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INTRODUCTION

Most of the energy used presently to keep buildings warm and to heat water for domestic purposes comes indirectly from the sun. The fossil fuels, coal, gas, and oil, burned in our furnaces and water heaters, were formed over thousands of years from decayed plants and animals that once depended on the sun for life and growth. These fossil fuels may accurately be thought of as "stored" solar energy.

Since the onset of the energy crisis just a few years back, we have become sharply aware that the supply of fossil fuels available to us is rapidly being depleted. If we continue to deplete our fossil fuel resources at current rates, thirty may, in time, run out completely. Before this happens, we must know how to make direct use of the vast amounts of solar energy the earth receives each day. For instance, on a global scale, two weeks of solar energy is equivalent to the fossil energy stored in all the earth's known reserves of coal, oil, and natural gas. The purpose of this publication is to explain means by which solar radiation can be put to work satisfying the thermal energy requirements for space and domestic water heating.

The direct utilization of solar energy is by no means an entirely new concept. Man's tentative approaches to harnessing the sun's power can be traced over many centuries. In the past 50 years or so, applications of solar energy systems for space heating and hot water have appeared in states, such as Florida, where sunshine is abundant and fuel expensive, and in countries such as Japan and Australia. The recent energy crunch has accelerated the development of solar technology, a field in which the copper and brass industry is playing a leading role.

Solar energy systems are very practical now for many applications in the building industry, such as space heating, water heating and swimming pool water heating. Space cooling is also showing great promise of being an economically feasible option.

Applying solar energy to buildings involves three things. It must be collected; it must be stored; and it must be "distributed"—put to work within the structure for some purpose. Collection and storage are areas featuring some new methods, components and systems. Distribution, on the other hand, can be accomplished by the familiar means used for the traditional fossil-fuel systems.

COLLECTION/STORAGE/DISTRIBUTION
Characteristics Of Solar Radiation

The sun is a star and source of most of our life and energy. Radiating in all directions, only a small percentage of its tremendous energy reaches the earth's atmosphere. The portion that actually reaches the surface of the earth is smaller still because of the reflective and filtering characteristics of the earth's protective atmosphere. Yet, despite all of these limiting factors, the amount of solar energy delivered to the earth each day is thousands of times greater than man's total daily use of energy for all purposes.

Solar energy covers a wide range of wavelengths in the light spectrum, ranging from the ultraviolet through visible light to the infrared regions. When it reaches the outer ring of the earth's atmosphere, about 30 percent of the solar radiation is immediately reflected back into space. As the remainder continues on its path through the atmosphere toward the earth, several other effects reduce its intensity. First, most of the ultraviolet and some of the infrared components are filtered out so that what is left is largely in the form of visible light.

As shown in Fig. 1, a significant portion of the incoming radiation is reflected by the clouds back into space. A smaller portion is absorbed by water particles in the atmosphere and another portion diffused by atmospheric particles, clouds, and pollutants. This last portion of the sun's radiation is called diffuse or scattered radiation.

The remainder of the radiation which is not affected in one of these manners will either pass more or less directly to the earth's surface from the direction of the sun. This is called direct radiation. The energy available for collection is the direct radiation plus a portion of the diffuse radiation.

**Figure 1: Distribution of incoming radiation**
Solar Geometry

The rate at which solar energy reaches the outer limits of the earth's atmosphere is the same at all times. This rate, known as the solar constant, is equal to 429 Btu (British thermal units) per square foot per hour falling upon a surface perpendicular to the direction of the sun's rays. Despite the fact that the sun's intensity remains the same, we experience a change of seasons as a result of the varying geometric relationships between earth and sun. These relationships are depicted in Fig. 2.

The earth revolves once each day around an axis, which passes through the North and South Poles. Because its axis is tilted with respect to the sun, the intensity of the sunshine reaching the earth's northern and southern hemispheres varies and falls as the earth makes its yearly orbit and the seasons change. The angle of this tilt, called the declination angle, is the primary reason for the variations in the distribution of solar energy over the earth's surface, for the varying number of hours of daylight and darkness over the year, and for the great differences in the intensity of solar energy received at any one location.

The amount of radiation which reaches the earth depends in part on the distance it travels through the atmosphere. As indicated in Fig. 3, solar energy impacts at various angles, depending upon the sun's position relative to the earth. This angle determines the length of travel. The longer its path through the atmosphere, the less direct energy will reach the earth's surface. The three classifications for lengths of travel shown are referred to as Air Mass 1, 2 and 3.

Air Mass 1 identifies the shortest path through the atmosphere and occurs when there is a 90-degree angle between the sun's radiation and the earth's surface. This position of the sun is referred to as the zenith position and it occurs at the Tropic of Cancer (23.5° deg North latitude) on the summer solstice. An Air Mass 2 exists when there is a 60-degree angle between the perpendicular to the earth's surface and the incoming angle of the solar radiation. In Air Mass 2, the sun's rays pass through twice as much atmosphere as in Air Mass 1. Similarly, in Air Mass 3, the sun's rays pass through three times as much atmosphere as in Air Mass 1.

Altitude and Azimuth

The characteristics of solar geometry have a significant effect on the physical parameters and performance of solar col-
lection systems. Fig. 4 illustrates typical altitude and azimuth positions of the sun at the equinox and solstice days. It can be seen from this diagram that at the summer solstice, the sun rises from a position north of due east, climbs to a high position in the sky at solar noon and sets at a position north of due west. On the equinox days, the sun rises at a position of due east, climbs to an intermediate position in the sky and sets at a position of due west. At the winter solstice, the sun rises south of due east, climbs to a low position in the southern sky, and sets south of due west. The angle of the sun's position in the sky with respect to the earth is known as the solar altitude. The position of the sun with respect to compass directions is referred to as the solar azimuth. The actual positions of solar altitude and azimuth vary each day of the year and, furthermore, are different for each position of latitude. These are two of the most significant factors in determining how a collector of solar energy should be positioned with respect to the sun.

Collector Tilt

Since the sun is low in the southern sky during winter, more solar energy will strike a flat collector if it is tilted up from the horizontal at a steep angle toward the sun. The effect of collector tilt is illustrated in Fig. 5. In summer, the flat collector will intercept more solar radiation in a horizontal position than it will if tilted up steeply from the earth. It can be seen that a collector tilted up toward sun during winter will intercept more solar radiation than the same sized collector in a horizontal position.

The actual angle at which a collector should be tilted is a function of the particular characteristics of the intended application. If the intention is to collect the most solar energy in the winter period, the collector tilt should be steep. Conversely, if the intention is to collect the most heat during the summer period, collector tilt should be relatively flat.

There are convenient rules-of-thumb for determining the most appropriate collector tilt. These are as follows:

A. To collect the most radiation in the winter period, tilt the collector at an angle equal to the latitude plus 15 degrees.

B. To collect the most solar radiation during the summer period, tilt the collector at an angle equal to the latitude minus 15 degrees.

C. To collect the most radiation averaged over the year, tilt the collector at an angle approximately equal to the latitude.

These rules should be taken as guidelines only and adjusted for the specific characteristics of an application.
SECTION 2
COLLECTION

Solar radiation out in space has a characteristic pattern of wavelengths and intensity. By the time this radiation reaches the earth, most of the ultraviolet component has been filtered out. What remains is mostly in the visible region of the spectrum, with a smaller portion covering the short infrared region, as shown in the left portion of Figure 7. This incoming radiation is converted to heat when absorbed by a surface, such as that of the blackened copper absorber plate in a solar collector.

Some of the absorbed energy will be lost from this surface, by either conduction, convection, or re-radiation. Conducted losses come from direct contact with a colder material, while convection losses arise from heat being carried away by air currents. Surfaces also re-radiate absorbed energy, but its wavelength will have changed to "long infrared", also shown in Figure 7. This outgoing energy is a significant factor in the design and performance of the collectors in the solar heating system.

There are many possibilities for the collection of heat from solar energy. Direct gain through window areas is one, but this often provides too much heat when and where it is not needed and the resulting energy is difficult to control. Aiming to store this energy for future use, most solar energy collection systems utilize a heat-transfer fluid—either a liquid or air—to move the collected thermal energy from the collectors to a heat storage material. The collectors are typically one of two basic types: concentrating collectors or flat-plate collectors. Concentrating collectors utilize lenses or reflective surfaces to focus the sun's rays onto a relatively small absorbing area, and are able to build up higher temperatures than flat-plate collectors. Concentrating collectors
are generally unable to effectively focus the diffuse component of solar radiation, and thus their performance is based largely upon available levels of direct insolation.

Flat Plate Collectors

Flat plate collectors take advantage of both the diffuse and direct radiation falling on the absorber plate. In order to collect as much energy as possible, the collectors are often covered with a glazing material, such as glass or certain plastics, which are highly transparent to the incoming solar radiation. The covers serve as insulation over the absorber plate, as they keep convective heat losses down. In addition, glass is virtually opaque to the outgoing long-wave infrared radiation, and thus traps this radiation inside the collector, a phenomenon known as the "greenhouse effect."

Figure 8 illustrates how this phenomenon affects the performance of three different collector types. In the first type, Flat Black Plate Without Glazing, much of the radiation absorbed by the absorber plate is lost from the top surface of the plate, with some lost through the back insulation. Some useful heat is retained without a glazing cover, but only if the temperature of the absorber plate is close to the temperature of the surrounding air.

In the second type, Flat Black Plate With Glazing Cover, the radiation absorbed by the black plate is re-emitted as it was in the previous type. But the glass cover blocks the loss of the re-emitted radiation to the outside. There is some heat loss through conduction and convection, but more heat is retained with a glazing cover. This is especially true as the temperature difference between plate and outside air becomes greater. It may be desirable to utilize more than one layer of glazing, depending upon the magnitude of the temperature difference.

The third portion of Fig. 8 illustrates a collector with a Selective Surface and Glazing Cover. A selective surface is a very thin layer of special material applied to the top of the absorber plate. The layer's thickness is approximately equal to the wavelength of the incoming solar radiation. The selective surface radiator is a much smaller portion of the absorbed energy, which makes the collector operate more efficiently. There is still some heat lost through conduction and convection to the outside air, but more heat is retained with a selective surface than with an ordinary flat black surface. A selective surface may be used with single or multiple glazing. Selective surfaces are especially useful in collectors that operate at high temperatures. They in-

FIGURE 8: THREE TYPICAL FLAT PLATE COLLECTOR DESIGNS
crease collection efficiency, but at the premium of higher cost than non-selective flat black surfaces.

**Collector Construction**

Flat plate collectors utilize liquid as the heat transfer medium. Typically, they have blackened copper absorber plates with an integral or attached array of copper tubes. This absorber plate may be packaged into a module collector panel, which is complete with glazing covers, insulation, and enclosure box, or the absorber plate may be incorporated as an integral part of a roof or other structure.

Figure 9 illustrates the major components of a typical modular liquid flat plate solar collector panel. There are one or two layers of glazing material held by a frame over a blackened copper absorber plate. The plate has an integral or attached array of tubes for circulation of a liquid. The liquid flow connection shown at the bottom of the collector is diagonally opposite the liquid outlet connection at the top. Usually, this configuration is used so the flow length is the same through every passage. The aim is to achieve a balanced flow of liquid through the collector and, thus, maintain a relatively uniform temperature pattern over the plate.

Site-fabricated collectors may have the absorber plate laid over or between structural members. Insulation is placed behind, and glazing covers, if appropriate, are installed over the absorber plate. Care must be taken to ensure that the cover and insulating materials are compatible with the high temperatures reached by the absorber plate. Properties of appropriate materials are covered in Section 6—Design Recommendations.

The solar collector must be protected from freezing in the winter and from very high temperatures which can occur when liquid is not flowing through the collector. Also, when cold water is put into a hot collector, a thermal shock can occur, damaging the collector. Methods of providing protection against thermal shock and freezing are covered in Section 6—Design Recommendations. Methods of freeze protection are also covered in Section 4—Distribution: Domestic Water Heating.

Beneath the absorber plate is an insulating material that retards loss of the absorbed heat through the back of the collector panel. Heat losses from the sides of the collector panel are minimized by maintaining a space or thermal break between the metal absorber plate and the collector framing.

It is helpful to maintain a moisture-free condition in the collector to retard the loss of heat which tends to be greater in moist air than in dry air. A second reason is to prevent condensation of water on the glazing covers which would reflect incoming solar radiation away from the collector. One method for keeping air within the collector dry is the incorporation of spacers made of a desiccant (moisture-absorbing) material. These spacers are inserted between cover and absorber plate and, also, between layers of multiple glazing covers.

**Collector Efficiency**

A collector's usefulness depends mainly on how much of the solar energy it can make available for heating. This is its efficiency. The operating efficiencies of several different types of collectors are compared schematically in Fig. 10. The significant improvement achieved by adding glazing covers is immediately apparent. Fig. 10 reveals several other general conclusions about the efficiency of typical collectors.
efficiency of collectors:

1. All collectors operate with highest efficiency when the temperature difference between the absorber plate and ambient air is lowest.
2. For the same temperature difference, efficiency will be higher if the incident solar radiation is higher. Thus, at the same temperature difference, higher efficiencies can be expected in summer when more solar energy is available than in winter when less solar energy is available at the collector surface.
3. The highest possible efficiencies are achieved when there is no temperature difference between the absorber plate and the surrounding air. But even under this condition, 100 percent efficiency is not achievable. This is because there are always losses caused by incomplete transmission through the glazing covers, reflectance from the blackened absorber plate, and incomplete transfer of heat absorbed by the absorber plate into the heat transfer liquid or air.
4. The choice of collectors should be related to the operating temperature difference, the amount of solar radiation available, and the cost of adding options such as selective black surfaces or additional glazing covers. It can be seen from Fig. 10, for example, that in the range of 0 to 20° F temperature difference, such as might exist in a swimming pool heater application, a collector with no cover plates is an appropriate choice. When high temperature differences are anticipated, such as in solar cooling operations, a selective surface may be needed to obtain these temperatures.
5. Collector efficiency is increased by minimizing the temperature rise from collector inlet to outlet. A common range is 7 to 10° F; this can be accomplished by circulating water at the rate of 1 to 3 gallons per square foot of collector per hour.

It is important to realize that Fig. 10 represents the instantaneous efficiency of solar collector operation. This is the efficiency at a particular time, usually stated as an hourly efficiency. The lines plotted on this graph are based upon a specific intensity of solar energy available at the collector plate. During the day, the amount of solar radiation available to the absorber plate varies continually. Fig. 11 illustrates the relationship between time of day and intensity of solar radiation. The horizontal line, marked "critical at threshold intensity," represents the point at which the heat losses from the absorber plate (determined by the temperature difference between the plate and the surrounding air, and collector design) are equal to the heat gain experienced by the plate.
Collector operation, for example, very little solar energy is collected in comparison with the collector's operational losses. The instantaneous efficiency of operation will be quite high at the midpoint of the period of collector operation. There is an important difference between instantaneous collector efficiency and day-long collector efficiency. The day-long collector efficiency is the amount of solar energy collected as a percentage of the total available for the entire day, including part of the low intensity at the collector's surface. Some collector manufacturer's judge their collector performance by instantaneous efficiency. While this indicates the collector's capabilities, the figures cannot be applied to the entire day's solar radiation.

**Collector Tilt and Orientation**

The amount of energy falling on the collector surface during the year at any position of latitude, depends upon the tilt and orientation of the collector. Fig. 12 shows how collector tilt affects incident radiation at 40° north latitude on a cloudless day. The radiation incident on a horizontal surface experiences a sharp peak during the month of June when the sun is high in the sky. It falls off very sharply toward the winter months when the sun is much lower.

Tilting the collector to 30° (equivalent to the position of latitude minus 10°) flattens the curve somewhat. Maximum productivity still occurs during summer, but there is a significant improvement in production during winter. Further increases in tilt (60° to 70°) equal to the latitude of the installation, to 90° (latitude plus 10°), and to 60° (latitude plus 20°) cause progressive shifts of the curve so that the maximum production occurs more toward the winter heating season. For this latitude, a collector tilted vertically experiences its greatest amount of incident energy during winter, but the collected energy drops off sharply during summer.

The dashed line on the top of the graph shows the amount of solar energy incident on a surface which is tilted 90° off the sun. Always adjusting its tilt and orientation so that solar energy was received at right angles. Although there is somewhat more incident energy on such a surface, the economics of building a mechanism to allow the collector to follow the sun may not be justifiable.

Orientation refers to the compass direction in which the collector faces. It also plays a significant role in determining the amount of incident energy, as shown in Fig. 13. Orientation of collectors used for space heating systems is especially important. It can be seen that in winter, when the sun rides south of due east and sets south of due west, an orientation of southeast or southwest (45° from due south) received only 70 to 80 percent of the radiation received by a south-facing surface at the same tilt. The actual percentage figure depends upon the latitude, with the more northern latitudes (which experience shorter days) suffering the greatest reduction in incident radiation for variations from a south orientation. In spring and fall, orientation becomes less critical. In summer, orientation is least critical, with south-facing surfaces actually receiving slightly less radiation during June than surfaces facing south-southwest or south-southwest.

Since collector heat production capacity is affected by the temperature of the surrounding air, local conditions at the point of collection are also important. In most areas, maximum air temperature is reached in the early afternoon, usually around 2 to 3 p.m. Also, many locations experience morning lows which clear by early afternoon. Where such conditions prevail, peak collection may be experienced by a collector which faces 10°-15° west of south, instead of the theoretical value of due south.

![Graph showing effects of collector orientations](image-url)
Approaches to Heat Storage

Allowing for the intermittent quality of sunshine, any practical system must include a capability for storing the collected solar energy until it is needed. However, in most applications it is not economically feasible to install storage capacity large enough to guarantee a supply of solar-heated water at all times. A more practical approach is to rely on solar energy for a portion of a building’s heating needs and supplement it with a second heat source, using electricity or one of the fossil fuels. The solar system can be sized to meet a portion of the normal space and water heating requirements, while the supplementary heat source supplies the remainder for times when there is no sunshine or when demand for heat is unusually high.

There are two basic types of storage: storeable heat storage and latent heat storage. Storeable heat storage is based on the principle that a definite amount of energy is required to raise the temperature of a unit volume of a given substance 1°F. "Unit heat capacity" is equal to the specific heat of the material times its density. Water, for example, has a specific heat of 1.0 and a density of 62.5 lb/ft³. Therefore, 1 cu ft of water will rise in temperature 1°F when 62.5 Btu is applied.

Table 1 indicates the sensible heat storage capacity of various types of solid and liquid materials. Liquid sensible heat storage materials are most commonly used with liquid flat-plate collectors. Similarly, solid sensible heat storage materials are most commonly used with air flat-plate collectors. A significantly greater volume of solid materials is required to attain the same amount of heat storage as water because the specific heat is much lower for solid materials than it is for water.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Heat (Btu/lb·°F)</th>
<th>Density (lb/ft³)</th>
<th>Unit Heat Capacity (Btu·ft³·°F⁻¹)</th>
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<tr>
<td>Water</td>
<td>1.9</td>
<td>82.5</td>
<td>62.5</td>
</tr>
<tr>
<td>Water (30%)</td>
<td></td>
<td></td>
<td>62.5 (62.5)</td>
</tr>
<tr>
<td>Limestone (10%)</td>
<td>.8</td>
<td>64.1</td>
<td>31</td>
</tr>
<tr>
<td>Scarp Iron</td>
<td>.112</td>
<td>459</td>
<td>55</td>
</tr>
<tr>
<td>Magnesite</td>
<td>.165</td>
<td>303</td>
<td>53</td>
</tr>
<tr>
<td>Scarp Aluminum</td>
<td>.215</td>
<td>188</td>
<td>56</td>
</tr>
<tr>
<td>Concrete</td>
<td>.27</td>
<td>140</td>
<td>30</td>
</tr>
<tr>
<td>Rock (Blast)</td>
<td>.20</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Brick</td>
<td>2</td>
<td>140</td>
<td>20</td>
</tr>
<tr>
<td>Rock Salt (NaCl)</td>
<td>.213</td>
<td>135</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 1: Sensible Heat Storage Materials

**FIGURE 14: LIQUID HEAT STORAGE OPTIONS**
for water. Solid materials must also make an additional allowance for the circulation of air around the materials to cause the heat transfer to take place. A common solid-to-void ratio is 70 percent solid to 30 percent void for solid sensible heat storage materials. Thus, solid heat storage volumes will be two to three times liquid heat storage volumes for the same storage capacity. Also, greater fan motor horsepower is often required to circulate air through the storage medium, the supply ducts and the collector.

Latent heat storage makes use of the principle that it takes considerable energy to change the physical state of a substance (such as from a solid to a liquid). The material gains sensible heat until it reaches the melting point. It then gains an amount of latent heat equivalent to its heat of fusion which causes a change of state. The temperature (dry bulb) of the substance remains constant throughout the change of state.

When water changes from a solid (ice) to a liquid, about 143.6 Btu are required per pound to make the change of state. After the solid has turned to a liquid, only 1 Btu per pound is required to rise the temperature of water 1°F. A total of 8970 Btu of heat are required to change one cubic foot of ice into water. Once the change of state has been accomplished, however, only 62.5 Btu are required to raise one cubic foot of water 1°F.

The volume of the storage required for solar energy systems would be much smaller if the principles of latent heat storage could be used effectively. The choice of a storage material which has a melting point near the temperature at which the heat is to be used is important. Materials called "eutectic salts" change state at temperatures in the range of 93 to 120°F. Latent heat storage utilizing eutectic salts is not recommended unless a dependable means of assuring the stability of eutectic materials through many changes of phase can be provided.

Water Storage Systems

Water is the most commonly used liquid heat storage material because of its availability and low volume requirement. There are many options for the containment of the water in a liquid sensible heat storage system. Some containers are illustrated in Fig. 14.

Domestic water heating systems require the use of tanks which are pressure tested. These tanks are frequently lined with a copper alloy material to provide protection from corrosion and to increase durability. Many manufacturers produce special domestic hot water tanks which are designed for solar systems. Some have an internal heat exchanger to permit a non-toxic anti-freeze solution to be used in the collector loop. Most have four pipe connections-two for collector supply and return tubing, one for fresh water supply and one for domestic hot water supply. With possible water in the collector loop, a standard water heater can be adapted for use in a solar system by connecting the cold water and the collector supply lines into the drain outlet of the existing hot water tank.

Space heating systems are normally not pressurized. When operating at atmospheric pressure, a variety of options exist for storing the water. Commercially available liquid storage containers are frequently used. The container also may be made of precast concrete, concrete block, pressure-intensified wood, or rammed earth. It is advisable to use a flexible liner in the site-built storage tank to prevent leaks. Sheet copper is an appropriate material for this application. It is important to minimize the "thermal inertia" of the storage system. If there is a large storage volume to heat up, it may take considerable time before the storage temperature is useful for the system application. In large systems, such as those in commercial projects, it is appropriate to use more than one storage tank to provide sufficient storage capacity without imposing a large thermal inertia on the system. Multiple tank storage systems require sophisticated controls to allow the automatic determination of the fluid pumping sequence from among the various tanks to the collector and the building load.

The most appropriate storage volume for economics and system performance in space heating systems is approximately one to two day's building heat requirement under average winter conditions. Fig. 15 shows the water storage volume requirements in gal/sq ft of collector area to achieve the best system performance. The line relating storage volume and collector area has a sharp curve at about 1.75 gal of water per sq ft of collector. If much less volume is provided, the load fraction supplied by solar will drop. If much more volume is provided, little benefit will be obtained. Therefore, the most appropriate storage size is 1½ to 2 gal of water per sq ft of collector.

![FIGURE 15: OPTIMUM WATER STORAGE VOLUME](image-url)
DISTRIBUTION: DOMESTIC WATER HEATING

General Requirements
Domestic water heating is an area of high potential for the application of solar energy in buildings. There are many approaches to the design of successful solar water heating systems. The principal difference among them relate to the ways in which the heat transfer fluid is circulated between collector and storage tank, the type of freeze protection provided and the means for introducing supplementary heat.

The approach chosen for a particular application will depend on variables such as climate, heat requirements, and available storage capacity. Despite the existence of such variables, all applications have several things in common:
1. Tidewater temperature requirements are fairly consistent and are compatible with the fluid temperatures obtainable from solar collectors.
2. The collectors, pipe connections, and storage tanks in solar energy systems that operate under pressure from city water mains or on-site pumps, must be capable of withstanding these pressures. These are similar to those pressures encountered in conventional water heating systems.
3. For most efficient operation, the water brought to the collector for heating should be the coldest available. Thus, the collector supply line should draw from the bottom of the storage tank where the coldest water is located. Return from the collector should enter near the top of the tank.
4. A three-way modulating valve should be used at the point where the storage tank feeds into the building’s hot water supply pipes. The purpose of this valve is to automatically maintain downstream water temperature in the 125-140°F range by blending hot and cold water. During the summer months, water stored in the tank could reach very high temperatures. The modulating valve effectively prevents scalding water from reaching the taps.

Collection: System Types and Configurations
Thermo-siphon System. In this most basic solar water heating system, the circulation of the water between tank and collector is maintained by the natural convection currents that are set up when water is heated. As shown in Fig. 16, there is no heat exchanger in the tank, and the same water that circulates through the collector will later appear at the hot water spigot. When the water in the solar collector becomes hotter than the
Because collected heat must be transferred through the heat exchanger, the collection fluid must be hotter, and thus this system is somewhat less efficient than one in which domestic water circulates through the collector directly. A check valve in the collector return prevents the re-injection of heat from tank to collector by thermo-siphon action on cold nights.

**Pumped Circulation with Freeze Control.** The system shown in Fig. 18 employs a circulating pump, but disperses the heat exchange. Because the collector circuit is not sealed off from the stored water, an antifreeze solution cannot be used. Instead, protection against freezing temperatures is

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**Figure 17:** Pumped Domestic Water Heating System with Heat Exchanger

**Figure 18:** Pressurized/Pumped Domestic Water Heating System with Heat Bleed Freeze Control
afforded by passing cold water from well or city mains through the collector sys-
tem. The rate of flow of this water is main-
tained high enough to prevent freezing before it leaves the collector.
A three-way solenoid valve is the key
control element in this system. During
normal operation, the valve is positioned
so that water circulates freely between
tank and collector. No cold water is admis-
ted to the system unless a hot water tap
is opened somewhere within the building,
in which case makeup water enters from
the supply source. When freezing
temperatures are encountered, the three-
way valve automatically cuts off the
storage tank and diverts return water
from the collector into a dry well or sump.
This sets up a constant flow of water from
the source through the collector circuit
and out to the sump.

**Pumped Circulation with Drain-
Down**. Fig. 19 shows a third method for
providing freeze protection in solar water
heating systems. This system, again, in-
corporates a circulating pump for collect-
for water, but does not employ a heat ex-
changer. With this method, the collector
circuit is drained of water when freeze-
ing temperatures appear imminent.
When a temperature sensor affixed to
the bottom of the absorber plate detects
a drop to about 40°F, it initiates closing of
the motorized valve in the collector sup-
ply. Reaching its fully closed position, the
valve cuts off both the pump valve and the
air relief valve. Water then drains freely
from the collector circuit and out of the
system. Typically, the amount of water
drained is not more than three or four gal-
lons, including that in all piping exposed
to freezing temperatures. The pres-
surized source water is prevented from
flowing to the collector by means of the
motorized valve in the supply line and the
one-way check valve in the return.
Whenever the absorber plate tempera-
ture rises to a pre-set differential above
storage, the motorized valve begins to
open, the circulating pump restarts, and
the dump valve and air relief valve close.
as the collector circuit refills, trapped air
is relieved through the automatic vent
and normal circulation of collector water
is resumed.

**Storage: Domestic Hot Water Tank Arrangements**
Most applications of solar water heating
require a back-up or auxiliary source of
heat for periods of low solar availability,
or high heat requirements. The manner
in which the solar heat and auxiliary heat
are employed in a system has a signif-
ificant effect on the amount of useful solar
energy which can be collected and ap-
plicated to the heating load.

**Separate Solar and Conventional
Domestic Hot Water Tanks**. One of the
many proven arrangements for introduc-
ing supplementary heat is illustrated in
Fig. 20. The larger tank is connected to
the collector loop and stores water
heated by the sun by one of the methods
described earlier. In tandem with the
storage tank is a conventional water heater
having a fossil fuel burner or an
electric heating element. The outlet line
of the solar storage tank is a pipe con-
ected to the "hot" or inlet line of the
conventional heater. When there is a de-
mand for hot water somewhere in the

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**FIGURE 20: DUAL DOMESTIC HOT WATER STORAGE TANKS**

**FIGURE 19: PUMPEO CIRCULATION DOMESTIC WATER HEATING SYSTEM WITH DRAINDOWN**
building, city water pressure forces water through the solar/storage tank, through the conventional tank, and out to a water tap or fixture.

When the solar-heated water is warm enough it will move through the conventional tank without affecting its thermostat or without requiring additional heat. However, should the conventional tank water drop below a preset temperature, it will cause the thermostat to trip, energizing the burner or electrode of the conventional heater. The heater then continues to operate in its normal fashion, cycling on and off as needed to maintain tap-water temperature at design levels. An advantage of this configuration is that only the relatively colder water in the large storage tank circulates through the collector which, thus, is permitted to function at a higher efficiency.

Single Storage Tank. It is also possible to provide both solar and auxiliary storage in the same tank as shown in Fig. 21. When this system is used, a large storage tank should be selected. The temperature of the auxiliary fuel input should be set to maintain a tank temperature of about 110-120°F. This will mean that the coldest water that can be circulated to the solar collectors will be 110°F unless some natural or artificial means of stratification is achieved in the tank. The primary disadvantage of the system is that because the water temperature which is circulated through the collector is higher than in the previous arrangement, the efficiency of the collector is much lower.

Combined Solar Space and Domestic Water Heating System. Fig. 22 shows the combination of solar space heating with a domestic water heating system. Water in the solar storage tank is warmed in the same way described earlier. If the solar storage tank temperature is high enough, cold domestic make-up water will flow through a heat exchanger in the storage tank to pick up sufficient heat to avoid drawing energy from the domestic water tank heater. Whenever the temperature of the domestic water tank drops below the storage tank temperature, the domestic water is pumped through the heat exchanger, transferring whatever heat is available. Final temperature boosting, if necessary, of the domestic supply is provided by an auxiliary heater in that tank.

It is possible to put the heat exchanger in the domestic storage tank and circulate water from the solar tank through it. It is also possible to combine a solar space heating system with a two-tank domestic water heating system, as shown in Fig. 20.
building, city water pressure forces water through the solar storage tank, through the conventional tank, and out to a water tap or fixture.

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**SECTION 5**

System Requirements

Solar energy collected at relatively low temperatures can be used effectively for space heating. However, the design requirements for space heating systems differ from those for domestic water heating, because space heating needs are seasonal and larger. These differences affect the choice of collector type, size, and tilt and influence the design of storage and distribution systems as well.

Fig. 23 compares space heating energy demand with collector production over a year's time. Available solar energy is least when heating needs are highest.

For this reason, it has been found advisable to design solar systems to handle only about 60 to 70 percent of the total annual space heating loads. Systems can be sized to supply the complete winter requirements, but these will not fully utilize collector potential in the summer months and, consequently, may allow a poor economic return on first cost investment. A second economic consideration stems from the fact that it is necessary to provide an auxiliary system capable of meeting 100 percent of space heating requirements at times when no solar contribution is forthcoming. Care should be taken, however, that the auxiliary system not be oversized.

Solar-collectors for space heating purposes are quite similar to those for domestic water heating. In general, collector temperatures will be higher. Collectors that operate at higher temperatures lose more heat. Thus the use of double glazing may be advantageous in some climates. For climates where freezing is a danger, liquid collection systems must be protected by draining the collectors and related tubing. Incorporating an antifreeze solution or other appropriate means is advisable.

There is an additional need for high-temperature protection in summertime when collectors continue to absorb solar energy even when there is little or no demand for heat in the building. Temperature build-up can be checked by mainlining the collector loop and incorporating means for rejecting heat. If circulation is to be stopped in warm weather and temperatures allowed to build, collectors and supporting structures must be engineered to withstand the severe thermal stresses that can result.

Whatever the high temperature protection, however, all collectors should be designed to withstand high thermal stresses to protect against unforeseen circumstances. Space heating systems can take many different forms, each with its own particular combination of the various approaches to collecting, storing and distributing solar energy. Four workable systems, each based on a different means of distribution, will serve to illustrate some of the possible combinations. Three of these involve direct distribution of stored heat by pump or blower. The fourth uses a heat pump to boost the level of stored heat to a higher temperature that is more compatible with the design requirements of the chosen space heating system. Three-use water as the medium for collecting and storing solar energy, while one uses air as the medium for collecting and solid metal as storage.

**System 1: Water Collection/Water Storage/Air Distribution.**

The system depicted in Fig. 24 and slight variations of it have found wide acceptance because they are simple to operate and control. The circulating pump in the collector-loop operation when collector temperature is higher than the temperature of storage tank water by a preset amount. When the pump stops, water in the collectors and pipe lines drains into the storage tank. To permit this automatic draining process, the return pipe must be coupled to the tank in such a fashion that the end of the pipe is kept above the level of the stored water so that the pipe must be vented by some other means.

When the building thermostat calls for heat, a pump circulates stored water through a heat exchanger coil in the return air duct upstream of the furnace. At the same time, the furnace fan begins to draw air through this heat exchanger coil and into the building. As long as the coil transfers sufficient heat to maintain supply air temperature high enough, the furnace burner or heating element remains inoperative. When the supply of solar heat falls short of the building's requirements, the furnace comes on to furnish supplementary heat.
There are several common methods for control of the input of auxiliary energy. One of these involves the conventional furnace thermostat which normally ignites the burners when furnace temperature drops below 100°F approximately. Resetting the furnace thermostat to about 100 to 110°F should be considered for improved efficiency. The furnace fan operates for a slightly greater period of time, but more benefit is derived from the solar system because it is useful at lower temperatures. Reducing the furnace temperature still further during the spring and fall seasons can save additional energy.

A second method uses a two-stage thermostat with the first stage controlling solar heat and the second, solar and auxiliary heat. When the thermostat calls for heat, the first stage is activated. If it is incapable of meeting the heating requirement, the second stage activates the auxiliary heat. This system could be modified somewhat by the addition of three-way valves to circulate water directly from the collector array to the heat exchange coil when heat is available in the solar collectors. Figure 24 shows a schematic arrangement of the system, which is designed primarily to distribute the heat from the solar system to a storage tank for storage.

**System 2: Water Collection/Water Storage/Air Distribution Space Heating System**

Solar energy systems using water collection and storage are highly suited for fin tube and radiant panel installations. Finned tube convectors, however, normally require a higher water temperature than fan-coil units to achieve an effective heat exchange. To compensate for the lower temperatures of solar heated water, therefore, it is usually necessary to specify a greater amount of tube than would normally be installed.

When finned-tube convector devices are used for heat distribution, there are two possible configurations: Figure 24 shows a simple configuration, in which the heat is supplied by either the solar system or the auxiliary boiler. When the solar storage tank is hot enough to supply the heating load, water is pumped from the storage tank through the finned tubes and by-passes the boiler. When the storage tank is not hot enough to supply the heating load completely, water is pumped through the boiler and then the finned tubes, bypassing the storage tank.

It is not advisable to pump water from the storage tank, through the boiler, and then through the finned tubes. This type of arrangement would actually use less solar energy and more auxiliary energy than the one described below.

The inset on page 18 shows a parallel distribution configuration, in which heat can be supplied by both the solar system and the auxiliary boiler simultaneously if necessary. If the heating requirement can be supplied by the water from the solar tank, the auxiliary boiler does not operate. When more heat is required than the solar system can supply alone, the auxiliary boiler begins operating, supplementing the solar heat. This arrangement permits lower temperature water in the solar system to be used to supply a portion of the heating load. The result is higher collector efficiencies, and more usable solar energy.

Larger systems sometimes employ outdoor-air temperature sensors to control boiler water temperatures. This feature provides flexibility in meeting fluctuating demands in the building’s heating load imposed by changing weather conditions. When outdoor temperature drops, for example, the boiler water temperature is raised automatically to compensate for increased heat load from the building. Like System 1, the hydronic system can be modified to allow collector water to be...
Pumped directly to convectors and radiant tubes, thus bypassing the storage tanks.

Even more compatible with the characteristics of water collection and storage are radiant panel heating systems employing copper tube embedded in concrete floor slabs and in wall and ceiling construction. Such radiant systems operate with lower fluid temperatures and, consequently, the utility of the solar heated water will be higher. Such a system is represented in Figure 26.

Experience dictates that the maximum surface temperature for a ceiling or wall radiant heating system is 120°F, for a floor panel, 85°F. Because of the higher distribution temperatures available, wall and ceiling radiant heating systems require less panel area than a floor panel, in order to meet the same load. However, any calculation of heat transfer from a radiant panel heating system to the room air must consider both the convective and conductive heat transfer rates. Technically, transfer of heat by convection is 0.4 Btu/hr per sq. ft. per °F for a ceiling panel, 0.8 Btu for a wall panel, and 1.1 Btu for a floor panel. In addition, there is the transfer of heat by radiation, which is...
System 3: Air Collection/Solid Material Storage/Air Distribution.

Air may be appropriate as the heat-transfer fluid in systems where the primary use of the energy is for the heating of living spaces. Air collection systems have several distinct characteristics when compared to circulating liquid collection systems:

- Air collectors are somewhat less efficient, requiring a greater area of solar panels.
- Rock storage requires greater volume than water because of its lower heat capacity, and the requirement for space around the rocks to permit the circulation of air. About 0.5 cubic feet of storage should be allotted per sq. ft. of collector for about 2-3 times the requirement for water storage.
- The collector supply and return ducts must be large enough to accommodate a flow of about 2 SCFM (Standard Cubic Feet per Minute) of air at ft. of collector. For most residential applications, this will necessitate an area of 3-5 square feet.
- Since large quantities of air must be circulated, and since there is a pressure drop through both the collectors and the storage container, greater fan motor horsepower may be required than pump motor horsepower in comparable water systems, reflecting higher costs.

- It is quite important to have a relatively clean, dust-free collector to maintain efficiency and reduce pressure drops. A high-quality filter which is regularly cleaned is important.
- It is important to waterproof the outside of the rock storage container to prevent the penetration of ground water. A warm, moist storage container is very conducive to the formation of fungi which can reduce air flow and distribute allergens throughout the house distribution system.
- Since the transfer of heat from air to water is not as efficient as from water to water, larger heat exchangers will be required to heat domestic water supplies.
- It is important to provide an air plenum above and below the storage container to permit a uniform flow of air. This is also necessary to flow warm air down through the storage container for collection, while distribution requires reversing and flowing up through storage.

Fig. 27 illustrates a typical air collection/rock storage/air distribution system. When heat is available for collection, and there is not a simultaneous demand in the house, the collector circulation fan begins operation drawing air down through the storage container. Motor operated damper number 3 is open wherever the collector fan is operating and closed at all other times. The
top portion of the storage container contents will heat first, and the heat will extend downward as more energy is collected. Motor operated damper number 4 is normally open. When heat is required by the space, but no heat is being collected, the centrifugal fan in the furnace begins operation, signaling dampers 1 and 2 to open. (These dampers are closed unless this fan is operating.) Return air is drawn upward through the storage, exiting at maximum temperature, and circulated to the house. Auxiliary energy is not added by the furnace unless the heating load cannot be provided by the solar system.

If there is a simultaneous collection of energy and demand for heat by the house, motor-operated damper 4 is closed. This damper is open unless both collection and distribution fans are operating simultaneously. Air is then circulated directly from the collector to the house. This is more important in air-to-air systems since the heat transfer into and out of storage is not as fast or efficient as water collection, water distribution systems.

**System 4: Water Collection/Water Storage/Heat Pump Distribution.**

Energy in the form of heat flows "downhill" from a warmer substance to a colder substance. The rate of flow is proportional to the thermal gradient, which is the temperature difference that exists between the warmer and colder materials. Thirteenth, the ability of a solar-heated fluid to feed energy into a space heating system depends on the thermal gradient between the solar-heated storage source and the air or water circulating in the heating system. As heat is taken from it, the, taxed water experiences a continual drop in temperature until a point is reached where the diminishing thermal gradient is insufficient to provide the flow of energy needed by the structure's space heating system.

In the three systems just described which make direct use of solar-heated storage, the thermal gradient may be considered inadequate to provide sufficient heat when storage temperature drops to, say, 90°F. The exact temperature for any system depends on whether that system is hydronic, or ducted air, the type of heat delivery equipment (fanned-tube baseboard, fan coil units, etc.), and the indoor design temperature. In any case, there is a low point at which the thermal gradient becomes insufficient, and supplementary heat must be introduced.

The electrically driven heat pump offers a new means of enhancing the flexibility and efficiency of solar systems. It has the capability of extracting heat from a cooler source and pumping it up to a higher temperature, thereby increasing the thermal gradient. This makes it possible to extract useful heat from the solar storage system even when its temperature has fallen below the room temperature.

Heat pumps most commonly used in small commercial and residential projects are of two types:

1. **Air-To-Air Heat Pump**—When heating is required, the heat pump extracts heat from one air source (usually the outside air), pumps it up in temperature, and warms the inside air.

2. **Water-To-Air Heat Pump**—When heating is required, the heat pump extracts heat from the storage
water, pumps it up in temperature and warms the room air. The heat pump is essentially a heat-transfer refrigeration device that puts the heat rejected by the refrigeration to good use. It is similar in design to a conventional refrigeration machine and has the same three basic components: compressor, condenser and evaporator. The uniqueness of the heat pump lies in its reversing valve which permits changing the direction of refrigerant flow. Because of the reversing valve, all heat pumps currently manufactured can provide cooling as well as heating. For space cooling, the process is the reverse of that described above.

Air-to-air heat pumps can be used in solar systems in several different ways. The simplest arrangement is similar to that shown in Fig. 28. All solar heating is done directly from storage, without the aid of temperature "boosting" by the heat pump. Using the fan unit of the heat pump to circulate the room air over the solar heat exchange coil. If the initial available from the solar storage is insufficient, the heat pump begins to operate, supplying additional heat to the air. Although this configuration does not permit the stored solar energy to be used below the space temperature, it greatly reduces the operational time of the heat pump, saving the electricity needed to operate its compressor. Other heat pump configurations are possible which permit the air-to-air heat pump to extract heat from water or solid storage at temperatures below the room temperature. These systems are more complex, however, and they require additional automatic controls. Unless they are carefully designed, they may not save as much energy as other solar heating systems.

Water-to-air heat pumps can also be used in solar heating systems as illustrated in Fig. 29. When the solar storage tank temperature is over a certain point (usually about 90°F), storage is used directly for space heating with the heat pump fan circulating the room air over the solar water coil. When the storage tank temperature falls below the temperature needed for direct heating, the control valve changes position and circulates the storage water into the heat pump. When the water flow to the heat pump has been proven by a flow switch, the heat pump compressor begins to operate, extracting heat from the water and pumping it up in temperature. It is then used for warming the room air. This continues until the heating load has been satisfied or the storage tank temperature drops to the lower operating limit of the heat pump (usually about 60°F). The actual operating temperature limits of the heat pump must be determined by the manufacturer and the solar system controls set accordingly. If this watter supply of appropriate temperature is available, it can be used when the available heat in the solar tank has been exhausted. It is usually necessary to supply a back-up heat source, such as electric resistance coils built into the supply ducting, to provide heat when the solar tank and other heat sources have been depleted.

Using this way, the solar system improves the actual performance of the heat pump by decreasing the thermal gradient through which it must pump. This reduces both the operating time of the heat pump, and its electrical consumption during operation. Water-to-air heat pumps are often used in applications which have multiple zones in the building, and may require simultaneous heating and cooling in different zones.
SECTION 6

DESIGN RECOMMENDATIONS

Introduction

All parts of the solar energy system must be carefully selected in order to obtain the best possible performance. Although most materials used in solar heating and cooling systems are well known to the construction trades, they must be chosen and assembled with special consideration for the unusual operating conditions under which the solar collectors and the associated plumbing system operate.

Absorber Plates

Copper, steel, aluminum and plastic are used for solar collector absorber plates. Copper has, by far, the longest and most successful history of use in this application. The most important characteristics for absorber plate material are thermal conductivity, corrosion resistance, ease of fabrication, mechanical strength and availability. The absorber plate must also readily accept the desired absorptive coating.

The thermal conductivity of an absorber plate should be high enough to conduct heat to the transfer fluid with a relatively small temperature drop. It is common practice to limit this temperature drop to 10 to 15°F or even less. Generally, this heat transfer is controlled by four factors: 1) thermal conductivity of the plate material, 2) plate thickness—thicker plates conduct more heat, but tend to be more expensive; however, and of slower response, especially at low sun conditions, 3) tube spacing—tubes spaced closer together permit the absorber plate to be thinner when highly absorptive materials are used, and 4) the thermal conductance of parts which occur between components. The thermal conductivity of copper (Copper No. 110) is 29% BTU-hrF/ft²F. If we set this value equal to 100, the corresponding conductivity for aluminum is about 54, and for carbon steel, about 12. This thermal advantage of copper is summarized in Fig. 29, which shows how, under typical conditions, thinner gauges of copper transfer the same amount of heat as thicker gauges of the other two metals. Since plastic acts as an insulator rather than a conductor, its use in absorber plates is limited to low-temperature, non-critical operations.

The excellent corrosion resistance of copper in both all-copper and mixed-metal systems. In addition to its superior thermal conductivity, have made it the most desirable metal presently used for absorber plates and fluid passages in flat plate solar collectors. Copper is readily available in various types of tube, fittings and sheet materials which are easily fabricated or joined by brazing, soldering, and mechanical fastening. The handling and fabrication of copper is familiar to the heating, ventilating and air conditioning trades, as well as to the other building trades. Copper has been widely used for roofing, plumbing, and HVAC systems since metals were first employed in these applications.

Copper has the needed mechanical strength, particularly at the elevated temperatures developed in absorber plates. In addition, copper readily accepts a wide variety of selective and non-selective surface coatings.

Absorber Plate Coatings

In addition to durability, the most important properties of absorber plate coatings are absorbance and emissance. The collector plate should absorb as much of the incident solar radiation as possible for maximum efficiency and performance. Surfaces which absorb radiation also "emit" a portion of the energy. Limiting this emission or re-radiation of long-wavelength energy improves the collector efficiency. A low emissivity is especially desirable at high collection temperatures, but absorbance should not be sacrificed to obtain low emissance. Coating stability, particularly at high temperatures, is important. A coating that has not been proven for solar absorber application might outgas volatile substances which can haze the glazing.

![FIGURE 30: FLAT PLATE SOLAR COLLECTOR ABSORBER PLATE DESIGN PLATE THICKNESS, TUBE SPACING AND ΔTso 150 BTU/HR-SQ. FT.](image)
covers and lowers solar energy transmis-
sion. Thus reducing collector efficiency.
The absorber coating must also prove
stable in the presence of moisture, and provide
equidity for the use of the collector.
A high performance flat plate paint has an
assurance of about 0.95, and about the
same emissivity. Several commercial
flat black paints are suitable finishes for
most collector absorber plate applica-
tions. Copper absorber plates, properly
cleaned, are easily painted, either on site or
in the factory where the collector is
assembled.
Selective surface coatings have been
developed which combine the desired
surface properties of low absorptance and
low emissivity. Copper surfaces can
be made reflective both by chemical
treatments and by electropolishing.
Commercially available selective surfaces of
both these types have emissance values
substantially lower than their absorptance
as shown in Table 2. Selective coatings are
particularly beneficial in applications
where collectors operate at higher tem-
peratures. The selective surface im-
moves re-radiation from the collector plate
to the gathering glass. In this way, heat
losses upward from the collector plate
are controlled, effectively utilizing col-
lector efficiency. Selective surfaces are
generally more expensive than flat black
paint coatings. Their potential benefits
should, therefore, be evaluated before
specifying their use.

Piping Systems
It is imperative that the fluid passages
in the absorber plate be compatible with a
corrosion standpoint, with the materials
used for the piping, storage tank, pump
and valve bodies. Conventional hydraulic
calculation methods are used to size pip-
ing in collector arrays. To avoid erosion
corrosion, flow should not exceed 4 to 6
feet per second. Pipe run should be as
short and straight as possible, free from
built-in "air-lock" that entraps air bubbles
which restrict cut-off flow. Connections
from the supply and return water lines to
the collectors should provide for thermal
expansion in each piping loop.
All piping should be pitched from
the high point of the system to ensure com-
plete drainage when necessary. In sys-
tems protected against freezing by drain-
ing, the piping is pitched at a minimum of
1 inch per 1 foot of run so that the fluid
drains completely.
Start-up of all liquid-carrying systems
should include a flushing operation to re-
move all dirt and debris accumulated dur-
ing installation. Follow manufacturer's
recommendations when flushing sys-
tems which use a heat transfer fluid other
than water.

Corrosion Protection
Solar systems can be expected to have a
long, useful life, if proper steps are taken
to control corrosion. There are three pri-
mary areas of concern in metal collector
systems: 1) corrosion between dissimilar
metals; 2) use of corrosive liquids; 3)
presence of air in the system.
When dissimilar metals are used in the
presence of moisture, corrosion can
occur. When copper is combined with
more other metals, such as aluminum or
deal, in the presence of moisture, the
copper will not corrode. The other metal
will, however, experience accelerated
corrosion in a water system. For exam-
ple, if copper tubing is used to connect platinum
collectors, the collector would
soon develop pinholes in the aluminum fluid
lines, which may cause leaks.
In a solar collector system, as in any
system involving a circulating fluid, it is
not sufficient simply to use dielectric
filters to separate the dissimilar metals
from direct contact. Copper ions cannot be
corrupted by the fluid and deposited on
the other metal, causing pitting. It is difficult,
as a practical matter, to exclude bronze
valves and pump impellers from collector
systems, especially considering the poss-
ibility of system modification or repair
once in service. Although corrosion sys-
tems of corrosion protection are available
for mixed-metal systems, the best solu-
tion simply is not to mix metals.
Corrosion is highly resistant to corrosion
when recommended plumbing practices
are followed: 1) It is especially resistant to
corrosion in re-circulating hot water.
There are, however, some unique circum-
stances which can cause corrosion in
cooler systems. Some liquids commonly
used as heat transfer media can lead to
corrosion in solar energy systems. Also,
some locations are supplied with aggres-
sive water which can portulate pitting
corrosion in metal collector systems. Such
aggressive waters typically are highly
mineralized, having a high level of
dissolved solids content including sulfates
and chlorides, pH values ranging from 7.3
to 7.8, high (over eight parts per million)
carbon dioxide content and the presence
of dissolved oxygen gas. A trouble free
history of copper plumbing in a locality
is usually not taken as evidence that its
water is not aggressive to copper. It may,
however, be aggressive to other metals.
In the absence of such evidence and in
undesirable areas, the water should be
chemically analyzed. A qualified water
treatment engineer should prescribe a
treatment to make problem water non-
aggressive to plumbing materials. In gen-
eral, this involves raising the pH and
neutralizing the free carbon dioxide.
If acid-free is added to the water, or if
special heat transfer fluids are used, the
possibilities for corrosion arise. Anti-
freeze are formulated products which
usually contain corrosion inhibitors. With
use, inhibitors may degrade, particularly
at high temperatures. The fluid then
becomes corrosive and must be moni-
tored and reinforced when necessary.
Recommendations for the anti-freeze
manufacturer should be carefully
obtained to avoid system damage. Two
major types of anti-freeze presently used
with water in solar collector systems are
propylene glycol or ethylene glycol-based.
Ethylene glycol has found major appli-
cation in industrial and automotive use.
It is available in both inhibited and unin-
hibited grades. Ethylene glycol formula-
tions with extensive extension are used
for automotive freeze protection. Less,
inhibited solutions are generally used for
industrial applications. There is a long
history of successful use with copper and
copper alloys, especially in the automo-
tive radiator. Inhibitors can be regen-
ergated via controlled additions of consti-
ituents based on standard tests for pH,
akalinity, phosphates, nitrites and organic
matter.

| TABLE 2 | TYPICAL PROPERTIES OF COPPER ABSORBER PLATE COATINGS |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 1. Flat Black Paint - as applied | 2. Commercial Spectral Rating | 3. Typical Black Primer on Copper |
| **ABSORPTION** | **TRANSMITTANCE** | **ABSORPTION** | **TRANSMITTANCE** | **ABSORPTION** | **TRANSMITTANCE** |
| .95 | .05 | .09 | .91 | .59 | .11 |

1 Recommended pipe fittings are approved by the Copper Development Association Inc. (CDA) and the Copper Tube Product Auxiliary (CTPA) (Ref. 404 Bit).
Propylene glycol is claimed to be non-toxic. For commercial use, the Food and Drug Administration requires propylene glycol solutions where contact with food products occur. The 10% inhibited propylene glycol solution, known as Food Freeze #35, meets FDA requirements. The size of additives (including water) may remove FDA Certification. There are presently no standard kits for monitoring propylene glycol chemistry. Since the solution involves only one or two inorganic inhibitors, laboratory tests for solution control focus on pH, alkali, and inhibitor concentration. Generally, inhibited propylene glycol, not ethylene glycol, should be used in solar heating systems for domestic water; unless a double walled heat exchanger is employed. For space heating purposes only, inhibited ethylene glycol may be used, if there is not a possibility of cross connections or back flow into the household plumbing system or building supply.

Propylene glycol is quite corrosive to aluminum, especially in the presence of sodium copper or brass. It will superficially attack copper but the attack is uniform as opposed to concentrated pitting.

In summary, many anti-freeze solutions require the addition of inhibitors and buffers for pH and corrosion control. In selecting inhibitors for glycol solutions, avoid oxidizing agents, such as chromates, which tend to promote rapid degradation.

Periodic monitoring, especially of pH, is required, with eventual solution replacement when the buffers are expended. Mixed metal systems should be avoided whenever glycol solutions are used. It is advisable to install filters to remove solids that may develop in the system.

Draindown systems provide protection from freezing by draining the liquid from areas which experience freezing temperatures. When draindown systems are used, special care should be taken in selecting the materials used in the system. Copper collectors and piping will withstand repeated exposure to air and water without difficulty. Aluminum and steel are much less resistant to the corrosive effects of alternating exposure to water and air.

### Collector Cover Glazing

The number of cover plates chosen depends on the desired collector operating temperature and performance. Although additional cover layers reduce heat loss, they also reduce transmission of solar energy. There is a point where additional glazing actually decreases the overall performance of the collector.

### Table 3: Solar Collector Cover Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (Inches)</th>
<th>Solar Energy Transmission (%)</th>
<th>Maximum Operating Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Line</td>
<td>1/8</td>
<td>65.0</td>
<td>409</td>
</tr>
<tr>
<td>Float Glass</td>
<td>3/16</td>
<td>81.0</td>
<td>500</td>
</tr>
<tr>
<td>1/4</td>
<td></td>
<td>78.0</td>
<td></td>
</tr>
<tr>
<td>Water/White</td>
<td>1/8</td>
<td>64.0</td>
<td>400</td>
</tr>
<tr>
<td>Crystal (Low Iron)</td>
<td>3/16</td>
<td>93.5</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>1/4</td>
<td>98.0</td>
<td></td>
</tr>
<tr>
<td>100% Acrylic</td>
<td>1/8</td>
<td>88.0</td>
<td>190</td>
</tr>
<tr>
<td>Colorless Cast</td>
<td>3/16</td>
<td>87.0</td>
<td></td>
</tr>
<tr>
<td>Sheet</td>
<td>1/4</td>
<td>85.0</td>
<td></td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>1/8</td>
<td>81.0</td>
<td>220</td>
</tr>
<tr>
<td>3/16</td>
<td>78.0</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>1/4</td>
<td>74.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Film</td>
<td>0.004</td>
<td>82.5</td>
<td>270</td>
</tr>
<tr>
<td>Fiber-300</td>
<td>0.060</td>
<td>82.9</td>
<td>220</td>
</tr>
<tr>
<td>(Sheathing)</td>
<td>0.030</td>
<td>86.0</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>0.090</td>
<td>17.0</td>
<td></td>
</tr>
<tr>
<td>Teflon Film</td>
<td>0.002</td>
<td>97.0</td>
<td>400</td>
</tr>
<tr>
<td>Mylar Film</td>
<td>0.001</td>
<td>85.0</td>
<td>220</td>
</tr>
<tr>
<td>Kolwall Sunlight Regular</td>
<td>0.025</td>
<td>93.0</td>
<td>140</td>
</tr>
<tr>
<td>Kolwall Sunlight Premium</td>
<td>0.040</td>
<td>86.0</td>
<td>140</td>
</tr>
<tr>
<td>Lexan Film</td>
<td>0.005</td>
<td>94.0</td>
<td>270</td>
</tr>
<tr>
<td>0.007</td>
<td>93.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 31: Spectral Transmittance of Cover Plate Materials](image)
TABLE 4: COMPARISON OF INSULATING MATERIAL PROPERTIES

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Loss</th>
<th>Moisture Resistance</th>
<th>Volatile Outgassing</th>
<th>Temperature Resistance</th>
<th>Durability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass</td>
<td>Good</td>
<td>Excellent</td>
<td>For</td>
<td>Poor</td>
<td>Not Recommend*</td>
</tr>
<tr>
<td>urethane</td>
<td>Excellent</td>
<td>Excellent</td>
<td>For</td>
<td>Poor</td>
<td>Not Recommend*</td>
</tr>
<tr>
<td>extruded polystyrene foam</td>
<td>Excellent</td>
<td>Excellent</td>
<td>For</td>
<td>Poor</td>
<td>Not Recommend*</td>
</tr>
</tbody>
</table>

The back of the collector is typically insulated with a 3 to 4-inch thick fiberglass blanket. The use of cellular plastics for this purpose requires special consideration. Under stagnant conditions, which occur when there is no flow of heat transfer fluid through the collector, the plate can reach temperatures approaching 400°F. Most foamed urethane insulations currently available undergo a permanent volumetric increase at approximately 250°F. Consequently, they can seriously damage if placed in direct contact with the absorber plate. Furthermore, foamed insulations are typically "blown" with chlorinated or fluorinated hydrocarbons which degrade at this temperature, producing hydrochloric and hydrofluoric acids. Both end products are corrosive to all metals.

A related problem is the outgassing of volatile elements from the insulation or from adhesives or wood products used in conjunction with the insulation. These volatile elements can condense on the inner surface of the glass and other portions of the collector. Polyurethane foam, which is "blown" with carbon dioxide, is not subject to this outgassing of such volatile materials. It may offer an alternative to fiberglass insulation, when not subjected to stagnation temperatures.

Insulation materials may be corned to obtain the most beneficial aspects of each. For example, a layer of fiberglass between the collector and a foamed plastic insulation protects the latter from thermal damage. Since some foamed insulations have higher insulating values than fiberglass, this approach has merit. Care must be taken to be sure that temperature-sensitive insulation is adequately protected from the high temperatures which will occur at stagnation conditions.

Freeze Protection and Heat Transfer Liquids

In climates where freezing is possible, protection must be provided to prevent damage to the collector. Two common ways of handling this problem are:
1. The use of an anti-freeze solution
2. The draining of the fluid from the collector array when temperatures approach freezing.

The basic heat transfer fluid used in liquid collectors is water. When other agents, such as anti-freeze compounds are added, a solution of pH 7.0 or higher should be maintained. The addition of any substance to water, or the use of heat transfer oil, (some of which have been developed for solar systems), reduces the specific heat and requires the circulation of more fluid in order to remove a given amount of heat from the collector plate which may require the use of a larger pump. Due to the cost of anti-freeze agents, it is seldom economical to treat all of the system water — including that in the storage tank. Therefore, a heat exchanger between the fluid circulated through the collector and the storage tank fluid would be required. Any heat exchange operation reduces overall system efficiency.

When a draindown method of freeze protection is used, air is permitted to enter the system and displace the water in the collector loop. The water drains into the storage tank or (in a separate fold-down tank) in a location not exposed to freezing temperatures. In some systems, an automatic air vent and an air solenoid valve are employed to permit the passage of air into and out of the system.
In atmospheric systems, which do not operate at an imposed pressure, it is often possible to allow the draining of the water in the collectors and the piping by the method shown in Figure 32. Because the return piping from the collector to the storage tank terminates above the water level in the tank, air can enter the piping through the vent in the tank lid. This breaks the suction at the high point of the system as air moves up the return piping. It is advisable to over-size the return piping slightly to facilitate air movement. 

This method of freeze protection has been successfully employed in a number of collector installations. To insure proper system operation, the air path up the return piping must be unrestricted. Each installation should be carefully evaluated when this method is used. At the piping must be pitched to drain from the high point of the system, so that the water flows unimpeded into the storage tank. There should be no low points or pockets to trap water in portions of the piping exposed to freezing temperatures. This method of freeze protection is illustrated in the solar space heating section. Figures 24, 25, 29, 28 (pages 17, 19, 18, 20, 21).

Some means for accommodating the expansion of fluid in all closed piping loops must be provided. All liquids expand when heated. Water, for example, expands about 4% per 100 °F temperature rise. 

In pressurized systems, such as domestic water heating systems, excess pressures due to expansion are normally provided for by using a pressure relief valve to drain excess water volume. A pressurized expansion tank or accumulator is appropriate for larger systems. In non-pressurized systems, expansion is accommodated by oversizing the storage tank and venting it to the atmosphere.

**High Temperature Protection**

Should fluid circulation through the absorber pipe stop while the sun is shining, the solar collector can reach extremely high stagnation temperatures. For a double-glass collector with a flat black surface, these temperatures reach 350 °F to 400 °F. Collectors with selective surfaces stagnate at even higher temperatures. The collector frame, piping connections, and insulation must all be able to withstand such temperatures.

Even when appropriate materials have been used, a system must be protected against the thermal shock produced when cool fluid is pumped into a collector that has reached stagnation temperature. This could be the case on initial system filling and start-up. This also might happen should a power failure prevent operation of the circulating pump. If power is not restored until after an hour or two of subsequent sunshine, the automatic restarting of the pump forces cool fluid through the collector which has reached stagnation temperatures. The resulting thermal shock can cause bucking of the absorber plate and breakage of the glass covers. 

Protection against thermal shock can be provided in several ways. One method uses a temperature sensor on the back of the collector plate to activate a cutout relay in the power supply to the circulating pump. When the collector plate reaches a preselected temperature, power to the pump is cut off preventing circulation of the collector fluid. An alternative method employs a timing device that prevents automatic restarting of the pump in the event of a power failure lasting more than a minute or two. A third method employs a temperature sensor to prevent pump operation when a preset temperature differential exists between the collector plate and the circulating fluid. The third method is generally more expensive than the previous, especially for residential applications.

**Circulating Pumps and Controls**

Pumps ordinarily selected for residential and small commercial solar systems are close-coupled, in-line or base-mounted centrifugal types with mechanical shaft seals and flexible drive couplings. Pumps used in potable water systems should be bronze bodied.

The designer should select a pump which has the proper combination of flow rate and lift characteristics for each application. In general, the pumps for solar collectors should be chosen to provide approximately one to three gallons of water per hour per square foot of collector surface in order to maintain a reasonable temperature differential across the collector plate. In open systems, pumps must have sufficient lifting capacity to raise water from the storage tank to the top of the collector circuit. For such systems which usually have a relatively high lifting requirement and low flow quantities, two small pumps connected in series may be better than one large pump. In closed systems, two pumps are needed only to overcome friction losses through the piping.

The pump should not be oversized to the point where its typical operating characteristics are at a low efficiency. In most small solar systems, the pumps will not exceed about 4 to 1/2 horsepower and may be as small as 1/6 to 1/20 horsepower in closed systems.

When centrifugal pumps are used, it is essential that they operate with a net positive suction head. This is most frequently accomplished by connecting the pump through the storage tank wall below the water level in the tank. Then, there is always a positive head of water in the tank above the pump. If the pump is not installed to operate with a net positive suction head, it will cavitate, causing damage to the pump.

The circulating pump in the collector loop is normally started and stopped by means of a differential temperature controller. This controller measures the collector temperature and the storage tank water temperature. When the collector temperature is higher than the tank water temperature, by a set amount, the controller actuates the circulating pump. When the collector water temperature...
approaches the tank temperature, the pump is turned off. This differential thermostatic control assures that maximum heat energy is retained in the tank under all weather conditions.

Several manufacturers offer a variety of low-priced differential temperature controllers. Options are available to suit a maximum storage tank temperature and to incorporate various freeze protection methods.

**Collector Installation**

Integration of collectors with the roof structure should be carefully considered. The construction should be water tight so that no leakage occurs into the collector or through the roof.

Collectors should be permitted to expand and contract freely. Temperatures will vary considerably in different sections of the collectors and the component parts will expand and contract at different rates. High temperature sealing (glazing) tapes must be used to maintain water-tight seals. Silicone tapes and caulking compounds usually have excellent high temperature properties.

External sealants should be used which do not exhibit 'thermal set' or a tendency to vulcanize when exposed to cycling temperatures. Thermal set can be a cause of leakage problems when contraction of the adjacent materials results from cooling. Maintenance of the collector should be considered when planning framing details. The collector should be easily removable for repairs when necessary.

When a particular collector is used, the manufacturer's recommended installation details should be followed without deviation. Neoprene glazing gaskets or commercial skylight framing systems are sometimes used. The manufacturer's recommendations for these products must be closely followed to assure a trouble-free installation. The return piping above the collector outlet should be pitched so that water is not trapped in the piping.

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The “Sun-Tronic House” is a prototype solar home in Greenwich, Conn., conceived and built by Copper Development Association Inc. The active and passive solar energy systems provide more than 85% of the home’s space heating and domestic hot water needs.
**Design Calculations**

Solar design engineering normally entails extensive hand calculations or computer analysis to optimize system performance and cost. However, a simplified approach that permits rapid evaluation of heat loads and collector area has been developed. The CDA Sun-Chart Hand Calculations, for determining space and water heating loads, collector performance and recommended collector area, are described on the following pages. This approach involves certain assumptions. In the majority of cases, these assumptions approximate normal conditions and generate results similar to those achieved by more extensive analysis. For most cases, results from these calculations have proved to be equal to, or slightly more conservative than, those achieved by computer analysis. The calculations are based on an average day for each month. In actual operation there will be overcast days when the solar collector may not operate, or very cold days when the requirements for heat will be higher. Generally, there is no reason to adjust the calculations unless an unusual situation exists. If the conditions on a particular application differ significantly from the assumptions, it is advisable to have the calculations checked by a professional experienced in solar system design. Each solar energy system must be engineered to meet the particular circumstances of its use. The Copper Development Association Inc. assumes no responsibility or liability of any kind in connection with the calculations or system designs set forth herein or their use by any person or organization and makes no representations or warranties of any kind.

**Determining End-Use Heat Requirements**

**Water Heating.** The amount of heat required to produce hot water depends on the number of gallons consumed, the inlet temperature of the cold water supply and the desired discharge temperature at the fixtures. Table 5 lists average monthly cold water supply temperatures, at the sources, for 14 cities in the United States. Deep wells, such as those in Miami, Albuquerque and Las Vegas, produce water at a relatively constant temperature that is related to locally prevailing deep earth temperatures. Water from shallow wells, lakes, and reservoirs varies in temperature throughout the year as the result of changing air temperatures.

<table>
<thead>
<tr>
<th>Source</th>
<th>Average Monthly Temperature in °F at That Source for Cold Water Supply in 14 Cities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>Average Monthly Temperature in °F at That Source for Cold Water Supply in 14 Cities</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Table 5:** Source and Monthly Temperature in °F at That Source for Cold Water Supply in 14 Cities
Contact local water suppliers for accurate information on average water temperatures. Hot water consumption is the major factor influencing annual heat requirements. It requires 8.33 Btu to raise one gallon of water 1°F. If one gallon of water is heated from 35°F to 105°F, 833 Btu are required. This is equal to the energy consumed by a 60 watt light bulb burning for over four hours. Authorities differ in their estimates for hot water consumption, with a range of 50-120 gallons per day for a family of four, including appliance usage. Typically, a family of four has been found to consume 60-90 gallons of hot water daily. However, the total consumption of hot water depends primarily on the individual's habits and upon the characteristics of the plumbing fixtures or appliances used. Figure 33 has been developed to determine the heat requirement for different levels of hot water consumption based on either the number of people served, or the anticipated consumption in gallons per day. Table 6 lists the heat required month-by-month to provide 105°F hot water for a family of four living in Nashville, Tennessee, using a dishwasher and clothes washer. It may prove advantageous to plot a graph of the data obtained from Figure 33, as a means of spotting mathematical errors. Figure 34 is a graph constructed from the data in Table 6. The graph should curve smoothly. A sharp deviation in any month is a clue that an error exists.

Space Heating. When heating load calculations are made for a conventional heating system, the custom is to first determine the highest rate of heat loss anticipated for the building. The computed amount is then increased by some percentage ("safety factor") to cover unforeseen circumstances. The adjusted figure is used as the basis for equipment selection.

This practice often leads to the installation of oversized space heating systems that operate less efficiently and thus consume more energy. Heating equipment, particularly fossil-fuel equipment, usually delivers its design efficiency only at full capacity. Below this, efficiency falls off. Oil and gas furnaces are often designed to an efficiency of about 75 percent at full load. Yet, when installed in a building, these furnaces may attain a seasonal efficiency of only 50 percent or less.

In contrast, solar systems are designed to handle only a portion of the highest anticipated heat loss. The designer, therefore, is more concerned with the average heating load per day. A solar system sized to handle average rather than peak loads requires supplementary heat input on the coldest days. The system will operate near its full rated output much of the time. Therefore, its overall seasonal efficiency should be higher.

---

**TABLE 6**

**DOMESTIC HOT WATER HEAT REQUIREMENTS**

<table>
<thead>
<tr>
<th>MONTH</th>
<th>COLD WATER TEMPS</th>
<th>HEAT REQUIREMENTS (THOUSANDS OF Btu/DAY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>46</td>
<td>6,750</td>
</tr>
<tr>
<td>February</td>
<td>46</td>
<td>6,750</td>
</tr>
<tr>
<td>March</td>
<td>53</td>
<td>8,200</td>
</tr>
<tr>
<td>April</td>
<td>63</td>
<td>5,600</td>
</tr>
<tr>
<td>May</td>
<td>65</td>
<td>5,200</td>
</tr>
<tr>
<td>June</td>
<td>65</td>
<td>5,900</td>
</tr>
<tr>
<td>July</td>
<td>71</td>
<td>4,850</td>
</tr>
<tr>
<td>August</td>
<td>73</td>
<td>4,700</td>
</tr>
<tr>
<td>September</td>
<td>75</td>
<td>4,500</td>
</tr>
<tr>
<td>October</td>
<td>71</td>
<td>4,850</td>
</tr>
<tr>
<td>November</td>
<td>75</td>
<td>5,900</td>
</tr>
<tr>
<td>December</td>
<td>53</td>
<td>5,200</td>
</tr>
</tbody>
</table>

---

Eligibility Criteria. The use of solar energy to provide space heating for a building should not be considered unless the building is energy conserving. To attempt to solar heat a building that is poorly designed from an energy standpoint is a waste of money. The investment for a solar energy system might be better spent on energy conservation features to reduce the building's heating requirements.

Many things contribute to the energy requirements of a building, including proportion, orientation (especially of large glass areas), exterior color, and the type of shell construction. Construction features which exert the greatest impact on energy conservation and are accounted for in design calculations are insulating glass or storm windows, control of the infiltration of outside air through points between materials, and the type and amount of wall and roof insulation.

Extreme care should be exercised in selecting the wall and roof insulation materials. Cellulosic fiber insulating materials containing ammonium sulfate as a fire retardant should not be used in contact with copper or other metals. The ammonium sulfate may leach from the insulation and cause serious corrosion damage to piping, electrical, and similar metal components.

Heat loss, measured in Btu per square foot per degree day, is a major criterion in judging whether or not a building is suited for solar space heating. In general, a solar system should be considered for a residence only when the space heating demand has been limited to approximately 8 Btu per square foot per degree day or less.

To apply this criterion to a building which is being considered for solar heating, calculate the building's energy requirements under peak design conditions. This calculation determines the heat required when the outdoor temperature is at the design point, and is normally done by the designer for the purpose of sizing conventional heating equipment. The design point temperature is based on hourly average temperatures for each hour of a total year. The average hourly temperatures will be above the design point temperature 95% of the year. In Nashville, Tennessee, for example, the heating design point temperature is 17°F. Heat loss calculation methods are well documented in existing texts and are not repeated here.

To determine the average heating requirements, instead of the peak heating requirements, the concept of degree days is used. A degree day is a standard used to measure the heating season's severity. The number of degree days in a calendar day is determined by subtracting the day's mean temperature from 65°F if the mean temperature on a given day is 50°F; subtracting 50°F from 65°F yields 15 degree days for that calendar day. By adding the number of degree days in each day, the average monthly conditions are identified. The average monthly and yearly degree days for cities in the United States and Canada are listed in Appendix A.

Sample Calculations. An example may help to illustrate how the heat loss is calculated to determine solar system feasibility.4 Consider a home in Nashville, Tennessee, which loses 30,000 Btu per hour, when the outdoor temperature is 17°F. If this temperature exists for a 24-hour period, the building heating demand is 30,000 x 24 = 720,000 Btu. Since the design point temperature is 17°F, (48 degree days per day), the house requires a net heat input of 15,000 Btu per degree day as shown below.

30,000 (Btu/hr) x 24 hours 1,000 (Btu) = 7,200,000 (Btu) 10,000 48 Design Point Temperature

If the home's floor area is 2,000 square feet, the required heat input is 3.6 Btu per square foot per degree day. Since this is less than the criterion of 8 Btu per square foot per degree day, the house is a good candidate for solar space heating.

In actual practice, most homes experience an annual heating requirement which is somewhat less than that obtained by the above calculation method. The reason for this difference is that the design heating load does not account for heat gain from other sources such as people, lights, and cooking. Also, the house itself acts as a solar collector to some extent.

The exterior surfaces, particularly windows, absorb or admit some of the incident solar energy. In the heating season, these heat gains lower the building heating demand. Since they are not always present, they are not included in the peak heat load calculation. They are, however, accounted for when the modified degree day procedure is used to calculate heating requirements on average days. This is done by using a "Degree Day Adjustment Factor" of 0.86 for average days.

The adjustment factor is used to calculate average monthly requirements from the peak design load information. For example, after determining the number of Btu per square foot per degree day, the average monthly average degree day can be calculated by obtaining the figure for monthly degree days from the Appendix. Dividing this figure by the number of days in the month gives the average degree days per day for that month. The building's average heating requirement per day for each month is then determined by multiplying the average number of degree days by the Btu per square foot per degree day.

The floor area in square feet and the adjustment factor. The adjustment factor is obtained from Figure 35, which compares the outside design temperature with the degree day adjustment factor. In this example, since the outside design temperature in Nashville is 17°F, the adjustment factor is 0.86.
For January, the calculation is as follows:

January—NASHVILLE, TENN.

778 Degree Days/Month, 25 Degree Days/Month

Average Heat Requirement (Btu/Day) = 25 Degree Days x 7.5 Btu/Sq. Ft. x 1,000 Sq. Ft. x 0.86 Adjuster = 322,500 Btu/Day

This calculation is repeated for each month of the heating season, and the results should be tabulated as in Table 7. These space heating monthly figures can be added to the monthly figures for domestic water heating in Table 6 to obtain total heating requirement. The three curves plotted on the graph in Figure 36 then represent hot water, space heating, and total heating requirements.

Heat Required vs. Energy Consumed. If the monthly heating requirements are supplied by a fossil-fueled furnace or boiler, the energy consumed is greater than the total heating requirement because of the inefficiency of combustion. For example, if the home in Nashville, which requires 30,000 Btu/hr for space heating at peak design conditions, has a furnace rated at 36,000 Btu/hr, the furnace is oversized by 20 percent. As shown in Figure 37, this means that the seasonal efficiency of the furnace is about 48 percent.

In January, then, when 322,500 Btu/day are required, it will take 671,875 Btu/day of some type of fossil fuel to supply this load. (322,500 Btu/day x 0.48) If fuel oil is used, which has a rated value of 140,000 Btu/gallon, 4.8 gallons are consumed per day to supply the average load. If a solar system could deliver 50 percent (165,250 Btu) of the average daily space heating requirement in January, it would supply the equivalent of 335,938 Btu of fuel oil energy.

The CDA Sun Chart Hand Calculations is an easy method to use to calculate the solar energy obtainable from collectors in residential space heating and domestic water heating applications. Normally, solar heat calculations use sophisticated computer analysis. Such analysis is required for large-scale solar energy applications, particularly those involving cooling, where it is important to determine the heat that can be collected on an hour-by-hour basis. For small-scale systems, however, this simplified method provides results which closely approximate those achieved by computer analysis. Heat pump systems in which the solar system and the heat pump are not directly linked, such as that shown in Figure 28, can also be analyzed reasonably well by this procedure. More sophisticated analytical methods are required for applications which use a heat pump to extract energy from a solar storage container.

The simplification is accomplished by making the following assumptions about the solar system characteristics:
1. The collector orientation is within 15 degrees of due South. For applications which differ significantly from this assumption, adjustments can be made by using the orientation graph in Figure 13 on p. 9 of this manual.
2. Collectors with circulating liquids are used to carry collected energy to storage or load.
3. Water storage capacity ranges from 1/10 to 1/2 gallons per square foot of collector array.

The CDA Sun-Chart Hand Calculations for determining collector heat production are best explained by referring to a tabulation chart, Figure 38, devised to guide and facilitate the computation procedures. The designer begins by entering in the first five columns (A through E) available data concerning the application. He then performs six mathematical operations using these basic data and enters the results in columns F through L. A final multiplication yields data for the "Result" column; i.e., the average daily heat produced during each of the 12 months by one square foot of collector at a given tilt angle, operating at a specific temperature and installed in a particular locality. All of the computations are basic mathematical functions easily performed on a pocket calculator or by hand.

In order to fully appreciate the logical process shown in the design chart, the user should understand the significance of each column. The following explanatory notes may be helpful.

### FIGURE 38: THE CDA SUN-CHART WORKSHEET

#### Data Input

**Columns A through E**

Column A is the collector heat gain factor. Each type of collector has a characteristic ability to absorb solar energy. This ability is determined, in part, by the quality of the glass and the absorptivity of the blackened absorber plate surface. Table B on p. 33 lists the collector heat gain factors for four representative types of copper flat plate solar collectors.

For specific flat plate solar collectors, this factor is determined from a performance graph as shown in Figure 39. A graph for any collector can be obtained from the manufacturer. The collector heat gain factor is the point at which the inclined line intersects the vertical axis of the graph.

### FIGURE 39: COLLECTOR PERFORMANCE CHARACTERISTICS/TYPICAL VALUES—COPPER FLAT PLATE COLLECTORS


*The graph in Figure 39 is based on the results of a test of collector produced in accordance with the ASHRAE Standard 15-1.0 (1971). Methods of Testing and Determination of Characteristics and Performance of Solar Heating Equipment, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., New York, N. Y., 1977, as a general acceptance standard.
Column B is the collector heat loss factor. When collectors absorb solar energy, they tend to yield back the heat gained to the surrounding air. To achieve good operating efficiency, this heat loss should be minimized by insulation and other techniques. Table 8 lists the collector heat loss factors for four types of flat plate solar collectors. For other types, this value can be obtained from manufacturers' data, as shown in Figure 39. The collector heat loss factor is equal to the slope of the line. The slope value is determined by dividing the point at which the sloping line intersects the vertical axis by the point at which it intersects the horizontal axis. Both collector heat gain factors and heat loss factors are a function of each particular collector and remain the same in each of the 12 months.

Column C is the average air temperature. Ideally, this temperature should be the daytime average air temperature, but this data is often not available. Average full day air temperature for each month is usually available from a local weather station. The daytime average air temperature can be found by adjusting the average full day temperature. This is done by adding a value equal to 1.75 of the daily temperature range (usually 15-20°F) to the average full day temperature.

Column D is the horizontal solar energy. This is the amount of solar energy received by a horizontal surface on an average day in each month. The information is given in the insolation table. Appendix B, expressed in Btu per square foot per day. Find the city nearest the location for which the calculation is being done.

Column E is the collector tilt factor. A surface inclined toward the sun receives an amount of energy in each month of the year that differs from the radiation incident on a horizontal surface. The collector tilt factor is a multiplier used to adjust the incident horizontal solar energy to obtain the amount received by a tilted collector. Appendix C gives the collector tilt factors based on collector tilt angles at various latitudes for each month of the year.

To determine the proper tilt factor, determine the "% Diffuse Radiation" from the same table and location from which the "Horizontal Solar Energy" was determined. Use this "% Diffuse" figure to select the proper tilt factor table. For example, in January, Nashville, Tennessee has a 4% diffuse factor of 68%. The latitude of Nashville is 38° North. If a collector tilt (angle to horizontal) of 51°

(latitude + 15°) is desired, we must interpolate between both the positions of latitude and the table for % diffuse. First interpolate for latitude on each of the two applicable % diffuse charts (60% and 80%). On the 60% chart, we interpolate between the January 51° value for collector tilt of latitude of 15°, for 32° latitude (.07) and for 40° latitude (1.00). Since the latitude of the site (38°) is midway between, the result is 1.485 (say 1.49). Similarly, for the 80% chart, the result is 1.28. Since the % diffuse for Nashville in January is 68%, an interpolation between 1.49 and 1.28 yields a tilt factor of 1.4375 (say 1.44). Therefore, 1.44 should be used in Column E for January.

Computation Section

(Colums F through L)

Column F is obtained by multiplying the quantities from Columns D and L. The result is the amount of solar energy incident on a tilted surface. This is not the amount actually collected, but the total amount that reached the outer glazing of the collector.

Column G is the assumed collector inlet temperature. In reality, the inlet temperature which the collector experiences varies throughout the day, depending upon the heating load and the available solar energy. These values, which are obtained from Table 9, were developed for these calculations only, and are different for each month.

Column H is the temperature difference between the collector inlet and the ambient air. It is obtained by subtracting Column C from Column G.

Column I is obtained by dividing Collector B by Column A and multiplying the result by 2 times the quantity from Column H. This yields the "critical intensity" for a specific collector in a given location and operating at a specific temperature. Critical intensity is indicative of the length of the time period in each day during which the collector produces energy. It is not necessary to know the actual period of collector operation.

Column K is obtained by dividing the result from Column I by the quantity from Column F. This is a continuation of the previous step, involving the critical intensity and the period of collector operation.

Column L is obtained by using Figure 40, Collectable Energy Graph, and the quantity obtained in Column K. The result is achieved by finding the point on the K axis which corresponds to the answer from the previous step, and moving to intersect the curved line which is a turning point from which the line is continued to intersect the L axis.

Output Data

Result Columns. The final result is the amount of heat collected in Btu per square foot per day. It is obtained by multiplying the values from Columns F and L. This is the energy collected on an average day in a particular month. No further adjustments are required.

Collector Sizing. Once the rate of energy output from the collector has been determined, the designer can proceed to find the collector area needed for a specific application. As previously indicated, it is normally not economic or practical to size solar systems to handle 100 percent of the heating requirements. Gener-
solar energy for 60-70 percent of the annual heating requirements. As a rule, the designer achieves these percentages of overall annual load when the system is sized to supply 100% of the hot water required during May for water heating during March for space heating.

To make a preliminary estimate of collector area for domestic water heating, the designer refers back to the month-by-month solar heating requirement tabulated and plotted in Table 8 and Figure 34. The monthly solar energy for May (52.3 GJ) is divided by the collector output rate calculated for that month. The collector area (ft²/ft²) that results, in theory, provides 100 percent of the May heat requirement.

The collector area obtained should be considered preliminary. Next, the designer determines the percentage of the annual solar heating requirement actually met by solar energy. For this last step, the estimated collector area is multiplied, in turn, by the collector heat production figure for each of the 11 remaining months. The result gives the total heat produced each month by the collector area selected and compares the total with the 12 month's solar heating requirements. (For each month in which the solar collector produces more than 100 percent of the heating requirement, only that portion actually used is included in the collector production total.) The result is the fraction of the total annual hot water heating requirement met by solar energy. If the percentage of the load handled by the solar array is too low or too high, adjustments are made to the collector area to bring it into the appropriate percentage range.

A graphical check is offered here, and can be done by superimposing the values of collector production on the domestic water heating requirements curve. The juxtaposed curves provide a clear comparison of the solar heating requirement versus solar energy available for each month of the year. A similar curve, representing space and water heating, is shown in Figure 41.

**Sample Calculation**

The following example illustrates how the computation procedures are applied to a combined space and domestic hot water heating application.

**Step 1.** List parameters of application.
Location: Nashville, Tennessee
Latitude: 36° North
Collector Type: Double Glazed with Selective Surface
Collector Tilt: 51°
Combined Space and Water Heating Heat Requirements: Shown in Table 10

**Step 2.** Work through the design chart to determine month-by-month solar heat output per square foot of collector surface. (Results are shown in Figure 42)

**Step 3.** In the completed chart (Figure 42), find the amount of heat available from the collector during March. This is 544 Btu/ft²/ft².

**Step 4.** Find the combined space and water heating requirement for the month of March. This is 275,200 Btu/day (Table 10).

**Step 5.** Make a preliminary estimate of required collector area by dividing 544 into 275,200. The answer is about 500 square feet.
Step 6. Make a numerical check of estimated collector area by dividing the total solar heat collected (1,715,750 Btu, from Table 10) by the annual heat requirement (2,188,920 Btu, from Table 10). (In any month, only that portion of the collectable energy which can be applied to the load is considered. Therefore, for example, in May when only 68,950 Btu/day are required, only this portion of the available solar heat is applied to the load.) The estimated collector area of 500 square feet would supply 76% of the annual load, as shown in Table 10. Since this is higher than desired, an adjusted collector area of 400 square feet is tried. This yields a result of 68% of the total load supplied by solar energy. This is consistent with the recommended 60-70 percent. A third trial is made, using 350 square feet as a collector area. This area provides about 62% of the annual heating requirement. The collector area which should be selected for this job would be between 350-400 square feet.

Step 7. A graphic check of the calculated results is made (Figure 41). The shaded area is the useful solar heat produced by 350 square feet of collector area.

---

**FIGURE 41: HEAT LOAD VS. SOLAR HEATING GRAPH:**

**EXAMPLE: NASHVILLE, TENN. SPACE AND WATER HEATING**

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**COLLECTOR TYPE:** Double Glazed Selective Surface

**COLLECTOR TILT:** 31° (Latitude - 15°)

**APPLICATION:** Space and Water Heating

---

**FIGURE 42: COMPUTED COLLECTOR PRODUCTION EXAMPLE: NASHVILLE, TENN. SPACE AND WATER HEATING**

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Appendix A, AVERAGE MONTHLY AND YEARLY DEGREES, CONTINUED.
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*The data for these normals were from the full ten-year period: 1931-1940*
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**Notes:**
- LATITUDE refers to the latitude of the location.
- COLLECTOR TILT = LAT - 15° adjusts the tilt angle by subtracting 15° from the latitude.
- COLLECTOR TILT = LATITUDE adjusts the tilt angle to match the latitude.
- The table provides adjusted tilt factors for solar collectors based on different latitudes and months.
The future is bright for tomorrow's supply of copper. Copper is plentiful in the United States. Natural abundance plus recycling make the nation essentially self-sufficient in copper. Moreover, copper's production is energy efficient.

Visualize the copper on earth as a cone of resources. Up to now man has found, extracted and put into recycling use a slice off the tip of that cone. Below that slice are the known reserves of copper waiting to be mined and used. Behind those reserves are the rest of the earth's copper resources, known to exist but which may not yet be precisely located or economically or legally recoverable. The most recent Bureau of Mines estimate is: copper in U.S. ore reserves, 202 billion pounds; copper in additional U.S. ore resources, 640 billion pounds. This total of 842 billion pounds of U.S. copper resources is about 250 times current annual U.S. requirements, which have averaged 3.2 billion pounds in the 1970s.

In addition to the plentiful supply of new copper, there is another naturally occurring copper resource that no other metal can match: ease of recycling. Today, almost half the copper in U.S. mill and foundry products comes from recycled scrap. During the 1970s, an average of 3.2 billion pounds came from newly-mined ore each year and 2.8 billion pounds (47% of total copper production) from U.S. scrap resources.

Although copper is mined around the world, the U.S. is essentially self-sufficient in copper. During the 1970s, the U.S. averaged nearly 92% in net total copper and copper alloy self-sufficiency, with a high of 97%, reached in 1970 and again in 1975. No other engineering metal can make such a claim.

Copper is favorably situated among the metals when it comes to "energy cost." Based on mid-seventies technology, the production of copper from ore in the U.S. requires the equivalent of from 12 to 17.5 kilowatt hours per pound, depending on ore type and grade. This includes both direct energy usage and indirect energy requirements represented by equipment usage and supplies consumed. It also includes losses due to the inefficiencies of energy conversion. Production from scrap is even more energy efficient. It is interesting to calculate the energy cost of the material in a solar collector panel. That is, how much energy is required to produce from ore the metal in the fins and tubes that make up one square foot of absorber plate? The answer for copper is about 47,000 BTUs. This means a copper collector installed in Tucson on January 1 can pay back its energy debt with useful heat by June 4 of the same year, based on data from an actual installation.

### COPPER BENEFITS Properties and Advantages for Solar Energy Systems

The copper metals, copper, brass and bronze, are uniquely suited for solar heating systems. Without copper, the outlook for solar energy in the U.S.A. would be nowhere near so bright as it is today.

- **Thermal conductivity**—unsurpassed among engineering materials, the key to cost-effective solar collectors and heat exchangers.
- **Corrosion resistance**—both in hot water and in glycol-water solutions, proven by decades of successful service.
- **Joinability and Ease of Fabrication**—in the factory and in the field, unsurpassed for solar heating system components.
- **Familiarity**—in building construction and throughout the plumbing, heating and cooling industry.
- **Availability**—abundant supply in the U.S.A., half of it from recycled scrap, both energy efficient sources.