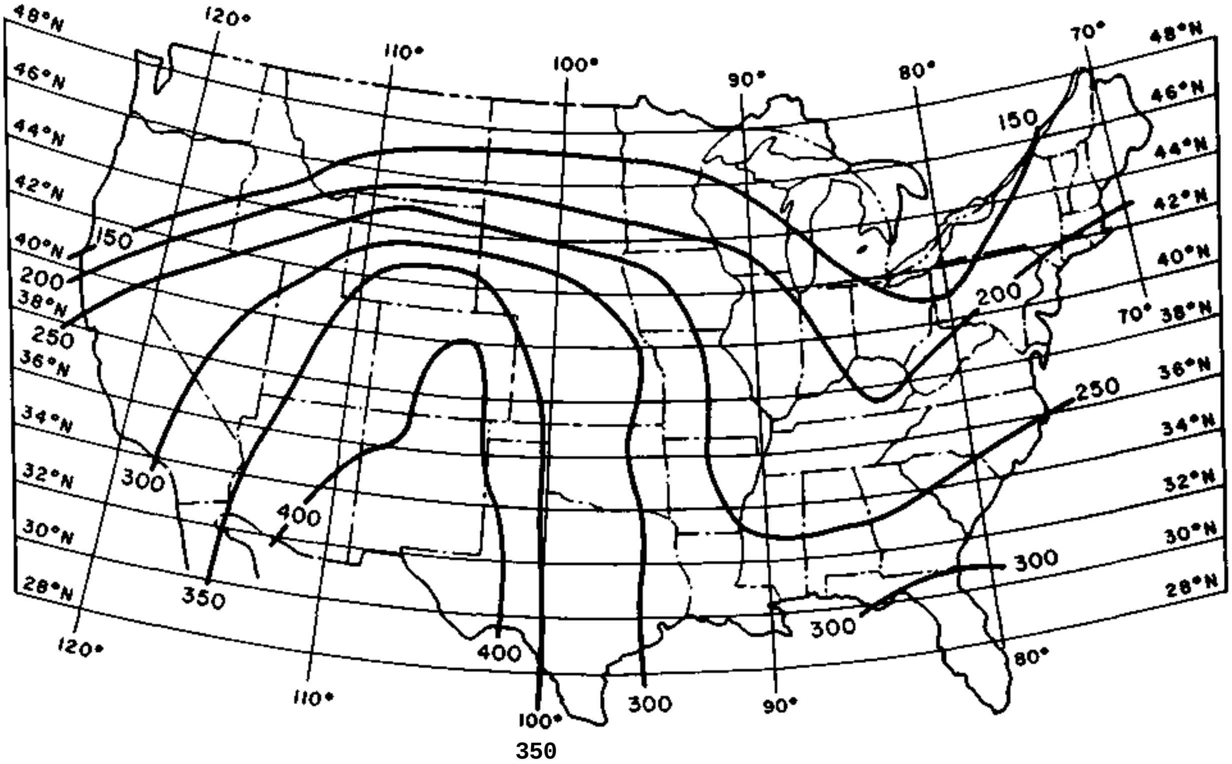


Figure B-7: Estimated average solar and sky radiation in langleys* per day incident upon a south-facing vertical surface in December (JOR).

*1 Langley = 3.69 Btu/ft^2

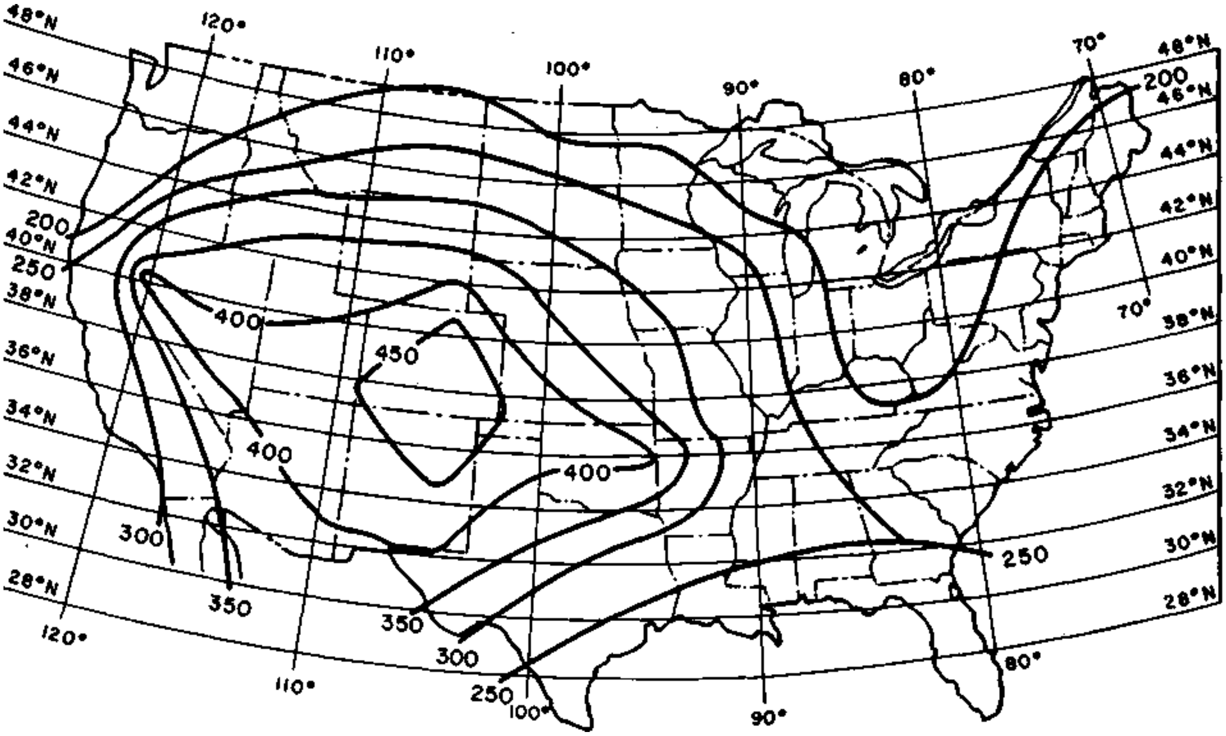


Figure B-8: Estimated average solar and sky radiation in Langleys* per day incident upon a south-facing vertical surface in January (JOR).

*1 Langley = 3.69 Btu/ft^2

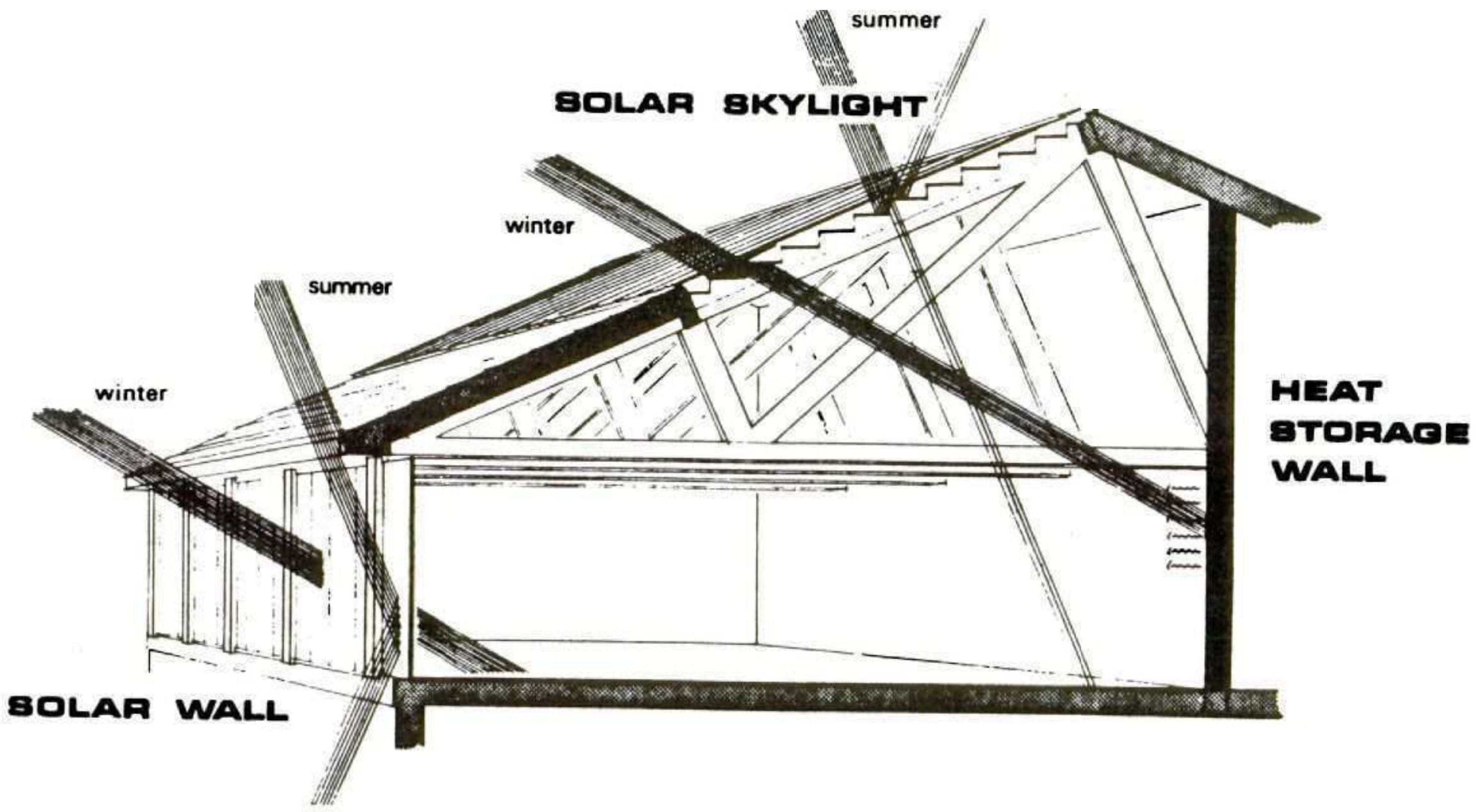


Figure B-9: Solar Staircase scheme at the Cambridge School, Weston, Massachusetts (SAU).

light comes through the first layer of glass and reflects off the horizontal treads and into the building. During the summer, when the sun is higher in the sky, most of the light is reflected from the building. In cold climates (more than 5,000 degree days) an inner glazing layer below the Staircase cuts heat loss even further.

B.3 SITING

Siting issues must be addressed early in the design process. If the site does not have proper solar exposure (sloped sharply north or darkly shaded by evergreens or large buildings, for example), the building designed for the site also has less chance for good solar exposure. In general, south-facing facades (including those east and west of south) should be exposed to sunlight during the winter months and shaded during the summer.

Solar land planning considerations particularly appropriate to housing subdivisions include the following:

Lot Orientation

South facing houses assure lower energy consumption during both summer and winter. Figure B-10 compares the solar radiation on vertical surfaces deviating from the south. Surfaces that are oriented up to 30° east or west of south receive nearly the same amount of solar radiation as surfaces facing due south. In fact, most theorists on the subject

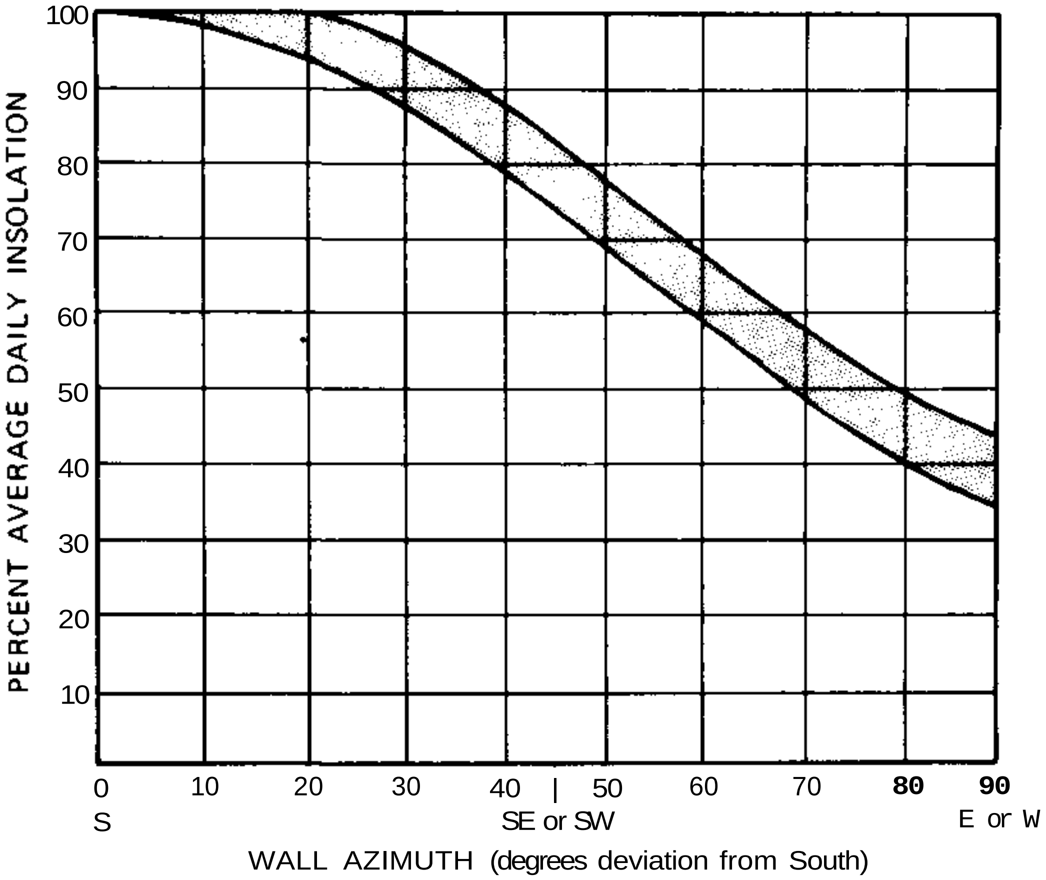


Figure B-10: The percentage of solar radiation on vertical walls for orientations away from true south (AND-2) of house orientation suggest that its principal facade should be within 22.5 of due south (between south-southeast and south-southwest), with due south preferred. It is much more important that windows be oriented south than walls. Victor Olgyay cautions against conclusions that generalize for all locations. Due south may not always be optimal, but it will almost always be better than 30° east or west of it (OLG-1). Except in complex terrain, this land planning change in subdivisions can be accomplished with little or no increased development costs.

Setback Flexibility and Minimum Lot Size

Large lots promote sprawl and increase the surface area of asphalt-paved access roads that are very hot during the summer. They also increase travel time and distance, and subsequent energy use. Setback flexibility permits proper orientation. In Davis, California, and elsewhere, Planned Unit Development Zoning and other innovative concepts permit house locations on extreme edges of lots to achieve proper orientation.

Solar Rights

In most construction situations, long-term, shade-free solar access is necessary to guarantee solar rights over the life of the building. Vegetation must be properly planned to permit access to breezes during the summer and to sunlight during the winter.

Street Width

Nonporous, heat-absorbing pavements dramatically affect the built environment. Although proper landscaping and land planning can reduce the impact of such surfaces, street design is also important. Narrow streets, for example, save valuable land and can be shaded more easily. They reduce the thermal heat load on people using the streets and reduce traffic speeds. They are more comfortable and, due to the resulting slower traffic, are often safer for bicyclists, pedestrians, and motorists. Parking bays rather than on-street parking can promote shading both over the bays and over the narrower streets. Pedestrian and bicycle systems are far more readily integrated into such a plan.

Landscaping

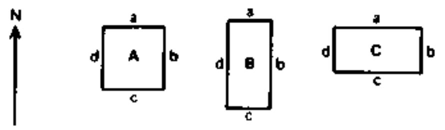
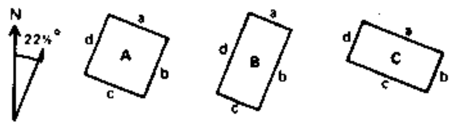
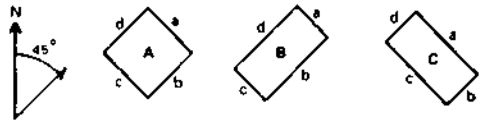
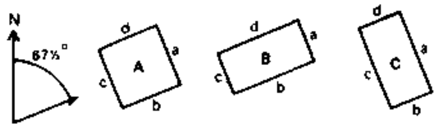
Proper vegetation and landscaping can provide environmental beauty, enhance comfort, and save energy. Large deciduous trees such as oak, hackberry, sycamore, ash, and maple provide shade, evapo-transpiration, and a

> quiet beauty that gives older neighborhoods much of their character and livability. They also shed their leaves in the winter to let the warm sun in.
>
> Proper landscaping can have subtle but multiplying effects on many energy-consuming activities. For example, shading and landscaping may often be determining factors when people decide to walk or bicycle rather than ride in air-conditioned cars. Glaring, unshaded asphalt creates desert-like microclimates in the summer. In addition, landscape design that encourages home gardening saves energy in the food sector. For each calorie of food produced by U.S. agriculture, 10 calories are expended. Home gardens do much better.

A futher consideration for siting is orientation. Knowing the relative amounts of solar radiation striking various facades can aid the designer in deciding on shape and orientation of buildings and the location of windows. Building orientations can be classified according to the four plan diagrams in Figure B-ll. Within these four orientations, the relationship between floor area and wall area have three basic variations:

A. The building has facades approximately equal in area; it is represented in the floor plan by a square.

B. The building has facades of greatly differing areas (a

FACADE ORIENTATIONS		INSOLATION ON WALL (Btu/day)				
		a	b	c	d	Total
	A	118	508	1630	508	2764
	B	84	722	1160	722	2668
	C	168	361	2320	361	3210
	DOUBLE B	118	1016	1630	1016	3780
	DOUBLE C	236	508	3260	508	4612
	A	123	828	1490	265	2406
	B	87	1180	1060	376	2703
	C	174	590	2120	188	3072
	DOUBLE B	123	1656	1490	530	3799
	DOUBLE C	246	828	2980	265	4319
	A	127	1174	1174	127	2602
	B	90	1670	835	180	2775
	C	180	835	1670	90	2775
	DOUBLE B	127	2348	1174	254	3903
	DOUBLE C	254	1174	2348	127	3903
	A	265	1490	828	123	2406
	B	188	2120	590	174	3072
	C	376	1060	1180	87	2703
	DOUBLE B	265	2980	828	246	4319
	DOUBLE C	530	1490	1656	123	3799

BUILDING SIZES: RELATIVE WALL AND FLOOR AREAS

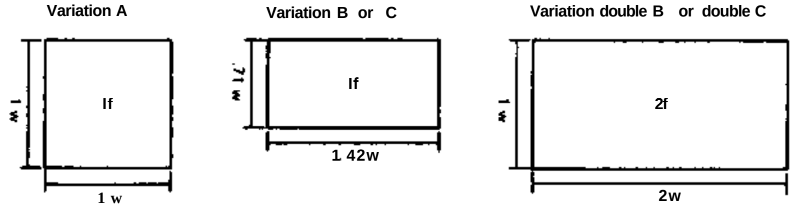


Figure B-ll: Relative irradiation on buildings of different shape and orientation — January 21, 40°N latitude. Listed values represent the irradiation on walls of a hypothetical building with w = 1 square foot. To get the daily irradiation on a building of similar shape with w = 100 square feet, multiply these numbers by 100 {AND-1).

ratio of 1 1/2:1 or greater); the long axis of the rectangle is in the direction of the compass orientation, along the left-hand edge of the figure.

C. The building has facades of greatly differing areas (a ratio of 1 1/2:1 or greater); the short axis of the rectangle is in the direction of the compass orientation, along the left-hand edge of the figure.

Figure B-ll also shows relative clear day solar radiation on resulting wall surfaces for combinations of orientation, shape, and floor and wall area. The relative values are based on clear day solar irradiation values from the ASHRAE Handbook of Fundamentals 1977 (ASH-2). This source contains data for numerous latitudes.

In the "Total" column of Figure B-ll, the total solar irradiation in January (3,210 Btu/day) on all four walls of a building with its long axis oriented in the east-west direction is greater than for a building oriented north-south (2,668) or for one that is square (2,764). In fact, east-west is the best of all variations shown. The least solar radiation is received by the square with facades facing northeast, northwest, southeast, and southwest.

When the floor area of the optimal design is doubled, the solar gain of 3,210 Btu increases by one-third (to 4,612 Btu) because the perimeter area increases by only one-third. If the floor area were doubled by adding a second floor, the perimeter area would double, as would the solar gain, to 6,420 Btu.

This summary of relative solar radiation on perimeter walls is a first step in determining floor area configuration, orientation, and window placement. A more detailed analysis would take into account the actual weather conditions, the solar impact on the roof, the variations in window location and size, the effect of heat loss, and the implications of windows for natural lighting.

B.4 LENGTH/WIDTH/HEIGHT RATIOS

In addition to proper orientation, a building benefits from optimal ratios of its length to width to height. The optimum shape loses the minimum amount of outward moving heat and gains the maximum amount of solar heat in the winter, and admits the minimum amount of solar heat in the summer. Olgyay has shown that (OLG):

- In the upper latitudes (40° N+), south sides of buildings receive nearly twice as much irradiation in winter as in summer. East and west receive 2 1/2 times more in summer than in winter.
- In the lower latitudes (35° N-) the winter-summer ratio for the south sides of buildings is even larger. During the summer, east and west walls can gain two or three times more heat than those on the south.
- Well-insulated buildings and those with shading devices on the south side show even greater variances, but those with

windows that are small or fully shaded show less.

- The square house is probably not the 'optimum' form in any location.
- All spaces elongated on the north-south axis work less efficiently than the square one in both winter and summer.
- The optimum form in every case is elongated along the east-west direction.

Besides saving energy, building shape involves other considerations. For instance, the orientation or size of the site may not accommodate the optimum shape; the needs and purposes of the building may require other shapes; or, if natural lighting is desired, more perimeter exterior surface areas and roofs may be needed for the placement of windows, clerestories, or skylights.

B.5 DAYLIGHTING

The bonus from natural daylighting in passive solar designs is impressive. In many cases, solar glazing may save more energy and money by reducing the need for artificial lighting than it saves by reducing fuel bills.

J.W. Griffith, past president of the Illuminating Engineering Society, reported on lighting studies at Southern Methodist University (GRI-1):

> "There is a considerable loss of contrast from overhead lighting when compared to . . . sidewall lighting systems. If it takes 10 to 15 percent more illumination to make up for each 1 percent loss of contrast, most of these tasks would require two to three times as much illumination. . . from overhead sources (as from) sidewall lighting."

In a 1977 ASHRAE report, Mr. Griffith said (GRI-2):

> "Daylight illumination from windows has been shown to be three to four times as effective in increasing visual performance as equal illumination from conventional electric lighting if properly utilized."

Years ago, classroom seating in many elementary schools was arranged so that daylight from sidewall windows would come in over right shoulders of left-handed people and over left shoulders of right-handed people. This kept glaring light sources out of what illuminating engineers call the offending or glare zone. As lighting contrast increases, visual performance improves rapidly.

Sufficient window area to deliver 720 lumens of "direct" sidewall window daylight in place of 1800 lumens from an overhead incandescent electric lamp will save energy and money in a variety of ways. For example, in an air-conditioned office it reduces the electric lighting load on the air-conditioning system by 93 percent.

Natural lighting systems, however, are relatively difficult to design and engineer; the Illuminating Engineering Society Handbook and other industry sources contain daylighting techniques and guidelines (IES).

SUBCHAPTER C1, FIVE PASSIVE SOLAR HEATING TECHNIQUES

DIRECT GAIN

Cl DIRECT GAIN

Cl.a INTRODUCTION

By far the most common way solar energy is used for heating buildings is its penetration through the windows of our country's 70,000,000 buildings. Without it, the U.S. would use an additional 2 to 3 percent more nonrenewable energy. Windows vary considerably in their thermal performance, however. Loosely-fitting, single-glazed windows, for example, usually lose more heat than they admit in the form of solar heat gain. On the other hand, a properly designed window facing south, with perhaps a reflective surface on the ground (such as snow or an aluminized mirrored surface) and with means of reducing heat loss significantly at night (such as movable insulation) , can supply more solar energy to a building than a good active solar collector of the same surface area. For example, properly designed solar collectors are supplying between 50,000 and 115,000 Btu per square foot of surface area per heating season in a climate of 50 percent possible sunshine. (This is equivalent to the energy from 1/2 to 1¼ gallon of home heating oil or from 15 to 35 kWh of electricity.) Winter-long solar gain through a square foot of south-facing, double-paned glass in the same climate is about 140,000 Btu. Annual conduction heat loss (ignoring air infiltration for the moment) is about 70,000 Btu in a 5,000 degree day climate. The net contribution to the building, then, is 70,000 Btu (140,000 solar gain less 70,000 heat loss). Therefore, ordinary double-glazed, south-facing windows can "produce" about the same amount of heat per square foot as solar collectors. Reflectors will boost heat production in both designs. Movable insulation and triple glazing can dramatically reduce heat loss from windows, greatly boosting their net energy gain.

In colder and cloudier climates, windows will provide less than 70,000 Btu, and in warmer and sunnier locations, more than 100,000 Btu. Another important factor determining the amount of energy provided is the size of the window area compared with the heating load. The larger the area compared with the heating load, the more excess, wasted solar heat and the lower is the contribution by each square foot of window.

Although knowledge in other areas of solar technology has vastly increased, knowledge of the thermal performance of glazed surfaces is relatively undeveloped. Although ASHRAE has produced Solar Heat Gain Factor tables to assist in sizing air conditioning equipment, corresponding tables do not exist for determining the total seasonal heat gain through windows of various types, of various orientations, and in various locations of the country. Fortunately, <u>heat loss</u> through the windows is fairly easily understood; yet, more needs to be learned.

Even as there is a dearth of knowledge regarding solar gain through windows, even less is understood of how that light energy is reflected, transformed, reradiated, and ultimately distributed once it enters a building. This lack of understanding has resulted in, and continues to result in, significant errors in the way glass is integrated into the fabric of buildings. Even today, many passively solar heated buildings that rely primarily on the direct gain of sunlight through south-facing glass and are designed by knowledgeable passive solar building designers do a poor job of satisfying human comfort (and other needs) of the building's occupants. Although the most thermally-elegant direct gain system can perform like a finely tuned machine and satisfy human comfort to a high degree, an improperly designed direct gain system can create discomfort.

The **design criteria** for properly designed direct gain systems include the following:

1. The timing must be right; the sun must enter the building at the right time of year. (Corollary: the sun must be kept out at the right time of day and year; i.e., solar heat gain must correspond to the comfort needs of the building's occupants.)

2. The <u>amount</u> of solar heat gain must correspond to the needs of the occupants. Therefore, the needs of the occupants must be clearly understood and accounted for. While some occupants may permit a wide range of temperature fluctuations, the designer should not necessarily count on it and make excuses for a poorly engineered direct gain system.

3. The right <u>type</u> of glazing should be used. Clear glass has its place, but so also do clear and translucent materials such as diffusing glass, plastic films, fiberglass-based glazings, and acrylics. Reflective glazings may be appropriate for reducing unwanted solar gains.

4. Heat loss back through the glazing should be reduced to as low a level as possible.

5. The manner in which sunlight enters the building must be compatible with the program needs of the building (i.e., the occupants). For example, many activities are not amenable to direct solar gain. Many people simply do not like working in direct sunlight. In fact, north light is often preferred. So also, in most cases, lighting from the side assists in proper distribution of light throughout a space, reducing glare. However, too much or improperly designed glass can contribute significantly to glare. Too much glass can also infringe on privacy inside a building space by creating a "fishbowl" effect.

Cl.b SOLAR GAIN

A growing awareness indicates that direct gain systems are easier to design if they are sized to provide only a limited portion of the heating load. For systems designed to only satisfy daytime heating requirements, usually around 30 percent, necessary glass areas can be easily incorporated into most building facades. Although heat storage requirements should not be ignored, they are not the overwhelming consideration that they are at high (50 to 80 percent) solar fractions. Most of the other problems associated with direct gain systems are also reduced.

Establishing the allowable interior temperature fluctuations during a sunny winter day is the first step for determining the largest desired window area. Doug Balcomb describes the subsequent analysis.* Glass area in excess of the resulting size will admit unnecessary and undesirable energy, and will reduce yearly fuel bills only slightly. In some cases, additional area can actually increase fuel bills.

The glass should be placed facing as close to south as possible. Since shading is more difficult during the summer, avoid deviations from due south beyond southeast and southwest. However, even in cold climates, east and west glass areas can admit somewhat more solar energy during the winter than they lose, assuming thermal shades cover the windows at night to reduce heat loss.

Glass placed vertically admits nearly as much heat during the winter as glass at the tilted angles that are optimum for many active system collectors. However, tilted glass is difficult to shade during the summer; left unshaded, it admits unwanted heat. In addition, large areas of tilted glazing may be difficult to integrate into a building's overall design; tilted glazing is noticeably more difficult to keep clean and (possibly) undamaged by flying objects. Many codes require the use of tempered glass in all tilted configurations located above occupied space.

Window area should be incorporated into the walls and roofs of buildings to distribute the heat to as much of the building as possible.

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*See Passive Solar Design Analysis by J. Douglas Balcomb.

Usually, the best means of doing this is for all rooms to have south-facing glass. To reach northern rooms, vertical clerestory windows for easier summer shading are preferred over sloping skylights. Sawtooth roofs distribute south sun throughout interior portions of large-roofed buildings.

A principal consideration in locating windows is to enhance the exposure of the thermal mass to direct sunlight. For example, if the building has heavy floors and walls, windows should be placed so that as much floor and wall surface as possible is bathed in light. Translucent glass with good transmittance will scatter the light through the space, distributing the heat to many surfaces at once. This can both keep interior temperatures down and improve the lighting quality. Translucent surfaces produce more glare, and this must be considered in their design.

In the final design, these many thermal considerations must be blended with aesthetics and with the overall purposes of the building.

Cl.c THERMAL MASS

Using mass heat storage in the design of residential buildings is as old as the concept of shelter itself. For centuries massive adobe Indian dwellings in the southwestern United States have tempered the effects of wide fluctuations in daily temperatures on interior comfort conditions. The centercore fireplace and hearth mass of New England homes stores heat from the fire during the day and slowly releases that heat at night to keep the houses warm as the fire dies.

A different phenomenon is represented by each of the above two examples. In the case of the adobe structures, the high mass exterior walls soak up large amounts of sunlight like a big thermal sponge. As their exterior surfaces warm during the day, the heat slowly moves through the adobe as each successive inch is warmed by the inward wave of heat.

Under steady-state conditions, i.e., when the indoor and outdoor temperatures are stable for long periods of time, the temperature of the masonry material (such as adobe and concrete) also becomes stable. Under these conditions, the masonry materials are poor insulators; heat flows easily through them. If, however, either the indoor temperature or the outdoor temperature or both fluctuates, so must the masonry. Each successive layer of the masonry mass must first change temperature before passing excess thermal energy on to the next layer in line, and this slow process somewhat impedes heat flow.

An advantage of masonry as heat storage material is that each layer can store a large amount of heat. Thus, if the sun is shining on a masonry wall, the masonry facing the sun is warmed before it transfers heat inward. Then the next layer is warmed by the surface layer and so on. The result in the adobe dwellings is that outdoor temperatures can fluctuate widely while the indoor temperatures remain relatively stable. (See Figure Cl-1.)

In contrast to the high thermal mass of the adobe buildings that "sponge up" the sun's energy, the thermal storage of the Colonials absorbs interior heat, storing excess daytime energy for use at night. Most of this stored heat is released to the building before escaping through its exterior skin.

The thermal mass need not be at the center of the room as long as it is insulated from the outdoors. It is important that as the room heats up from the sun, the masonry absorbs the heat and loses as little of it to the outside as possible. Although having the mass entirely within the space assures that every stored Btu is first used by the building, heavy insulation on the exterior surface can provide a similar effect.

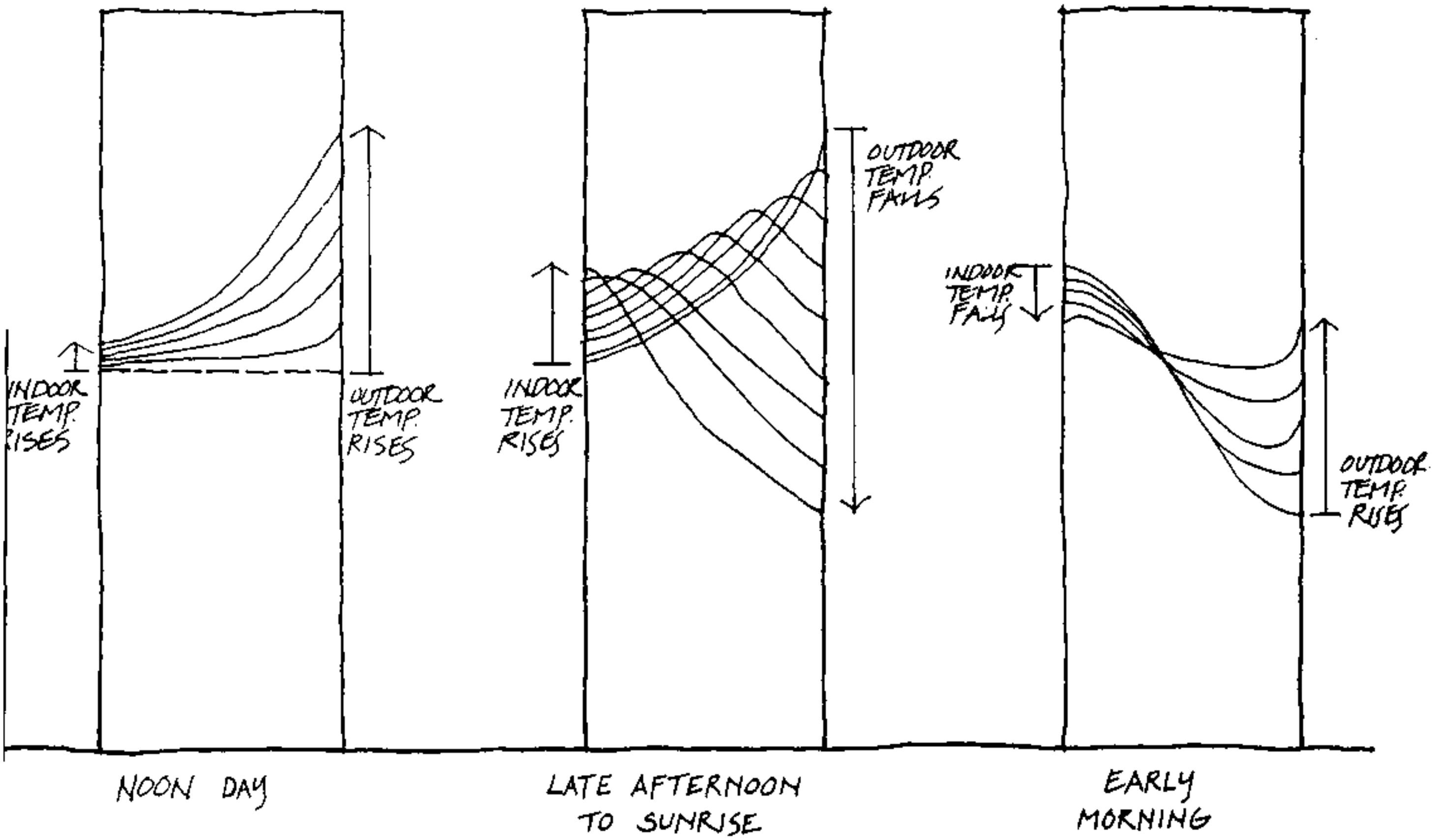


Figure Cl-1: Diagrammatic daily temperature profiles through a thick, masonry wall (PUT).

The wave of heat through the masonry walls is similar to the heat waves through sunbathed adobe walls. The temperature of masonry adjacent to exterior-mounted insulation fluctuates very little due to the small R-value of the masonry compared to the larger R-value of the insulation. Therefore, when outdoor temperatures change, most of the temperature fluctuations in the wall occur in the insulation before reaching the concrete. The masonry, then, changes temperature as the building changes temperature, adding to its thermal capacity.

Mounting insulation on the outside of the concrete entails detailing problems. In some cases, this may cost more than interior-mounted insulation. The cost-benefit of exterior insulation must be analyzed on a case by case basis.

Although fluctuations in room temperature cause thermal mass to change temperature, the thermal mass can be raised to a higher temperature and can store more heat by direct exposure to sunlight.

Of course, the primary reasons for incorporating thermal mass into buildings are to temper the effects of large amounts of sunlight entering a building on the indoor temperature by absorbing the excess thermal energy for later use when the sun is not shining into the building.

Generally, the more thermal mass the better. The greater the exposure of the mass to solar irradiation, the smaller will be the interior temperature fluctuations.

The effects of fluctuating outdoor temperatures on indoor temperatures are shown in Figures Cl-2, Cl-3, and Cl-4. For example, the effect a sharp drop in outdoor temperature has on the indoor temperature of various types of buildings is shown in Figure Cl-2. Note that an unheated, lightweight building (e.g., wood-framed) drops in temperature relatively quickly even if it is well-insulated. A heavy, massive, well-insulated structure built of concrete, brick, or stone maintains its temperature over a longer period of time. (The insulation should be located outside the thermal mass.) The third indoor air temperature shown in the figure is for a building that not only contains a great deal of heat storage capacity but also is buried into the side of a hill or is covered with earth. The temperature drops very slowly and levels off at a temperature close to the earth's.

During the summer, the opposite conditions prevail. If the building is shaded so that little direct solar irradiation penetrates, the heat gain will be limited primarily to conduction through the roof, walls, and windows — in effect, a reverse heat loss. When outside air is cool-

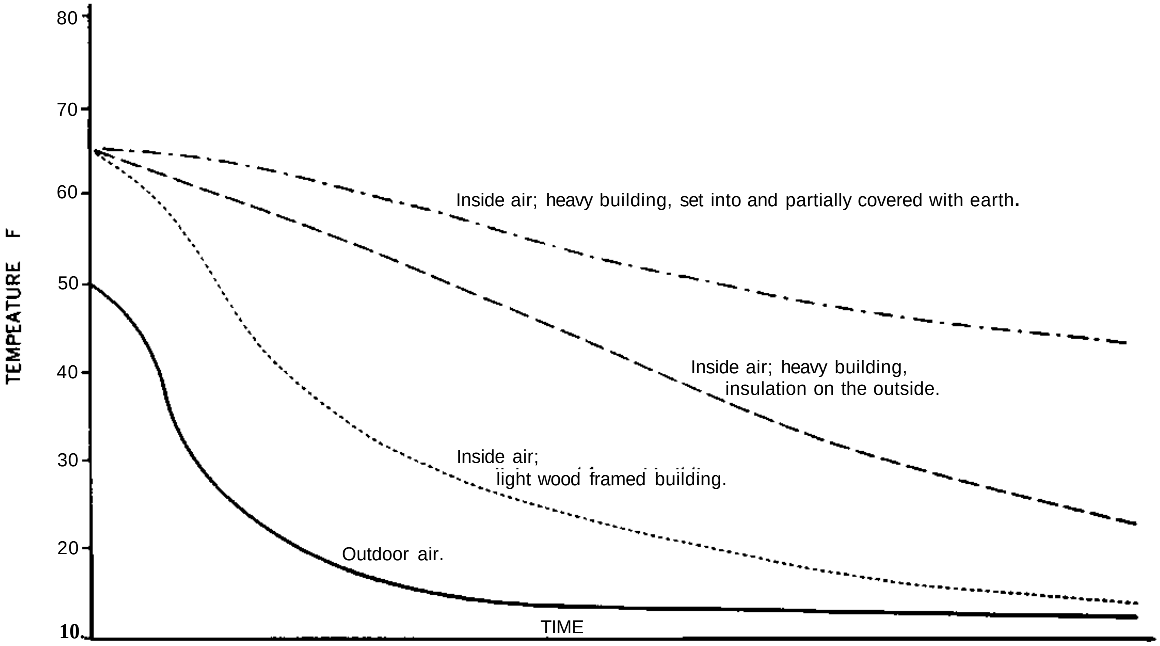


Figure C1-2: Effect of a drop in outdoor temperature on indoor temperature for various construction types, assuming no source of heat energy within the building (AND-2).

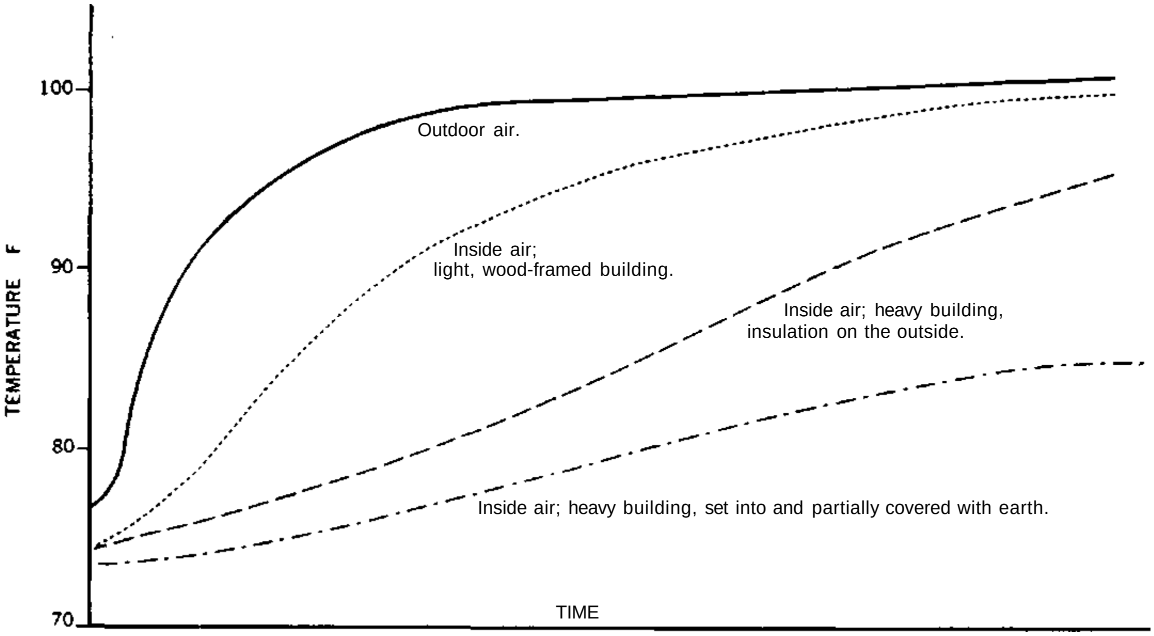


Figure Cl-3: Effect of a rise in outdoor temperature on indoor temperature for various construction types, assuming no source of cooling energy within the building (AND-2).

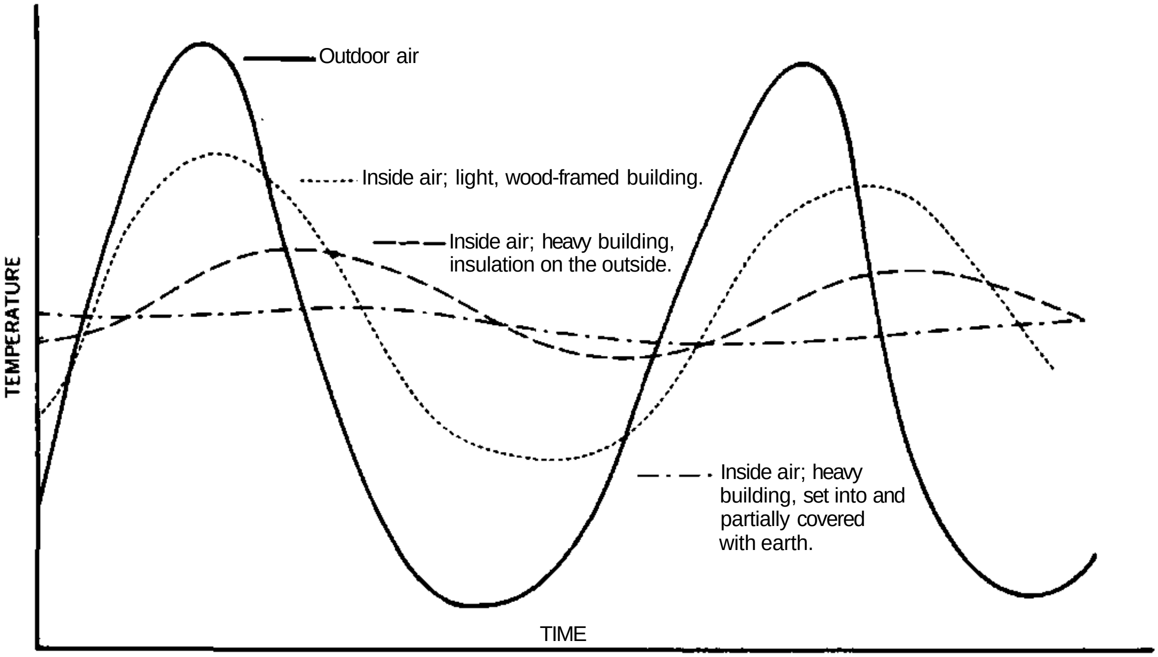


Figure Cl-4: Effect of fluctuations in outdoor temperature on indoor temperature for various construction types, assuming no source of heating or cooling energy within the building (AND-2).

er at night than it is during the day, ventilation of that air into the building, either naturally through openings such as vents or windows or mechanically with fans, can cool the thermal mass, delaying the need for daytime air conditioning. (See Figure Cl-3.) The savings is not usually sufficient to justify expensive thermal mass and is usually regarded as a summer bonus of the passive heating system.

Figure Cl-4 combines the effects of rising and falling outdoor temperatures. Without any internal sources of heat such as furnaces and stoves, the inside air temperature of the lightweight building fluctuates widely, and the air temperature of the earth-embedded building remains almost constant. Notice that increased building mass not only attenuates the amplitude of the temperature fluctuations but also causes a longer time lag between fluctuating interior and exterior temperatures.

All materials vary in their heat storage capacity. The ability of a material to store heat is measured by "specific heat," the number of Btu required to raise one pound of the material 1 degree F in temperature. Water, for example, has a specific heat of 1.0, which means that one Btu is required to raise one pound of water one degree. The pound of water, in turn, releases one Btu when it drops one degree.

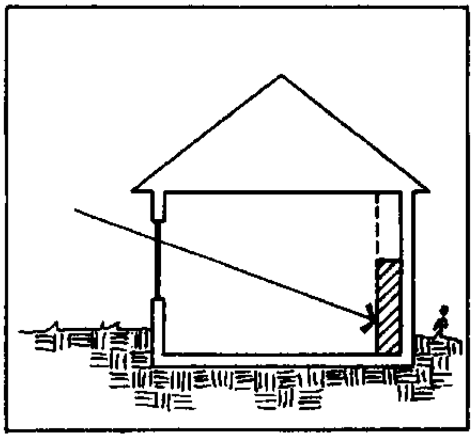
The specific heats of the various materials that might be considered in the construction of buildings are listed in Appendix 2. Note that concrete (specific heat of 0.2) stores only one-fifth the energy stored by the same weight of water. However, the density of concrete is greater than the density of water. The second column of the table shows the relative densities. To obtain a material's heat capacity per cubic foot, multiply its specific heat by its density. The product, which is the heat capacity per cubic foot, is listed in the third column. Note that the density of water is least among the materials listed but that its heat capacity per cubic foot is still highest because of its high specific heat. In spite of the low specific heat of concrete, its heavy weight compensates somewhat, and it stores considerable heat (28 Btu per cubic foot per degree F for concrete versus 62.4 for water).

The effectiveness of a building's thermal mass should not be taken for granted. Designing to permit direct solar irradiation to strike the thermal mass can greatly interfere with a building's program requirements. For example, many people prefer to close their drapes to keep out the sun's direct rays. Very often, the thermal mass is covered with other materials, such as carpet over concrete floors, that nearly negate its thermal storage effectiveness.

The effectiveness of thermal mass also depends on its location. If the mass is located in direct sunlight, it is heated without the room air being heated in the process. The temperature of the mass, therefore, is not limited by the temperature swings tolerable in the living area. The opposite situation occurs when the mass is located in a back room completely removed from direct sun effects. In this case, the solar heat first must be transferred to the room air and then the warm air heats the mass. This two-step process is much less effective than directly heating the mass. In fact, a general rule-of-thumb is that four times as much mass is required to store the same amount of heat if the mass is heated indirectly (by room air) rather than directly. Mass that lies within a direct gain space, such as the enclosing walls of that space, receives some heat directly as a result of scattered sunlight and infrared heating by lightweight objects in the space. The effectiveness of this mass lies somewhere in between, depending on color, location, and the sunlight scattering characteristics of both the room and the glazing.

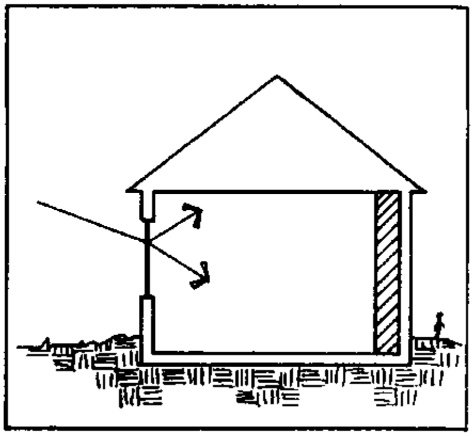
An alternative to direct solar irradiation through clear glazing is glazing that diffuses the light and distributes it over all of the interior surfaces. Although particular surfaces may not get unduly warm, such dispersion of solar radiation more readily assures an even heat distribution to all surfaces, resulting in more even temperatures. It also results in smaller fluctuations in the temperatures of a particular mass. Heat movement into the mass is accomplished much more quickly without overheating the space. Glare may be worse with this system than with clear glazing.

Ed Mazria and others have analyzed these effects. With large surface areas to absorb the heat, room air temperature fluctuations are moderated. Figures Cl-5, 6 and 7 show three different system types. System 1 represents a directly exposed interior thermal mass surface area of 1.5 times the area of glass. System 2 has three times the area in direct sunlight, and System 3 has nine times the area. System 3 is typical of spaces constructed of masonry materials and translucent glazing. In computer simulations, System 3 maintains the highest



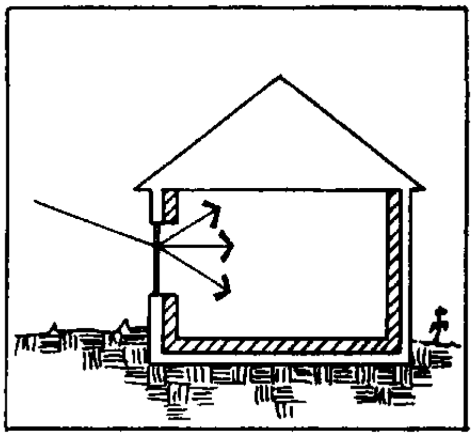
System 1

Exposed surface area = 1.5 × glass area



System 2

Exposed surface area = 3 × glass area



System 3

Exposed surface area = 9 × glass area

Figures Cl-5,6, and 7: Three different system types (MAZ-1) minimum air temperatures and the smallest daily temperature fluctuations. Both Systems 1 and 2 required some ventilation to prevent overheating during the day. The designs were for 8-inch-thick walls and floors; glass area was 25 percent of the floor area. The overall heat loss of the building was in the range of 10 to 12 Btu/ft^2 -degree day (MAZ-1).

Each heat storage material has a different effect on interior temperature fluctuations. The higher the conductivity of the thermal mass, the more readily it absorbs heat and the smaller the temperature fluctuates. Ed Mazria has simulated the performance of concrete (stone), brick (common), brick (magnesium additives), adobe, and water (contained in cans, representing an "isothermal" mass). These materials have the physical properties listed in Figure Cl-8.

Figure Cl-9 shows interior temperature profiles for the five different types of thermal mass in Mazria's System 2. The thermal storage materials are 8 inches thick (MAZ-1). The largest interior air temperature fluctuations occur using adobe, which has the poorest conductivity. The best performance, resulting in the smallest temperature fluctuations, occurs using brick having magnesium additives and using conventional building materials. Water ("isothermal") is better than any of the common construction materials.

Rules of thumb for thermal mass size have been established. If the mass is directly irradiated by solar energy, each square foot of the glass requires enough mass to store 30 Btu for each degree F change in temperature. (See Doug Balcomb's Passive Solar Design Analysis.)

MATERIAL	CONDUCTIVITY (k) BTU/HR FT^{2}F (W/M^2 °C)	SPECIFIC HEAT(C_p) BTU/LB F (KJ/KG °C)	DENSITY (ρ) LB/FT (KG/M^3)
CONCRETE (STONE)	12.0 (1.70)	0.20 (0.84)	140.0 (2,240)
BRICK (COMMON)	5.0 (0.72)	0.20 (0.84)	120.0 (1.920)
BRICK (MAGNESIUM ADD.)	26.4 (3.80)	0.20 (0.84)	120 (1,920)
ADOBE	3.6 (0.52)	0.24 (1.00)	106.0 (1,700)
WATER (ISOTHERMAL)	-	1.00 (4.19)	62.4 (1,000)

Figure C1-8: Thermal storage material properties (MAZ-1)

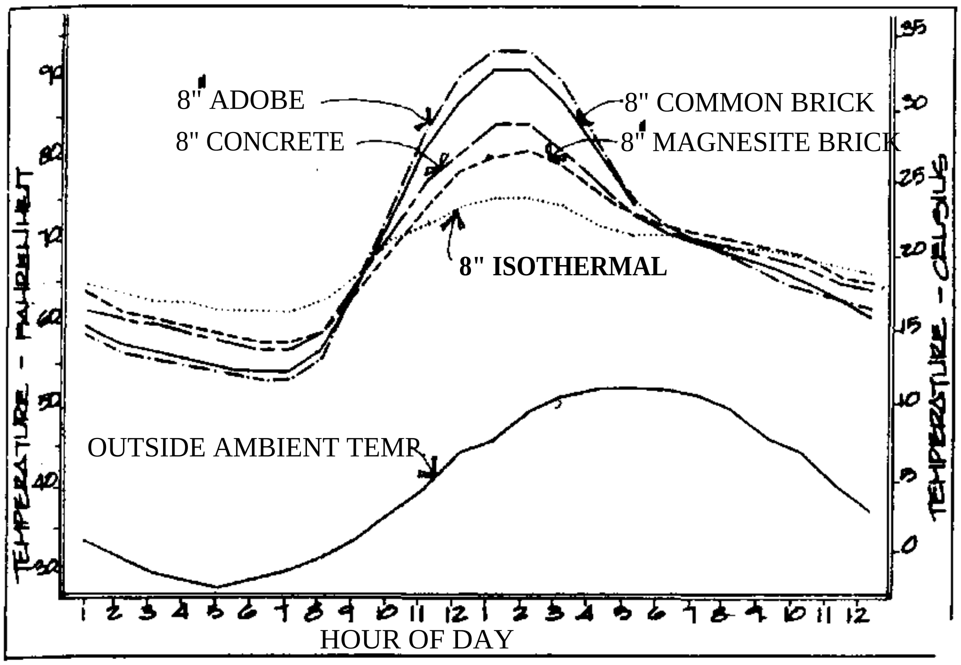


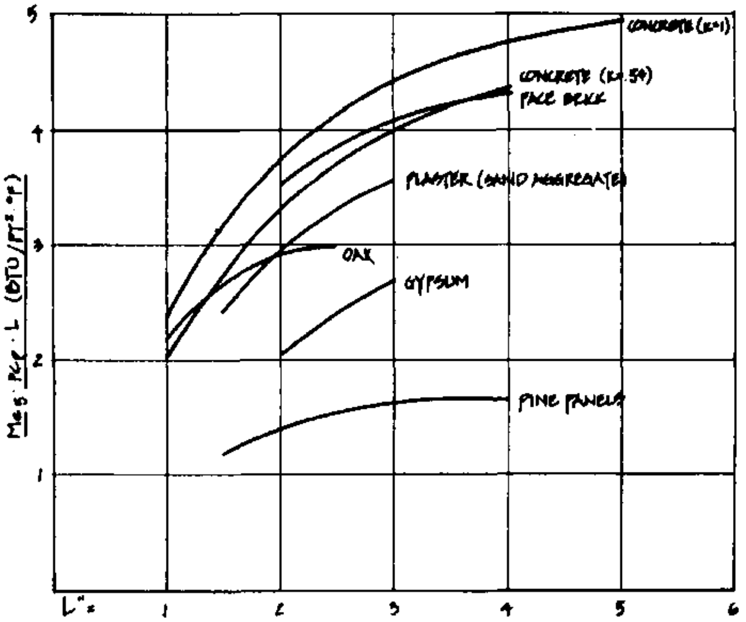
Figure Cl-9: Comparison of materials (MAZ-1).

For mass exposed only to heated room air, four times as much is required. Concrete stores roughly 30 Btu/ft^3 for each degree change in temperature, and water 62.4 Btu/ft^3.

When the mass is in direct sunlight, the temperature swing of the room air will be approximately half the temperature swing of the storage. If the mass is not directly irradiated, the temperature swing of the room air will be approximately twice the temperature swing of the storage.

If less storage is used, the temperature swing of the room air will increase. This may decrease comfort and increase heat loss from the building (especially if the occupants open windows to reduce the overheating) . Conversely, more mass will increase the comfort and efficiency of the passive system.

The effectivness of mass depends on its thickness and on its thermal conductivity. The mass that is located at depth is not nearly as effective as the mass at the surface because it is insulated from the room by the surface layers. For example, if the wall is concrete, then mass within 4 inches of the surface is nearly as effective as mass at the surface; but beyond a depth of about 8 inches the mass is almost completely ineffective. (See Figure Cl-10.)



Effective thermal storage per square foot of surface area of non-solar irradiated mass materials listed and thickness, t.
Free standing wall, t = 2L
Back insulated wall, t = L

Figure Cl-10 (MIC)

The actual performance of a thermal mass system designed to use solar energy inputs to meet space heating needs can be measured in two ways:

1) Fractional Savings
2) Fractional Utilization

Fractional savings is the ratio of the energy savings (due to useful solar gains) to the heating or cooling load before solar. Fractional utilization is the ratio of useful solar gains used to meet the heating or cooling load to the total available incident solar radiation.

When assessing cost-benefits, fractional savings is more commonly used. However, for understanding the behavior of different thermal mass systems, fractional utilization is more informative. This ratio indicates the efficiency with which the mass converts available solar radiation to useful solar energy for heating or cooling.

For any ratio of available solar radiation to gross heating or cooling loads (solar-load ratio), the actual performance of the system is dependent on the total mass heat storage capacity and on the mass effectiveness. The mass effectiveness factor (M_e) is defined as the ratio of heat storage actually achieved to the maximum possible heat storage.

In an idealized system, the mass effectiveness is 100 percent, and the system performance is a straight-line function of solar-load ratio (see Figure Cl-11). If, for example, in these cases the available solar radiation is half the heating load, the solar-load ratio is 0.5 (50 percent), and the fractional utilization is 1.0 (100 percent). All of the solar radiation can be used to reduce the space heating load.

For less than perfect systems in which the mass effectiveness is less than 100 percent, the actual performance will be lower. Since heat transfer into the mass is less than perfect, some overheating of the space will occur. Higher space temperatures mean that extra heat is lost to ambient, and, therefore, less energy will be available to fulfill heating needs during the evening.

For any given thermal mass system (a given storage capacity and mass effectiveness), the fractional savings will increase toward 1.0 and the fractional utilization will decrease toward 0 as the solar-load ratio increases. The graphs in Figure C1-11 qualitatively show this relationship for storage systems of different mass effectivenesses.

When the solar-load ratio is small, the fractional utilization tends to be good since there exists a relatively large heating load to which solar gains can be immediately applied without need for storage. Since storage plays a small role at this point, differences in mass effectivenesses among different systems are less important. As shown in Figure C1-11, system performance is not a function of mass effectivenesses at solar—load ratios below 0.25.

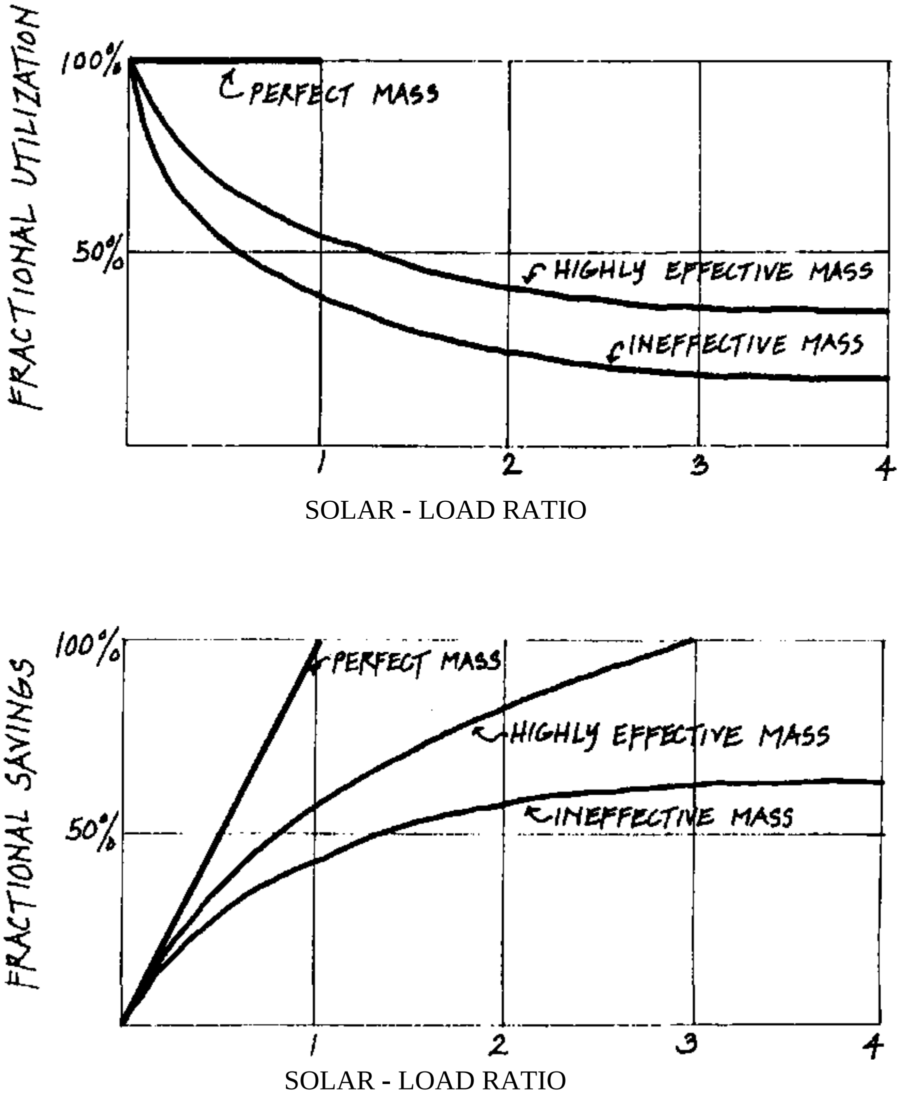


Figure Cl-11: Sensitivity of thermal mass system performance, diagrammatic (TEA).

As the solar-load ratio increases, the fractional utilization for all systems (except the perfect storage system) drops off. Fractional savings increase more and more slowly as it becomes more difficult to store the solar energy gains until they are useful.

An example will illustrate this point. Take two well-insulated houses in Concord, New Hampshire. One has 111 square feet of south-facing windows, and the other has almost twice this window area (221). Furthermore, assume that on a monthly basis the mass effectiveness of the storage system for both houses is 100 percent. This implies that all the available solar radiation can be used up to the point where the monthly heat load is met. None can be saved for the following month. Figures C1-12 and C1-13 show the performance of the two houses. Note that in house one the available solar radiation exceeds the house heating requirement from May through October. During these months, the utilization is less than 1.0 (not all of the solar radiation is useful). The fractional savings in this case is 0.37, and the fractional utilization is 0.56.

In house two (with the larger window area), the available solar radiation exceeds the heating load from April through October. In this case, April is added to the list of months when not all of the solar radiation can be usefully applied to the heating load. The fractional savings for this house is 0.66. Note that this is not twice the fractional savings for house one, and the fractional utilization is less (0.49) than that for house one. This means that the second 110 square

Month	Average Daily Radiation	Monthly Incident Radiation	Monthly Heat Load	Solar-Load Ratio	Useful Heat
Jan	536	1.84 (10^6Btu)	7.36 (10^6Btu)	0.25	1.84 (10^6Btu)
Feb	609	1.89	6.13	0.31	1.89
Mar	602	2.07	5.06	0.41	2.07
Apr	544	1.81	2.27	0.80	1.81
May	482	1.66	0	—	0
Jun	460	1.53	0	—	0
Jul	472	1.62	0	—	0
Aug	523	1.80	0	—	0
Sep	606	2.02	0	—	0
Oct	665	2.29	1.34	1.71	1.34
Nov	473	1.58	3.58	0.44	1.58
Dec	427	1.47	6.53	0.23	1.47
	Btu/ft^2 day	21.58×10^6	32.27×10^6		12.00×10^6

$$\text{Fractional Savings} = \frac{12}{32.37} = 0.37$$

$$\text{Fractional Utilization} = \frac{12}{21.58} = 0.56$$

$$\text{Productivity} = \frac{12 \times 10^6 \text{ Btu/yr}}{111 \text{ ft}^2} = 108{,}108 \text{ Btu/ft}^2 \text{ yr}$$

Figure Cl-12: Monthly performance of 111 square feet of window area on a well-insulated house in Concord, New Hampshire.

Month	Average Daily Radiation	Monthly Incident Radiation	Monthly Heat Load	Solar-Load Ratio	Useful Heat
Jan	536	3.67 (10^6Btu)	7.36 (10^6Btu)	0.50	3.67 (10^6Btu)
Feb	609	3.77	6.13	0.62	3.77
Mar	602	4.12	5.06	0.81	4.12
Apr	544	3.61	2.27	1.59	2.27
May	482	3.30	0	—	0
Jun	460	3.05	0	—	0
Jul	472	3.23	0	—	0
Aug	523	3.58	0	—	0
Sep	606	4.02	0	—	0
Oct	665	4.56	1.34	3.40	1.34
Nov	473	3.14	3.58	0.88	3.14
Dec	427	2.93	6.53	0.45	2.93
	Btu/ft^2 day	42.98×10^6	32.27×10^6		21.24×10^6

Fractional Savings $= \dfrac{21.24}{32.27} \approx 0.66$

Fractional Utilization $= \dfrac{21.24}{42.98} = 0.49$

Productivity $= \dfrac{21.24 \times 10^6 \text{ Btu/yr}}{221 \text{ ft}^2} = 96{,}109$ Btu/ft^2 yr

Figure C1-13: Monthly performance of 221 square feet of window area on a well-insulated house in Concord, New Hampshire.

feet of windows added to house two are not performing as well as the first 111 square feet. This trend continues as window area is added.

Variations in the fractional utilization caused by the efficiencies of different thermal mass systems becomes more obvious as the solar-load ratio increases. The final cost-effectiveness becomes more sensitive to these variations than at low solar-load ratios. At large solar-load ratios, the overall effectiveness of a thermal mass system can translate to substantial differences in absolute energy savings. Systems that combine low heat capacity and low mass effectiveness will reduce purchased energy consumption less than systems that combine high heat capacities and high mass effectiveness factors.

The first cost of systems with large heat capacity and high mass effectiveness may be steep so that the most cost-effective system is not always the one that produces the highest utilization factor. However, if the fractional utilization is very low, as will be the case with little or no mass at high solar-load ratios, then the reduction in conventional energy use will be again insignificant. Therefore, at moderate-to-high solar-load ratios, thermal mass systems of adequate capacity and effectiveness should be used to keep the utilization and fractional savings high.

Since mass is heavy and since floors are adjacent to windows, a common method for storing heat in a direct gain system is in the floor.

Yet even the best floors designed for solar exposure are very often covered or shaded by rugs and furniture, and can be rarely counted on for heat storage. If not directly exposed to the sun, floors store little heat as the room fluctuates in temperature since convectively coupled heat transferred downward is generally low.

In any case, the floor need not be thicker than 4 inches. Additional thickness saves only marginally more heat. Dramatic thicknesses, for example several feet of earth topped by a floor slab, will have a tempering effect on interior temperatures during long, cold, cloudy spells, but the extra cost can be rarely justified solely on the basis of reduced fuel bills. Nevertheless, in combination with extremely tight construction, these extra-thick floors can enable buildings to coast through bad weather with little or no backup heat if temperatures are permitted to drop.

Thermal mass is often costly and its inclusion can inconvenience the construction process. For example, extra floor area may be needed to accommodate thick masonry walls. If the use of mass requires a different type of construction than normal, this may jeopardize the building's sale.

Remote thermal mass in the form of gravel beds has been used in an attempt to counteract these problems. Gravel beds are often 2 feet deep and are usually located beneath the floor slab of the building. Overheated room air is blown horizontally through the bed. The heat rises through the floor slab directly into the space. Unfortunately, due to the moderate temperatures of overheated rooms, large volumes of air must be moved. This requires large fans and considerable energy. Also, the temperature of the gravel bed increases so slightly that it stores little heat. Gravel beds are not advised for direct gain systems unless room air temperatures in the 80's and 90's can be stored. But they can be considered for attached sunspaces and are discussed in more detail in Chapter C5.

On-site, indigenous, local building materials should not be underestimated as a means of simply and less expensively adding large quantities of mass to buildings. Local materials require less energy to transport. Adobe buildings in the Southwest demonstrate some of the possibilities. This type of regional approach to building design will help relax the demand on other more depletable resources such as wood, metals, and plastics (PLI).

C1.d MOVABLE INSULATION

An inescapable fact of building thermal performance is the high heat loss rate of glass compared to the low rate for well-insulated walls. In fact, a single sheet of glass has a heat loss rate of close to 30 times that of a high-quality wall. Insulating glass has one-half the heat loss rate of single glass and, if facing south, gains more heat than it loses during the winter nearly everywhere in the country.

Reducing heat loss through glass is one of the best ways to improve the performance of direct gain systems. Adding layers of glazing is one of the best alternatives, especially in cold climates. In climates of more than 5,000 degree days, triple glazing is justifiable by many methods of economic analysis. Although each layer of glass also blocks 10 to 20 percent of the solar gain, more than three layers is sometimes cost-effective in cold climates, especially if installed inexpensively. Multi-layered glazing systems (four and even five) that use high transmittance glazings (up to 0.97) are becoming available. Low heat loss glazings are also being developed. Chapter E, for example, describes the Heat Mirror™ , an ultra-thin coating applied to both sides of a plastic film.

Insulating the glass at night is growing in popularity. The essence of the concept is transforming a high heat loss window that gains large quantities of solar heat during the day into a low heat loss wall at night. The number and range of choices is large (SHU-2). Examples include:

- Sheets of rigid insulation manually inserted at night and removed in the morning
- Roller-shade devices using wood or plastic slats such as those commonly used in many European countries
- Framed and hinged insulation panels
- Roller-like shade devices of one or more sheets of aluminized mylar, sometimes in combination with cloth and other materials

- Sun-powered louvres, such as Skylid™ , that automatically open when the sun shines and close when it doesn't
- Mechanically-powered systems, such as Beadwall™ , that use blowers to fill the air space between two layers of glazing with insulating beads at night

The R-values of most movable insulating devices range from 4 to 10. Figure C1-14 shows the effect on the U-value of different glazing systems when movable insulation is added. Also listed are U-values that are averages for glazings covered by insulation during different amounts of time. More degree days occur at night than during the day; therefore, approximately two-thirds of the daily degree days occur when the movable insualtion is in place for 12 hours at night. About three-fourths occur when it is in place 16 out of the full 24 hours.

To find the annual reduction in conduction heat loss using movable insulation, multiply the resulting difference in the U-value times the number of degree days times 24 hours per day. The equation is:

$$E = (U_{g1} - U_a) \left(\frac{\text{degree days}}{\text{year}}\right) \left(\frac{\text{24 hours}}{\text{day}}\right)$$

where:

E is the annual energy savings in Btu/ft^2 yr;

U_{g1} is the U-value of the glass without insulation, in Btu/hr ft^2 F;

U_a is the average U-value of the glass with the insulation in place part of the time.

Solar Transmission Values	Single* Glass	Double Glass	Triple Glass
Nominal Solar "Transmittance"	0.87	0.76	0.66
Approximate Seasonal Transmittance	0.80-0.85	0.64-0.72	0.51-0.61
U-values (winter)**			
Nominal U-value	1.15	0.55	0.35
With R-4 Insulating Cover	0.21	0.17	0.14
Average U-value with R-4 Cover in Place, 16 hr/day (3/4 of the degree days)	0.45	0.27	0.20
Average U-value with R-4 Cover in Place, 12 hr/day (2/3) of the degree days)	0.52	0.29	0.21
With R-10 Insulating Cover	0.09	0.085	0.078
Average U-value with R-10 Cover in Place, 16 hr/day (3/4 of the degree days)	0.36	0.20	0.15
Average U-value with R-10 Cover in Place, 12 hr/day (2/3 of the degree days)	0.44	0.24	0.17

*for 1/8-inch grade B window glass only.
**values are slightly different in summer.

Figure C1-14: U-values for glazing with movable insulation.

For example, suppose that an R-10 panel is considered for double glazing in Minneapolis. It is assumed that the insulation will be in place two-thirds of the time. From Figure C1-14, the U-value of the glass, U_{g1} , is 0.55 Btu/hr ft^2 F. U_a is 0.24. Minneapolis averages 8382 degree days per year. The above equation becomes:

$$E = (0.55 - 0.24)\ (8382)\ (24) = 62{,}362\ \text{Btu/ft}^2\ \text{yr}$$

This is roughly equivalent to the heating energy obtained from 18 kWh of electric resistance heating, 1 gallon of oil burned in a poorly adjusted furnace, or 1 square foot of an active solar collector of average design. A tight-fitting shutter also reduces air infiltration losses and raises the mean radiant temperature and corresponding feeling of comfort.

Glass loses heat at a rate directly related to the temperature of the air space between it and the shutter. Many insulating shutters do not save as much energy as they theoretically should because they do not seal tightly when closed. As a result, room air finds its way between the glass and the shutter, and the temperature of the air space increases. Subsequent heat loss is greater, and the insulating effect of the shutter is diminished.

A few cautioning words are in order. Insulating material on the inside surface of one or more layers of glass is similar in design to a flat-plate collector. It will get hot when the sun hits it, and thermal stresses can cause glass breakage. The more tightly the shutter fits, the hotter the glass will become. A highly reflective surface on the material facing the glass is the best solution but may not be foolproof.

Another caution is to beware of condensation. If the insulation is located on the indoor side of the glazing, then the inside glass surface will be only slightly above outside air temperature. Condensation of moisture out of the air between the insulation and the glazing is probable, especially if the inside humidity is high and the outside air temperature is low. Water droplets or ice will form on the glass. In one installation in Sweden (Termeroc House) this caused such a problem that the insulation was removed.

Insulation may also be located outside the glazing (or in rare cases between the glasses in double glazing as in Beadwall) with resulting advantages and disadvantages. If the insulation is outside the glazing, then tight sealing is even more important due to wind and infiltration of outside air into the space between the insulation and the glazing. Operation of the movable insulation is more difficult. However, because the insulation is outside, the inner glass surface remains warm and condensation is not a problem. Also, as a shade in the summer, the insulation is much more effective if it is located outside. The overheating problem described above does not occur.

The design of the south-facing glazing system affects the contribution to the heating load that solar can provide with the assistance of the thermal mass. As Figure C1-15 indicates, without night insulation, single glazing, regardless of size, can provide up to only 30 percent of the heating needs, even with unlimited storage. Double glazing dramatically improves the annual solar heat fraction, but night insulation is even more important.

C1.e EXAMPLES OF DIRECT GAIN BUILDINGS

C1.e.1 David Wright's House, Santa Fe, New Mexico

Direct gain is through the south side of this semi-cylindrical house which has 384 square feet of insulating glass. There are few windows elsewhere. Seventeen-inch-thick adobe walls and a 2-foot-thick adobe floor are insulated on the outside by 2 inches of polyurethane foam. The house loses about 13,000 Btu per degree day. On a clear January day, as much as 500,000 Btu enter the house through the south windows. The temperature of the house is permitted to fluctuate between 60 to 80 F. This fluctuation, in combination with the large expanse of glass and large volume of thermal mass, permits 90 percent of the heating needs to be satisfied by solar in the 6200 degree day climate of Santa Fe, New Mexico.

At night, heat loss through the south-facing glass is reduced by folding, insulating shutters made of 2-inch-thick foam insulation covered

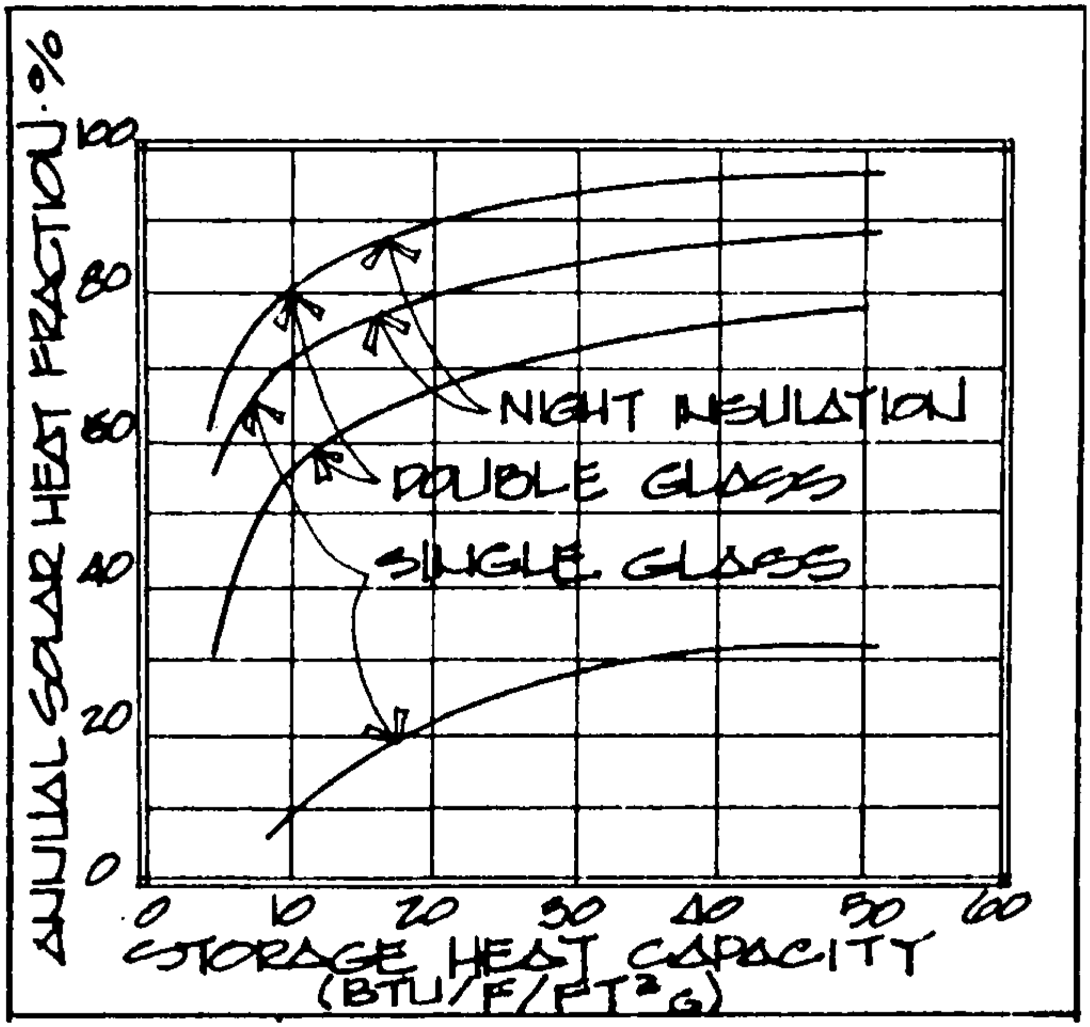


Figure Cl-15: The size of the annual solar heat fraction varies with the design of the glazing system and with the amount of heat storage capacity that is coupled to the glazing system (MAZ-1). Original figure by Balcomb.

with canvas. (See Figure Cl-16.) Since the shutters have no side seal, they are not as effective as they would be if tightly sealed.

C1.e.2 St. George's School, Wallasey, England

St. George's School is located on the west coast of England at 53.4° north latitude. Despite rather poor winter solar conditions, it annex has operated with nearly no backup heat since 1962. More than half its heat comes from the double-glazed south wall, 230 feet by 27 feet. Approximately one-third of the heat comes from the electric lighting and the balance from the metabolic heat of the students. The two layers of glass are spaced 24 inches apart, permitting entry between them for repairs and other operations. The inner glass has a rippled surface, diffusing the penetrating light to the floor, walls, ceilings, students and furniture. Several operable windows with clear glass provide both a view and ventilation. There is no movable insulation. (See Figure C1-17.)

The building has considerable thermal mass. The floors are 9- to 10-inch-thick concrete. The partitions are 9-inch brick, as is the upper portion of the north wall. The sloping roof is 7-inch concrete. Five inches of expanded polystyrene are outside the sloping ceiling.

The lights are operated on a timer, typically from 6:00 a.m. to 8:00 p.m., and are used as little as possible in the summer.

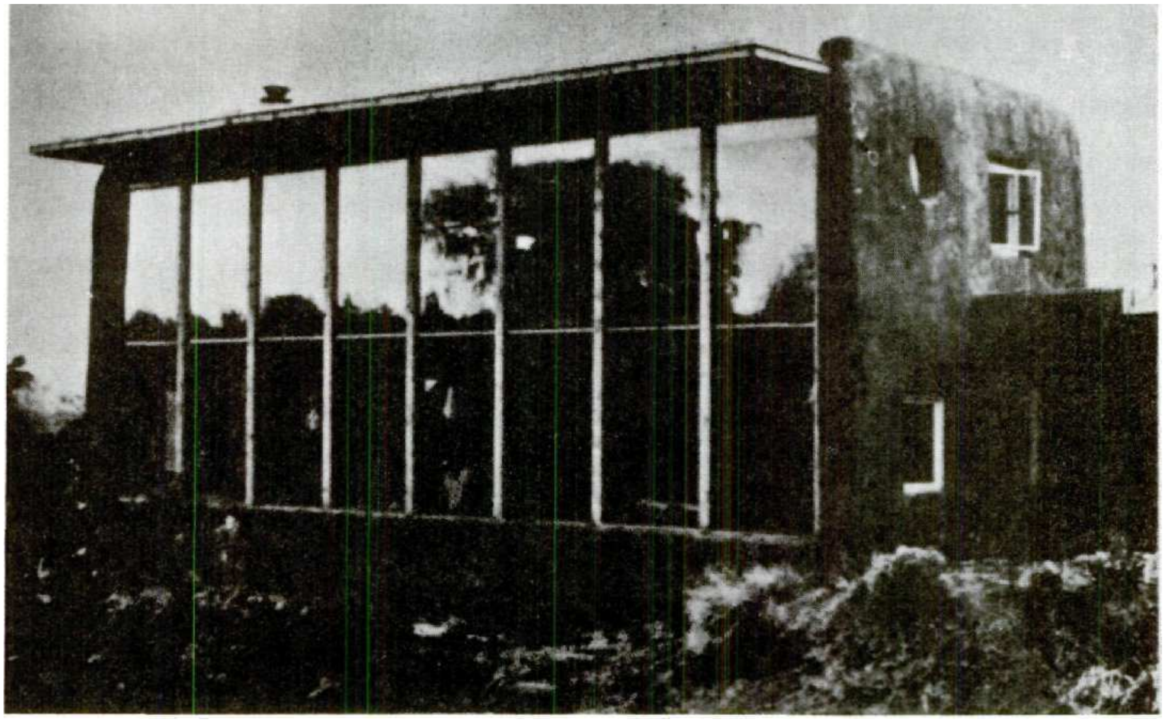


Figure C1-16: A house by David Wright, Santa Fe, New Mexico (AND-1)

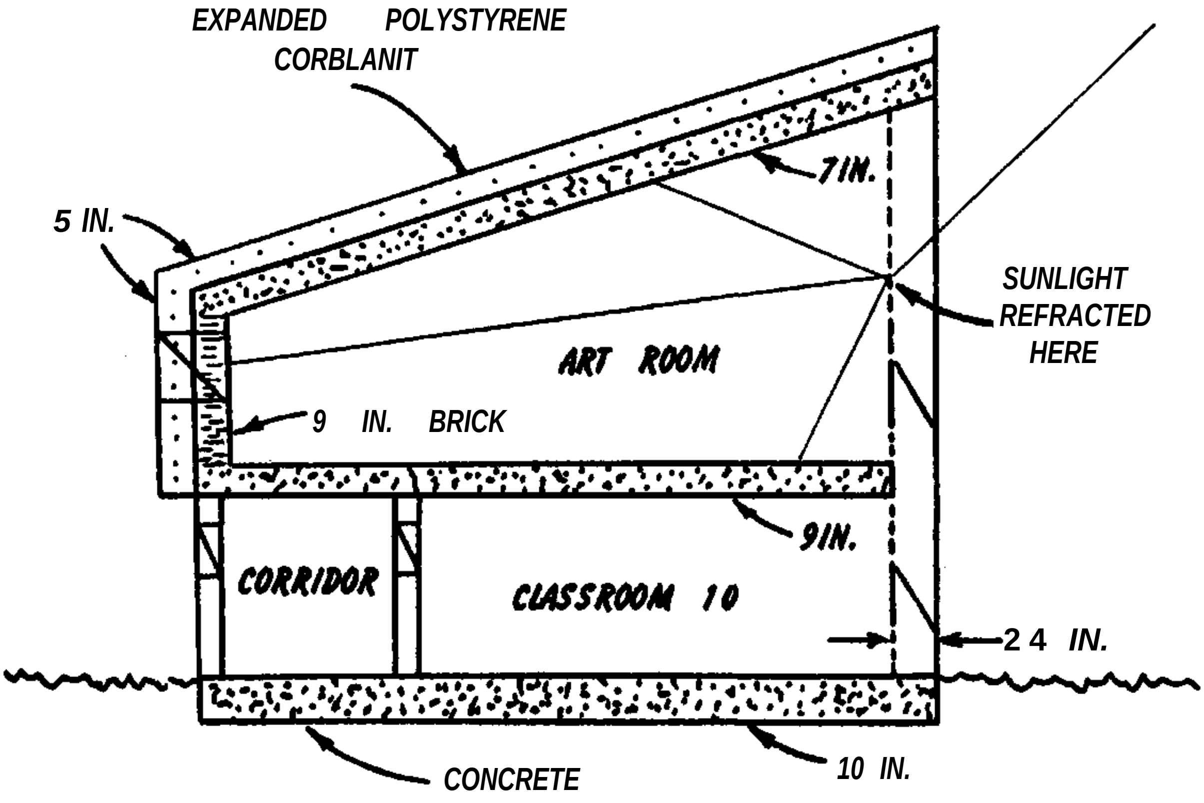


Figure Cl-17: St.George's School Annex, Wallasey, England (PER)

There is no mechanical ventilation of fresh air. Windows and vents are relied upon entirely, with mixed success. One limitation of this system is noise from students in the corridors, preventing opening of vents for cross-ventilation from various classrooms. Students and teachers use different amounts of clothing as necessary. This adjustment in clothing occurs almost automatically.

C1.e.3 MIT Solar Building V, Cambridge, Massachusetts

Large interior temperature swings, adequate amounts of thermal mass, and heat loss through large expanses of south-facing glass are basic problems in direct gain systems. In 1978 the Massachusetts Institute of Technology (MIT) completed its Solar Building V in Cambridge, Massachusetts, to demonstrate new solutions to these problems. (See Figure C1-18.)

The 866 square foot building uses three new materials that have been under development for several years. The first two — Heat Mirror™ and phase-change ceiling tiles — are described in Chapter E. Briefly, the thin-filmed Heat Mirror™ is a transparent insulation that, when applied to the building's 180 square feet of south glass, admits solar heat and greatly reduces heat loss by reflecting heat back into the building.

The ceiling tiles, 1.25 inches thick, have two layers of a Glauber's salt mixture, each 3/8 inches thick. The tiles absorb heat, melting

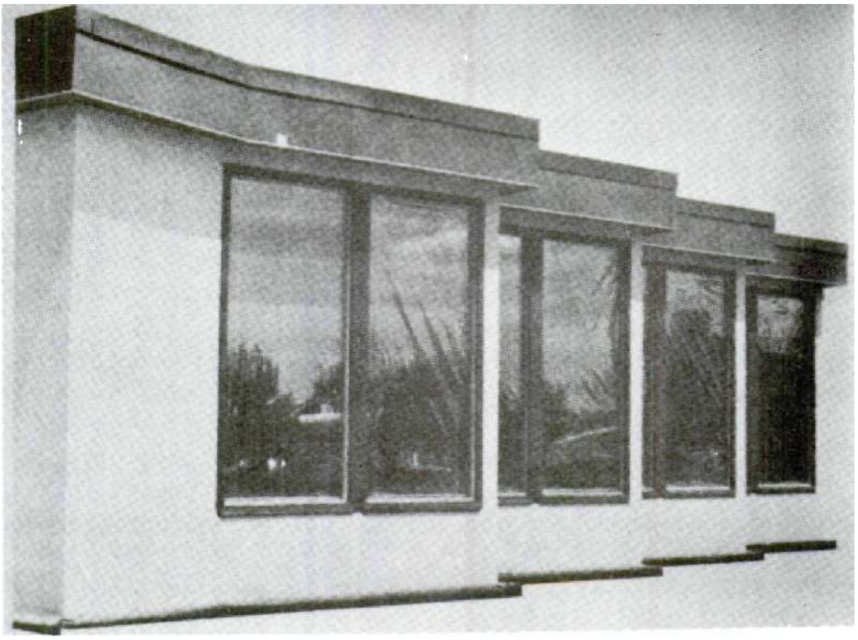


Figure Cl-18: The south facade of MIT Solar Building V in Cambridge, Massachusetts (MAH).

the salts at 73 F. The salts freeze as they slowly release their stored heat to the building at night.

The third product is a mirrored Venetian blind-type louvre that reflects the solar irradiation up to the ceiling tiles. It also reduces glare problems and sends natural lighting deep into the room as some of the light reflects off the ceiling. Figure C1-19 shows the operation of these three components.

This direct gain system is expected to provide about 75 percent of the annual heating needs of the building. During February 1978, interior temperatures ranged from the low 60's to 74 F.

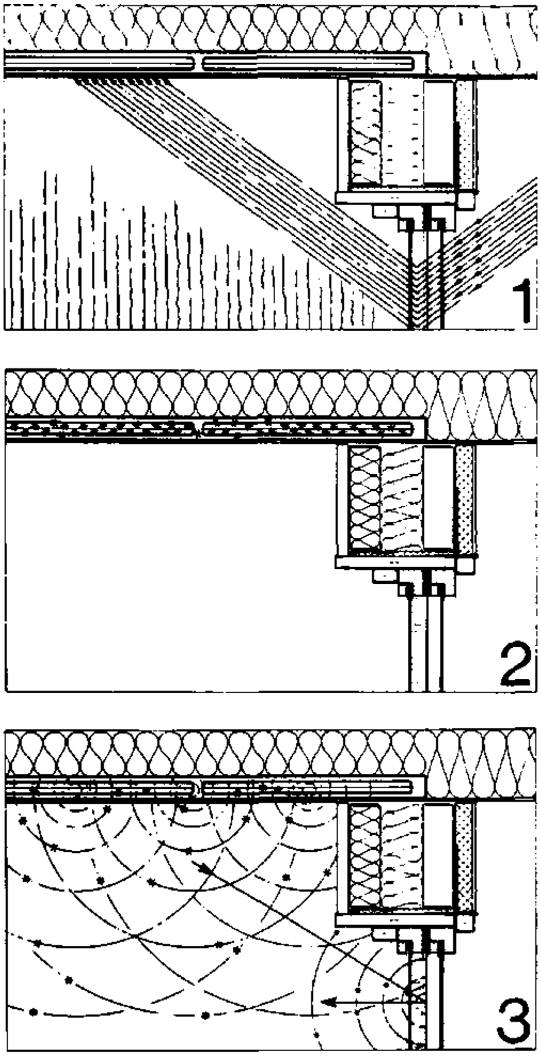


Figure C1-19: Component Operation. The half-inch-wide solar louvers are sandwiched between the double glazing just inside the Heat Mirror.™ Their concave shape directs light toward the ceiling (1), where rising room heat is also collected. The tiles hold heat when temperatures are above 73 F (2); it is released when the room cools (3) as phase-change salts recrystalize (MAH).

SUBCHAPTER C2, FIVE PASSIVE SOLAR HEATING TECHNIQUES

CONVECTIVE LOOPS

C2 CONVECTIVE LOOPS

C2.a INTRODUCTION

Of the five major types of passive heating systems featured in this Handbook, convective loops are the only ones that do not lose heat when the sun is not shining (provided the design includes reverse flow prevention devices) and are most similar to conventional active systems.

Second to direct gain, convective loops are the most widespread application of solar heating in the world. Hundreds of thousands of thermosiphoning water heaters have been used for decades. In a domestic hot water system, the solar collector is at an elevation below that of a hot water tank. (See Figure C2-1.) Warmed liquid rises through the collector and up to the water tank where it is stored. In some systems, an electric heating element is located in the top third of the tank to boost the temperature of the water when cloud cover prevents the sun from providing the required amount of heat. In other systems, the solar tank serves to preheat the water prior to final heating in a conventional water heater. Thermosiphoning systems can provide most of the domestic hot water throughout the year in the southern states. In the north, freeze protection is a major concern.

As convective loops become better understood, they will be used more widely. A significant application will be their use as wall panels

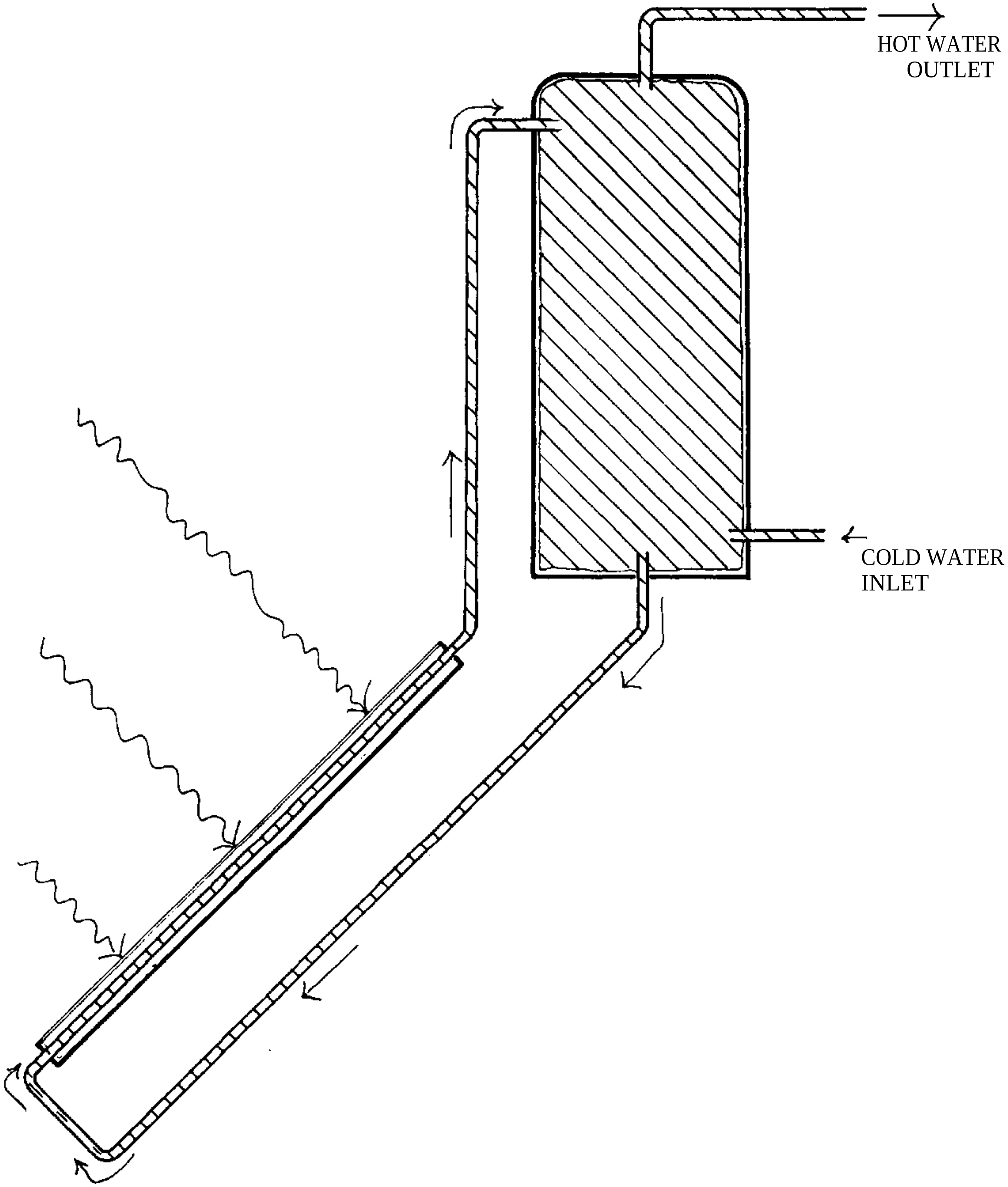


Figure C2-1: Convective loop: water heating (PUT) to complement south-facing windows in supplying solar heat directly to buildings. The amount of supplemental thermal mass will depend on the correlation between the heating needs of the building and the amount of heat supplied by the panels. For example, many existing buildings have high heat loss rates compared to available solar gains on south-facing wall surfaces. The surfaces can be converted to convective loop panels that supply solar heat only when the sun shines and when the building needs heating. In conventional wood-framed, residential construction, up to 25 percent of the heating load can be supplied in this manner without supplemental thermal storage.

C2.b DESIGN FUNDAMENTALS

C2.b.l Basic System Design

A convective loop panel is similar to an active flat-plate collector. A layer or two of glass or plastic covers a black absorber. Depending on the design, the air may flow in a channel in front of or behind the absorber. The air may also flow <u>through</u> the absorber if the absorber is perforated. The collector is backed by insulation.

In Figure C2-2 the convective loop collector is mounted on or is integral with the wall. Openings at the bottom and top of the wall permit convective airflow from the building, through the hot collector, and back to the building.

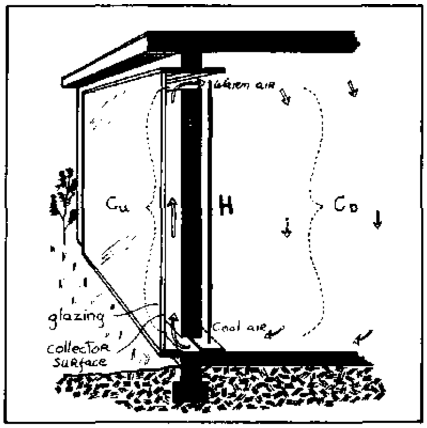


Figure C2-2: A convective loop wall-mounted collector (MOR-1).

(H = midpoint of opening at bottom of wall to midpoint of opening at top of wall.)

The slowly moving air must come in contact with as much absorber surface area as possible without being slowed too much. In fact, the amount of heat transfer from the absorber to the flowing air is in direct proportion to the heat transfer coefficient, h. Typical values for h in convective loop systems range from 1 to 3 Btu/h ft^2 F.

Steve Baer and others have used up to six layers of expanded metal lath. The air rises in front of the lath, passes through it, and leaves the collector through a channel behind the lath. (See Figure C2-3.) The value for h in this design is about 3.

A flat or corrugated metal surface has a heat transfer coefficient of less than 2 in convective loop panels.

These collectors should be constructed as carefully as active collectors. Exposed, unglazed portions should be well-insulated, particularly the upper areas which are likely to be hottest. Avoid the use of polystyrene insulation in the collector as it has a melting temperature of about 180 F. If the collector stagnates during a sunny day, its temperature can reach over 300 F. Wood construction is usually satisfactory, but use only good-grade lumbers and make sure that any shrinkage will occur evenly throughout the frame. Allow a 3/16-inch slack around each piece of glazing and generously apply silicone caulk (MOR-2).

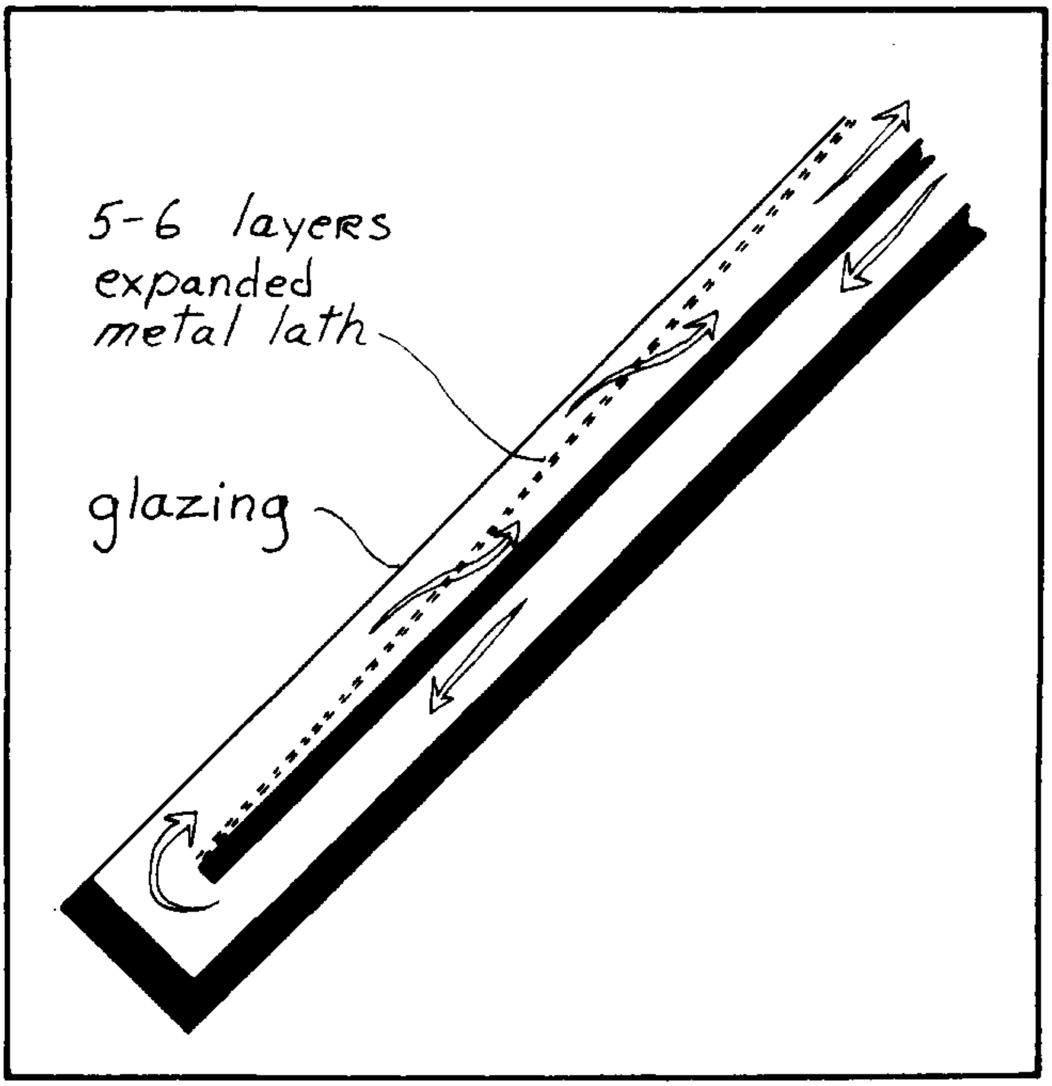


Figure C2-3: Typical airflow through a convective loop collector with expanded metal lath as the absorber (MOR-1).

The storage system must be designed to maximize heat transfer from the air stream to the storage material without noticeably reducing airflow. Rocks with small diameters have large amounts of surface area for absorbing heat and yet have passages for airflow. The cross-sectional area of the rockbed receiving air from the collector should range from 50 to 75 percent of the surface area of the collector.

The rocks should be close to uniform in size (i.e., do not mix 1-inch with 4-inch). The warm air from the collector should flow down through the rocks, and the supply air to the house should flow in the reverse direction. Optimum rock size depends on rockbed depth. Baer recommends gravel as small as 1 inch for rockbeds that are 2 feet deep and up to 6 inches for depths of 4 feet (BAE-1). However, for best heat transfer, bed depths in active systems are normally at least 20 rock diameters. That is, if the rock is 4 inches in diameter, the bed should be at least 6½ feet deep to remove most of the heat from the air before it returns to the collector. This should be considered a maximum depth for convective loop rockbeds.

C2.b.2 Airflow

> "Designing a convective air loop system is a somewhat tricky and difficult task. If you aren't very respectful of the the will of the air, the system won't work." (BAE-1)

As with active collectors, the hotter the absorber, the greater the heat loss and the lower the collector's efficiency. Good airflow keeps the absorber cool and transports the maximum possible amount of heat into the building. Flow channels should be as large as possible, and bends and turns in the ducts should be minimized.

In contrast to conventional air heating collectors in which the air stream is powered by a fan and the air channel is only ½ inch to 1 inch deep, the air stream past the absorbers in a convective loop is usually from 3 to 6 inches deep. In fact, Steve Baer's rule-of-thumb is that it be 1/15 the vertical length of the collector. Others suggest 1/20. Therefore, if the collector is 15 feet long, the air stream should be 8 to 12 inches deep. Baer also recommends that the air ducts to and from the collector have a cross-sectional area of about 5 percent of the collector area. Thus, if the area of the collector is 150 square feet, the cross-sectional area of the air duct to and from the rockbed should be about 7½ square feet (BAE-2).

Convective airflow is created by a difference in temperature between the two sides of the loop (for example, the difference between the average temperature in the collector and the average temperature of the adjacent room). It is also affected by the height of the loop.

To obtain the best airflow of the system in Figure C2-2, it is necessary to:

- Increase the temperature of the collector, C_U
- Decrease the temperature of the room, C_D
- Increase the height of the columns

The pressure driving the airflow is obtained from the following equation:

$$\left(\frac{\bar{t}_U + \bar{t}_D}{\bar{t}_D + 460} \right) H = P$$

where:

$\bar{t}_U$ is the average temperature at U, in F;

$\bar{t}_D$ is the average temperature at D, in F;

H is the height of the air column, in inches; and

P is the resulting driving pressure, in inches of air.

The 460 degree figure converts the denominator to the absolute temperature scale.*

The resulting pressure driving the airflow in Figure C2-2 is calculated as follows:

Suppose the collector is 8 feet (96 inches) tall. Its average temperature is 120 F. The average room temperature is 70 F. The pressure driving the air is:

---

*Temperature scale on which the zero point is absolute zero (-460 F)

$$\left(\frac{120 - 70}{70 + 460}\right) (96 \text{ in.}) = 9 \text{ in. of air}$$

This is equivalent to about 0.0075 inches of water pressure. In a properly designed thermosiphoning collector with unrestricted vent openings, flow rates can be as high as 5 cubic feet per minute per square foot of collector on clear sunny days. This is about two times the flow rate of most active air systems. Figure C2-4 is a graph that plots the flow rate against the difference in air temperature between hot and cold sides of the loop. The larger the Δt, the greater the flow rate. This relationship, in fact, helps to regulate the airflow. The greater the solar radiation, the hotter the collector and the faster the airflow. During non-sunny hours when the temperature drops, the airflow stops completely. Figure C2-4 also plots the effect of restricted airflow when vent sizes are reduced to one-half and one-fourth the sizes recommended above.

For two identical "half-wall" collectors positioned as shown in Figure C2-5, the collector in B will show better efficiences because the entire C_U side is hot, whereas the lower half of C_U in A is cool air. Thus the average Δt in B is greater than Δt in A, and the flow rate will be better in B.

The vertical height* (not simply the length) of the collector should be at least 6 feet to obtain the necessary stack (chimney) effect. It should be tilted at a pitch of no less than a 45° angle

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*measured vertically from the middle of the bottom opening to the middle of the top opening.

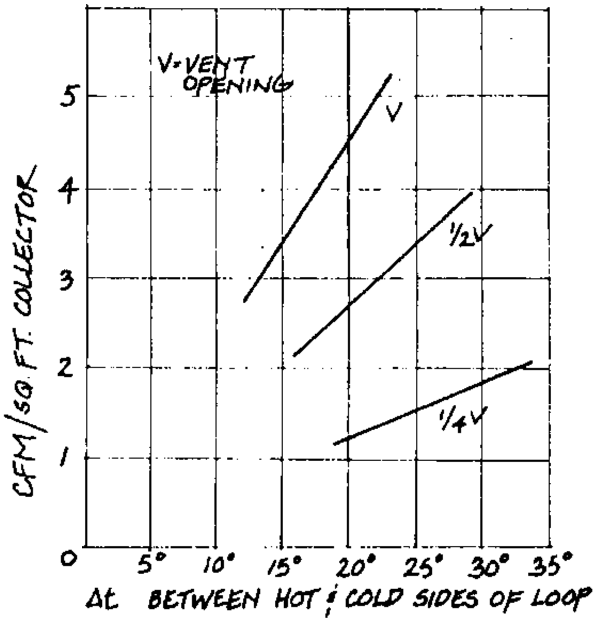


Figure C2-4: Flow rates through convective loops for vent openings of various sizes (MOR-3).

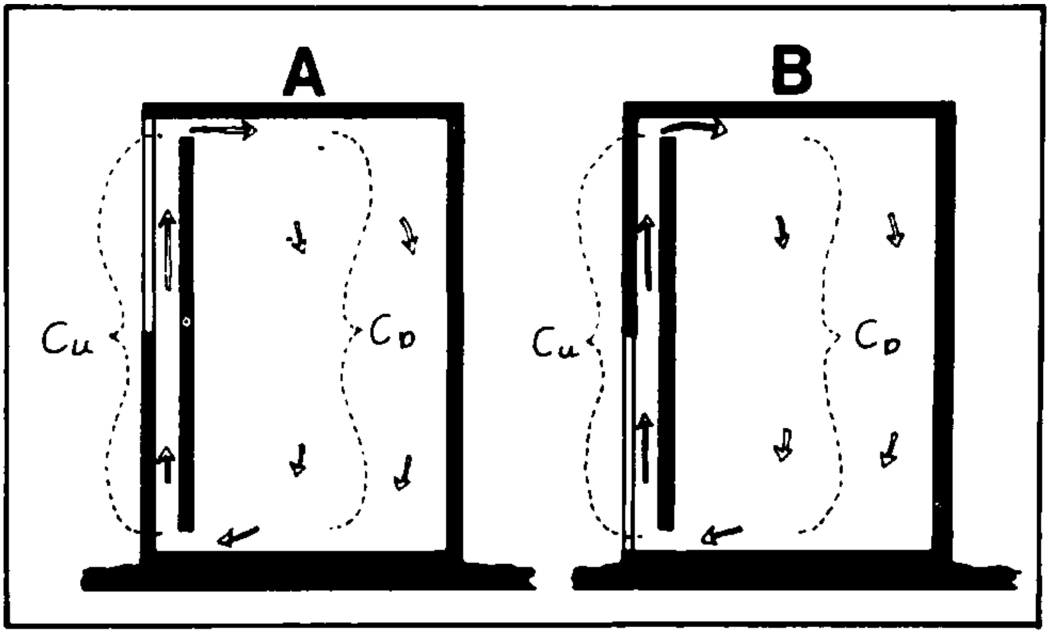


Figure C2-5: Alternative configurations for half-wall collectors (MOR-1).

with the ground, both to best receive the sun and to allow the air to flow freely upward.

An alternative flow path for the air through a thermosiphoning collector is shown in Figure C2-6. Here, in effect, the collector is double-glazed. The incoming cool air flows down the front channel between the exterior and the interior glazings and rises by convection up the back channel between the inner glazing and the absorber plate. The primary advantage of this reverse geometry is that the hot air can be ducted under a masonry floor before entering the building without requiring complicated duct work. This floor can then act as a radiant heating element. The efficiency of this collector is nearly identical to that of the conventional thermosiphoning design (MOR-3) (SAT).

In an improperly designed system, reverse convection can occur when the collector is cool. A cool collector can draw heat from the house or from storage. Up to 20 percent of the heat gained during a sunny day can be lost through this process by the following day (MOR-3)

Three primary methods prevent reverse convection automatically. One is to build the collector in a location below the heat storage and below the house. A second is to install backdraft dampers that automatically close when air flows in the wrong direction. The collector designed for existing walls in Figure C2-7 uses lightweight, thin plastic film. Warm airflow gently pushes the dampers open.

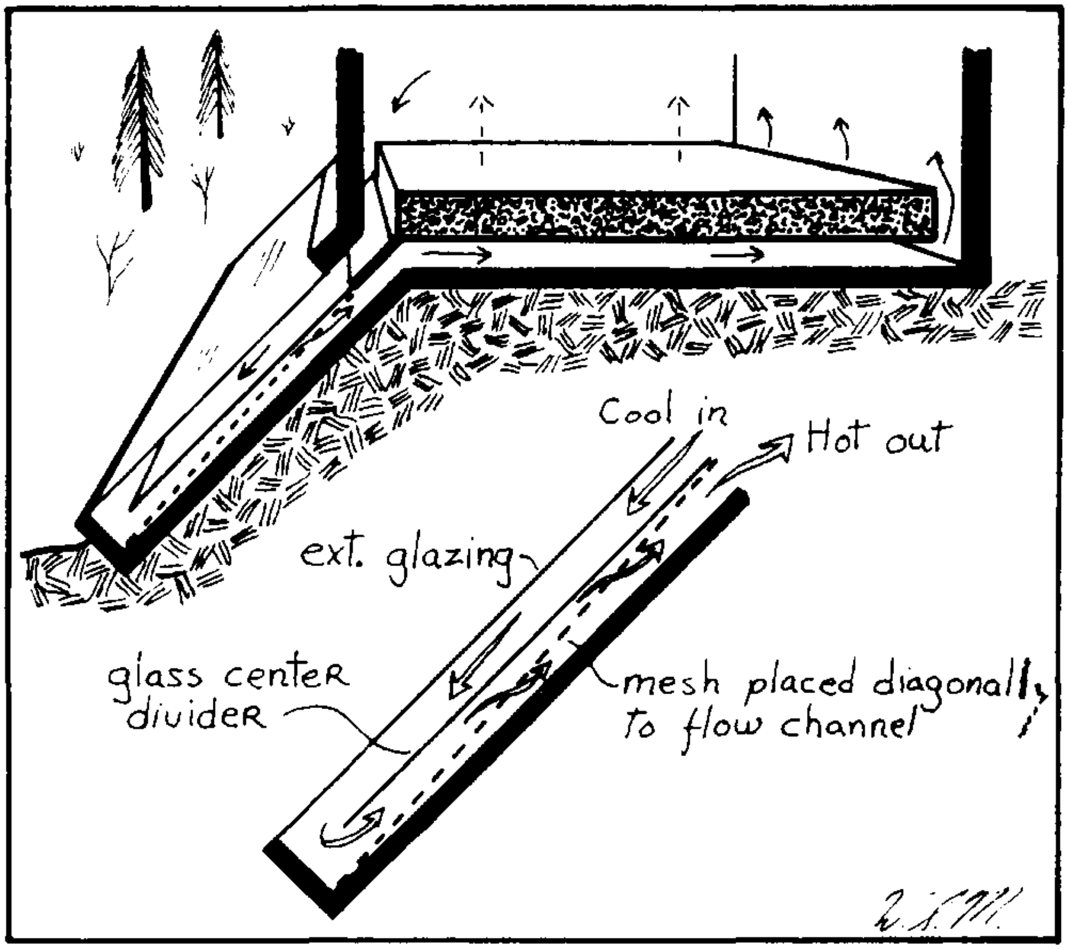


Figure C2-6: Center-glazed collector with masonry floor heat storage (MOR-1).

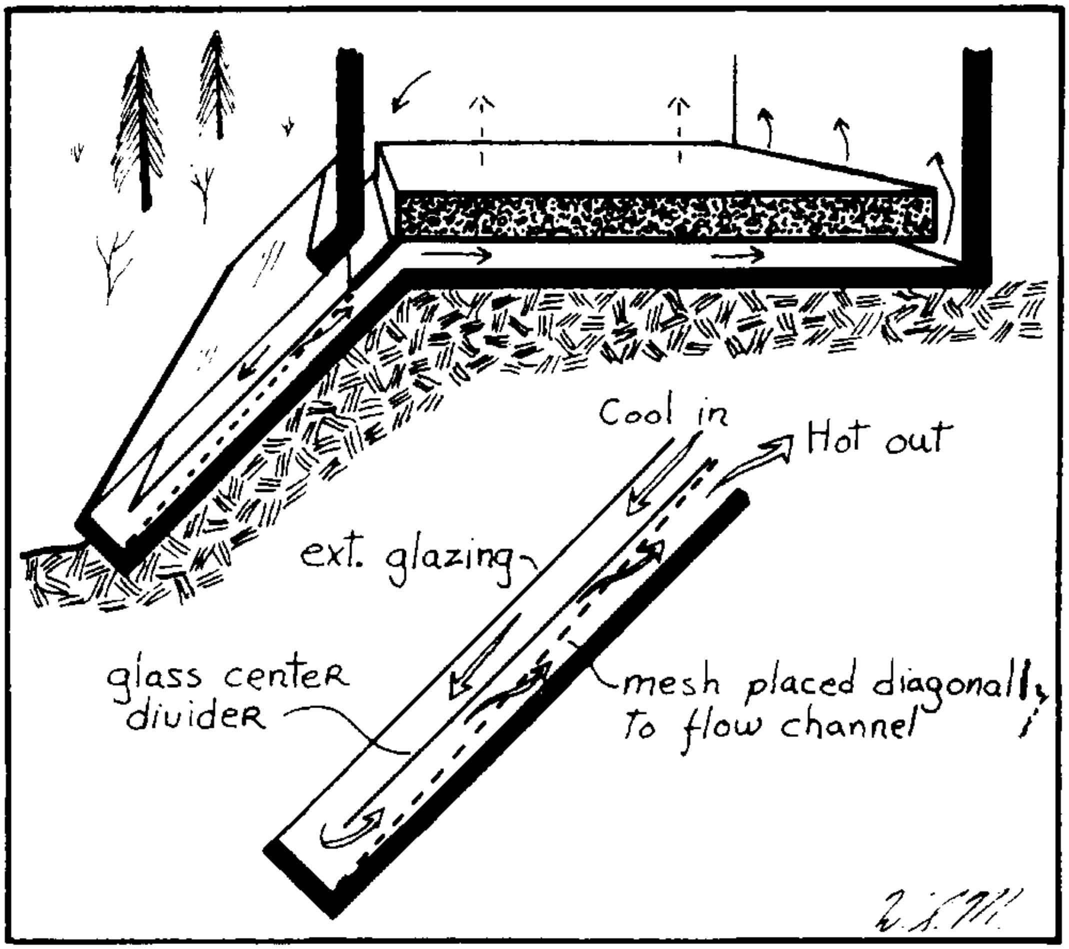


Figure C2-6: Center-glazed collector with masonry floor heat storage (MOR-1).

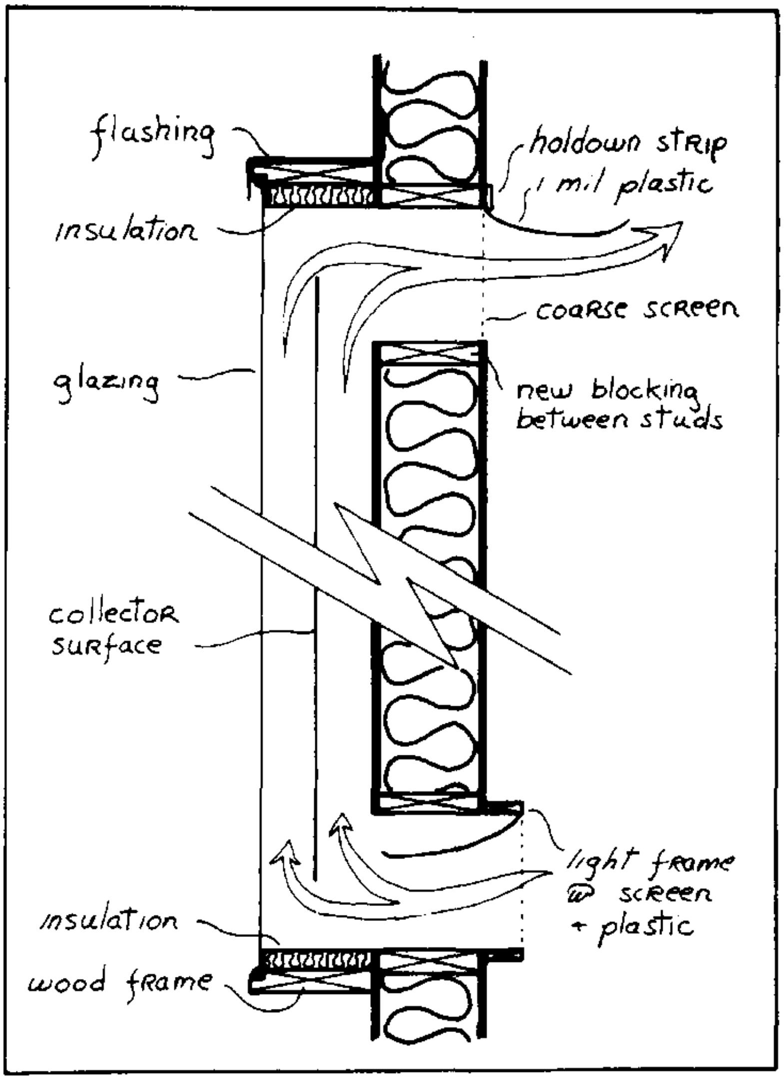


Figure C2-7: Simplified construction details — convective loop collector for existing walls. Note plastic backdraft damper (MOR-1)

Reverse cool airflow causes the plastic to fall back against the screened opening, stopping airflow. Ideally, both top and bottom vents should be equipped with such dampers.

Figure C2-8 shows the third method of minimizing reverse convection. Both the intake and outlet vents are near the top of the panel. The back of the absorber is insulated (about R-4) and is centered between the glazing and the walls. Inlet cool air drops into the channel behind the absorber. The solar heated air rises in the front channel. During no-sun conditions, the air in both channels cools and settles to the bottom of the "U-tube". Only minor reverse convection occurs.

The main office building of the National Scientific Research Center in Odeillo, France, now more than ten years old, uses this type of thermosiphoning wall panel in combination with windows. Together, the windows and wall panels contribute about 50 percent of the building's heat. (See Figure C2-9.) No provision has been made to store the heat other than in the building's thermal mass, which is reinforced poured concrete. The panels are designed to be easily closed and "turned off" during warm weather. Their design allows cool air to settle to the bottom of the air passages and inhibits reverse thermocirculation of cold air in the panels at night back into the building.

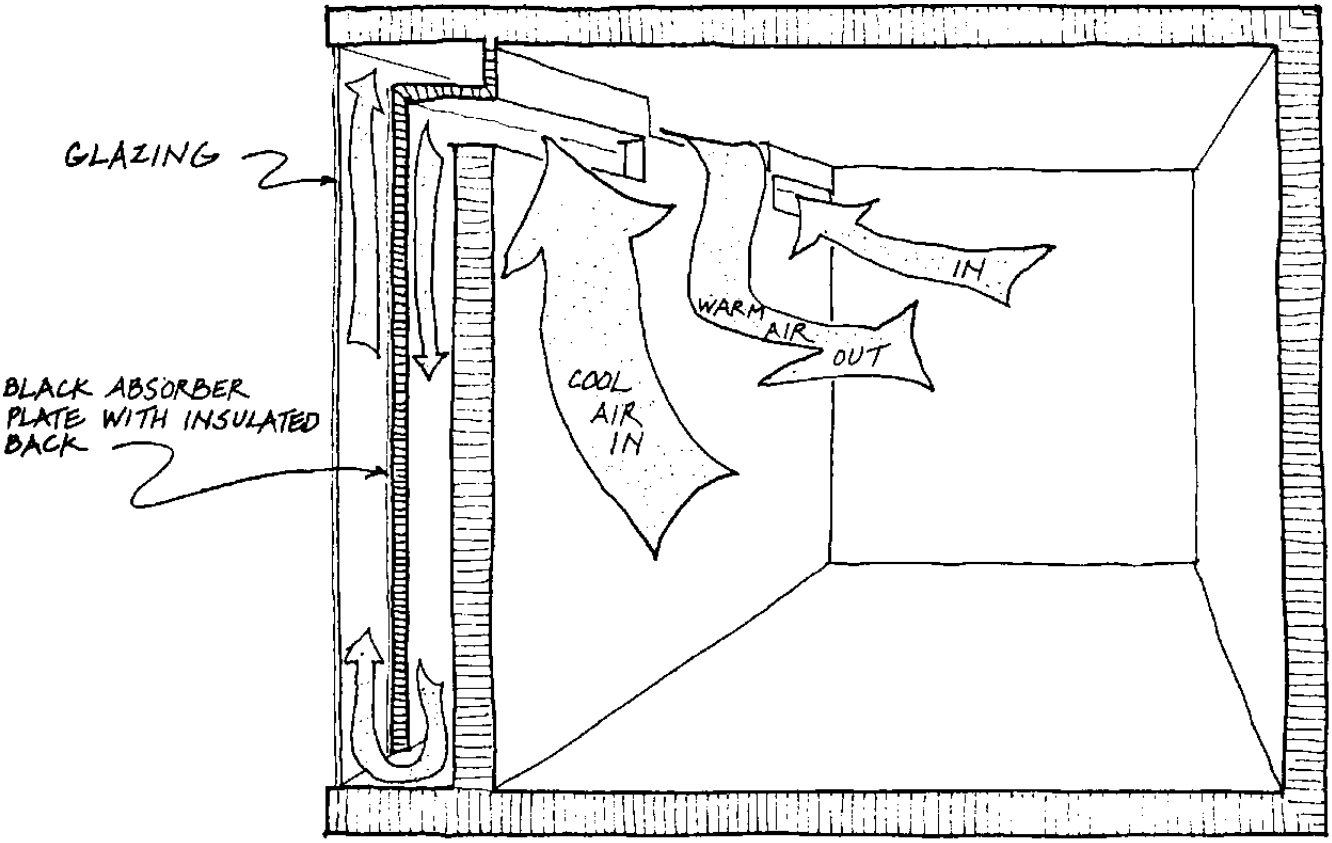


Figure C2-8: A "U-tube" collector designed to effectively prevent reverse convection (BA/PUT).

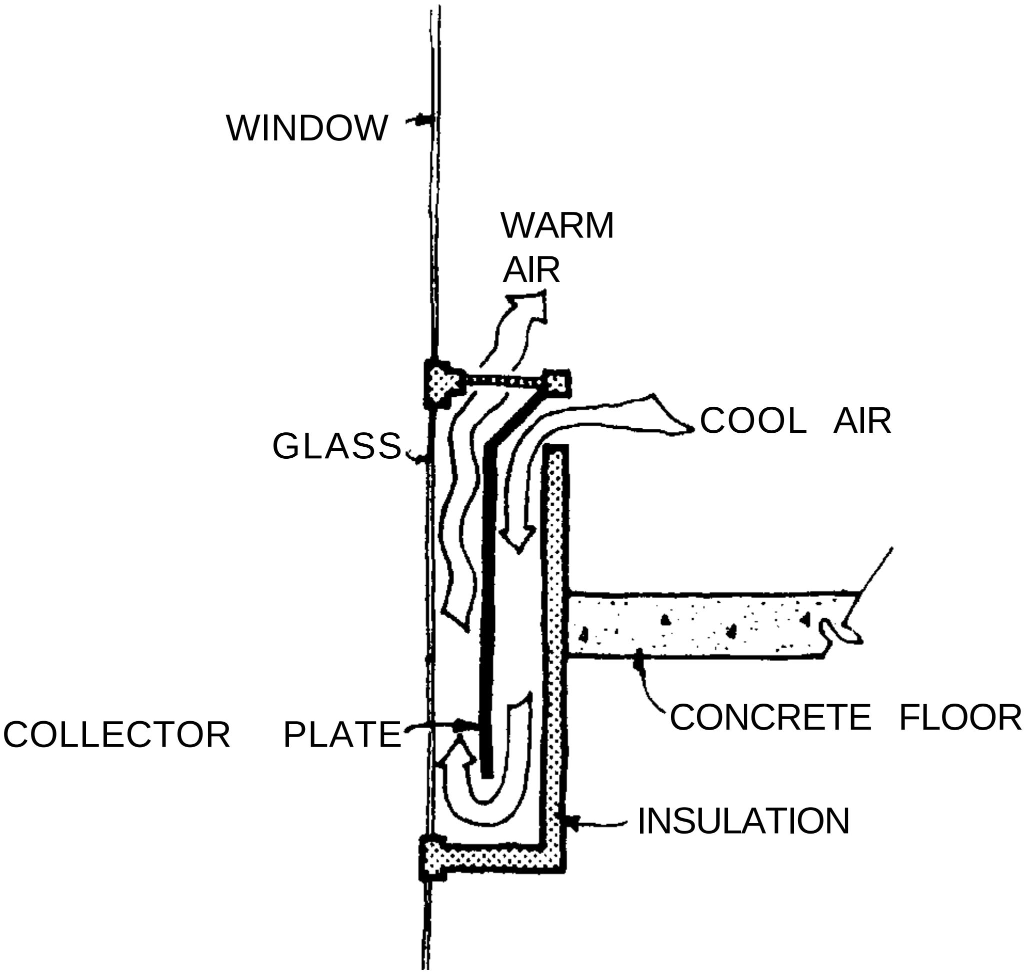


Figure C2-9: Odeillo Office Building: thermosiphoning wall panel (HON).

C2.b.3 Applications

Convective loop air-heating collectors are best suited to structures where the heating load is large compared to the collector area. If all of the heat can be used immediately by the building, additional thermal storage, which can increase the total system cost, is unnecessary. And any thermal storage added will necessarily be indirect (i.e., not as effective as directly irradiated mass). Schools and low-rise office buildings are examples of such structures. The intermittent, predominatnly daytime-only use of these buildings matches the collectors' daily heating cycle. The air heaters can also be used in both single-family and multi-family housing. Additional thermal mass may be required. Without it, the low heating loads (especially in well-insulated housing) mean that a smaller fraction of the building's total heat can be supplied.

Architecturally, convective loop collectors, with their conventional wall construction and glass-surfaced appearance, are well-suited for integration into most new commercial construction. With minor design modifications, the heater can be a cost-effective retrofit application over existing exterior walls.

Costs

First costs for convective loop collectors depend primarily on labor. Most materials are supplied by a number of competitive manufacturers and are widely available. For manufactured panels, initial shop fabrication costs may be high given the unconventionality of the product, but the contractor will value its convenience. Estimates of installed cost range from $4.50 to $18.00 per square foot, depending on construction methods and building types. Operating costs are nonexistent, and maintenance costs should be very low.

Thermal Performance

Performance depends largely on the delicate natural convection currents set up in the system. Airflow is low to nonexistent at times of little or no sun, but it increases rapidly under sunny conditions. Flow rates are generally higher than in thermal storage walls (up to 5 cubic feet per minute per square foot of collector were noted earlier). The resulting output of 90 Btu/hr ft^2 represents collection efficiency during good sunshine conditions similar to that of low temperature, flat-plate collectors used in standard active system designs.

The chief determinant of overall performance is the ratio of the building's heating load to collector area. Per unit area of collector, effective performance deteriorates rapidly with increasing collector size. Estimates of useful delivered energy using simplified analyses range from 30,000 to 120,000 Btu per square foot per heating season. The high numbers in this range are typically associated with low solar heating fractions and sunny climates, and the low numbers with high solar heating fractions or very cloudy climates. 80,000 Btu per square foot per heating season is typical in moderate climates such as Boston, Massachusetts, when the solar contribution is 40 percent of the heating load. The output of the collectors drops to 50,000 Btu when sized to provide 60 percent of the load.

To increase solar performance, increase thermal mass to store excess solar heat effectively. To maximize system performance, especially in well-insulated (low load buildings), additional heat storage, such as doubling the thickness of gypsum board, should be considered. Overheating, with resulting poorer performance and lower comfort levels, may result whenever systems are designed to provide over 30 percent of the seasonal load.

Economics

Based on a capital recovery fraction of 10 percent, combined performances and first-cost estimates establish a probable energy cost between a high of $18.00 and a low of $10.00 per million Btu. This is an extremely economical range when compared to current $17.50 per million Btu for 6c/kWh electricity. Future conventional energy costs are sure to increase. Energy cost estimates for specific cities are shown in Figure C2-10.

City	Btu/ft^2 yr$^{(1)}$	Cost/MMBtu$^{(2)}$
Fort Worth, Texas	51,000	$17.25
Medford, Oregon	61,000	$15.25
Boston, Massachusetts	63,000	$14.25
Madison, Wisconsin	80,000	$12.70
Boulder, Colorado	96,000	$10.40

(1) Delivered energy levels are averages of estimates prepared by Total Environmental Action, Inc. for four different building types and various building load/system size ratios.

(2) Effective energy costs are obtained by applying a capital recovery factor of 10 percent to an average first cost estimate.

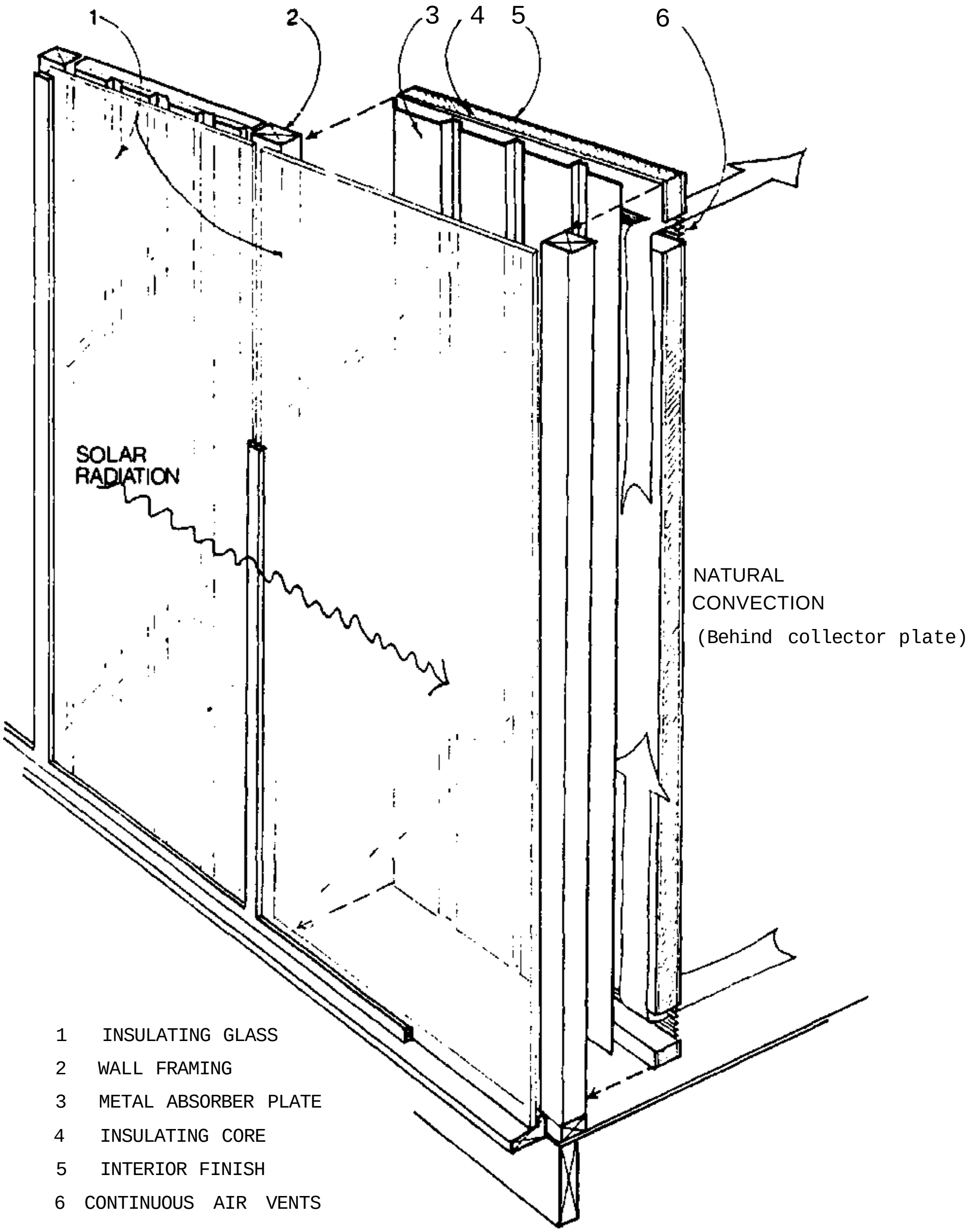
Figure C2-10: Delivered energy and associated costs for convective loop air collectors (HON).

C2.c A CONVECTIVE LOOP COLLECTOR

The air heater in Figure C2-11 has an exterior glazing that covers a composite wall consisting of the absorber plate, rigid insulation, and interior finish. Trim, air grills and backdraft dampers complete the design. Its low mass, insulated construction will cause it to undergo greater temperature fluctuations than thermal walls. Consequently, sealants, glazings, and other materials must withstand greater thermal ranges.

This design uses tempered insulating glass. Economy of installation and availability for replacement is assured by using stock sizes manufactured for sliding glass doors (normally 34 × 76, 34 × 90, 46 × 76, or 46 × 90 inches). The glazing supports should minimize thermal contact with the absorber behind the glazing. This particular design doubles as a wood-framed, structural wall; the glazing details are also wood, a natural insulating material. The core of the wall if highly insulated. The interior surface can be a conventional interior finish.

The absorber plate is corrugated metal siding, a readily available building material that can be purchased complete with compatible fasteners and pre-formed EDPM or neoprene closure strips. This simplifies construction of an airtight, durable convective loop heater. The ribs provide structural stability. Space the plate the proper distance from the wall. For an 8 foot high panel, the rule-of-thumb calls for 5 to 6 inches.



1 INSULATING GLASS
2 WALL FRAMING
3 METAL ABSORBER PLATE
4 INSULATING CORE
5 INTERIOR FINISH
6 CONTINUOUS AIR VENTS
(backdraft dampers required. See Figure C2-12)

Figure C2-11 : A typical thermosiphoning air collector (HON).

The absorber plate is mill-finished aluminum and must be prepared for painting with an etching cleaner; pre-painted aluminum is available from some suppliers. The recommended finish is a thin coat of flat black enamel such as the high temperature spray paints commonly used for wood stoves, barbeque grills, and engine blocks.

The panel is vented to the heated space through a full-width register that provides manual control of the airflow. Continuous linear diffusers normally available for commercial HVAC systems can be used.

Backdrafts at night or during cold, cloudy weather can be prevented by using very lightweight (1 mil) plastic film, one-way dampers. The example in Figure C2-12 must be specially fabricated The plastic film is attached with double-sided adhesive tape to a punched or die-cut 24-gauge galvanized sheet.

C2.d HEAT COLLECTION AND STORAGE SYSTEMS

Convective loop systems should include heat storage if they are large enough to supply more than 25 to 30 percent of a building's heat. Some heat can be stored within the enclosing walls of a building. but this is quite limited since the heat transfer from warmed air to the interior wall surfaces is fairly poor and especially poor to the floor. The amount of heat stored depends directly on the room

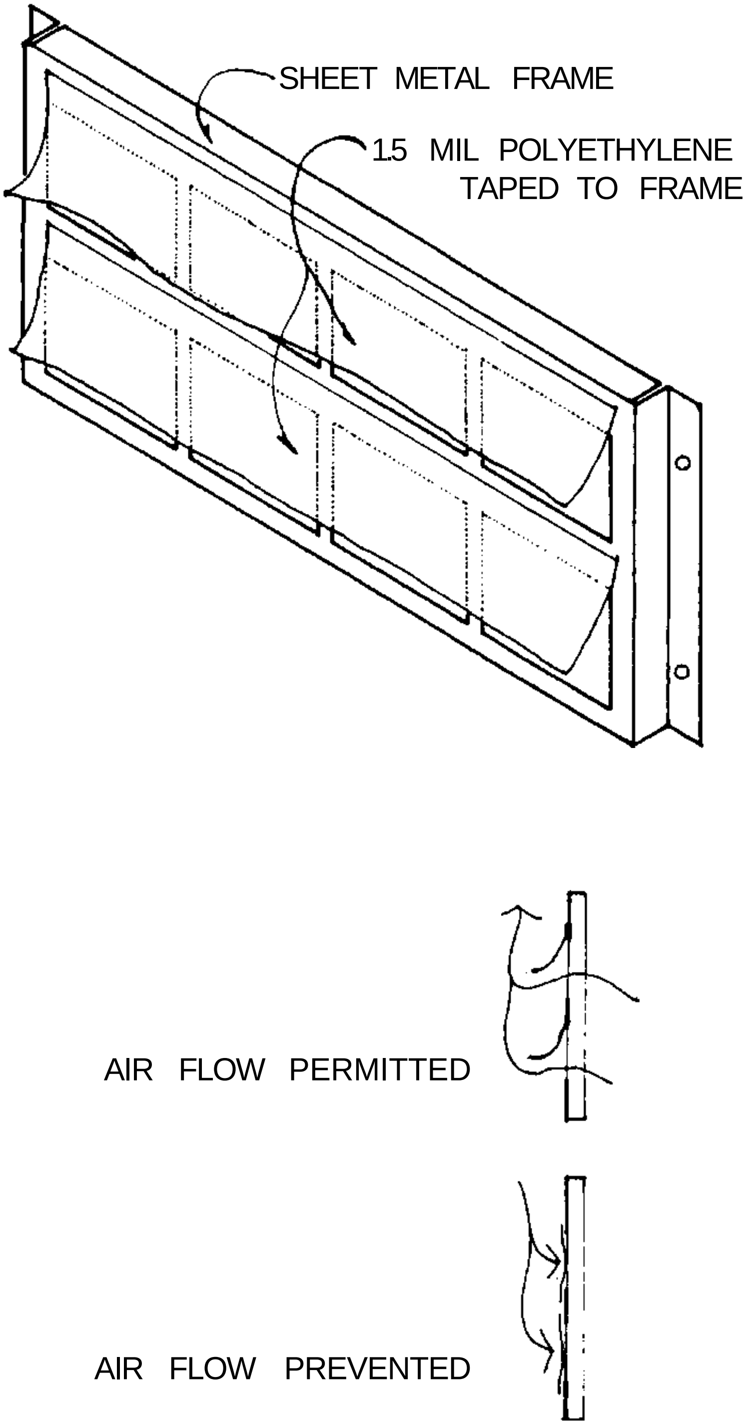


Figure C2-12: A Backdraft damper design for a thermosiphoning collector (HON).

air temperature swing, and so the occupants' tolerance to temperature fluctuations must be considered. In a residence for an elderly couple, for example, a swing of 5 to 8 F may be the tolerance limit, whereas 20 F or more may be acceptable in a warehouse. The following chart gives an indication of the daily heat storage capability of some wall materials per degree of room air temperature swing per square foot of wall surface:

sheetrock	½	in. thick	0.84 $Btu/ft^2 \cdot F$
brick	4	in. thick	3.60 $Btu/ft^2 \cdot F$
concrete	4	in. thick	4.40 $Btu/ft^2 \cdot F$
concrete	8	in. thick	4.20 $Btu/ft^2 \cdot F$

Thus, if a 1000 square foot house, which has 1000 square feet of interior sheetrock surface, has a 10 F temperature swing, the heat stored (and released) daily is:

$$(1000) \times (10) \times (.84) = 8400 \text{ Btu}$$

This is not much storage compared to an average daily heat load of perhaps 400,000 Btu for such a house in midwinter (outdoor temperatures in the 30's). The situation is somewhat better if the surfaces are 4-inch brick or concrete, in which case perhaps 10 percent of the daily heat load may be stored. Because downward heat exchange to the floor is so poor, flow mass should not be included in such a calculation.

Another option for heat storage is to use a rockbed (as in the case of the Paul Davis house discussed later). In this case, the storage is separate from the building. The storage should contain at least 200 pounds of rock per square foot of collector. It should be located as high above the collector as possible, but below the house (MOR-2). These systems will collect and deliver 30 percent of the solar irradiation that strikes them in cold climates, and 50 percent in mild climates.

C2.e EXAMPLES OF CONVECTIVE LOOP SYSTEMS

C2.e.l Davis House, Albuquerque, New Mexico

The Davis House has used a convective loop air-heating collector in combination with a rockbed since 1972. The system was designed by Steve Baer. Airflow is shown in Figure C2-13. The collector (36 feet wide, 12 feet long) is incorporated into the support structure of the porch at an elevation below that of the house. A single layer of glass covers the absorber, which consists of six layers of expanded metal lath. Warm air rises through the collector, becoming heated in the process. From there it travels through the rockbed (10 feet wide, 4 feet deep) located below the porch and containing 330 pounds of fist-size rock per square foot of collector. As the air moves through the rocks, it loses its heat and falls back to the collector inlet.

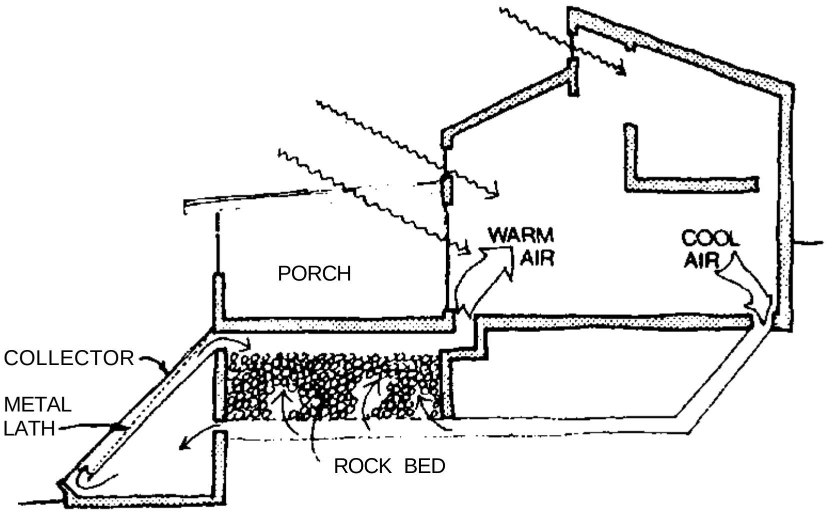


Figure C2-13: The Davis House — air thermosiphoning plus rockbed (HON)

At night, a damper between the collector and storage is closed to prevent convection. Floor registers allow a convection loop to heat the house from storage. If the house needs heat during the day, the floor registers admit hot air from the collector, bypassing storage.

This system supplies over half of the heating load of this 1,000 square foot house. Storage is sufficient to carry through two gray winter days. The backup is wood heat.

C2.e.2 The Jones House, Santa Fe, New Mexico

This 2,650 square foot house combines a convective loop for collecting and storing solar heat with a forced air distribution system (HUN). The collector is 34 feet wide and 18 feet long. The absorber is three layers of 3/8-inch mesh wire lath set on top of black galvanized sheetmetal pans. A single layer of fiber-reinforced plastic covers the absorber. Thirty tons of ½ to 3 inch diameter, washed gravel, or 100 pounds per square foot of collector, fill the 4-foot-deep rockbed. (See Figures C2-1A and C2-15.)

Behind the collector and next to the rockbed is a greenhouse. Portions of the absorber and collector backing were intentionally omitted during construction to permit light to enter. The greenhouse acts as the return air plenum since the air, which moves slowly but in large volumes, must pass through it enroute from storage to the collector.

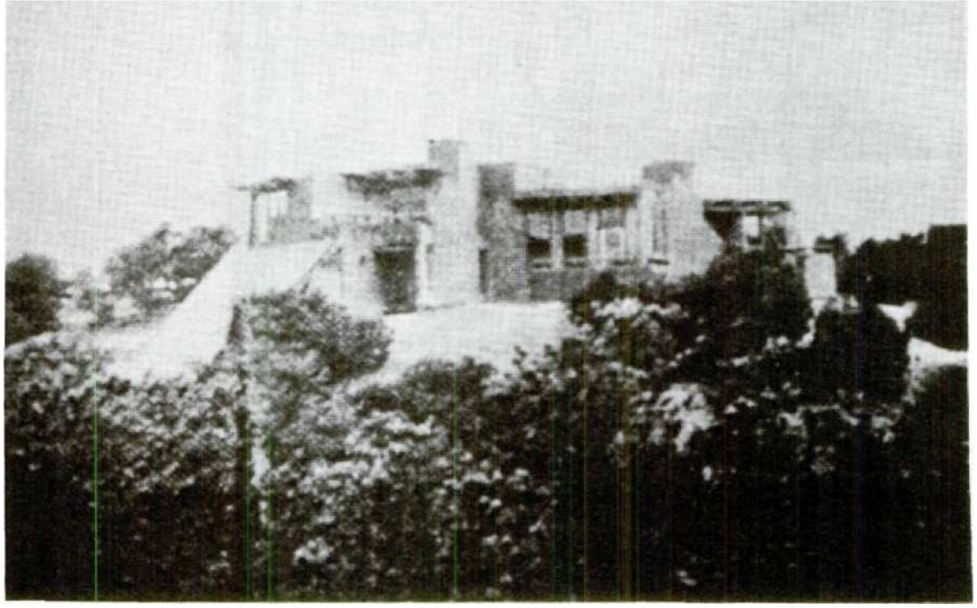


Figure C2-14: The Jones House — Santa Fe, New Mexico

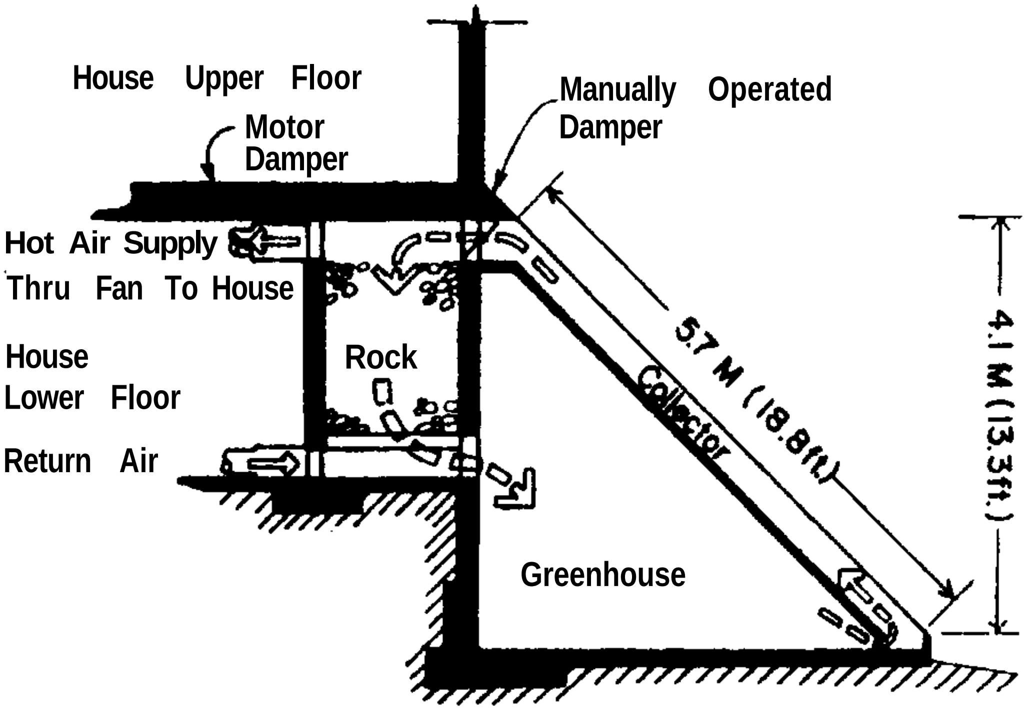


Figure C2-15: The Jones House — cross-section of the solar system (HUN-1).

The performance of the system is being monitored by Los Alamos Scientific Laboratories. The results of a representative, two week period, from December 26, 1978 to January 8, 1979, are in graph form in Figure C2-16. From December 29 to December 31, the weather was cloudy (top curve), and all of the heat from the rockbed was depleted (upper center set of four curves). The outlet temperatures of the collector (lower center set of two curves) soared to more than 170 F during sunny weather and heated the top of the rockbed to nearly 150 F. The rockbed is nearly empty of heat each morning. The greenhouse temperature is, with rare exceptions, in the range for supporting plant growth.

A 1,000 cfm fan, in response to a house thermostat, supplies solar heat by drawing air from the top of the rockbed. Return air from the house enters the rockbed at the bottom. Air distribution to the house is through a conventional duct system. A 15 kW electric strip heater provides backup, but it was not need in the first winter of operation which began in February 1978. The total installed cost of the solar system was $12.22 per square foot of collector or about $6,500.

C2.e.3 A Thermocirculation Water Heater

Zomeworks, Inc., Albuquerque, New Mexico manufactures a passive solar domestic hot water system that operates by thermocirculation. It consists of a 66 gallon, glass-lined storage tank with an

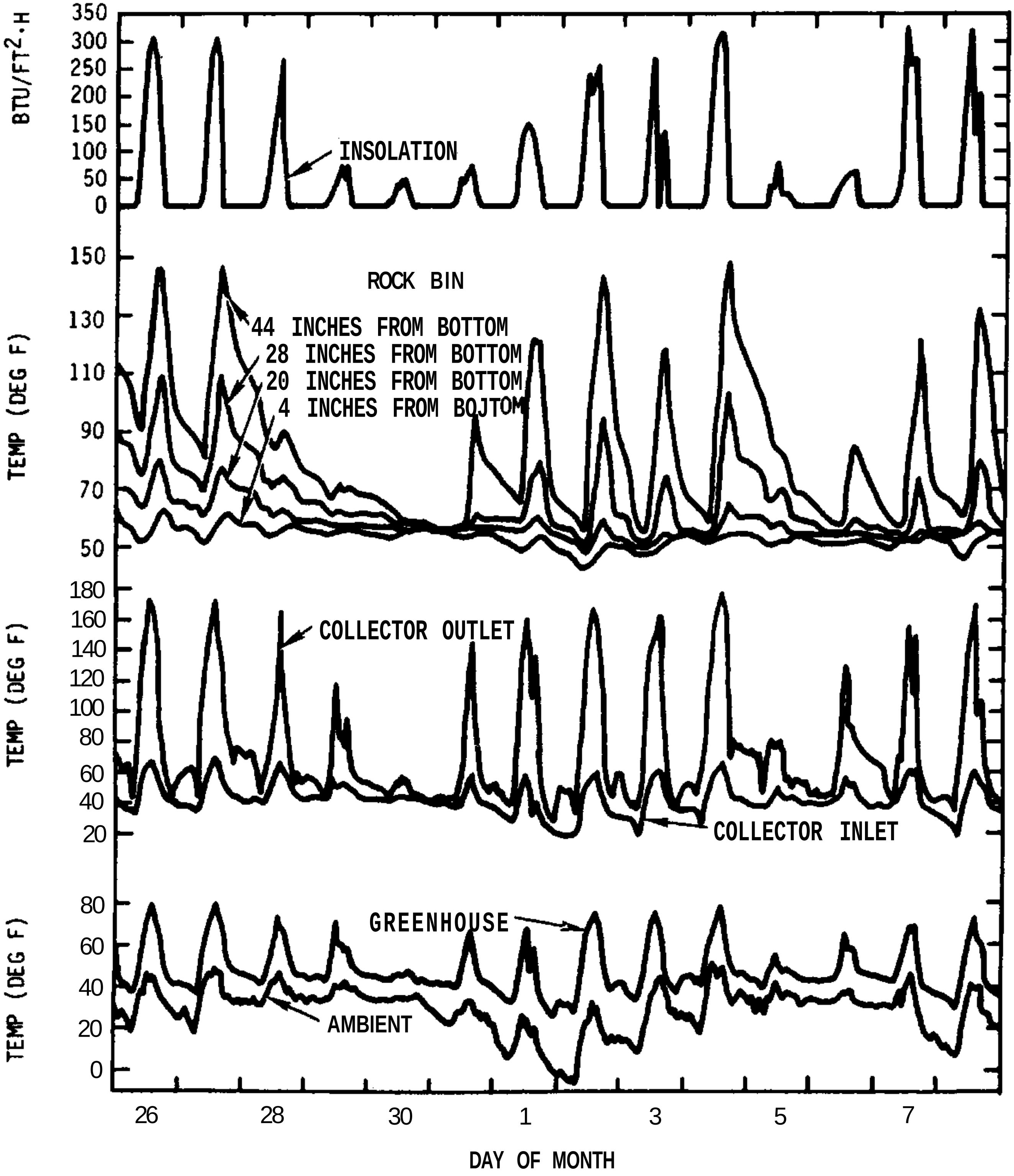


Figure C2-16: Representative performance of the convective loop system of the Jones Residence, Dec-Jan, 1978-79. Prepared by Los Alamos Scientific Laboratories (SAN) integral heat exchanger, two 17 square foot collectors with low-iron single glazing, and an expansion tank and relief valve. The heat transfer fluid in the collector loop is a nontoxic antifreeze.

The storage tank is positioned above the collectors. When sunshine heats the solar collectors, a thermal gradient develops, and the antifreeze rises and gives up its heat to the water in the storage tank. After doing so, it cools and sinks to the collectors again. This system requires no pump to move the fluid through the collector loop. Figure C2-17 shows a typical system. Some manufacturers now make similar systems that use Freon™ rather than water or anti-freeze as a heat transfer fluid.

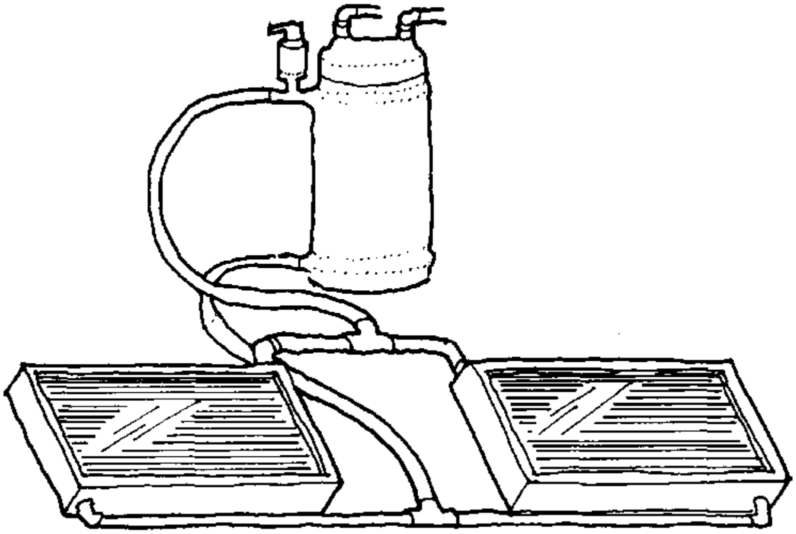


Figure C2-17: Zomeworks thermocirculation hot water heater.

SUBCHAPTER C3, FIVE PASSIVE HEATING TECHNIQUES

THERMAL STORAGE WALLS

C3 THERMAL STORAGE WALLS

C3.a INTRODUCTION

Thermal storage walls are, in many ways, a combination of both direct gain systems and convective loops. However, thermal storage walls compensate for many of those systems' disadvantages by placing the heat storage mass between the glass and the space to be heated. For example, many direct gain houses overheat, a result of either insufficient thermal mass to absorb the heat or incorrectly-placed mass due to poor building design. Further, because the mass in convective loop systems cannot be directly heated, convective loops require large amounts of heat storage to supply more than 30 percent of the heating demand. However, heat gain can be controlled more readily than in direct gain systems by opening and closing vents manually or automatically. Thus, thermal storage walls simplify comfort control.

Per unit of thermal storage mass used, the thermal storage wall makes best use of the material. This is because the temperature swing in the material is greatest. Temperature swings in the heated space can still be relatively small.

C3.b THERMAL STORAGE WALL SYSTEMS

C3.b.l Basic Designs

There are two types of thermal storage walls. One uses heavy masonry material (concrete, adobe, brick, etc.) about 1 foot thick.

The wall is painted a dark color and heats as the sun passes through the glazing and strikes it. Usually, but not necessarily, vents are placed at the bottom and top. If vents are used, cool room air is drawn in at the bottom, rises in the warm space between the mass and the glazing, and enters the room through the top vents. Such systems are usually called "Trombe walls" after Felix Trombe of Odeillo, France, who with architect Jacques Michel substantially boosted their development in the 1960's by building several homes incorporating this design in the Pyrenees. The concept was originated and patented by E.L. Morse of Salem, Massachusetts, in the 1880's. His walls, complete with top and bottom dampers, used slate covered by glass.

The second general type of thermal storage wall uses water. An example of a waterwall in Figure C3-1 uses modules of cast fiberglass-reinforced polyester. The black modules are about 8 feet long, 2 feet high, and 16 to 20 inches wide. They nest inside one another during transport from factory to site (E^3E).

In some instances, waterwalls are more convenient to use than concrete. Because water maintains a more uniform temperature throughout the thickness of the wall, its absorption surface remains at a lower temperature than the absorption surfaces of Trombe walls. This is the primary reason that waterwalls are slightly more efficient than Trombe walls.

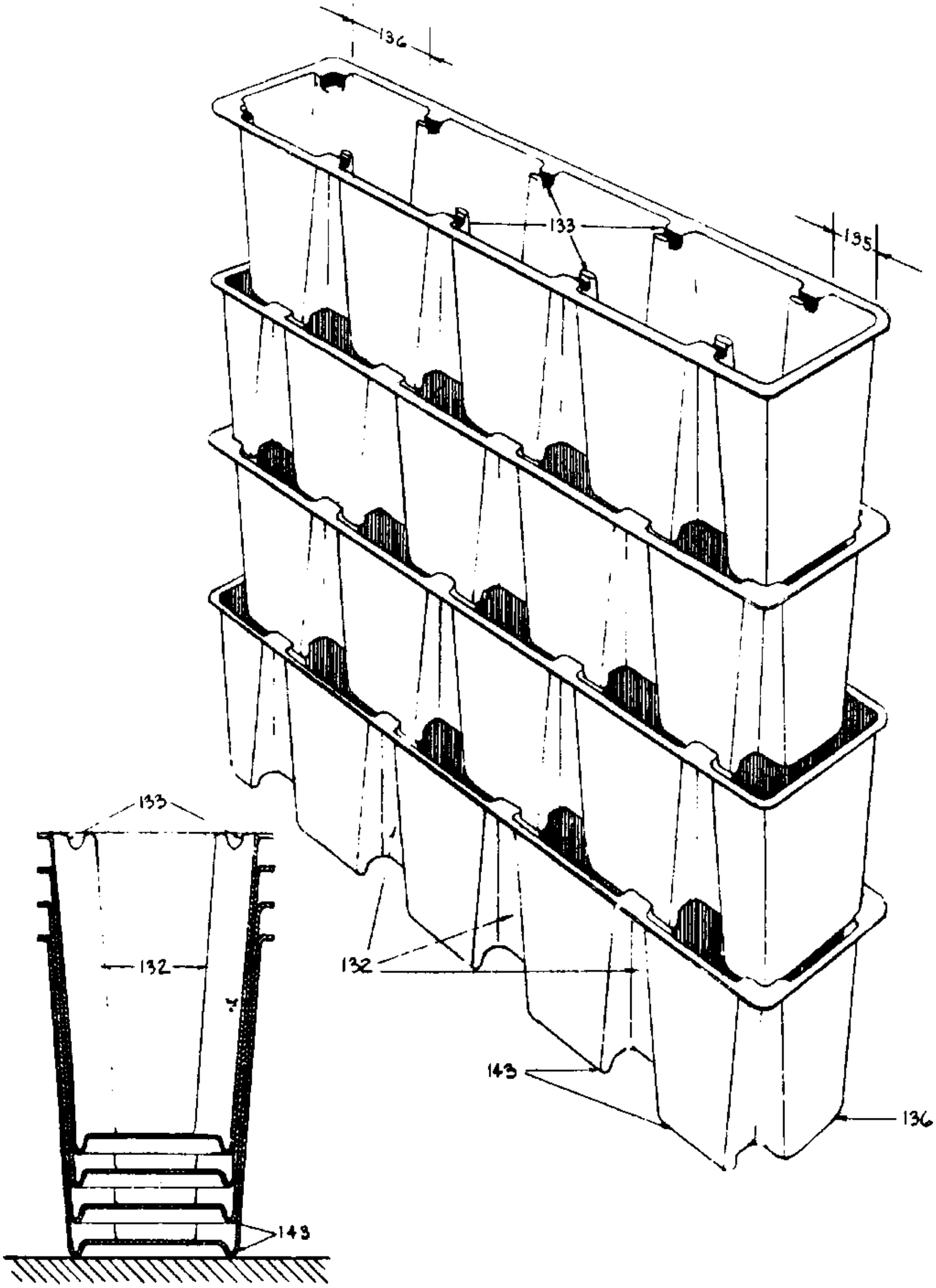


Figure C3-1: Waterwall modules by One Design, Inc. (MAL)

C3.b.2 Design Variations

Figure C3-2 combines movable insulation with a concrete thermal storage wall. Beadwall, reflective Mylar roller shades, and hinged or sliding insulating shutters have been used. The economic value of movable insulation in passive systems increases as the climate becomes more severe. However, most concrete storage wall systems to date have not used movable insulation because it increases first costs and is inconvenient. Triple glazing is regarded increasingly as an alternative.

Another variation is to use thermal storage walls to induce ventilation. Dampers are positioned as shown in Figure C3-3. The solar heated air between the glass and the warm concrete is exhausted through the vent, creating a "chimney effect." This draws warm room air to the base of the collector, and cool outdoor air enters the house through vents in other exterior walls. This system should not be considered unless the dampers can be closed tightly during the winter since air leaks can be a major source of heat loss.

An alternative to the solid concrete wall facing south is Vertical Solar Louvers, a set of rectangular columns situated directly behind south-facing glazing and oriented in the southeast-northwest direction. The Louvers admit morning sunlight and solar heat into the building and store heat from the afternoon sun in the masonry. (See Figure C3-4.)

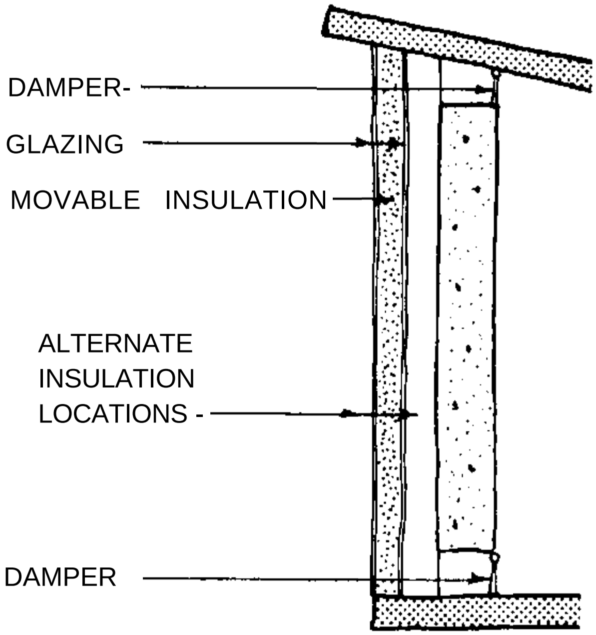
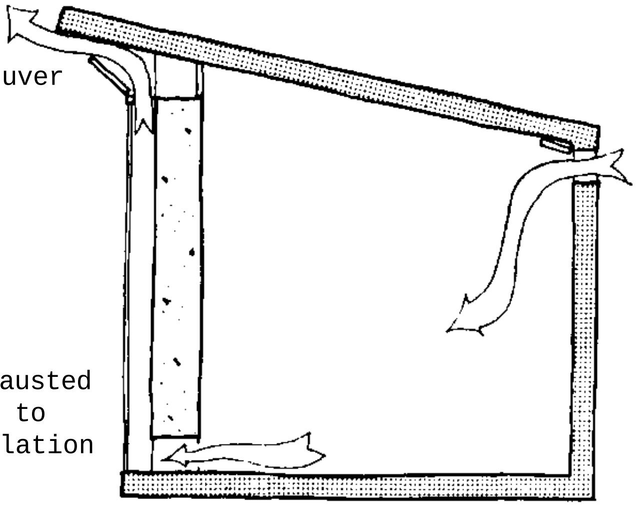


Figure C3-2: Movable insulation with a concrete thermal storage wall (nighttime operation) (HON).



Seasonally operated louver

Cooler, outdoor ventilating air

Solar heated air exhausted from the Trombe wall to induce natural ventilation

Figure C3-3: Thermal storage wall — cooling (HON).

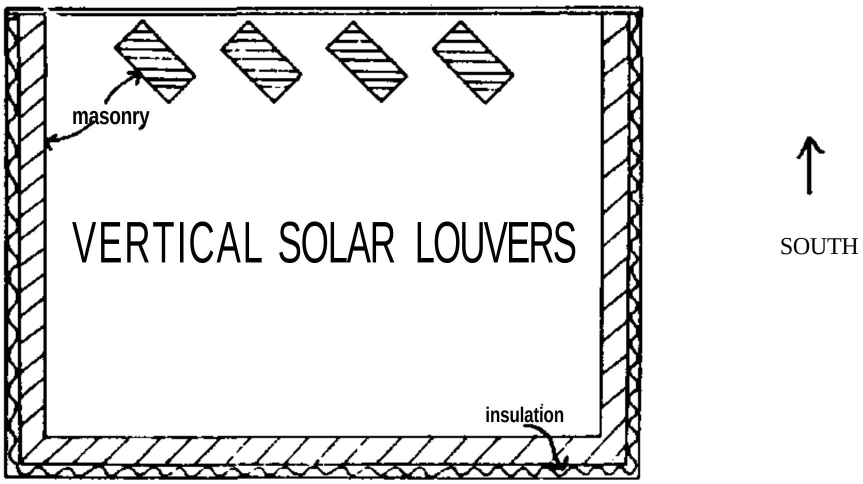


Figure C3-4: Vertical solar louvers (BIE).

In a sense, this system combines direct gain and Trombe wall. It can quickly heat the building early in the morning through direct gain, and the wall columns can absorb afternoon heat from the sun. This system also permits access to the glazing system for cleaning and maintenance and more -readily allows the use of movable insulation between the glazing and the walls.

Note that the heat wave through the concrete louvers will be delayed by several hours due to their westerly orientation. The main disadvantage of this system is that the louvers protrude into the living space (BIE).

Figure C3-5 is an example of one type of water wall. This system, called Drumwall,^{TM} was first developed by Steve Baer of Zomeworks Corporation. It uses 55-gallon drums filled with water. Insulating panels hinged at the base of each wall cover the single layer of glass at night to reduce heat loss. When the panels are open and lying flat on the ground, the aluminum surface reflects additional solar irradiation onto the drums. During the summer, the panels in the closed position shade the glass.

The water wall in Figure C3-6 uses water-filled vertical tubes. As an added level of comfort control, the tubes are separated from the living space by a wall through which room air can pass and sweep past the warm tubes. A fan controls the flow of air. A thermal curtain closes between the tubes and the glass at night to reduce heat loss.

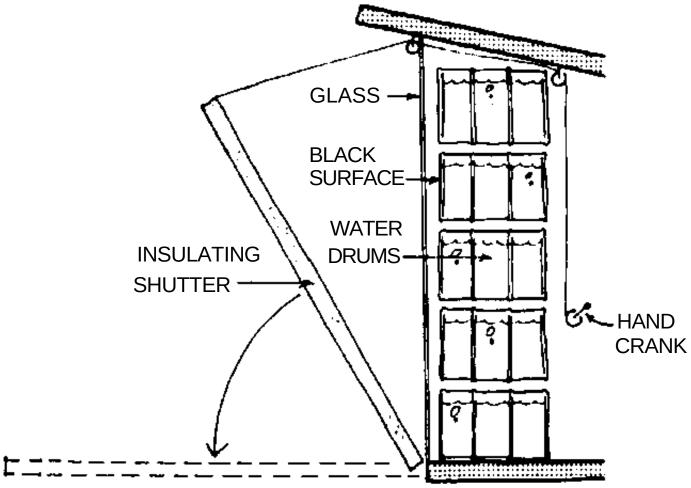


Figure C3-5: Hand-operated insulating shutter with water drum storage by Zomeworks Corporation (HON).

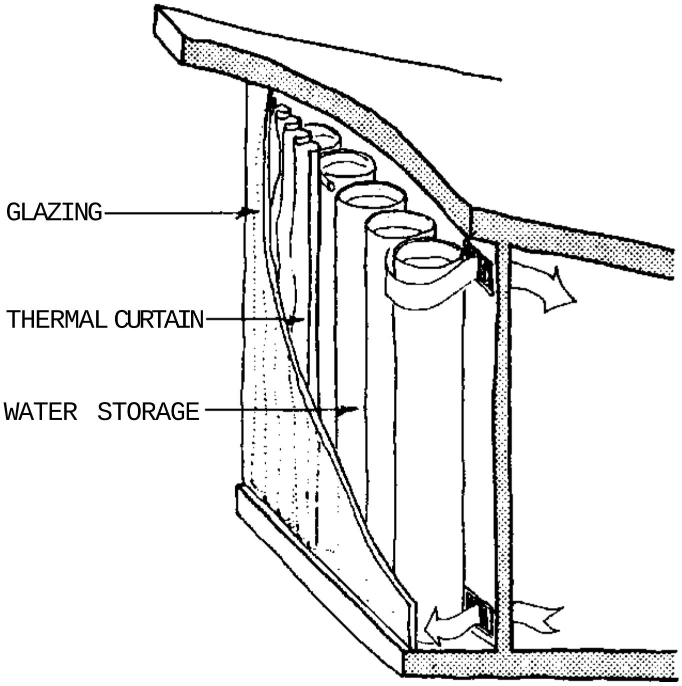


Figure C3-6: Thermal curtain with water tube storage by Kalwall Corporation (HON).

Figure C3-7 gives the heat storage capacity for cylindrical tubes of various diameters. Corrugated, galvanized culverts and fiberglass reinforced polyester are the most commonly used cylinders.

To overcome the high cost of concrete and at the same time store large amounts of heat, Wayne and Susan Nichols, designer/builders in Santa Fe, New Mexico, developed a "water-loaded Trombe wall." It consists of cast concrete tanks, 4×8 feet × 10 inches (outside dimensions); the tank wall is 2 inches thick, leaving a 6-inch cavity. After the wall is installed, a plastic bag filled with water and sealed is placed in the cavity. At night the single-glazed wall is covered outside by a Steve Baer-style hinged, insulating, reflecting shutter.

Data taken on the wall indicate that the thermal resistance of the outside 2-inch concrete wall is too great during the changing mode. Temperature differences of 40 F are observed across this wall. Temperature differences across the water and inner wall are small (5 F or less). The Nichols have concluded that walls of this type should be thicker for more heat storage and that the outer wall should be metal to reduce the resistance to heat flow.

New materials and components are being developed for thermal storage walls. For example, paraffin and other phase-change materials are being explored as substitutes for the heavy weight of concrete and water. These and other advances are covered in Chapter E.

Tube Diameter	8 in.	12 in.	18 in.	24 in.
Volume/lin. ft	0.34 ft^3	0.788 ft^3	1.77 ft^3	3.14 ft^3
Weight of contained water/lin. ft	21.7 lbs	49 lbs	110 lbs	196 lbs
Heat storage capacity/ lin. ft	21.7 Btu/F	49 Btu/F	110 Btu/F	196 Btu/F

Figure C3-7 : Heat storage capacity per linear foot of cylindrical containers of water for thermal storage.

C3.c DESIGN CHARACTERISTCS

C3.C.1 Building Integration

Thermal storage walls provide temperature stability in passive buildings and are appropriate for a variety of building types. The air vents for thermocirculation somewhat control the time when heat is delivered to the space. Since the wall is opaque, it eliminates the excessive glare associated with direct sunlight. Ultraviolet damage to goods and furnishings is avoided, which is particularly advantageous if used in retail stores and commercial buildings. Trombe walls are fire resistant. They provide security for warehouses and manufacturing plants and structural stability in high rise construction. Finish details can be very rough to suit manufacturing and industrial applications, yet they can be more polished to fit residential designs. Windows placed at suitable intervals will provide daylighting and give the occupants visual contact with their environment.

C3.C.2 Costs

First costs vary with differences in construction and detailing of the thermal storage wall and the exterior glazing. Where poured concrete and masonry block construction above grade are common, the wall is generally inexpensive. If an experienced subcontractor is available, or if materials can be obtained cheaply through local suppliers, the exterior glazing will be low-cost. Other types of thermal storage walls, including waterwalls, are comparable in price.

Cost estimates prepared for the Trombe wall design described in Section C3.d (with plaster interior finish) vary from a low of $11 per square foot to a high of $27.00 per square foot in 1980 dollars. To obtain a true net additional cost for passive solar heating, the cost of conventional construction that is replaced by the thermal wall should be subtracted. Since the most expensive conventional residential exterior wall, including insulation and interior finish, usually runs between $2.50 to $4.00 per square foot, the true first cost of the Trombe wall is estimated at $9.00 to $15.00 per square foot.

Operating costs for these walls are zero, and little or no maintenance is required. Maintenance in many climates is comparable to that for vinyl siding: occasional (every 2 to 4 years) washing of the exterior glazing is advised. Harsh industrial environments may degrade plastic glazing; "refinishing" coatings are available from leading manufacturers and may be applied on a 3- to 5-year basis.

C3.C.3 Thermal Performance

Thermally, these walls perform reliably. Heat losses, even under worst conditions, are not very different from those experienced with conventional construction. The overall U-value of 0.23 (reverse thermocirculation prevented) enables these walls to meet ASHRAE 90-75 standards for single-family residences located in climates not exceeding 5200 degree days. If solar gains are considered, they are net heat producers. In a sense, then, this results in a negative U-value over the course of the heating season.

Solar energy collection takes place at low to moderate temperatures, generally not exceeding 150 F for Trombe walls and lower for waterwalls. This provides good instantaneous efficiencies (generally comparable to active system flat-plate collectors). Except in the deep south, the vertical south wall orientation results in good winter heating performance and minimal summer overheating. Air is delivered to the room at moderate temperatures through the vents, generally not exceeding 90 F (or temperatures 20 to 30 F higher than the room air entering the space between the glazing and the wall). Normal airflow is approximately 1 cfm per square foot.

Although there are many ways to analyze the benefits of thermal storage walls of various thicknesses, 6 to 12 inches is the optimum range for both Trombe walls and waterwalls.

Figure C3-8 shows the calculated seven-day temperature fluctuations of the room side and sun-side surfaces of three Trombe walls without vents in Los Alamos, New Mexico. The ratio of the building load to the glass area is 0.5 Btu/h ft^2 F. One wall is 6 inches thick, another 12, and the third 24. The daily fluctuations on the inside wall surface are markedly different for the three cases. They are very pronounced, 45 F, for the thin wall and nonexistent for the thick wall. The long-term effect of two days of cloudy weather is observed on the inside of the thick wall as a 10 F variation.

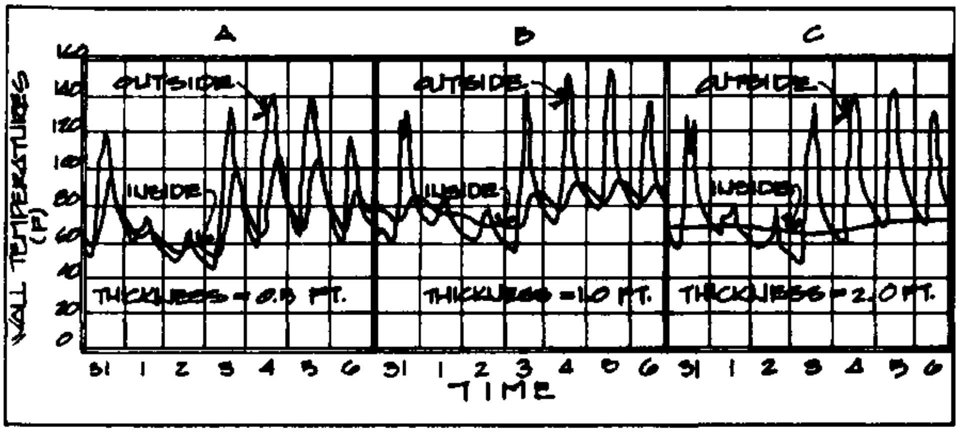


Figure C3-8: Time response, masonry wall, 1-week period (BAL)

The net annual thermal contribution of different thicknesses of walls is not markedly different. (See Figure C3-9.) The 1-foot-thick wall is the best of the three, giving an annual solar heating contribution of 68 percent. Although the net contributions of the thin wall and thick wall cases are nearly the same, the amount of thermal control required to limit fluctuating room temperatures is less. Note that the solar fraction continues to increase for waterwalls of increasing thicknesses (represented by the curve of infinite conductivity).

Trombe walls can be different thicknesses for different time delays of the heat wave from the hot, sunny side to the room side. In general, a building can be heated by direct gain or convective loop systems during the day and then by the thermal storage wall at night. Figure C3-10 gives the variation in inside surface temperature swing and the time delay between the irradiation and the occurrence of peak temperatures on the inside surface. These characteristics are for a double-glazed solid concrete wall during sunny days.

Depending on the heat storage capacity of a house, heat from the wall may not be needed until far into the night. This may call for a thick wall, perhaps as much as 18 inches, since it will be well past midnight before room temperatures begin to drop.

In commercial design, on the other hand, heat may be needed during the day. For example, most academic buildings are restricted to daytime use. Unless there is sufficient heat during the day from people,

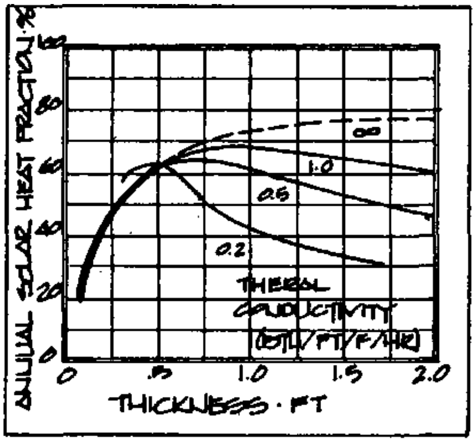


Figure C3-9: Annual solar fraction provided by thermal storage walls of different conductivity and thickness (BAL)

(Note: Thermal conductivity of 1.0 represents the thermal mass wall (Trombe wall); infinity represents water; 0.5 probably represents a concrete block wall.)

Wall Thickness (inches)	Inside Surface Temperature Swing (F)	Time of Temperature Peak at Inside Surface
8	27	6:00 pm
12	13	8:00 pm
16	6.5	10:30 pm
20	3.0	1:30 am
24	1.3	4:30 am

Figure C3-10: Characteristics of a solid concrete wall during sunny days with outside double glazing (Volume II of this Handbook).

lights, and direct gain through windows, the wall should be as thin as possible. In fact, a Trombe wall may be a poor choice, and a thermosiphoning collector or even an active collector with no storage would be better. Alternatively, heat from the Trombe wall can be used at night during temperature setback conditions.

Figure C3-11 shows the annual percent of solar heating for various cities in the country from various types of thermal storage walls: water walls (WW); solid walls without vents (SW); Trombe walls with vents and with backdraft dampers to prevent reverse thermocirculation (TW); Trombe walls with vents opened at all times (TW(A)); and Trombe walls with thermostatic vent control (TW(B)).

The calculations are for a thermal storage mass of 45 Btu/ft^2 F glass area (18 inches of concrete or 8.6 inches of water). No night insulation is used. All thermal storage wall designs seem to be viable for solar heating in all climates studied. Note that particularly in cold climates such as Madison and Bismark, the prevention of reverse thermocirculation through the vents is an important part of the design. Thermostatic control of the vents does little to improve the heating performance but does reduce the tendency for the vents to overheat the building during mild, sunny weather. Night insulation dramatically improves performance of thermal storage walls, especially in cold climates. The R-value, and therefore the panel construction, need not be substantial. An R of 4 to 6 will provide about 75 percent of the heat loss reduction of R-9. Only rarely will R-values higher than

	Annual Percent Solar Heating				
City	WW	SW	TW	TW(A)	TW (B)
Santa Maria	99.0	98.0	97.9	97.3	98.0
Dodge City	77.6	69.1	71.8	62.8	73.6
Bismarck	49.8	41.3	46.4	31.1	47.6
Boston	60.0	49.8	56.8	44.9	56.7
Albuquerque	90.8	84.4	84.1	81.8	87.5
Fresno	85.5	82.4	83.3	78.0	83.4
Madison	43.1	35.2	41.6	24.7	42.0
Nashville	68.2	60.7	65.2	54.1	65.4
Medford	59.0	53.3	56.1	42.2	56.8

TW(A): Trombe wall w/vents open at all times
WW: Water wall TW(B): Trombe wall w/thermostatic vent control
SW: Solid wall (no vents) TW: Trombe wall (no rev. vent flow)

Figure C3-11: Annual results for various thermal storage wall configurations in various climates (BAL). (Note that these are Solar Heating Fraction values, not Solar Savings Fractions).

9 be economically warranted. A simple time clock is the only control necessary for opening and closing the insulation.

In nearly all climates, thermal walls should have at least two glazings. An alternative to movable insulation in cold climates is an additional glazing layer or two. Movable insulation with more than two glazings is rarely economical. Multiple glazings have a greater effect on performance at higher solar load fractions than at lower ones.

Of course, the real measure of performance is annual energy savings by the solar wall. Annual values for 25 cities are given in Figure C3-12. The case is for the 18-inch-thick Trombe wall with no reverse thermocirculation. The vent size is 0.074 square feet (10.5 square inches) for each linear foot of wall. The heating load coefficient of the building varies with climate. The allowable temperature range in the space is 10 F, from 65 to 75 F. Night insulation is used in the colder climates.

The low annual savings for really sunny climates, such as El Paso, Texas, and Phoenix, Arizona, are due to the short heating season and the fact that night insulation was not used.

C3.C.4 Economics

Estimates of heat energy output and cost per million Btu are shown for representative cities in Figure C3-13. For comparison with

Case: 18 in. Trombe Wall; No reverse thermocirculation
Thermal conductivity = 1 Btu/ft/hr F
Heat Capacity = 30 Btu/ft^3 F
Vent Size = 0.74 ft^2/ft of wall length (each vent)
Temperature band = 65 F to 75 F

City	Heating Degree Days	R9 Insulation used on Trombe Wall at night*	Load, Btu/F-Day (Exclusive of TW)	Solar Savings Fraction	Solar Savings, Btu/yr per sq ft of Trombe Wall
Los Alamos, NM	6359	Yes	20	70	89,000
El Paso, TX	2678	No	30	57	45,700
Ft. worth, TX	2382	No	30	49	35,000
Madison, WS	7730	Yes	20	48	74,200
Albuquerque, NM	4292	No	20	56	48,100
Phoenix, AZ	1552	No	40	65	40,400
Lake Charles, LA	1498	No	40	50	30,000
Fresno, CA	2650	No	30	51	40,500
Medford, OR	4930	Yes	30	49	72,500
Bismarck, ND	9044	Yes	20	47	85,000
New York, NY	4848	Yes	20	57	55,300
Tallahassee, FL	1563	No	40	55	34,400
Dodge City, KS	5046	Yes	20	70	70,600
Nashville, TN	3696	No	20	42	31,000
Santa Maria, CA	3053	No	30	67	61,400
Boston, MA	5621	Yes	20	55	61,800
Charleston, SC	2146	No	30	52	33,500
Los Angeles, CA	1819	No	40	70	50,900
Seattle, WA	5185	Yes	20	60	62,200
Denver, CO	6016	Yes	20	72	86,600
Edmonton, ALB	10268	Yes	20	46	94,500
Vancouver, BC	5515	Yes	20	57	62,900
Winnepeg, MAN	10679	Yes	20	45	96,100
Ottawa, ONT	8735	Yes	20	49	85,600
Dartmouth, NS	7361	Yes	20	52	76,600

Note: Night Insulation used for greater than 4500 DD. This was arbitrary. Performance is much improved with night insulation, but cost and inconvenience are greater.

Figure C3-12: Annual energy savings by thermal storage walls. Data generated by J. D. Balcomb based on Appendix F of Vol. II of this Handbook.

City	Btu/ft^2 yr	Cost/MMBtu
Fort Worth, Texas	35,000	$28.90
Madison, Wisconsin	74,200	$20.47
Boston, Massachusetts	61,800	$24.58
Medford, Oregon	72,500	$20.95
Los Angeles, California	50,900	$19.89
Denver, Colorado	86,600	$17.54

1) These estimates were prepared by J. Douglas Balcomb at Los Alamos Scientific Laboratories, based on data from Fig. C3-12 using installation and life-cycle cost data from (HON). It was assumed that the cost of the Trombe wall with night insulation is 50% greater than without it.

2) These figures are the effective energy cost obtained by applying a capital recovery factor of 10% (corresponding to a 7-1/2% interest rate and a 20 year term) to estimated first costs.

Figure C3-13: Saved energy and associated costs for Trombe walls.

current conventional energy costs, consider the following: electricity at 6c/kWh is equivalent to an energy cost of $17.60 per million Btu; number 2 fuel oil burned at a seasonal efficiency of 0.50 at $1.00 a gallon results in an energy cost of $14.28 per million Btu. Actual performance will vary with the ratio of system size to building load. Future conventional energy costs will be much higher. Like all solar energy systems, oversized thermal storage walls will be less cost-effective. Within architectural constraints of normal building designs, however, it is difficult to oversize these systems, and the performance estimates provided are representative for initial project development.

C3.d A BASIC TROMBE WALL CONFIGURATION

Although a variety of Trombe walls have been built and although the design can be optimized for specific climates, the design in Figure C3-14 is basic and cost-effective for heating in most of the United States. The modular dimensions and particular construction details used here should help to simplify the tasks of designers and builders. Although this drawing has been prepared to show many details and specific dimensions, the exact configuration of a Trombe wall may vary considerably without adversely affecting its performance.

C3.d.1 Materials

This basic design consists of an outer glazing system, an inner thermal energy storage wall, backdraft dampers for airflow control, and

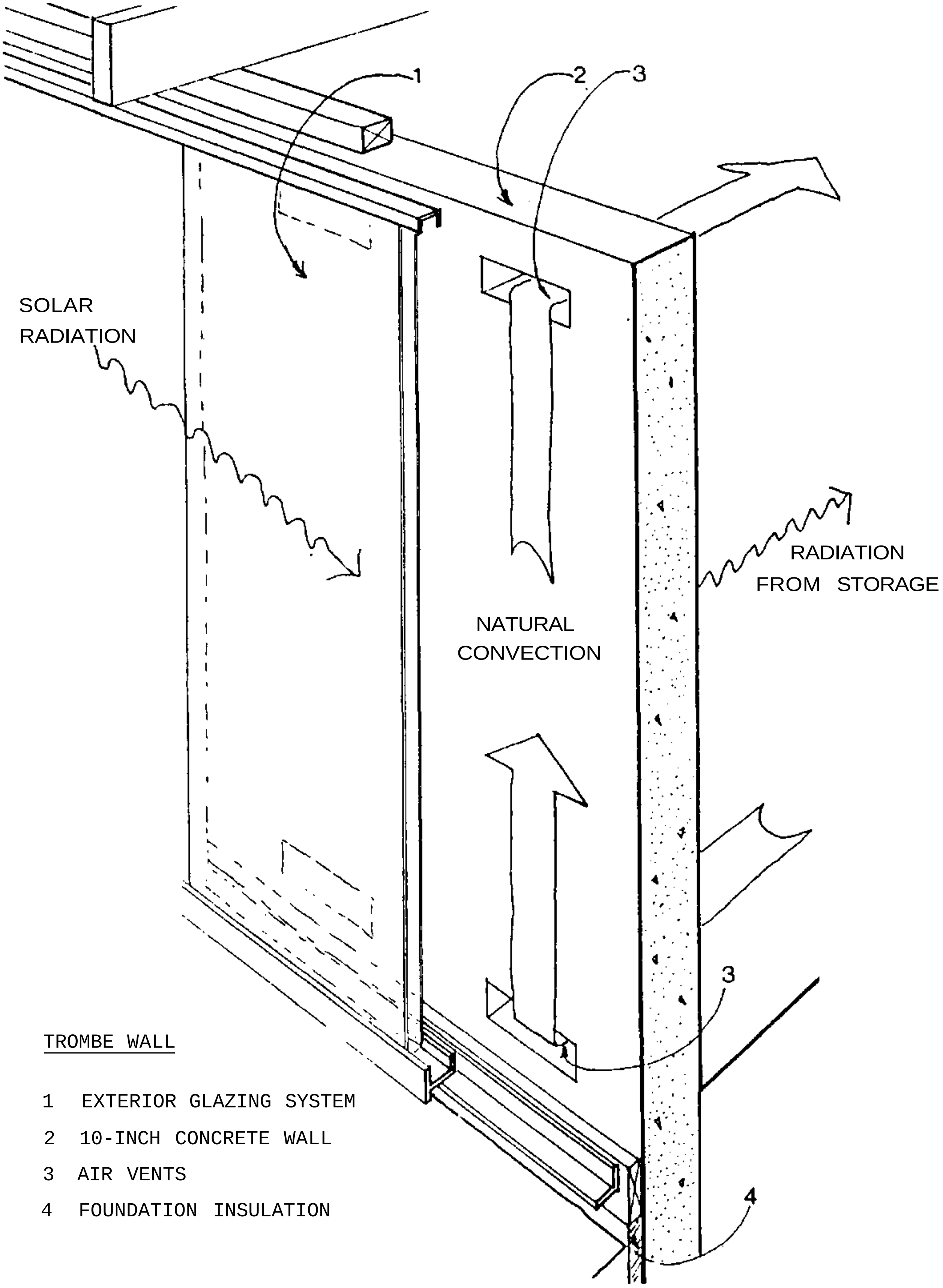


Figure C3-14: Trombe wall design (HON)

various optional trim and structural integration details.

The outer curtain wall/window wall system is aluminum framing in combination with two layers of glass or translucent or semi-transparent low-cost plastic. Unlike a direct gain passive system, views <u>out</u> are not possible; views <u>in</u>, showing the rough concrete wall surface, may be undesirable. Maximum system temperatures, even under stagnation conditions, range from 150 to 180 F, well below the stagnation temperatures of metal flat-plate collectors. Heat resistant plastics easily withstand the lower temperatures experienced by the glazing.

The thermal storage wall is concrete, either cast-in-place or laid with solid concrete masonry units and concrete mortar. The concrete should be regular stone concrete (about 140 lbs/ft^3) ; lightweight aggregates should not be used. When, as in most cases, the Trombe wall serves also as a structural wall, the necessary reinforcing wire or bar and any structural anchors can be added without altering the wall's solar performance characteristics. In general, the junction between the inner storage wall and the foundation, floors, adjacent side walls, and roof should be treated as normal construction. A primary exception is to eliminate or change details that permit direct conduction of heat to masonry or metal exposed to the weather. For this reason, the concrete wall is thermally isolated from the metal frame of the glazing system by wooden blocking and from adjacent conventional concrete construction by preformed vinyl or rubber control joints. Foundations directly below Trombe walls should be protected with rigid insulation in the same way as are perimeter heating systems in slab-on-grade construction.

Backdraft dampers serve the same function as backdraft dampers in HVAC systems, that of preventing air circulation in the "wrong" direction. However, in Trombe walls, slowly rising solar heated air in the cavity between the concrete wall and the glazing exerts a slight pressure to open them while falling cool air exerts a slight reverse pressure, forcing them to close. No one commercially supplies these dampers, and present installations use either custom-fabricated dampers (see Figure C2-12) or do without. In many cases, as discussed earlier, vents need not be used.

Any interior finish on the Trombe wall must not prevent its heat from reaching the room. Conventional architectural concrete finish such as exposed aggregate and sandblasted or brushed surfaces may be used. The surface may be sealed and painted any color. A plastic skim coat or plaster may be used. However, sheet materials, such as wood or hardwood paneling should not be used. Gypsum board can be used only if excellent continuous contact between the board and the wall can be obtained, a difficult task indeed.

The exterior surface should be cleansed with a masonry cleaner prior to painting. Although any dark color may be used on particularly rough-textured walls, flat black paint is preferred.

C3.d.2 Design

The concrete storage wall in this basic design is 10 inches thick and nominally 8 feet high. A 7-foot, 10-inch height is suitable for cast-in-place construction. Walls can be any length. Vent holes, if used, should be provided at intervals across the entire length. Vent holes in concrete block walls are nominally 3 5/8 inches by 15 5/8 inches. Single blocks are left out of lower and upper courses. In poured concrete walls, 4-inch by 15-inch openings are preferred. The total cross-sectional area of the vents (upper plus lower) need not be greater than one percent of the total wall area. The upper and lower vents are placed as close to the ceiling and floor as is practical, and in no case should the vertical distance between vents be less than 6 feet. Decorative grills or registers are installed over these openings on the interior face. The lower grill includes the backdraft damper.

The exterior glazing system is mounted 3 to 4 inches away from the outer darkened concrete surface. Where the aluminum glazing supports are attached to the wall, wood or other insulating material should be used as a thermal separator. The glazing should extend above and below the face of the storage wall, fully exposing it to the sun. Since glazing is the weather skin of the building, it must be airtight and water resistent.

Trombe walls without vents are easier to build if windows are incorporated into the wall. The direct gain through these windows will heat the building during the day. Simultaneously, the Trombe wall will store the day's heat for use during the night. Figure C3-15 is an example of such a wall. This wall is used in the "Brookhaven House," designed by Total Environmental Action, Inc., for Brookhaven National Laboratories under a DOE contract. The wall consists of two layers of paving brick covered by triple-glazed, float glass panels mounted in milled wood strips. In the summertime when the sun is high in the sky, the wall is shaded by a retractable canvas awning.

C3.d.3 Construction and Installation

Building the Trombe wall described in Figure C3-14 normally requires only general contracting skills. Depending on contractor preference, the installation of the glazing system can usually be handled by the manufacturer's representative. This enables the building owner to obtain a better warranty on its weather-tightness. The storage wall should be constructed at the lowest cost possible given the thermal, structural, and interior finish requirements outlined above. If the contractor or his subcontractors normally use poured concrete only in foundation work or if multi-story installations are planned, the solid masonry unit wall is usually preferred.

Work scheduling presents no problem if the contractor carefully reviews construction requirements in advance. The glazing system is usually fabricated to site dimensions; therefore, to avoid delays in closing the building, these dimensions should be established early in construction and orders should be placed early for the glazing. Con-

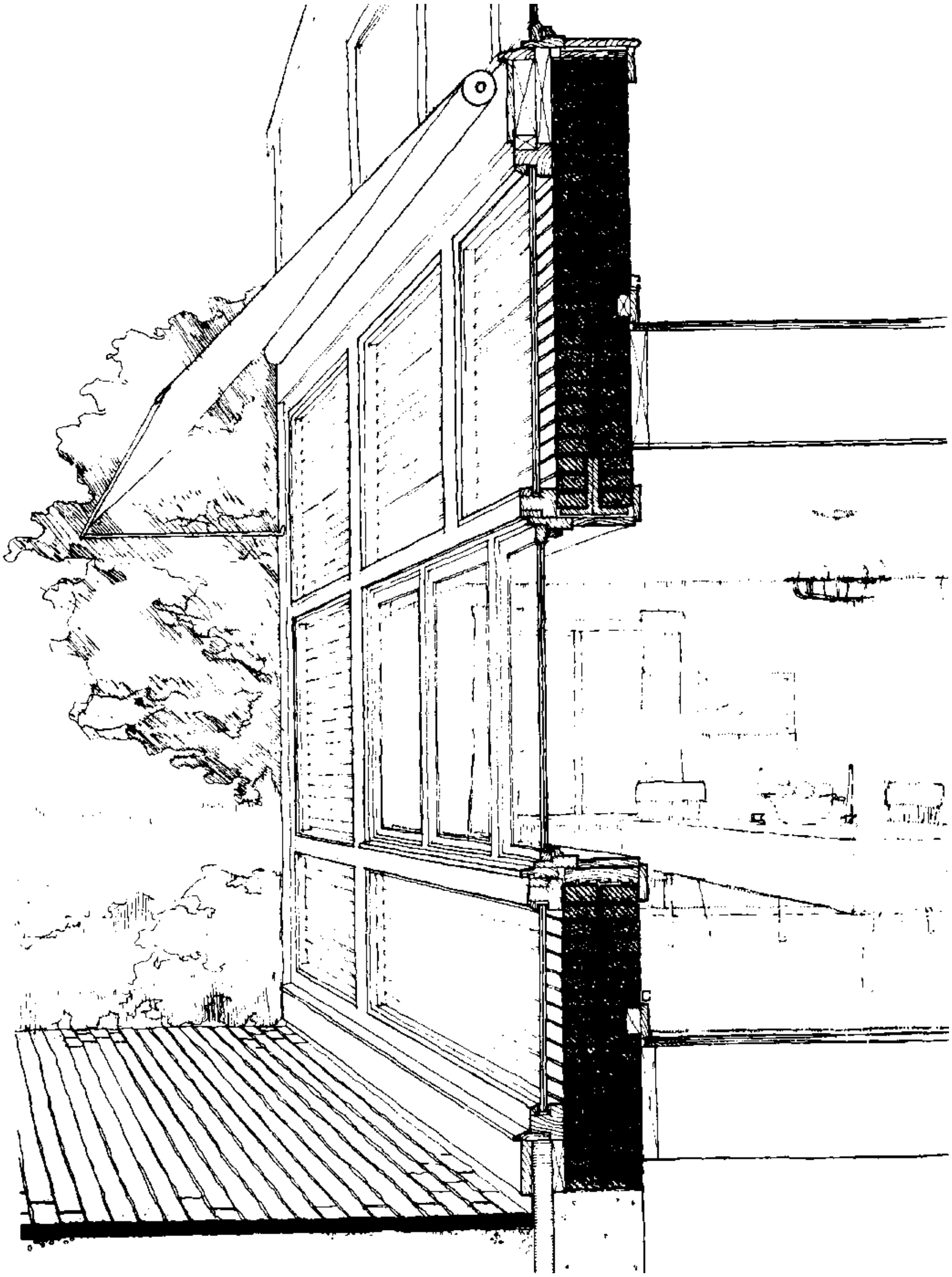


Figure C3-15: The Brookhaven House (TEA-2) crete finishing work may require the appropriate trades on the job site at other than the normal times.

C3.e EXAMPLES

C3.e.1 Benedictine Monastery, Pecos, New Mexico

Ten miles south of Santa Fe, New Mexico, a 9,320 square foot office/warehouse building for the book publishing operations of a Benedictine Monastery combines direct gain with a Drumwall^{TM} (Figure C3-16)

The south surface is almost entirely glass; window area is 1,356 square feet with 440 square feet of Drumwall. The Drumwall consists of 138 oil drums enclosed in an insulated cabinet. The top of the cabinet is a countertop work surface in the 2,660 square foot offices. The heat passes by natural convection through vents in the cabinet, eliminating the need for fans.

Insulating panels are hinged to the exterior base of the wall. In the louvered, horizontal position, they reflect additional solar radiation onto the Drumwall. In the raised position, they reduce heat loss. During the summer, they shade the wall.

The 4,900 square foot warehouse is heated by direct gain through clerestory windows. Excess warm air from the offices is occasionally vented into the warehouse. (See Figure C3-17.) The building is masonry

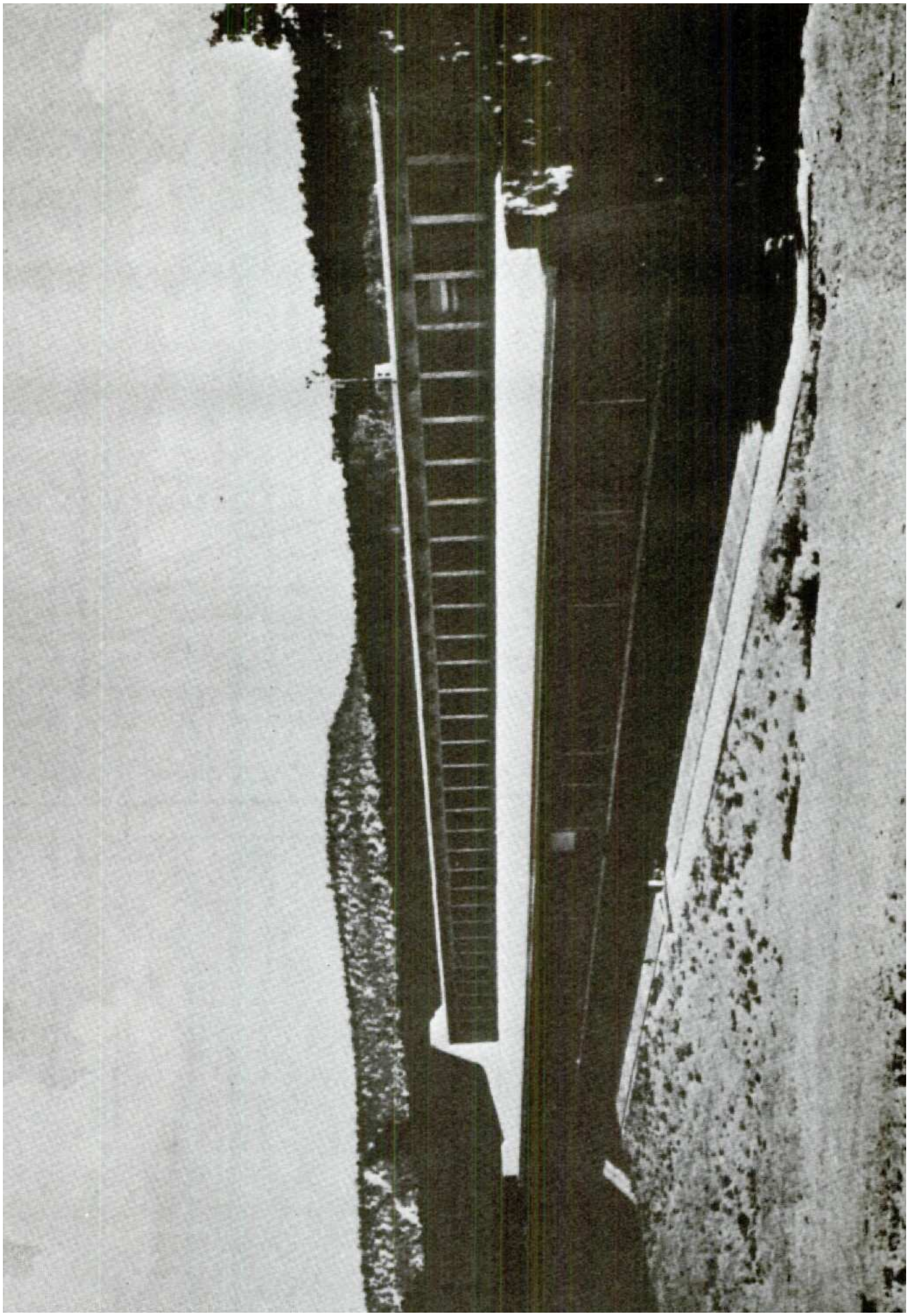


Figure C3-16: The Benedictine Monastery Warehouse (STR).

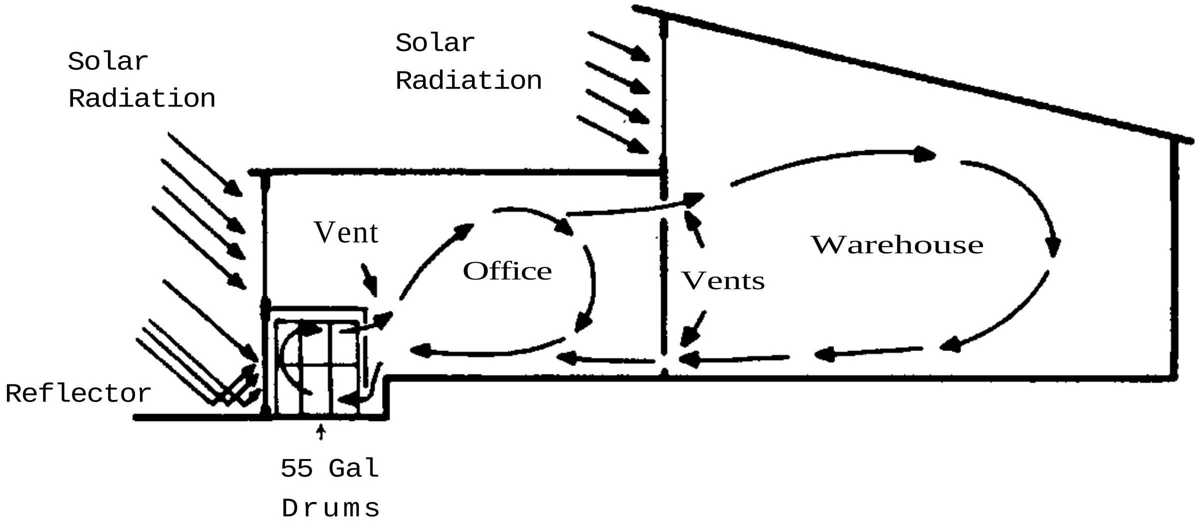


Figure C3-17: A cross-section of the Benedictine Monastery Warehouse showing the solar heating systems (SAN) with rigid foam insulation applied to the exterior surface.

The sun provides 90 percent of the heat. The office has a temperature swing of 15 F, with an average low of 63 F. The warehouse has a temperature swing of 10 F, with an average low of 48 F.

C3.e.2 The Kelbaugh House, Princeton, New Jersey

Architect Doug Kelbaugh, Princeton, New Jersey, designed his own two-story Trombe wall house (Figure C3-18). North, east and west walls are standard wood frame censtruction and have minimal window areas. Windows on the south side are incorporated into the Trombe wall. The Trombe wall also incorporates a standard, commercially available greenhouse. The total south wall collection area, including the greenhouse and a two-story Trombe wall, is 600 square feet. (See Figure C3-19.)

Using conventional heat loss analyses, the design load is 65,000 Btu/hr. The empirically determined load is 56,300. Estimated consumption of gas in the backup heating system was 121 ccf during a 4500 degree day winter. Actual consumption during its first winter of operation (with 4500 degree days) was 338 ccf and during its second year, 246 ccf (5556 degree days).

Indoor temperature swings were 3 to 6 F during a 24-hour cycle. The seasonal low and high temperatures were 58 and 68 F downstairs

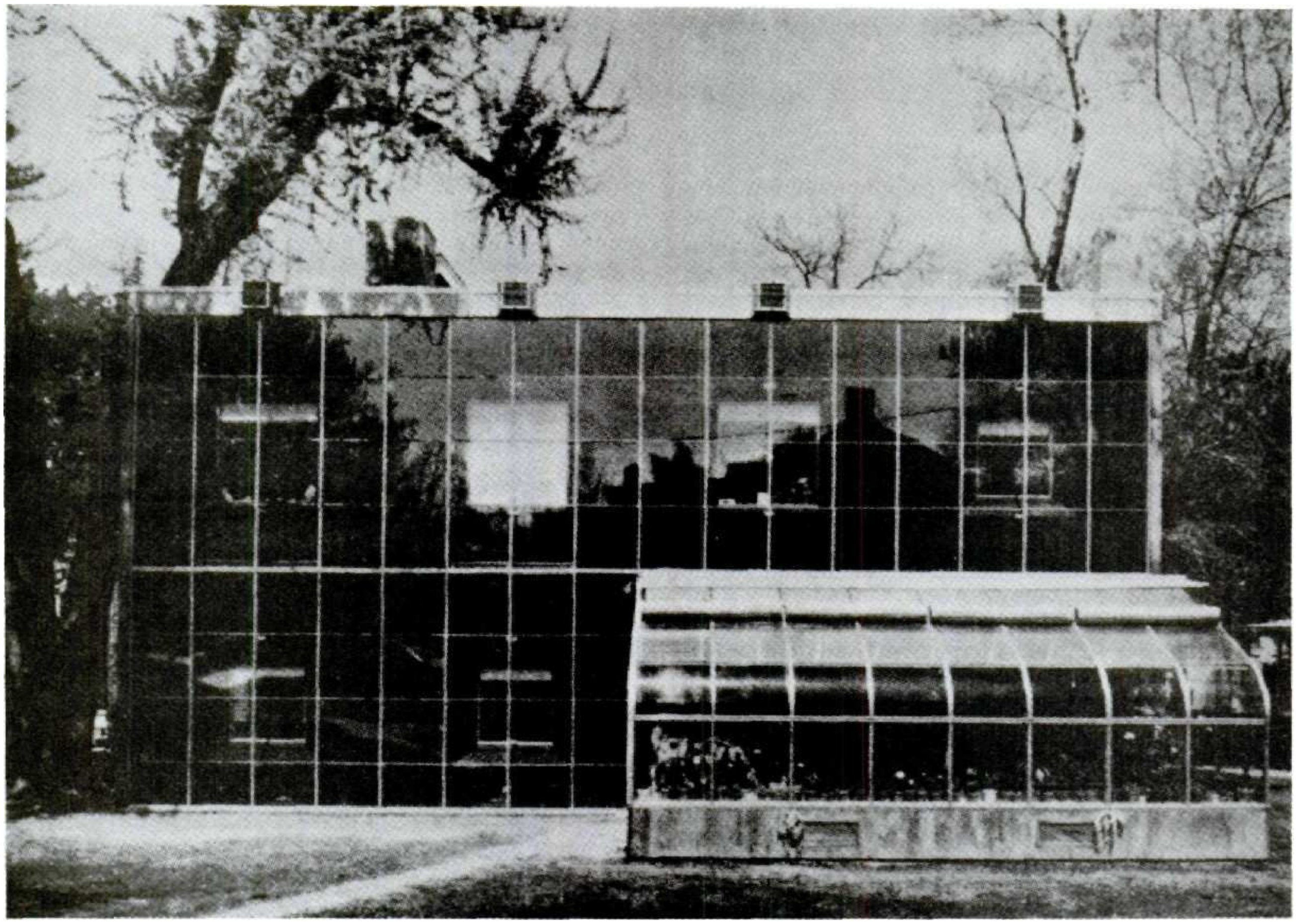


Figure C3-18: Doug Kelbaugh's house — south elevation (KEL-1)

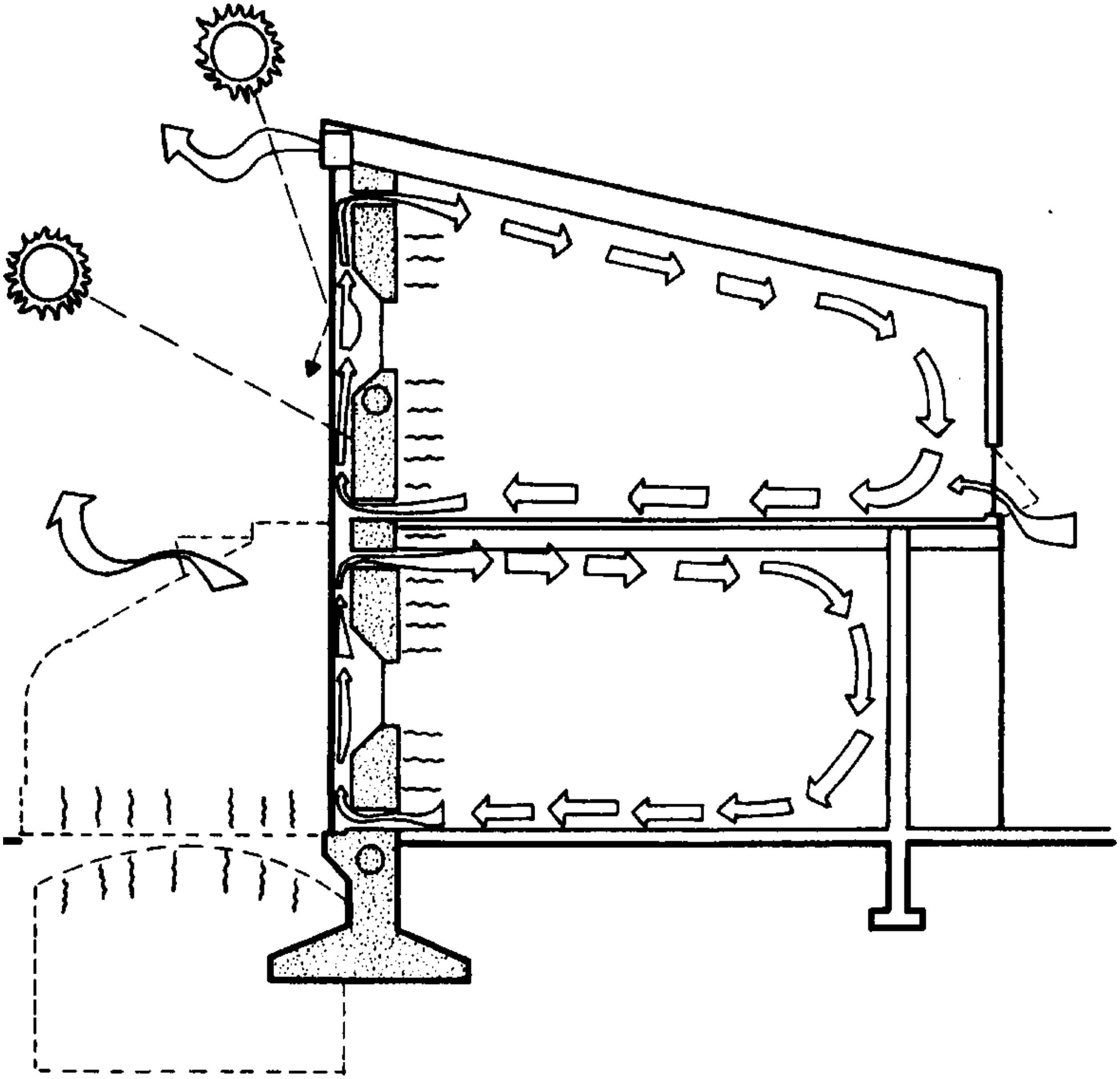


Figure C3-19: A cross-section of the Kelbaugh house showing heat flows (SAN).

and 62 and 72 upstairs. The estimated averages were 63 F downstairs and 67 F upstairs. (Actual comfort levels were somewhat higher due to the radiant warmth from the Trombe wall.)

In addition to the vents at the top of the Trombe wall, four fans are used to ventilate the wall during the summer. The wall, in turn, ventilates the entire house by pulling air across the rooms from windows on the north wall (KEL-1) (KEL-2) (KEL-3).

SUBCHAPTER C4, FIVE PASSIVE SOLAR HEATING TECHNIQUES

THERMAL STORAGE ROOFS

C4 THERMAL STORAGE ROOFS

C4.a INTRODUCTION

In many respects thermal storage roofs (roof ponds) are similar to thermal storage walls: the collector and heat storage are part of the same unit.

Roof ponds consist of waterbed-like transparent bags filled with water that, when exposed to solar irradiation, collect, store, and distribute heat. This heat passes downward from the supporting metal ceiling to the living space, gently warming it. In the summer, heat passes upward to the ceiling and into the water-filled "thermo-ponds", cooling the house. Then during the night, the water gives up its heat to the sky by thermal radiation, convection, and evaporation. Movable insulation is used to enhance the roof pond's performance. (See Figure C4-1.)

Water can store more energy per unit weight than other common building materials, and roof ponds typically have water depths of 8 to 12 inches. Because of the free convection of water within a water bag, the bags operate isothermally, thereby quickly transfering any temperature gain (or loss) to the building space. This is quite different from concrete thermal storage walls that exhibit a time lag effect from the time the outer surface changes temperature to the time when the inner surface changes.

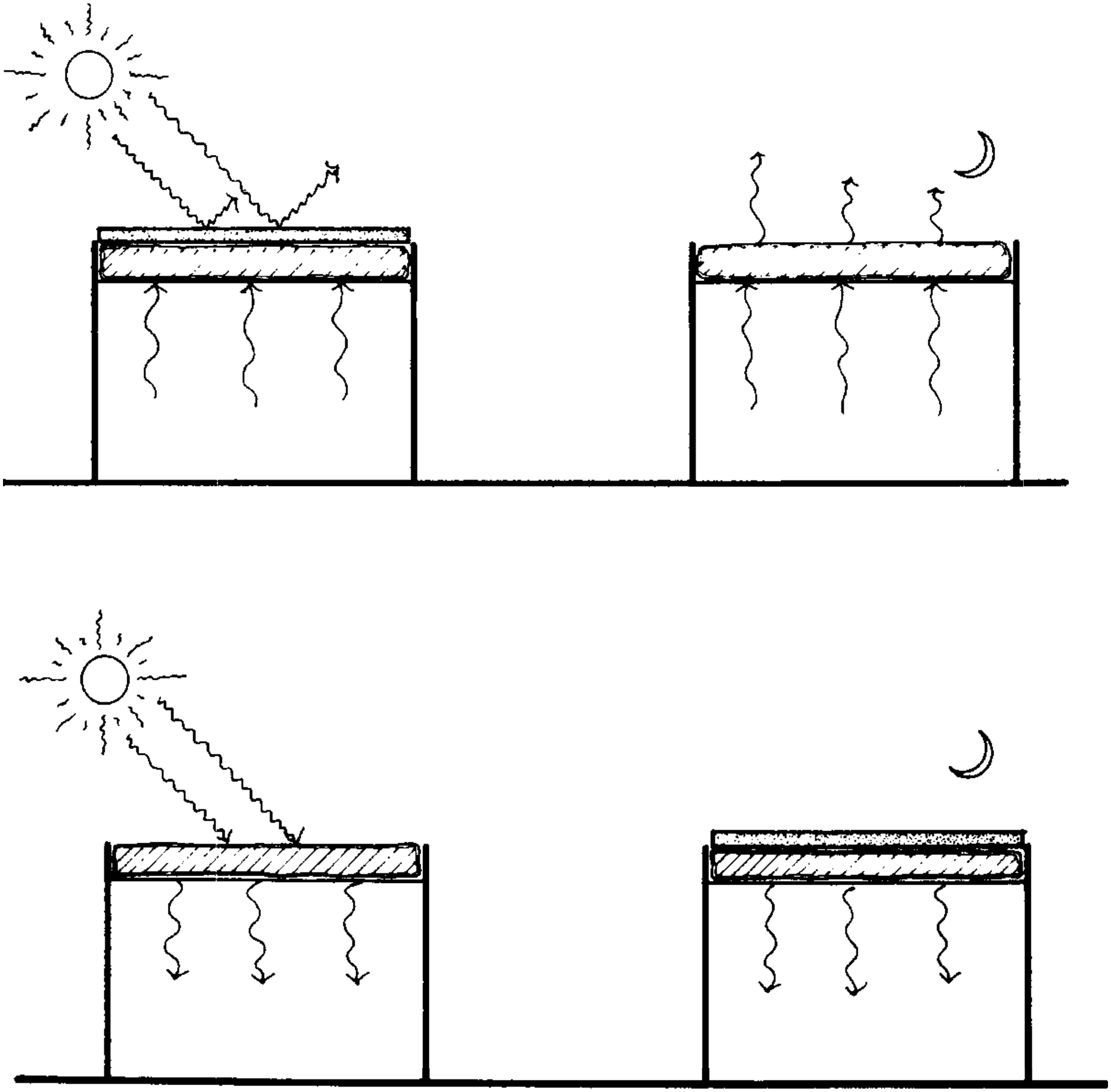


Figure C4-1: "Skytherm"^{R} thermal storage roofs: summer and winter operation (HON).

Initially, it may seem that the lack of a time-delay would be a serious disadvantage of roof ponds since it would eliminate the natural diurnal cycling. However, the movable insulation largely controls the roof pond's temperature. The temperature drops as low as 65 F in summer and is permitted to climb as high as 85 F in the winter. Typical day-long heat collection efficiency is 45 percent (YEL-3). Less than half of the heat is transferred downward into the house; the remainder is lost through and around the closed insulation panels.

C4.b BASIC SYSTEM CONFIGURATION

Thermal storage roofs have been built in two basic configurations: flat and south-sloping. Generally the flat roof system is used in the lower latitudes where the sun rises high enough in winter to bathe the ponds with sufficient solar irradiation. In more northern latitudes, south-sloping glazing admits the low-angled solar irradiation and sheds snow. The roof ponds, however, lie flat above the ceiling of the house. The other surfaces of the space that is formed are well-insulated and are faced with reflective foil.

C4.c EXAMPLES

C4.c The Atascadero House

Figure C4-2 is a cross-sectional view of the roof pond and movable insulation system used on a house in Atascadero, California, designed by Harold Hay (NIL). The house was designed according to earthquake codes. The ceiling of the approximately 1,100 square feet of living space is completely covered with 8 inches of water. The water is sealed in clear ultraviolet-inhibited, 20 mil, polyvinyl-chloride water bags as shown. Underneath these 53,600 pounds of water is a layer of black polyethylene to help absorb solar irradiation at the bottom of the bags. Aditionally, an air cell of inflated clear plastic sheet above the water bags enhances the greenhouse effect during the heating season. This air cell is deflated in the summer months to enhance radiative cooling. A 40 mil steel deck roof/ceiling supports the water bags and provides good heat transfer to and from the living space. Above the roof ponds, a system of movable insulating panels is mounted on horizontal steel tracks. The insulation is 2 inches of rigid polyurethane faced on both sides with aluminum foil. The panels are moved by a 1/6 hp motor operating about 10 minutes per day.

Thermal storage roofs are unique in that they are the only passive solar heating system that can also provide substantial cooling effects. Within the building, comfort is accomplished by radiation to the cool

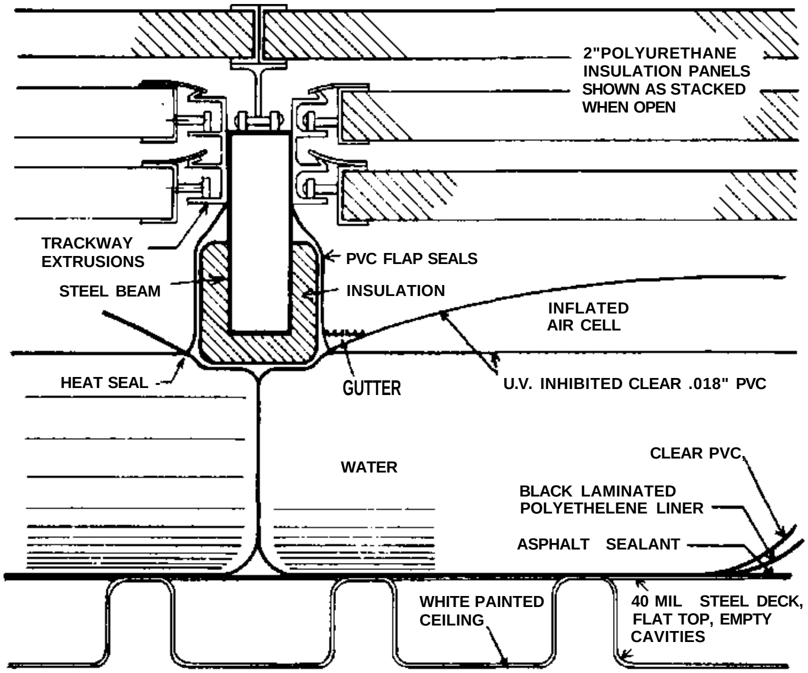


Figure C4-2: Cross section of water bag and panel System (NIL).

ceiling with combinations of night-sky radiation, night air convection, and, when the water bags are covered with additional water, by evaporative cooling.

Figure C4-3 shows the overall performance for a 9 month period after construction. As the figure indicates, only small variations occurred in indoor temperature. During the winter and summer, temperatures typically fluctuated between 66 and 73 F while the outdoor average daily temperature fluctuated between 47 and 82 F throughout the entire year. This house is 100 percent solar heated and cooled and has no backup system. Occupants have found the heating and cooling to be "superior" to conventional systems previously experienced (NIL).

Cloud cover and relative humidity will reduce radiative heat transfer to the sky; clear skies and low relative humidity permit the best heat transfer rates. It is best if the water bags "see" the entire night sky — the flat configuration in the Atascadero house does this. The south-sloping glazing configuration does not see the entire night sky, nor does the glazing easily transmit heat. Therefore, radiative heat transfer to the sky is poor. However, this design is intended for use in northern latitudes where cooling is not essential.

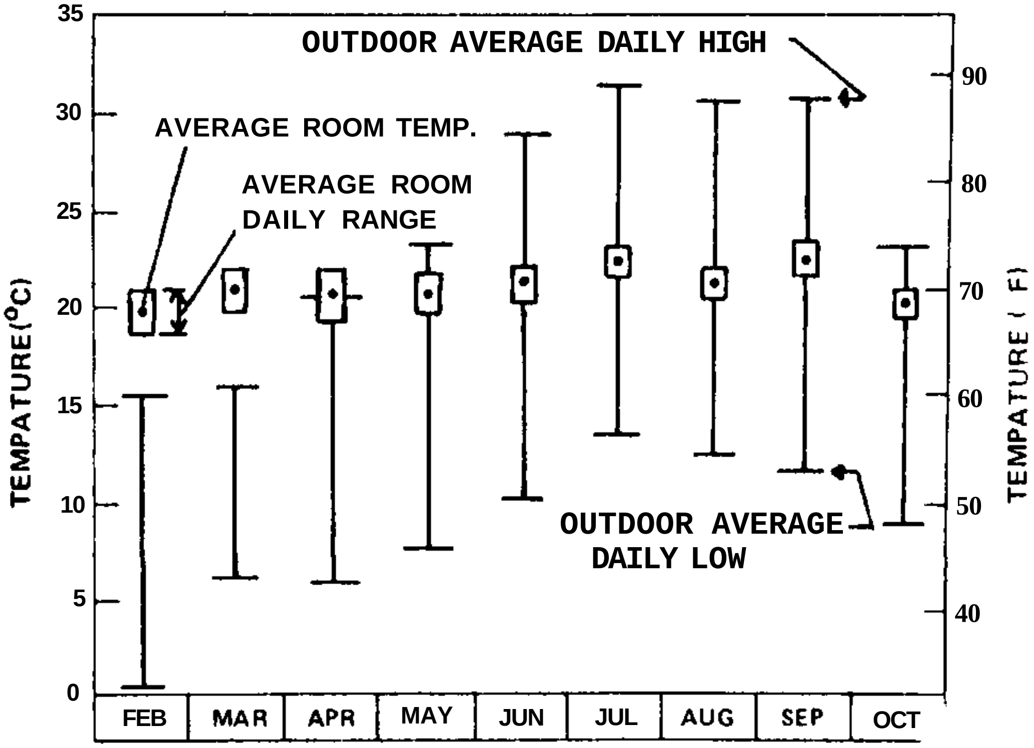


Figure C4-3: Monthly average temperatures of the Atascadero House (NIL).

C4.d.2 The Winters House

A variation on the house at Atascadero was designed by John Hammond and built in Winters, California. Winters has approximately 2600 heating degree days and 1300 cooling degree days per year. The average temperature in the hottest summer month (July) is 78 F with an average daily maximum of 97 F and an average daily minimum of 59 F. In the coldest winter month (January) the average temperature is 45 F with an average daily maximum of 54.5 F and an average daily minimum of 35 F. The 1,250 foot house is wood-framed on a concrete slab. Walls and ceilings are R-11 and R-19 respectively. Windows are single-paned with movable insulating shutters. There are approximately 120 square feet of south-facing windows and approximately 100 square feet of windows on the other three walls.

Running the length of the center of the house are a series of 6 feet by 8 feet by 12 inch deep galvanized steel pans coated with tar on the inside. They cover one-third of the roof area and hold approximately 13,200 pounds of water. The bottom of the pans form the ceiling of the house. The pans have a vinyl cover to prevent evaporation and to reduce heat loss. Eight-foot-square insulated lids cover the pans (see Figure C4-4). Conventional hydraulic pistons open and close the lids.

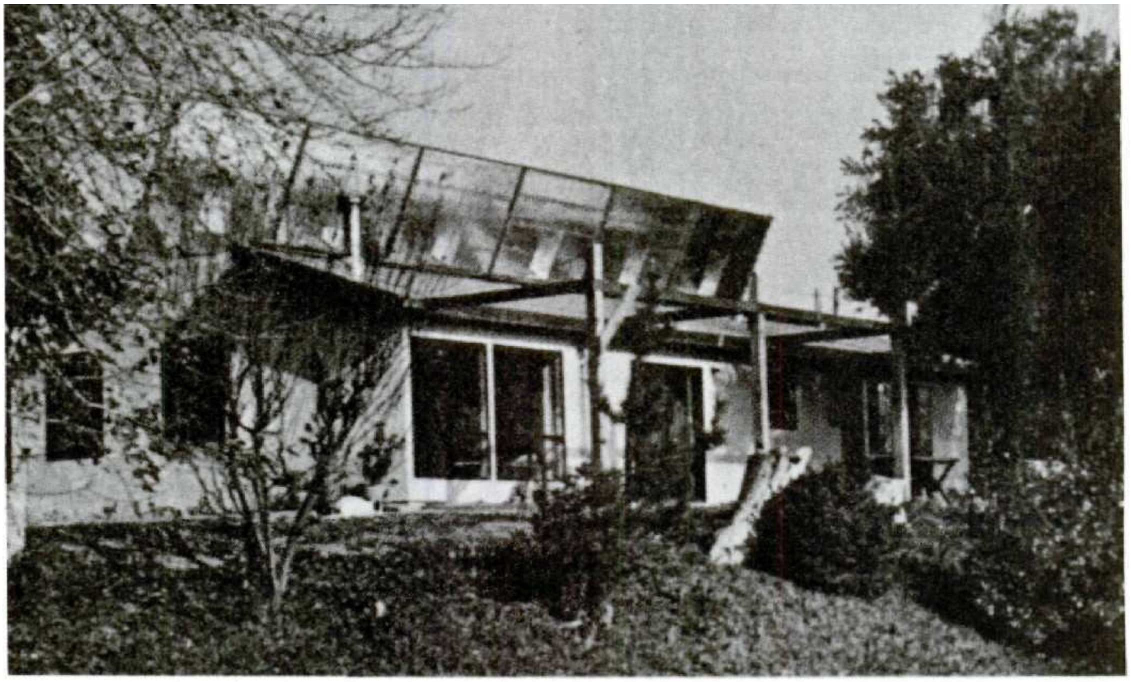


Figure C4-4: The Winters House

The house was completed in 1975. Even during the hottest summer weather, the maximum interior temperature has not exceeded 78 F. Cooling is obtained both by ventilating the house at night and by opening the lids so the ponds can radiate to the cool night sky. As with the south-sloping glazing configuration described earlier, night-time radiative cooling is somewhat inhibited by the angled lids.

The performance of the house was closely monitored. During the winter of 1975 - 1976 no auxiliary heating was used except for occasional fires in a Franklin stove. The natural gas space heater was never used. During a typical day, the temperature fluctuation was between 3 and 7 degrees. The average daily maximum was above 70 F and the average daily minimum was above 65 F (HAM). Chapter D2.d discusses radiative cooling in more detail.

SUBCHAPTER C5, FIVE PASSIVE SOLAR HEATING TECHNIQUES

ATTACHED SUNSPACES

C5 ATTACHED SUNSPACES

C5.a INTRODUCTION

Perhaps the greatest disadvantage of direct gain systems is the potential in poorly designed systems for wide fluctuations in indoor temperatures. However, if wide fluctuations can be permitted, reducing the thermal mass will substantially reduce the costs of direct gain systems. Similarly, the thermal mass required to temper wide temperature fluctuations in commercial greenhouses (from over 100 F on a cold, sunny day and dropping dramatically at night) is usually expensive. A mechanical system to circulate the overheated air to a gravel bed for later use is also expensive. Fortunately, some spaces in buildings can easily tolerate wider-than-normal temperature fluctuations, and extra efforts to moderate them may be unnecessary. Examples of such spaces include greenhouses, atriums, sunporches, and garages. A south-facing, glazed corridor is an example in larger buildings.

Although building costs are high even for such very simple and unrefined spaces, these spaces can take significant advantage of the sun's energy. Although in some sense these are still direct gain systems, the term "Attached Sunspace" designates spaces that fluctuate widely in temperature because of the direct gain of the sun. The overheated air can be used immediately to help heat the adjacent building, or it can be stored for later use when the sun is no longer shining. At virtually all times of the day, the attached sunspace has an indoor temperature higher than the outdoor temperature. Such higher temperatures tend to moderate the heat loss from the building. With the sunspace both supplying solar heat and reducing heat loss by acting as a buffer zone, that portion of the building adjacent to the sunspace "sees" a milder outdoor climate.

Ordinary south-facing buffer zones can be changed to sunspaces by adding south-facing transparent surfaces. This space can, in turn, provide solar heat to the attached building. Buffer zones in other orientations can have a similar, but not so dramatic, effect.

North-facing buffer zones, although not providing solar heat, will have temperatures between those of the indoors and the outdoors, resulting in a moderation of heat loss from the adjacent building. Placement of auxiliary spaces around the building, such as garages, corridors, restrooms, and other areas not requiring constant temperatures, is becoming an increasingly important option for conserving energy.

East- and west-facing buffer zones can be regarded as sunspaces but will not provide as much energy as south-facing buffer zones, and they may have serious overheating problems in summer. An east-facing greenhouse can provide early day sunlight, heat, and humidity. With moderate amounts of thermal mass reducing the speed with which the space cools, it can continue to act as a buffer zone throughout the rest of the day. The east side of the building, adjacent to this sunspace, may be the kind of space that requires higher temperatures early in the day and permits cooler temperatures at night. Kitchens are often such spaces. On the other hand, living rooms and bedrooms might remain cool during the day and become warm in the afternoon from the heat gained from west-facing sunspaces. In any case, the living patterns of the occupants should be considered. East and west buffer zones should not use very much east or west glass since the high solar gains in the summer will cause severe overheating.

Although sunspaces can be relatively simple to build, it may be expensive to bring the construction to the same level of quality and durability as the rest of the building. For example, it is possible to build a simple lightweight frame onto a house to support thin-film plastics. The resulting enclosure will be an excellent sunspace and provide considerable heat to the building. The temporary nature of the structure (compared with the construction of the rest of the building), the lack of permanent and firm foundations, and the tenuous connections to the building, detract little from the thermal performance. On the other hand, commercial-quality construction, coupled with commercially-available greenhouse structures, can be expensive. In general, sunspaces are most economical when they have purposes in addition to providing heat and are built to a standard of quality that will enhance the appraised value of the building. In many urban and suburban locations, zoning or aesthetic regulations effectively prohibit the construction of the least expensive sunspaces.

An important function of sunspaces can be the growth of garden and house plants. If plant growth is important, design considerations increase in complexity. Glazing types, temperature fluctuations, humidity levels, and auxiliary heat must be viewed differently.

For example, cold-weather plants, such as the lettuce and cabbage, can tolerate cold, sometimes mildly freezing temperatures. Few house plants tolerate freezing temperatures, but many can endure rather cool temperatures. On the other hand, a few plants require stable or high temperatures. When such conditions are needed, it is difficult for the sunpsace to provide excess amounts of energy to the adjacent building. Although there frequently will be excess solar heat during sunny weather, greenhouses in most climates will require other heat to maintain high or stable temperatures during long, cold, cloudy spells. Multiple-layer glazings (up to three and four) have been used to reduce the use of auxiliary energy. Also, movable insulation may be used to cover the single or double glazing at night or during cloudy weather.

Warm ground temperature and proper light levels are the two most critical elements for successful plant growth. Multiple-layered glazing can reduce light levels. This is a crucial issue in cloudy climates, particularly those having less than 50 percent possible sunshine. Circulation of overheated sunspace air through gravel beds under the plants can raise planting bed temperatures, increasing growth rates of most plants.

Although information regarding plant influence on the microclimate of a sunspace is greatly lacking, evaporation of water from planting beds and transpiration by the plants are two factors known to significantly influence this microclimate. The resulting humidity can affect thermal performance since large amounts of energy are required to evaporate water (approximately 1,000 Btu per pound of water). In fact, peak temperatures can be significantly reduced. Excessively humid air, coupled with potentially unpleasant odors, may, in some cases, make it undesirable to circulate overheated greenhouse air into the building. On the other hand, the odor-cleansing capabilities of plants and the moist air are often considered benefits of house plants.

Greenhouse environments are rather complex ecological systems. Unexpected, and often undesirable, plant and animal growth is sure to proliferate. Many greenhouses, built onto existing houses to provide both solar heat and vegetable production, have had significant insect and plant disease problems. Although little is yet known about such potential problems, preliminary findings indicate that the more complex the ecology of the sunspace, the more likely a natural balance can eventually be achieved.

C5.b CONTROLLING HEAT FLOWS

C5.b.l Reducing Heat Loss

Single Glazing

For maximum light transmission, whether for plant growth or for solar heating buildings, single glass or plastic is preferred as a glazing for sunspaces. However, a single layer loses extraordinary amounts of heat. A properly designed sunspace with single glazing and adequate thermal mass, and attached to a building, will successfully stay above freezing the entire winter (without backup heat) and provide heat to a building in climates where temperatures rarely drop below zero and where the sun shines at least half the time. In colder climates, with the same 50 percent possible sunshine, the sunspace will continue to provide excess amounts of heat to the building during sunny weather, but auxiliary heat will be needed to keep the sunspace from freezing during long, cold, cloudy spells.

Double Glazing

Most sunspaces are built with double glazing and without additional methods for reducing heat loss. However, heat loss is still high. For the same conditions described above, a properly designed, double-glazed, attached sunspace in a 50 percent possible sunshine climate will remain above freezing the entire winter in all but the coldest continental U.S. climates. However, if heat conservation and production is desired beyond merely keeping the sunspace above freezing to assist plant growth, additional layers are necessary in most climates of greater than 6000 degree days per year.

Triple and Quadruple Glazing

Each additional layer of glazing tends to require increasingly complex design decisions. In order to maintain sufficiently high levels of light transmission, the third and fourth layers must be a very clear film or very clear glass. Particular care must be taken to prevent structural damage from potential condensation of moisture between glazings.

Light transmission of the composite layers should be in excess of 65 percent. U-values for triple and quadruple glazing can be as low as 0.35 and 0.24 Btu/hr ft^2 F, respectively.

Movable Insulation

Movable insulation is necessary to permit maximum levels of sunshine and minimal heat loss at night. As with direct gain systems where the insulation is applied to ordinary building glazing, this presents numerous design constraints. The most critical is placement of the insulation during the day when it is not covering the glazing. A second significant issue is the potential interference of plant life with the movement of the insulation. A third is obtaining a tight fit when the insulation is covering the glazing. A fourth major consideration is cost. These four issues are similar to those for movable insulation in direct gain systems.

Additional considerations include vulnerability to mold and other plant growth, to unwelcome insect life, and to long-term decay in both thermal performance and physical integrity from high moisture levels.

Designers are increasingly realizing the advantages of "embedding" the sunspace into the building. By so wrapping the building around the sunspace, many advantages accrue:

1. Heat loss from both the sunspace and building is significantly reduced.

2. Heat is easily transferred directly from the sunspace to a large portion of the building adjoining it.
3. Large amounts of natural lighting can penetrate deep within a building that might otherwise rely entirely on artificial light. Heat loss through the glass into the sunspace is negligible.
4. The sunspace is easily heated by the building through the large amount of wall surface common to both.
5. In such a location, the sunspace is more likely to be incorporated as part of an expanded living space.
6. The building itself can be built more compactly, while the wall area that it has in common with the sunspace can provide a feeling of large exterior surface area.
7. Building costs are somewhat reduced compared to sunspaces attached to the south side of buildings. For example, the common walls between the sunspace and the building are less costly than those exposed to the outdoors. In addition, their foundations do not need protection from frost and, therefore, do not need to be as deep. The compact building design results in less perimeter foundation work and less total exterior area.

Attic space is often a practical location for a sunspace. The roof is framed in a conventional manner. The south slope is glazed.

End walls and north-sloping surfaces, as well as the floor, are well-insulated. The surfaces are then covered with a dark surface such as black-painted plywood; other less durable materials will do. When the house calls for heat, a thermostat triggers a fan to circulate solar heated sunspace air from the attic to the house. If the only purpose of the solar attic is to provide heat to the house, the choice of glazing is relatively unimportant. A single layer of glass or plastic is sufficient. However, if the sunspace is to have other functions, such as growing food, measures to keep the temperatures from dropping too low at night must be introduced.

C5.b.2 Ventilation

Even the most well-designed sunspaces will require ventilation during intense sunshine and hot weather. Even during winter heating conditions, some controlled ventilation may be required to reduce humidity and to maintain normal carbon dioxide levels. If mechanical ventilation is used, it should be able to accommodate up to six air changes per hour to prevent extreme overheating.

Natural ventilation is preferred to energy-consuming mechanical ventilation. Exhaust vents should be as close to the ridge as possible and intake vents as low as possible. Airflow rates and, in turn, necessary vent sizes can be estimated. The velocity of the air, V, in feet per minute, is approximately:

$$V = 486\sqrt{\frac{h\ (t_u - t_D)}{t_D + 460^\circ}}$$

where: h is the distance between the intake vent and the exhaust vent, in feet;

t_u is the average temperature at the exhaust vent, in degrees F; and

t_D is the average temperature at the intake vent, in degrees F.

For example, if the outdoor temperature is 85 F, and the desired temperature at the peak of the sunspace exhausting through the vent is no higher than 100 F, and the height is 10 feet, then the velocity is:

$$V = 486\sqrt{\frac{10(100-85)}{85 + 460}} = 255\ \text{ft/min}$$

The formula is based on a uniform cross-sectional area of the airflow path. Since a sunspace tapers at the top, only one-half the value, or 130 ft/min should be used. Each square foot of vent, therefore, will permit the flow of 130 cubic feet per minute. The heat capacity of air is 0.018 Btu/ft^3 F. Therefore, the amount of heat exhausted through one square foot of vent per hour is:

$$(130\ \text{ft}^3/\text{min})\times(15\ \text{F})\times(0.018\ \text{Btu/ft}^3\ \text{F})\times(60\ \text{min}) = 2106\ \text{Btu/hr ft}^2$$

A representative value for heat gain through glass is 200 Btu/hr ft^2. Therefore, each square foot of vent can accommodate 10 square feet of glass. Heat storage capacity will temper the amount of heat that must be vented. Most sunspaces perform well with a square foot of vent for each 20 to 30 square feet of glass.

C5.b.3 Thermal Storage

The floor is the easiest and most obvious place to locate thermal mass in sunspaces. Whether of earth or of manmade materials such as concrete or tiles (laid directly onto the earth), the floor has a vast storage capacity and thus moderates temperature fluctuations. Foundation walls should be insulated down to the footers — to R-12 in cold climates, if possible. The floor should not be insulated from contact with the ground since the ground is a source of heat when sunspace temperatures drop below ground temperatures.

Walls between the sunspace and the building are by far the most effective way to include thermal mass in new construction. These walls receive full sunshine during the winter months and conduct some of their heat into the house; the remining heat warms the sunspace. A single glazing cover over the wall will trap more heat for the building, keeping the sunspace cooler. These walls are easily shaded during the summer. Most of the design guidelines for conventional thermal storage walls apply when used in sunspaces.

Containers of water will also provide thermal mass. Two to 4 gallons per square foot of south glass is adequate, depending on the tolerable temperature swings.

The circulation of warm (and often humid) sunspace air through gravel beds is still in the exploratory stages, and little quantifiable information is available. As with remote gravel beds, discussed in the direct gain section, airflow is in one direction only. Air circulation from the building through the gravel bed is unnecessary. In fact, in some cases, it may be undesirable since the air will often be too humid. If the gravel bed is located underneath an uninsulated floor slab, the heat will conduct through the slab and radiate and convect into the building.

In cold climates with less than 50 percent possible sunshine, the sunspace will probably need the excess heat at night. If the gravel beds are located beneath the planting beds, the warmed gravel will heat the soils, aiding plant growth. In some sunspaces, the same gravel bed is used during the summer; a fan circulates cool night air through the gravel bed where it is stored for use during the day. The energy savings of this application, however, has yet to be substantiated.

Ordinary washed gravel of 1 to 2 inches in diameter is appropriate for most situations. If the gravel is the only thermal mass in the sunspace (except the floor), approximately 2 cubic feet per square foot of south-facing aperture is required. The gravel need not be more than 2 to 3 feet deep. The air should flow as shown in Figure C5-1. For sunspaces having no other thermal mass, approximately 10 ft /min per square foot of south-facing aperture will be required to keep temperatures from rising above 85 F. The right fan size for this

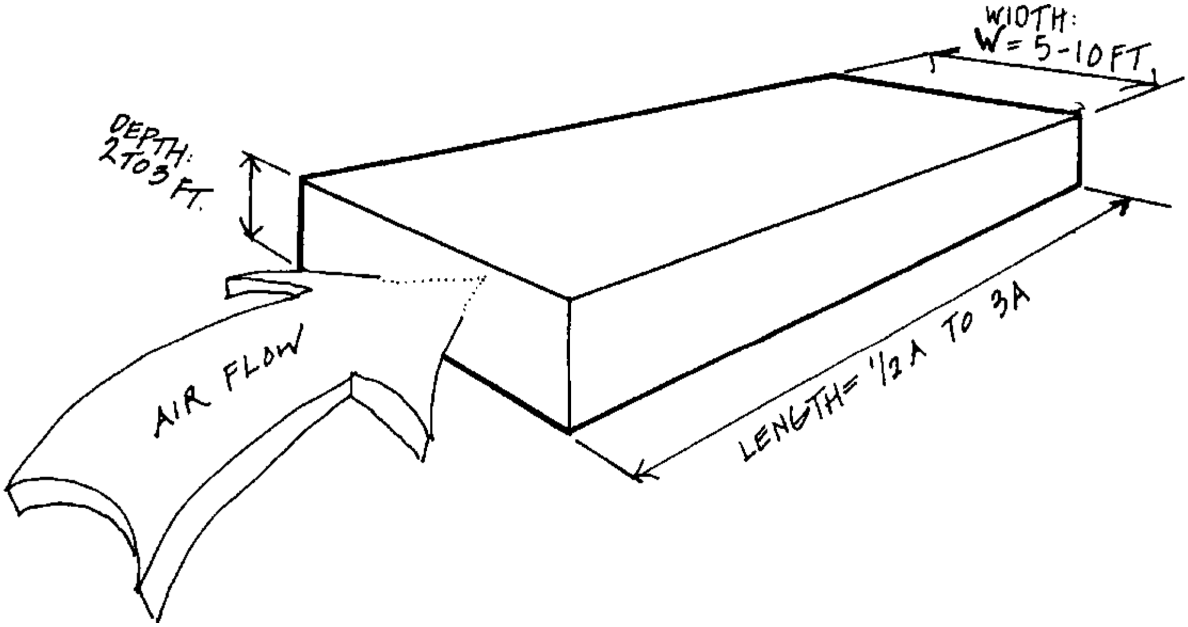


Figure C5-1: Preferred configuration for horizontal gravel beds under floor slabs and planting beds (PUT).

amount of airflow through gravel beds of the configuration in Figure C5-1 is in the range of 1/4 hp per 500 ft^3/min.

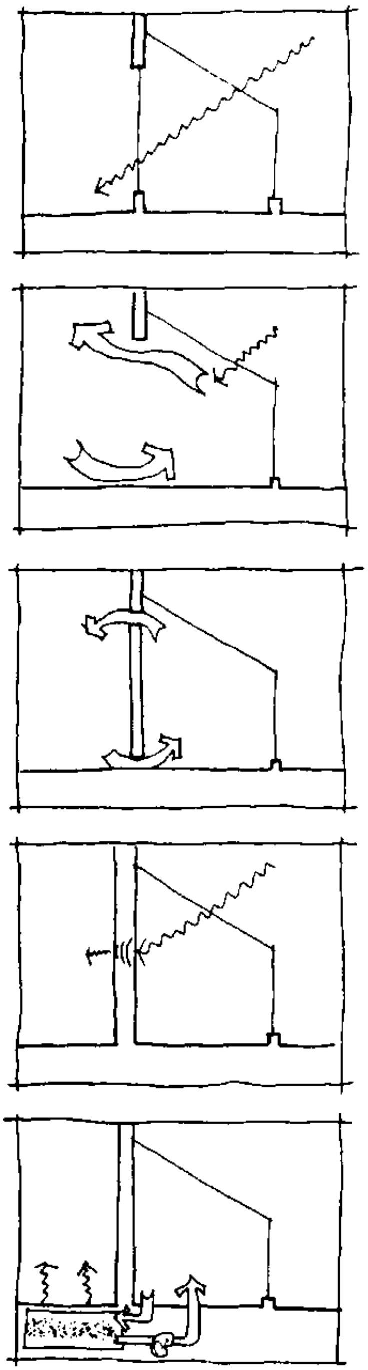
In many designs, the sunspace is only large enough to supply up to 20 percent of the heating needs of the building (the daytime loads only), and the exchange of air between the sunspace and building is not considered undesirable. In such cases, no thermal mass is needed in the sunspace. Instead, excess heat is circulated to the building during the day. At night, building heat, if desired, is circulated to the sunspace.

C5.c METHODS OF HEAT TRANSFER FROM SUNSPACE TO BUILDING

The four basic methods for transferring thermal energy from sunspaces into buildings are (see Figure C5-2) :

I. Direct solar transmission
II. Direct air exchange
III. Conduction through common walls
  - Massive walls
  - Frame construction
IV. Storage in and transfer from gravel beds

Although each of these basic themes is discussed separately here, they can also be used in combinations. For example, in addition to a common heat storage wall to conduct heat from the sunspace to the building, forced or natural airflow (direct air exchange) can be used to supplement heat transfer.



A *DIRECT SOLAR TRANSMISSION*

B NATURAL *DIRECT AIR EXCHANGE*

C FORCED(FAN) *DIRECT AIR EXCHANGE*

D CONDUCTION THROUGH WALLS

E AIR CIRCULATION TO GRAVEL BED
RADIATION FROM BED TO BUILDING

Figure C5-2: Heat transfer methods — sunspace to building (PUT)

I. Direct Solar Transmission (Figure C5-2A)

Some portion of the common wall between the sunspace and the building is frequently glass. Depending on the design, a significant percentage of the light that penetrates the sunspace can enter the building directly through this common glass, especially when the sun is low in the sky during winter months. Both thermal mass and plants can intercept sufficient amounts of energy to maintain sunspace temperatures and sustain healthy plant growth. The resulting environment acts as a buffer zone, reducing heat loss through the glass. A properly designed sunspace also helps shade the glass during the summer to help keep the building cool. Warm greenhouse air can be vented by natural convection to the outside. The vented air can induce natural ventilation through the building into the sunspace.

Whether the common glass is single- or double-glazed depends on the strategy for maintaining air temperatures in the sunspace. If, for example, the sunspace is expected to remain above 45 F most of the time, heat loss through the glass to the temperate environment of a sunspace will be small, and single glazing will suffice. In fact, what heat loss there is will help keep the sunspace above the desired 45 F. Double glazing is recommended when air temperatures in the sunspace are likely to drop below 45 F for long periods of time. For example, if the space is permitted to freeze so frequently that only cold weather vegetables (such as the cabbage family) are able to grow, double glazing is a logical choice for limiting heat loss from the building to the sunspace.

Whether single or double glazed, this common glass wall is protected from outdoor weather by the sunspace, making the highest-quality construction unnecessary and reducing building costs.

II. Direct Air Exchange (Figures C5-2B and 2C)

Sunspace heat can be transferred directly to the building in two primary ways: by natural air convection or with fans.

Often there may be no common wall between the sunspace and the building. Instead, devices as simple as curtains can be used to separate the sunspace thermally and physically from the building as desired. If common walls are used, however, large windows and doors can be opened and closed automatically or manually to permit natural air convection. The greater the vertical distance between the vents, and the warmer the sunspace, the greater the airflow.

Heat transfer rates can be computed approximately as follows:

$$\text{Btu/h} = 1.08\ (\text{ft}^3/\text{min})\ (t_S - t_b)$$

$$\text{ft}^3/\text{min} = 9.6\ A\sqrt{h\ (t_S - t_b)}$$

where:

ft^3/min is cubic feet per minute of airflow between the building and the sunspace,

t_S is the temperature of the sunspace at the inlet to the building, F

t_b is the temperature of the building at the inlet to the sunspace, F, A is the area of the outlet vent openings in square feet, and

h is the vertical distance between the vent openings, ft.

Various strategies can operate a fan for transferring warm air to the building:

1. Manually: The fan can be turned on or off according to the observations of the user.
2. Electric Clock Switch: At a certain time every day, the fan automatically comes on and at another time, automatically switches off.
3. Temperature Sensor Control: When the sunspace reaches a certain temperature, the fan switches on; when it drops below a certain temperature, it switches off. A thermostat in the building can, if necessary, override the sunspace sensor to keep the building from becoming overheated. Automatically dumping heat to the outside may be required.

Fans can direct the air to locations in the building, such as the north side, that would not otherwise receive solar heat. In large buildings, sunspace air might be used as a source of warm fresh air for ventilation or as makeup air to exhaust fans.

Moisture content, odors, and insects must be considered when evaluating this method of transferring sunspace heat to the building. Although many sunspaces will be relatively dry, others will be very moist if large amounts of water are used for plants.

III. Conduction Through Common Walls (Figure C5-2D)

- Massive Walls

A mass wall effectively connects a sunspace to the adjacent building. The wall should not be insulated. In effect, the wall functions very much like a Trombe wall — the sun's heat is absorbed on the sunspace-facing surface and is conducted to the inside where it is radiated and convected to the space. The mass of the wall buffers the interior of the building from the extremes of the sunspace. This mass effect works equally well in the summer to buffer the building from the daytime highs in the sunspace; shading will prevent the wall from delivering heat to the interior of the building. Design considerations for the mass wall — thickness and material choices — are similar to those for Trombe walls. In effect, the sunspace represents an expansion of the vertical air space on the Trombe wall design to function as a useful space.

- Frame Construction

In general, common walls between the building and the sunspace need little or no insulation. Significant exceptions are walls exposed to the sun during the summer and through which heat gain is undesirable. During the winter, only small amounts of heat will be conducted into the house through wood-frame walls, even if they are poorly insulated.

IV. Storage In and Transfer From Gravel Beds (Figure C5-2E)

As described in the section on thermal storage in sunspaces, overheated sunspace air can be blown by fans through gravel beds. These gravel beds may be located in the building under uninsulated floor slabs. Heat radiates up through the floor slab directly into the room to be heated. Due to the low (65 to 75 F) temperatures in the gravel beds, the rooms will not overheat, and controlling the radiation through the slab from the gravel bed is unnecessary. The fans can be left off during mild weather. Although using fans to circulate air from gravel beds to the building rather than letting it radiate through the floor is tempting, this is ineffective because of the relatively low storage temperatures. Radiant floor heating is a much more effective and comfortable method of distributing the heat to the building.

Moisture must be kept out of gravel beds, just as it must be kept away from floor slabs. Since temperatures in gravel beds are similar to those in the building, insulation levels need to be only slightly in excess of what they would be for floor slabs in good energy conserving construction.

C5.d A COMPROMISE SUNSPACE DESIGN

It is difficult to sort through the confusing multitude of design options for attached sunspaces. Few engineering details have been analyzed in sufficient depth to develop sound rules of thumb. The thermodynamics are so complicated that they preclude easy analysis for use in the architectural design process. Figure C5-3 is a "compromise sunspace design." It is applicable in most U.S. climates and satisfies many possible uses of sunspaces. Although its net energy contribution to the building will vary depending on climate use, it is a good compromise.

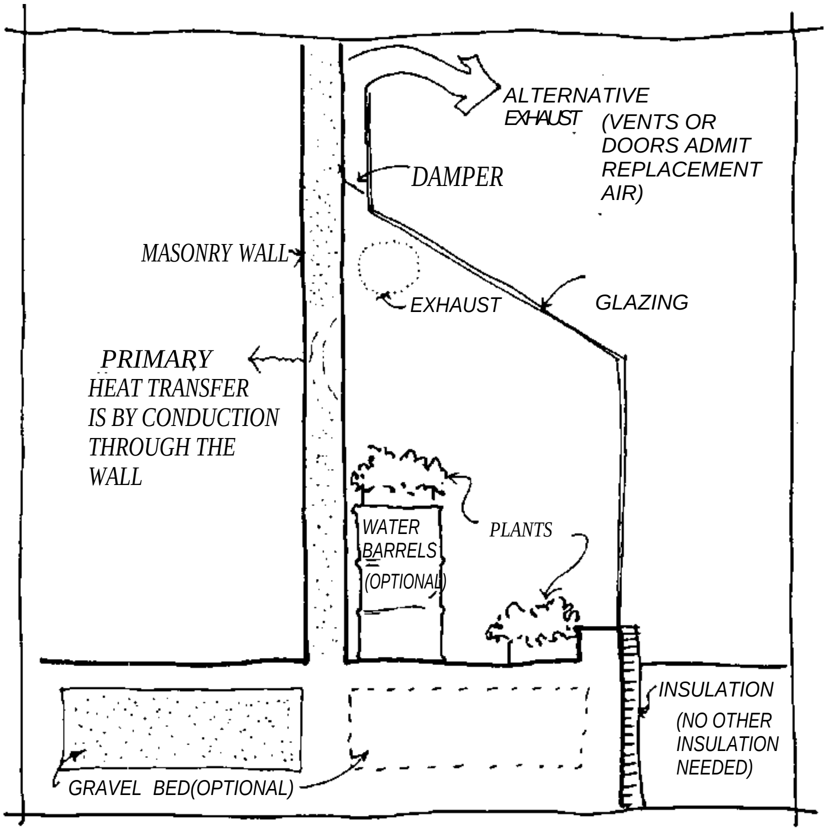
C5.e EXAMPLES

C5.e.l Unit I:First Village

Unit I (see Figure C5-4) is located in First Village, a small, planned environmental community designed and built by Susan and Wayne Nichols six miles south of Santa Fe, New Mexico. The basic floor plan of the 2300-square-foot, two-story home (Figure C5-5) wraps the living space around a triangular-shaped, 20-foot-high greenhouse located on the south side of the building. The south wall and the roof of the greenhouse are two layers of glass totaling 409 square feet. The roof is mounted at a 50 angle. The walls in common with the house are adobe. The wall is 14 inches thick at the first floor level and 10 inches thick at the upper level.

Solar heat is absorbed by the wall during the day and works its way through the wall into the living spaces at night. The wall tends to average the fluctuations between the surface temperature on the darkened adobe mass wall during the day and the temperature in the unshuttered greenhouse at night. On a sunny winter day, the outside surface

DOUBLE



Summer temperatures can be kept close to outdoor temperatures with adequate ventilation. Mechanical ventilation and/or shading will be needed in hot, humid climates.

Winter temperatures are likely to be as follows:

Up to 8000 DD and more than 70% possible sunshine:	45 - 85 F	
Up to 8000 DD and less than 70% possible sunshine: More than 8000 DD and more than 70% possible sunshine:	35 - 85 F	with occasional need for auxiliary heat
More than 8000 DD and more than 70% possible sunshine:	Up to 85 F	with frequent need for auxiliary heat

Figure C5-3: A compromise sunspace design for many climates and many uses (PUT).

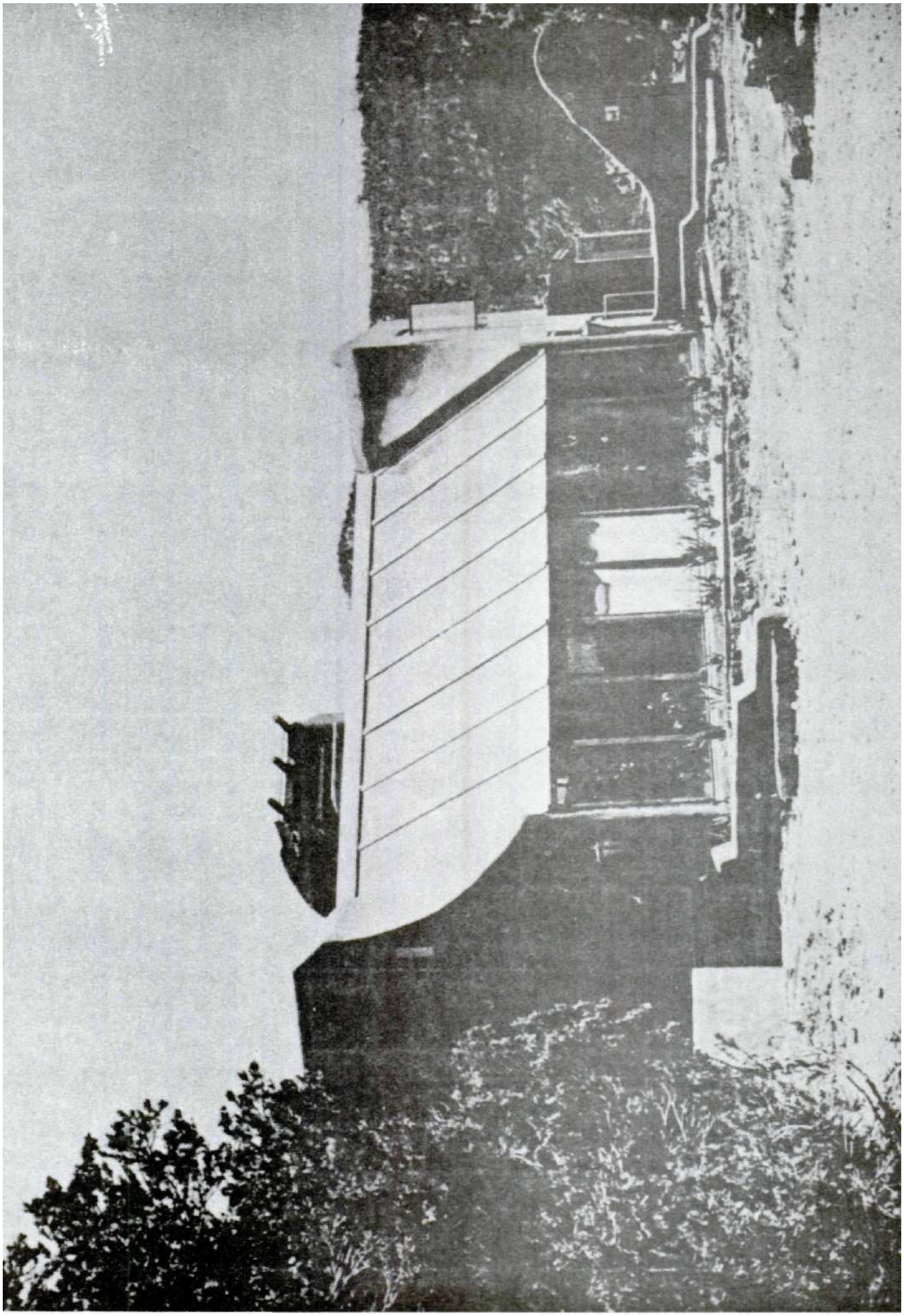


Figure C5-4: Unit I, First Village (STO)

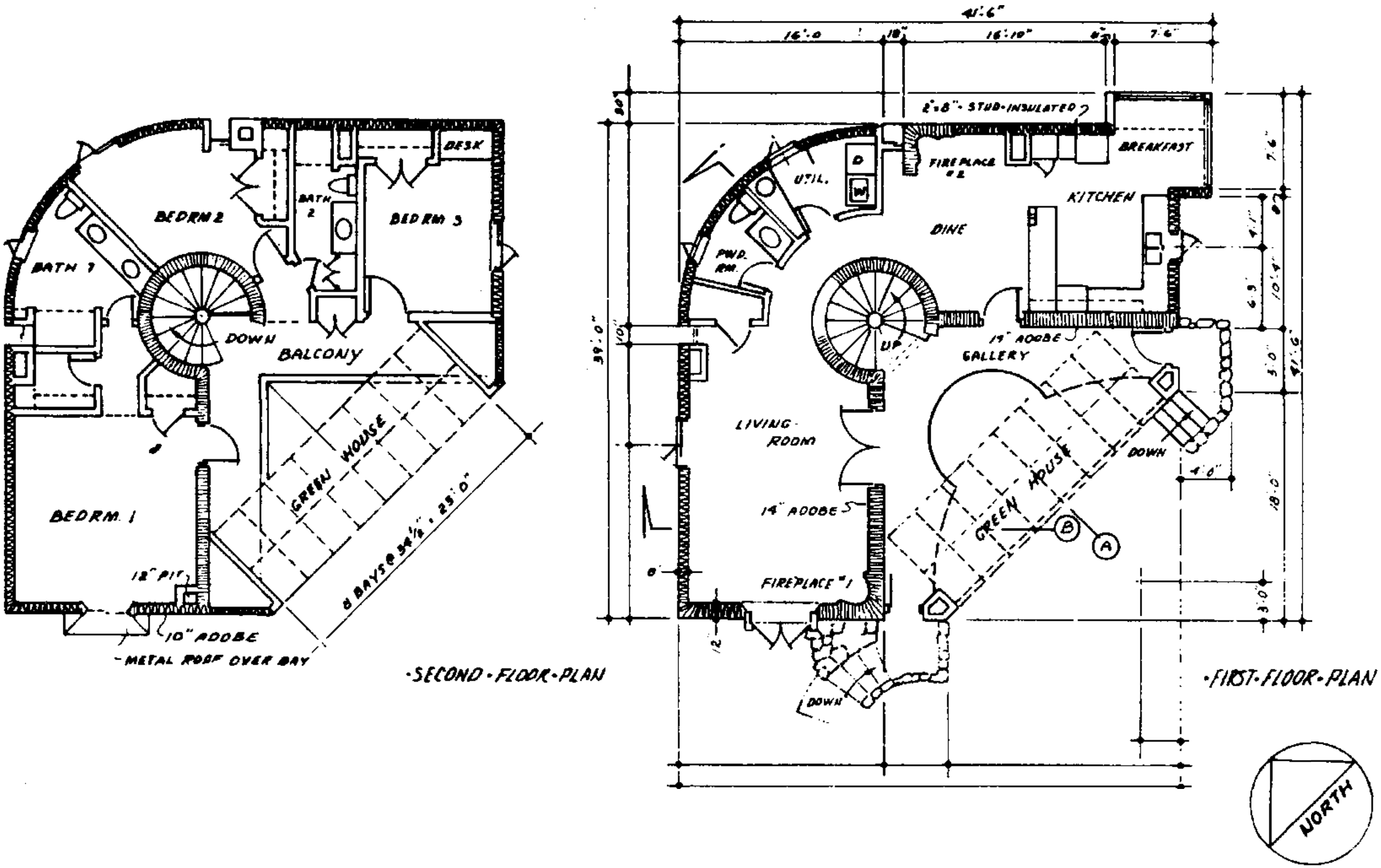


Figure C5-5: Unit I, Floor Plan (SAN).

temperature of the wall can be as high as 110 F, and it can drop to 45 F on a very cold (0 F) winter night. The average surface temperature is about 80 F.

Excess heat from the greenhouse can be circulated by two 1/3 horsepower fans through two gravel beds located beneath the house (see Figure C5-6). The air, approximately 2 ½ ft^3/min per square foot of glass, is then circulated back to the greenhouse. The heat stored in the gravel conducts through the 7-inch floor slab, which is covered with quarry tile. One horizontal rockbed is located underneath the living room and the other under the dining room. The beds are 2 feet deep and 10 feet wide. One is 19 feet long; the other is 15 feet long. The gravel beds contain a total of 24 cubic yards of 3- to 6-inch round riverbed rock. Floor temperatures range between 75 F during sunny weather to about 65 F after a cloudy spell. Baseboard electric heaters with individual thermostats provide backup heat in each room.

Cool indoor summer temperatures are maintained in several ways. First the adobe mass wall is almost totally shaded by the balcony over the first floor and by the roof over the second. The large thermal mass of the house, along with the mild average summer temperatures in Santa Fe (about 75 F) and the large day/night fluctuations in outdoor temperature (35 F), keeps indoor temperatures comfortable. Although the greenhouse temperatures vary greatly (65 to 95 F), air vents, windows, and doors can be opened near the base of the greenhouse, and

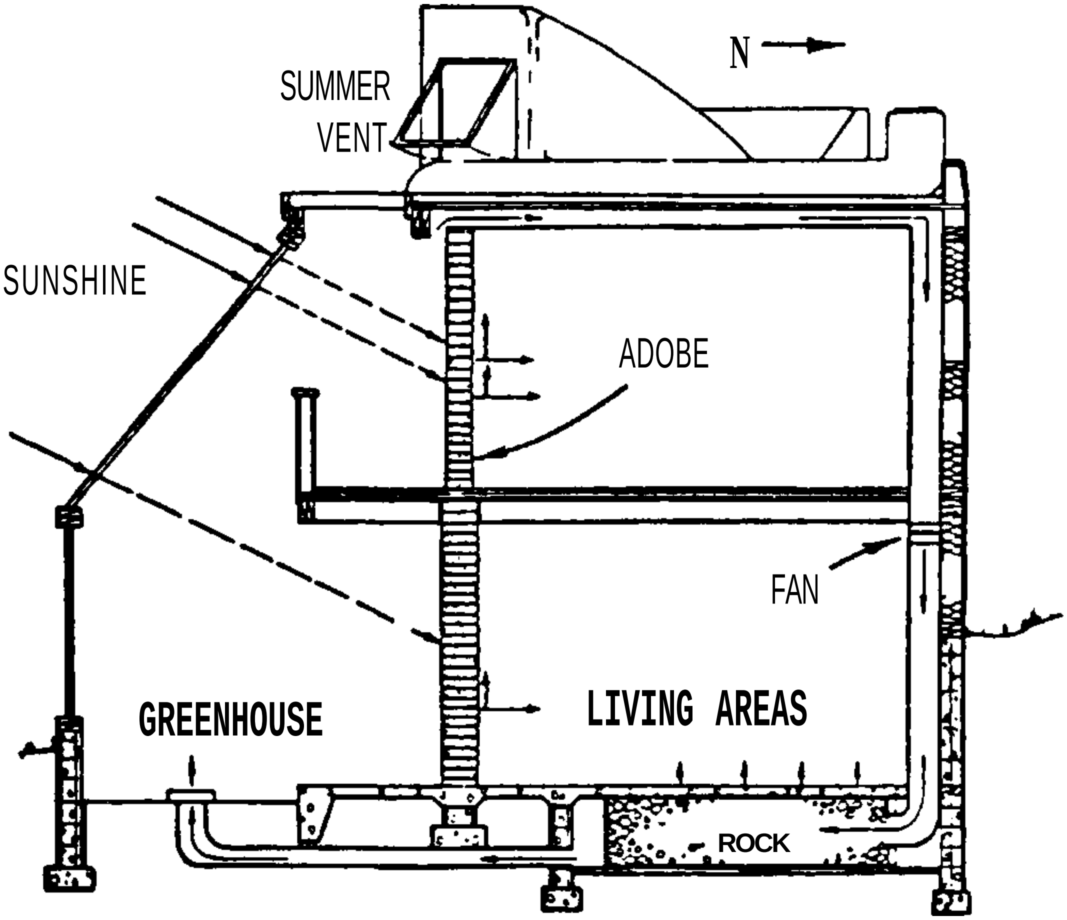


Figure C5-6: Unit I, First Village — solar heating system (BAL-3) a large vent window at the highest point can be opened to allow the warm air to exhaust. Greenhouse interior temperatures rarely exceed exterior temperatures.

Figure C5-7 shows a plot of data gathered during the period from December 26, 1978 to January 8, 1979. These data are generally representative of the lowest outside temperatures normally experienced in the Santa Fe area and illustrate the thermal stability of the house, the temperature fluctuations of the sunspace, and the consumption of electric heat. During most of the winter, internal temperatures both upstairs and downstairs normally hold in the upper 60's, and the gravel beds (which supply heat through the floors) normally maintain a temperature of 68 to 72 F on sunny days.

The peak temperature for the lower level in the living room of the house during the summer was 76 F, despite peak outdoor temperatures of 95 F. Peak afternoon temperatures of 85 F have been recorded in the upstairs bedrooms, but they quickly drop after sunset to 70 F or less.

Doug Balcomb, the present owner, estimates that the sunspace saves over $500 a year in heating costs; quoting Balcomb, "It works all the time. I simply take it for granted. The sun will heat it for as long as the house stands. It is very comfortable, very stable in temperature in the living area, and uses almost no auxiliary heat. Over an entire 1-year period in our 6000 degree day climate, my auxiliary heating energy amounted to 857 kWh, which is a total of about $38. And I have a pretty house and good greens in the bargain!"

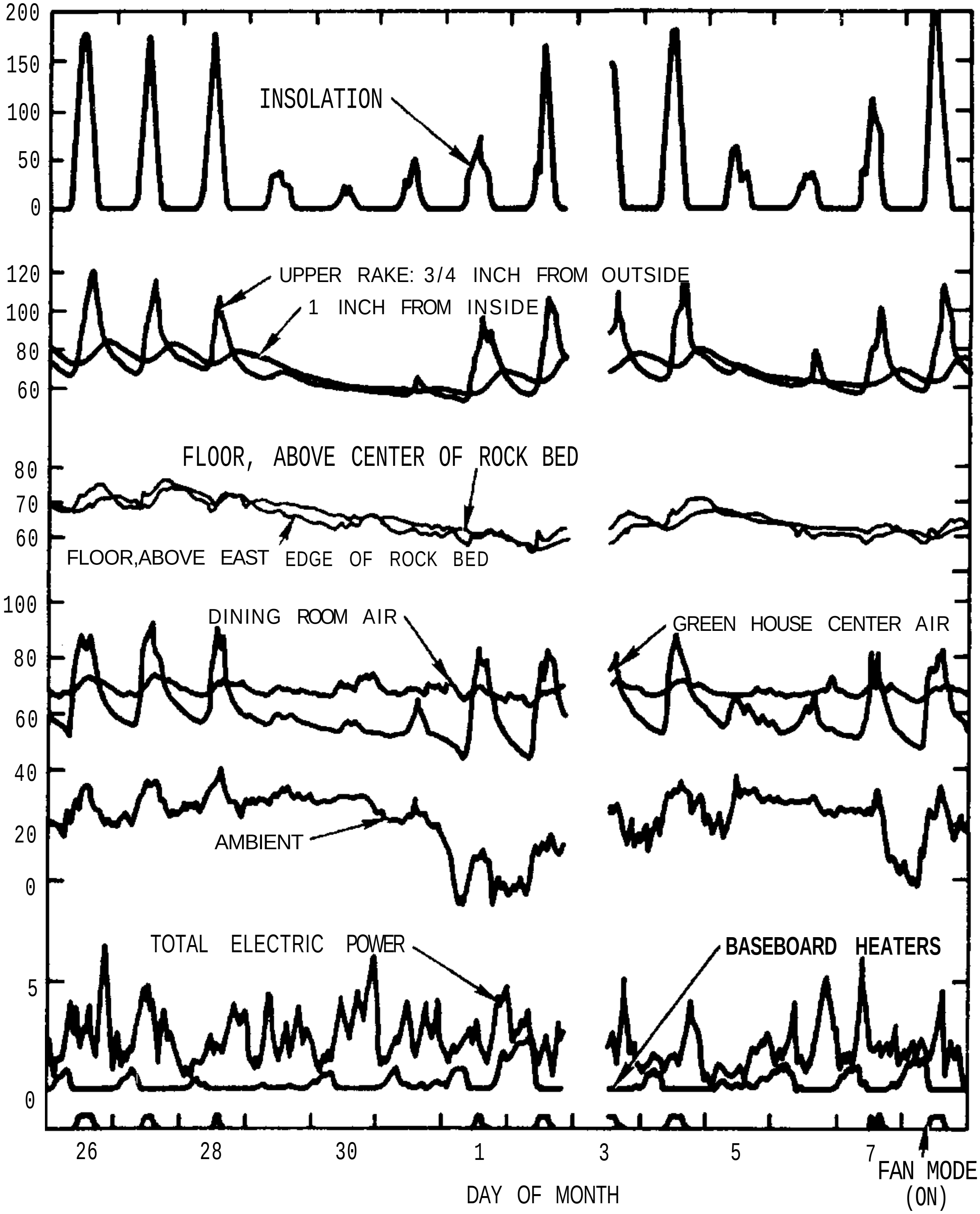


Figure C5-7 : Representative performance of Unit I, First Village, Dec to Jan 1978-1979. Prepared by Los Alamos Scientific Laboratories (SAN).

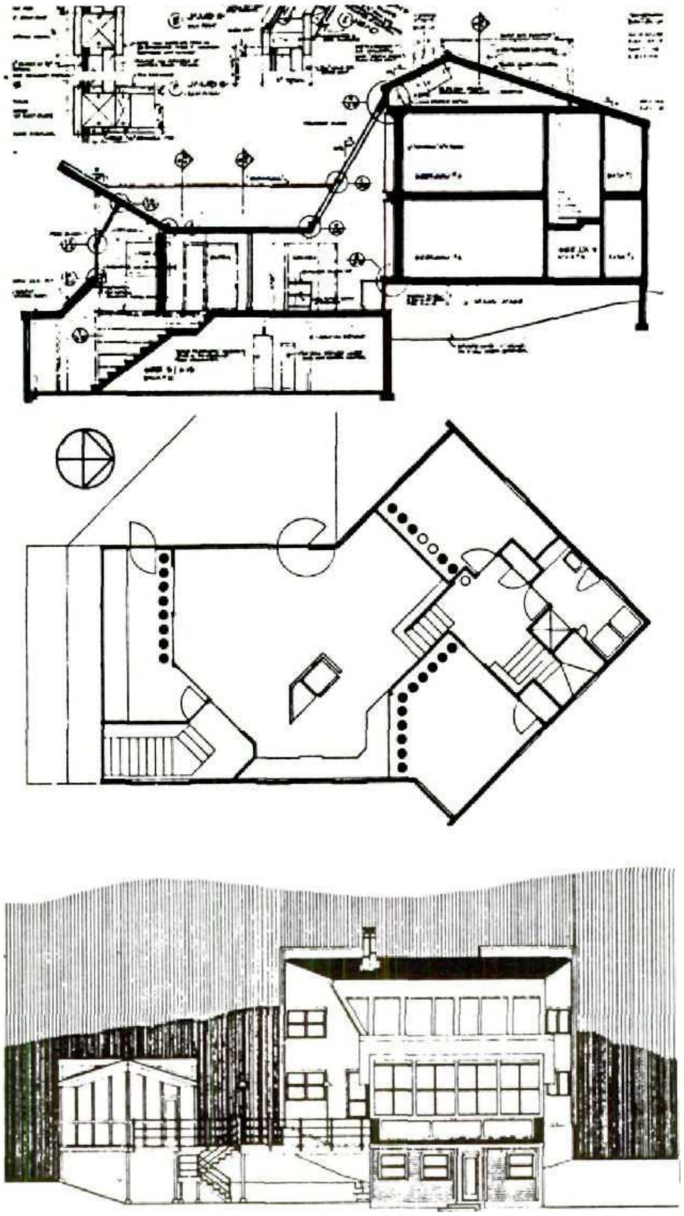
C5.e.2 The Cook House

The Cook House, designed by Dan Scully of Total Environmental Action, Inc., is a 1950-square-foot, four bedroom home on a south sloping hill above Lake George in Ticonderoga, New York (Figure C5-8). Resembling a well-insulated, solar-absorbing reincarnation of a steamboat, the prow is buried into the protective hill. Interior partitions exposed directly to sunlight from the central skylight are single layers of glass. Behind them are 12-inch-diameter translucent fiberglass tubes filled with water. Beadwall^{R} insulates the skylight at night.

A double-glazed greenhouse lies to the south of the main fLoor; single-glazed sliding doors separate the two. Twelve-inch-diameter tubes of water stand in front of the glass on the greenhouse side of the wall.

Two sets of movable insulation cover the greenhouse glass at night. (Figure C5-9.) Insulation panels for the tilted glazing pivot at the top for easy movement. For the vertical glass, insulation panels are mounted in tracks similar to those of double-hung windows.

Both sets of panels are 1-inch polystyrene insulation faced on both sides with 1/8-inch masonite. The completed assembly is framed in wood.



South Elevation

Figure C5-8: The Cook House (SCU).

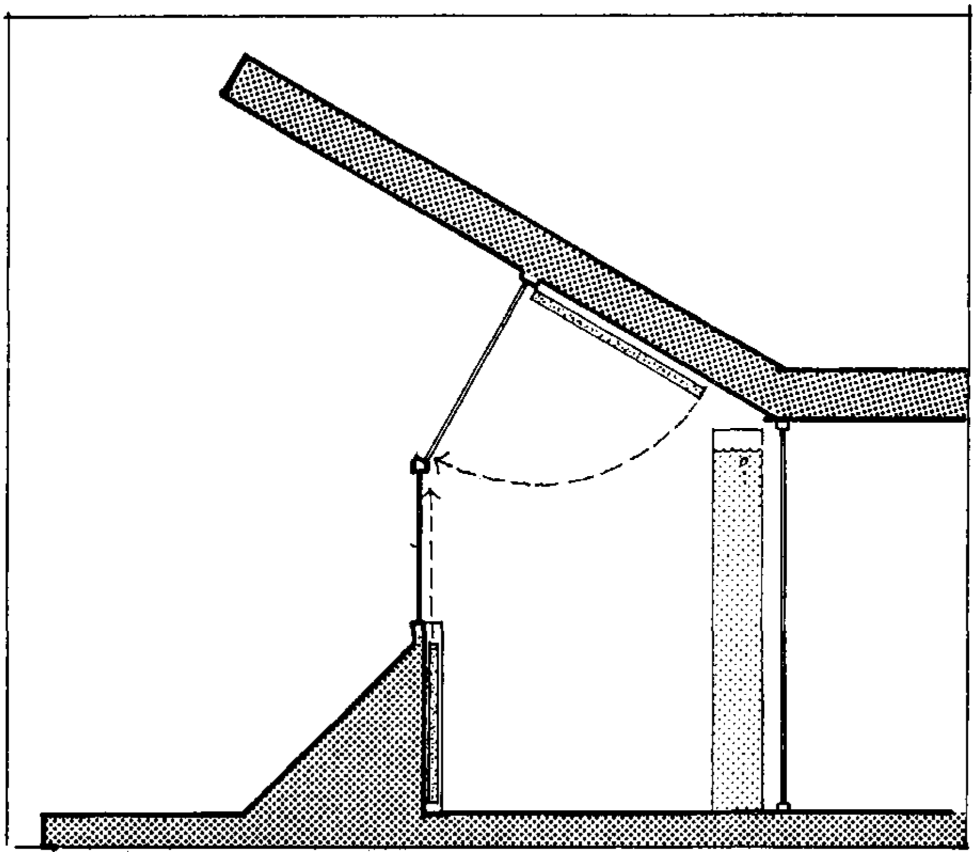


Figure C5-9: The Cook House — movable insulation detail (PUT)

CHAPTER D

PASSIVE SOLAR COOLING

D PASSIVE SOLAR COOLING

D.1 INTRODUCTION

Just as there is a distinction between active and passive solar heating, so also there is one between active and passive solar cooling. Although many passive solar cooling techniques are not strictly "solar," they are included here to represent cooling methods that require little or no mechnical power.

Fortunately, in virtually all climates, buildings can be designed and constructed not only to reduce building temperatures but, in most cases to eliminate completely the need for mechanical cooling methods by using passive methods instead.

By far the most important and first step is solar control — keeping the sun's energy from hitting and entering the building. Other methods discussed here include:

Convective cooling
Evaporative cooling
Radiative cooling
Ground cooling

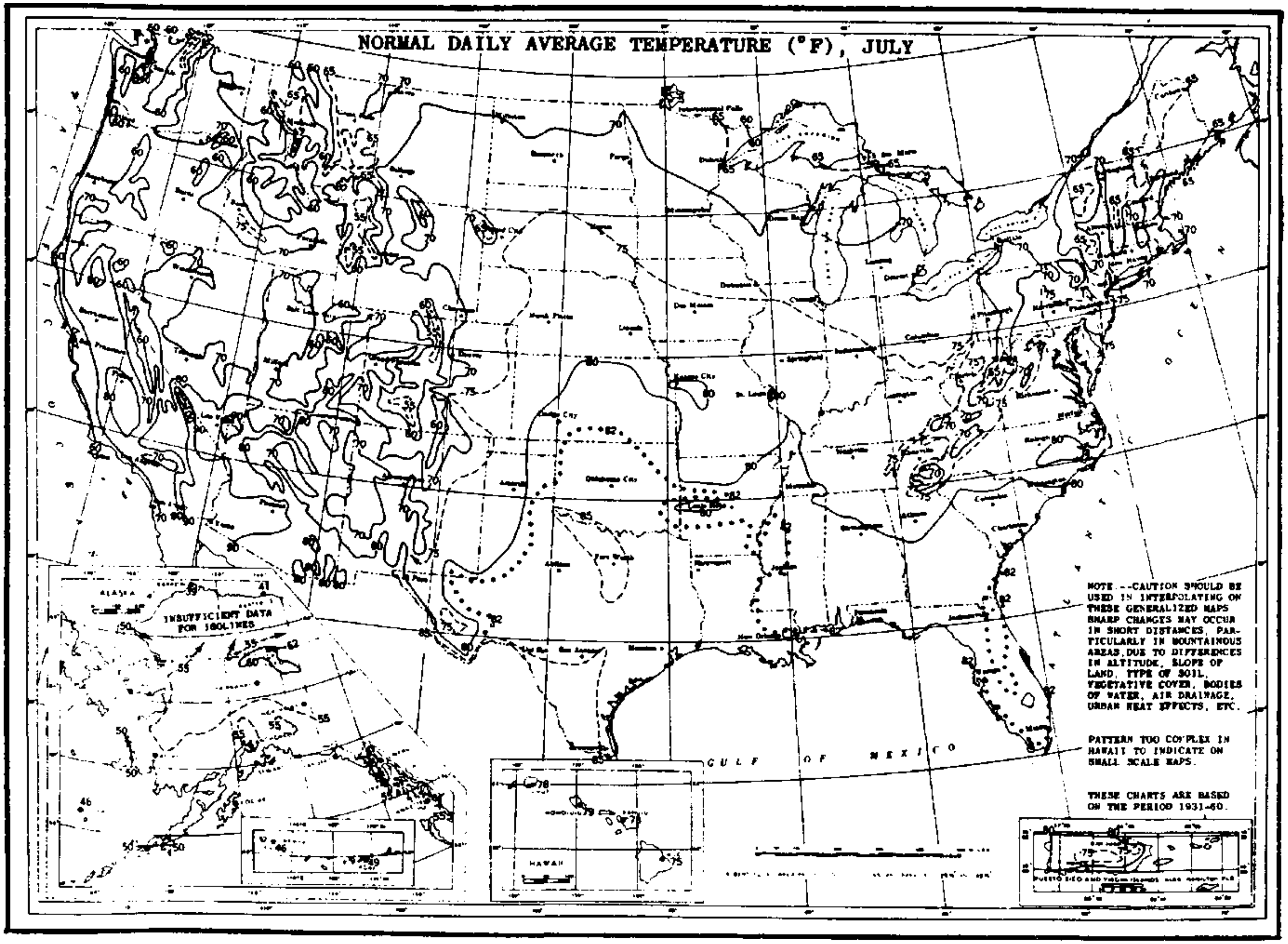
The state-of-the-art for passive cooling lags that of solar heating. Necessary climatic data for making wise decisions are sparse. Analytical codes are nearly nonexistent. Little hardware is available. The short length of this chapter is indicative of the situation. As of this writing, the U.S. Department of Energy has a small but important R&D program in this area.

D.2 COOLING TECHNIQUES

D.2.a Solar Control

The least costly yet most effective means of "solar cooling" is keeping the sun's energy out of the buildng. The most effective way to keep the sun's energy out is to keep its rays from striking the building by shading the windows, walls, and roof. In fact, where monthly mean temperature averages are less than 80 F, controlling solar heat gain can virtually eliminate the need for other forms of cooling. Figures D-1 and D-2 are maps showing the normal daily average temperatures for July and August. As an approximation, the band of the U.S. along the 80° line indicates the geographical limit where the use of solar control can eliminate the need for other forms of cooling.

Most techniques for reducing heat loss from residences during the winter are also effective for reducing unwanted heat gain during the summer. For example, heavily insulated walls permit very little heat penetration during the summer. So also, multi-layered windows reduce heat flow into the building during hot weather. Weatherstripping restricts uncontrolled hot airflow into the building. Proper orientation of windows, especially minimization of east and west glazing in favor of winter-heat-gaining south glass, is most important in reducing summer solar heat gain. Where east or west glazing is used, it is especially important to shade it effectively, a difficult job because of the low and variable sun angles; vertical, movable devices may work the best.



NOTE.--CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS. SHARP CHANGES MAY OCCUR IN SHORT DISTANCES, PARTICULARLY IN MOUNTAINOUS AREAS, DUE TO DIFFERENCES IN ALTITUDE, SLOPE OF LAND, TYPE OF SOIL, VEGETATIVE COVER, BODIES OF WATER, AIR DRAINAGE, URBAN HEAT EFFECTS, ETC.

PATTERN TOO COMPLEX IN HAWAII TO INDICATE ON SMALL SCALE MAPS.

THESE CHARTS ARE BASED ON THE PERIOD 1931-60.

Figure D-1: Normal daily average temperature (degrees F), July (USD).

NORMAL DAILY AVERAGE TEMPERATURE (°F), AUGUST

NOTE.--CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS. SHARP CHANGES MAY OCCUR IN SHORT DISTANCES, PARTICULARLY IN MOUNTAINOUS AREAS, DUE TO DIFFERENCES IN ALTITUDE, SLOPE OF LAND, TYPE OF SOIL, VEGETATIVE COVER, BODIES OF WATER, AIR DRAINAGE, URBAN HEAT EFFECTS, ETC.

PATTERN TOO COMPLEX IN HAWAII TO INDICATE ON SMALL SCALE MAPS.

THESE CHARTS ARE BASED ON THE PERIOD 1931-60.

Figure D-2: Normal daily average temperature (degrees F), August (USD).

Shading walls and roofs is critical in many hot climates. Heavily insulated walls and roofs need less shading than poorly insulated ones. However, in general, the better the insulation, the higher the exterior surface temperatures of the sun-struck walls and roof.

Light-colored surfaces can also be used to reduce heat gain. A dark sunlit roof may be 60 to 80 F hotter than a light roof. Again, heavy insulation reduces the need for such considerations.

The shape of a surface can also affect heat gain. Much of the heat that escapes from a hot surface is caused by the flow of air across it. Many surfaces can induce their own natural convection currents due to their shape. Exposure to breezes helps considerably.

Although shading the building is important, shading windows is far more so. Information is abundant on controlling solar heat gain. The most significant sources include the 1977 ASHRAE Handbook of Fundamentals; Solar Control and Shading Devices by Aladar and Victor Olgyay; and Architectural Graphic Standards by C.G. Ramsey and B.R. Sleeper (ASH) (OLG) (RAM).

The most effective shading prevents the sun from striking the building and employs devices such as overhangs or awnings on the outside of buildings. Unfortunately, the amount of shading that fixed overhangs provide coincides with the seasons of the sun rather than with the climatic seasons. The middle of the sun's summer is June 21, the solstice, but the hottest weather occurs from the end of July to the end of August when the sun is lower in the sky. A fixed overhang designed for optimal shading on August 10 causes the same shadow on May 1. The overhang designed for optimal shading on September 21, when the weather is still somewhat warm and solar heat gain is unwelcome, causes the same shading on March 21 when the weather is cooler and the solar heat gain is welcome.

Shading from deciduous vegetation more closely follows the climatic seasons and, therefore, the energy needs of buildings. On March 21, for example, most trees are bare and sunlight will pass readily. On September 21, however, the trees are still full and provide necessary shading. Deciduous trees in front of south-facing windows can provide shade from the intense midday summer sun. An overhanging trellis with a climbing vine that sheds its leaves in winter is an excellent alternative. However, a deciduous tree completely bare of leaves still blocks 20 to 40 percent of the sun's direct radiation, reducing solar gain proportionately. This may be too severe a penalty in a cold climate.

Operable shading devices are even more versatile and adaptable to human comfort. But such devices attached to the outsides of buildings are difficult to maintain, and most designs deteriorate rapidly. Efforts to make them more durable are usually unsuccessful. However, with rising fuel prices and greater emphasis on shading, increased efforts have been made to produce better operable shading devices. Awnings are perhaps the simplest and most reliable operable devices, but their aesthetic appeal is limited. The requirement for human participation (operation of the devices) in providing comfort should not necessarily be considered a drawback.

Shading east- and west-facing glass is difficult because when the sun is in the eastern and western skies, it is at a low altitude in both summer and winter (Figure D-3). Overhangs do not prevent the penetration of the sun during the summer any more than they do during the winter. Vertical louvres or other vertical extensions of the building are probably the best means of shading such glass.

Where view and light are important on east and west facades, window area can be minimized by using eye-level, shallow, horizontal windows under deep overhangs. The time during which the sun penetrates the windows is short, and the solar impact is minimized.

One method of shading glass on east and west walls is to orient the glass to face either north or south. By facing the glass north, only the indirect: irradiation will be admitted, a favorable lighting effect for many human tasks. By facing the glass south, however, solar heat is admitted during the winter. Figure D-4 shows a method for orienting the glass toward the south to provide full shading during the summer.

The notion of Shading Coefficient is important in comparing the relative effectiveness of various shading devices. By definition, a

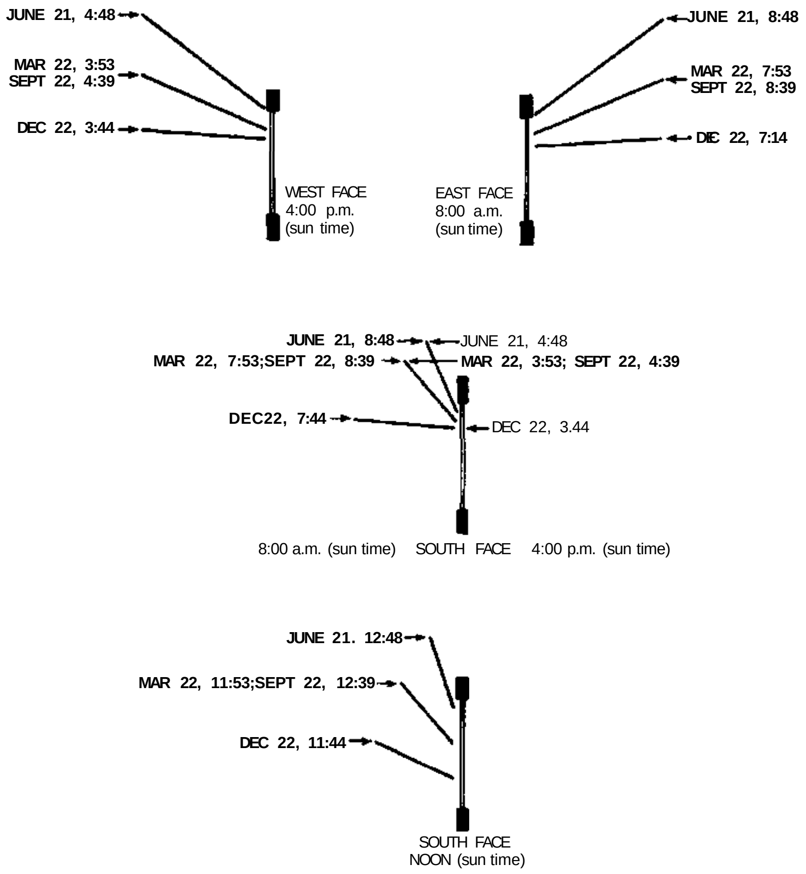


Figure D-3: Sun angles for various dates, directions, and times, 40°N latitude (AND-2).

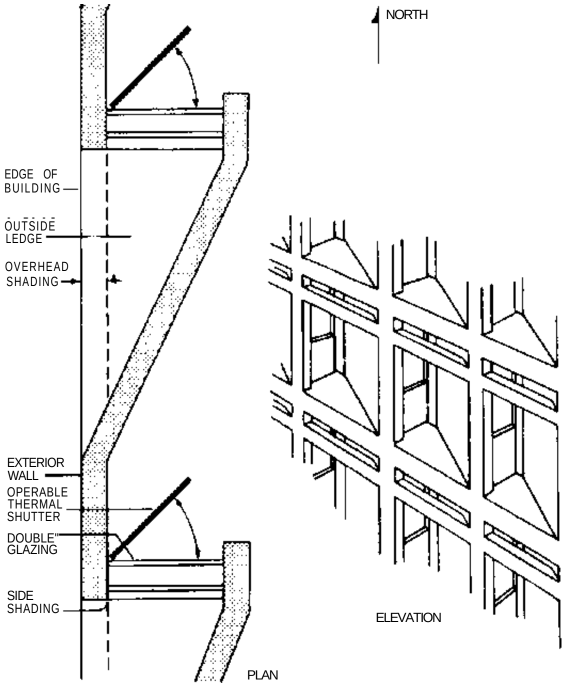


Figure D-4: Sawtooth arrangement for windows on the west facade of a building allowing solar heat gain during the winter but excluding it during the summer (AND-2).

single layer of clear, double-strength glass has a Shading Coefficient of 1.00. The Shading Coefficient for any other glazing system in combination with shading devices is the ratio of the solar heat gain through that system to the solar heat gain through the double-strength glass under the same solar conditions. Thus, solar gain through a glazing system is the product of its Shading Coefficient times the solar gain for clear, double-strength glass. Figure D-5 shows some typical Shading Coefficients for various shading conditions.

Using different types of glass for different sun orientations is one method of sun control. Where reducing heat gain is critical, heat-absorbing and -reflecting glass can help, especially on east and west facades. The important factors to consider in their use include the following:

1. Such glass reduces solar heat gain; although this can be an advantage in the summer, it is as much (or more) of a disadvantage in the winter.
2. Except for glare control, heat-absorbing and -reflecting glass are almost always unnecessary on north, north-northeast, and north-northwest orientations. Little solar heat is gained on these facades except in the latitudes south of 30^{o}N, where they might be considered.
3. In almost all latitudes, except those north of 40°N, heat-absorbing and -reflecting glass usually should not be considered for south-facing windows (except as a means of

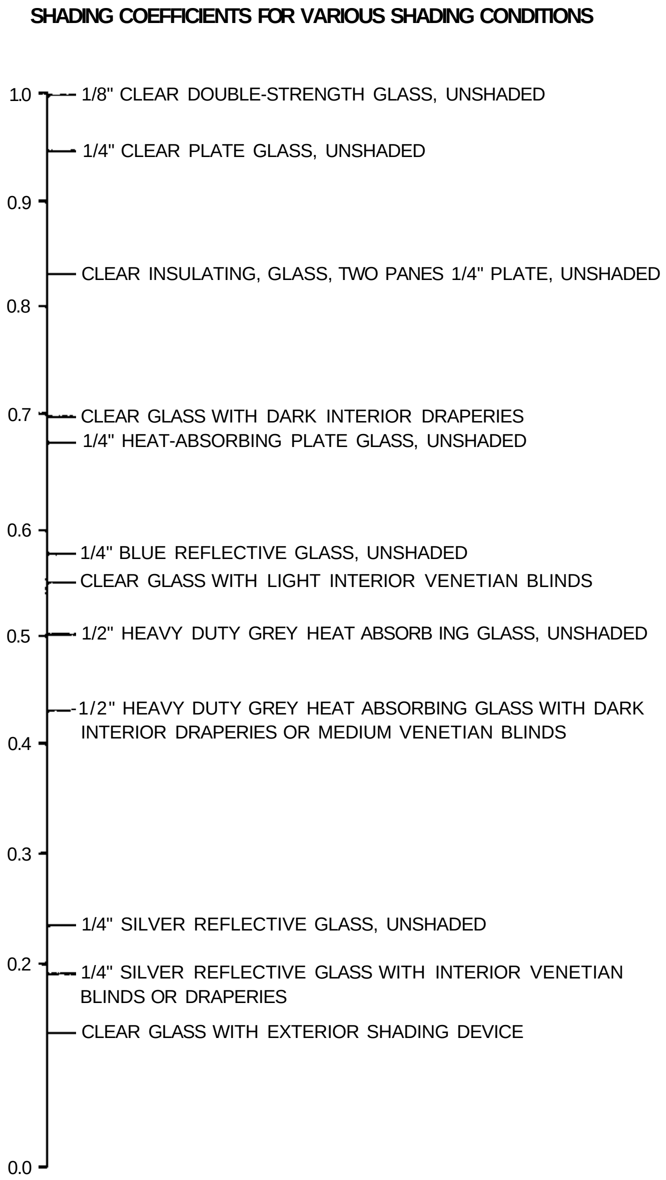


Figure D-5: Shading coefficients for various shading conditions (AND-1).

controlling glare or excluding winter solar heat, if necessary, e.g., in large office buildings). The heat gain through south-facing glass is relatively small in the summer (see Figure D-6).

4. Vegetation and operable shading devices are more sensible solutions than heat-absorbing or -reflecting glass for south, southeast, and southwest orientations. Shading devices are most effective on the exterior of the building; those between two layers of glass (such as Venetian blinds) are the next most effective; and interior devices such as blinds, shades and draperies are least effective since they stop the sun's rays after, instead of before, they have penetrated the building (see Figure D-7). Even so, highly reflective devices are only slightly less effective on the inside than between the two layers of glass. That is, since a highly reflective device is effective anywhere it's placed, it's location is not as important as the location of shading devices that are not reflective.

5. Some advertisements for heat-absorbing and -reflecting glass suggest that these products will reduce both the initial cost of air-conditioning equipment and the cost of its operation, especially as it affects energy consumption. The savings, however, are usually obtained by comparing costs with those for all-glass buildings rather than those for buildings already designed to conserve energy. Rarely

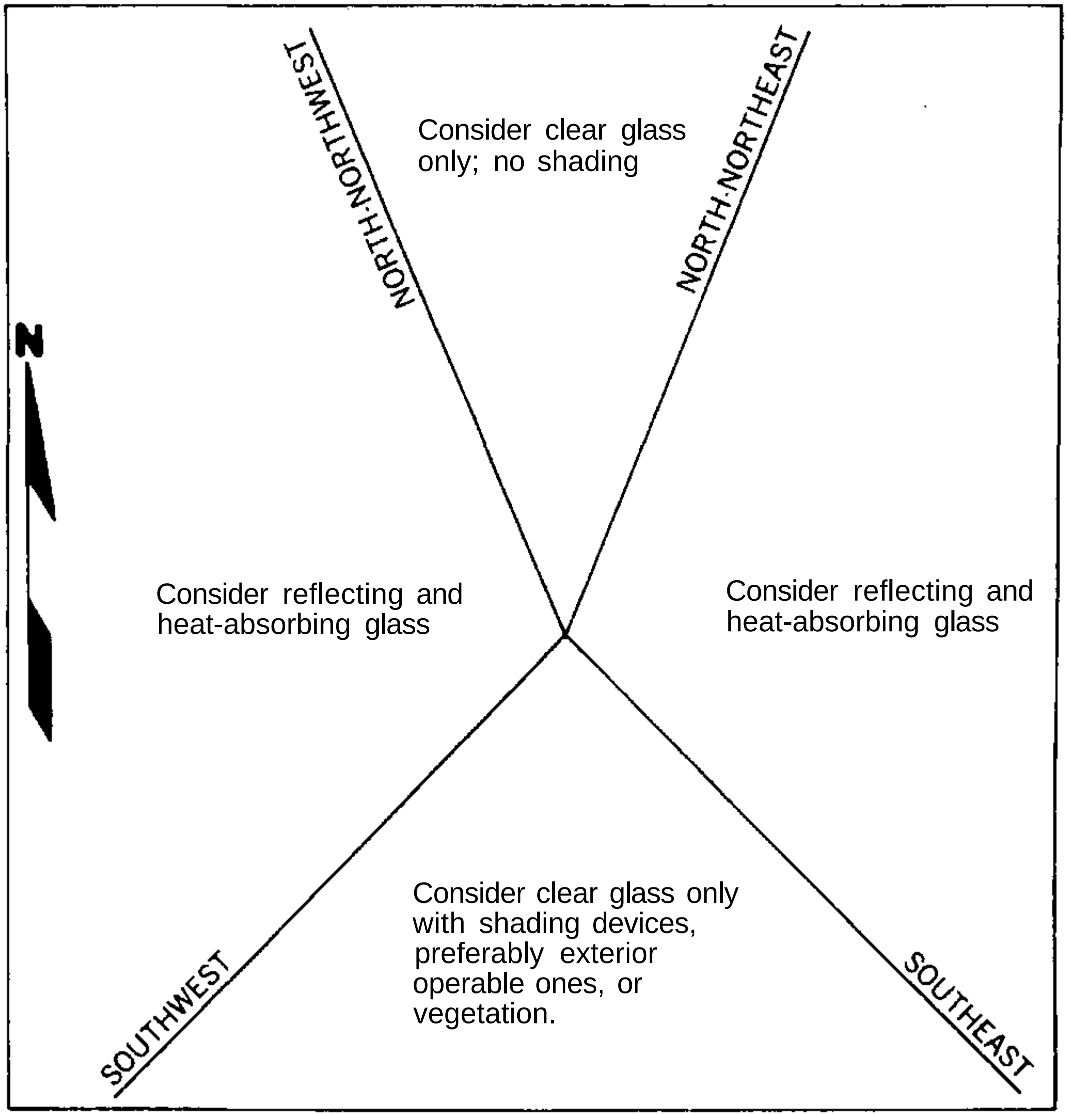


Figure D-6: Considerations for glass types for various orientations of windows (approximations for Continental United States) (AND-2).

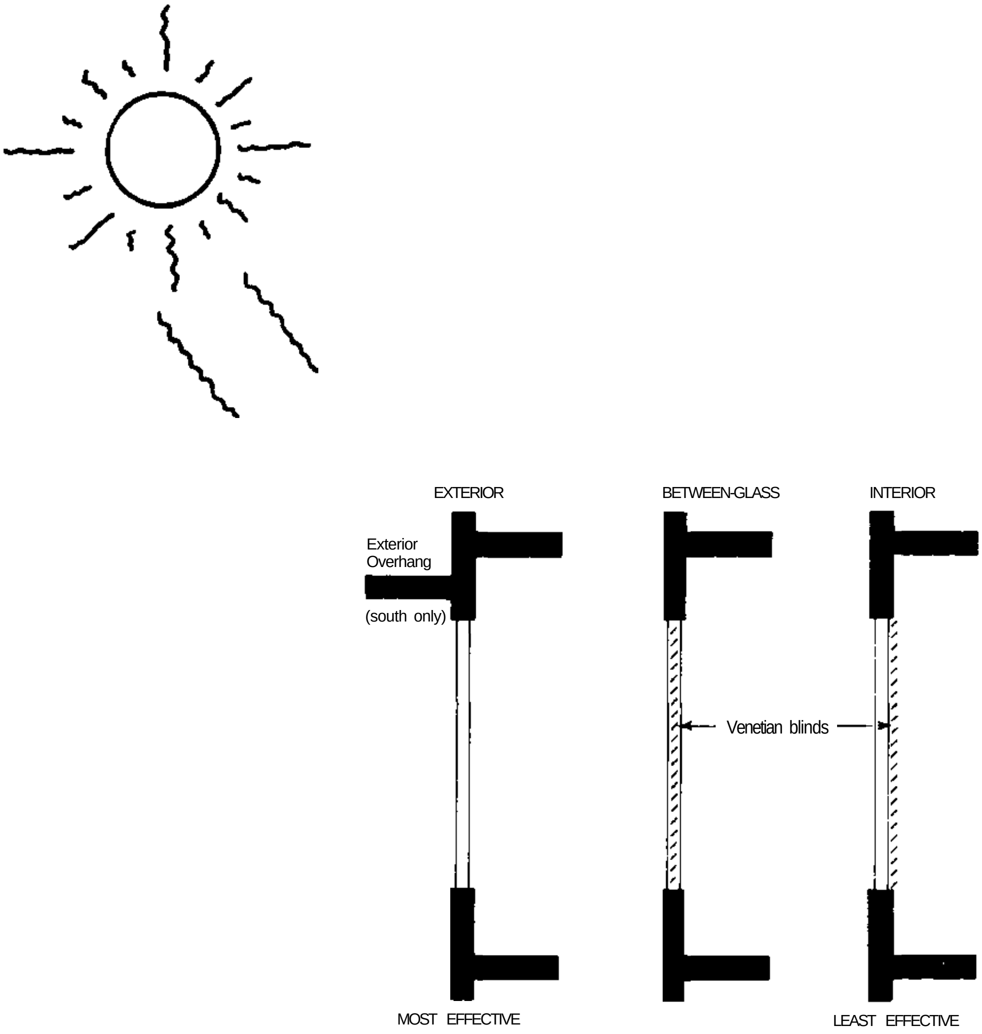


Figure D-7: Possible locations for shading devices (AND-2)

> is it mentioned that substantial savings could be achieved by switching to opaque, well-insulated walls with reduced glass areas on the north, east, and west walls and to a well-designed building that allows the sun to penetrate through the south glass during the winter with shading during the summer.

All four (or more) facades of buildings need not, and in fact should not, be of identical appearance. This is particularly true of buildings that use large areas of glass. Although there may be economic, social, and personal reasons for building glass boxes, glass clearly has been misused as a design element.

Large buildings with small exterior wall and roof areas compared to large amounts of interior floor area often require air-conditioning year-round. This is because tremendous amounts of internal heat are generated from the activities of people, burning lights, and operation of equipment. The use of glass that is shaded 12 months a year instead of only during the summer will be the most successful solution in these buildings. Every effort should be made to reduce the amount of heat that is produced by lights and machines. The most energy-conscious designs for such buildings now commonly employ waste heat recovery systems that remove heat from overheated areas and deliver it to those that need it. Heat not immediately required may be stored for later retrieval. The dependence on artificial lighting should be reduced by using more natural lighting (through windows), by lowering lighting levels, or by placing lighting fixtures directly where light is needed (task lighting).

Designers should also consider the shading effects of buildings on one another and on the surrounding environment, i.e., whether the shading occurs on buildings that directly or indirectly use the sun's heat or light, or on wild vegetation or gardens that need sun in order to grow.

D.2.b Convective Cooling

At temperatures below 100 F, the movement of air across human skin creates a cooling sensation caused by heat leaving the skin through convection and the evaporation of persipiration. Air movement up to 50 feet per minute goes unnoticed. Over 200 feet per minute, it becomes annoying. Movement above 300 feet per minute adversely affects health and reduces indoor work efficiency (OLG).

The most common way to create air movement without using mechanical power is to open windows and allow breezes to blow into a building. This simple concept is often forgotten. Although an open window can admit dust, pollen, and, in many cases, warm air, its cooling effect should not be underestimated. Proper window location can aid natural ventilation. The air inlet location governs the airflow pattern in the building. An inlet window high in the wall will create an airflow above the living area. Lower openings will direct the air through the occupied area. The outlet location has almost no effect but should be as large as possible, much larger than the inlet (OLG). "Deep" plans (e.g., two to three rooms stacked "in series," and very large, deep offices) are notorioualy difficult to ventilate using windows only.

Land planning also influences natural ventilation through buildings. Natural breezes should not be blocked from entering buildings. Building shape, proper clustering of buildings, and other landscaping features such as vegetation and fences can enhance natural wind flow patterns (GUY).

The "stack" effect in buildings can induce ventilation even when there is no breeze. This occurs when warm air rises to the top of a tall space. An opening at the top naturally exhausts the warm air while openings at floor level admit outdoor air to replace it. Natural ventilation can be further induced by using belvederes, wind vanes, and wind scoops.

In Figure D-8, a solar collector exhausts its hot air to the outdoors and pulls house air thorugh it, creating natural ventilation. Many variations of this "solar chimney" have been used widely in the past and are being developed again today. In some active solar system designs that use air as the heat transfer medium, the collectors are

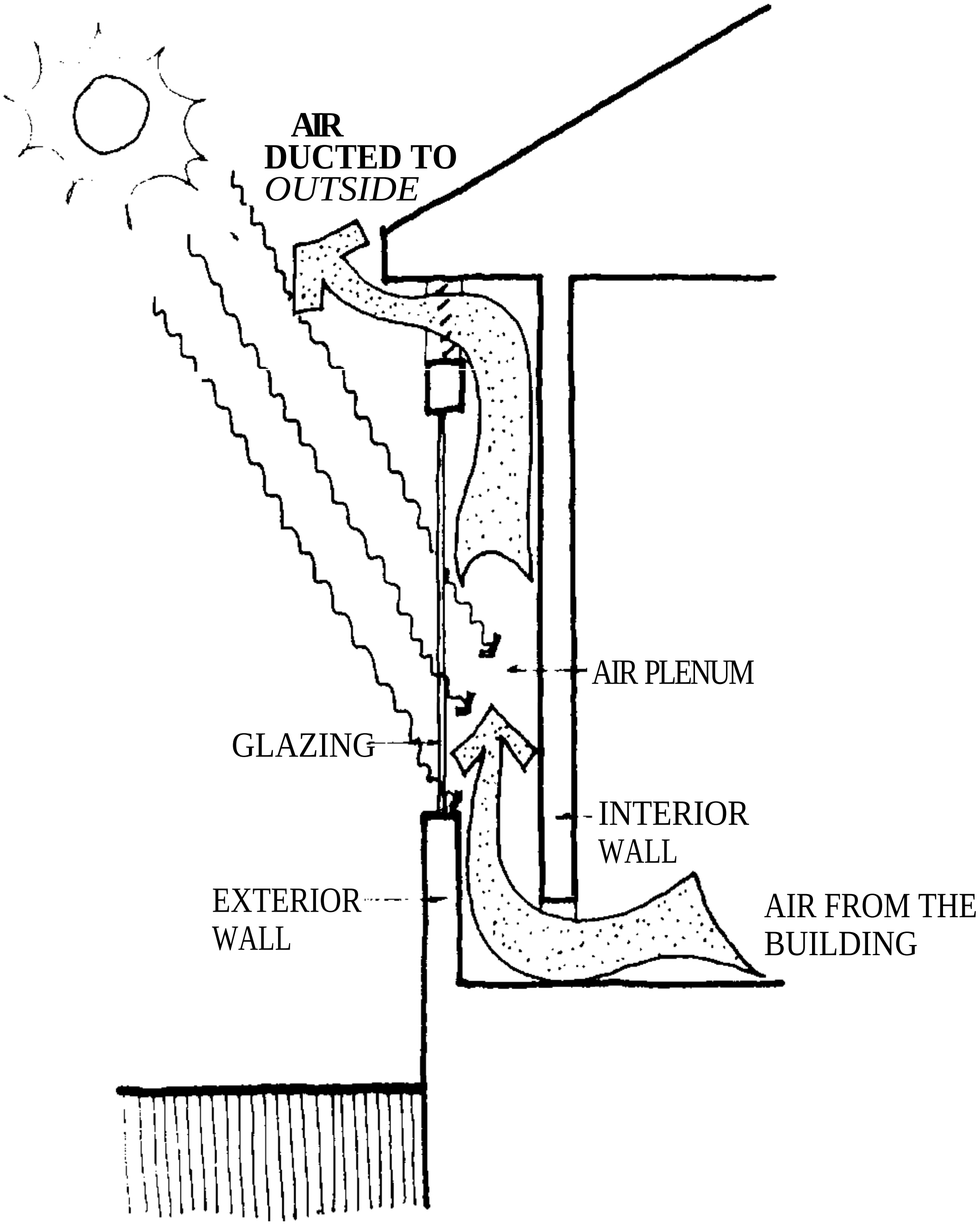


Figure D-8: A wall design is a solar collector to induce ventilation through a building (CRO) (PUT).

vented to the outside during the hot summer weather, pulling building air through them to induce ventilation.

In designing for stack-effect ventilation, the greatest airflow is achieved by maximizing both the height of the stack and the temperature of air in the stack. Recall that the airflow is proportional to the inlet area and to the square root of the height times the average temperature difference as follows (see Chapter C5):

$$\mathrm{ft}^3/\mathrm{min.} = 9.6A\sqrt{h(t_1 - t_2)}$$

where: ft^3 /min. is cubic feet per minute of airflow

A is the area of the inlets in ft^2

h is the height in feet between inlets and outlets

t_1 is the average temperature of the air in the "chimney," F

t_2 is the average temperature of the return air (normally just the ambient outside temperature), F

Thus, it is better to add heat (presumably using a passive air-heating collector) at the bottom of the chimney or stack than at the top. In this way the entire column of air in the chimney is hot, creating the buoyancy required to cause the air to flow.

The expression given above must be adjusted if outlet sizes are appreciably different than inlet sizes according to the following ratios:

Area of Outlets Area of Inlets	Value to be substituted for 540 in above expression
5	745
4	740
3	720
2	680
1	540
3/4	455
1/2	340
1/4	185

A common fixture in Iranian architecture is the wind tower (or wind catcher) that harnesses the prevailing summer winds to cool a building by first cooling the air and then circulating it through the building. Wind towers resemble chimneys with one end in the basement and the other end rising well above the roof.

When the air in and around the tower changes temperature, its density also changes. The difference in density creates a draft that pulls air either up or down through the tower. Doors open into the basement at the lower part of the tower and into a central hall on the main floor. By opening and closing these and other doors, airflow through different parts of the building is controlled.

Wind conditions and time of day control the tower's operation. During the day the tower walls absorb solar heat. The thick walls of the tower provide sufficient heat storage capacity and heat transfer capacity to warm the air at the top of the tower. The warmer air is less dense, air pressure at the top of the tower is reduced, and an upward draft is created. Air in the building is drawn up through the tower, and cool outdoor air is pulled into the building through doors and windows.

When there is wind, the air is forced in the opposite direction down the chimney. Although the cool night air is warmed slightly by the warmed tower walls, the cooling can still bring the temperature in the building close to that of the outdoors.

During calm days, the tower operation is the reverse of the chimney. The walls at the upper part of the tower are cooled from the previous night. The hot outside air cools and becomes denser when it comes in contact with the cool walls, and the cool air sinks down into the tower, creating a downdraft. The cool air enters the building at the bottom of the tower; room air exits through doors and windows. When there is wind during the day, the rate of downdraft increases.

The cooling effect will increase if the operation of a wind tower is combined with evaporation of water from pools and fountains.

Thermal mass in buildings can be advantageous in areas where nighttime temperatures drop below comfort levels. Such temperatures below the comfort range are often called "temperatures of opportunity." The cool late night and early morning air can be circulated through a building. The coolness is "stored" in thermal mass for use during the day. Mechanical systems that use outdoor air for comfort purposes are often termed "economizer cycles."

An alternative to thermal mass inside the building is a fan circulating night air through a rock storage bed. During the day, room air is circulated through the cool rockbed, cooling the building.

Figure D-9 shows the inside air temperature of a night-air-cooled office building near Davis, California, that fluctuates from a low of 65 F (the low nighttime outdoor temperature) to a high of nearly 80 F. Meanwhile, outdoor daytime temperatures soar well over 100 F.

Where mean daily temperatures drop to less than 60 to 65 F, nighttime ventilation in combination with thermal mass should be seriously considered. Figures D-10 and D-11 are U.S. maps of normal daily minimum temperatures for the months of July and August. As an approximation, the band along the 65 F line indicates the limitations of night air cooling.

D.2.c Evaporative Cooling

Evaporation of water can provide comfort. When the dry bulb temperature of air is higher than the wet bulb temperature, humidification will cool it. The cooling effect of moving air is enhanced if

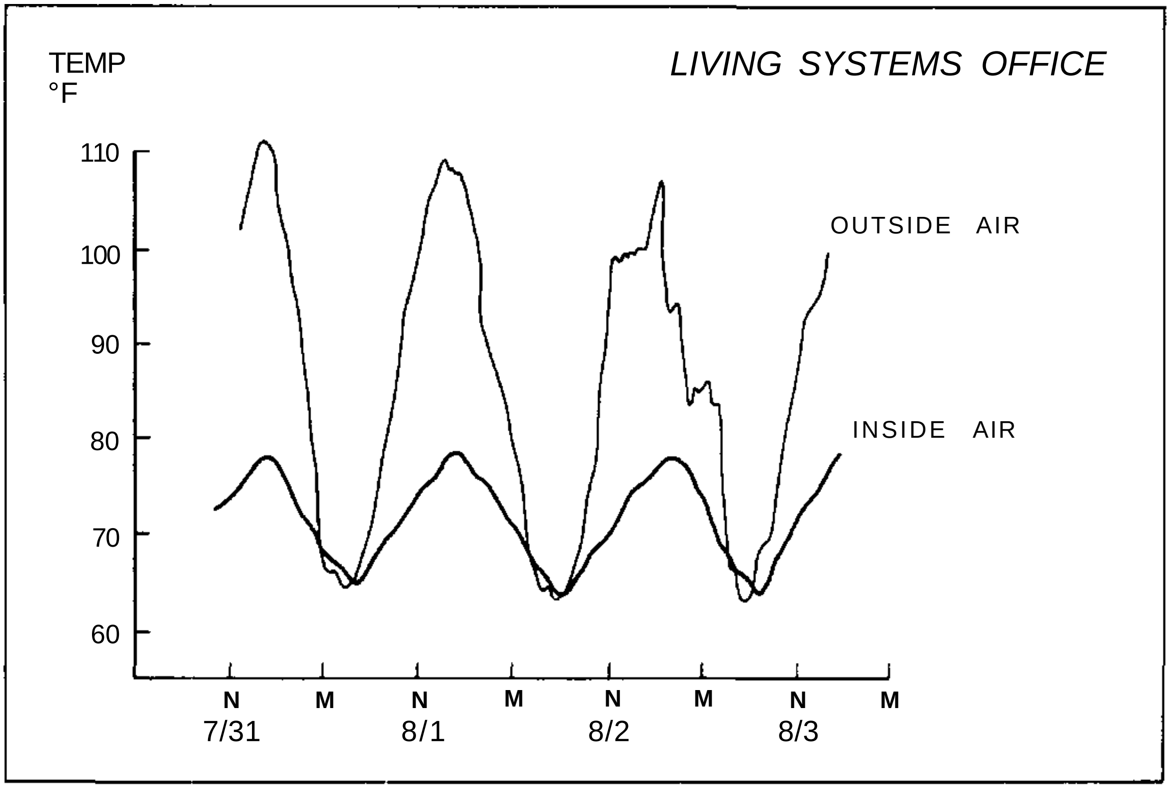


Figure D-9: Indoor temperature fluctuations of an office building in Davis, California, cooled by the circulation of nighttime outdoor air (BAI).

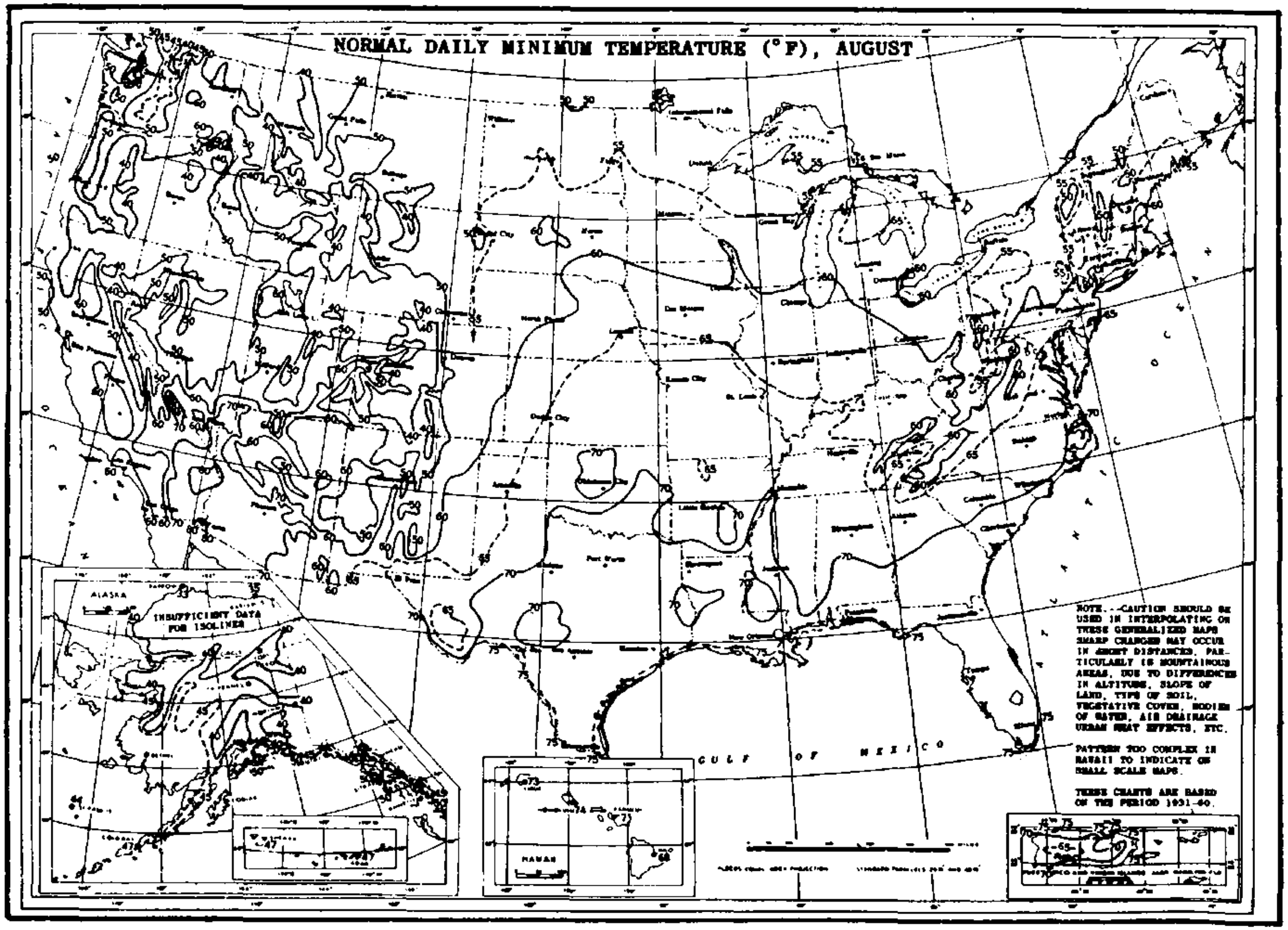
NORMAL DAILY MINIMUM TEMPERATURE (°F), JULY

NOTE.--CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS SHARP CHANGES MAY OCCUR IN SHORT DISTANCES, PARTICULARLY IN MOUNTAINOUS AREAS, DUE TO DIFFERENCES IN ALTITUDE, SLOPE OF LAND, TYPE OF SOIL, VEGETATIVE COVER, BODIES OF WATER, AIR DRAINAGE, URBAN HEAT EFFECTS, ETC.

PATTERN TOO COMPLEX IN HAWAII TO INDICATE ON SMALL SCALE MAPS.

THESE CHARTS ARE BASED ON THE PERIOD 1931-60.

Figure D-10: Normal daily minimum temperature (degrees F), July (USD).


NORMAL DAILY MINIMUM TEMPERATURE (°F), AUGUST

NOTE.--CAUTION SHOULD BE USED IN INTERPOLATING ON THESE GENERALIZED MAPS SHARP CHANGES MAY OCCUR IN SHORT DISTANCES, PARTICULARLY IN MOUNTAINOUS AREAS, DUE TO DIFFERENCES IN ALTITUDE, SLOPE OF LAND, TYPE OF SOIL, VEGETATIVE COVER, BODIES OF WATER, AIR DRAINAGE URBAN HEAT EFFECTS, ETC.

PATTERN TOO COMPLEX IN HAWAII TO INDICATE ON SMALL SCALE MAPS.

THESE CHARTS ARE BASED ON THE PERIOD 1931-60.

Figure D-11: Normal daily minimum temperature (degrees F), August (USD).

it contacts water prior to passing in contact with people. Although evaporating water into the air occurs in many ways, the most important is to have large water-to-air surface contact and to increase the turbulence or movement of water in contact with the air. For example, large shallow ponds increase surface contact. Moving streams and sprays from water fountains increase turbulence and surface area. Air blowing across the surface of the water can do both.

Mechanical evaporative coolers can increase this evaporative cooling effect, usually with an energy requirement substantially below conventional compression and absorption air conditioning.

Evaporative cooling can also keep roofs of buildings cool. Flooded roofs, roof sprays, and roof ponds have been used successfully in severe cooling climates such as Arizona and Florida.

In fact, water performs two functions: it protects the roof materials from ultraviolet damage, and it cools the roof through the evaporation of water. The most important effect is the evaporation of water. For an evaporation rate of 10 to 15 inches per month, a cooling rate averaging between 115 to 175 Btu/ft^2 per day can be obtained (SEL).

Wind is a prime factor in the rate of evaporation. Therefore, wind flows across the roof ponds should, if possible, be enhanced.

Proper lip and edge design is critical to prevent a separation of wind flow from the surface, with the subsequent reduction in evaporation rate (GEI). Only crude calculations of evaporative cooling potential are possible because of limited data on wind speed. However, where wind speed is known, rough approximations of evaporative cooling effects are possible.

Some problems associated with evaporative cooling include insect and plant growth and a build-up of salts, such as lime, on evaporative surfaces.

Water sprays are effective in preventing temperature build-up on rooftops on hot summer days (YEL-2). For example, during the intense sunshine of Arizona summers, spraying horizontal roofs approximately 40 seconds out of each minute keeps the roof surface within 5 F of the ambient dry bulb temperature. During early morning and afternoon hours, spraying reduces roof temperatures well below the dry bulb temperature to within a few degrees of the wet bulb temperature. Approximately 0.3 pounds of water per square foot of roof surface is needed to accomplish this. Assuming that the power required to pump the spray must be charged against the cooling process and that 10 psi is needed to make the sprays function properly, approximately 0.01 hp (7.46 watts) of power is required per 1000 square feet of roof area. The cooling effect is approximately 300 Btu/hr ft^2 (88,000 watts) (YEL-2).

The cooling capacity of sprayed roofs at night has not yet been explored in detail. Interest in roof sprays has been primarily to offset solar effects. However, evaporation from roof ponds can produce a significant cooling effect. Evaporation of 11.4 pounds of water an hour at 75 F produces the equivalent of 1 ton of refrigeration (YEL-2) (YEL-3).

D.2.d Radiative Cooling

A constant exchange of thermal energy occurs between objects that can "see" each other. A net transfer of energy occurs from the warmer object to the cooler object. The earth, for example, radiates heat to clear night skies that are very cold even during hot weather. The north sky can also be quite cool during the day. This radiation to the sky is primarily at wavelengths between 6 and 15 microns (BUD).

One of the best sources of engineering data and analyses of radiative cooling is a publication by Raymond W. Bliss, Jr., "Atmospheric Radiation Near the Surface of the Ground: A Summary for Engineers" (BLI). Figure D-12 shows the net radiative exchange, R, (i.e., the net radiative losses) from an exposed, thermally black, horizontal surface at air temperature. It provides estimates of heat (radiation) loss rates from a horizontal surface to the sky. First, determine any two of the three parameters: air temperature, humidity level, and dewpoint. Note that the graph shows that

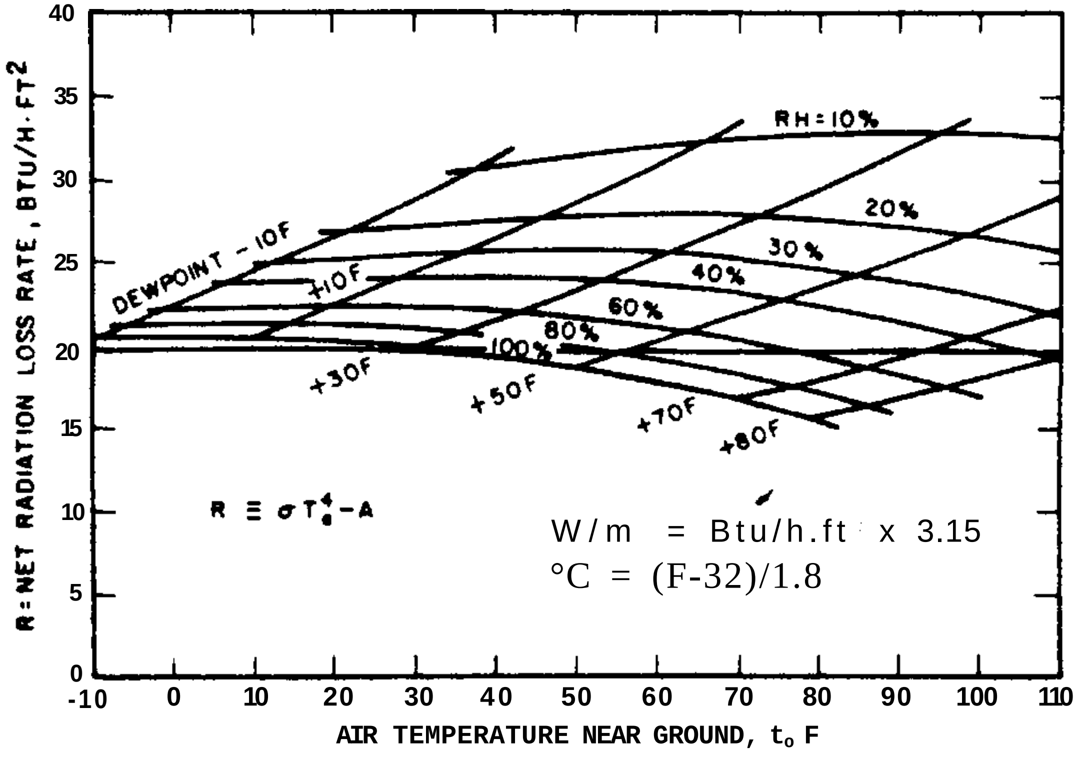


Figure D-12: Typical values of radiation loss from horizontal surfaces to the sky at sea level (BLI).

the heat loss rate (cooling effect) is usually between 15 to 30 Btu/hr ft^2. During a 10-hour night, the total cooling effect is between 150 to 300 Btu/ft^2 . Note that this range holds in many climates, making night radiative cooling widely applicable. However, it is far less effective in humid climates where the dewpoint is high. Radiative cooling effects in such climates have yet to be substantiated. To be effective, the radiating surface must be carefully protected from the warming effects of breezes.

This can be compared with a good solar heat collection system that produces as many as 1,000 Btu/ft^2 during a sunny day and an average of 200 to 500 Btu/ft^2 a day during a heating season.

Most outgoing radiation to the sky occurs at night. The amount of radiation varies greatly from one part of the sky to another, from 100 percent possible directly overhead at the zenith to virtually none at the horizon. The most effective radiant cooling surface is horizontal. Obstructions such as trees and walls reduce night sky cooling (BAI).

A vertical surface with no obstructions yields about 40 percent of the radiant cooling of a horizontal surface. For additional information on radiative cooling see the following references: (ABR) (BAI) (BAR) (BRO) (DUB) (GEI) (KEL) (KNO) (NEU) (PIT) (PLE) (REI) (SEL).

Probably the classic radiative cooling concept was first developed by John Yellott and Harold Hay. Hay continued its development and called it "Skytherm."^{R} "Skytherm"^{R} uses roof ponds with water contained in black plastic bags. (See further discussions of this concept in Chapter C4, Thermal Storage Roofs.) The water cools by nocturnal radiation. During the day, the ponds are shaded by sliding panels above them.

The cooled water cools the house by absorbing room heat through the metal ceiling. The bags can be flooded with water to provide additional cooling by evaporation. With only slight inputs of mechanical power, 600 to 1300 Btu/ft^2 can be dissipated during a summer night to the sky through a combination of radiation and evaporation (ROB).

This system has successfully and comfortably 100 percent cooled a house in Atascadero, California (Figure D-13). Annual temperature profiles, inside and outside, are shown in Figure D-14 for an earlier prototype having similar performance characteristics.

Figures D-15 to D-17 show three examples of design concepts using radiative cooling. Figure D-15 is a house developed in 1975 by John Hammond in Winters, California. It is a form of the roof pond system. The percentage of roof covered by the system is smaller, and the sliding insulation panels are replaced by a hinged panel powered by a hydraulic ram. Even during the hottest weather, the air temperature in this house has not exceeded 78 F.

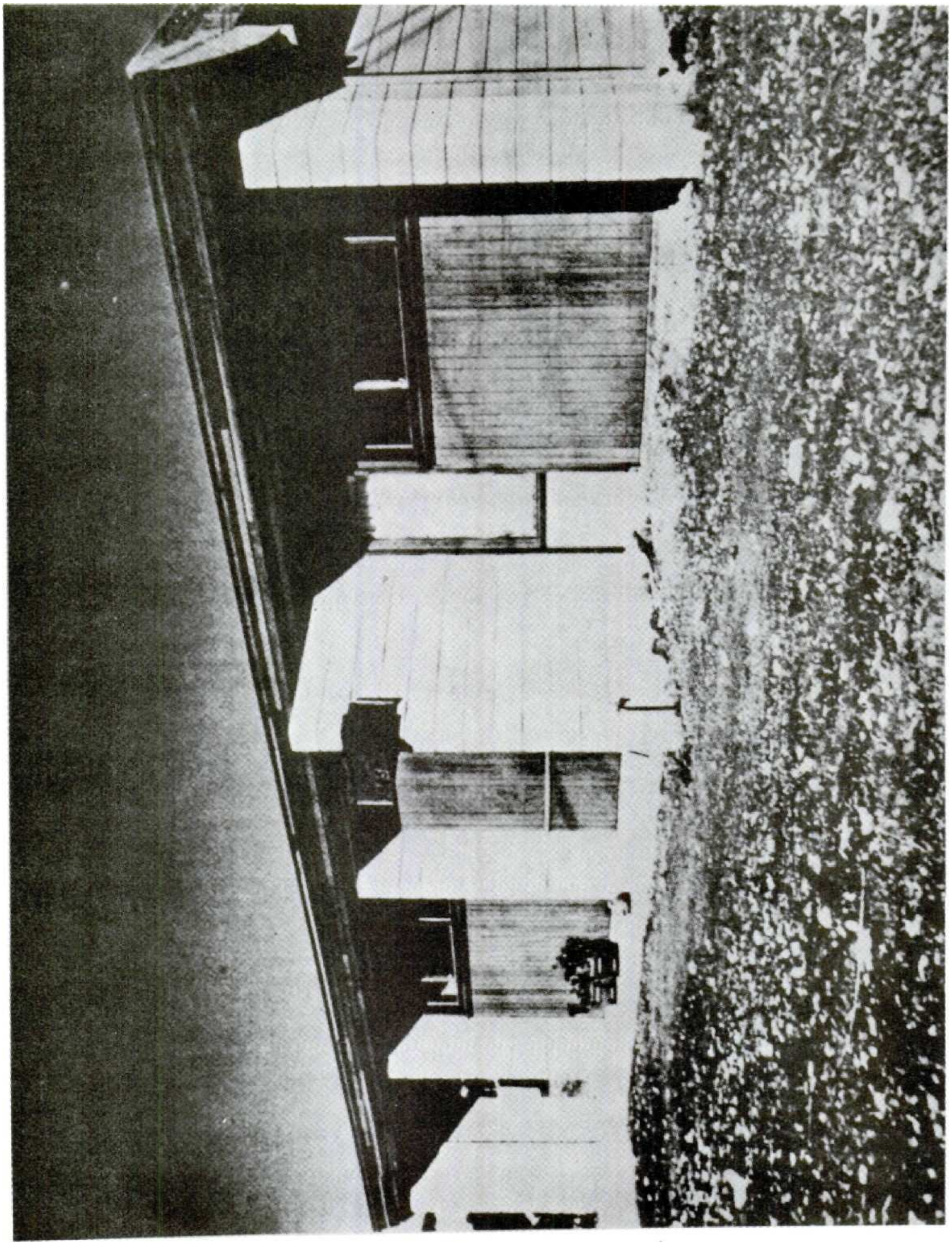
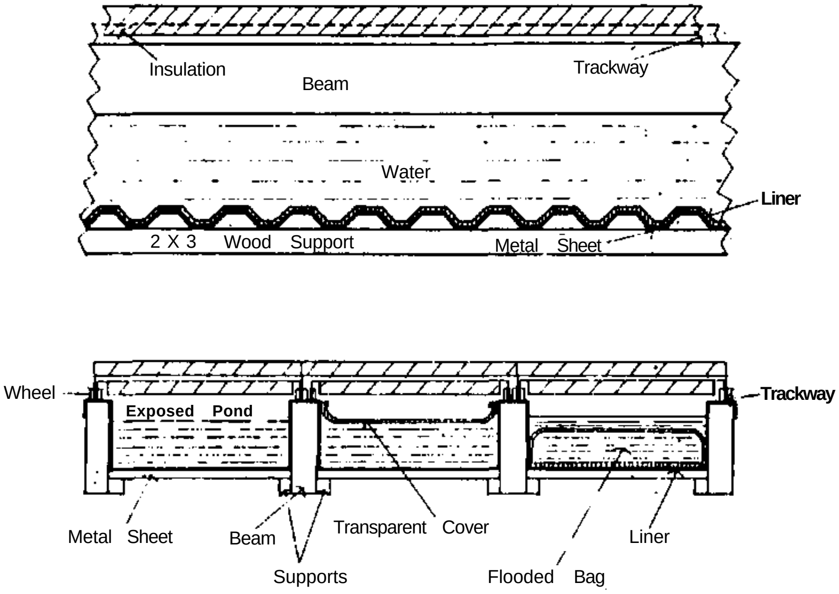


Figure D-13: Harold Hay's Atascadero House (SAN)



Cross-section of ceiling ponds.

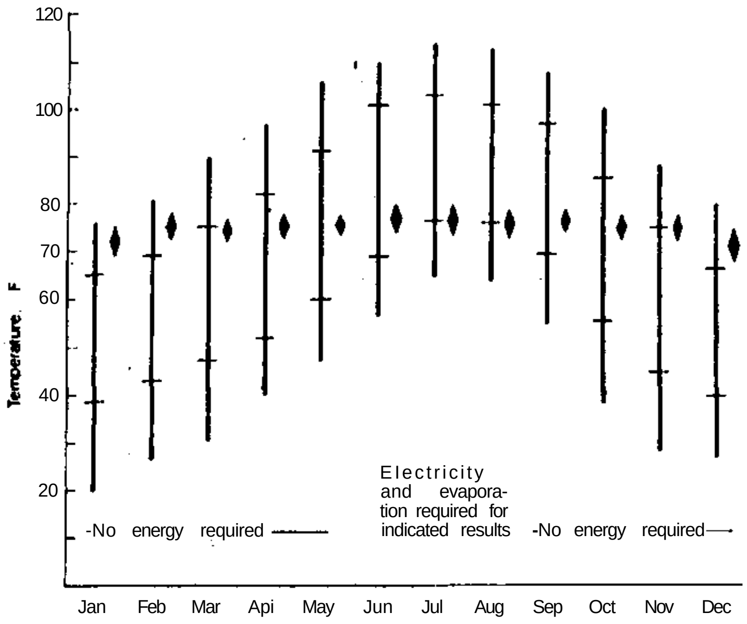
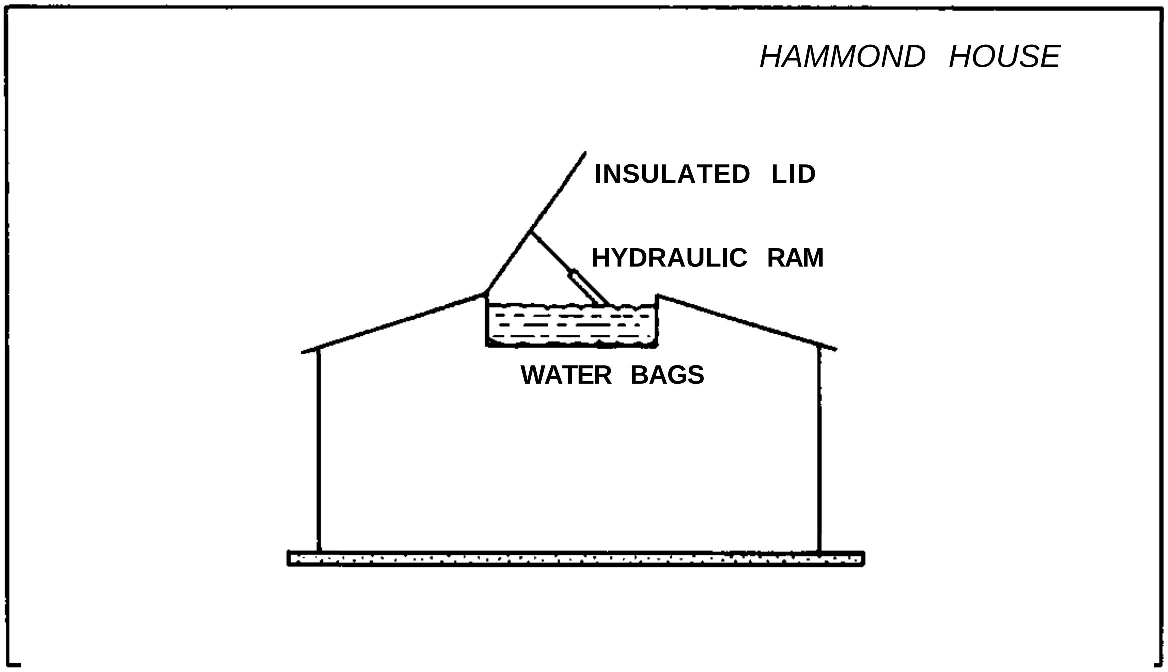


Figure D-14: Natural air conditioning (YEL-3)



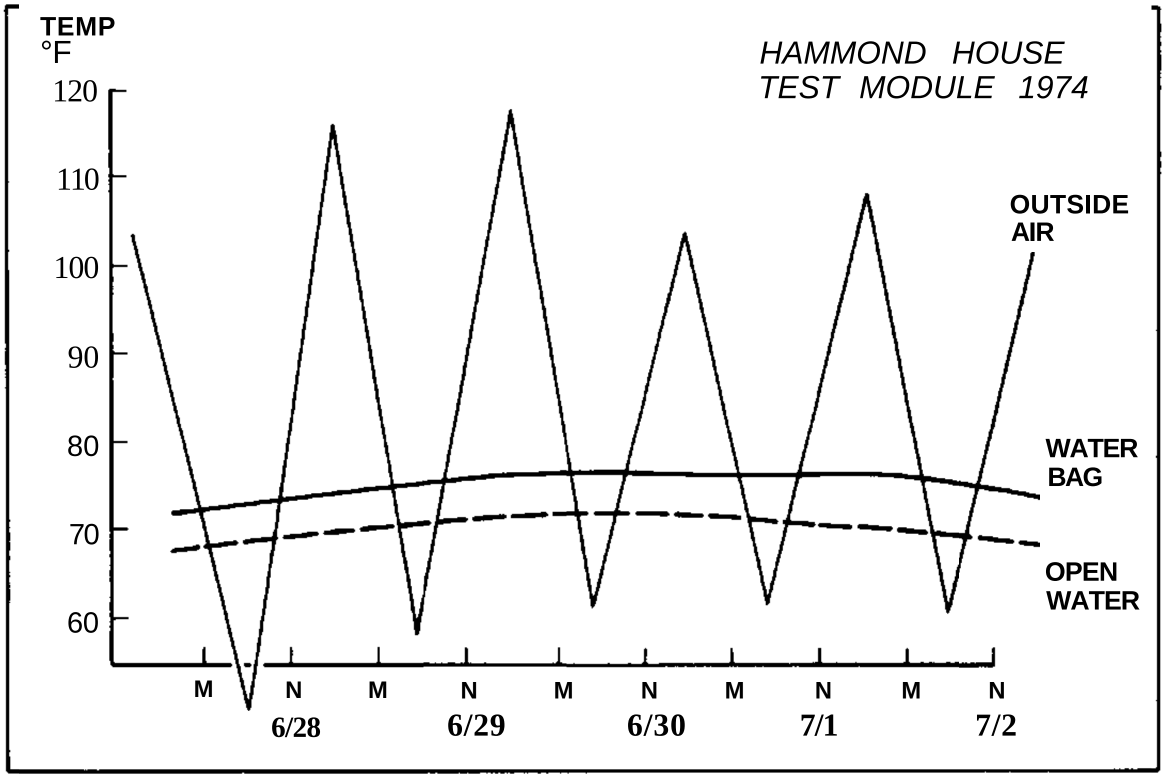


Figure D-15: John Hammond House: diagram (top and performance records (the design is a modification of the "Skytherm"^{R} radiative cooling system) (BAI).

The "Cool Pool" concept, Figure D-16, was developed and tested by Living Systems in Davis, Indio, and Sacramento, California. The roof pond radiates its heat to the sky. The coolest water settles down into the radiant wall panel, cooling the house.

David Bainbridge used a thermosiphon cool slab concept (Figure D-17). Having the tank on the ground level makes maintenance easier. A modification of this concept is a nocturnal air cooling system being developed for integration into the structure of a building. The heat dissipator is a sill wall inclined 45° to the sky with a ducted metal plate and a selective cold-body surface coating (see Figure D-18). The warm room air is ducted through the heat dissipator when it is cooled. From there, it passes through ducts in a concrete floor slab that "stores" the coolness. Airflow can be enhanced by using fans. A research program on this subject is being funded by the U.S. Department of Energy. This system can be easily integrated into multi-story construction. With modifications, solar heating can be included in this system.

Other radiative cooling concepts are mentioned in Chapter C4, Thermal Storage Roofs.

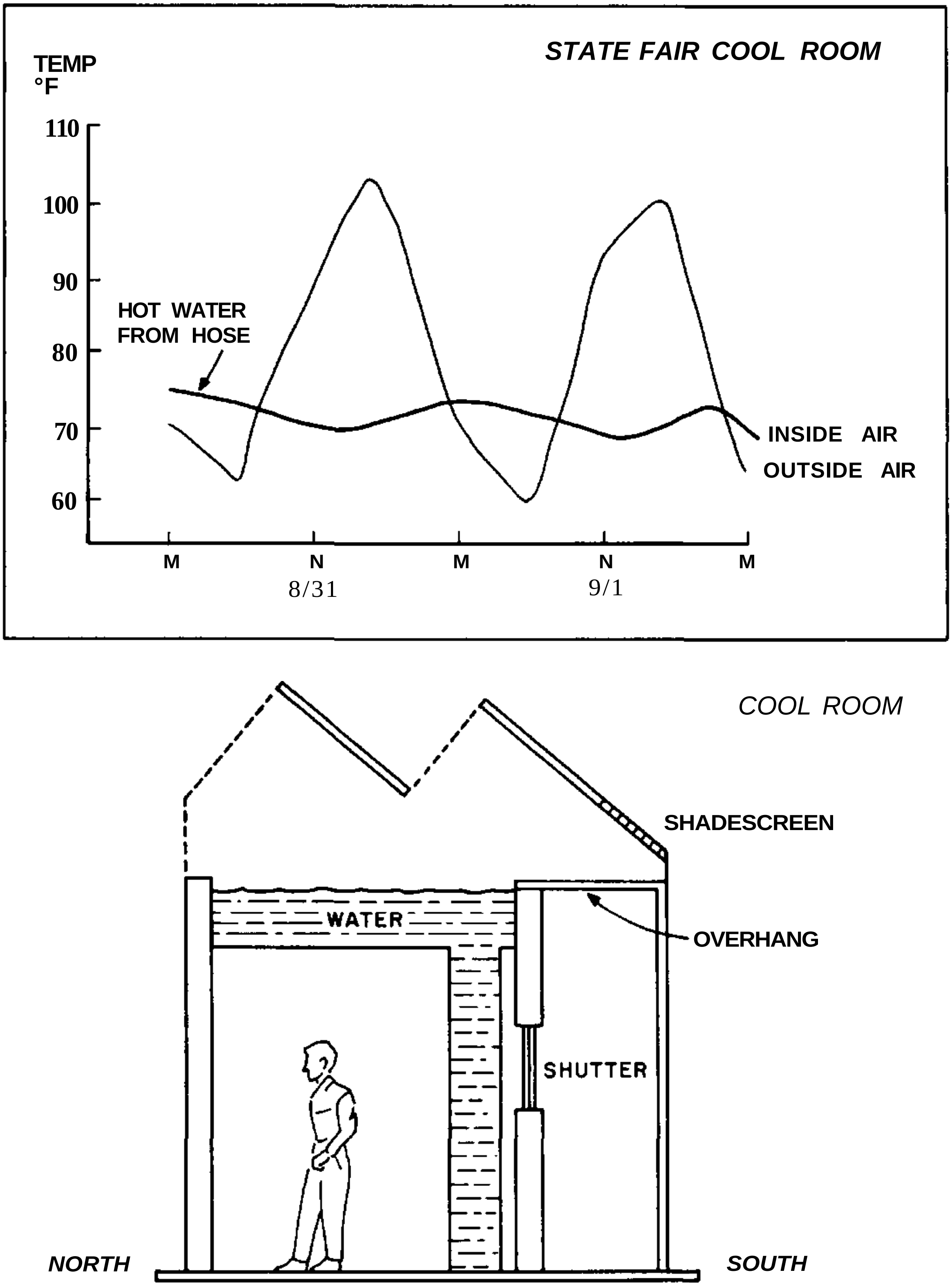


Figure D-16: The Cool Pool concept by Living Systems: performance (top) and schematic design (BAI).

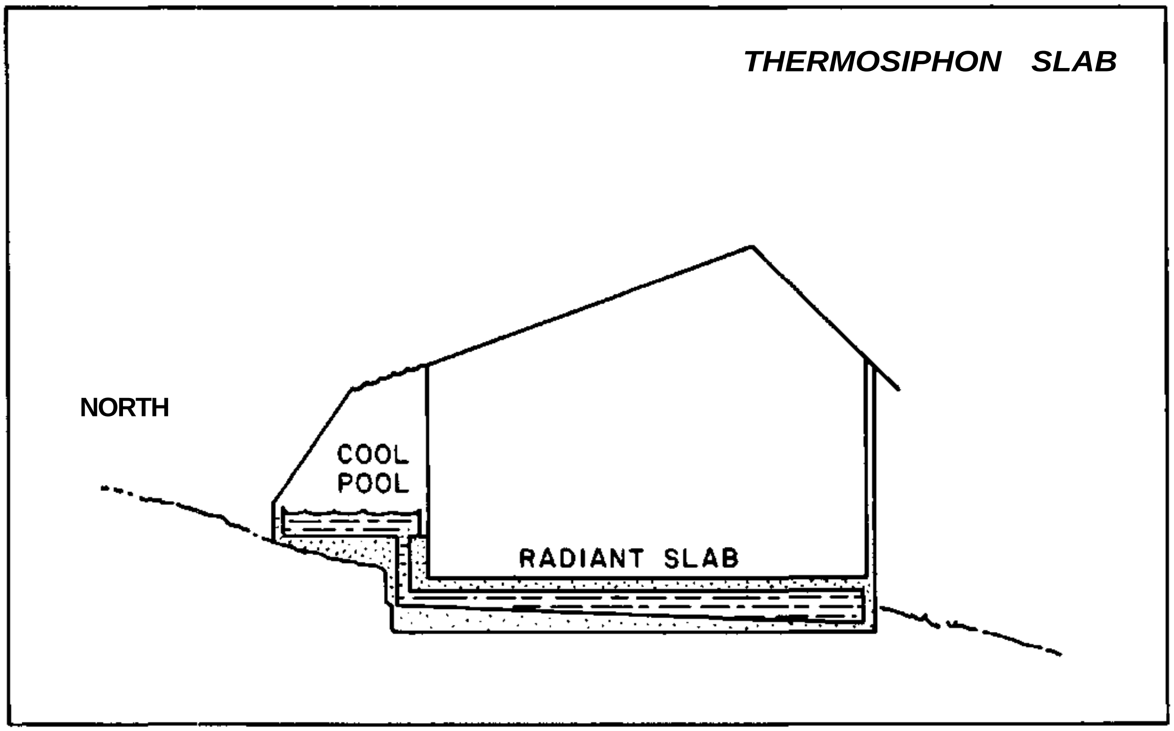


Figure D-17: A thermosiphon cool slab concept by Living Systems (BAI).

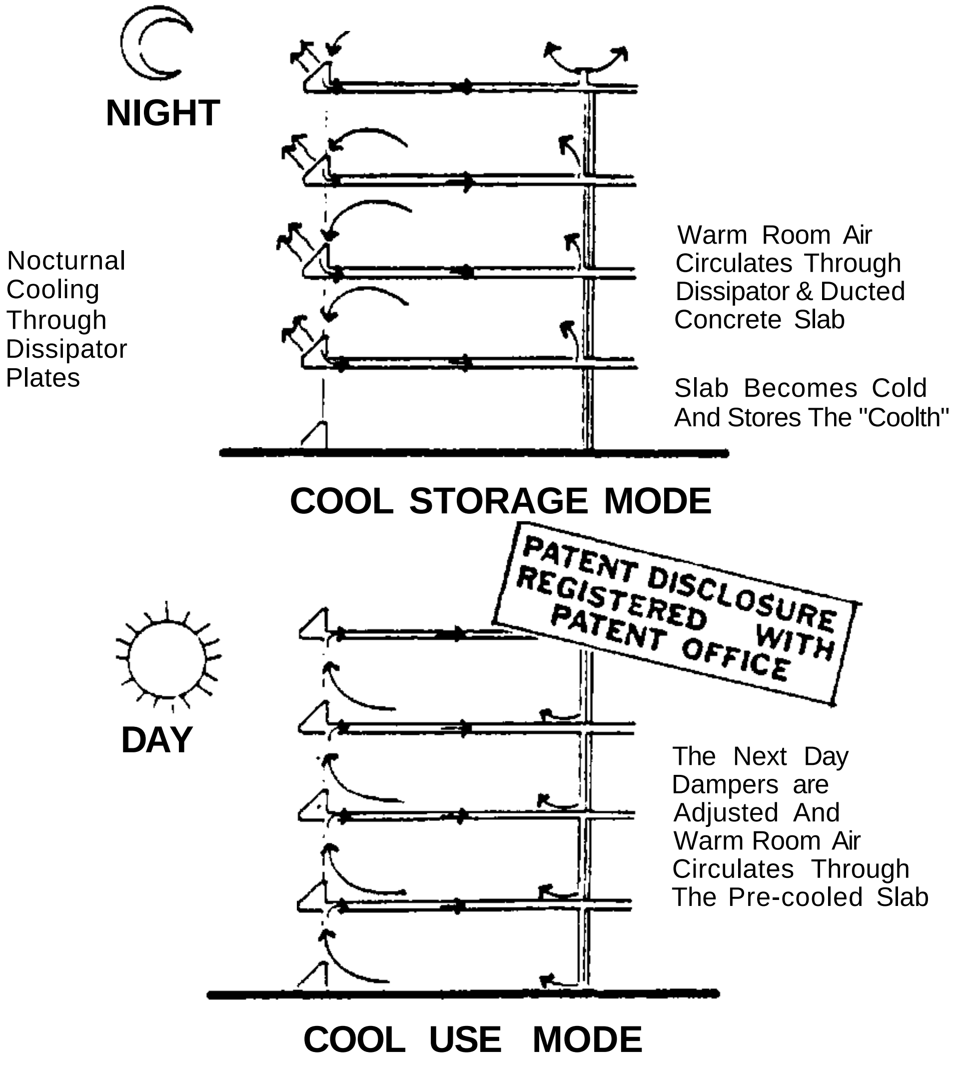


Figure D-18: A nocturnal air cooling system for multi-story buildings (PIN).

D.2.e Ground Cooling

Since the ground is nearly always cooler than the air when cooling is required, the more a building is in contact with the ground, the cooler it will be. Situating a building below grade or into the side of a hill is the easiest way to obtain more ground contact. Berming earth as high as possible or covering buildings with earth are additional ways. High levels of comfort and serene quiet usually accompany well-designed underground housing.

Underground housing in cold climates requires well-insulated walls in contact with the ground. The insulation keeps the interior surface of the walls warm and dry. In hot climates, the walls in contact with the earth should remain uninsulated. The resulting cool interior surface will tend to be damp from condensation, especially in humid climates. Particular care should be taken to waterproof the surface of the wall in contact with the ground.

D.3 PEAK LOAD REDUCTION

Natural cooling and natural energy storage in a building's mass can significantly reduce peak cooling loads and therefore lower the need for new power plants. For example, approximately 50 square feet of west-facing glass, unprotected from the intensity of solar radiation, increases the cooling demand by 1 ton of air conditioning equipment. This requires approximately 2 kilowatts of electrical generating capacity. Since this demand occurs during the summer peak, proper placement of glass can reduce peak demands.

So also, thermal mass can absorb heat during the day, delaying the need for cooling until after the afternoon's peak demand. During the later hours, the required cooling can be delivered at lower rates, reducing required equipment size.

Other means of reducing cooling loads can also reduce peak loads. Frequently, electrical cooling can be eliminated entirely. In addition, natural cooling systems that incorporate thermal mass, such as roof pond concepts, can be integrated with off-peak cooling systems. In general, if the required mechanical equipment is operated at night to "store" cooling for use during the day, the cooling equipment operates more efficiently and avoids electrical consumption during peak hours.

D.4 APPLICATIONS TO LARGE BUILDINGS

As with passive solar heating, passive cooling need not be limited to residential-scale structures. Perhaps the first step toward making large buildings compatible with passive cooling is to decrease the cooling load of the building. In many cases, major savings can be realized with natural lighting and natural ventilation by increasing the exterior surface area of the building. Wise thermal design of the increased external wall area (by using high levels of insulation and thermally efficient glazing systems) can compensate. The potential annual energy savings from the integration of natural lighting with winter solar heat gain and summer natural ventilation should not be underestimated.

Passive cooling methods present several challenges when applied to large buildings. For example, it is difficult to provide sufficient amounts of airflow through the building during nighttime ventilation. With the relatively warm water resulting from the radiative and evaporative cooling effects, the challenge is to cool effectively. Most mechnical systems are designed to cool using water below 65 F.

Night Air Ventilation

The larger the building, the more likely it is that mechanically driven fans will be required to circulate cool night air. The electrical consumption of these large fans must not exceed that of conventional cooling systems. Analytical methods to determine the net cooling effect of night air ventialtion on a seasonal basis still need to be developed. However, estimates can be made.

As a general guideline for buildings in climates such as Sacramento, California, 1 ft^3/min per square foot of floor area can provide about 35 Btu of cooling per day per square foot of floor area. Building mass should be about 40 pounds per square foot of floor area, with an exposed surface area of about 1 3/4 ft^2 per square foot of floor area. Larger airflows are desirable. Airflows of 3 to 4 ft^3/min. per square foot or larger, in combination with interior building mass of 75 to 150 pounds per square foot of floor area, can provide about 100 Btu of cooling per day per square foot of floor area. Similar cooling effects of the building mass for other areas of the country will occur where the minimum daily temperature is 60 to 65 F or below during most of the cooling season. The building mass will, for this same temperature range, be cooled to 65 to 70 F (ROB).

CHAPTER E

NEW DEVELOPMENTS FOR FUTURE USE

E.1 SUNTEK

E.1.a Transparent Insulation™ (Heat Mirror)
E.1.b Optical Shutter™ (Cloud Gel)
E.1.c Thermocrete™

E.2 THERMAL STORAGE

E.2.a Paraffin
E.2.b Salt Hydrates
E.2.c Calcium Chloride Hexahydrate
E.2.d Heat Pipes

E.3 THERMIC DIODE

E NEW DEVELOPMENTS FOR FUTURE USE

E.1 SUNTEK

Suntek Research Associates in Corte Madera, California, is developing three building materials specifically for passive systems (CHA).

E.1.a Transparent Insulation™ (Heat Mirror)

Transparent Insulation reduces heat loss through windows and skylights and from greenhouses and solar collectors. The primary components in these materials are heat mirror coatings that are transparent to short wavelength solar radiation and reflective to long-wave infrared radiation. These coatings are about 1,000 atoms thick and can be attached to any plastic film. When used with a dead air space, they have insulating properties equivalent to about 1 inch of plastic foam or glass wool insulation. When coated onto both sides of a plastic film, the heat mirror has a solar transmittance of 81 percent and an emittance of 0.11. With dead air spaces on both of its sides, its thermal conductance is 0.13 Btu/hr ft^2 F. These coatings still suffer from short lifetimes and high costs, and they are still in the development stage.

E.1.b Optical Shutter TM (Cloud Gel)

Optical Shutter materials vary their transmission of solar radiation as they change temperature. Such materials can be used in windows, greenhouses, and other glazing areas to prevent overheating. The product "Cloud Gel" is a plastic film laminated between two sheets of glass or two films of plastic. It is transparent and indistinguishable from ordinary plastic until it is heated above a certain critical temperature. At that point it turns into an opaque white that reflects light without absorbing it. Its solar transmittance drops to 15 percent. As soon as the film cools below its critical temperature, it becomes transparent again. The change from clear to white to clear occurs instantaneously over a temperature range of only 3 F. The critical temperature can be tuned to any value between 32 and 212 F by adjusting the proportions of its constituents. The materials continue to be difficult to fabricate and are expensive.

E.1.c Thermocrete TM

Thermocrete is a structural concrete that is filled with a phase-change material for heat storage. The main ingredient is calcium chloride, the material used for melting ice off streets. The material permeates the fine pores in the foamed concrete blocks, which are sealed with a plastic coating. As the phase-change material melts, the concrete block, without changing temperature, stores twenty times more heat than ordinary block. The material can also be packaged as a 1-inch -thick tile for walls, floors and ceilings.

Future developments in packaging eutectic salts in concrete are promising for heat storage in both passive and active systems. Stratification and supercooling do not occur. The very fine concrete particles act as seeds for crystal growth when the temperature falls to the freezing point of the salt. Moreover, the concrete acts as a cheap structural container. If these building systems can be mass-produced inexpensively and sealed reliably, they will provide new approaches to heat storage design — walls or floors receiving direct sunlight, stacks of hollow core blocks for ample heat storage in active systems' interior walls, and partitions built from hollow-core blocks through which solar heated air could be blown. The building itself could store millions of Btu with only a small temperature rise. Long-term heat storage would be the rule, not the exception.

Figure E-1 shows an integration of the Thermocrete™ with the Heat Mirror and Cloud Gel. It is essentially a thermal mass wall with insulation always in place; no moving parts are required to insulate the wall at night. Thermal performance is not necessarily better than full-thick thermal storage walls. Chemical compatibility between the salt and the concrete must be achieved, and the cost must be reduced.

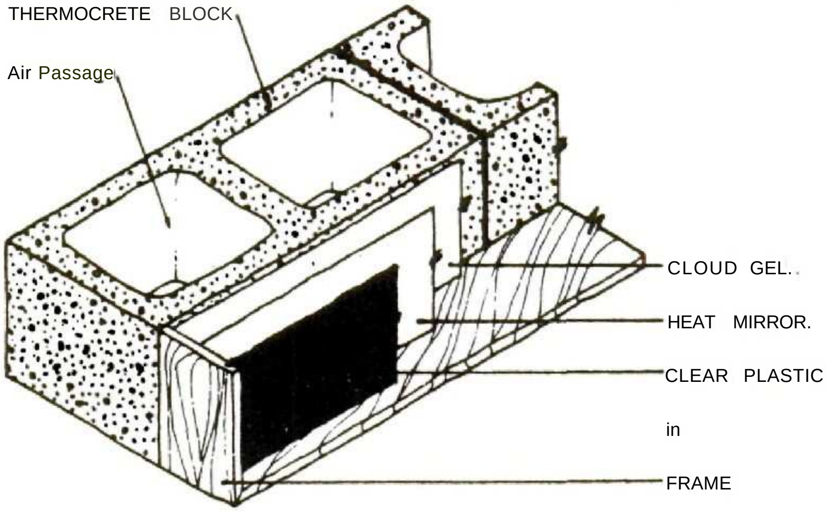


Figure E-1: Block for passive heating and cooling wall (CHA-2).

E.2 THERMAL STORAGE

Phase-change systems other than Thermocrete™ are being developed. One example is the integration of a layer of phase-change material with a layer of insulation into a set of louvers. The set of louvers is located behind south-facing glass in place of the thermal storage wall. During a sunny day, these phase-change materials absorb heat. At night the louver pivots, and the phase-change material releases its heat to the room. The insulation, which is now between the phase-change material and the glass, reduces heat loss from the phase-change material to the outside.

During the summer, the phase-change material can absorb excess heat from the building during the day. A reflective surface on the insulation will further reduce solar heat gain. At night, the louver is reversed, and the phase-change material releases some of its heat to the outside. Note that for such an application, the glazing must be transparent to long-wave infrared (ASK) (E^3E).

E.2.a Paraffin

Eikonix Corporation is developing a method for passive heat storage using Paraffin (HAU). Mixtures of stearic acid, paraffin, and dyes are encapsulated in both poroplastic and clear polycarbonate plastic sheets. The 1/4-inch-thick assemblies store up to 80 Btu per square foot. Multiple layers may replace the heavy materials in conventional thermal storage walls.

E.2.b Salt Hydrates

Dr. Maria Telkes is developing a thermal storage wall that uses phase-change materials (Glauber's salt) contained in 1.5-inch-diameter tubes. The tubes are located behind a polyhedral wall that transmits more than 80 percent of the solar energy that strikes it. The wall also has an insulating value equal to that of 1-inch-thick foam insulation. (See Figure E-2.) Behind the phase-change materials is an insulating wall.

The salt hydrate weighs about 10 pounds per square foot of wall area and can store up to 1,000 Btu per square foot. Preliminary estimates place the cost of the wall structure at less than $4 per square foot, including both the polyhedral insulating glazing and thermal storage wall. The aim is to develop complete wall structures in the form of modular panels, perhaps 4 feet × 8 feet × 2 inches thick and weighing less than 20 pounds.

Glauber's salt is available in practically unlimited quantities in the form of anhydrous sodium sulphate at a cost as low as $20 per ton. It is made into sodium sulphate decahydrate by adding the appropriate amount of water (56 percent). Nucleating and thickening agents are added to maintain large numbers of freeze/thaw cycles. The normal melting point of Glauber's salt is 89 F. However, with

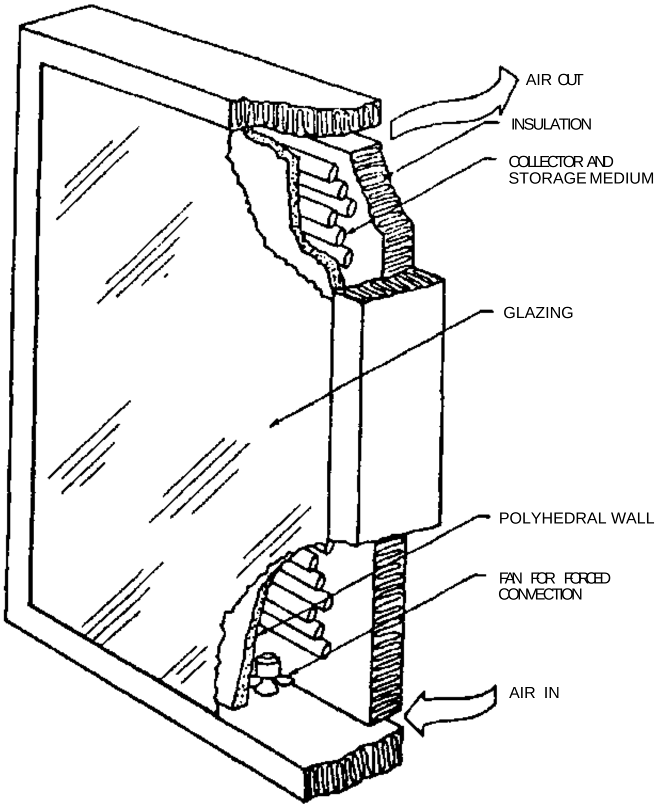


Figure E-2: Cutaway of a thermal storage wall using phase-change materials (FAU).

various additives that form eutectics with involved phase-change reactions, the melting point drops into the 70 to 75 F range.

E.2.c Calcium Chloride Hexahydrate

The Dow Chemical Company is investigating calcium chloride hexahydrate ($CaCl_2 6H_2O$), a low-cost phase-change material. Its melting point is 81 F with a heat-of-fusion of 82 Btu per pound. As a solid, its specific heat is 0.34 Btu per degree F; as a liquid its specific heat is 0.53. Its specific gravity is 1.71 when frozen and 1.54 when melted. Projected cost is less than 10 cents a pound. Dow Corning is testing thermal energy storage units consisting of closets filled with 1- to 2.5-inch-diameter tubes encapsulating the calcium chloride hexahydrate. Sixteen-ounce polyethylene bottles are also being used. Heat transfer is by direct solar gain or by the flow of air from either a solar collector or an overheated room (FAU).

E.2.d Heat Pipes

Basically, a heat pipe is a high-performance thermal conductor. It can take small temperature differences in a passive system and move heat rapidly into storage. It conducts heat in one direction only, a thermic diode effect. Therefore, it can move heat into storage but will not conduct it back out in the same direction.

The basic principle of heat pipe operation is shown in Figure E-3. It is essentially a hollow tube sealed at the ends. Prior to sealing it is partially filled with a working fluid such as Freon^{R}, ammonia, or water. The pipe transfers heat through evaporation and condensation. As shown in Figure E-3, the heat pipe is angled to take advantage of gravity. When the fluid is in the liquid state, it collects near the bottom of the heat pipe. When the heat pipe is warmed (e.g., by solar irradiation), some of this liquid evaporates. The vapor travels up the heat pipe to the slightly cooler upper end. The liquid condenses, giving up its heat, and drains by gravity back to the bottom of the pipe where the process repeats.

An example of a heat-pipe-augmented passive system is shown in Figure E-4. An absorber plate collects the solar heat; heat pipes are attached to the absorber plate and pass through insulation that separates the absorber from the storage wall, which in this case is water. The heat pipes transfer heat from the warm absorber to the cool storage. At night, however, when the absorber is cooler than storage, the heat cannot transfer in the other direction because the liquid is at the end of the heat pipe in contact with the absorber and cannot be warmed by the storage.

In computer simulations by Battelle Columbus Laboratories, a well-designed single-glazed heat pipe system in Columbus, Ohio,

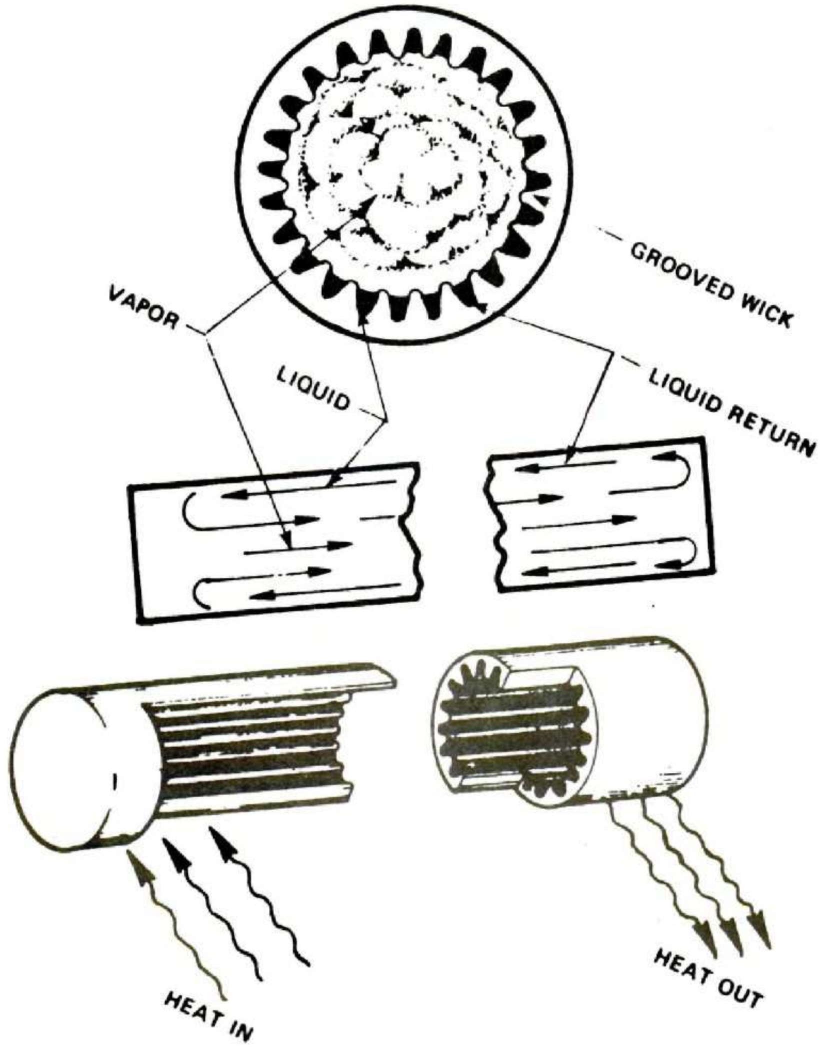


Figure E-3: Schematic of heat pipe operation (COR).

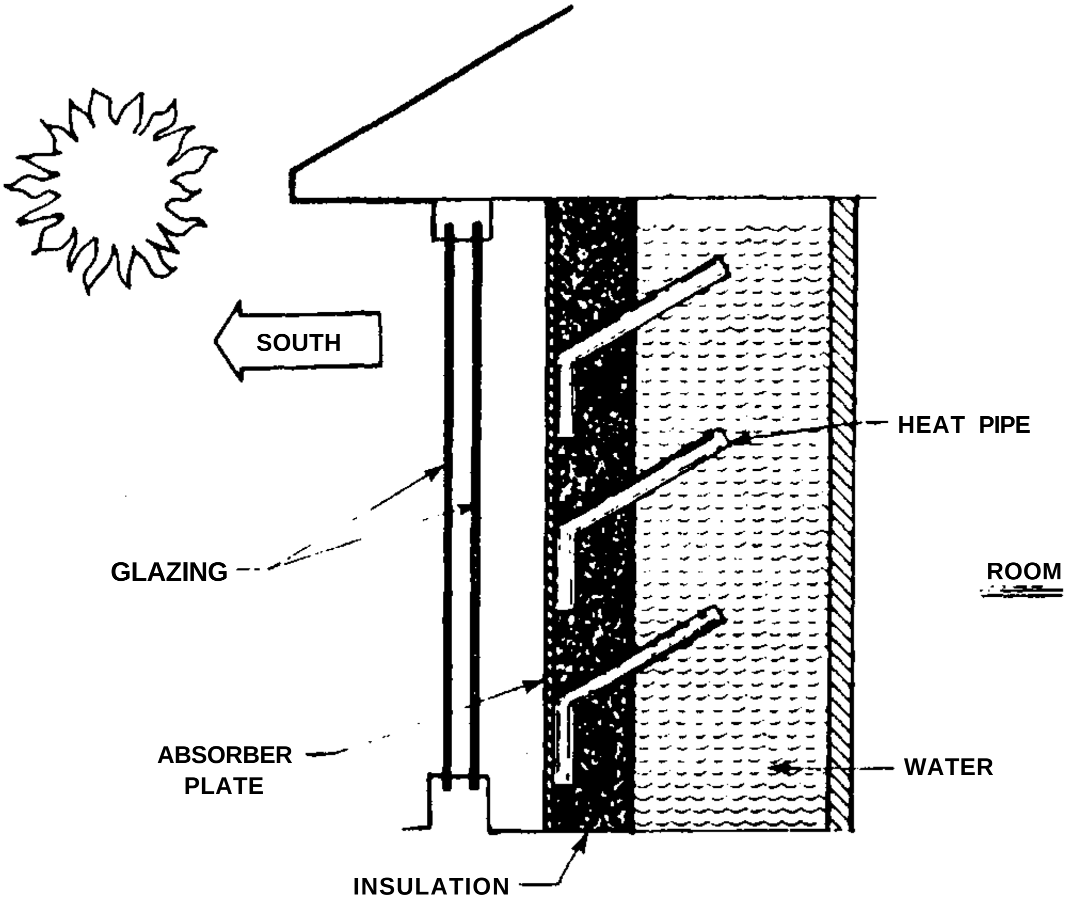


Figure E-4: Heat pipe augmented water wall concept (COR).

produces more than twice the useful heating output of a conventional 6-inch-thick double-glazed water wall.

Three heat pipe applications are being developed to reduce reliance on mechanically operated systems:

1. In liquid or air-heating collectors, heat pipes may move the heat from the absorber plate to a heat transport manifold, eliminating liquid or air circulation through the collectors.

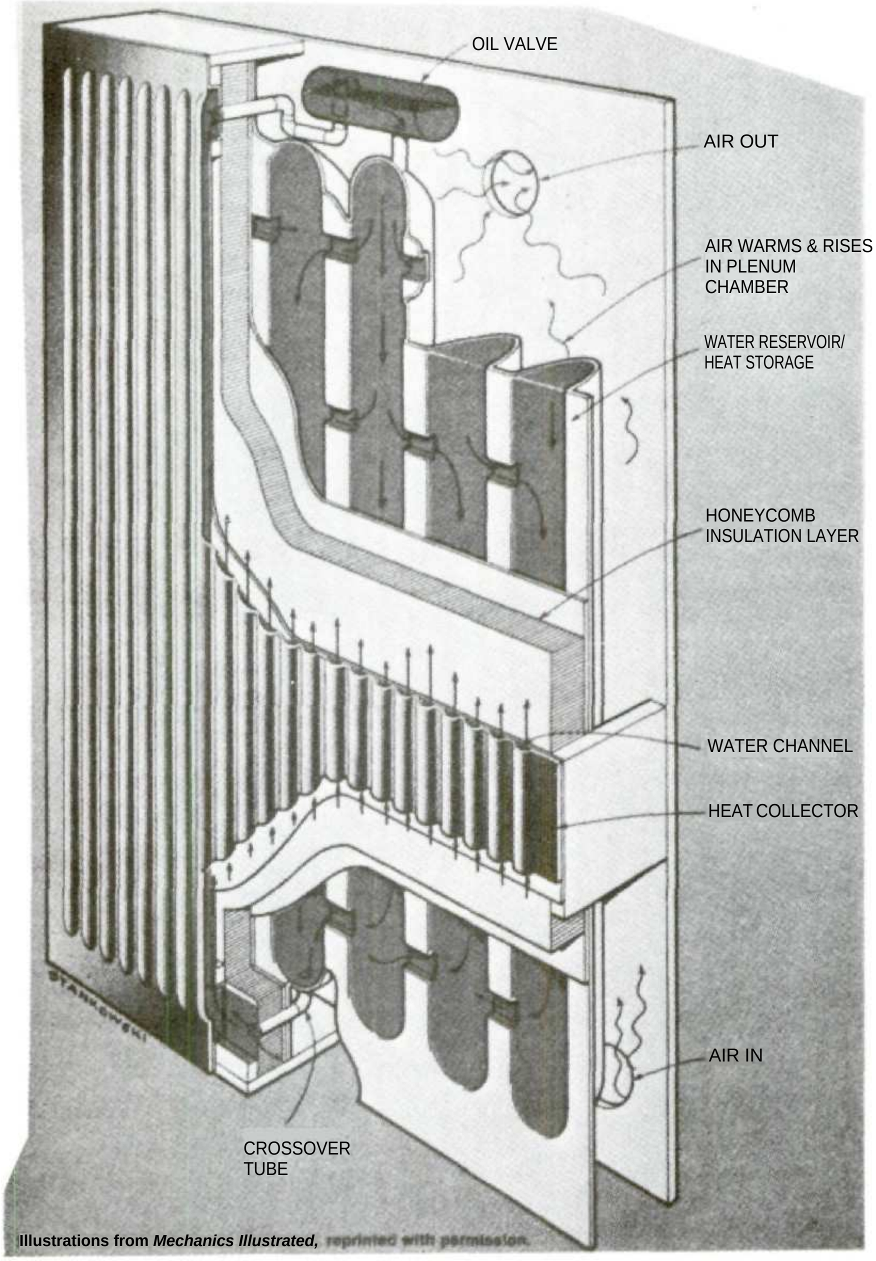
2. Heat pipes may transport heat from the collectors to storage or to the distribution system, replacing the conventional fan and pumped-based transport loops.

3. At night, heat pipes can remove heat from inside the building and transport it to external radiators.

The principal barrier to using heat pipes has been high cost.

E.3 THERMIC DIODE

Thermic diode solar panels combine all the elements of a complete solar energy system (collectors, controls, storage, heat exchangers, ducting) into a 4-foot by 8-foot module. They have no moving parts and need no external power. (See Figure E-5.)

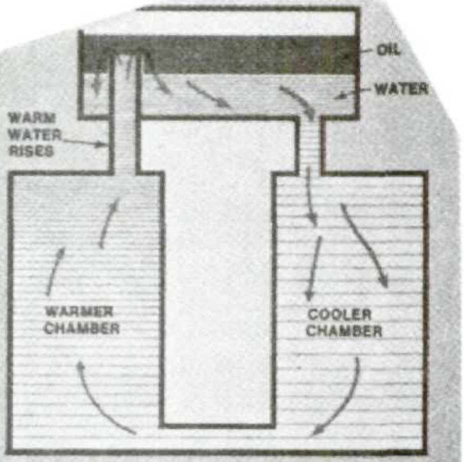


Illustrations from *Mechanics Illustrated,* reprinted with permission.

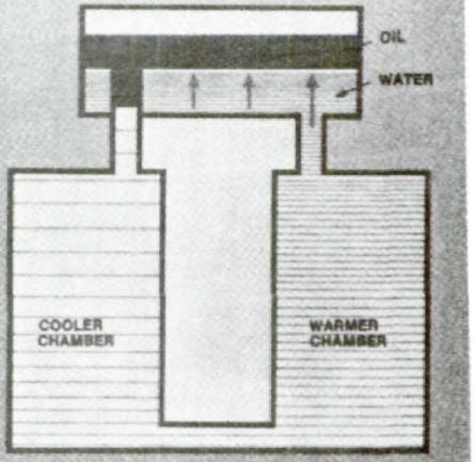
Figure E-5: Thermic diode solar panel (KAS).

Each panel is composed of two layers: a thin solar absorber/collector forming the outside of the building and a thicker heat storage layer on the building side of the panel. They are separated by insulation so that little heat can be conducted from one to another. Both are filled with water. Tubing connects the layers at the top and bottom. When the sun heats the water in the outer panel, that water reaches a higher temperature than the storage water. The water convects from the collector to storage through a check valve inserted into the upper connecting tubes between the panels. The check valve is a thermic diode in that it permits the warm water to move from the collector to the storage but prevents reverse thermocirculation; this keeps the warm storage water from flowing in the opposite direction at night when the collector panel surface is cold. (See Figure E-6.)

The panel, developed by MIT professor Shawn Buckley, is in manufacturing prototype stages. It consists of an aluminum-skinned, plastic-backed solar collector panel, foam-filled paper honeycomb insulation, and a molded fiberglass storage/heat exchange layer. Pressure-active adhesive binds all three together. Room air is heated by flowing through vents at the bottom of the panel. The air comes in contact with the warm storage/heat exchange layer and returns back into the room through the vents at the top of the wall (KAS).



Day; sun-heated water in collector rises into diode valve, flows under oil layer to cooler storage chamber below.



Night: warmer waterin storage tries to thermosiphon through diode valve, down standing pipe, and into collector— but cannot force oil in diode down pipe.

Figure E-6: Operation of the thermic diode (one-way heat flow valve) (KAS).

Glossary

References

Bibliography

Appendix

GLOSSARY

Active system - solar heating or cooling system that requires external mechanical power to transfer thermal energy.

Altitude - the angular distance from the horizon to the sun.

ASHRAE - abbreviation for the American Society of Heating, Air-Conditioning, and Refrigerating Engineers.

Auxiliary heat - the heat provided by a conventional heating system for periods of cloudiness or intense cold when a solar heating system is not sufficient.

Azimuth - the angular distance between the south and the point on the horizon directly below the sun.

Btu (British thermal unit) - the quantity of heat needed to raise the temperature of 1 pound of water 1 degree Fahrenheit.

Calorie - the quantity of heat needed to raise the temperature of 1 gram of water 1°C.

Coefficient of heat transmission (U-value) - the rate of heat flow in Btu per hour through a square foot of wall or other building surface when the difference between the indoor and outdoor air temperatures is 1 F.

Degree-day - a unit that represents a 1 F deviation from some fixed reference point (usually 65 F) in the mean daily outdoor temperature. If the average outdoor temperature is 40 F for one day, then twenty-five (65 minus 40) degree days result. Used to determine the demand of a heating season for different locales.

Double-glazed - covered by two panes of glass or other transparent material.

DOE - U.S. Department of Energy. Responsible for commercial, institutional, and industrial solar demonstration programs and for the general coordination of Federal solar energy research and development.

Emittance - a measure of the ability of a material to give off thermal radiation.

Eutectic salts - a group of materials that melt at low temperatures, absorbing large quantities of heat. As they re-crystallize, they release that heat. Used for storing solar energy as heat.

Glauber's salt - sodium sulfate ($Na_2SO_4 \cdot 10H_2O$). An eutectic salt that melts at 90 F and absorbs about 104 Btu per pound as it does so.

Gravity convection - the natural movement of heat through a body of fluid that occurs when a warm fluid rises and cool fluid sinks under the influence of gravity.

HUD - U.S. Department of Housing and Urban Development. Responsible for residential solar demonstration programs.

Heat capacity - a property of a material, defined as the quantity of heat needed to raise the temperature of one cubic foot of material 1 F.

Irradiation - solar radiation, direct, diffuse and reflected, that strikes a surface.

Nocturnal cooling - the cooling of a building or heat storage device by the radiation of heat to the night sky.

Resistance (R-value) - a measure of the tendency of a material to retard the flow of heat.

Retrofitting - the application of a solar heating or cooling system to an existing building.

Shading Coefficient - the ratio of the solar heat gain through a specific glazing system under a given set of conditions, to the total solar heat gain through a single layer of clear, double-strength glass under the same conditions.

Shading mask - a section of a circle that is characteristic of a particular shading device. This mask is superimposed on a circular path diagram to determine the time of day and the months of the year when a window will be shaded by the device.

Solar house (solar tempered house) - a dwelling that obtains a large part, though not necessarily all, of its heat from the sun.

Specific heat - the quantity of heat, in Btu, needed to raise the temperature of 1 pound of material 1 degree Fahrenheit.

Sun path diagram - a circular projection of the sky vault, similar to a map, that can be used to determine solar positions and to calculate shading.

Thermal mass - mass included in a solar system for the purpose of storing heat.

Thermosiphoning - see Gravity convection.

U-value - see Coefficient of heat transmission.

Thermocirculation - see Gravity convection.

Vapor barrier - a layer of material, impervious to water in the vapor state, used to prevent condensation of water within insulation.

Veiling reflection - a blinding or obscuring glare.

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APPENDIXES

Appendix 1: Properties of Glazing Materials (TEM).

	Thickness (In.)	Cost ($/ft^2)	Transmittance	Weight/Area (lb/ft^2)	Thermal Expansion ($^{\circ}F^{-1}x10^{-3}$)	Ease in Handling	Strength	Sheet Size (ft)	Remarks
Water white glass "Solatex" (ASG)	0.125	0.99	0.90	1.60	0.47	Poor	Good (tempered)	2. 3. or 4x8	Very durable—no degradation
Float glass	0.125	2.35	0.84	1.60	0.47	Poor	Good (tempered)	4x8	Very durable—no degradation
Window glass (ASG SS Lustra-glass)	0.090	1.80	0.91	1.20	0.47	Poor	Poor (non-tempered)	4x7	Fragile
Sunlite Premium II (Kalwall)	0.040	0.60	0.88	029	2.00	Excellent	Very good	4 or 5 width rolls	Maximum temperature 300°F
Filon w/Tedlar (Vistron Corp.)	- -	1.00	0.86	0.25	2.30	Very good	Very good	4.25x16	Maximum temperature 300°F
Flexiguard 7410 (3M)	7 mil	0.38	089	0.053	- -	Fair	Good	4x150 roll	Maximum temperature 275°F
Tedlar (Dupont)	4 mil	0.05	0.95	0029	2.80	Fair	Good, some embrittlement	up to 5.33 width roll (64 in.)	4-5 yr. lifetime at 150°F
Teflon FEP 100A (Dupont)	1 mil	0.58	0.96	0.02	5.85	Poor	Fair, not for exterior glazing	4.83 width roll (58 in.)	Maximum temperature 300°F
Swedcast 300 Acrylic (Swedlow Inc.)	0.125	0.81	093	077	4	Excellent	Very good	9 wide	Maximum service temperature 200°F
Lucite Acrylic (Dupont)	0.125	1.14	0.92	0.73	4	Very good	Very good	4x8	Maximum temperature 200°F
Tuffak-Twlnwall (Rhom & Hass)	- -	1.25 (2 layers)	Equiv. to 0.89 for 1 layer	025	3.3	Very good	High impact strength fatigue cracking	4x8	5% reduction in transmittance over 5 years
Acrylite SDP (Cyro)	- -	2.15 (2 layers)	Equiv. to 0.93 for 1 layer	1.00	4	Very good	Good	6x6	Maximum temperature 230°F
Sun-lite Insulated Panels (Kalwall)	- -	2.50 (2 layers)	Equiv. to 0.88 for 1 layer	0.7	- -	Good	Good	4x8 4x10 4x12 4x14	Maximum temperature 300°F
Solar Glass Panels (ASG)	- -	2.99 (2 layers)	Equiv. to 0.90 for 1 layer	4.5	0.47	Poor	Good	3 or 4x6 3 or 4x8	Very durable

When choosing materials for a passive system, the most important considerations are appearance, durability, performance, and cost. Since the glazing is the face of a system, the glazing material has a large overall impact. Whether the glazing is clear or cloudy, shiny or dull, flat or bowed, all dramatically affect the appearance of the system. Durability is a critical factor, since the glazing provides the outermost barrier to water, cold air, ultraviolet radiation, and long-term weathering. Finally, the transmittance (both short- and long-wave) of the glazing directly affects the overall efficiency of the system.

Although many factors influence the selection of a proper glazing for a passive system, the choice is not as crucial as for active collectors since the conditions are not as demanding. The temperatures reached by a Trombe wall, for example, are not as high as those by a stagnating active collector since the Trombe wall mass has a moderating effect on peak solar gains. On the other hand, the glazing for a convective loop collector should meet the same requirements as those for active collectors since the thermal mass of the convective loop absorber plate is usually similar to that of active collectors. A stagnating convective loop collector could be expected to reach peak temperatures close to those reached by stagnating active collectors.

The most desirable qualities in a glazing material are 1) resistance to degradation from heat, light, and weather, 2) high transmittance of solar radiation and low transmittance of infra-red or thermal radiation, 3) low cost, 4) ease of handling and fabrication, and 5) attractive appearance.

Glass

Glass is often more expensive than other glazing materials, but when all factors are taken into account, it is a popular choice. Glass can be purchased either tempered or non-tempered. Although non-tempered glass is less expensive, fully-tempered glass is usually preferred due to its greater resistance to breakage; when it does break it produces only tiny fragments instead of dangerous shards.

For high transmittance the recommended glass is the fully-tempered "water white" sheet glass which has a very low iron oxide content (0.01 percent) and thus the highest transmittance (91 percent for all thicknesses). Tempered float glass is less expensive but has a higher iron oxide content (0.12 percent) and a transmittance between 79 percent and 86 percent, depending on the thickness (for this example, between 1/4 inch and 1/8 inch). Various low-iron tempered float glasses are manufactured; one, for example, has an iron content of 0.05 percent and a transmittance that varies between 88 and 89 percent for thicknesses of 3/16 inch to 1/8 inch. As the iron content decreases, the dependence of transmittance on thickness also decreases. Window glass (non-tempered) has a low iron oxide content and a transmittance of 91 percent; however, its use should be limited to low stress applications such as vertical window glazing.

Glass is rigid, attractive, highly durable, and resistant to weathering and chemical and light deterioration. Unfortunately, its high density (weight) makes it difficult to handle.

The price of glass varies significantly depending on the vendor, the location, and the amount purchased. Tempered low-iron sheet glass (water-white) usually has the same retail price as float glass, roughly $2 to $2.50 per square foot. However, the price may be reduced as much as 50 percent when buying in large quantities directly from the manufacturer.

Fiberglass-Reinforced Polyester

Several manufacturers have developed fiberglass-reinforced polyester (FRP) glazing materials that are formulated to resist ultraviolet and thermal degradation. Although FRP glazings appear cloudy, their solar transmittance (84 to 90 percent) is only slightly less than that of low-iron glass.

Some FRP glazings are available in flat sheets or in 4- and 5-foot-wide rolls and in thicknesses of 0.024, 0.040 and 0.060 inches. Most FRP's are easy to cut, drill, and install. However, two problems are often apparent. One is a wavy appearance due to buckling from expansion. These materials have a relatively large coefficient of thermal expansion. The problem may become progressively worse as the material continues to undergo thermal cycling. In order to minimize this problem, at least one manufacturer has developed double-glazed panels where the FRP is "stretched" onto an" aluminum frame. The theory is that since aluminum and the FRP have nearly the same coefficient of thermal expansion, the glazing will be tight regardless of the temperature. These panels reduce but do not entirely eliminate the wavy effect. Some FRP's are available in a corrugated form that also reduces buckling.

The second potential problem relates to thermal degradation at high temperatures. Some FRP's experience losses in transmission of 1 percent, 3 percent, and 11 percent when exposed to temperatures of 150 F, 200 F, and 300 F, respectively, for 300 hours. For most passive applications this will not be a problem, but for some, such as non-vented thermal storage walls, it must be considered seriously.

The FRP glazings are particularly suitable for greenhouse and sunspace applications where the operating temperatures are lower than, for instance, a stagnating Trombe wall. Do-it-yourselfers will appreciate their ease of handling.

Films

Plastic films offer high transmittance and are relatively inexpensive. Although some plastic films have an excellent resistance to temperature, a high coefficient of expansion make them tend to sag at higher temperatures. They can also be difficult to seal and handle, bowing between supports and sticking- to certain surfaces due to a tendency to acquire an electrostatic charge. In addition, they may be relatively transparent to infrared radiation, thus reducing solar collection efficiency.

Embrittlement in some plastic films is caused by direct exposure to ultraviolet radiation, and this effect is tremendously accelerated at higher temperatures. Used at low temperatures, they may last 4 to 5 years before embrittlement is likely to occur. Any hot spots (e.g., near a hot metal support) may embrittle much earlier. Recently developed films are expected to be less susceptible to ultraviolet degradation.

One type of plastic film is often heat-shrunk in order to make it taut and thus improve its appearance and its useful life. As a result of heating, two effects occur. First, upon heating, temporary expansion takes place at a level determined by the coefficient of thermal expansion. Second, as it cools, it shrinks permanently. Because the two effects are opposite, one cannot observe the extent of the shrinkage until the material has cooled. As a result, the shrinkage is often too great, and the tension in the film warps the frame. Perhaps the safest procedure is to not artificially shrink the material but to install it and let the shrinkage occur slowly as a result of normal operating temperatures.

One major disadvantage of all thin plastic films is their significant transmittance of long-wave thermal radiation, between 4 and 2 µm. This reduces efficiency by increasing the heat loss through the glazing. Glass has a transmittance in this region of less than 1 percent, but the transmittance for the films ranges from 17 percent to 57 percent.

Clear Thermoplastics

Rigid plastic glazings have high impact and fracture resistance, ease of handling and fabrication, and attractive appearance. Most of the products can be categorized as either acrylics or polycarbonates.

Acrylics have a slightly higher transmittance than tempered water-white glass and exhibit good resistance to ultraviolet light and weathering. They are usually clear and are as attractive as glass if they are not scratched.

Acrylics do suffer problems at higher temperatures, but, excepting stagnating Trombe walls and convective loop collectors, this should not be a concern for most passive applications. These plastics have a large coefficient of thermal expansion, tending to bow in on the hot side and exerting severe stresses on the glazing supports. This effect can be reduced by employing a mounting detail that allows freedom of movement, but this is at the expense of creating a more critical sealing detail.

Polycarbonates are stronger and can operate at higher temperatures than acrylics, but they have lower transmittance and suffer from ultraviolet degradation (yellowing upon prolonged exposure to the sun). Polycarbonates also have a high coefficient of thermal expansion and tend to bow inward at higher temperatures.

Insulating Panels

Some glazing materials are manufactured in double layer "insulating" panels that consist of a rigid sandwich of two glazing layers with an air space between. The higher initial cost of these components may be offset by the substantial labor savings during installation.

Although a panel using polycarbonate material can be relatively inexpensive, it has the same serious disadvantages of any polycarbonate: ultraviolet degradation, low transmittance, and a large coefficient of thermal expansion. Likewise, panels using acrylics have the disadvantages associated with acrylics: a low melting point and a very large coefficient of thermal expansion.

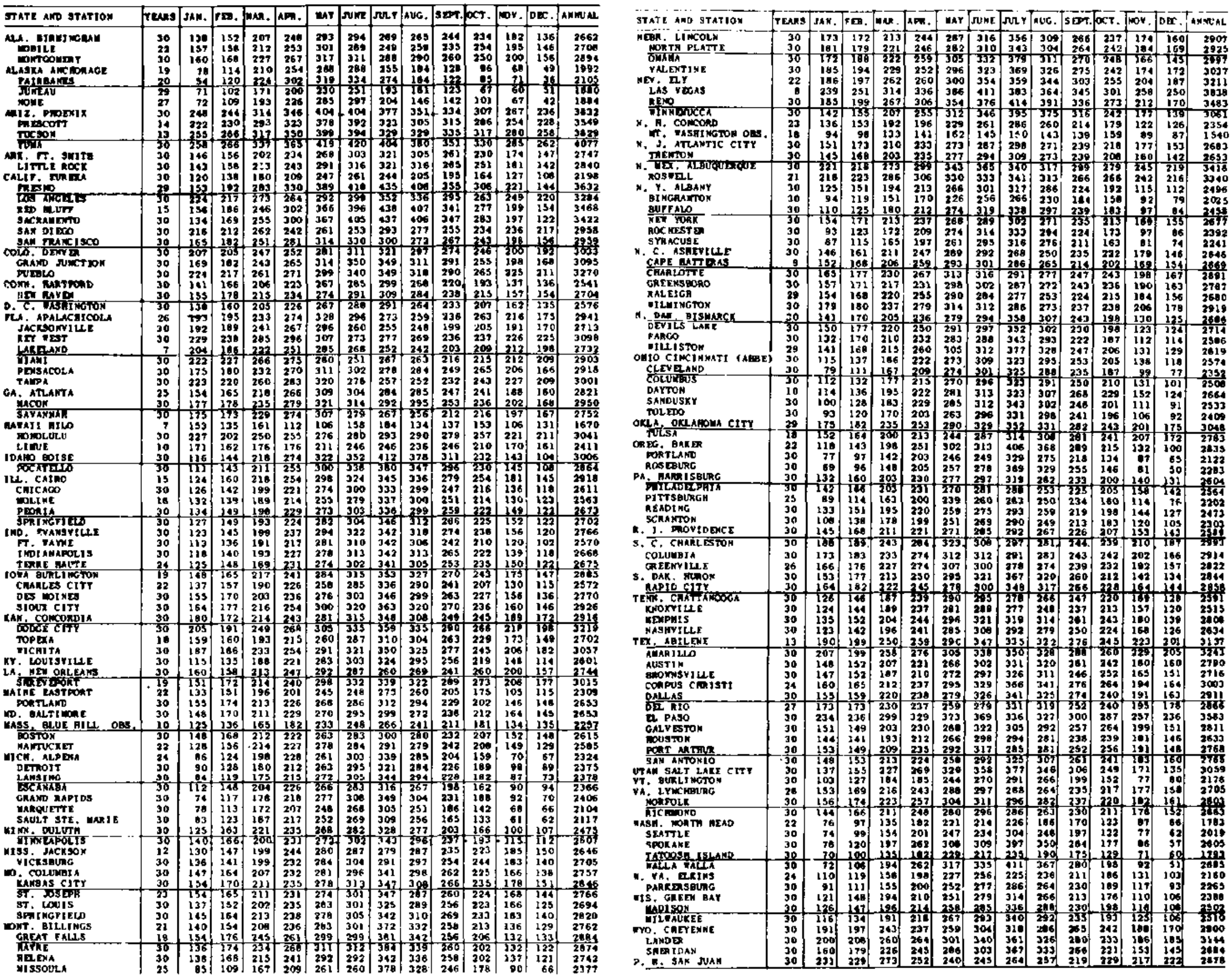
One manufacturer sells double solar glass panels that are designed specifically for solar applications. Two layers of glass are hermetically sealed with a half-inch dessicated air space between. The edges are sealed with a combination of polyisobutylene and silicone caulk and are designed to tolerate high temperatures. If purchased directly from the manufacturer, they are relatively inexpensive.

A serious consideration when using any plastic glazing material in either passive or active systems is the possible fire and fume inhalation dangers. This consideration is particularly important in systems where air is moved from behind the plastic glazing and distributed to the living area.

Appendix 2: Specific Heats and Heat Capacities of Materials (on an equal volume basis).

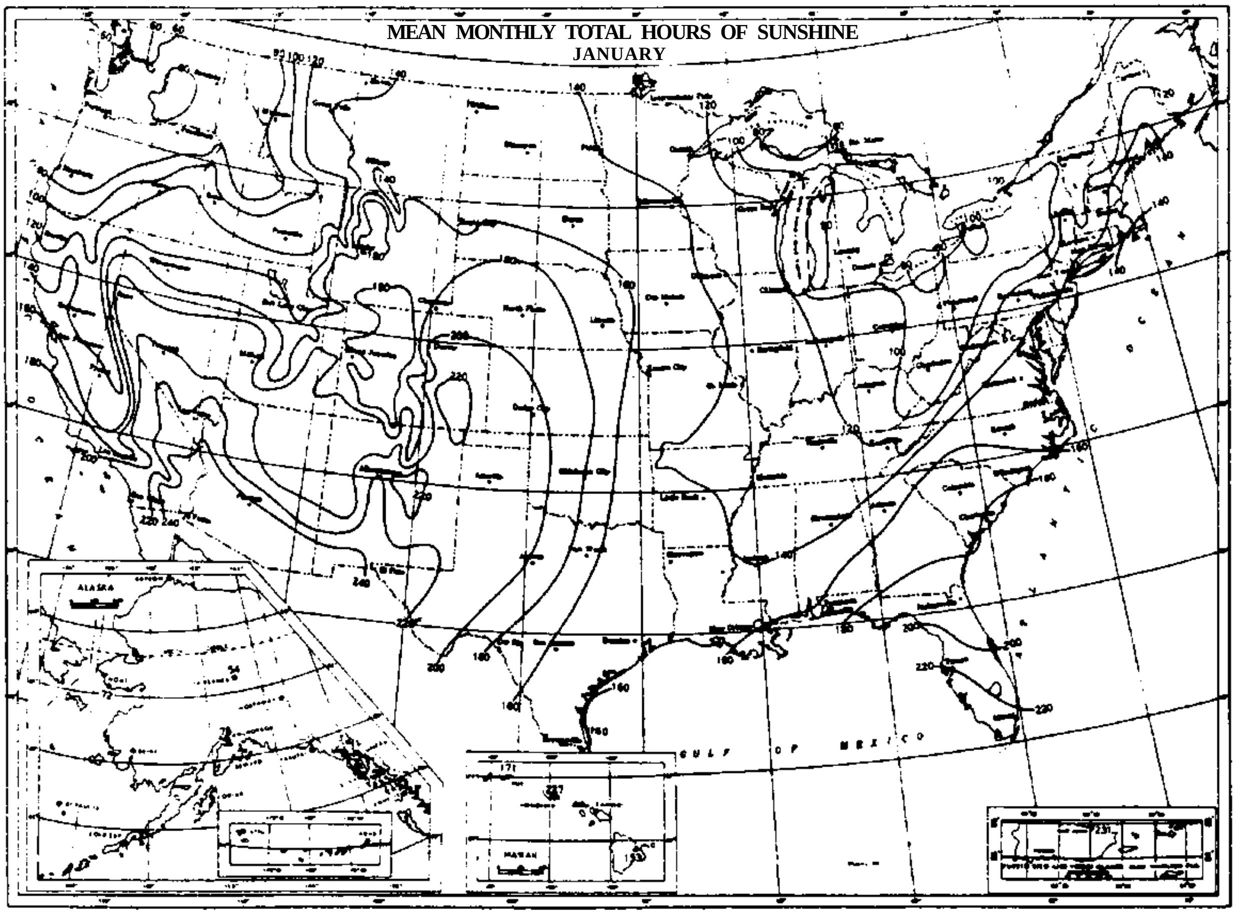
Material	Specific Heat (Btu/lb F)	Density (lb/ft^3)	Heat Capacity (Btu/ft^3 F)
Copper	0.092	556	51.2
Aluminum	0.214	171	36.6
Asphalt	0.22	132	29.0
Glass	0.18	154	27.7
White Oak	0.57	47	26.8
Limestone	0.217	103	22.4
Gypsum	0.26	78	20.3
Sand	0.191	94.6	18.1
White Pine	0.67	27	18.1
White Fir	0.65	27	17.6
Clay	0.22	63	13.9
Air (75 F)	0.24	0.075	0.018
Water	1.00	62.5	62.5
Iron, Scrap	0.112	489	55
Concrete	0.27	140	38
Brick	0.20	140	28
Marble	0.21	180	38

Appendix 3: Mean Number of Hours of Sunshine (AND-1).

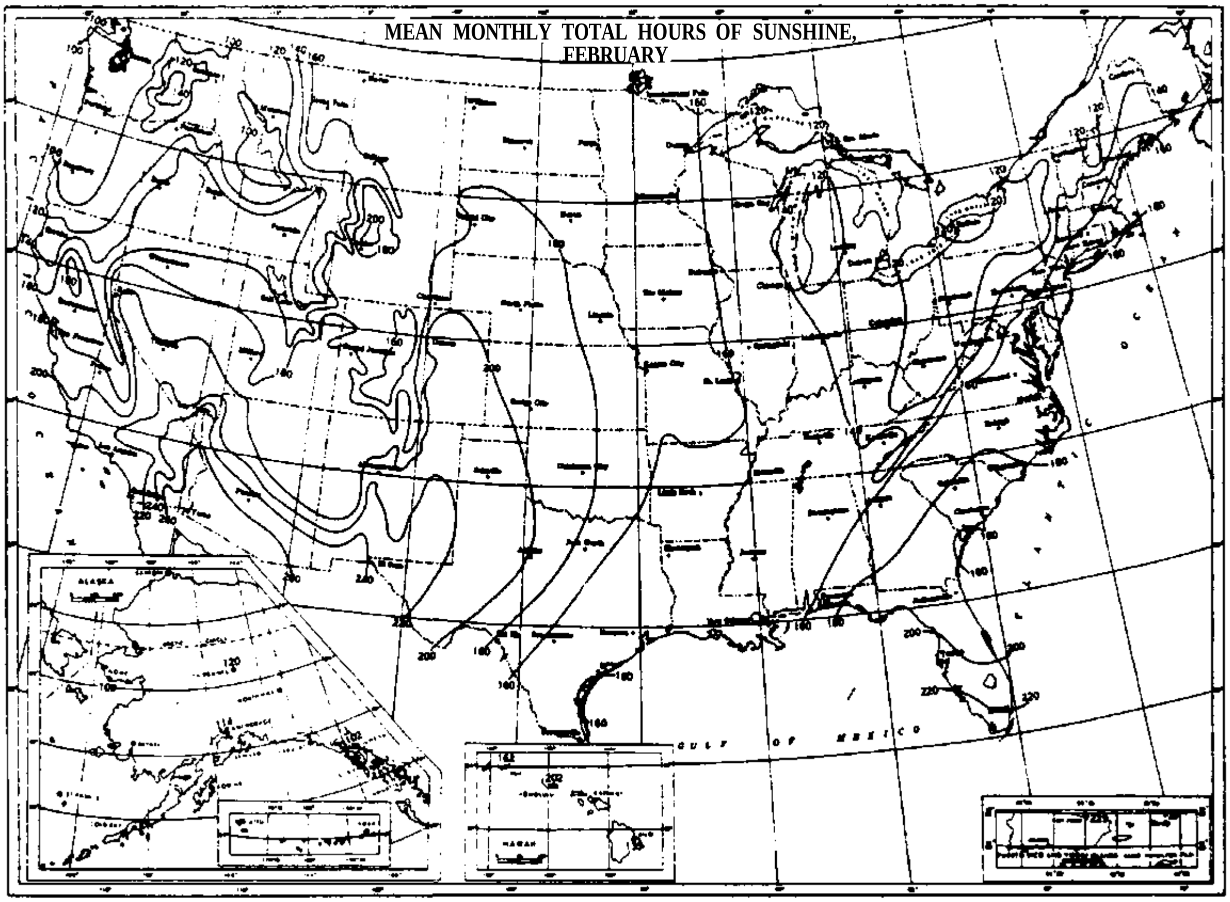


STATE AND STATION	YEARS	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	ANNUAL
ALA. BIRMINGHAM	30	138	152	207	248	293	294	269	265	244	234	182	136	2662
MOBILE	22	157	156	212	253	301	289	249	258	235	234	195	146	2708
MONTGOMERY	30	160	168	227	267	317	311	288	290	260	250	200	156	2894
ALASKA ANCHORAGE	19	78	114	210	254	268	288	255	184	128	86	68	49	1992
FAIRBANKS	20	54	120	224	302	319	334	274	184	122	85	71	36	2105
JUNEAU	29	71	102	171	200	230	251	193	181	123	67	60	31	1680
NOME	27	72	109	193	226	285	297	204	146	142	101	67	42	1884
ARIZ. PHOENIX	30	248	244	314	346	404	404	377	351	334	307	267	236	3832
PRESCOTT	14	222	230	293	323	378	392	323	305	315	286	254	228	3549
TUCSON	13	255	266	317	350	390	394	329	329	335	317	280	258	3829
YUMA	30	258	266	337	365	419	420	404	380	351	330	285	262	4077
ARK. FT. SMITH	30	146	156	202	234	268	303	321	305	261	230	174	147	2747
LITTLE ROCK	30	143	158	213	243	291	316	321	318	265	251	181	142	2840
CALIF. EUREKA	30	120	138	180	208	247	261	244	205	195	164	127	108	2198
FRESNO	29	153	192	283	330	389	418	435	408	355	306	221	144	3632
LOS ANGELES	30	224	217	273	264	292	298	352	336	295	263	249	220	3284
RED BLUFF	15	156	186	246	302	366	396	438	407	341	277	199	154	3468
SACRAMENTO	30	134	169	255	300	367	405	437	406	347	283	197	122	3422
SAN DIEGO	30	216	212	262	242	261	253	293	277	255	234	236	217	2958
SAN FRANCISCO	30	165	182	251	281	314	330	300	272	267	243	198	156	2939
COLO. DENVER	30	207	205	247	252	281	311	321	297	274	246	200	192	3033
GRAND JUNCTION	30	169	182	243	265	314	350	349	311	291	255	198	168	3095
PUEBLO	30	224	217	261	271	299	340	349	318	290	265	225	211	3270
CONN. HARTFORD	30	141	166	206	223	267	285	299	268	220	193	137	136	2541
NEW HAVEN	30	155	178	215	234	274	291	309	284	238	215	157	154	2704
D. C. WASHINGTON	30	138	160	205	226	267	288	291	264	233	207	162	135	2576
FLA. APALACHICOLA	26	193	195	233	274	328	296	273	259	238	263	216	175	2941
JACKSONVILLE	30	192	189	241	267	296	260	255	248	199	205	191	170	2713
KEY WEST	30	229	238	285	296	307	273	277	269	236	237	226	225	3098
LAKELAND	7	204	186	222	251	285	268	252	242	203	209	212	198	2732
MIAMI	30	222	227	266	275	280	251	267	263	216	215	212	209	2903
PENSACOLA	30	175	180	232	270	311	302	278	284	249	265	206	166	2918
TAMPA	30	223	220	260	283	320	276	257	252	232	243	227	209	3001
GA. ATLANTA	25	154	165	218	266	309	304	284	285	247	241	188	160	2821
MACON	30	177	178	235	279	321	314	292	295	253	236	202	168	2950
SAVANNAH	30	175	173	229	274	307	279	267	256	212	216	197	167	2752
HAWAII HILO	7	153	135	161	112	106	158	184	134	137	153	106	131	1670
HONOLULU	30	227	202	250	255	276	280	293	290	279	257	221	211	3041
LIHUE	10	171	162	176	176	211	246	246	236	246	210	170	161	2411
IDAHO BOISE	30	116	144	218	274	322	352	412	378	311	232	143	104	3006
POCATELLO	30	111	143	211	255	300	338	380	347	296	230	145	108	2864
ILL. CAIRO	15	124	160	218	254	298	324	345	336	279	254	181	145	2918
CHICAGO	30	126	142	199	221	274	300	333	299	247	216	136	118	2611
MOLINE	18	132	139	189	214	255	279	337	300	251	214	130	123	2563
PEORIA	30	134	149	198	229	273	303	336	299	259	222	149	122	2673
SPRINGFIELD	30	127	149	193	224	283	304	346	312	286	225	152	122	2702
IND. EVANSVILLE	30	123	145	198	237	294	322	342	318	274	238	156	120	2766
FT. WAYNE	30	113	136	191	217	281	310	342	306	242	210	120	102	2570
INDIANAPOLIS	30	118	140	193	227	278	313	342	313	265	222	139	118	2668
TERRE HAUTE	24	125	148	169	231	274	302	341	305	253	235	150	122	2675
IOWA BURLINGTON	19	148	165	217	241	284	315	353	327	270	243	175	147	2885
CHARLES CITY	22	137	157	190	226	258	285	336	290	241	207	130	115	2572
DES MOINES	30	155	170	203	236	276	303	346	299	263	227	156	136	2770
SIOUX CITY	30	164	177	216	254	300	320	363	320	270	236	160	146	2926
KAN. CONCORDIA	30	180	172	214	243	281	315	348	308	249	245	189	172	2916
DODGE CITY	30	205	191	249	268	305	335	359	335	290	266	218	198	3219
TOPEKA	18	159	160	193	215	260	287	310	304	263	229	173	149	2702
WICHITA	30	187	186	233	254	291	321	350	325	277	245	206	182	3057
KY. LOUISVILLE	30	115	135	188	221	283	303	324	295	256	219	148	114	2801
LA. NEW ORLEANS	30	160	158	213	247	292	287	260	269	241	260	200	157	2744
SHREVEPORT	19	151	172	214	240	298	332	339	322	289	273	208	177	3015
MAINE EASTPORT	22	133	151	196	201	245	248	275	260	205	175	105	115	2309
PORTLAND	30	155	174	213	226	268	286	312	294	229	202	146	148	2653
MD. BALTIMORE	30	148	170	211	229	270	295	299	272	238	212	164	145	2653
MASS. BLUE HILL OBS.	10	125	136	165	182	233	248	266	241	211	181	134	135	2257
BOSTON	30	148	168	212	222	263	283	300	280	232	207	152	148	2615
NANTUCKET	32	128	156	214	227	278	284	291	279	242	208	149	129	2585
MICH. ALPENA	24	86	124	198	228	261	303	339	285	204	159	70	67	2324
DETROIT	30	90	128	180	212	263	295	321	284	226	189	98	89	2375
LANSING	30	84	119	175	215	272	305	344	294	228	182	87	73	2378
ESCANABA	30	112	148	204	226	266	283	316	267	198	162	90	94	2366
GRAND RAPIDS	30	74	117	176	218	277	308	349	304	231	188	92	70	2406
MARQUETTE	30	78	113	172	207	248	268	305	251	186	142	68	66	2104
SAULT STE. MARIE	30	83	123	187	217	252	269	309	256	165	133	61	62	2117
MINN. DULUTH	30	125	163	221	235	268	282	328	277	203	166	100	107	2475
MINNEAPOLIS	30	140	166	200	231	272	302	343	296	237	193	115	112	2607
MISS. JACKSON	12	130	147	199	244	280	287	279	287	235	223	185	150	2646
VICKSBURG	30	136	141	199	232	284	304	291	297	254	244	183	140	2705
MO. COLUMBIA	30	147	164	207	232	281	296	341	298	262	225	166	138	2757
KANSAS CITY	30	154	170	211	235	278	313	347	308	266	235	178	151	2846
ST. JOSEPH	23	154	165	211	231	274	301	347	287	260	224	168	144	2766
ST. LOUIS	30	137	152	202	235	283	301	325	289	256	223	166	125	2694
SPRINGFIELD	30	145	164	213	238	278	305	342	310	269	233	183	140	2820
MONT. BILLINGS	21	140	154	208	236	283	301	372	332	258	213	136	129	2762
GREAT FALLS	18	154	176	245	261	299	299	381	342	256	206	132	133	2884
HAVRE	30	136	174	234	268	311	312	384	339	260	202	132	122	2874
HELENA	30	138	168	215	241	292	292	342	336	258	202	137	121	2742
MISSOULA	25	85	109	167	209	261	260	378	328	246	178	90	66	2377
NEBR. LINCOLN	30	173	172	213	244	287	316	356	309	266	237	174	160	2907
NORTH PLATTE	30	161	179	221	246	282	310	343	304	264	242	184	169	2925
OMAHA	30	172	188	222	259	305	332	379	311	270	248	166	145	2997
VALENTINE	30	185	194	229	252	296	323	369	326	275	242	174	172	3037
NEV. ELY	22	186	197	262	260	300	354	359	344	303	255	204	187	3211
LAS VEGAS	8	239	251	314	336	386	411	383	364	345	301	258	250	3838
RENO	30	185	199	267	306	354	376	414	391	336	273	212	170	3483
WINNEMUCCA	30	142	155	207	255	312	346	395	375	316	242	177	139	3061
N. H. CONCORD	23	136	153	192	196	229	261	286	260	214	179	122	126	2354
MT. WASHINGTON OBS.	18	94	98	133	141	162	145	150	143	138	159	89	87	1540
N. J. ATLANTIC CITY	30	151	173	210	233	273	287	298	271	239	218	177	153	2683
TRENTON	30	145	168	203	235	277	294	309	273	239	208	160	142	2653
N. MEX. ALBUQUERQUE	30	221	218	273	299	343	365	340	317	299	279	245	219	3418
ROSWELL	21	218	223	286	306	330	333	341	313	266	266	242	216	3340
N. Y. ALBANY	30	125	151	194	213	266	301	317	286	224	192	115	112	2496
BINGHAMTON	30	94	119	151	170	226	256	266	230	184	158	92	79	2025
BUFFALO	30	110	125	180	212	274	319	338	297	239	183	97	84	2458
NEW YORK	30	154	171	213	237	268	289	302	271	235	213	169	155	2677
ROCHESTER	30	93	123	172	209	274	314	333	294	224	173	97	86	2392
SYRACUSE	30	87	115	165	197	261	295	316	276	211	163	81	74	2241
N. C. ASHEVILLE	30	146	161	211	247	289	292	268	250	235	232	179	146	2646
CAPE HATTERAS	9	152	168	206	259	293	301	286	265	214	202	169	154	2669
CHARLOTTE	30	165	177	230	267	313	316	291	277	247	243	198	167	2891
GREENSBORO	30	157	171	217	231	298	302	287	272	243	236	190	163	2787
RALEIGH	29	154	168	220	255	290	284	277	253	224	215	184	156	2680
WILMINGTON	30	179	180	237	279	314	312	286	273	237	238	206	178	2919
N. DAK. BISMARCK	30	141	170	205	236	279	294	358	307	243	198	130	125	2686
DEVILS LAKE	30	150	177	220	250	291	297	352	302	230	198	123	124	2714
FARGO	30	132	170	210	232	283	288	343	293	222	187	112	114	2586
WILLISTON	29	141	168	215	260	305	312	377	328	247	206	131	129	2819
OHIO CINCINNATI (ABBE)	30	115	137	186	222	273	309	323	295	253	205	138	118	2574
CLEVELAND	30	79	111	167	209	274	301	325	288	235	187	99	77	2352
COLUMBUS	30	112	132	177	215	270	296	323	291	250	210	131	101	2508
DAYTON	10	114	136	195	222	281	313	323	307	268	229	152	124	2664
SANDUSKY	30	100	128	183	229	285	312	343	302	248	201	111	91	2533
TOLEDO	30	93	120	170	203	263	296	331	298	241	196	106	92	2409
OKLA. OKLAHOMA CITY	29	175	182	235	253	290	329	352	331	282	243	201	175	3048
TULSA	18	152	164	200	213	244	287	314	308	281	241	207	172	2783
OREG. BAKER	22	118	143	198	251	302	313	406	368	289	215	132	100	2835
PORTLAND	30	77	97	142	203	246	249	329	275	218	134	87	65	2122
ROSEBURG	30	69	96	148	205	257	278	369	329	255	146	81	50	2283
PA. HARRISBURG	30	132	160	203	230	277	297	319	282	233	200	140	131	2604
PHILADELPHIA	30	142	166	203	231	270	281	288	253	225	205	158	142	2564
PITTSBURGH	25	89	114	163	200	239	260	283	250	234	180	114	76	2202
READING	30	133	151	195	220	259	275	293	259	219	198	144	127	2473
SCRANTON	30	108	138	178	199	251	269	290	249	213	183	120	105	2303
R. I. PROVIDENCE	30	145	168	211	221	271	285	292	267	226	207	153	143	2589
S. C. CHARLESTON	30	188	189	243	284	323	308	297	281	244	239	210	187	2993
COLUMBIA	30	173	183	233	274	312	312	291	283	243	242	202	166	2914
GREENVILLE	26	166	176	227	274	307	300	278	274	239	232	192	157	2822
S. DAK. HURON	30	153	177	213	250	295	321	367	320	260	212	142	134	2844
RAPID CITY	30	164	182	222	245	278	300	348	317	266	228	164	144	2858
TENN. CHATTANOOGA	30	126	146	187	239	290	295	278	266	247	220	169	128	2591
KNOXVILLE	30	124	144	189	237	281	288	277	248	237	213	157	120	2515
MEMPHIS	30	135	152	204	244	294	321	319	314	281	243	180	139	2808
NASHVILLE	30	123	142	196	241	285	308	292	279	250	224	168	126	2634
TEX. ABILENE	13	190	199	250	259	296	347	335	322	276	245	223	201	3137
AMARILLO	30	207	199	258	276	305	338	350	328	288	260	229	205	3243
AUSTIN	30	148	152	207	231	266	302	331	320	281	242	180	160	2790
BROWNSVILLE	30	147	152	187	210	272	297	326	311	246	252	165	151	2716
CORPUS CHRISTI	24	160	165	212	237	295	329	366	341	276	264	194	164	3003
DALLAS	30	155	159	220	238	279	326	341	325	274	240	191	163	2911
DEL RIO	27	173	173	230	237	259	279	331	319	252	240	195	178	2866
EL PASO	30	234	236	299	329	373	369	336	327	300	287	257	236	3583
GALVESTON	30	151	149	203	230	268	322	305	292	257	264	199	151	2811
HOUSTON	30	144	141	193	212	266	298	294	281	238	239	181	146	2633
PORT ARTHUR	30	153	149	209	235	292	317	285	281	252	256	191	148	2768
SAN ANTONIO	30	148	153	213	224	258	292	325	307	261	241	183	160	2765
UTAH SALT LAKE CITY	30	137	155	227	269	329	358	377	346	306	249	171	135	3059
VT. BURLINGTON	30	103	127	184	185	244	270	291	266	199	152	77	80	2178
VA. LYNCHBURG	28	153	169	216	243	288	297	268	264	235	217	177	158	2705
NORFOLK	30	156	174	223	257	304	311	296	282	237	220	182	161	2803
RICHMOND	30	144	166	211	248	280	296	286	263	230	211	176	152	2663
WASH. NORTH HEAD	22	76	97	135	182	221	214	226	186	170	133	87	66	1783
SEATTLE	30	74	99	154	201	247	234	304	248	197	122	77	62	2019
SPOKANE	30	78	120	197	262	308	309	397	350	264	177	86	57	2605
TATOOSH ISLAND	30	70	100	135	182	229	217	235	190	175	129	71	60	1793
WALLA WALLA	30	72	106	194	262	317	335	411	367	280	198	92	51	2685
W. VA. ELKINS	24	110	119	158	198	227	256	225	238	211	186	131	103	2160
PARKERSBURG	30	91	111	155	200	252	277	286	264	230	189	117	93	2265
WIS. GREEN BAY	30	121	148	194	210	251	279	314	266	213	176	110	106	2388
MADISON	30	126	147	196	214	258	285	336	288	230	198	118	108	2502
MILWAUKEE	30	116	134	191	218	267	293	340	292	235	193	125	106	2510
WYO. CHEYENNE	30	191	197	243	237	259	304	318	286	265	242	188	170	2900
LANDER	30	200	208	260	264	301	340	361	326	280	233	186	185	3144
SHERIDAN	30	160	179	226	245	286	303	367	333	266	221	153	145	2884
P. R. SAN JUAN	30	231	229	273	252	240	245	264	257	219	229	217	222	2878

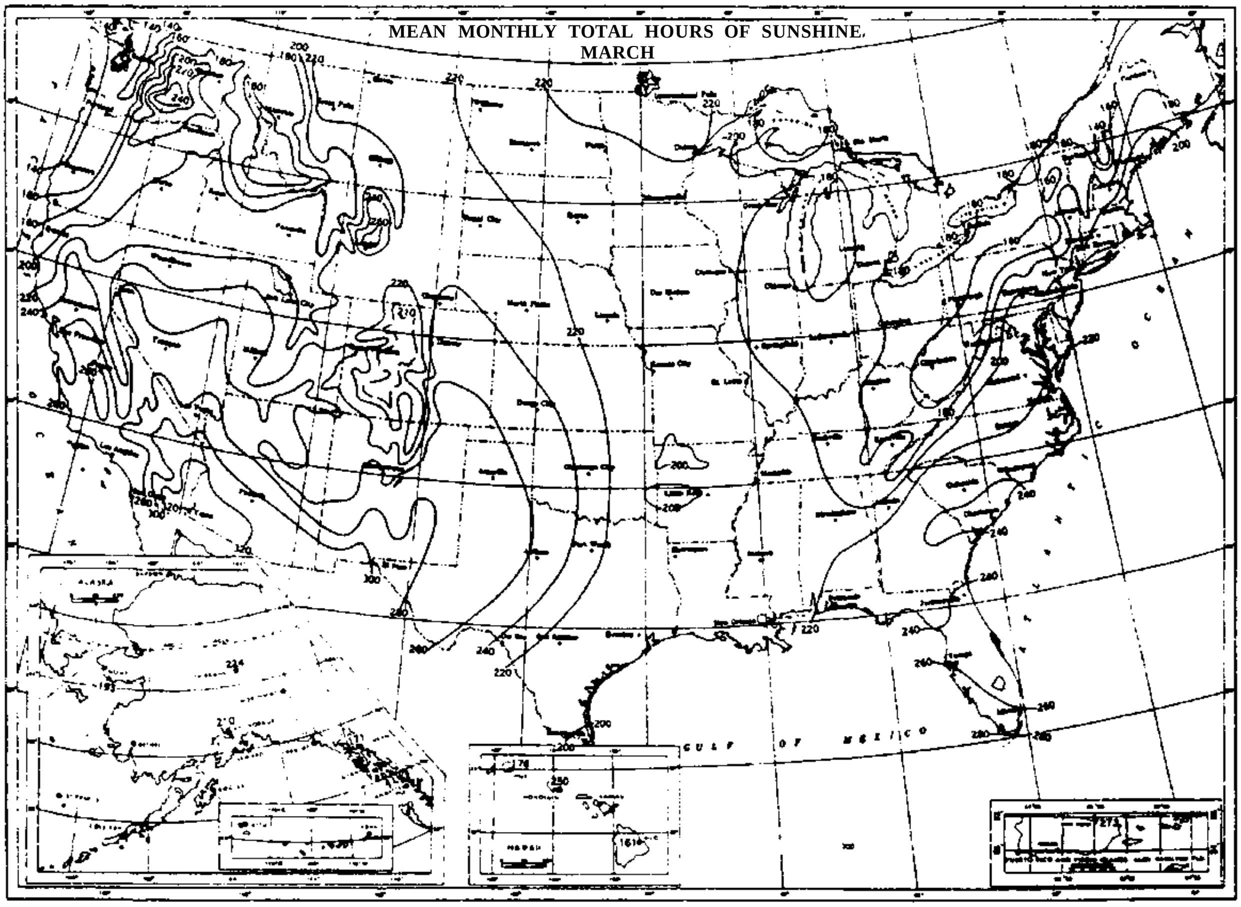
Appendix 4: Mean Monthly Total Hours of Sunshine Map - January (USD)



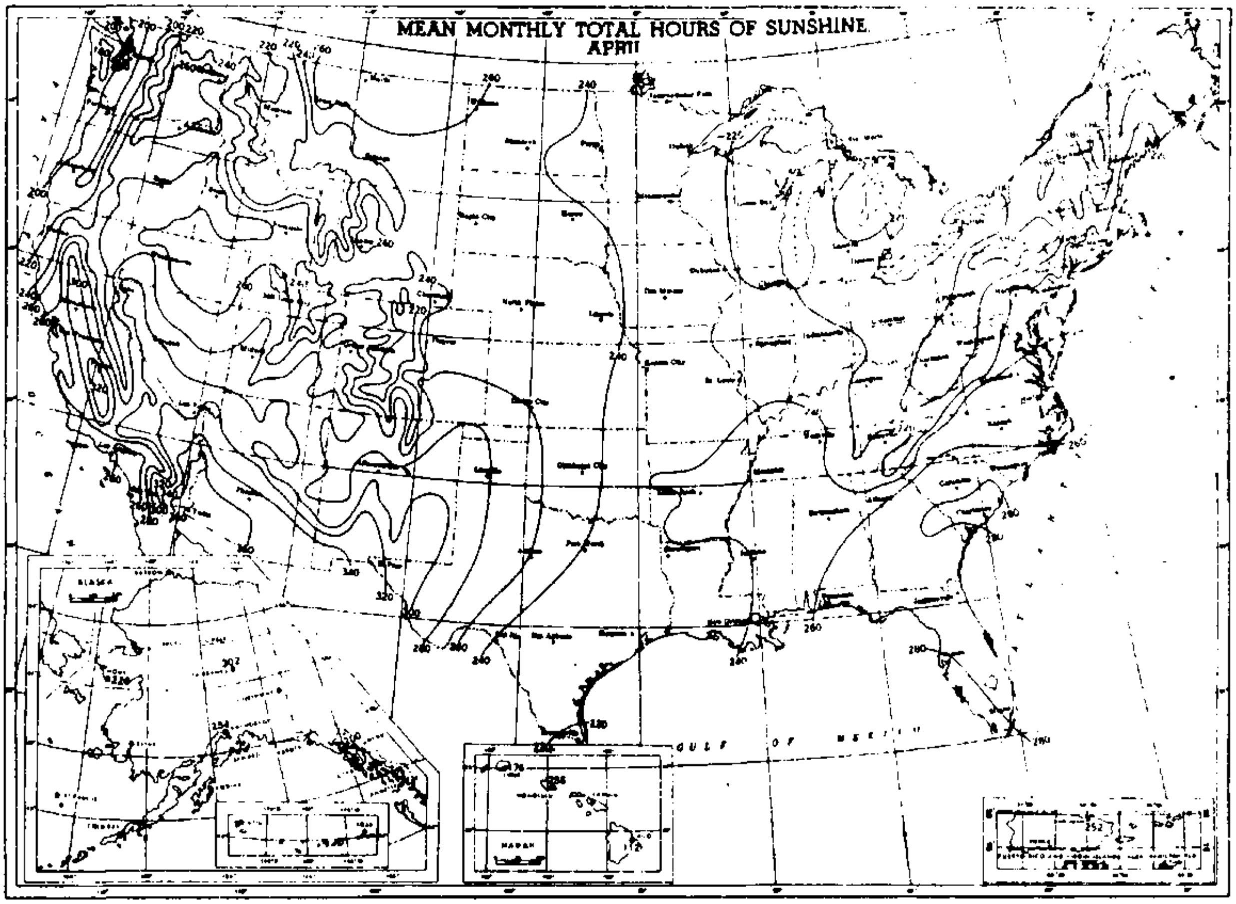
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine Map - February



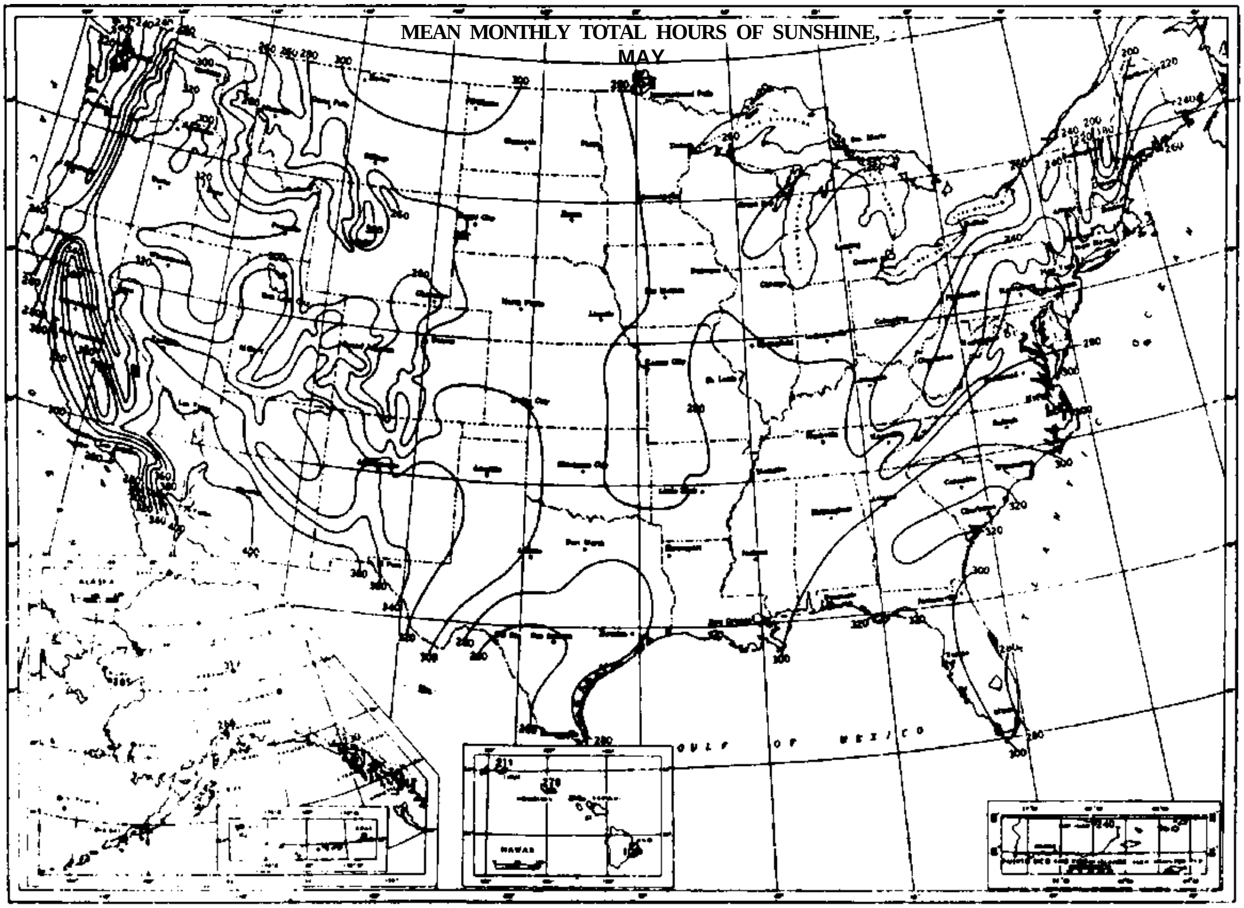
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine Map - March



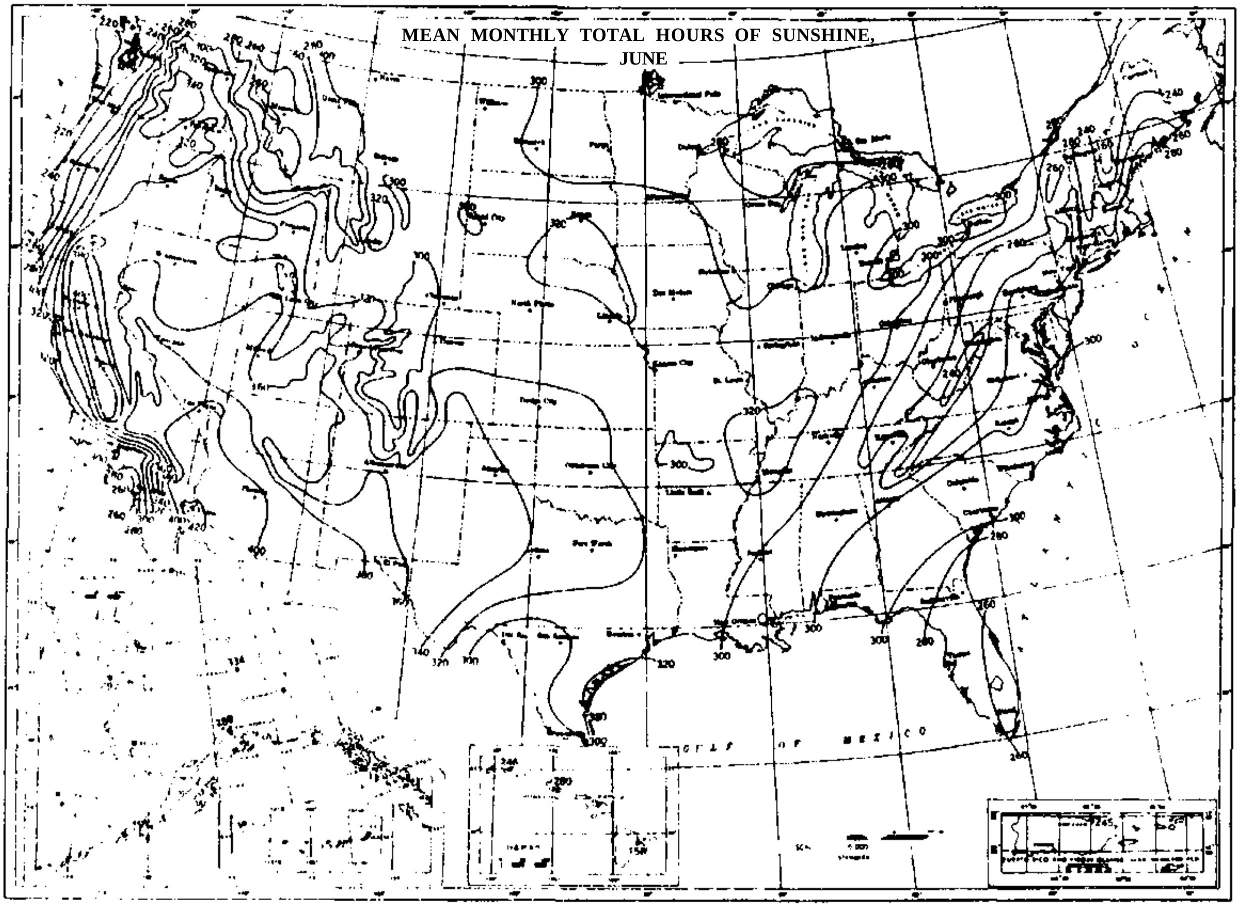
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine Map - April



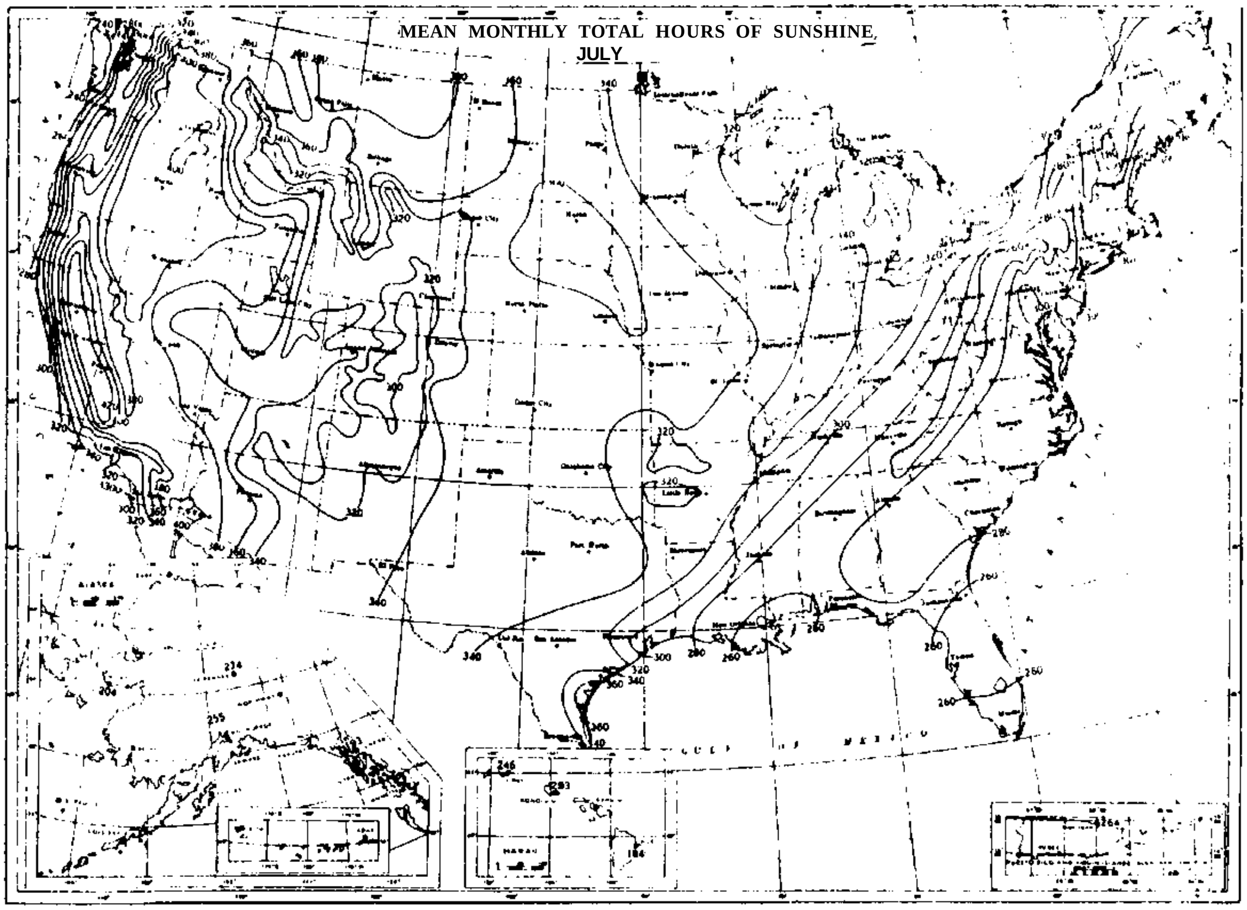
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine Map - May



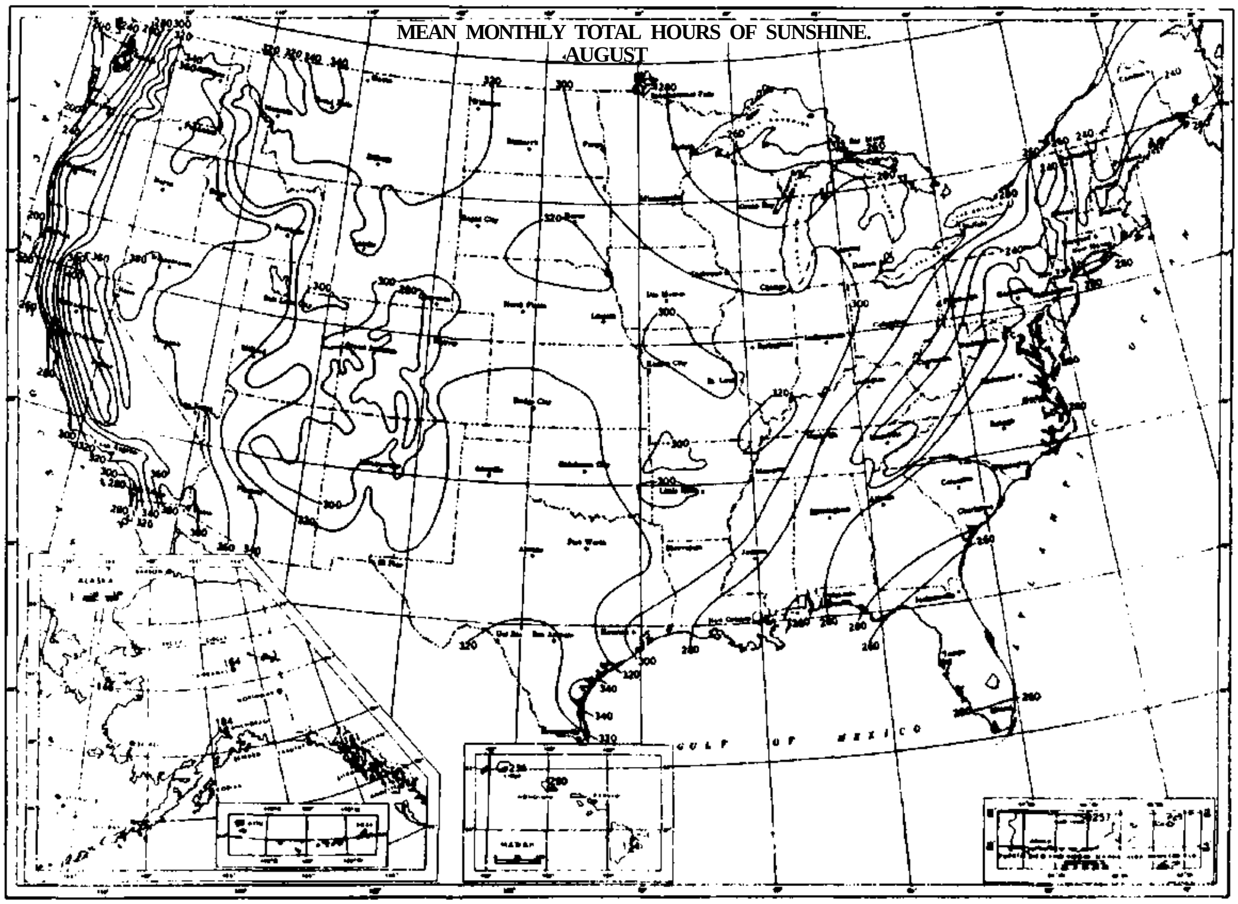
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine Map - June



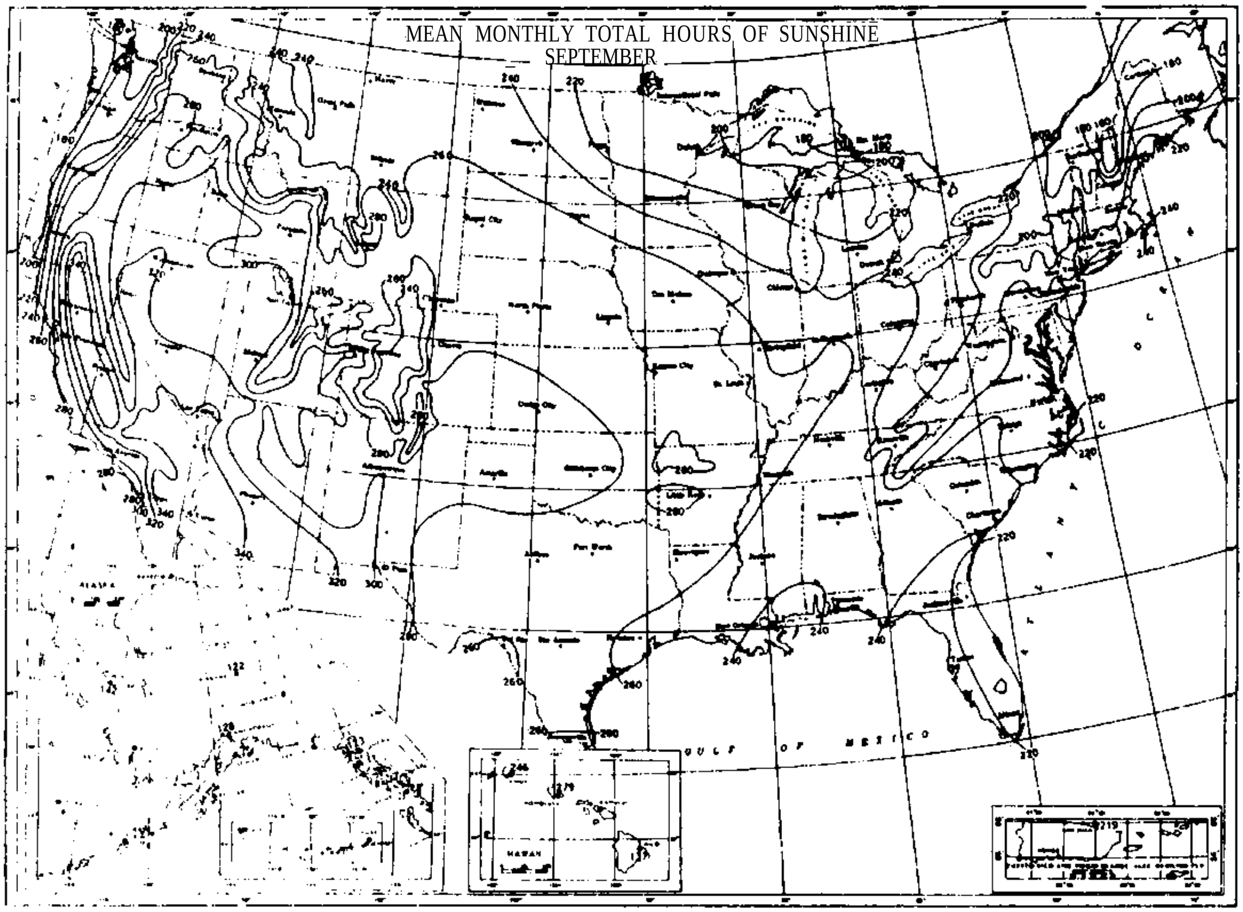
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine - July



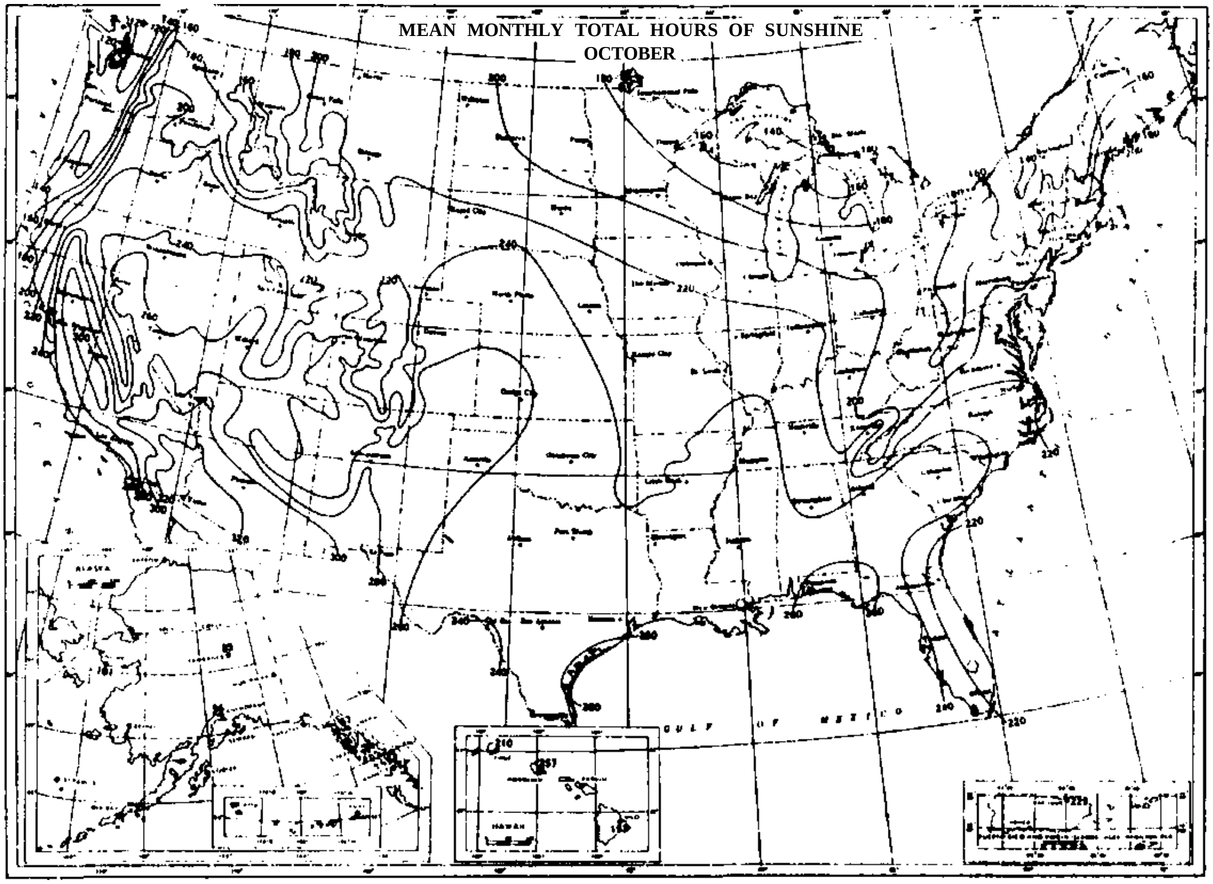
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine - August



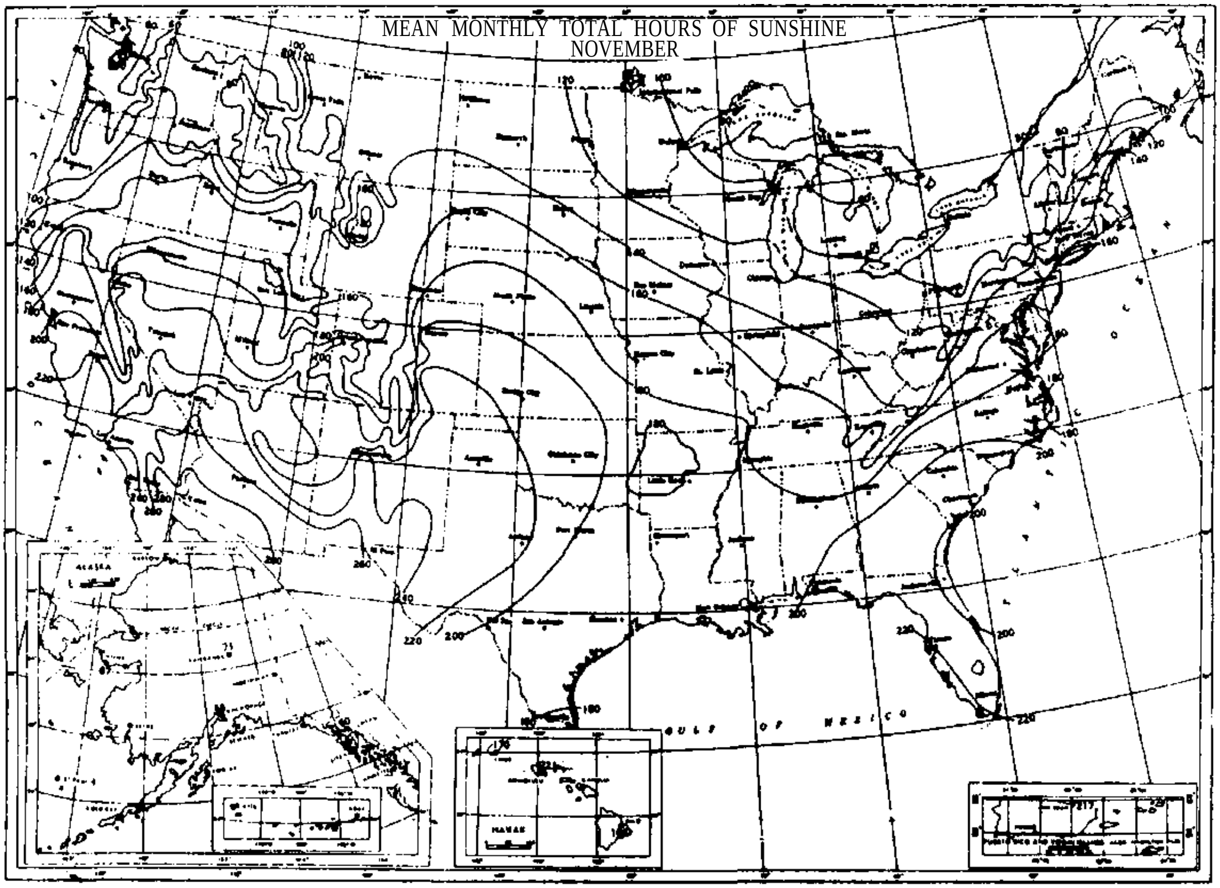
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine - September



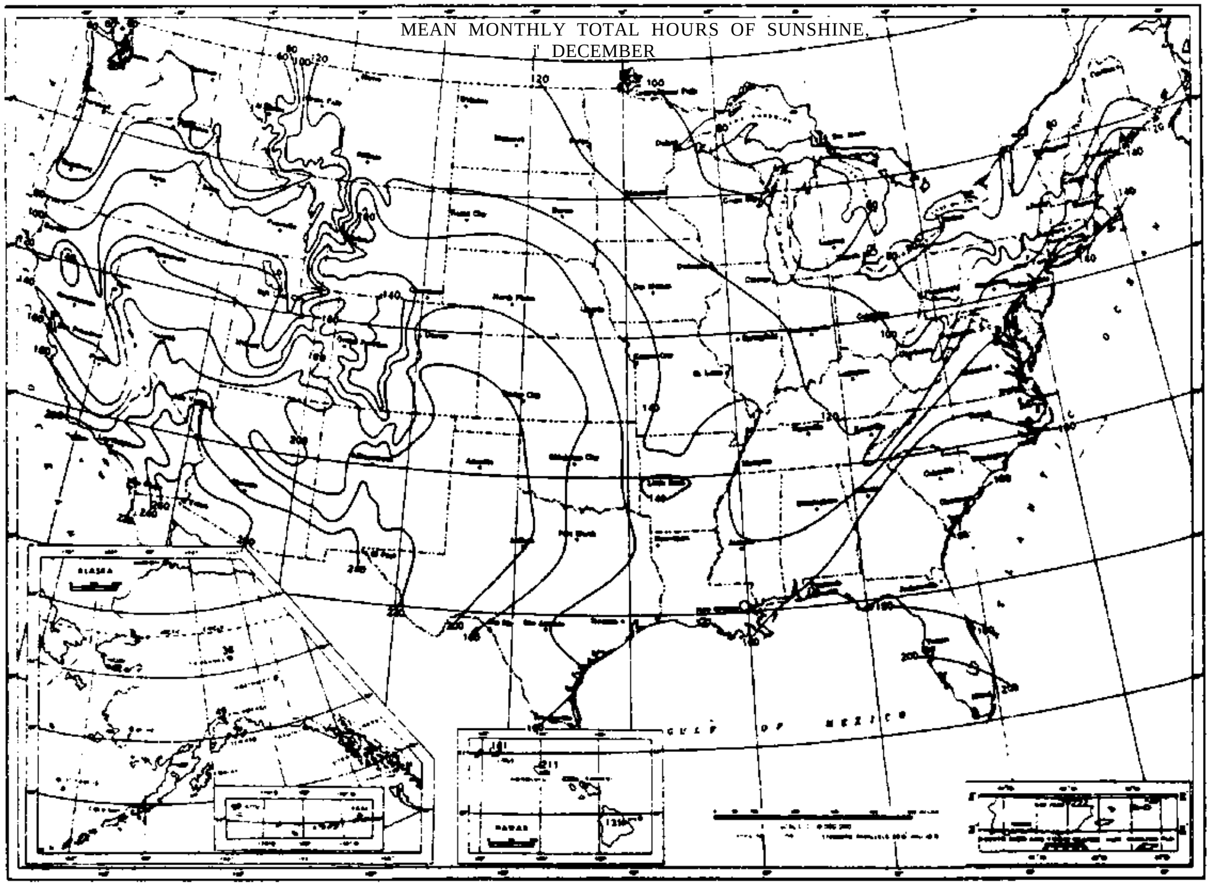
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine - October



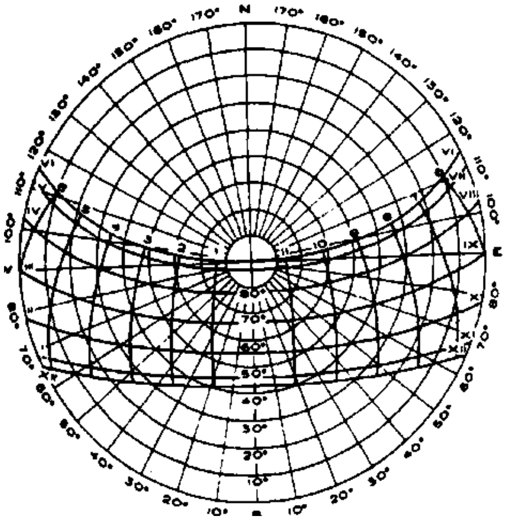
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine - November



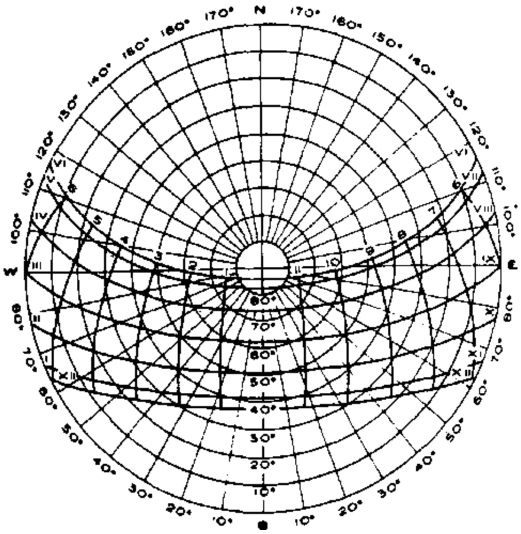
Appendix 4, cont'd.: Mean Monthly Total Hours of Sunshine - December



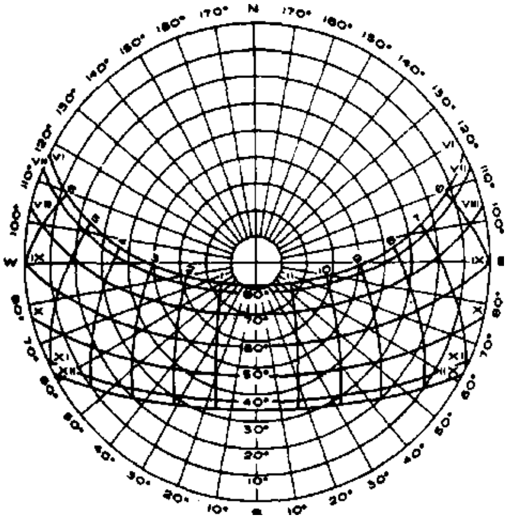
Appendix 5: Sun Path Diagrams (RAM)



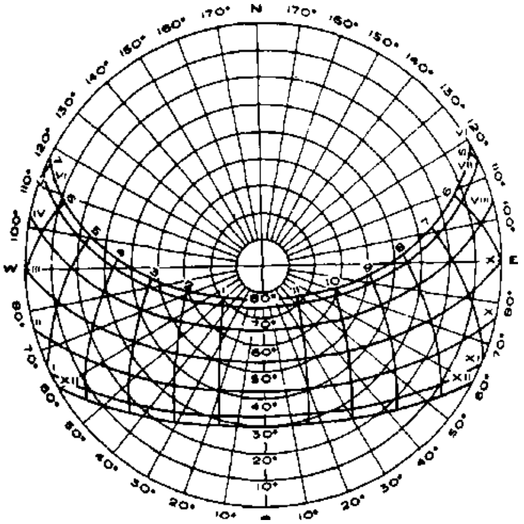
24 degrees N latitude



28 degrees N latitude

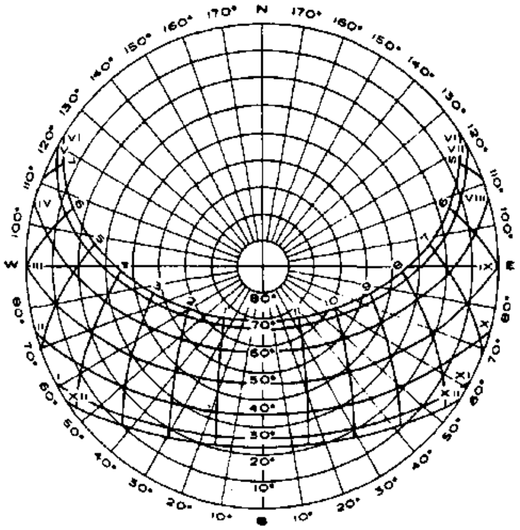


32 degrees N latitude

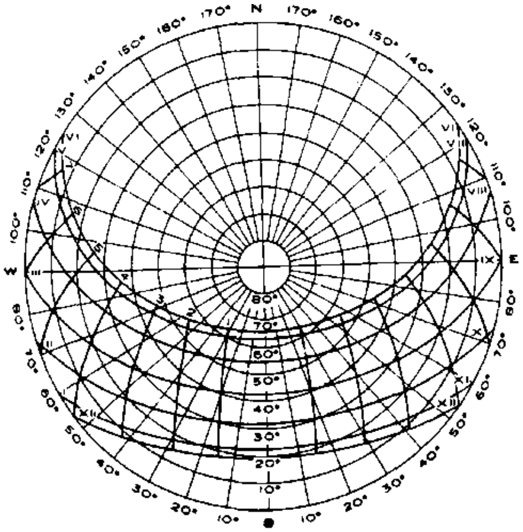


36 degrees N latitude

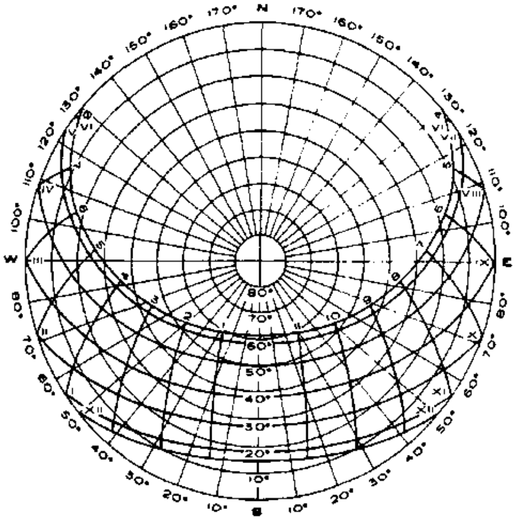
Sun Path Diagrams, cont'd.



44 degrees N latitude



48 degrees N latitude



52 degrees N latitude

Appendix 6: Conversion Factors

1 Btu = 1.05506 kJ
1 Btu/lb F = 4.1868 kJ/kg °C
1 Btu/hr = 0.293 W
1 Btu/hr ft^2 F = 5.678 W/m^2 °C
1 Btu/hr ft F = 1.731 W/m °C
1 cfm = 0.471947 liter/s
1 ft = 0.3048 m
1 ft/min = 0.000508 m/s
1ft^2 = 0.0929 m^2
1ft^3 = 28.3168 liters
1 hp = 0.7457 kW
1 in H_2O =249.089, liters
1 kWh = 3.6 MJ
1 lb = 0.453592 kg
1 mile/hr = 0.44704 m/s
1 psi = 6.89476 kPa
1 U.S. gal = 3.78544 liters

1ft^3 = 7.48 gal
1 foot of water = 0.4335 psi
1 foot of water = 0.88265 in of Hg
1 gallon of water = 8.3453 lb
1 kWh = 3413 Btu
1 therm = 100,000 Btu
1 ton of refrigeration = 12,000 Btu

Appendix 7: Cost of Energy (AND-1)

The following chart helps calculate the actual cost of providing heat. It converts the unit price of the energy source — whether gas, oil, or electricity — into the cost per million Btu produced inside the building,

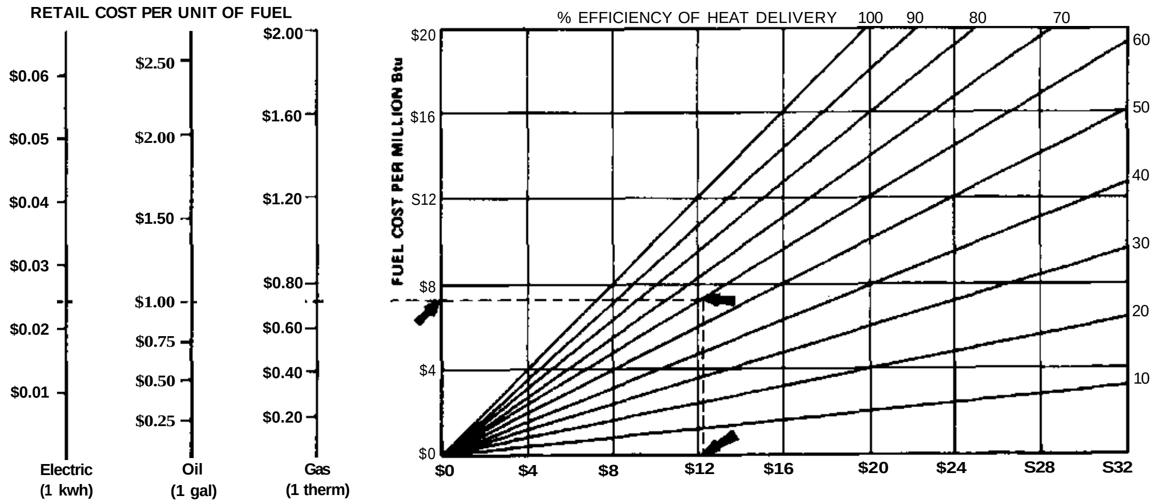
Typically, only 50 to 75 percent of the heat content of gas or oil is delivered inside the building. The rest goes up the chimney. Electrical resistance heating is 100 percent efficient.

1) Find the point on the appropriate vertical scale that corresponds to the retail price of the fuel — for example, oil at $1.00/ gallon (or equivalently, electricity at $0.025/kWh and gas at $0.74/therm);

2) Move right to find the retail cost for 1 million Btu of that fuel, or $7.40;

3) Continue right to intersect the oblique line representing the efficiency of heat delivery, or 60 percent in this case;

4) Drop down to find the actual cost per million Btu of heat produced, or $12.35.



Appendix 8: Thermal Performance Values for Materials, Air Spaces, and Windows (ASH-1)

R-VALUES OF BUILDING MATERIALS

Material and Description		Density (lb/ft³)	R-value*	
			per inch thickness	for listed thickness
Building Boards, Panels, Flooring				
Asbestos-cement board		120	0.25	–
Asbestos-cement board	1/8"	120	–	0.03
Gypsum or plaster board	3/8"	50	–	0.32
Gypsum or plaster board	1/2"	50	–	0.45
Plywood (see Siding Materials)		34	1.25	–
Sheathing, wood fiber (impregnated or coated)	25/32"	20	–	2.06
Wood fiber board (laminated or homogenous)		26	2.38	–
Wood fiber, hardboard type		65	0.72	–
Wood fiber, hardboard type	1/4"	65	–	0.18
Wood subfloor	25/32"	–	–	0.98
Wood, hardwood finish	3/4"	–	–	0.68
Building Paper				
Vapor-permeable felt		–	–	0.06
Vapor-seal, 2 layers of mopped 15 lb felt		–	–	0.12
Vapor-seal plastic film		–	–	negl.
Finish Materials				
Carpet and fibrous pad		–	–	2.08
Carpet and rubber pad		–	–	1.23
Cork tile	1/8"	–	–	0.28
Terrazzo	1"	–	–	0.08
Tile (asphalt, linoleum, vinyl, rubber)		–	–	0.05
Gypsumboard	1/2"	–	–	0.45
Gypsumboard	5/8"	–	–	0.56
Hardwood flooring	25/32"	–	–	0.68
Insulating Materials				
Blankets and Batts:				
Mineral wool, fibrous form (from rock, slag or glass)		0.5	3.12	–
		1.5-4.0	3.70	–
Wood fiber		3.2-3.6	4.00	–
Boards and Slabs:				
Cellular glass	90°F	9	2.44	–

R-VALUES OF BUILDING MATERIALS

Material and Description		Density (lb/ft³)	R-value*	
			per inch thickness	for listed thickness
	60°F		2.56	–
	30°F		2.70	–
	0°F		2.86	–
Corkboard	90°F	6.5-8.0	3.57	–
	60°F		3.70	–
	30°F		3.85	–
	0°F		4.00	–
	90°F	12	3.22	–
	60°F		3.33	–
	30°F		3.45	–
	0°F		3.57	–
Glass fiber	90°F	4.0-9.0	3.85	–
	60°F		4.17	–
	30°F		4.55	–
	0°F		4.76	–
Expanded rubber (rigid)	75°F	4.5	4.55	–
Expanded polyurethane (R-11 blown; 1" thickness or more)	100°F	1.5-2.5	5.56	–
	75°F		5.88	–
	50°F		6.25	–
	25°F		5.88	–
	0°F		5.88	–
Expanded polystyrene, extruded	75°F	1.9	3.85	–
	60°F		4.00	–
	30°F		4.17	–
	0°F		4.55	–
Expanded polystyrene, molded beads	75°F	1.0	3.57	–
	30°F		3.85	–
	0°F		4.17	–
Mineral fiberboard, felted				
core or roof insulation		16-17	2.94	–
acoustical tile[1]		18	2.86	–
acoustical tile[1]		21	2.73	–
Mineral fiberboard, molded acoustical tile[1]		23	2.38	–
Wood or cane fiberboard				
acoustical tile	1/2"	–	–	1.19
acoustical tile	3/4"	–	–	1.78
interior finish		15	2.86	–

R-VALUES OF BUILDING MATERIALS

Material and Description		Density (lb/ft^3)	R-value*	
			per inch thickness	for listed thickness
Insulating roof deck[2]	1"	–	–	2.78
	2"	–	–	5.56
	3"	–	–	8.33
Shredded wood (cemented, preformed slabs)		22	1.67	–
Loose Fills:				
Macerated paper or pulp		2.5-3.5	3.57	–
Mineral wool	90°F	2.0-5.0	3.33	–
	60°F		3.70	–
	30°F		4.00	–
	0°F		4.35	–
Perlite (expanded)	90°F	5.0-8.0	2.63	–
	60°F		2.78	–
	30°F		2.94	–
	0°F		3.12	–
Vermiculite (expanded)	90°F	7.0-8.2	2.08	–
	60°F		2.18	–
	30°F		2.27	–
	0°F		2.38	–
Sawdust or shavings		0.8-15	2.22	–
Masonry Materials–Concretes				
Cement mortar		116	0.20	–
Gypsum-fiber concrete (87½% gypsum, 12½% concrete)		51	0.60	–
Lightweight aggregates		120	0.19	–
(expanded shale, clay or slate;		100	0.28	–
expanded slags, or cinders;		80	0.40	–
pumice; perlite or vermiculite;		60	0.59	–
cellular concretes)		40	0.86	–
		20	1.43	–
Sand and gravel or stone aggregate (oven dried)		140	0.11	–
Sand and gravel or stone aggregate (not dried)		140	0.08	–
Stucco		116	0.20	–
Masonry Units				
Brick, common[3]		120	0.20	–
Brick, face[3]		130	0.11	–

R-VALUES OF BUILDING MATERIALS

Material and Description		Density (lb/ft^3)	R-value*	
			per inch thickness	for listed thickness
Clay tile, hollow				
1 cell deep	3"	–	–	0.80
1 cell deep	4"	–	–	1.11
2 cells deep	6"	–	–	1.52
2 cells deep	8"	–	–	1.85
3 cells deep	10"	–	–	2.22
3 cells deep	12"	–	–	2.50
Concrete block, 3 oval core				
Sand and gravel aggregate	4"	–	–	0.71
	8"	–	–	1.11
	12"	–	–	1.28
Cinder aggregate	3"	–	–	0.86
	4"	–	–	1.11
	8"	–	–	1.72
	12"	–	–	1.89
Lightweight aggregate	3"	–	–	1.27
(expanded shale, clay	4"	–	–	1.50
slate or slag; pumice)	8"	–	–	2.00
	12"	–	–	2.72
Concrete blocks, rectangular core				
Sand and gravel aggregate				
2 core, 36 lb[4]	8"	–	–	1.04
same, filled cores[5]		–	–	1.93
Lightweight aggregates				
3 core, 19 lb[4]	6"	–	–	1.65
same, filled cores[5]		–	–	2.99
2 core, 24 lb[4]	8"	–	–	2.18
same, filled cores[5]		–	–	5.03
3 core, 38 lb[4]	12"	–	–	2.48
same, filled cores[5]		–	–	5.82
Stone, lime or sand		–	0.08	–
Granite, marble		150-175	0.05	–
Plastering Materials				
Cement plaster, sand aggregate		116	0.20	–
Gypsum plaster				
Lightweight aggregate	1/2"	45	–	0.32
Lightweight aggregate	3/8"	45	–	0.39
Same, on metal lath	3/4"	–	–	0.47
Perlite aggregate		45	0.67	–
Sand aggregate		105	0.18	–

R-VALUES OF BUILDING MATERIALS

Material and Description		Density (lb/ft^3)	R-value* per inch thickness	R-value* for listed thickness
Same, on metal lath	3/4"	–	–	0.10
Same, on wood lath	3/4"	–	–	0.40
Vermiculite aggregate		45	0.59	–
Roofing Materials				
Asbestos-cement shingles		120	–	0.21
Asphalt roll roofing		70	–	0.15
Built-up roofing	3/8"	70	–	0.44
Slate roofing	1/2"	–	–	0.05
Wood shingles		–	–	0.94
Siding Materials				
Shingles				
Asbestos-cement		120	–	0.21
Wood, 16" with 7½" exposure		–	–	0.80
Wood, double 16" with 12" exposure		–	–	1.19
Wood, plus insulating backer board	5/16"	–	–	1.40
Siding				
Asbestos-cement lapped	1/4"	–	–	0.21
Asphalt roll siding		–	–	0.15
Asphalt insulating siding	1/2"	–	–	1.46
Wood, drop (1" X 8")		–	–	0.79
Wood, drop (½" X 8" lapped)		–	–	0.81
Wood, bevel (¾" X 10", lapped)		–	–	1.05
Plywood, lapped	3/8"	–	–	0.59
Plywood	1/4"	–	–	0.31
	3/8"	–	–	0.47
	1/2"	–	–	0.62
	5/8"	–	–	0.78
	3/4"	–	–	0.94
Stucco		116	0.20	–
Sheathing, insulating board	1/2"	–	–	1.32
(regular density)	25/32"	–	–	2.04
Woods				
Hardwoods (maple, oak)		45	0.91	–
Softwoods (fir, pine)		32	1.25	–

R-VALUES OF BUILDING MATERIALS

Material and Description		Density (lb/ft^3)	R-value* per inch thickness	R-value* for listed thickness
	25/32"	32	–	0.98
	1–5/8"	32	–	2.03
	2–5/8"	32	–	3.28
	3–5/8"	32	–	4.55
Wood Doors				
Solid core	1"	–	–	1.56
	1–1/4"	–	–	1.82
	1–1/2"	–	–	2.04
	2"	–	–	2.33

*Representative values intended for use as design values of dry building materials in normal use.

[1] R-values of acoustical tile depend upon the board and the type, size and depth of perforations; these are average values.

[2] Roof deck insulation is made in thicknesses to meet these standards; thickness may vary somewhat with manufacturer.

[3] Face brick and common brick do not always have these densities and R-values.

[4] Weights of blocks approximately 7–5/8" high by 15–3/8" long.

[5] Vermiculite, perlite, or mineral wool insulation.

SOURCE: ASHRAE *Handbook of Fundamentals*. 1967. Reprinted by permission.

R-VALUES OF AIR FILMS

Type and Orientation of Air Film	Direction of Heat Flow	R-value for Air Film On: Non-reflective surface	R-value for Air Film On: Fairly reflective surface	R-value for Air Film On: Highly reflective surface
Still air:				
Horizontal	up	0.61	1.10	1.32
Horizontal	down	0.92	2.70	4.55
45° slope	up	0.62	1.14	1.37
45° slope	down	0.76	1.67	2.22
Vertical	across	0.68	1.35	1.70
Moving air:				
15 mph wind	any*	0.17	–	–
7½ mph wind	any†	0.25	–	–

*Winter conditions.

†Summer conditions.

SOURCE: ASHRAE, *Handbook of Fundamentals*, 1972. Reprinted by permission.

R-VALUES OF AIR SPACES

Orientation & Thickness of Air Space		Direction of Heat Flow	R-value for Air Space Facing:‡		
			Non-reflective surface	Fairly reflective surface	Highly reflective surface
Horizontal	¾"	up*	0.87	1.71	2.23
	[illegible]"		0.94	1.99	2.73
	¾"	up†	0.76	1.63	2.26
	4"		0.80	1.87	2.75
	¾"	down*	1.02	2.39	3.55
	1½"		1.14	3.21	5.74
	4"		1.23	4.02	8.94
	¾	down†	0.84	2.08	3.25
	1½"		0.93	2.76	5.24
	4"		0.99	3.38	8.03
45° slope	¾"	up*	0.94	2.02	2.78
	4"		0.96	2.13	3.00
	¾"	up†	0.81	1.90	2.81
	4"		0.82	1.98	3.00
	¾"	down*	1.02	2.40	3.57
	4"		1.08	2.75	4.41
	¾"	down†	0.84	2.09	3.34
	4"		0.90	2.50	4.36
Vertical	¾"	across*	1.01	2.36	3.48
	4"		1.01	2.34	3.45
	¾"	across†	0.84	2.10	3.28
	4"		0.91	2.16	3.44

‡One side of the air space is a non-reflective surface.

*Winter conditions.

†Summer conditions.

SOURCE: ASHRAE, *Handbook of Fundamentals*, 1972. Reprinted by permission.

U-VALUES OF WINDOWS AND SKYLIGHTS

Description	U-values[1]	
	Winter	Summer
Vertical panels:		
Single pane flat glass	1.13	1.06
Insulating glass—double[2]		
3/16" air space	0.69	0.64
1/4" air space	0.65	0.61
1/2" air space	0.58	0.56
Insulating glass—triple[2]		
1/4" air spaces	0.47	0.45
1/2" air spaces	0.36	0.35
Storm windows		
1-4" air space	0.56	0.54
Glass blocks[3]		
6 X 6 X 4" thick	0.60	0.57
8 X 8 X 4" thick	0.56	0.54
same, with cavity divider	0.48	0.46
Single plastic sheet	1.09	1.00
Horizontal panels:[4]		
Single pane flat glass	1.22	0.83
Insulating glass—double[2]		
3/16" air space	0.75	0.49
1/4" air space	0.70	0.46
1/2" air space	0.66	0.44
Glass blocks[3]		
11 X 11 X 3" thick, with cavity divider	0.53	0.35
12 X 12 X 4" thick, with cavity divider	0.51	0.34
Plastic bubbles[5]		
single-walled	1.15	0.80
double-walled	0,70	0.46

[1] in units of $\text{Btu/hr/ft}^2/^\circ\text{F}$

[2] double-and triple refer to the number of lights of glass.

[3] nominal dimensions.

[4] U-values for horizontal panels are for heat flow *up* in winter and *down* in summer.

[5] based on area of opening, not surface.

SOURCE: ASHRAE, *Handbook of Fundamentals*, 1972. Reprinted by permission.

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