Passive and Active Solar Heating Systems

WORKSHOP IN

THE PRACTICAL ASPECTS OF

SOLAR SPACE AND DOMESTIC WATER HEATING SYSTEMS

FOR

RESIDENTIAL BUILDINGS

MODULE 4

PASSIVE AND ACTIVE SOLAR HEATING SYSTEMS

SOLAR ENERGY APPLICATIONS LABORATORY

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INTRODUCTION

The purpose of this module is to describe the types of solar and domestic water heating systems that are available and in current use, and to explain the functions of key components in each system. Solar heating systems are classed as active and passive depending upon the extent to which solar equipment and building design features are utilized to heat the house with solar energy.

OBJECTIVES

At the end of this module, the trainee should be able to:

1. Identify the different types of passive-heating design concepts
2. Distinguish between air-heating and liquid-heating solar systems
3. Identify and describe the basic function of key components of space and domestic water heating systems
4. Describe basic expectations of performance from different types of solar systems.

SOLAR SYSTEMS

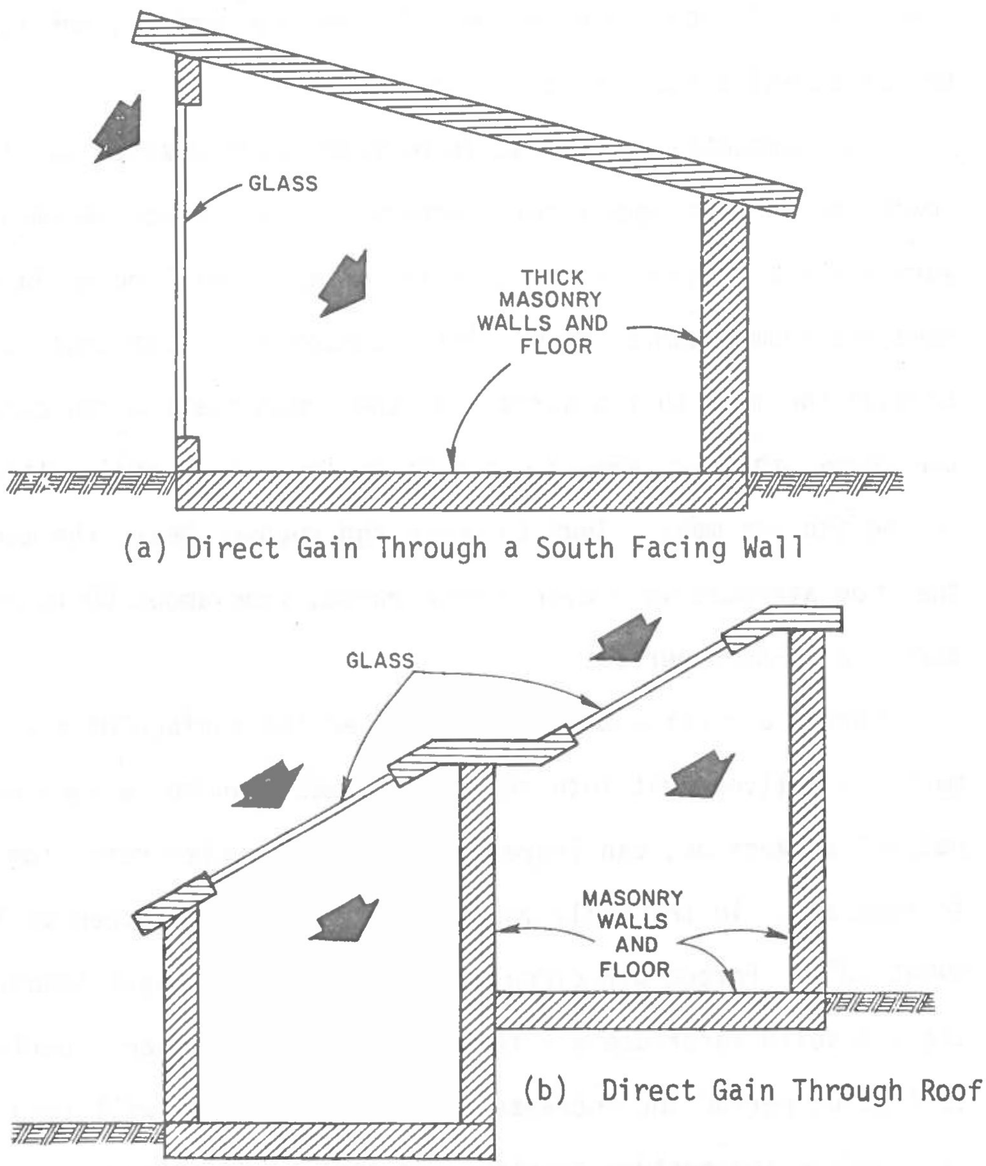
Any system which utilizes solar energy to heat a building is a solar heating system. With the numerous varieties of solar heating systems that have been constructed and many more conceptually possible systems, it is useful to separate them into at least two categories. The terms commonly used to identify the two categores are "active" and "passive" systems. Classifying a particular solar system into one category or the other is not always simple for there are "hybrid" systems which combine active and passive elements into a system design. Indeed, every building with fenestrations can have a net gain of solar-generated heat to the interior during certain times of the year and during certain hours of the day. Any attempt to establish clear-cut definitions for the terms "active solar system" and "passive solar design" will be met with numerous objections. Yet, it will facilitate communication in this workshop if we establish what is meant by the terms.

For the present purpose, an active system is one which involves collector hardware and fluid-moving equipment to circulate fluid to collect and distribute solar heat in the building. By hardware and fluid movers we mean pumps and blowers, and other devices such as motorized dampers and valves to direct fluid flow in the system. Passive design is incorporated into the building design and does not depend primarily on forced circulation of a fluid either to collect or distribute solar heat to various parts of the building. Alternatively passive heating could be defined as one in which thermal energy flows by natural means. Natural circulation of heat in buildings, however, is always present, whether a passive or active system is used, and the latter definition is technically inadequate. Some systems which involve moving equipment, but not fluid movers, may well be placed in the category of passive heating. A few illustrations will clarify the meaning of the terms active and passive systems.

PASSIVE HEATING CONCEPTS

DIRECT GAIN

The simplest type of passive heating uses direct solar gain, in which solar radiation enters a building enclosure through glass walls or roofs and is absorbed by massive walls and floors within the building. Illustrations of direct gain passive designs are shown in Figure 4-1.



(a) Direct Gain Through a South Facing Wall

(b) Direct Gain Through Roof

Figure 4-1. Direct Gain Systems

In Figure 4-1(a), solar radiation enters the south-facing glass wall and heat is stored in the mass of the floor and opposite wall. In Figure 4-1(b) solar radiation is shown entering the rooms through ceiling panels. In the process of storing solar heat, radiant energy on the surfaces of the storage mass is converted to heat resulting in increased surface temperature. If useful heat is to be stored, the surface temperature must rise above the temperature of the interior of the storage mass. Heat then flows into storage. However, because room air is in contact with the solar heated surface, the room will also be heated while heat is being stored.

The conductivity of heat through the mass must be sufficient to lower the surface temperature, otherwise the surface becomes excessively warm and the transfer of heat to the room air will be so large as to make the room uncomfortable. After sunset heat must conduct readily through the mass to the surface so that room heating can occur. To heat the rooms, the air temperature must be lower than the surface temperature of the storage mass. Thus to store and recover heat, the temperature of the room air must vary over a wide range, from about 60 to 80°F degrees during a 24-hour period.

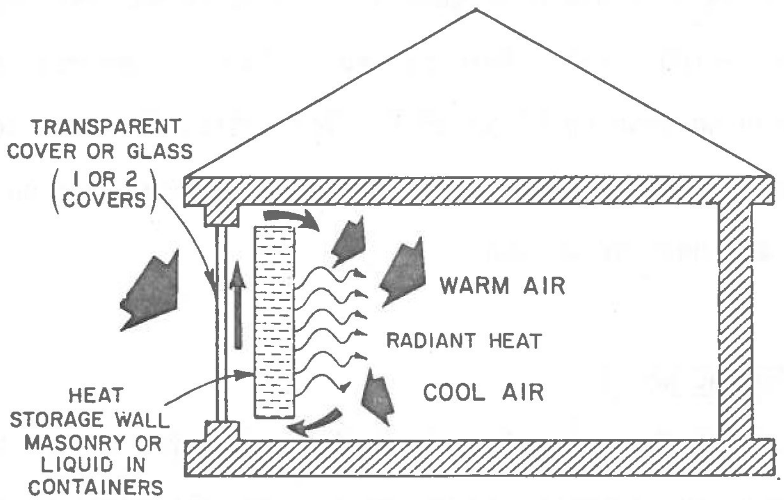
Forced air circulation created over the surface of the storage mass, to deliver heat into the room in addition to radiant exchange and natural convection, can increase the heat transfer rate from the surface to room air. In the early morning temperatures may then be limited to about 60°F. Forced air circulation increases the heat transfer rate at the air-solid interface and tends to cool the surface. During the collection period the increased heat transfer rate will tend to lower the surface temperature causing less heat to be stored.

The use of auxiliary heat in the rooms to maintain minimum room temperature will increase surface temperature of the storage mass during the day and raise the room air temperature during collection periods. The storage temperature will generally be 60 to 65°F at the start of the collection period, rather than say 65 to 70°F if the room air temperature were allowed to drop to 50 or 55°F. Very often the room temperature during the day will exceed comfortable levels, ventilation becomes necessary and heat is wasted.

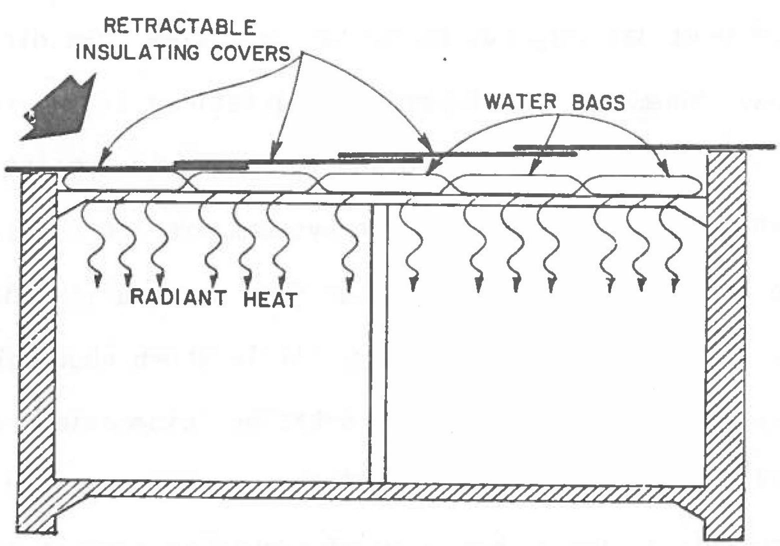
THERMAL STORAGE WALLS

The use of thermal walls along the south side of the building or a thermal roof, as indicated in Figure 4-2 are alternative passive solar heating possibilities. In addition to storage in the interior walls and floors, heat is stored in a masonry wall or water containers along the south wall. With an insulating curtain behind the thermal wall, the rate of heat delivery can be better regulated than direct gain passive systems. However, the temperature variations of the room air may be large if heat is to be stored and recovered in the interior walls.

While passive solar heating systems are the oldest forms used by man to provide heat to his habitat (not necessarily the types shown in Figure 4-1 and 4-2) there is very little known about the performance of such systems. With the lack of detailed information, designs of systems for different geographical locations are difficult and too often speculative, particularly in the modern view of providing comfort conditions expected in buildings.



(a) Thermal Wall



(b) Thermal Roof

Figure 4-2. Thermal Storage Wall Systems

ACTIVE SYSTEMS

The manner in which heat is delivered to the building space does not necessarily dictate the type of active solar heating system to be used, but convenience and economy may limit the options. An active solar heating system involves heating a fluid in a solar collector, delivering the heat to storage by circulating the fluid, and retrieving the heat from storage to a conventional heat distribution system. Either air or liquid may be used for collecting solar heat, and the same medium may be used to supply heat to the building space. Heat exchange with another fluid may be provided in which case the manner of heating the building is not dependent upon the type of heat transfer medium. For example, a liquid-heating solar collector may be used in a system with a water storage tank. The stored hot water may then be used as the heat source for one of the conventional hydronic heating systems. Alternatively, by means of a central heat exchanger, air may be used as the medium of heat transfer to the rooms. If air is the heat transport medium, direct delivery of the air to the rooms is practical.

The temperature at which heated fluid must be supplied to the rooms is dictated primarily by the amount of heat transfer surface available. With liquid systems, the smaller the heat exchanger surface, the greater must be the liquid temperature. The heat exchanger which delivers heat to the rooms therefore affects the entire system because the requirement for high liquid temperature ultimately lowers collection and system efficiencies.

LIQUID-HEATING SOLAR SYSTEM

A schematic drawing of a liquid-heating space and domestic water heating system is shown in Figure 4-3. Heat from the solar collectors is always delivered to the storage unit. In regions where freezing does not occur, water may be used as both the collection and storage medium and a heat exchanger between the collector and storage is not required. However, in freezing climates a non-freezing liquid is commonly used in the collector loop while water is used in storage and the two liquids are separated by a heat exchanger.

Collection and Storage

There are many different designs for collectors and normally a flat-plate collector is used with two transparent covers, a blackened absorber surface with attached tubes, and insulation below the absorber plate. The liquid flows through the tubes and heat is transferred from the absorber plate to the liquid medium. These collectors operate under slight positive pressure and the flow rate is optimized to maximize heat energy gain compared to pump energy for operation. A self-draining collector may be used in lieu of circulating a non-freezing liquid and using a heat exchanger in the collector loop. Provisions for collector drainage include automatic liquid drain and air venting valves, both activated by ambient temperature, solar radiation or by the pump shut-off circuit. Alternatively, an unpressurized vented collector may be designed to drain into storage whenever the circulation pump stops.

The penalties in using a heat exchanger in the collector loop are increased fluid temperature through the collector, additional capital expenditure for the heat exchanger and extra pump, and cost of electricity

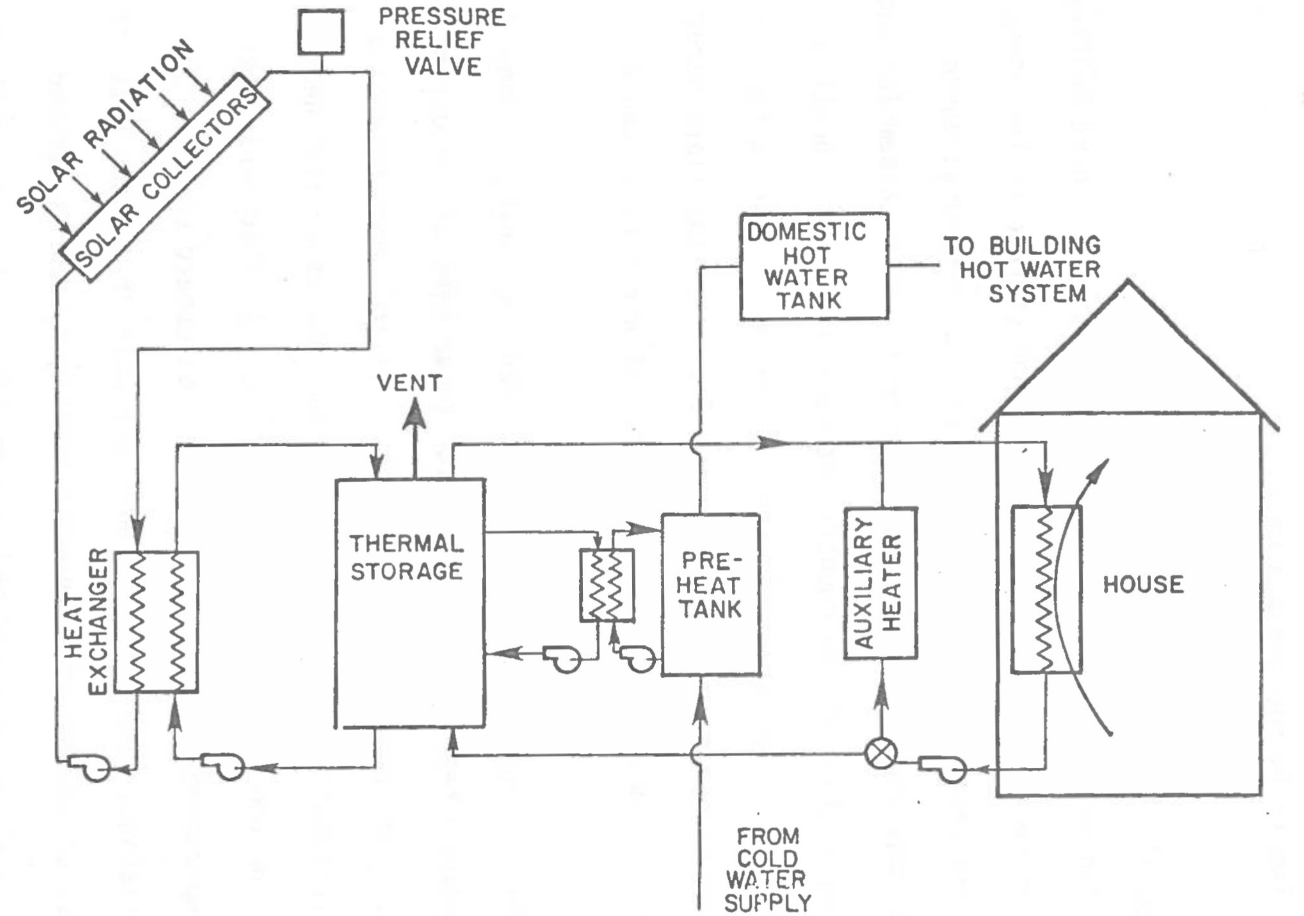


Figure 4-3. Schematic Diagram of a Liquid-Heating Space and Water Heating System

for pump operation. These disadvantages can be weighed against questions of reliability of the drainage system, accelerated corrosion of the collectors and pipes in the flow loop, or a large cost for providing a non-freezing liquid in the storage unit.

Space Heating with Solar and Auxiliary

In addition to the collector and storage unit, the liquid-heating system requires means for transferring heat from storage to the rooms and an auxiliary water or air heater which uses conventional energy. There are numerous ways in which these components can be assembled and operated. Many regions of the country use central warm air heating systems, and installation of a water-to-air heat exchanger in the central distribution system is convenient. Either an auxiliary water heater, shown in Figure 4-3, or an auxiliary hot air furnace can be utilized.

Water from storage may be circulated to fan coil units, radiant panels or baseboard heating elements. With these heat distribution systems an auxiliary water heater would be utilized. Most baseboard elements for residential buildings are designed for convective heat exchange with the room air and consequently operate effectively with high water temperatures. There are, however, baseboard elements for industrial buildings, with large fin area per unit of length, that can be used with solar systems if a hydronic heating system is desired.

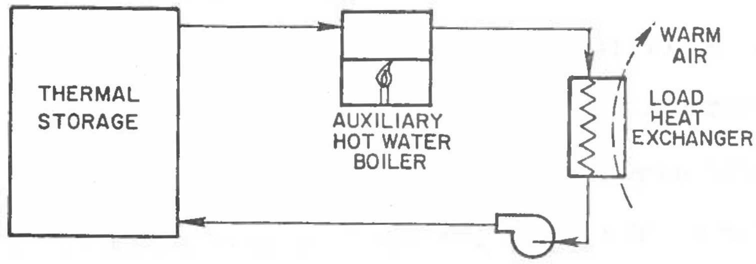
To obtain maximum collector and system efficiencies, the collector should be supplied with liquid at the lowest available temperature, whereas the warmest water should be supplied to the load. Water from the bottom of storage is therefore supplied to the collector (or to the collector heat exchanger), and heated water from the collector (or heat exchanger) is delivered to the top of the tank. The load loop is supplied with hot water from the top of the tank and the cooled water is returned to the bottom.

Under normal operating conditions the temperature rise through the collector is 10 to 20°F and the load heat exchanger is designed for approximately the same temperature drop. Although storage temperature could be 10 to 20°F greater at the top than the bottom, stratification is difficult to achieve because of high pumping rates and mixing in the storage tank. Practical designs should normally be based on an assumption of uniform storage tank temperature.

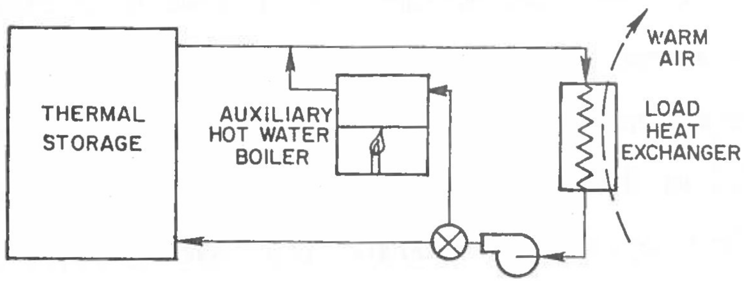
There are many options to locate the auxiliary heater in the system such as (a) in the collector loop, (b) adding heat to storage, (c) in the load loop or (d) in a separate loop from the solar system. Maximum benefit is gained by assembling the unit either in the load loop or in a separate loop. Assembling the auxiliary heater in the load loop minimizes capital cost and the auxiliary energy used is substantially the same as in (d) above.

Arrangements (a) and (b) results in forcing the collector to operate at higher temperature than necessary with corresponding lower collector efficiency. Adding heat to storage also results in some of the heat storage capacity being utilized for auxiliary heat rather than the solar heat for which it is designed.

The auxiliary heater in the load loop may either be installed in "series" so that the solar-heated water can be pumped through the auxiliary hot water boiler on its way to the load heat exchanger as shown in Figure 4-4(a) or in "parallel" as shown in Figure 4-4(b).



(a) Auxiliary Heater in Series



(b) Auxiliary Heater in Parallel

Figure 4-4. Auxiliary Heater Arrangements in the Load Loop

The series arrangement is simpler to install but the use of auxiliary fuel is minimized by the second arrangement. Although the auxiliary boiler can be controlled in different ways, normally the auxiliary heater in series would be used to "boost" the temperature of the water from storage only when the water temperature in the storage tank is too low to meet the heating requirement in the building. The temperature of the water returning to storage may frequently be higher than the water temperature drawn from storage, thereby a portion of the auxiliary heat is added to the solar storage tank.

For example, if the auxiliary heat is added when the storage temperature is at 95°F, because that temperature is insufficient to meet the heating requirements of the building under a particular set of conditions, the temperature of the water leaving the heater may be 140°F and the return temperature from load could be 100 to 110°F. Continued operation under this condition would gradually increase storage temperature thereby utilizing the storage tank to store auxiliary heat.

In the parallel arrangement solar-heated water is used exclusively under all conditions when the heating load can be met by the temperature of the stored water. When this heat supply is insufficient to maintain the desired temperature in the house, circulation of solar heated water is discontinued and the auxiliary boiler is used exclusively. With this strategy, when the outside air is very cold and heat losses from the building are large, comparatively warm water in storage may go unused for a time while the auxiliary supply is meeting the large load demand. However, stored solar heat will be called upon when the load is less severe or when storage temperature has been increased by addition of solar heat.

An alternative arrangement for auxiliary boosting that is better than either the series or parallel arrangement is shown in Figure 4-5 where a central air distribution system is provided in the building. The top coil (in the figure) supplies solar heat to the air whenever heat is needed in the building and provided that storage temperature is greater than some practical minimum, about 80°F. A second coil in the air stream is coupled to the auxiliary boiler so that when air cannot be adequately heated by the solar coil, the auxiliary unit is activated and the air temperature is increased. This method insures the maximum use of solar heat and minimum use of fuel. The penalty paid for this arrangement is the increased capital cost of a second load heat exchanger, another pump, and operating cost for the extra pump.

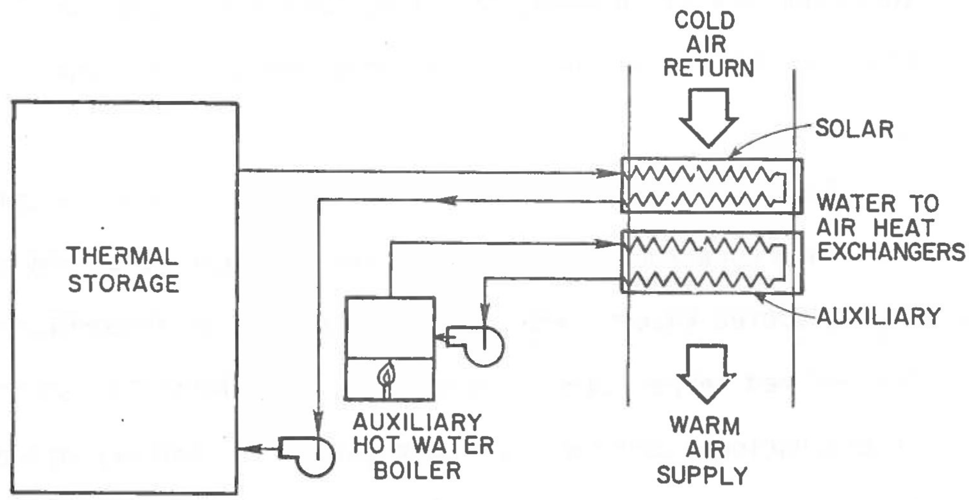


Figure 4-5. Solar Heating with Auxiliary Boosting

In warm air systems the most economical means of auxiliary heat supply is a warm air furnace located immediately following the solar heating coil (water-to-air heat exchanger). The system arrangement is illustrated in Figure 4-6. The furnace, sized for peak heating requirements of the building, can either boost the air temperature from the solar coil, as in Figure 4-5, or provide all of the heating if necessary.

Hot Water Heating

The economic advantage of solar heating can be improved if the domestic hot water (DHW) supply is also solar heated. Although an entirely separate system can be assembled for domestic water heating from the solar space heating system, integrating the DHW and space heating system is usually more cost effective because the collectors and storage, which would otherwise be idle during the summer, can be used to supply nearly all of the hot water requirements (in the summer months).

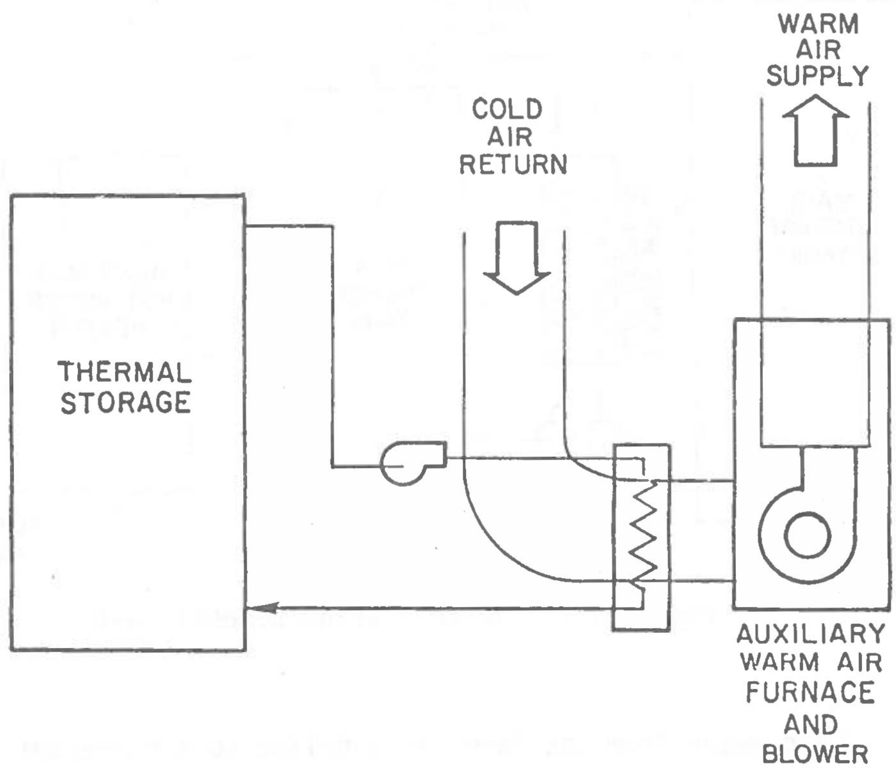


Figure 4-6. Solar Heating with Auxiliary Furnace

As is the case for space heating, there is a variety of arrangements possible for the DHW system. A two-tank system is shown in Figure 4-7. Solar heat is transferred from the main solar storage tank to a smaller domestic water tank where the cold water from the water main is preheated before entering the auxiliary water heater. The water in the main storage tank is generally non-potable and a double-wall heat exchanger is required to separate the non-potable from the potable water.

Whenever a reasonable temperature difference exists between the preheat tank and the main storage tank, circulation occurs and the domestic water is heated.

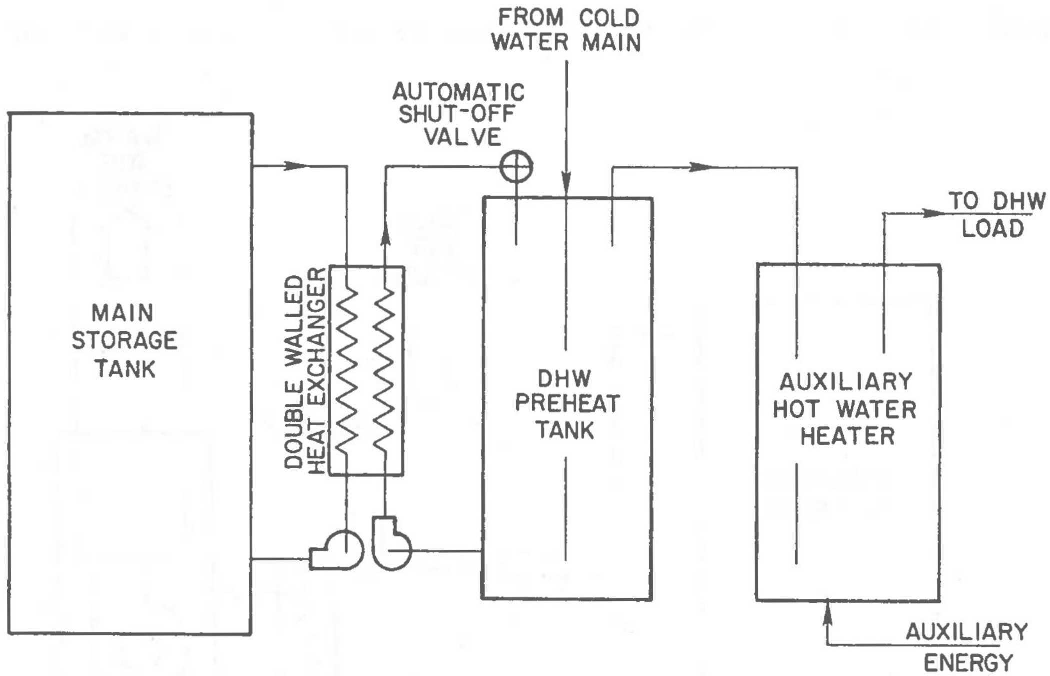


Figure 4-7. Solar Heating Domestic Water

Cold water from the mains is supplied to the preheat tank when a hot water tap is opened and warm water flows into the auxiliary hot water heater. The auxiliary unit is a standard hot water heater and the preheat tank has a volume about twice that of the auxiliary tank, and nearly equivalent to one day's use of hot water by the occupants. If the system is properly sized, auxiliary heat will seldom be required in the summer, but in winter the main storage tank temperature will not always be as high as the set temperature in the auxiliary heater, so that auxiliary energy will be required to raise the temperature of the water from the preheat tank after entering the auxiliary tank.

Water heating from solar and auxiliary sources may be combined in one tank, but because a set temperature will be maintained in the tank, the solar contribution may be considerably less than a dual tank system. A single tank may be workable if auxiliary heat is supplied in the upper portion, as in electric water heaters, and only the lower part of the tank is used in a circulation loop through the heat exchanger.

Still another type of auxiliary heater is an in-line, high input heater which has very little storage and simply boosts the temperature of water passing through it. A disadvantage of this booster or flash heater is the variable temperature of the solar heated water supplied to it and the resulting variable delivery temperature from it.

Alternate Heat Exchange Arrangements

The heat exchanger in the collector loop shown in Figure 4-3 is a conventional tube-and-shell, liquid-to-liquid type. An alternate arrangement is the use of coils of tubing inside the storage tank as shown in Figure 4-8. Forced convection is obtained inside the tubing, but only natural convection in the storage tank is realized on the outside surface of the coils. The total surface area of these coil-type exchangers must be considerably larger than the area of a tube and shell heat exchanger but the cost may be less. Only one pump is required in the collector loop but the electric energy use may be as large as that required for two pumps because of the larger pressure drop through the long tubing. Comparison of alternatives should include such considerations as accessibility for maintenance and assurance of leak detection.

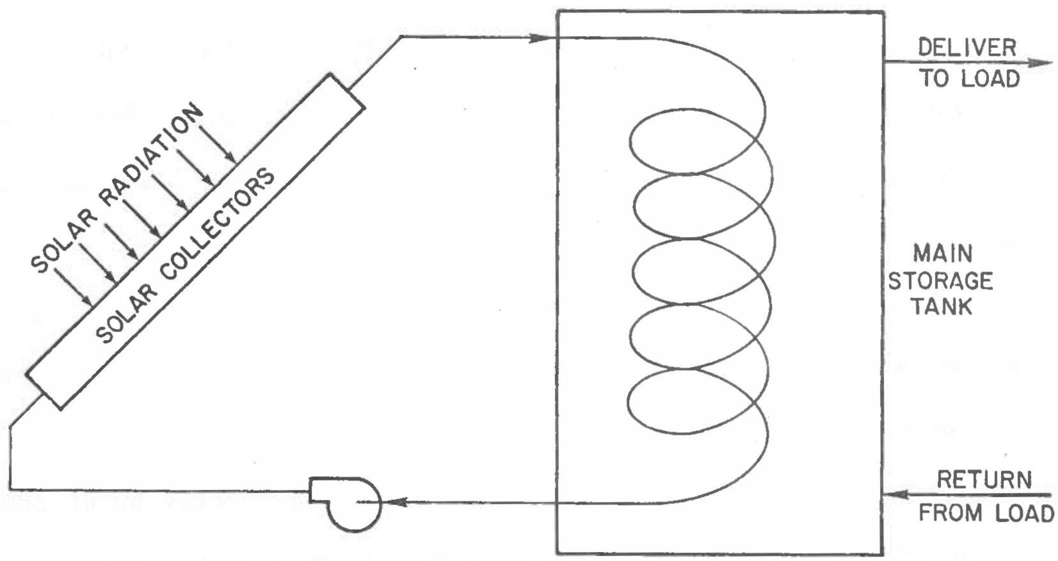


Figure 4-8. Coiled Heat Exchanger

Although a heat exchange coil could in principle be used for the domestic hot water system, when non-potable water is used for solar storage or in the collector loop, a minimum of two walls or interfaces are required by the HUD minimum property standards. Another option for solar heating the domestic water is to immerse the preheat tank in the main storage tank. Heat can be conducted through the wall of the preheat tank, but the rate of heat transfer is low. Unless the tank is double walled, the terms of the MPS cannot be met. Accessibility for inspection and replacement of an immersed preheat tank is difficult.

System Operation and Control

Collecting Solar Heat - The controls for a liquid-heating solar system are normally temperature driven although other control procedures are possible. Sensors at or near the top of the collector in the liquid and one near the bottom of the main storage tank are used to control the pumps in the collection loop. Whenever the temperature difference between the liquid in the collector and the liquid in storage reaches a preset amount because solar energy heats the collector liquid, circulation is initiated and heat is transferred from the collector to storage. When the collector can no longer provide useful heat to storage the pumps shut off.

Electrical or expansion-type temperature sensors can be used in the circuit. The collector sensor should be located on the absorber plate or in the fluid passage near the collector exit close enough to be influenced by the temperature in the collector even though the pump is not operating. Another arrangement which reduces on-off cycling of the pump at start-up periods involves the use of a sensor mounted external to the collector in a glass covered cavity having a black absorber surface and a heat cavity approximately equal to that of the collector. By calibration, appropriate on and off differential temperatures can be set. With such a thermometer, on-off cycling is minimized by avoiding the influence of cool liquid in the collector supply lines at start-up times.

<u>Delivering Heat to Load</u> - The best control strategy for delivering solar heat, and when necessary auxiliary heat, to load involves a room thermostat with a double set point. When the rooms cool, the first contact on the thermostat completes a circuit and water from the storage tank is pumped through the load heat exchanger. If storage is warm enough, the room temperature rises, the thermostat contact opens, the

circuit is broken and water circulation stops. If however, the stored water is not warm enough, the heat delivered through the load heat exchanger is insufficient to meet the demand and the room continues to cool. The second contact in the thermostat is made, another circuit is completed and the auxiliary heater is turned on. Depending upon the arrangement of the auxiliary heater in the circuit, as shown in Figures 4-4, 4-5 or 4-6, the solar-heated water circulation continues or is shut off.

There is usually a minimum set temperature which controls circulation of the solar-heated water for parallel or auxiliary boosted systems. A water temperature near 80°F is about the lowest temperature from which useful heat can be extracted in direct circulation systems. (Heat pumps can, of course, extract useful heat from solar-heated water far below this temperature).

The thermostat increases all the way to the null point, passing the solar set point (the temperature at which the first stage contact is made in the thermostat), or when the solar set point is regained the auxiliary heater is shut off and the solar system restarted. In the first case, the entire system will shut off until the next demand for heat, and in the second, the auxiliary unit turns on and off alternately while the solar system continues, or the solar and auxiliary systems alternate in a parallel-arranged system. The second mode prevents needless use of auxiliary, but the delivery system may operate continuously in severely cold weather because the room thermostat may not reach the set comfort temperature. If the solar-heated water is at a temperature equal to or below the limit set temperature, then the auxiliary heater will continue to heat the rooms until the comfort temperature is reached and the heat delivery system will then stop.

There are many other ways to control the operation of the heat delivery system. Probably the simplest method for controlling heat supply from storage involves a temperature sensor controlled in the storage tank. When storage temperature is above a fixed set point, say 110°F, solar heated water is supplied to the load by the pump on command from the room thermostat. If the storage temperature is below the set point, auxiliary heat is supplied to the load. This arrangement is not the best for minimizing auxiliary energy use, and fails to provide solar heat when a moderate heating load could be met by the solar-heated water.

Another load control system involves the room thermostat activating the solar heat supply which is operated for a preset length of time. If the room temperature is restored to the set comfort temperature within the time interval the system stops automatically. If not, the timing device activates the auxiliary as a replacement, or supplement, depending on the auxiliary heater arrangement in the heat delivery circuit. This system has been used for many years, but use of auxiliary energy is likely greater than with the double-contact thermostat method first described.

Collector-Storage Sizing

While the actual area of collectors and volume of storage selected for a particular installation depends upon many factors such as physical limitations of space to mount collectors and place storage tanks, economic factors and weather conditions, the volume of storage relative to collector area is reasonably established. Even so, there is a wide range from which storage volume can be selected because of the wide range of collector efficiencies and practical fluid delivery temperatures from the collectors. The results of many studies generally concur that within practical and economic limits 1 to 2 gallons of water per square foot of collector is reasonable for the types of collectors that are presently commercially available.

Design of solar systems to provide more than 80 percent of the load from solar heat can seldom be justified economically and the purpose of a large volume of storage is to increase the solar fraction of the total load. There is only a small increase when the storage volume is increased beyond 2 gallons per square foot of collector. Also, once the heat from a larger volume of storage is depleted during the heating season, the solar heated water temperature will remain low, and depending upon the type of load heat exchanger used in the system, a large amount of auxiliary energy may be required for the balance of the heating season.

AIR-HEATING SYSTEMS

A schematic diagram of an air-heating space and domestic water-heating system is shown in Figure 4-9. As with the liquid-heating systems, there are numerous options for integrating the solar air collector and thermal storage into a complete building heating assembly. The system in Figure 4-9 is a one-blower system. A two-blower system is shown on Figure 4-10. The principal advantages with air as the transport medium are that special freeze-protection measures for the collectors are not required, and boiling is not a problem as it could be in a liquid-heating system with certain types of liquids.

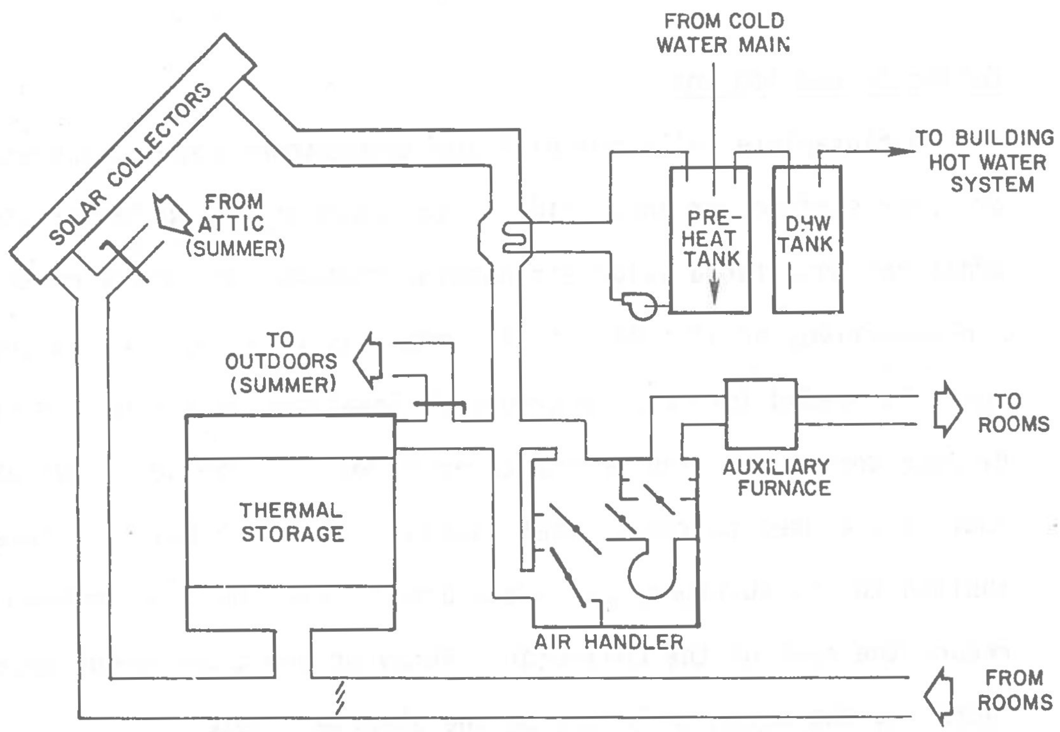


Figure 4-9. Schematic Diagram of an Air-Heating Space and Domestic Water Heating System

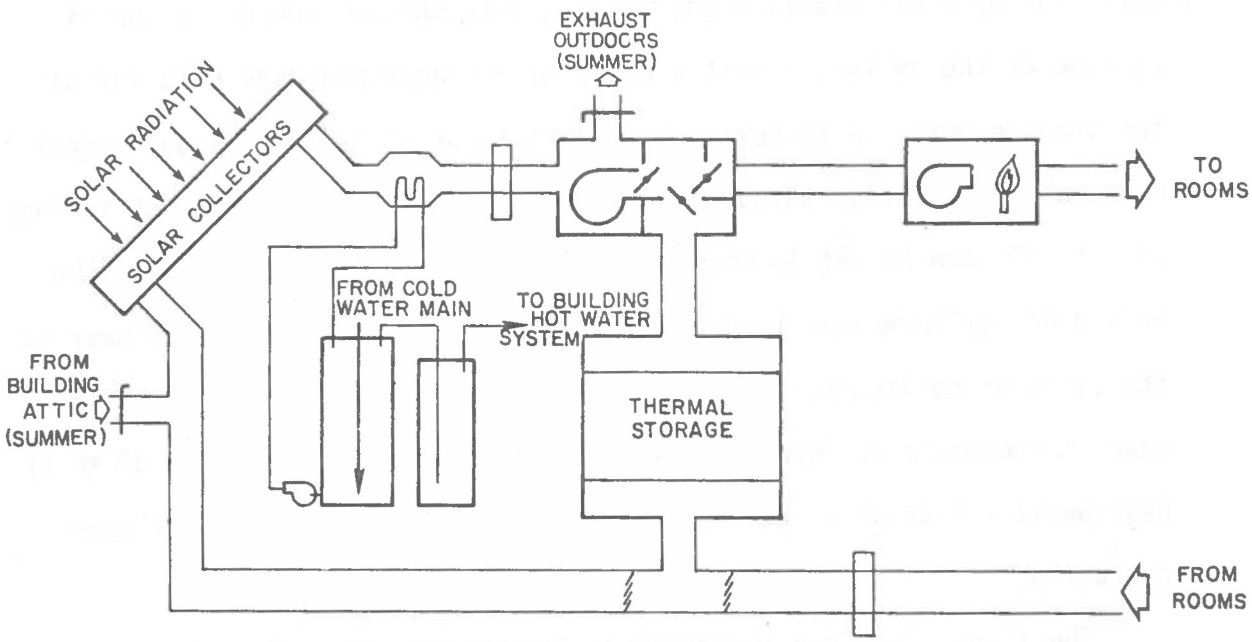


Figure 4-10. Schematic Diagram of a Two-Blower Air System

Collector and Storage

A flat-plate collector with two transparent covers, a blackened absorber surface and insulation on the back of the collector is a practical unit for a solar air-heating system. The black coating may be non-selective, or if a selective surface is used, only one transparent cover is needed for many geographical locations in the United States. Because the second transparent cover as well as the selective absorber coating are used to reduce heat losses, when a selective surface is applied to the absorber, one transparent cover could be removed to reduce the cost of the collector. Removing one transparent cover also increases the solar radiation on the absorber plate.

Solar heat is collected and stored whenever a sufficient temperature can be achieved in the air passing through the collector. The blower is activated by a differential thermostat, with the hot sensor in the air passage at the collector exit and the cold sensor near the cold end of the storage unit. A temperature difference of 10 to 20°F is sufficient to start air circulation through the collector, and a temperature difference of 2 to 3°F can be set to stop air circulation. The hysteresis in the on and off differential temperatures is to prevent cycling the blower at the start of collection and at the end of the collection period. The lower temperature difference should be set to permit collection of solar heat until the value of collected heat is equal to the cost of blower operation.

The signal from the differential thermostat controller which activates the blower motor also positions the dampers so that hot air from the collectors passes to the hot end of storage and the air from the cold end of storage returns to the collector.

The thermal storage operates both as heat exchanger and storage medium. A practical material to use in storage is rock pebbles, or gravel. The material is readily available and low in cost compared to other solid heat storage materials. With pebble sizes of 1 to 2 inches (small diameter dimension) there is a large amount of surface area provided per unit volume of storage material, and heat is transferred readily to the stones from the air. As a consequence the air is rapidly cooled as it passes through the pebble bed and emerges from storage at a temperature which is near the temperature of the pebbles at the exit. The thermal stratification in storage is a distinct advantage to collector operation, for the air enters the collector at the coldest possible temperature and enables the collector to operate efficiently all during the day.

A typical temperature rise in an air collector is about 70 to 80°F at mid-day on a typical winter day with an air flow rate of 2 cfm/ft^2 of collector. The air enters the collector at a temperature of 70°F (or near room air temperature) and is heated to 140 or 150°F. Because the solar intensity varies during the day, the air temperature emerging from the collector will vary from 80 to 90°F in the morning, to 150°F at noon and cooling to 72 or 73°F just before the air circulation through the collector stops. The temperature of the air entering storage therefore varies, and there is a "hump" in the thermal profile through the pebble bed. The quantity of heat conducted from pebble to pebble is very low because of the "point" contact between pebbles, and the temperature stratification in storage is maintained so that the discharge end of the pebble bed is always at room temperature (during the winter months).

Collector-Storage Sizing

The volume of pebbles, like the volume of water in liquid systems, is limited by economics. There is no advantage in oversizing storage volume relative to collector area unless a seasonal storage strategy is contemplated (where heat collected during the summer is to be retained in storage for use during the winter months). Annual or seasonal storage concepts have not been sufficiently explored to yield definitive answers, but the possibility of practical use in some climates merits consideration. Where winter sunshine is severely deficient, but heating loads are not exceptionally large, a moderately-sized solar collector array delivering heat to a large total volume of storage from May through September could provide sufficient energy for most, or possibly all, of the winter demands. If the total volume of storage is compartmentalized, the advantage of thermal stratification may also be retained throughout the summer and fall heat collection periods, as well as retaining some advantages in heat delivery from storage to the load.

In most geographical regions, collecting heat during the day for overnight use is the proper economic strategy. For such systems, storage volume should be one-half to one cubic foot/ft^2 of collector, with a depth of 4 to 5 feet of pebbles to minimize floor area occupied by the storage container. During mild weather and on most clear days, sufficient heat may be supplied to storage during a single day to heat the entire building throughout the night. With cold night-time temperatures, there may not be sufficient heat in storage and auxiliary heating may be necessary.

The direction of air flow in the pebble bed is usually limited by general design requirements and placement, but whenever possible, vertical flow is preferred to horizontal flow. Unless there is some practical reason to do otherwise, heated air should be supplied to the top of the bed when heat is extracted from storage, the air flow is reversed with room air entering the bottom and warm air emerging from the top.

Space Heating with Solar and Auxiliary

The auxiliary heater in an air-heating system is advantageously located in "series" with the collector or the storage heat retrieval loop so that when necessary, the auxiliary heater always boosts the temperature of the solar-heated air. When heat can be provided from the collector, the solar-heated air is directly circulated to the rooms and during the night, solar-heat stored in the pebble bed is retrieved and circulated to the rooms.

Daytime Space Heating - When heat is needed in the building, a room thermostat signals the control unit to move dampers and direct the flow of heated air from the collectors to the rooms. As shown in Figure 4-9 and 4-10, the air flows through a duct furnace or a standard furnace with a second blower. When the rooms receive sufficient heat to restore a set comfort temperature, the dampers in the system reposition to circulate the solar-heated air through storage. During the space-heating cycle, should the heat from the collectors be insufficient to restore the set comfort temperature in the rooms, the auxiliary furnace is turned on automatically to add heat from the collectors. The furnace should always be sized to meet the largest heat demand in the building, without assistance from the solar system, to ensure that comfort temperatures can always be maintained.

Space Heating from Storage - When the room thermostat signals the control unit to provide heat from storage, the circulation loop is configured so that room air enters the cold end of storage and exits from the warm end. In most systems, the reversed direction would be from the bottom toward the top. If the temperature of the air stream, consequently the heat flow from storage, is sufficient to meet the space heating demand, the room comfort temperature is regained and air circulation is stopped. If, however, the heat flow from storage is not sufficient to meet the demand, the auxiliary furnace is activated and supplementary heat is added to the solar-heated air.

The "series" installation of the auxiliary heater enables all of the solar heat to be extracted from storage. Air at a temperature of 80°F and less would generally be insufficient to meet the heating load, but rather than to by-pass storage with a separate duct and additional control dampers, the air continues to flow through storage extracting heat from the pebbles, although at low temperatures. The penalty for this arrangement is additional blower operating cost if the pressure drops though storage is large. However, in practical designs, the pressure drop through storage is insignificantly greater than the pressure drop through a by-pass duct so that a by-pass is not advantageous. The value of heat recovered from storage, even at low temperatures is greater than the operating cost of the blower.

In a one-blower system such as shown in Figure 4-9, a balanced design is needed to ensure proper air flows through the collectors and to the rooms with the single constant speed motor drive. In the two-blower arrangement of Figure 4-10, only the furnace blower is used to extract heat from storage and also to distribute the heat to the rooms.

Only one blower is needed to circulate air to the collectors, but both blowers would be activated to circulate air from the collectors directly to the rooms.

Hot Water Heating

A finned coil in the hot air duct between the solar collector and the storage unit can be arranged to supply as much of the hot water requirements as desired. Air passing through the air-to-water heat exchanger will be cooled a few degrees depending upon the effectiveness of the heat exchanger and both air and water flow rates through the heat exchanger.

In winter, heat supplied to domestic water by the solar unit is not available for space heating, so it is immaterial to which use the solar heat is actually applied, if the same auxiliary energy is used for water and space heating. In the summer, however, when solar energy is not needed for any other purpose, nearly all of the domestic hot water requirements can be supplied by the solar system. Hot air from the solar collector can be vented outside, as shown in Figures 4-9 and 4-10. Air to the collector can be supplied from the building space, the attic, or from outdoors. Another alternative is a closed-loop through a duct providing air from the collector to recirculate after passing through the heat exchanger and by-passing storage. The recirculated air will become very warm, the heat exchange rate to the water will increase and all of the domestic water heating requirements can be met by the solar system.

Water from the preheat tank can be circulated through the exchanger coil by either a small circulation pump at a rate of 1 to 3 gallons per minute, or by Thermosiphon calculation if the preheat storage tank is supported above the level of the heat exchanger coil. The cold water main is connected to the preheat tank, a conventional hot water heater follows the solar preheat tank where water temperature is maintained at a preset temperature, normally 140°F. If the water circulation pump through the solar coil is provided with a temperature limit switch, the temperature of the preheated water can be controlled so that it will not exceed 140°F. If a limit switch is not provided, the preheated water temperature can exceed 140°F, and it would be advisable for reason of safety to the occupants, to provide a mixing value in the hot water delivery line to limit the temperature of the hot water at the tap.

System Operation and Control

Collecting Solar Heat - The controls for an air-heating solar system are normally temperature driven, but as with the liquid-heating system other control devices can be used. With temperature driven controls, sensors are needed in the collector, at the cold end of storage, at the bottom of the preheat tank, and a two-stage thermostat in the heated space. The sensors in the collector and at the cold end of storage control the blower for air circulation through the collector and storage. The sensors in the collector and the bottom of the preheat tank controls the water circulation pump, and in the summer also controls the air circulation blower. The first stage of the two-stage room thermostat controls air circulation to the rooms. If heat is available from the collectors, the dampers are positioned approximately to circulate solar heated air directly from the collectors. If heat is not available from the collectors, air is circulated through storage and heat is extracted from the pebbles. In both modes, if the solar heat is insufficient to meet the load demand, the second stage of the room thermostat controls the auxiliary furnace and supplementary heat is added to the solar-heated air.

Comparison of Air and Liquid Systems - The relative merits of solar air-heating and liquid-heating solar systems have been a subject of considerable attention. There appears to be sufficient evidence for both systems to be considered of practical and economic utility. There are however, advantages and disadvantages to each system which bear on the types of use, the geographic locations most suitable, and the future potential for wide-spread application.

Liquid systems have had larger attention and use, but most applications have been experimental except for solar water heaters. The conduits for transfer of heated fluid between collector and storage are conveniently small, and the high specific heat of water makes it a compact storage medium. The currently available air-conditioning system which can be solar operated requires hot water for its energy supply. The disadvantages of the liquid system are the freezing of water in outdoor piping and collectors in most sections of the United States, the corrosive effects of water in the presence of air on many metals commonly used, and the damage which can result from accidental leakage from a solar system, and problems associated with boiling under conditions which can occasionally be encountered in solar collectors. These problems and hazards can all be satisfactorily handled but at cost disadvantages imposed by heat exchangers, self-draining and self-venting collector arrangements, pumping energy cost increases, corrosion-resistant metals or corrosion-inhibitor additives, leak-proof fillings and control requirements.

Air systems have advantages and disadvantages essentially reverse of those associated with liquid systems. Bulky air conduits (ducts) are required (compared to pipes in liquid systems) to move heated air between collector and storage, a storage volume about three times that of water storage is required, and there are no commercial air-conditioners which can be operated with solar-heated air. Advantages of the air system are freedom from hazards associated with corrosion, freezing, boiling and leakage in the collector and storage systems and the connections between them. Additional advantages are the direct cycling of the solar-heated air to the rooms without heat exchangers in the system, at temperatures compatible with most warm-air heating systems in the United States.

If solar-operated cooling equipment is required, and if outdoor freezing temperatures are not encountered a liquid system using water in the collector and storage has compelling advantages. Moreover, in commercial and industrial applications, air-conditioning is usually required and system sizes are large so the compactness and air-conditioning capability of liquid systems are important. At the other extreme, where freezing climates are encountered and air conditioning is seldom used, particularly in residential applications, solar air systems avoid the use of expensive measures which liquid systems require. In those circumstances, air collector and pebble bed installations appear to be more durable and reliable compared to liquid systems with long-term cost advantages. Commercial and industrial buildings in nearly all climates require air conditioning, so the use of air-heating solar systmes would require conventional cooling facilities. The potential of solar-operated cooling is not yet clear, so even commercial and industrial building in freezing climates are candidates for solar air-heating. Buildings which are heated by warm air are particularly well adapted to solar air system, whereas those using hydronic systems with water at moderate temperature are better suited to solar hot water systems.

A critical determinant of system type is the cost-effectiveness of the solar heat supplied. The total cost of the installation, amortized at a suitable interest rate over its useful life, plus operating and maintenance costs, divided by the total heat delivered over the same period is one basis for comparison. Other economic calculations can be made to determine cost-effectiveness, but unless solar systems can provide useful heating at costs which can compete with conventional energy systems, wide-spread use is not likely. Solar systems can be economically justified in many sections of the United States currently (1978), and although further development is likely in the years ahead, such systems as described in this module and in the balance of this manual are practical and ready for application. Waiting for "break-throughs" t provide lower-cost solar systems can prove frustrating, for it is unlikely that solar heat can be collected and delivered with simpler devices than those described, which are material intensive, and waiting to a later day can only increase the costs of materials, and labor to install the systems, thereby increasing the costs of solar heating. A realistic expectation is that improvements in the future can off-set the rising costs for both materials and labor.

REFERENCES

1. Löf, G. O. G. (1977) "Systems for Space Heating with Solar Energy" Chapter XII, Applications of Solar Energy for Heating and Cooling of Buildings. ASHRAE GRP 170.