Reference Note 47

Passive Solar Heating Design

Passive solar heating is the direct use of sunlight for space heating. The concept is simple, but creating a successful installation may be complex. Passive solar heating is not a concept for casual experimentation, because failure is almost certain to leave a big mess. In general, the larger the fraction of the building's heating that is provided by passive solar, the more complex the design must be to avoid adverse effects.

Passive heating should include daylighting wherever possible, since both involve the controlled intake of solar energy through glazing. However, combining the two is not easy.

Passive solar heating is a broad concept. The following discussion presents the general principles. Use them as a basis for developing specific applications.

System Components

Figure 1 shows the basic conceptual scheme of a passive solar installation, which includes these components:

- large glazing units, to collect the thinly concentrated energy of sunlight
- variable shading devices, to control solar input
- removable glazing insulation, to limit heat loss during darkness
- devices to absorb sunlight and emit heat at desired locations within the space
- thermal storage mass, to provide heating during periods of darkness
- shading devices to control the flow of sunlight into the storage mass
- adjustable insulation, to control the flow of heat from the storage mass
- light diffusion and distribution devices, to make the incoming sunlight suitable for illumination as well as for heating.

This description is conceptual. Probably no real system would have all these elements. For example, it is simpler to control the release of heat from the thermal storage mass by exploiting the inherent time lag of the material, rather than by using adjustable insulation.

The term "passive" implies the absence of moving parts. However, Figure 1 shows that a passive system may require moving parts. These are potentially the most troublesome part of the system. These components are not presently available as standard equipment, and it may be difficult to fabricate them for many installations. The future evolution of passive solar depends largely on eliminating custom components. This will reduce cost, simplify design, and improve reliability.

Figure 2 shows a rationally designed passive solar installation for a house. It makes an interesting contrast with the comprehensive system depicted in Figure 1.

Comparison between Active and Passive Solar

Active and passive solar systems have almost nothing in common, except for the advantage of collecting free solar energy. Active solar systems are primarily mechanical systems, which have architectural ramifications. Passive solar is primarily an architectural feature, which must be tightly integrated with the building's mechanical systems. Table 1 summarizes the main areas of difference between the two.

Where to Consider Passive Solar Heating

In terms of geography, there is sufficient sunlight for passive solar heating throughout the middle latitudes. The coldest weather in these latitudes is associated with the passage of cold fronts, which are followed by clear skies. So, passive heating is often available when it is needed the most. The value of passive solar is greatly reduced in locations that tend to be cloudy or foggy in winter.

Of course, solar energy is available only during the daytime. Winter days become shorter at higher latitudes. More northerly latitudes tend to be ineligible because they have few hours of sunlight in winter, and because their lower average temperatures cause greater heat loss through the glazing.

In terms of building configuration, passive heating requires exposure to the sun. Therefore, passive solar requires an orientation that is generally toward the south, or facing upward. The acceptable range of orientation is fairly narrow. In winter, the sun rises well to the south of due east, and sets well to the south of due west. Also, the sun remains low in the sky all day. (Reference Note, 24, Characteristics of Sunlight, covers the geometry of solar motion in greater detail.)

Reference Note 46, Daylighting Design, points out that it is difficult to get sunlight to penetrate far into the building interior. This is generally not a limitation for passive heating, because building heat loss occurs through the envelope. Passive heating can be quite effective as a perimeter heating system. However, passive heating is limited to sides of the building (including the roof) that face the sun.

In a building that consists of tall, open space, such as a warehouse, the geometry of the space may allow passive solar to heat the entire building. If sunlight can be delivered from overhead, it is possible to provide widespread daylighting along with heating.

Advocates of passive solar heating tend to promote it for residential and small commercial applications. However, passive solar heating is especially well adapted to many industrial activities, for these reasons:

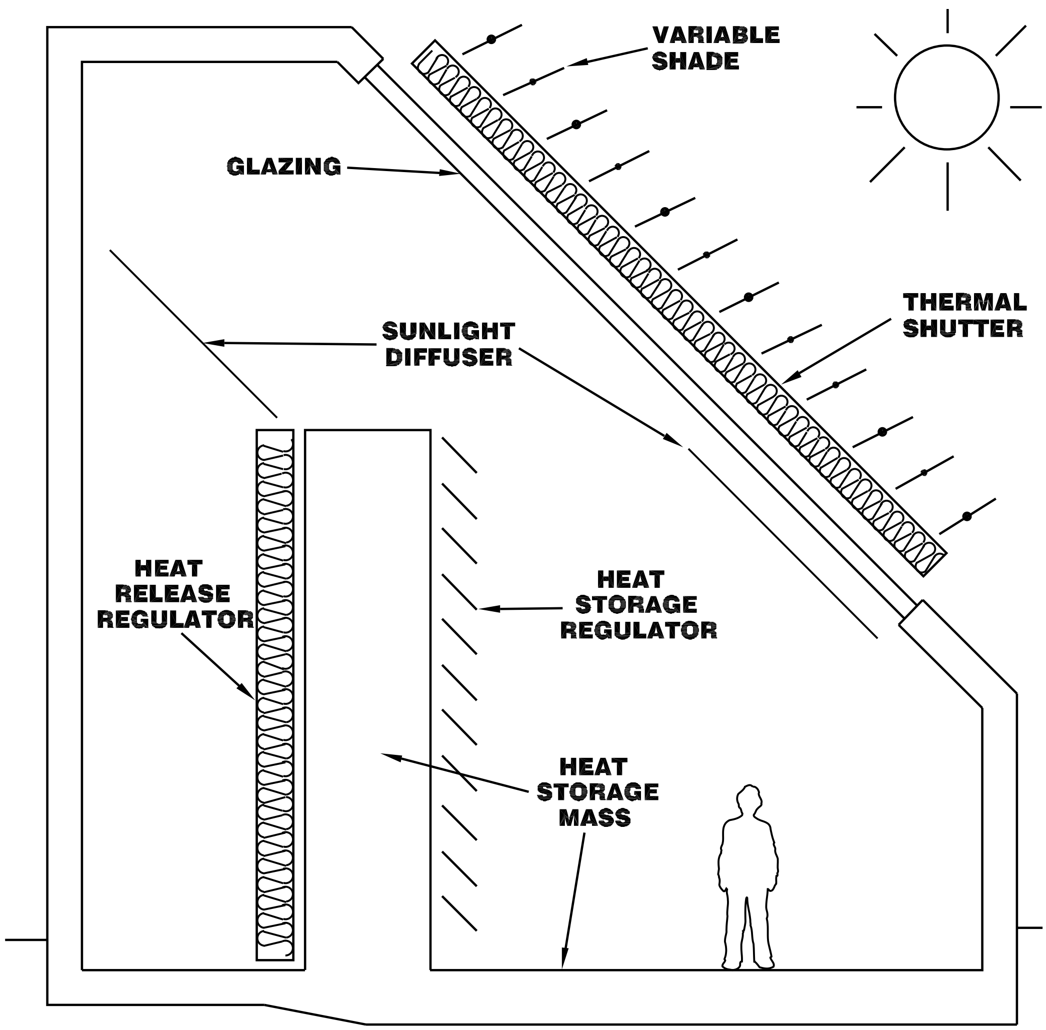

Fig. 1 Complete passive solar heating system This conceptual drawing symbolizes all the functions that any passive heating system should have. Bear in mind that any passive heating system is also a daylighting system, and it must perform well in both roles. In real installations, the clever designer will combine these functions wherever possible, and will exploit the inherent features of the building, such as heat storage mass.

- they are less sensitive to passive solar's lack of precise control of heat gain and illumination. Industrial work involves physical exertion, which makes people less sensitive to small temperature changes that would annoy sedentary workers.
- most industrial tasks are tolerant of a greater range of illumination levels than is office work
- in industrial-type structures, it is often practical to substitute glazing elements for conventional roof and wall materials
- unconventional sunlight control devices are less likely to create an appearance problem in the industrial environment
- industrial facilities tend to have high inherent thermal storage because of the mass of equipment and exposed floor slabs
- availability of skilled maintenance personnel is an important advantage for passive solar installations that have unusual mechanisms.

The need to integrate passive solar heating with both the external and internal design of the structure tends to limit passive solar heating to new buildings, where passive heating is an integral part of the design. This being said, do not overlook the possibility of exploiting passive solar in existing buildings, especially if conditions, such as climate, glazing exposure, and internal layout, are favorable.

Energy Saving Potential

■ Heating

The heating capability of sunlight is weak in comparison with the heat losses that can occur from a poorly insulated building in cold weather. (See Reference Note, 24, Characteristics of Sunlight, for the heat content of sunlight.) Therefore, the effectiveness of solar heating is dominated by the quality of the building envelope. If a building has good envelope insulation and little air leakage, passive solar may provide over half of the heating requirement in most eligible climates. This assumes that the building does not have a large ventilation requirement.

Passive heating does not necessarily have to provide a large part of total heat input to be worthwhile. In fact, passive solar is most economical as a supplemental heat

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Fig. 2 Rationally designed passive solar installation Two large sunlight collectors are installed in the cathedral ceiling of the living room of this house. Each has an insulated cover, one shown fully open, and the other fully closed. Actuators to control the position of the covers are not yet installed. Before the covers were installed, the surface area proved adequate to maintain the temperature of the space during most winter weather, without other heat. Satisfactory temperature was maintained throughout the night, probably because of heat absorption in the gypsum wallboard. However, the uninsulated glazing sweated profusely at night, causing damage to the frame and floor. The lighting level is bright, but not oppressive, except when reading. Placing the reading chairs in the shaded portion of the room solved this problem. During warm weather, holding the covers in a slightly open position provides very pleasant daylighting with minimal cooling load. The slope of the roof faces southeast, which is not optimum for collecting sunlight in winter. Therefore, the covers are hinged on the right side. They are intended to track the sun so that sunlight will reflect into the space from the white underside of the covers. The actuators, not yet installed here, are the only serious challenge. They must hold the covers rigidly against strong wind in both directions, and they must not be too ugly for the neighborhood. Sliding covers would have been a much easier solution if the roof had faced toward the south.

Table 1. COMPARATIVE CHARACTERISTICS OF ACTIVE AND PASSIVE SOLAR SYSTEMS

	Active Solar	Passive Solar
Heating Capacity	Can be increased indefinitely by adding collector area and storage capacity. In practice, limited by economics and weather patterns.	Limited to faces of the building that have a generally southern orientation, and to adjacent spaces.
Daylighting	Does not provide daylighting.	Inherently provides daylighting in heated spaces. Requires specialized techniques, separate from the control of heating, to make it satisfactory.
Heat Distribution	Heat is distributed with conventional equipment. Space temperature can be controlled precisely.	Heat distribution is dependent on interior space layout and exterior orientation of building. Heat release is subject to relatively wide temperature fluctuations, unless highly unusual features are included.
Dependence of Heat Collection on Temperatures	Cannot absorb solar heat until the temperature of the fluid in the collector rises above the distribution and/or storage temperature of the heating application. Collector performance declines with ambient temperature.	Outside and inside temperatures have virtually no effect on the amount of energy collected. Heat gain through glazing is almost always higher than heat loss during hours of sunlight. Low ambient temperature during dark hours creates major heat loss, unless system has insulating components.
Heat Loss from Spaces	Does not increase heat loss.	Large glazing areas create a serious heat loss path during hours of darkness. Requires troublesome insulating components, especially in colder climates.
Controlling Excess Solar Gain	Excess solar input is easily isolated from the spaces. Protecting collectors from excess temperatures may be troublesome.	Tends to create extreme space cooling load. May require troublesome components to prevent this.
Integration with Building Structure	Collectors are distinct from the building structure. Attaching the collectors to the structure may require strengthening. Cost cannot be reduced by substituting for other building components.	Integral with building structure. Likely to require radical change to structural design. Collectors may substitute for conventional windows and skylights. Other components are extra. Designing external movable components to resist wind and precipitation is a challenge.
Space Requirements	Heat distribution systems are the same as for conventional heat sources. In addition, a large storage tank is needed. Collectors require a large exterior area.	No internal space is needed for equipment. The layout for distributing sunlight and heat within the building may require additional space, and may require unconventional features, such as multi-story spaces adjacent to the walls.
Long-Term Survival	Collector components are subjected to ultraviolet degradation, oxidation, and daily cycles of thermal expansion over a large temperature range. Metal and glass components are durable, but soft components require periodic replacement.	Metal and glass components are durable, but soft components are a potential source of leakage from precipitation. Plastic glazing has limited life. Systems are likely to have unusual moving components requiring maintenance. Movable components can be designed to shield vulnerable components at night and during warm weather.
Appearance	Solar collectors are ugly, but they can be separated visually from the structure. Supporting structures can be hidden.	Components are large and unusual, a major visual element of the structure. Can make the entire building irreparably ugly if the designer is not clever.
Component Availability	Collectors and controls are the only specialized components, and are widely available.	Large glazing elements are the only specialized components available as common items, and these are not entirely satisfactory. Other specialized components must be fabricated on an experimental basis, which makes them expensive and unpredictable.
Maturity of Design Doctrine	Extensive experience has been accumulated with many designs. Extensive documentation exists. Best designs are not yet clearly distinguished. Methods of rejecting excess collector heat are not entirely resolved. Design of active system can evolve largely in isolation from other aspects of building design.	Design doctrine has not yet started to evolve in a serious way. Most design issues are not yet generally recognized. There have been few successful installations, if any, to serve as models for various building types. Evolution of passive design requires difficult interactions with conventional practices of architecture, interior design, lighting design, and HVAC design. Design of custom components requires creativity, along with engineering skills outside the conventional realm of building design.
Economics	Costs are well known. Prices have leveled out. Payback period is long, and will remain so. Variations in design result in relatively small cost differences.	Costs can vary widely. Component costs are high because they are still custom items. Major opportunity for cost reduction remains. Payback period remains to be demonstrated.

source. Probably the best approach is to add as much passive solar capacity as possible without requiring elaborate and expensive features.

■ Lighting

See Reference Note 46 about the energy saving potential of daylighting. If cleverly designed, a passive heating system can provide as much illumination as a system designed primarily for daylighting.

Primary Design Issues

Success with passive solar requires attention to an array of considerations that initially appears bewildering. As with any complex matter, the best approach is to identify all the elements, attack them individually, and then figure out a clever way to combine them. The following are the major issues of passive solar design.

■ Glazing Area

Because of the low energy density of sunlight, passive heating requires large glazing areas, unless the climate is mild. There is a trend of diminishing returns as glazing area is increased. That is, adding more glazing results in a greater number of hours per year when heating capacity exceeds need.

Daylighting requires much less glazing area than passive heating. To avoid excessive brightness, convert most of the sunlight to heat before it is seen by the occupants.

■ Glazing Location

Heat is released into the space at points where the sunlight is absorbed, rather than where it enters. Therefore, consider the location of glazing in relation to the locations of the heat absorbers and the heat storage masses. You may have a great deal of flexibility in making these arrangements. Furthermore, as with conventional heaters, convection can be exploited to distribute heat through the space. You need to tailor the location of glazing more carefully for daylighting than for heating.

Sunlight absorbers, which may consist of nothing more than dark pieces of cloth, can easily be moved to accommodate the glazing. However, the geometrical relationship between the glazing and the heat storage masses is fixed. For example, if you use a masonry wall as a heat storage element, locate the glazing so that sunlight falls primarily on the wall.

■ Absorption, Distribution, and Control of Sunlight Within the Building

Many attempts at passive solar failed because they simply dumped sunlight into the space without regard to consequences. Each location in the space where sunlight is absorbed acts as a heating unit, so these locations must be planned. For example, painting a sunlit wall in a dark color causes heat and light to be absorbed there, whereas painting the wall in a light color causes heat and light to reflect throughout the space.

People cannot work at most indoor tasks in full sunlight. Also, strong sunlight eventually destroys organic materials, such as upholstery, wallpaper, etc. Therefore, provide shading for sensitive areas. For example, install diffusing screens over individual work areas.

Activities within the building may move repeatedly, so design the passive heating system to adapt easily to changing activities.

■ Regulating Heat Input

One of the crippling flaws of passive solar has been failure to provide effective methods of blocking excess sunlight. The most efficient approach is to stop the sunlight outside the building with exterior shading. This may be difficult. External shading devices are large, they must be monumentally strong to resist wind forces and snow loads, and they require mechanisms that are cumbersome and unattractive. In addition to being an engineering challenge, they radically change the appearance of the building.

A less efficient method of controlling excess heat gain is to vent warm air from the space. This method generally is limited to spaces with tall or sloped ceilings. Relying on vents poses the risk of serious heat loss through convective leakage. Vent dampers are the kind of equipment that tends to be forgotten, so they are not operated or maintained properly.

Glazing with controllable opacity may come to market at an acceptable price. This would be a major advance for passive solar, because it would allow control of heat input without the external apparatus.

■ Limiting Heat Loss

Another major problem with passive heating is the high conductive heat loss of glazing, especially during hours of darkness, when there is no heat input and outside temperatures are lowest.

With skylights and other glazing that is slanted, the problem is especially severe. ASHRAE data indicate that multiple-glazed units have two to three times more conductive heat loss when they are installed in a heavily slanted orientation than when they are installed in a vertical orientation. In addition, slanted glazing requires more frame structure and stiffeners to resist sagging, and these components conduct heat.

The low thermal resistance of glazing, especially of skylights, allows the inside surfaces to get cold at night, causing condensation problems. In facilities that have humidification or other moisture sources, skylights may sweat prodigiously. The sweating is unsightly, it grows mildew, and it destroys wooden or steel framing. The condensation may be copious enough to drip on the space below, causing moisture damage inside the space. Condensation usually is not serious during daylight hours, because enough solar heat is absorbed by the glazing to keep it above the dew point of the inside air.

The large, cold surfaces of bare glazing may create discomfort at night, especially if people are close to the glazing.

The heat loss problem was recognized early in the history of passive solar, although it probably was underestimated. Many concepts were devised to add insulation to the glazing during hours of darkness. This conceptual class of insulation has been given a variety of names, including "movable insulation" and "thermal shutters." Unfortunately, all the methods that have been popularized so far have serious practical problems.

At first glance, the easy approach seems to be installing movable insulation inside the glazing. In fact, many types of internal insulation have been tried. These included various types of quilted shades, movable panels of various designs, and insulating shutters. Unfortunately, all these methods fall afoul of condensation problems. Interior insulation keeps the glazing at outside temperature. Moisture infiltrates past the insulation and condenses on the glazing. The insulation traps the moisture against the glazing and its surrounding structure, promoting mildew, rot, and rust.

Another approach is installing movable insulation on the outside of the building. This approach avoids condensation problems. It also protects the glazing from hail, snow, etc. However, the insulating panels must be as large as the glazing. Large external movable panels are an engineering headache. They must be able to withstand wind, they must be designed to prevent air leakage between the panels and the glazing, and they must not look too bizarre for the neighborhood.

A third approach is installing movable insulation inside the glazing, between the panes. For example, one briefly popular concept was blowing foam beads into the space between the panes overnight. This method fell out of favor because the beads stick to the glazing from electrostatic attraction. It is a pity that this did not work. Installing movable insulation between the panes avoids condensation problems, provided that the space is vented to the outside. Adjustable insulation inside glazing units merits more development effort.

Since you need adjustable shading to control heat gains, try to design the exterior movable insulation to act as an adjustable shading device. Needless to say, this involves additional complications.

The oppressive need for movable insulation would disappear entirely if glazing were available for skylights that has a high thermal resistance. Depending on climate, a minimum R-value between 6 and 15 would be sufficient to eliminate the need for movable insulation. For passive heating and daylighting, the glazing would not have to be transparent, only translucent, with a reasonably high light transmission. Such glazing may become available within the foreseeable future.

■ Amount of Heat Storage Mass

Heat storage is a necessary part of almost any passive heating system, because the sun does not shine continuously. With passive systems, storage occurs by the absorption of sunlight in mass. Storage capacity is determined primarily by the amount of mass that is exposed to direct sunlight. Ideally, enough solar energy should be absorbed in the storage mass during the daytime to carry through the hours of darkness.

Buildings are heavy, so a large heat storage potential exists in the building structure. For example, a typical office space may contain several tons of gypsum board that can serve as an effective thermal storage medium if it receives sufficient exposure to sunlight. Concrete floors and masonry walls often have enough mass to provide all the thermal storage mass that may be desired, provided that it is exposed to sunlight. Heavy machinery has a significant amount of heat storage capacity. The clever designer will exploit the mass of the building and its contents as much as possible.

The storage effectiveness of mass is reduced if it is covered by insulating materials, such as carpets, and wall finishes installed over furring strips.

In new construction, the heat absorbing capacity of massive components, such as floor slabs, often can be increased inexpensively by adding more material.

The usual candidate material for thermal storage mass is some type of masonry, such as concrete, brick, stone, tile, etc. Water also has been used. The weight of material required for storage is depends on the material's specific heat. (Specific heat is the heat capacity per unit of weight, in comparison with the heat capacity of water.) The specific heat of water is 1.0, of concrete and most masonry products is between 0.20 and 0.27, of steel is about 0.12.

The volume of the thermal storage mass depends on both the specific heat and the specific gravity of the material. (Specific gravity is the density of a material in comparison with the density of water.) The specific gravity of water is 1.0, of concrete and most construction stone is between 2.0 and 3.0, of steel is about 7.7.

If you multiply the specific gravity of each of these materials by its specific heat, you get the heat storage capacity per unit of volume. By coincidence, water and most bulk construction materials have about the same heat storage capacity on a volumetric basis.

■ Mechanical Properties of the Storage Medium

The heat storage mass is subject to thermal expansion and contraction. Centuries of experience have taught designers how to deal with this in common structural materials.

Masonry tolerates expansion well, but it must be kept loaded in compression, like the bricks in a wall. Tiles cemented to a surface are likely to break loose because of differences in thermal expansion between the tile and the masonry behind it.

Water is cheap. It has exceptionally high specific heat, which reduces structural loading, but it cannot serve as a structural element itself. It has no thermal lag. Convective currents in water prevent thermal lag, and also cause vertical temperature stratification. If water is stored in a transparent container, a dye should be added to it to absorb sunlight.

■ Location of Heat Storage Mass

When masses are releasing heat, they act as huge, low-temperature radiators, which provide comfortable heating throughout a large area. Their location tends not to be critical.

As with any heating system, it is desirable to release the heat near the envelope, to offset the envelope heat losses. From this standpoint, for example, it is better to absorb sunlight in a floor slab close to the exterior wall than to absorb sunlight in an interior wall.

■ Control of Heat Storage Input and Output

Using heat storage efficiently involves three factors: the rate of heat absorption, the rate of heat release, and the timing of heat storage and release. Fortunately, in keeping with the concept of a "passive" system, it is often possible to design these factors into the system without resorting to devices that need to be controlled.

The rate of heat absorption is determined by the surface area exposed to sunlight and by the absorptance of the surface. Mass is effective for heat storage only if it is directly illuminated by sunlight. Therefore, the relative placement of the glazing and storage mass is critical. The motion of the sun causes different parts of the interior to be illuminated throughout the day, which may be advantageous. Warming the space in the morning can be accelerated, at the expense of delaying heat storage, by using internal heat absorbing screens to shade the mass.

The absorptance of the storage mass is determined entirely by its surface. In general, dark colors absorb the most sunlight. "Color" indicates absorptance only in the visible portion of the solar spectrum, which accounts for only about 35% of total solar energy. Absorptance in the infrared portion of sunlight is more difficult to determine. Refer to Measure 8.2.2 for methods of determining the absorptance of particular materials.

The rate of heat output from the storage mass is determined by the surface area and by the emittance of the surface. The emittance of most solid materials used for heat storage is about 0.8, which is satisfactory for the purpose. There is generally no need to tinker with emittance. (Refer to Measure 8.2.2 if you want to learn more about it.)

The timing of heat release in most passive solar systems depends on the thermal lag of the storage mass. Thermal lag is a delay in the release of heat from a mass after the heat has been absorbed. Using thermal lag to control the timing of heat release is usually the preferred method. It is not precise, but it minimizes the need for maintenance or active control.

Thermal lag in a material results from the interplay of its thermal conductivity, heat capacity, and geometry. As heat is absorbed by the sunlit surface of a material, the temperature of the surface is raised, and the rise in temperature forces the heat deeper into the material. When the surface is no longer illuminated, the process reverses. The surface emits heat and becomes cooler, which creates a flow of heat toward the surface. Of course, this is not an on-and-off process. Heat is continuously emitted from the surface, whether it is sunlit or not. As the space cools at night, the increased temperature differential across the surface draws more heat out of the mass.

The thermal lag is much longer and more distinct if the storage mass is heated by the sun on one side and the space being heated is located on the other side. In such cases, there is a distinct peak in heat emission into the space that may occur many hours after sunset.

Calculating thermal lag is somewhat complex. It can be done using some of the more sophisticated energy analysis computer programs. The U.S. National Institute of Standards and Technology has done much of the work in calculating thermal lag in buildings. They offer guidance in this subject.

Water has virtually no thermal lag, because convection keeps transferring heat to the outer surface of the container. The thermal lag of metals is minimal because of their high thermal conductivity.

In some cases, it may be desirable to use adjustable insulation to bottle up heat within the storage mass until needed.

■ Coordinate with Daylighting

Try to exploit daylighting if you use passive heating, since the sunlight is coming into the space anyway. By the same token, you need to consider lighting conditions in a passive solar installation to avoid intolerable brightness and glare.

The methods you use to control sunlight for illumination are quite different from the methods you use for passive heating. Daylighting is desirable any time that sunlight is available, but passive heating is desirable only when there is a heating load in the building. Illumination requires much less glazing area than passive heating, but more careful distribution of sunlight. Daylighting requires still more auxiliary devices, such as light diffusers.

■ Coordinate with Electric Lighting

Refer to Subsection 9.5 for methods of controlling electric lighting to exploit daylighting.

■ Coordinate with Heating and Cooling Equipment

To avoid wasting heating and cooling energy, be sure to design the thermostatic controls of the conditioning equipment so that they do not fight the passive heating system. Passive heating results in swings of temperature. If the passive system is designed properly, the temperature swings remain small enough to avoid discomfort. Design the thermostatic controls to keep heating and cooling equipment turned off as long as temperatures remain within acceptable limits. This is called "deadband." See Measure 4.3.4.2 for details.

■ **Longevity of Materials and Installation Methods**

Your choice of the materials and installation methods has a major effect on longevity and maintenance requirements. There is a strong temptation, when buying large expanses of glazing, to use short-lived materials to reduce cost. Your successors will curse you for this if you succumb. If you cannot afford the right materials, forget about passive solar. See Measure 8.3.2 about selecting materials for longevity.

■ **Water Leakage**

Large expanses of glazing tend to be vulnerable to water leakage, especially if the glazing is non-vertical. See Measure 8.3.2.

■ **Wind**

Shading devices and movable insulation for passive solar systems have a large amount of surface area, which makes it important to design them strongly. In many applications, wind is the greatest impediment to using external devices.

■ **Snow**

Fortunately, skylights tend to shed snow, provided that they have even a modest slope. Heat loss through the glazing, combined with the insulating property of snow itself, causes the bottom layer of snow to melt and slide off the smooth surface of the glazing. Also, sunlight penetrates snow and warms the surface underneath.

Nonetheless, snow can be very heavy. Skylights should be designed to resist the weight of an overnight wet snowfall. If insulating covers are used, they can be designed to carry the snow load. This requires reliable controls that respond automatically to snowfall. Snow melts and turns to ice, so external mechanisms must be designed to avoid jamming by ice.

■ **Maintenance**

In theory, passive solar systems should require minimal maintenance. Good design places priority on achieving this ideal. If mechanisms are necessary, such as movable shading devices and thermal shutters, design these for ruggedness and easy maintenance.

■ **Esthetics**

Daylighting and passive solar heating have a major effect on both the exterior appearance and internal layout. Blending these elements into the design of a building requires imagination and a fine esthetic sense. These qualities are not prevalent in contemporary architecture, and many buildings heated by passive solar are lovely only to their designers. Sadly, many attempts at passive solar design have been so ugly that they degrade the value of the building. The only solution is for owners to be aware of this potential problem, and to cast a critical eye on the esthetic aspects of the design.

■ **Cost Efficiency**

The clever designer will attempt to satisfy all the functions symbolized in Figure 1, while minimizing the hardware and complexity required. For example, it may be possible to dispense with specific thermal storage devices if the mass of the building is exploited effectively for thermal storage. Considerable thermal storage may be added cheaply by increasing the quantities of inexpensive masonry materials in floor slabs and walls.

In new construction, it may be possible to minimize materials costs by substituting glazing for other roof and wall surfaces.