however, if air is substituted for water as the working fluid. The collector is located obliquely below the space to be heated. Heat produced in the collector causes air to rise into the space to be heated; cool air from the return duct system enters the bottom of the collector to complete the loop. Very small systems of this type have been designed for retrofit. In such systems, a single collector is inserted in an existing window opening in the building. Solar flux striking the collector causes a circulation of air, and some space heating can be accomplished. However, since the window area in most buildings is too small to provide collector area for more than 20 or 30 percent of heating, this type of system cannot be used as a baseload solar heating system.

Large gravity-flow systems using several hundred square feet of collector area have been built for heating of residences. One difficulty is the interface with storage. If the solar system is to carry more than one-third of the heating load, storage is required. Rock-bed storage presents significant pressure drop to be overcome only by natural circulation, although the use of larger-than-normal (6- to 7-in diameter) rocks can reduce the storage-bed pressure drop.

Operating Modes for Passive Heating Systems

Although most passive systems have no active control system which selects the mode of operation, there are several distinct operating modes. Thermal circulation in indirect systems causes space heating to occur when solar intensity levels are sufficiently high. At night, a reverse flow can occur if the cavity between the south-facing glazing and the wall becomes cool. A number of ways of controlling reverse circulation have been used. The most common method of backflow control is a backdraft damper at the outlet of the upper wall air slot. This damper is made of a very light material (e.g., 1-mil polyethylene) and is pushed open easily by the forward circulation of warm air. When air tends to back-circulate, the backdraft damper closes.

The control of movable insulation is either manual by the owner or automatic with a sun sensor or clock. In direct-gain spaces, the manipulation is usually manual. Movable insulation must seal to the south-facing glazing to avoid reverse circulation between the glazing and the insulation. For thermal-storage-wall (TSW) systems, an automatic system for positioning night insulation seems most appropriate, since the owner may often forget to lower the insulating shade if it is not visible from inside. Most movable insulation controls contain (1) a sun sensor which is positioned in an unobstructed location south of the glazing area and (2) a small motor which is used to roll and unroll the movable insulation. The function of this system is shown shortly in an example system design. The details of movable insulation and its controls are given in Chap. 4.

Heat dumping in summer is accomplished by opening operable glazing or by positioning the movable insulation in the down position.

Example Passive Space-Heating System

The Gunnison County Airport located in western Colorado is one of the first large commercial structures heated by a combination of passive systems in the West. This building serves a small community with several general-aviation airlines and has approximately 10,000 ft^2 of gross floor area. The passive systems used on the building include a combination of direct-gain and thermal-storage-wall elements on the south facade as shown in Fig. 2.25. Additional direct gain and daylighting are provided by the clerestory. Active air circulation occurs between the thermal wall and the north zones, where the heat load is higher.

The building incorporates many energy-conservation features. The roof is insulated to R-30 and walls to R-20. All glazing is insulated to R-10 after sunset; R-10 perimeter insulation is used to prevent heat loss from the floor slab. Airlocks are used for all passenger entries and night setback to 55°F is used during periods when the terminal is closed. Infiltration is reduced by using zero building pressure provided by makeup air, and the low building profile further reduces wind infiltration. Thermal-buffer spaces on the north side of the building are maintained at only 45°F. No nocturnal ventilation is used when the facility is closed. The average installed lighting level is 1.5 W/ft^2. No mechanical cooling is used, and a reduced fenestration area of 9 percent of the floor area was specified. The aspect ratio of the building is exactly 2 to 1 to maximize winter solar gain and minimize summer gain. Stratification is reduced in the building by an air-circulation system between the roof peak and lower levels, thereby reducing roof heat loss normally present in multistory buildings.

Figure 2.26 is a section drawing of the thermal-storage wall. The double glazing is a standard manufactured window and is tightly sealed to the insulated walls at the top, bottom, and sides. A movable insulation curtain roll is positioned above the aperture and is controlled by a sun sensor placed in an unshaded location on the south wall. A 12-in masonry wall is used for collection and heat storage; the concrete is dyed dark-brown. Upper and lower wall vents, each having an area equal to approximately 2 percent of the total TSW area are used. The upper wall vent is connected to the heat-recovery system duct.

During winter, heavy snowfall is common in western Colorado, and the reflection from snow immediately south of the window is expected to improve performance by approximately 22 to 30 percent. Snow will not be removed from this area during the entire winter. The overhang serving the passive aperture is designed to block solar gains for approximately 4½ mo in summer. Although Gunnison does have a small space-heating load in summer, it is expected that this will be carried for the most part by internal heat sources, and the passive system will not serve as a heating system in summer. In the summer, the insulated louvers at the top of the passive wall are opened, and a natural circulation of air through them cools the thermal wall overnight and provides a small space-conditioning effect during the day. Large day/night temperature excursions of 30 to 35°F occur each summer night in this area, and the use of the TSW for cool storage will permit improved comfort in the building.

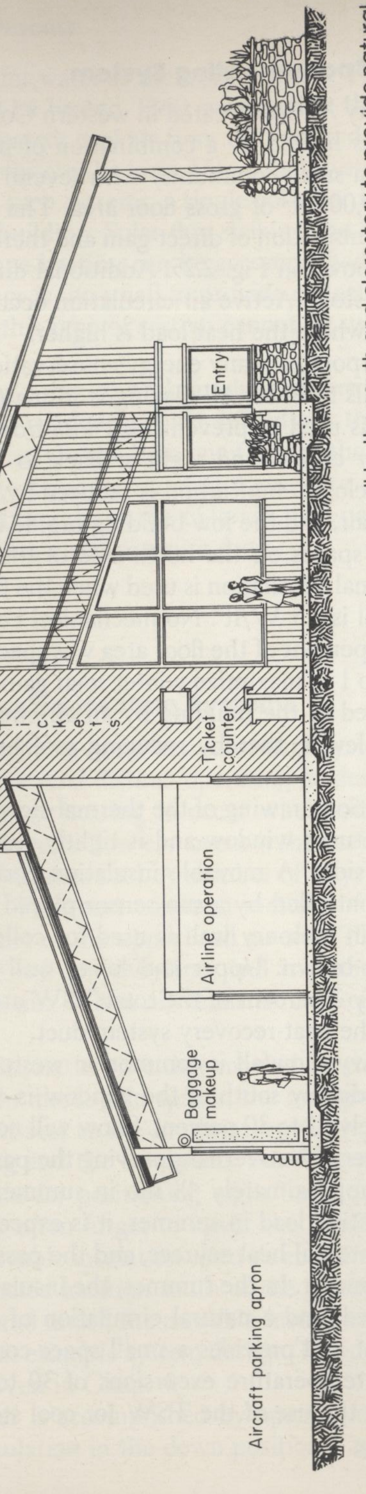


FIG. 2.25 Building section of the Gunnison County Airport Terminal showing thermal-storage wall to the south and clerestory to provide natural lighting as well as direct-gain heating. *(Courtesy of Associated Architects of Crested Butte, Colo.)*

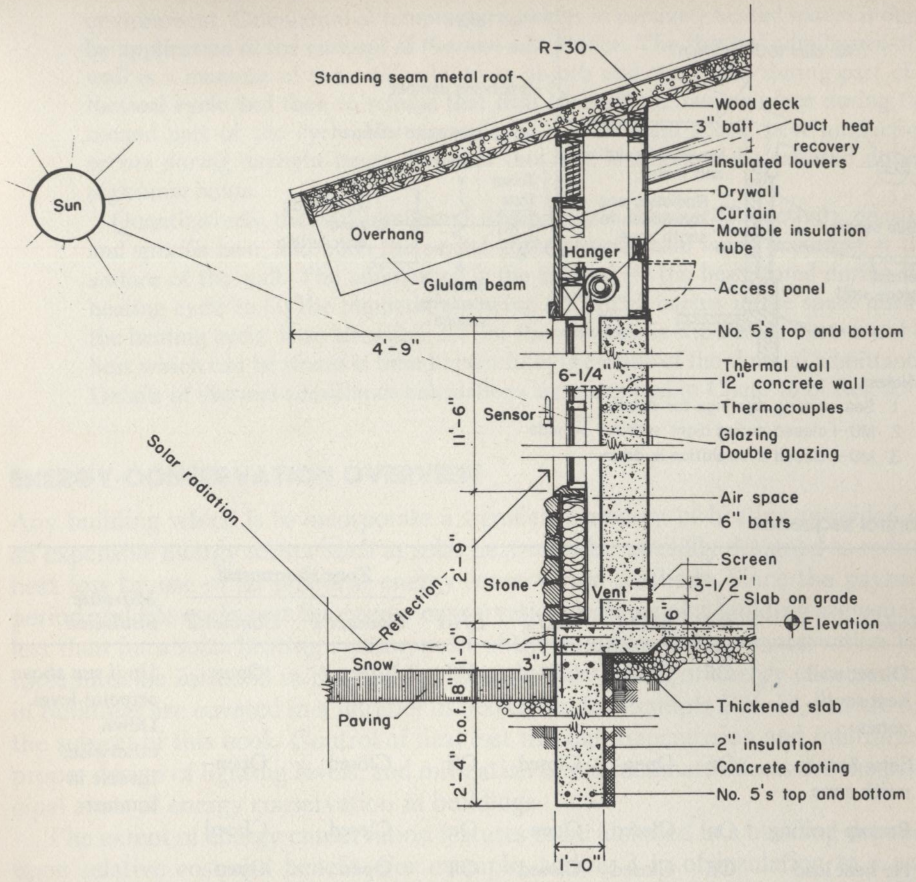
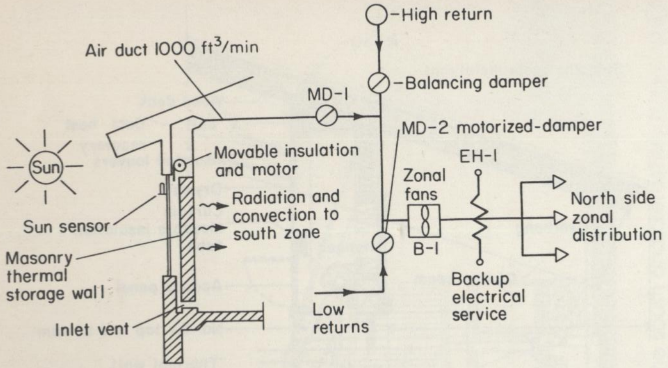


FIG. 2.26 Section of thermal-storage-wall section of the Gunnison County Airport showing aperture, storage wall, movable insulation, wall vent, and heat-recovery duct. *(Courtesy of Phil Tabb Architects, Boulder, Colo.)*

Operating Modes

Figure 2.27 is a schematic airflow diagram for this example project as well as a listing of the control sequences. Mode 1 is the mode by which the south zones are directly heated by radiation and convection from the thermal-storage wall. In this mode, blower B1 does not operate and the dampers are closed. This type of heating, which occurs whenever there is heat in the thermal-storage wall, is not subject to active control by the control system.

The second mode is active delivery of solar-heated air to the north zones of the building. This is accomplished by operating blower B1 and opening motorized damper MD1. The flow rate is 1 ft^3/min per square foot of TSW area. Airflow from the storage-wall cavity is directed to the north zonal distribution system. The thermal wall cavity is an air preheater; the final heating input is provided by the electric



Notes:
1. See working drawings for details
2. MD-1 closed during night setback periods
3. MD-1 closed if insulation is down

Control sequence

Mode	*B-1*	*MD-1*	*MD-2*	*EH-1*	*Zone thermostat* *Contact 1*	*Zone thermostat* *Contact 2*	*Movable insulation*
1. Direct wall heat south zones	Off	Closed	Closed	Off	Open	Open	Up if sun above setpoint level. Down otherwise; reverse in summer
2. Solar heat to north zone	On	Open	Closed	Off	Closed	Open	
3. Backup heating	On	Closed	Open	On	Closed	Closed	
4. No heat load	Off	Closed	Closed	Off	Open	Open	

FIG. 2.27 Energy flow diagram for Gunnison County Airport and table of operational modes. *(Courtesy of JFK Associates, Boulder, Colo.)*

heating element EH1, which consists of several steps of resistance heat activated by the control system.

When no heat is needed, blower B1 is off, and the damper MD1 is closed. Movable insulation is controlled by the level of sunlight independently of the heating control system. Whenever movable insulation is in the down position, motorized damper MD1 is interlocked closed. The air-distribution system also includes a high return from the clerestory shown in Fig. 2.27 to reduce stratification. This passive solar system is expected to provide 50 percent of the annual heating requirement for the building. Additional energy savings are realized by the natural daylighting via the clerestory.

○ **Thermal Admittance.** Temperature control in passive heating systems may not be as precise as in active systems, since the release of heat from thermal-storage-wall surfaces is determined by the thermal characteristics of the wall as well as the environment. Calculation of temperature swings in passively heated spaces is done by application of the concept of thermal admittance. The thermal admittance of a wall is a measure of the wall's ability to absorb and store heat during part of a thermal cycle and then to release that heat through the same surface during the second part of the cycle. For example, in a direct-gain space, heat production occurs during daylight hours. Some of this heat is stored to be released during nighttime hours.

Quantitatively, thermal admittance depends upon thermal conductivity, density, and specific heat, and upon the period of the temperature swing occurring at the surface of the wall. The admittance is the ratio of (1) the heat stored during the heating cycle to (2) the temperature swing ΔT which occurs in the space during the heating cycle. If an allowable ΔT for the room air is stipulated, the amount of heat which can be stored is then known from the value of the thermal admittance. Details of thermal-admittance calculations are contained in Chap. 16 of Ref. 9.

ENERGY-CONSERVATION OVERVIEW

Any building which is to incorporate a significant amount of heating provided by an expensive energy source such as solar heat must be carefully designed to reduce heat loss by use of all practical energy-conservation methods. Since the payback period and life-cycle cost for energy-conservation features of a building are usually less than for a solar heating system, most of the common energy-conservation features must be included in the building design. The details of energy conservation in buildings are covered in a number of textbooks, for example Ref. 14, but are not the subject of this book. Control of heat lost through transmission and infiltration, proper design of lighting levels, and mitigation of microclimate effects are the principal areas of energy conservation in buildings.

The extent of energy-conservation features to be included in a building depends upon relative cost and benefit. For example, adding 3 in of insulation to a wall already incorporating 12 in of insulation would not be as cost-effective as providing double glazing on a single-glazed window. One of the principal heat transmission losses from buildings occurs through windows. It is more cost-effective to reduce that loss by 50 percent than to reduce the loss through an already well-insulated wall by 20 percent, since the transmission loss may account for less than one-third of the total heat loss. Energy-conservation economics is considered in Ref. 1, where recommendations are made about the best mix of various energy-conservation strategies.

"Superinsulated" residences carry energy conservation to the extreme. Heat losses are so small that internal gains provide most heat required. Although cost-effectiveness is not yet clearly established and very low fresh-air exchange rates may cause problems, the concept is worth considering. Shurcliff (64) presents the best treatment of this new concept.

The use of thermal mass within a building may also be considered an energy-conservation feature. Studies at the National Bureau of Standards have shown that thermal mass does not have much impact on the annual heating requirement but can reduce the peak heating load significantly. In many locations, peaking energy

TABLE 3.2 Schematic design sizing rules

Component characteristic	*Active water heating*	*Active space heating—liquid*	*Active space heating—air*	*Passive space heating*
Storage capacity	1.5–2.0 gal/ ft_c^2	1.5–2.0 gal/ft_c^2	½–¾ $\text{ft}^3/\text{ft}_c^2$	8–12 in masonry or water equivalent
Heat-exchanger effectiveness	$E_{hx} \geq 0.8$	$E_{hx} \geq 0.8$		
Pump or fan flow*	0.02 gal/ $(\text{min}\cdot\text{ft}_c^2)$	0.02 gal/ $(\text{min}\cdot\text{ft}_c^2)$	2.5 ft^3/ $(\text{min}\cdot\text{ft}_c^2)$	1 $\text{ft}^3/(\text{min}\cdot\text{ft}^2)$ if hybrid
Load heat-exchanger effectiveness		$E_{hx} \geq 0.5$		
Collector tilt angle	Latitude	Latitude +15°	Latitude +15°	Normally vertical for TSW; to favor winter sun for others
Collector azimuth angle	Within 25° of due south for all systems			
Collector area	0.8–1 $\text{ft}_c^2/(\text{gal}\cdot\text{day})$	*There is no rule of thumb for collector area!*†		

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*Liquid flow rates are based on water. If water is not used, make the proper adjustments for density and specific heat. For air, flow rates are at sea level; make proper adjustment for reduced density at high altitude.

†See performance prediction and economic analysis section, pages 137–153.

Additional Sizing Information for Passive Schematic Designs

The schematic design of passive heating systems cannot be isolated from the overall building design. Therefore, certain design criteria for passive systems must be included in the building design as well as in the heating system design. In this section, additional information on direct gain, thermal-storage wall, and greenhouse passive heating systems is provided.

Direct Gain. Direct-gain systems consist of three generic types—south vertical walls, clerestories, and skylights. South-facing glazing is the most common direct-gain aperture. In order for direct gain to heat the adjacent space directly, the depth of that space should be no more than 2½ times the height of the south-facing window. This rule is based on the position of the sun in winter. Of course, south-facing direct-gain apertures must be confined to azimuth angle ranges between southeast and southwest, with due south being preferred.

One particularly troublesome feature of direct-gain systems is the likelihood of objectionable glare and overheating within the space during a sunny day. This is particularly a problem in offices where high internal gains already exist in the daytime. By proper choice of materials, placement of furnishings, and so forth, the impact of glare can be reduced somewhat, but never eliminated. The person choosing materials exposed to sunlight in a direct-gain space must take into account the tendency for intense sunlight to fade dyed fabrics and to deteriorate plastic materials, particularly if blue and near-ultraviolet rays are present.

Other types of direct-gain systems include skylights and clerestories. A clerestory used for both natural daylighting and space heating is shown in the example passive system described in Chap. 2 (see Fig. 2.25). Skylights and clerestories can provide heat to a space if they reflect both heat and light to a lower level. Clerestories may consist of one large vertical section or may be arranged in a sawtooth configuration. The spacing of sawtooth clerestories is governed by the same considerations that apply to flat-plate collectors on a flat roof (Fig. 3.10). Their performance can be enhanced by a reflecting surface of approximately the same area, placed horizontally to the south of the vertical window.

Skylights are apertures in the roof plane which are used for both natural daylighting and heating. Skylights do not have an ideal orientation for space heating since the sun is relatively low in the sky in winter and an aperture at typical roof angles intersects relatively little sunlight during the deep heating season. In addition, the large solar incidence angle results in significant reflective losses. The performance of a skylight can be enhanced by placing a nearly vertical (or adjustable) reflecting surface above and to the north of the skylight to direct additional sunlight through its aperture. One difficulty with skylights is their orientation ensuring large heat gains in summer when the sun is high. Therefore, any skylight design must include some method of summer shading. The reflector mentioned above, if shaped properly, can be used as a summer skylight cover. It can permit a small amount of sunlight to enter, giving natural daylighting in summer.

The amount of storage recommended for direct-gain systems in Ref. 19 is as follows. Interior walls and floor of solid masonry should be 8 in thick. If water storage is used, approximately 2 to 3 ft^3 of water are required in an interior water wall for each square foot of direct-gain glazing. The larger the amount of storage, the smaller the day-to-night temperature excursion. Insulation should be exterior to all indirectly illuminated storage components.

Indirect-Gain Thermal-Storage-Wall Systems. Thermal-storage-wall systems are used to provide a more controlled passive space-heating behavior than is possible with direct-gain systems. In addition, the glare problem and effects of directly illuminating furnishings and carpets are avoided by means of a wall. The thermal-storage wall need not be a solid masonry element but can be pierced with window openings as desired. Part of the heat delivered to the space by a thermal-storage wall is by thermal radiation in the far infrared. Therefore, the depth of the room to the north of a thermal-storage wall is limited to approximately 20 ft. Beyond this distance, the effectiveness of thermal circulation and radiation heating are reduced. This constraint by itself results in a fairly linear building design with an aspect ratio of 2 or 3 to 1, favoring a long south wall.

The amount of passive wall aperture area for a TSW system may be in a range similar to that for direct gain—approximately ¼ to ⅜ ft^2 of aperture per square foot of heated floor area.

Storage in TSW systems is by a solid masonry wall between 8 and 12 in thick or by a water wall 6 in or more thick. The amount of storage is determined by the time lag desired between initial heating of the wall and release of the heat to the space after sunset. If a high-conductance material is used for storage, the wall must be thicker to provide a given time-lag effect. Water and masonry have been most commonly used because of their availability and low cost.

Another determinant of wall thickness is comfort. Although TSW systems with 8- and 12-in walls may produce the same heating energy per year, the 12-in wall will have reduced temperature savings vis-à-vis the 8-in wall. Thinner walls may feel too warm on sunny, mild days and too cool on overcast, cold days.

Wall outer surface color is important. Darker colors with an absorption coefficient above 0.60 should be used. Table A.12 in the appendix contains absorptance values for many passive wall materials and coatings.

Passive solar systems carrying a relatively small percent of the load produce most of their heating effect during the day; storage is often not fully charged. For these systems, the thermal circulation vents are relatively large (2 to 3 percent of wall area) to pemit rapid heat up during the day. Passive systems carrying most of the heating load use smaller vents (1 to 2 percent of wall area). Small vents protect against overheating during the day, a potential problem if large TSW vents are used. Details of vent sizing are presented in Chap. 4.

Greenhouses. Greenhouses are essentially enlarged thermal-storage-wall cavities placed to the south of storage. Since greenhouses have a larger glazing area per square foot of wall area than a TSW system, heat losses will be greater and solar gains higher. Overall, the energy delivery through the storage wall to the building space to be heated will be less than for a pure TSW system. Reference 19 suggests that approximately 50 percent more greenhouse aperture area is required to heat the same space for the same percent of time as a TSW system.

Sloped greenhouse glazing presents many problems vis-à-vis vertical glazing:

Higher cost
More leaks
More collected dirt
More summer heat gain
Reduced load-carrying capacity
Increased snow load
More difficulty in construction

Heat storage for an attached greenhouse is provided in the common wall between the greenhouse and the building. The amount of storage to be used is roughly the same as for the TSW system described above. If the greenhouse is used in a free-standing mode and not as an attached greenhouse, the amount of thermal mass may need to be larger. Storage suitable for a free-standing configuration can easily be determined by experiment. Detailed sizing rules do not yet exist. Storage is added until the day-to-night temperature swing is within the range which can be tolerated by plants in the greenhouse—about 20°F or so.

Other design guidelines for greenhouses are similar to those for systems described above. For example, since solar gains in winter are much larger on a south face than on an east or west surface, the south wall will be the largest and a linear building configuration will be the most efficient. East and west windows are net winter heat losers. Insulated walls work better. Summer solar-gain controls must be used to prevent overheating; heat rejection via high vents should be included. Greenhouse design studies have lagged behind those for direct-gain and TSW configurations; therefore, the design guidelines are less clearcut.

Schematic System Diagram

The component sizes shown in Table 3.2 are expressed on a unit-collector-area basis. Once the collector area has been estimated, the sizes of all other components in the solar heating system are, therefore, known. These sizes are used in preparation of the schematic diagram of the solar heating system. The schematic diagram shows the main features and interrelationships of all system components. The diagram shows all fluid-flow loops and control sequences used in the design recommended at the end of SD. Figure 3.11 is an example schematic diagram of an active liquid-based system. The diagram shows the sizes of the collector, pump, heat-exchanger and storage backup system, and terminal delivery device. The domestic water-preheating system is also shown.

Major component sizes shown on the schematic diagram are the basis of the SD cost estimate. This becomes a part of the schematic-design-phase cost statement and will be approved by the owner if solar heating is to be used. The determination of the economic viability of solar heating must be made by means of a feasibility study. The feasibility study will determine the relative cost of solar heating equipment and operation costs vs. the savings in conventional fuels.

A second determinant beyond that of cost competitiveness frequently enters into the heating system selection process. This constraint is the availability of initial funding for a solar system. Although the investment may be shown to be economically viable on a year-by-year basis, initial budget constraints may make the initial, relatively large investment impossible. At this point the solar consultant can assist by suggesting to the owner possible tax credits and sources for funding including low-interest loans from the Solar Development Bank.

Building models are often prepared as a part of schematic design. Figure 3.12 shows an example of an SD scale model useful for client review, shading studies, and daylighting experiments.

PERFORMANCE PREDICTION AND ECONOMIC OPTIMIZATION AT THE SCHEMATIC DESIGN LEVEL

The sizing of a solar system is determined by trade-offs of projected fuel savings vs. the cost of the associated solar system. This type of economic study is not required for conventional heating systems, which always provide 100 percent of the annual heating load. Solar systems are almost never sized at the 100 percent level. At the schematic design level, an approximate economic analysis is made

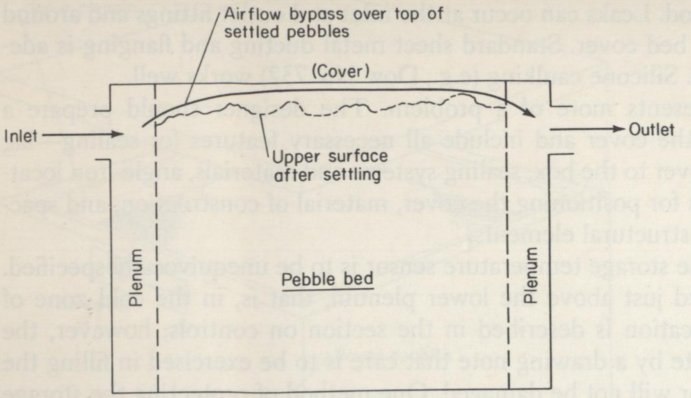

FIG. 4.10 Horizontal pebble bed showing possibility of airflow bypass after settling has taken place.

unused crawl space below the inhabited level of the building. This normally requires the use of horizontal flow in the bed. Horizontal flow has two difficulties. The first is the problem of maintaining a proper vertical interface between hot and cold zones of storage. Since hot air tends to rise, the flow in the pebble bed may become two-dimensional. Instead of moving in plug flow through the pebble bed, the air may rise toward the outlet plenum.

The second difficulty with horizontal flow is shown schematically in Fig. 4.10. After the storage bed has been filled, the material may settle. This will cause a gap at the top of the box. Then, an air short circuit above the pebble bed from inlet to outlet occurs. Consequently, very little heat storage occurs.

If horizontal storage must be used, flow baffles or seals are needed between the cover and the top of the pebbles. For example, a high-temperature compressible foam several inches thick could be attached to the cover when the cover is clamped in place. The foam is compressed against the pebbles and offers an effective barrier for airflow. Vertical flow through the storage container avoids these problems.

○ **Flow and Heat Transfer in Pebble Beds.** Pressure drops and heat-transfer coefficients in pebble beds have been measured by several investigators (1). One method for calculating the pressure drop through a pebble bed is given in Eq. (4.3).

$$\Delta p = \left(\rho V_s^2\right)\left(\frac{L}{D_s}\right)\left[\frac{(1-\epsilon_v)^2}{\mathrm{Re}\,\epsilon_v^3}\right]\left(1.24\frac{\mathrm{Re}}{1-\epsilon_v}+368\right) \qquad (4.3)$$

where $D_s = \left(\frac{6}{\pi}\,\frac{\text{net total volume of particles}}{\text{number of particles}}\right)^{1/3}$ = effective particle diameter

ρ = fluid density
$\dot{m}$ = mass flow rate
$V_s = \dot{m}/\rho A_b$
A_b = bed volume/bed length
L = bed length

ϵ_v = void fraction, usually 0.35 to 0.5
Re = Reynolds number based on the superficial mass velocity v_s and the particle diameter D_s

Equation (4.3) is valid for Reynolds numbers between 100 and 13,000.

Figure 4.11*a* shows the pressure drop measured in rock beds for various pebble sizes and superficial velocities. Pressure drop is expressed as inches of water per foot of bed length, that is, $\Delta p/L$. The figure shows that velocities are usually relatively small.

The heat-transfer coefficient in pebble beds between air and rock is shown in Fig. 4.11*b* in English units. The heat-transfer coefficient is on a volumetric basis rather than the usual area basis. In equation form, the volumetric heat-transfer coefficient in a pebble bed is given by Eq. (4.4), from Ref. 1.

$$\bar{h}_c = 0.79\left(\frac{G}{D_s}\right)^{0.7} \qquad (4.4)$$

where h_c = heat-transfer coefficient, Btu/(h·ft²)
G = the superficial mass flow rate (based on bed cross section area), lb/(h·ft²)

The total particle surface area A_p is given by Eq. (4.5) below.

$$A_p = \frac{6(1-\epsilon_v)A_bL}{D_s} \qquad (4.5)$$

In the DD rock bed design, the heat-transfer coefficient is normally not required information, but it is included here for specialized designs which may require its calculation. However, the pressure drop Δp is always required in DD designs in order to size air movers. Figure 4.11 can be used for preliminary estimates, but final design should be based on the use of Eq. (4.3).

Design of Storage for Passive Heating Systems

The two most common materials used for passive storage in passive systems are masonry and water. Storage requirements per unit collector area in passive systems are greater than in active systems by a factor of 2. Typical passive-system storage is between 30 and 40 Btu/(°F·ft²). The larger storage is necessitated by the slower exchange of heat with storage in passive systems.

Storage in most passive systems is located in intimate contact with the collector surface; the sun-facing side of the storage is the collecting surface. In direct-gain systems, the storage is frequently a massive floor or a south-facing wall positioned several window heights behind the aperture. Storage surfaces are dark in color ($\alpha > 0.6$) and are made of masonry, plastic, or metal (which may be selectively coated). It is possible to decouple storage from the collector in passive water-storage systems. The heated water can be pumped from the collector wall to holding tanks for later use. This hybrid method affords more heat delivery control. This is useful in spring and fall; afternoon overheating can thereby be avoided. Most passive systems, however, have closely coupled collector, storage, and delivery surfaces.

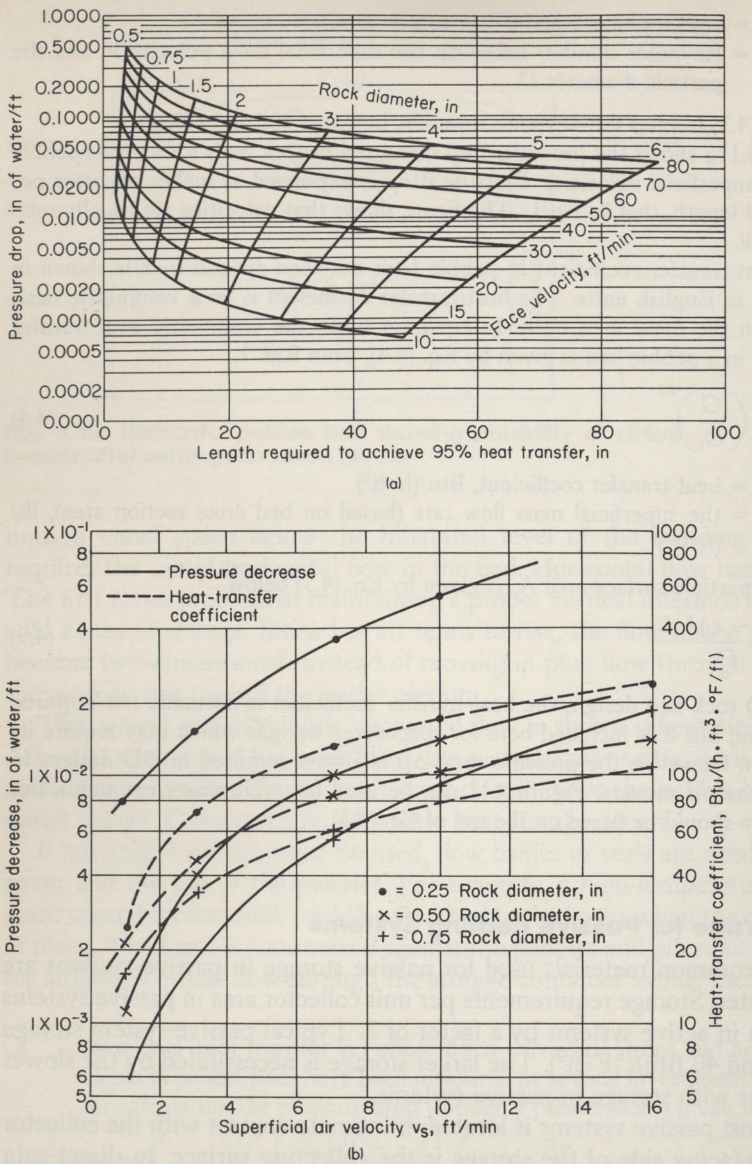

FIG. 4.11 (*a*) Rock-bed performance map showing pressure drop and air path length for various rock sizes and air velocities for sea-level conditions. *(From Ref. 57 with permission.)* (*b*) Heat-transfer coefficients and pressure drops per foot of depth for pebble beds of various size. *(From Ref. 28 with permission.)*

Absorptance. The color of conventional passive storage is determined in part by thermal requirements but more importantly by appearance. A dark color, of course, is essential; however, the color need not be black. A green or gray dye or paint may have an absorptance of 80 percent—10 percent less than black paint—but may be more acceptable from an appearance viewpoint. Slate colors have an 89 percent absorptance; red paint has between 75 and 80 percent absorptance. Since these absorptances are below the value of black paint, a somewhat larger aperture area is required to achieve the same thermal performance.

The absorptance of unfinished concrete is only 60 percent and is probably too low for an economical passive system. See appendix Table A.12 for a tabulation of absorptances.

The designer should specify the finish to be used on both sides of storage walls. It is not essential that the surface of masonry walls be perfectly flat. Since the flow over these walls is laminar, the pressure drop is not sensitive to the microcharacteristics of the surface. Therefore, an attractive texturing of these surfaces is possible with little thermal performance effect. This is particularly noteworthy regarding the interior wall surface. A decorative design can even be cast into the wall as it is poured.

The interior of TSW's should not present a barrier to heat transfer. At most, only paint should be applied. No paneling, insulation, or other heat-flow obstructions are permitted on the inner surface of the storage element. Further, the DD drawings should contain a note specifying that no large furniture or other obstructions to natural air circulation or radiation be placed immediately adjacent to the wall. Of course, baseboard heaters should be placed on walls other than those used for storage.

Weight. Thermal storage for passive systems is heavy. The design of the structure and foundation to support storage is the responsibility of the structural engineer, who must know the storage mass to be used before the foundation can be designed. Soil properties collected during the programming phase will be used by the structural engineer to size and shape the foundations below passive storage walls. In locations with expansive soils, the foundation may be rather complex and the cost high. This cost must be included in the economic analysis of solar heating described later in this chapter.

Wall Construction. The designer must consider the method by which the storage wall will be assembled. Windows in the wall require structural support above them. The size and shape of storage-wall vents has structural implications. If a relatively wide but narrow vent is used, the structural impact is great since the remaining relatively small nonvent area must support the entire wall mass above the lower vent. Preferably, use a relatively tall vent with reduced width achieving the same flow area.

The designer must also include instructions on the drawings requiring the concrete contractor to properly fill the wall area below the vent. The vents will normally be formed by 2 × 4 knockouts. It is important that concrete fill the entire area below the vents—approximately 6 to 8 in above the floor elevation. Proper vibration of concrete ensures that no entrained air is trapped in the wall.

Wall Air Gap. The space between the sun-facing surface of thermal storage walls and inner glazing of passive windows is normally 3 to 4 in wide. This dimension is not critical and may be adjusted to accommodate specific designs of movable insulation and windows. The window-to-wall gap should not be made excessively large, since a thermal circulation loop could be formed between the relatively cool glass and the wall. Heated air rising along the surface of the storage wall loses heat to the glass. The cooled air sinks to the base of the wall. Useful heat flow into the space is thereby reduced.

Insulation of passive walls is described on pages 240 to 242.

Storage Sizing

Active Systems. Most active heating systems of standard design have storage volumes independent of geographical area. For liquid systems, the storage amount is between 1.5 and 2 gal of water per square foot of net collector aperture area. For air systems, ½ to ¾ ft^3 of rock per square foot of collector area is normally used. These are not critical values, and variations of 10 or 15 percent will have almost no effect on thermal performance.

The key to proper storage sizing is to use a volume that is not below the knee of the performance curve (e.g., Fig. 4.5). For example, liquid systems with a storage volume below 1.2 $\mathrm{gal/ft}^2$ will have poor performance. However, doubling liquid storage will result in only a 5 to 10 percent increase in annual energy delivery. Oversized storage is expensive and will rarely pay itself off in increased fuel savings. Seasonal storage is not economical in small installations and is not considered in this book. For larger district installations, the inverse heat-loss relation to size may result in economies of scale sufficient to justify the method. Further, seasonal storage may be appropriate in certain severe climates where sunlight is rarely available in winter if a very large storage volume can be charged in summer.

Passive Systems. The sizing of passive system storage is a trade-off between comfort and thermal performance. For example, a TSW system will have roughly the same thermal performance for an 8-in wall as for a 15-in one. The designer would select an 8-in wall because of its 50 percent lower cost. However, relatively thin walls will have large temperature excursions at the inner surface. These temperature swings affect the mean radiant temperature and hence thermal comfort.

An increase in wall thickness to 12 in is recommended to maintain good comfort levels. The 50 percent volume increase is determined by comfort and not by thermal performance criteria. The amount of storage in water walls is approximately the same, on a thermal basis, as in masonry walls. Between 30 and 40 British thermal units per degree Fahrenheit per square foot of aperture area are required. This is equivalent to 4 to 5 gal of water per square foot of net aperture. If storage is increased beyond these nominal levels, little performance gain is achieved and costs rise because of larger container costs and larger foundation requirements to support the increased storage mass.

The amount of storage surface area required in direct-gain systems using indirectly illuminated heated storage is approximately 3 times that for directly illuminated storage (25).

HEAT EXCHANGERS

The solar designer must minimize the detrimental effects of heat exchangers, subject to the constraint of cost effectiveness. In large system designs, this is done during the DD economic study. The designer of smaller systems can use information in this section to size the heat exchanger without going through a detailed economic analysis. The conclusions below are based on the trade-off of heat-exchanger cost and the value of energy penalty incurred by the heat exchanger.

This section will describe three types of heat exchangers used in active systems: (1) between the collector loop and the storage tank in liquid systems or between the storage tank and a domestic water-preheat tank; (2) between storage and the heated space; (3) between solar-heated air and the domestic water preheat system, as shown in Chap. 2. Performance characteristics for heat exchangers are presented in Chap. 2 and are not repeated here.

Liquid-to-Liquid Heat Exchangers

Liquid-to-liquid heat exchangers used in solar heating systems are of the tube-and-shell configuration. Since the effectiveness of the heat exchanger, as described in Chap. 2, must be relatively high for solar applications, counterflow designs are most often specified. Counterflow heat exchangers have the largest effectiveness for a given number of transfer units (NTU) and given capacitance ratio $(\dot{m}c_p)_{\min}/(\dot{m}c_p)_{\max}$. Immersed-coil heat exchangers have low heat-transfer coefficients, requiring relatively large heat-transfer areas to achieve a given UA product. However, submerged coils are less expensive than shell-and-tube exchangers and they may be appropriate for some applications. The design of submerged-coil heat exchangers is a mixture of art and science since the convection cells set up within the storage tank surrounding an immersed coil have not been carefully measured. Therefore, the free-convection heat transfer is not well represented by empirical equations useful to the designer. An understanding of the physical processes accompanying free convection in containers is useful to the designer, who must specify coil diameter, location, and size.

In solar designs, the heat exchangers are specified by their effectiveness. Heat-exchanger manufacturers do not use the effectiveness concept in their computerized design programs but rather use the log-mean-temperature method. It is the responsibility of the solar designer to translate an effectiveness specification into a form which can be used by the heat-exchanger manufacturer. The steps of the method are relatively straightforward. The designer selects an effectiveness, usually 70 to 80 percent for liquid-to-liquid heat exchangers. This effectiveness and the age. The performance of a system can be checked by repeatedly reinserting the same instrument in several locations to measure either pressure or temperature.

In summary, pressure and temperature instrumentation should be inserted at each point in a fluid loop where either a pressure rise or heat addition takes place. Included are heat exchangers, collectors, storage tanks, terminal load devices, pumps, and heat-rejection loops.

Gaskets and Seals

If improper materials are used for seals and gaskets, they will have a very short lifetime since the operating conditions in solar collector loops are quite severe, especially if organic fluids at high temperatures are used. An excellent summary of the proper materials to be used for gaskets and seals in liquid-based solar systems is provided in Ref. 33. Most solar component manufacturers are aware of these restrictions, and the designer need only check these details.

DESIGN DEVELOPMENT CONSIDERATIONS FOR PASSIVE HEATING SYSTEMS

Most of the material in this chapter on design development has dealt with active systems for space and water heating. The reason for this is twofold. First, field experience with active systems far outweighs that for passive systems. For example, during the solar demonstrations sponsored by the U.S. Department of Housing and Urban Development in the mid- and late 1970s, hundreds of active systems and only a very few passive systems were built. It was only in the late 1970s and early 1980s that passive systems were explicitly funded for federal demonstration. Performance data from these systems operating over several years are not yet available. A second reason for the emphasis on active systems in the previous part of this chapter is that the design effort for active systems is hardware-oriented. That is, the specification of the system requires the specification of the performance of many components, each of which is used in a slightly different fashion than in a conventional heating system.

Passive systems are not hardware-oriented. Therefore, the specification of these systems is less lengthy than for active types. However, the design of passive systems is no simpler than for active systems. The added complexity comes not from hardware requirements and detailed control strategy design but rather from the proper interaction of passive-heating-system dynamics with building dynamics. This is an area in which much is yet to be learned and few design guidelines currently exist. In this section, the DD-level information required to specify systems of the TSW or direct-gain type as well as hybrid system is described. Since field experience on passive systems is so minimal, the coverage of passive design cannot be as exhaustive as the preceding coverage for active design.

Passive System Apertures

Passive system apertures are usually vertical in orientation, south-facing, and composed of one or two glass panes. The selection of the glass to be used must consider the loading on the glass, solar transmittance, and thermal properties. It is desired, within the constraints of cost, to have the highest transmission and the lowest absorption possible. This can be accomplished theoretically by using low-iron glass, although this material is frequently not available in the large sheets useful for passive glazing.

A more important consideration in the selection of a glazing material is the structural strength. Large south-facing glass surfaces near ground level present tempting targets for vandals; tempered glass is therefore to be specified. Tempered glass is also essential for the inner surface of double-glazed passive apertures. This glass in summer can reach temperatures in the vicinity of 200°F, and untempered glass is certain to break eventually from thermal stresses which occur at shadow lines. The designer should ascertain in addition that the edges of all glass panes have been smoothly polished prior to tempering. Any nicks can cause a stress concentration and fracturing of the glass. This is a particular problem during part-load periods of the year when the glazing will be partially in sun and partially in the shadow of the glazing overhang. The temperature difference between the two parts of the same sheet of glass can be considerable and any imperfection in the glass will tend to promote fracture.

It is essential that glazing be properly sealed to the building to avoid infiltration losses which can destroy the proper function of a thermal circulation loop. Seals must be selected with somewhat more care than conventional fenestration. Seals will be subjected to substantial levels of ultraviolet radiation with concurrent elevated temperatures. These two conditions, when combined, result in relatively rapid chemical reaction rates in the seals, and their deterioration can be rapid unless proper inhibitors are present. If operable vents for summer heat rejection are provided, these too must be sealed to withstand wide ranges of operating temperature during the course of a year.

Adjacent glazing panels are frequently overlaid with a common cap strip for appearance and sealing purposes. As with any other component of the glazing subsystem, these strips will be subject to significant expansion and contraction during the course of a year. Any holes, for example, used for mounting these strips to the passive aperture structure must be relatively large compared with the screw diameter to accommodate motion which is certain to occur.

The location of windows is another feature of passive-aperture design. For daylighting purposes, it is desirable to have windows located as high in the space as possible. However, from a heating standpoint it is desirable to have windows lower in the space so that stratification is minimized and lower as well as upper parts of the space are equally heated. In addition, the relative magnitude of direct-gain aperture vs. TSW aperture should be considered by the designer. These matters have not been quantified in sufficient detail to provide regional guidelines on the relative percentages of each. Experience in a few limited locations has indicated that approximately one-quarter to one-third of the total passive aperture should be direct gain to provide a quick warm-up in the morning. The balance of the passive aperture used for heating should be backed with storage elements to insert a phase lag between the capture of heat and its release to the space.

The design of daylighting systems is an ancient art which has been lost in recent times. The rediscovery of principles of daylighting and the size of aperture required to achieve a given footcandle level is presently being reestablished, although guidelines useful at the DD level do not presently exist. Reference 36 is an introduction to the use of natural daylighting in buildings.

The recommendation of Lam (36) is to prepare a scale model using proper materials with appropriate absorptance and reflectance values, and to carry out daylighting design and glare analysis in this fashion. The use of models is a typical architectural exercise but the use of daylighting models will require more care in the construction of internal spaces. A model is useful since it can be oriented in any direction. A set of daylighting readings taken inside the model at critical locations by a small photometer will indicate expected daylight levels in the final building.

Passive Storage Elements

The general characteristics of passive storage have been described earlier in this chapter in the section on thermal storage for passive and active systems (pages 179 to 182). In this section, specific details of the design of passive storage walls are presented.

Passive storage design determines the rate of release of solar heat to a space. The thickness of the wall, as described earlier, is determined more by comfort considerations than strictly by technical criteria such as the annual solar fraction $\bar{f}_s$. Since a TSW is a source of heat, it must be insulated from the environment. Insulation from the exterior during the day is achieved over the large aperture area by using double-glazed windows. The insulation at the bottom of the wall is more difficult but equally important. Since the mass of storage walls is very large, it is not possible in most cases to interpose a layer of structural insulation between the wall and the foundation. Heat loss control is best accomplished by adding insulation to the perimeter of the floor slab as well as underneath the slab in the vicinity of the TSW. A complete thermal break is rarely possible, but all sources of conduction from the wall to the environment should be identified and minimized by design during the DD phase.

Thermal storage for direct-gain systems is best distributed around the space to be heated to expose the maximum storage area possible (37). This storage can be thinner than that used in a directly illuminated TSW, but no thinner than 4 in. Performance of direct-gain systems increases as storage mass is added, the limit being the available surface of all walls in a direct-gain space. This is contrary to the performance of a TSW system, where an optimum amount of mass storage exists of the order of 30 to 40 Btu/(ft^2 · °F). For larger masses, the performance of a TSW system begins to fall off, whereas for a direct-gain system it continues to improve. Although an upper limit to the amount of storage for a direct-gain system does not exist from a technical point of view, economic limitations and the sheer physical size of direct-gain storage do place an upper limit on the storage mass.

The optimal amount of storage for most passive systems corresponds to diurnal storage—that is, storage adequate to carry the building through a night following a sunny day. Storage amounts capable of carrying the building through more than two or three sunless days are frequently uneconomical. This consideration is the basis of the rules suggested above for the size of storage.

Thermal-storage walls incorporate thermal circulation vents in most parts of the United States. The sizing of these vents is determined by the solar load fraction as described in Chap. 3. For small solar fractions, the vents are relatively large. Figure 4.35 shows the recommended vent size vs. solar heating fraction (37). The optimum solar heating fraction to be used depends upon aperture area and cost as described in Chap. 3. Once the cost-optimal solar fraction has been identified, the proper vent area can be read from the curve. Note that Fig. 4.35 applies for *one-story walls;* taller walls require more airflow and bigger vents to prevent excessive air overheating. No quantitative information is available.

Thermal circulation vents require backdraft dampers. Backdraft dampers are best placed at the inner surface of the upper vent as shown in Fig. 4.36. The upper vent is blocked by the damper when any tendency to backflow occurs. The same effect could be achieved by a backdraft damper placed at the outer surface of the lower vent, but repair of this damper would be impossible, and therefore the upper location is preferred.

The inlet to the lower vent should be located several inches above the floor to make certain that no obstructions are placed in front of it. In addition, a coarse

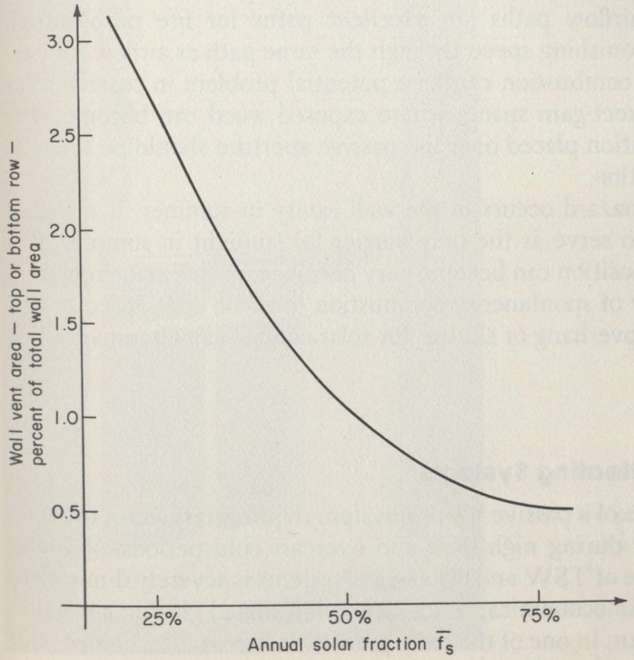

FIG. 4.35 Thermal-storage-wall vent size as it relates to annual solar heating fraction.

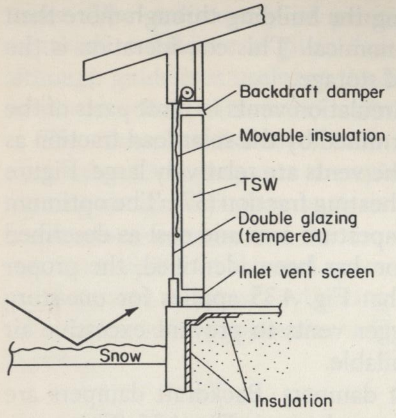

FIG. 4.36 TSW cross section showing vents with backdraft damper and inlet screen.

screen covers the opening. This prevents anything from being placed in the duct or in the wall cavity. A screen with ¼-in mesh is adequate for this purpose.

The potential for fire should be considered. In the design of the wall cavity and heat circulation path, the designer tries to optimize the free movement of air within the structure so that passive heat can contribute as much as possible to the heating load. However, passive airflow paths are excellent paths for fire propagation. Flames can move with astonishing speed through the same path as airflow for passive system. Spontaneous combustion can be a potential problem in passive solar buildings, especially in direct-gain spaces where exposed wood can become very dry. In addition, the insulation placed over the passive aperture should be selected with regard to fire prevention.

Another potential fire hazard occurs in the wall cavity in summer. If movable insulation is relied upon to serve as the only barrier for sunlight in summer, this insulation in the lowered position can become very hot since no thermal circulation will occur. The possibility of spontaneous combustion must be considered in this context as well. Use of an overhang or shutter for solar control can circumvent this particular difficulty.

Insulation for Passive Heating Systems

The optimum performance of a passive heating system requires insulation to retain solar heat in the building during nighttime and overcast cold periods. Without insulation, the performance of TSW and direct-gain systems is severely diminished and in many cases will be uneconomical, since large uninsulated glazing areas permit large heat losses to occur. In one of the early passive demonstration homes built in the United States in the mid-1970s, insulation was not used for cost reasons. As a result, in winter, the thermal-storage wall dropped to 20 or 30°F below the room temperature during long cold periods and was a source of great discomfort to the occupants. A surface at 40°F located in a room at 70°F acts as a large heat sink.

Several types of movable insulation have been developed. The insulation for a TSW passive system must be capable of being raised in the wall cavity. This can be accomplished by using a roll-up insulation of the type shown in Figs. 4.36 and 4.37 or some alteration in this design, or by using a system composed of particles of styrofoam which are blown into and out of the cavity between the two double-glazing panes. This approach has seen some difficulties because of the static charge which accumulates on styrofoam beads. Some beads remain stuck to the glazing as a result. For appearance purposes, many designers have rejected the use of beads. Movable insulation is currently available from only a very few manufacturers. It is assumed that other manufacturers will market new products in the next few years as a result of the federal incentive for passive-component design initiated in 1980.

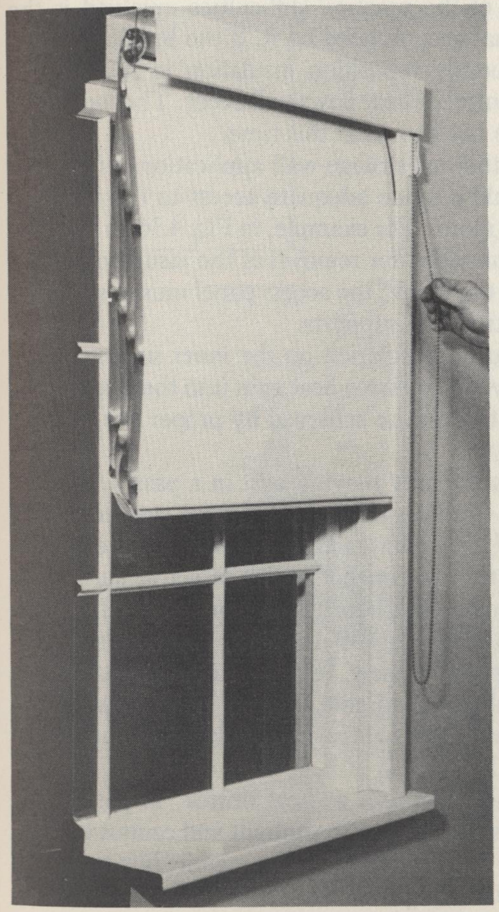

FIG. 4.37 Example of movable passive insulation. *(Courtesy of Insulating Shade Co.)*

A nominal value for insulation for passive TSW applications is approximately R-9. Other R values can be used, and the effect on solar heating fraction based on the R-9 level can be calculated from Eq. (4.15), which is from Ref. 37.

$$\frac{\bar{f}_{S,R} - \bar{f}_{S,R=0}}{\bar{f}_{S,R=9} - \bar{f}_{S,R=0}} = \frac{1 + R_0/9}{1 + R_0/R} \tag{4.15}$$

where $\bar{f}_{S,R}$ = the annual solar fraction with insulation level R
R_0 = the wall R value for no insulation; equal to 3.2 for water wall, 4.6 for TSW
R = wall resistance value other than R-9

Passive apertures can be insulated outside the wall glazing instead of inside the glazing. Although a less common approach than the internal glazing method, this approach is technically feasible. One of the practical difficulties involved is the moving of insulation after a snowfall has accumulated on it. If the building owner or manager is not present to continuously reposition insulation in response to changing weather, less than optimal control of heat flows will occur. The long-term durability of exterior insulations is also not known at this time.

Servicing of movable insulation in thermal-storage-wall applications presents a potential difficulty. The designer should provide adequate access to the thermal-storage-wall retraction mechanism and motor. For example, in Fig. 4.36 an opening above the upper TSW vent could be provided for removal of the insulation roller. Since the insulation is the full width of the TSW, the access panel must also be the full width and not be interrupted by structural supports.

Some systems have been designed using insulation on the inner surface of the thermal-storage wall in summer to prevent excessive heat gain into the space. This feature is not necessary since heat control can be achieved by proper use of movable insulation and overhangs.

Since movable insulation represents the only moving part in a passive system, alternative, more reliable methods for heat-loss control have been studied. Many owners reject movable insulation out of hand owing to its perceived poor reliability and human input for operation. An alternate concept uses a selective surface on the TSW. Computer studies have shown that heat losses from a selective wall surface are only slightly greater than from an R-9–insulated wall surface (57). Although promising from a technical point of view, few buildings have used this approach to date. If used, it is essential that a durable thermal bond between the wall and the selectively plated metal exist at all points. This is absolutely necessary to ensure proper transfer to storage.

Another method of reducing wall heat loss uses a "heat mirror" as part of the passive glazing system. A heat mirror is transparent to sunlight and cannot be seen by the naked eye. It is a reflector in the far infrared radiation regime, however, and does not permit low-temperature heat radiating from the TSW to be absorbed and reradiated by the glass. Heat mirrors have been used in Europe for several years and are beginning to become available in the United States.

Heat Rejection

The rejection of heat during low-heat-load periods of the year is as much a problem with passive systems as it is with active systems. The principal methods of heat control for vertical surfaces are shutters, louvers, and overhangs as shown in Fig. 4.38. Overhangs when properly sized can provide a complete cutoff of direct sunlight to a TSW. The size of overhang is determined by the period for which shad-

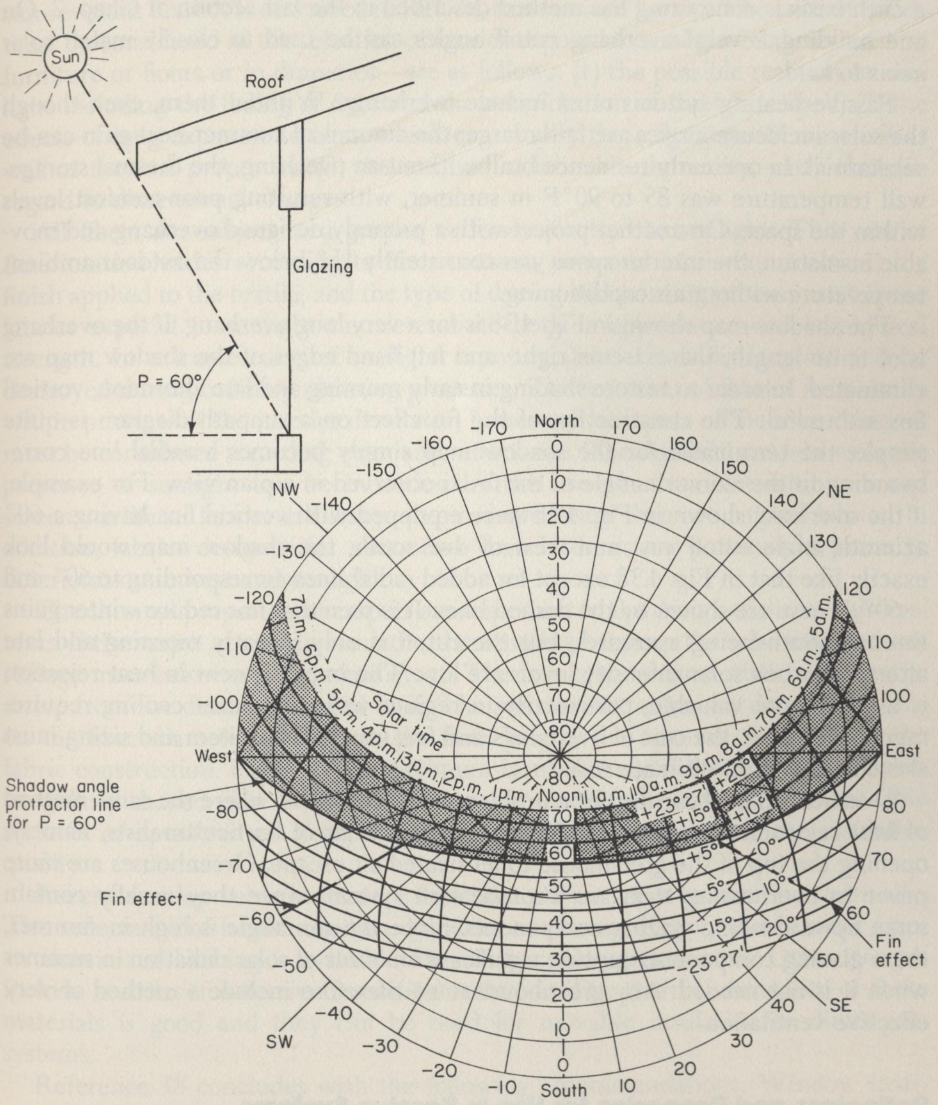

FIG. 4.38 Roof overhang design by sunpath-diagram method; 60° profile angle corresponds to heavy line; 60° azimuth fins add triangular zones shown by dashed lines.

ing is desired. The sunpath-diagram approach described in Chap. 3 can be used for quick design of these systems. For example, when the image of the overhang shown in Fig. 4.38 is superimposed on a sunpath diagram for 40° north latitude, it is clear that shading will occur from mid-April through the end of August. If the profile angle *P* shown (60°) results in either too long or too short a solar blockage period, the overhang can be adjusted accordingly. The sunpath diagram shows that the cutoff of sunlight does not completely occur on a given day but progressively during approximately half a month. The calculation of the shading effects on a month-by-month basis is done using the method described in the last section of Chap. 2. On one building, several overhang cutoff angles can be used to closely match solar gains to loads.

Passive heating systems must include overhangs. Without them, even though the solar incidence angles are fairly large, the amount of summer heat gain can be substantial. In one early residence built without an overhang, the thermal-storage-wall temperature was 85 to 90°F in summer, with resulting poor comfort levels within the space. On another project with a properly designed overhang and movable insulation, the interior space was consistently 15° below the outdoor ambient temperature without air conditioning.

The shadow map shown in Fig. 4.38 is for a very long overhang. If the overhang is of finite length, the extreme right- and left-hand edges of the shadow map are eliminated. In order to restore shading in early morning and late afternoon, vertical fins are useful. The construction of the fin effect on a sunpath diagram is quite simple; the terminator for the shadow map simply becomes a radial line corresponding to the azimuth angle of the fin as observed in a plan view. For example, if the overhang shown in Fig. 4.38 were equipped with vertical fins having a 60° azimuth angle cutoff east and west of due south, the shadow map would look exactly like that in Fig. 4.38 except for added radial lines corresponding to 60° and −60°. These are shown by the dashed lines. It is seen that fins reduce winter gains through south-facing apertures, but the cutoff is only in early morning and late afternoon when solar intensity levels are low. The improvement in heat rejection is usually more valuable, particularly in regions with significant cooling requirements. However, the cost of overhangs and fins is not a small item and sizing must also consider their ultimate cost.

Overheat control can also be a problem in greenhouses, where the same method of heat rejection has been used by many generations of horticulturalists, namely, opening the top of the greenhouse to let heated air escape. Greenhouses are more prone to overheating than are Trombe wall systems since they usually contain some upward-facing glazing components. Since the sun angle is high in summer, these glazing components capture significant amounts of solar radiation in summer when it is not needed. Any greenhouse must therefore include a method of very effective ventilation.

Reflectors and Draperies for Use in Passive Systems

The performance of a passive heating system can be significantly enhanced by placing a horizontal reflector immediately to the south of the aperture. The reflection effect can cause a 30 to 40 percent increase in the amount of solar radiation striking the passive collector. Practical difficulties occur with the use of reflectors, the most notable of which is the accumulation of snow and dirt. The reflection effect of clear snow can be nearly as significant as that for a reflecting surface such as weathered aluminum.

Direct-gain solar systems place severe requirements on fabrics and materials used in the space to be heated. These requirements are not present in TSW systems; this is one of the advantages of TSW systems. The method of selection of sun-resistant textiles is described in Ref. 38, summarized herein. The criteria which must be considered in the selection of fabrics exposed to sunlight—fabrics used on furniture or floors or in draperies—are as follows: (1) the possible reaction to sunlight including the fading of dyes and the deterioration of the fabric itself; (2) the effects of long exposure to heat, which can modify the reflectance of materials as well as thermal properties; (3) the reaction of fabrics to humidity, particularly in regard to dimensional changes.

All fibers are subject to a greater or lesser reaction to sunlight. This rate of deterioration varies according to fiber content, yarn and fabric construction, the finish applied to the textile, and the type of dyeing and printing process used. Some fabrics exposed to sunlight can deteriorate both in appearance and in physical strength. In extreme cases of sunlight exposure, fabrics can disintegrate and be destroyed during ordinary cleaning processes. The selection of fabrics is normally within purview of the interior decorator; however, the inputs of the solar designer must be considered regarding color and reflectance. The durability of fabrics in the presence of sunlight can be increased by the use of ultraviolet inhibitors and screens; artificial fabrics are less prone to degradation than are natural fabrics. In addition, fabrics designed for uses other than interiors are particularly prone to deterioration in heat and sunlight.

The thermal properties of carpets are important in the design of direct-gain systems. If the carpet acts as an insulator, the coupling between the solar heat and any storage mass below will be nonexistent. The insulative characteristics of a textile arrive from the dead air trapped in it. The amount of trapped air depends in turn on the fiber diameter and shape, the fiber length, the amount of twist, and the fabric construction. Fabrics with maximum insulative characteristics use crimped, irregularly shaped fibers with low-twist yarns made from crimped filament. Pile surfaces or open weaves along with expanded foam mats increase the insulative quality.

Recent developments in drapery materials permit them to function thermally. The reflectance of fabrics used on draperies can be significant, and in some cases an aluminized backing is available for summer solar gain control. Other designs include multilayer reflective insulation materials. The thermal durability of these materials is good and they can be used for movable insulation in direct-gain systems.

Reference 38 concludes with the following recommendations. Window treatments can use acrylics, fiber glass, nylon, and polyester fabrics. Upholstery exposed to sunlight can best use acrylics, cotton, and leather as well as linen, nylon, polyester, silk, vinyl, and wool. Leather and vinyl have negligible moisture absorbency,

TABLE 4.4 Use conditions for metals in contact with aqueous heat-transfer fluids in closed solar heating systems*

Generally unacceptable use conditions	*Generally acceptable use conditions*
Aluminum	
When in direct contact with untreated tap water with pH <5 or >9.	When in direct contact with distilled or deionized water which contains appropriate corrosion inhibitors.
When in direct contact with liquid containing copper, iron, or halide ions.	When in direct contact with stable anhydrous organic liquids.
When specified data regarding the behavior of a particular alloy are not available, the velocity of aqueous liquids shall not exceed 4 ft/s.	
Copper	
When in direct contact with an aqueous liquid having a velocity greater than 4 ft/s.	When in direct contact with untreated tap, distilled, or deionized water.
When in contact with chemicals that can form copper complexes such as ammonium compounds.	When in direct contact with stable anhydrous organic liquids.
	When in direct contact with aqueous liquids which do not form complexes with copper.
Steel	
When in direct contact with liquid having a velocity greater than 6 ft/s.	When in direct contact with untreated tap, distilled, or deionized water.
When in direct contact with untreated tap, distilled, or deionized water with pH <5 or >12.	When in direct contact with stable anhydrous organic liquids.
	When in direct contact with aqueous liquids of $5 < \text{pH} > 12$.
Stainless steel	
When the grade of stainless steel selected is not corrosion-resistant in the anticipated heat-transfer liquid.	When the grade of stainless steel selected is resistant to pitting, crevice corrosion, intergranular attack, and stress corrosion cracking in the anticipated use conditions.
When in direct contact with a liquid which is in contact with corrosive fluxes.	When in direct contact with stable anhydrous organic liquids.
Galvanized steel	
When in direct contact with water with pH <7 or >12.	When in contact with water of pH >7 but <12.
When in direct contact with an aqueous liquid with a temperature $>55°$C.	
Brass and other copper alloys	
Binary copper-zinc brass alloys (CDA 2XXX series) exhibit generally the same behavior as copper when exposed to the same conditions. However, the brass selected shall resist dezincification in the operating conditions anticipated. At zinc contents of 15 percent and greater, these alloys become increasingly susceptible to stress corrosion. Selection of brass with a zinc content below 15 percent is advised. There are a variety of other copper alloys available, notably copper-nickel alloys, which have been developed to provide improved corrosion performance in aqueous environments.	

TABLE 4.4 (*Continued*)

*From Ref. 33.

so comfort levels are reduced when compared with the other fabrics listed. Floor covering materials exposed to direct sunlight can include acrylic, nylon, polyester, and natural wool. Dyed wool is not recommended, since it has little resistance. The optimum properties of any fabric exposed to sunlight include minimal loss of tensile strength, good heat resistance, minimum moisture absorptance and dimensional change, and good resistance to air pollution. Carpet and fabric manufacturers have long been aware of the problems with textiles exposed to sunlight, and consultation with an informed vendor may be the best method of quickly acquiring this information.

OTHER SYSTEM DESIGN CONSIDERATIONS

The information presented in the preceding sections of this chapter covers most of the detailed component information required for active and passive system design. Of course, the general material to which these details refer was presented in Chaps. 2 and 3. In this remaining section, three additional systems considerations are described. The first is the selection of materials for use in liquid systems, the second is the effect of the law of diminishing returns on solar system performance, and the third is flow balancing in collector arrays.

In the selection of piping, storage, and collector materials, the relative electromotive activity of each must be considered. This has been described earlier. Additional considerations, however, are present in water-based systems because of special chemical interactions. A convenient summary of these data is contained in Table 4.4, in which the acceptable and unacceptable use conditions for five common metals used in closed liquid-based systems are given—aluminum, copper, steel, stainless steel, and galvanized steel.

Table 4.4 was presented in Ref. 33, the Minimum Properties Standards for solar heating systems. The most common materials used in liquid-based systems are copper and steel, which have few unacceptable use conditions in the table. Galvanized piping should not be used at temperatures above 140°F because of the reversal of the electromotive relationship between the galvanizing and the steel pipe above that temperature. Reference 33 contains a table for open systems similar to Table 4.4. Open systems are much less frequently used than closed systems because of not whipped about by the wind. In many cases, the sensor wiring is attached to the collector piping with cable ties for this purpose. Wiring can be run within the insulation of collector piping but future troubleshooting is rather difficult. The wiring should also be kept away from foot traffic. Sensor and controller wiring should be of the proper gauge, soldered, and color-coded.

Thermostats. The zone thermostats should be located in accordance with standard practice. They are located on interior walls and not exposed to either sunlight (important in direct-gain systems) or drafts. Likewise, they are to be kept away from radiant heat sources, including fireplaces, stoves, electronic appliances, and reflected sunlight.

Dual-point thermostats used in solar heating systems should be adjusted at the factory. The temperature band should be checked, however. The second contact should close 2 to 3°F below the closure of the first contact. This can be checked by setting the thermostat at a relatively high temperature. An ohmmeter across both contacts checks the thermostat as it is heated slightly with a hair dryer or other low-temperature heat source. The temperature of the thermostat can be monitored using a standard dial thermometer located near the temperature sensor.

Controller Location. The location of the control unit is important. Most controllers use solid-state devices requiring a relatively uniform temperature throughout the year. The location chosen should be ventilated, have easy access, and be away from heat sources such as the solar storage tank or safety valve release points where steam could be present.

The controller should be wired on an unswitched circuit so that an inadvertent operation of the switch would not deactivate the control circuit, with associated serious problems of overheated collectors, etc. The control should be capable of being deactivated, however, by means of an internally grounded shutoff switch. If the control unit is located in the mechanical space where moisture may be present on the floor, a wooden platform should be provided for persons working on the control box.

Before the control system is tested, all wiring should be rechecked. Solid-state circuits are easy to destroy by application of a voltage of the wrong type at the wrong place. Warranties do not cover this. Color-coded wires are useful. Control triac failures are the most common and result from incorrect wiring, shorts, or voltage spikes.

Passive Heating Systems. It is noted at the beginning of this section that the installation of passive systems is less complicated vis-à-vis active systems. The opportunity for error is reduced since the mechanical complexity of the system is less and the number of components involved is smaller.

Backdraft dampers used in TSW systems require careful installation. There is only a very small density difference available to hold backdraft dampers closed; therefore, a flat-seal surface must be provided for these light-gauge plastic valves. Rectangular or round openings can be used as specified on the drawings. The backdraft damper must be free to open.

Concrete Work. Passive systems using either water or masonry storage require larger foundations as shown on the drawings. The inspection of these pours must be made early in the construction process to assure that the proper thickness has been used.

The pouring of large masonry storage walls is a major process. The size of walls used in passive systems is of the proportion of major structural elements of bridges or large buildings. Walls are typically 8 to 10 ft high, 10 to 20 in thick, and as long as the side of a building. The pressure imposed on forms used for pouring walls of this size is enormous. It is possible to pour the wall in sections. However, a monolithic wall is best relative to good heat transfer.

Plywood forms are normally used for passive walls unless a specific wall texture is required, but metal and plastic forms can also be used and reused. Ties holding both sides of the form together are usually made from metal and remain within the wall after the forms are removed. Framing for the forms uses sheeting lumber, nails, wire, and cable ties. Large 2 × 4 or 2 × 6 units (called whalers) are used for additional structure and support near the bottom edge of the wall. The basic wood materials used are 4 × 8 × ¾ plywood and 2 × 4's.

The openings in thermal-storage walls are formed by knockout inserts within the form. The location of window openings and thermal-storage-wall vents can be drawn on the form itself during its assembly. As one form wall is located (perfectly plumb and level), the window openings in that area should be laid out on the form. Beveled window openings ensure proper removal of their forms. One piece of the window form is attached to the standing form panel and the second half is suspended from the first. A chamfer strip around windows and along the top of the wall will eliminate sharp edges on the concrete which would be potential breakage points.

The placement of reinforcing steel occurs next. Horizontal steel is wired to vertical steel on 16-in centers, and the vertical steel is wired to anchors projecting from the wall foundation. Additional steel over window openings or vent areas is installed at this time. If temperature sensors are to be used in the wall, they can be supported by the steel during this part of the wall-construction process. Next, the second surface of the form is installed, and bulkheads are added to close out the ends of the wall. The form is completed by the addition of whalers.

The concrete is injected into the form by pump or crane and bucket. The mixture must be vibrated to prevent air pockets from occurring and to distribute concrete evenly within a form. The pour should be made all at once if possible. Particular attention to areas beneath TSW lower vents is suggested. Following wall curing, the form is removed by breaking off the snap ties just inside the wall surface. Final touch-up and repair of the wall are done at the same time.

The curing of concrete occurs in two separate ways. Concrete is able to support its design load within a matter of weeks. However, the hydration reaction which converts concrete to a masonry unit may take several years. During this time, moisture deep within the wall reacts to form a chemical hydrate. The heat of reaction is in part solar heat (causing the energy delivery of the passive system to be below design for the first 2 or 3 yr). The wall can be painted, however, in a much shorter time. See Ref. 71 for further details.

Glazing and Insulation. Glazing is installed to the south of the thermal-storage wall after it has been poured and the forms removed. (Glazing is difficult to install in winter.) Since glazing inner surfaces are not accessible after installation, it is absolutely essential that they be perfectly clean. Construction dust can collect on the inner surface of the glass, and therefore all thermal-storage-wall openings and vents should be taped since the glass cannot be cleaned easily once installed.

Automatic movable insulation requires adjustment of the limit switches controlling the position of the insulation. If the roll-up type of insulation is used, the limit switches are adjusted at the bottom and top of specified travel. Proper insertion of the shade in its track is also essential to proper function. Adjustment of the insolation sensor is completed during start-up, as described below.

Liquids. After the leak test, the working fluid can be installed. If the collector fluid is to be mixed on site to achieve the specific gravity required for freeze protection, this can be done using the information given in Table 5.3. The pH is also to be checked at this time if the solution is an electrolyte. A toxic fluid which has not been color-coded can be dyed with a vegetable dye at this time. The dye identifies the fluid as a nonpotable liquid in case it leaks in the future. If a collector loop is filled from the roof with glycol, it is important to keep it off the roof. Glycols dissolve some roof materials. (See page 339, "System Cleaning.")

Instruments. Instrumentation installation for system performance monitoring is detailed in several references produced by the National Solar Data Network. This exercise is not a part of the normal system installation effort and is not described herein. However, most solar systems will have instrumentation present at least for simple functional checks. The location of this instrumentation is called out on the working drawings.

Sensors for temperature readout should be isolated from external heat sources by insulation. Pressure gauges should be installed with shutoff valves. Flowmeters require the proper length of straight pipe both upstream and downstream in accordance with manufacturer's requirements (see Fig. 5.6).

TABLE 5.3 Glycol specific gravity vs. freeze point*

	Ethylene glycol		*Propylene glycol*	
Freeze point, °F	*Percent by weight*	*Specific gravity*	*Percent by weight*	*Specific gravity*
20	16	1.028	19	1.021
10	26	1.044	29	1.035
0	33	1.055	36	1.047
−10	40	1.069	43	1.058
−20	45	1.078	48	1.066
−30	49	1.086	52	1.072
−40	53	1.094	55	1.077
−50	56	1.102	57	1.081

*Adapted from Ref. 32 with permission.

If a solar-radiation sensor is to be installed in the vicinity of the collector array, it must not be shaded at any time during the year. Other instrumentation such as level alarms, site gauges, and pump hour meters are installed in the normal manner.

System Start-up

At the completion of construction, the solar system will have been leak-checked and the controls debugged. The start-up of liquid systems is treated first in this section and is followed by a discussion of air systems and passive heating systems.

System Cleaning. Before the working fluid is installed in a liquid system, the system should be flushed with a low-sudsing detergent. Alternatively, solutions of trisodium phosphate (1 lb to 50 gal), sodium carbonate (1 lb to 30 gal) or sodium hydroxide (1 lb to 50 gal) can be used. Commercial products such as Betz Labs 346, Calgon Vantage, Chemed Corp. BC-45, Drewsperse-78, or Nal Clean 8910 work well. The purpose of flushing the system is to remove any metal particles, solder flux, or other material left from system assembly. The refuse entrained in the circulating water is trapped in the strainer and drained periodically during flushing. After the coarse material has been collected by the strainer, the filter may be installed. Increasing pressure drop across the filter indicates that the filter element is removing additional material from the fluid stream. The element may be replaceable or cleanable. The element is cleaned and reinstalled until a steady filter pressure drop occurs. A strainer or filter must be present in the fluid loop from the first operation in order that the collector, pumps, and valves remain clean.

If several collector subarrays are connected in parallel to form the full array, each collector bank can be isolated in turn by shutting off all others to increase the flow velocity through that bank. For example, if four rows of collectors are involved in an array, the shutoff valves for three of the four can be closed and all available fluid pumped at high velocity through the remaining bank. This higher flow rate will entrain any material in relatively low-flow-velocity areas of the array. This procedure is carried out in turn for each row of the entire collector array, ensuring the maximum possible cleaning effect. At the end of the row-by-row cleaning step, of course, each collector row valve will be reopened. After the system has been flushed, the flushing solution should be drained and washed from the fluid loops. The volume drained can be used to estimate the required amount of fluid needed for the final fill.

The flushing of systems which do not use water-based working fluids is somewhat more difficult. Since organic and silicone oils are very expensive, it is not practical to flush the system with these oils and then discard the fluid. The only method which seems appropriate for these fluids is to repeatedly empty the strainer and filter.

System Charging. The first step of start-up for a liquid system is charging the various fluid loops. Prior to filling the collector loop with antifreeze solution, the system should be filled with water and as much air as possible ejected through

TABLE A.12 Solar Absorptance of Various Passive Wall Materials

Optical flat black paint	0.98
Flat black paint	0.95
Black lacquer	0.92
Dark-gray paint	0.91
Black concrete	0.91
Dark-blue lacquer	0.91
Black oil paint	0.90
Stafford blue bricks	0.89
Dark-olive-drab paint	0.89
Dark-brown paint	0.88
Dark-blue-gray paint	0.88
Azure blue or dark-green lacquer	0.88
Brown concrete	0.85
Medium-brown paint	0.84
Medium-light-brown paint	0.80
Brown or green lacquer	0.79
Medium-rust paint	0.78
Light-gray oil paint	0.75
Red oil paint	0.74
Red bricks	0.70
Uncolored concrete	0.65
Moderately light buff bricks	0.60
Medium-dull-green paint	0.59
Medium-orange paint	0.58
Medium-yellow paint	0.57
Medium-blue paint	0.51
Medium-Kelly-green paint	0.51
Light-green paint	0.47
White semigloss paint	0.30

NOTES: 1. Materials with absorptance values below 0.50 are of little use for passive wall outer surfaces.

2. This table is meant to serve as a guide only. Variations in texture, tone, overcoats, pigments, binders, etc., can vary these values.

3. Data derived from G. C. Gubareff et al., *Thermal Radiation Properties Survey*, 2d ed., Honeywell Research Center, Minneapolis-Honeywell Regulator Company, Minneapolis, Minnesota, 1960; from S. Moore, Los Alamos Scientific Laboratory, Solar Energy Group, unpublished data; and from Ref. 57 with permission.

The altitude and azimuth of the sun are given by

$$\sin a = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h \qquad (1)$$

and

$$\sin \alpha = - \cos \delta \sin h / \cos a \qquad (2)$$

where a = altitude of the sun (angular elevation above the horizon)
ϕ = latitude of the observer
δ = declination of the sun
h = hour angle of sun (angular distance from the meridian of the observer)
α = azimuth of the sun (measured eastward from north)

From Eqs. (1) and (2) it can be seen that the altitude and azimuth of the sun are functions of the latitude of the observer, the time of day (hour angle), and the date (declination).

Figure A1 (*b-g*) provides a series of charts, one for each 5° of latitude (except 5°, 15°, 75°, and 85°) giving the altitude and azimuth of the sun as a function of the true solar time and the declination of the sun in a form originally suggested by Hand. Linear interpolation for intermediate latitudes will give results within the accuracy to which the charts can be read.

On these charts, a point corresponding to the projected position of the sun is determined from the heavy lines corresponding to declination and solar time.

To find the solar altitude and azimuth:

1. Select the chart or charts appropriate to the latitude.
2. Find the solar declination δ corresponding to the date.
3. Determine the *true solar time* as follows:
   (a) To the *local standard time* (zone time) add 4′ for each degree of longitude the station is east of the standard meridian or subtract 4′ for each degree west of the standard meridian to get the *local mean solar time.*
   (b) To the *local mean solar time* add algebraically the equation of time; the sum is the required *true solar time.*
4. Read the required altitude and azimuth at the point determined by the declination and the true solar time. Interpolate linearly between two charts for intermediate latitudes.

It should be emphasized that the solar altitude determined from these charts is the true geometric position of the center of the sun. At low solar elevations terrestrial refraction may considerably alter the apparent position of sun. Under average atmospheric refraction the sun will appear on the horizon when it actually is about 34′ below the horizon; the effect of refraction decreases rapidly with increasing solar elevation. Since sunset or sunrise is defined as the time when the upper limb of the sun appears on the horizon, and the semidiameter of the sun is 16′, sunset or sunrise occurs under average atmospheric refraction when the sun is 50′ below the horizon. In polar regions especially, unusual atmospheric refraction can make considerable variation in the time of sunset or sunrise.

Altitude and azimuth in southern latitudes. To compute solar altitude and azimuth for southern latitudes, change the sign of the solar declination and proceed as above. The resulting azimuths will indicate angular distance from *south* (measured eastward) rather than from north.

(*a*)

FIG. A.1 Sun-path diagrams for various latitudes.