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An Introduction to Solar Cooling Systems

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1. INTRODUCTION. The state-of-the-art of solar cooling has concentrated primarily on the developmental stages of systems in the last few years. Various methods have been researched, and some demonstrated, but only a few systems have been installed for other than research purposes. Solar cooling systems are attractive because cooling is most needed when solar energy is most available. If solar cooling can be combined with solar heating, the solar system can be more fully utilized and the economic benefits should increase. Solar cooling systems by themselves, however, are usually not economical at present fuel costs. Combining solar heating and cooling systems is not easy because of the different system requirements. This can best be understood by summarizing the different solar cooling techniques. As with solar heating, the techniques for solar cooling consist of passive systems and active systems. The passive systems are not part of this course. For active solar cooling systems the three most promising approaches are the heat actuated absorption machines, the Rankine cycle heat engine, and the desiccant dehumidification systems. A brief summary of these systems is given here and a more detailed explanation can be found in other sources in the literature.

2. ABSORPTION COOLING. Absorption cooling is the most commonly used method of solar cooling. An absorption refrigeration machine is basically a vapor-compression machine that accomplishes cooling by expansion of a liquid refrigerant under reduced pressure and temperature, similar in principle to an ordinary electrically operated vapor-compression air conditioner. Two refrigerant combinations have been used: lithium bromide and water, and ammonia and water. There have been a number of proposed solid material absorption systems also. Figure 1 shows a typical lithium bromide (LiBr) absorption cooler. In the absorption cooler, heat is supplied to the generator in which a refrigerant is driven from a strong solution. The refrigerant is cooled in the condenser and allowed to expand through the throttling valve. The cooled, expanded refrigerant receives heat in the evaporator to provide the desired cooling, after which the refrigerant is reabsorbed into the cool, weak solution in the absorber. The pressure of the resulting strong solution is increased by pumping and the solution is available to repeat the process.
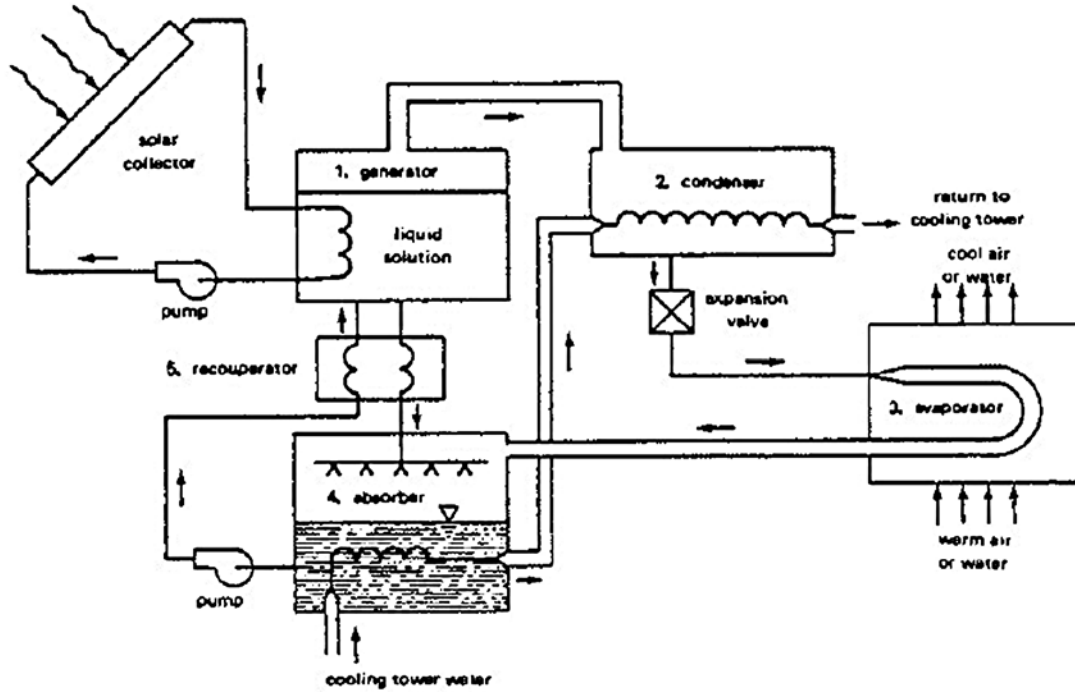
Figure 1

Schematic of Lithium Bromide Absorption Cooler

The performance of the system is governed largely by the temperature difference between the generator and the condenser and absorber units. Since the generator temperatures in solar driven systems are only moderate, it is important to keep the condenser and absorber temperatures as low as possible. The LiBr system is preferred over ammonia systems for solar energy applications because of the lower generator temperatures required. Permissible generator temperatures for a water-cooled LiBr system range from 170 deg. F to 210 deg. F (76 deg. C-99 deg. C) compared to the 205 deg. F to 248 deg. F (95 deg. C-120 deg. C) temperatures required for a water-cooled ammonia absorption system. Most, if not all, of the commercially available absorption units use LiBr and water as the absorbent-refrigerant fluid pair. Because the LiBr will crystallize at the higher absorber temperatures associated with air cooling, these units must be water cooled. A prototype ammonia-water unit, amenable to direct air cooling, has been built by Lawrence Berkeley Laboratories.

A number of equipment requirements and limitations must be considered in the analysis and design of solar powered absorption systems. The first consideration involves the type of collector used. The temperatures required by absorption coolers are obtainable with flat plate collectors but at low collection efficiencies. Collection efficiency is improved with an increased number of glazings and with a selective surface, therefore, it may be cost effective to improve the collector rather than to simply oversize. Concentrating or evacuated tube collectors are usually used in these applications. If concentrating collectors are used, the associated higher costs and potentially increased maintenance for the tracking mechanism must be considered. In general, concentrating collectors operate at higher efficiency at these higher temperatures. However, the higher temperatures are usually not required to operate the space heating system. Therefore, the relative importance of the two thermal loads must be considered when selecting a system. The second consideration involves the means of delivery of the heated fluid to the absorption cooler. Since, in many climates, the cooling load is simultaneous with and often proportional to the solar insolation, it may be desirable to allow the heated collector fluid to bypass the storage unit. Other climates may require a hot storage unit but one of considerably smaller size than the one used for heating purposes. The important requirement is that high temperatures be available during periods of heavy cooling load. A third consideration deals with the problem of reduced efficiency of the absorption cooler under start up and transient conditions. Typical absorption coolers do not reach operating efficiency until after an hour or more of operation time. A machine which is cycled on and off regularly will have a drastically reduced average coefficient of performance when compared to a machine in steady state performance. This problem has been overcome in at least one installation by the use of a cold storage unit. The cold storage unit permits continuous operation of the absorption cooler and thus allows some reduction in the system and cooler size.

A fourth consideration is the need for some means of cooling the absorber and the condenser. A cooling tower or some other low temperature cooling system must be used to obtain reasonable performance. All of the commercially available units require a cooling tower which is another maintenance item. Current research is underway to develop units that do not have a separate cooling tower.

3. RANKINE CYCLE HEAT ENGINE COOLING. Rankine cooling systems are still in development with only a few in operations. In these systems the shaft power produced by a heat engine drives the compressor in a conventional vapor compression-type cooling machine. The thermal energy input to the heat engine can be from a solar collector or from a solar collector and a fossil fuel combustor. The fossil fuel can supplement solar energy, or it can be used alone as the auxiliary energy supply when no solar energy is available. Alternatively, electricity can be used as the auxiliary energy supply by coupling an electric motor directly to the compressor shaft. Another option is a motor-generator using a heat engine for generating electricity when solar energy is available and there is little or no cooling load.

From state-of-the-art considerations, two types of fluid heat engines are primarily feasible in solar cooling units. In one type of engine, the working fluid cyclically changes phase from liquid to gas and back to liquid. The most widely used engine of this type operates on the Rankine cycle. In the other type, the working fluid remains in the gaseous state. These engines operate on various cycles, including the Stirling and Brayton cycles. For relatively low thermal energy input temperatures (less than 400 deg. F), Rankine cycle engines are superior in performance to gas cycle engines. At higher temperatures, gas cycle engines equal or better the performance of Rankine cycle engines.

Relatively low temperatures are attainable with state-of-the-art thermal solar collectors, so the heat engine-vapor compression development projects involve Rankine cycle engines. In a Rankine cycle engine, fluid in the liquid state is pumped into a boiler where it is evaporated and possibly superheated by thermal energy. The vapor generated in the boiler is then expanded through a device such as a turbine, a piston-cylinder (reciprocating) expander, or a rotary vane expander. The expansion process lowers the temperature and pressure of the vapor, and effects a conversion of thermal energy into shaft work. The fluid leaves the expander either in the vapor phase or as a liquid-vapor mixture and flows into a condenser, where it returns to the liquid phase by

giving the energy of condensation to cooling water or ambient air. This liquid is then pumped into the boiler, and the cycle is repeated. In some systems under development, the same working fluid is used in both the Rankine engine and the vapor compression chiller, which permits the use of common condenser and the elimination of special seals to maintain fluid separation in the expander-compressor unit. These systems have areas that need development in matching the solar heat engine with the mechanical compressor units of the cooling equipment. Since most compressors are designed for certain speed and torque inputs, the varying operation of a solar heat engine will probably reduce the overall coefficient of performance (COP) of the unit. Also the solar heat engine is at high efficiency at high storage tank temperatures whereas the solar collectors are at low efficiency which will also affect the COP of the system. These systems are designed for large cooling load applications.

4. DESICCANT COOLING. The Rankine engine vapor compression and the absorption cooling units operate on the basis of closed cycles-fixed amounts of working fluid are circulated within sealed equipment; the working fluids do not come in contact with the building air. Desiccant cooling systems, on the other hand, may be designed for open-cycle operation, since the only circulating fluids involved are air and water. The basic concept is to dehumidify air with a desiccant, evaporatively cool the dehumidified air, and regenerate the desiccant with solar-derived thermal energy.

Two basic open-cycle arrangements are feasible: the ventilation mode and the recirculation mode. In the ventilation mode, fresh air is continually introduced into the conditioned space. In the recirculation mode, exhaust air from the conditioned space is reconditioned and returned to the space. Figure 2 illustrates a ventilation system in which a solid desiccant material mounted on a slowly rotating wheel provides the basis for obtaining a cooling effect. The hot desiccant material absorbs moisture from incoming ventilation air and increases the dry-bulb temperature. This dry air stream is cooled in two steps. First, it is sensibly cooled by heat exchange with the building exhaust air. Then it is evaporatively cooled and partially rehumidified by contact with a water spray. The exhaust air from the building is evaporatively cooled to improve the
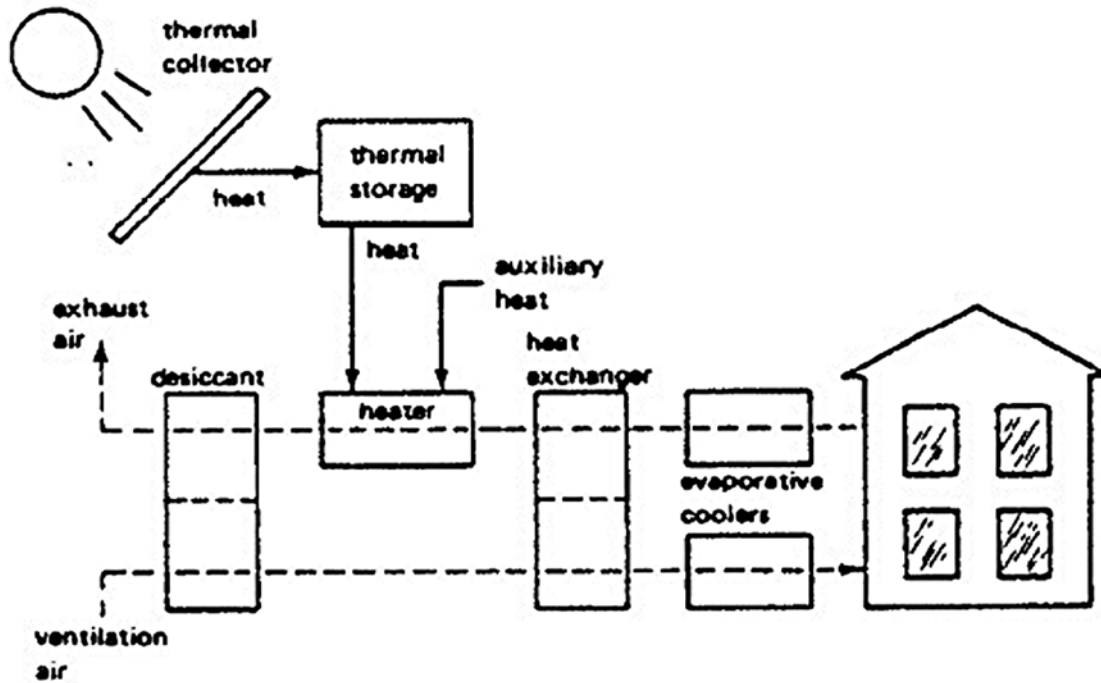
Figure 2

Schematic of Solar Desiccant Cooling

performance of the heat exchanger. After being heated by heat exchange with the incoming air, the exhaust air is further heated by energy from the solar system and/or from an auxiliary energy source. The hot exhaust air passes through the desiccant material and desorbs moisture from it, thereby regenerating it for continuation of the process. Desiccant systems have faced problems of high parasitic power and large space requirements relative to capacity. Because of their bulkiness, the systems may have primary application in the low capacity range (i.e., residential systems) if and when ways can be found to reduce parasitic power requirements to acceptable levels.

The Institute of Gas Technology (IGT) has been investigating design modifications in a prototype 3-ton system. AiResearch is developing a 1-l/2-ton desiccant cooling system around a radial flow design. Illinois Institute of Technology is developing a dehumidifier of a cross-flow design that will provide more compact and efficient operation than

previous designs. Zeopower is developing a unique closed cycle desiccant system in which the desiccant is integral with the collector.

5. OTHER COOLING METHODS. Other methods, using solar heating equipment but not direct solar energy, should also be considered. These methods chill the thermal storage unit of the system during the night and use the chilled medium to provide the daily cooling load. Methods of chilling the storage include radiation of the heat to the night sky and heat exchange with the night air cooled or uncooled by auxiliary means. The chilled storage is used directly, via heat exchange with the building air. Both rockbed and water storage are suitable since the only additional hardware required is that to route the fluid. A heat pump can be used during the day to cool the building and reject heat to the thermal storage unit. The thermal storage is then cooled by using the solar collectors for night sky radiation. From experimentation in Arizona, Bliss obtained a nightly heat rejection quantity of 360 Btu/night/ft^2 for a black cloth radiator. Analytical estimates can be obtained using an effective clear sky temperature of 25 deg. F (14 deg. C) lower than the ambient air temperature. The advantage of this system is that the same equipment (collectors and heat pump) can also be used for heating. In systems with dual storage units, the heat pump transfers heat from one to the other - cooling the first and warming the second. The cool fluid in the first unit is circulated to the house while the concentrated heat in the second is discharged to the outdoors. An evaporative cooler can be used coupled with a rockbed storage unit. Night air is evaporatively cooled and circulated through the rockbed to cool down the pebbles in the storage unit. During the day, warm air from the building can be cooled by passing it through the cool pebble bed. This method is not very effective in humid geographical areas.

The storage volume can also be cooled using a small refrigeration compressor. Most through-the-wall air conditioners use such compressors to cool the indoor air. This unit acts as the backup or auxiliary cooling system - analogous to the backup heating system. If operated only at night, its capacity can be as small as half that of an independently functioning unit and still meet peak cooling demands. Nighttime operation

will be particularly wise if electric companies charge more for electricity during times of peak loads on hot summer afternoons. An even smaller compressor can be used if it operates continuously night and day - cooling the storage when not needed by the house.

6. ESTIMATING SYSTEM SIZE. The sizing of cooling system components is dependent on hardware, climate, and economic constraints. The cooling unit must be sized so as to provide the maximum cooling load under conceivable adverse conditions of high humidity and low or erratic solar insolation. The collection area required is dependent on the fraction of the cooling load to be provided by solar. Very large collector areas may be required for 100% solar cooling under adverse conditions of high humidity and low insolation. Although a detailed calculation method is not available for solar cooling, an estimate of the required collector area can be made by the equation:

$$A = \frac{\text{Cooling load/COP}}{I_T \ [\text{eta}]\text{collect} \ [\text{eta}]\text{delivery}}$$

where: Cooling load = the portion of the total cooling load provided by solar calculated using ASHRAE techniques or others.

        COP = Coefficient of Performance of the cooling unit. COP is the ratio of heat energy removed to energy supplied from external sources. Manufacturing data is recommended for determining COP (3413 Btu = 1 kWh).

        I_T = average instantaneous solar insolation on collector surface (i.e., at tilt angle).

        [eta]collect = average collector efficiency under design conditions.

        [eta]delivery = delivery efficiency which takes into account heat exchanger efficiency and thermal losses.

In general, the collector area required to provide the majority of the cooling load is larger than the collector area of typically sized heating only systems. Collector areas for heat engine systems are larger than the areas for absorption cooling systems due to the thermal efficiency of the heat engine, which should be included in the preceding equation.

7. SYSTEM CONTROLS. System controls are used to turn on a circulating pump or blower to the collector only when the sun is providing heat. Differential thermostats are commercially available to turn on the collector pump only when the collector plate temperature is a preset number (usually 20 deg. F) hotter than the storage tank bottom temperature. A typical control strategy is shown in Figure 3 and the hookup in Figure 4.

Differential thermostats are available with high temperature protection and low temperature (freeze) protection. High temperature protection is important, especially in evacuated tube collectors, in that it prevents a very "hot" collector from suddenly receiving a supply of cold water thus producing a thermal shock that could damage the collector components. Another type of control called proportional control is available. It is similar to the ON/OFF differential controller in operation. The difference is that the proportional controller changes the threshold ON and OFF points and controls the flow such that less than full flow can be achieved if the sun is at less than full intensity. The advantage is that the proportional control can "turn on" the system when the other controller (the ON/OFF type) is waiting for more sun to become available. This is an advantage on cloudy days and early morning start ups. Overall system efficiency is increased slightly with the proportional control. These controls are more expensive and one such experiment at NCEL has shown that proportional controls result in considerably more cycling of the pump motor which could shorten pump life. It is recommended that the control manufacturer be consulted on this point before a proportional control is used. As the building requires heat, other controls must direct pumps or blowers to provide heat from the storage tank to the load. This control is the conventional thermostat. The same room thermostat may control the auxiliary heater; however, a delay timer or a two-step room thermostat must be incorporated into the auxiliary heater control circuit so that the auxiliary heat will not come on if heat is available from storage. Ten minutes has been suggested as a typical time delay before
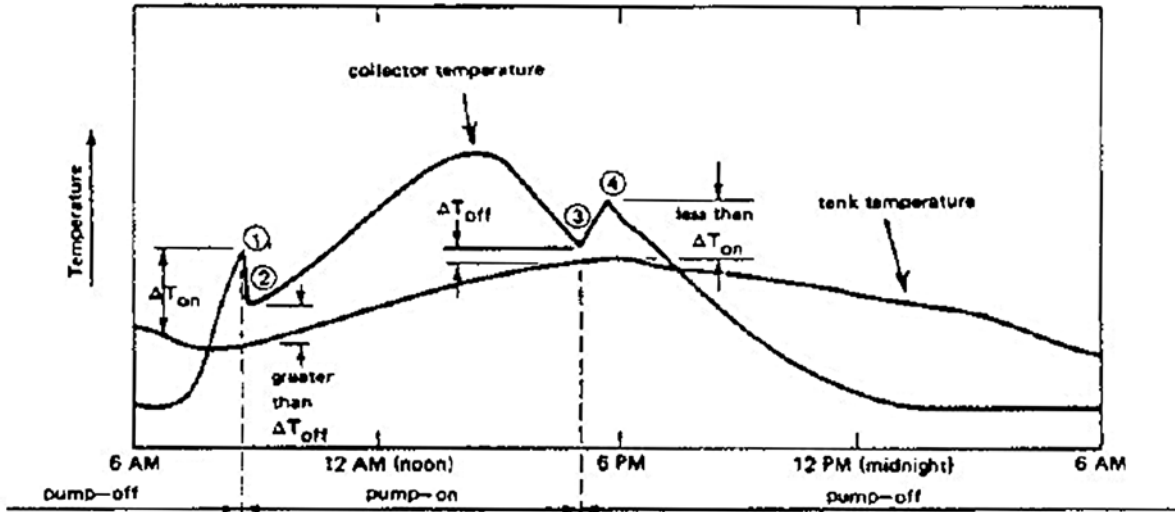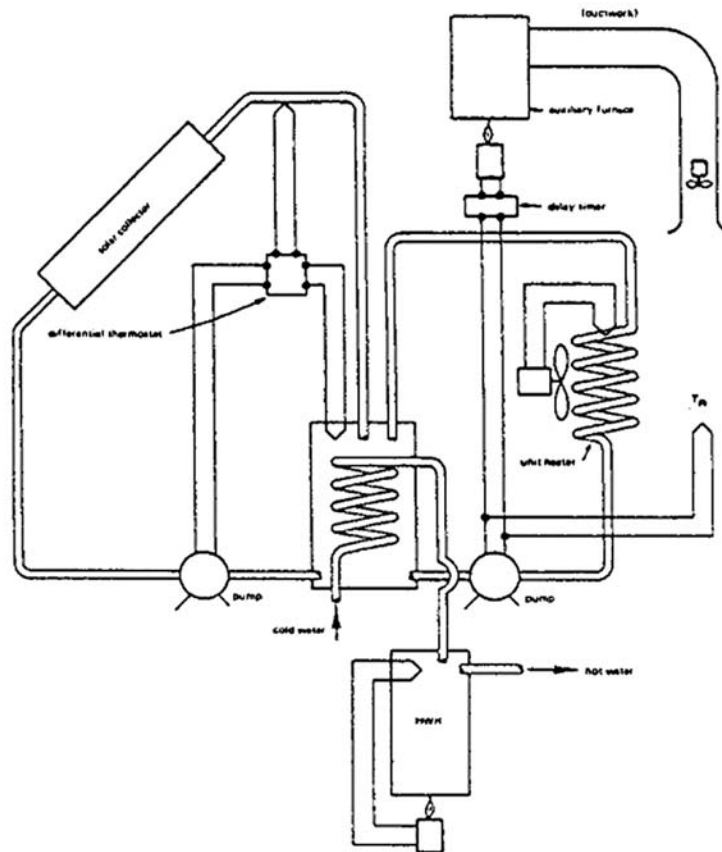
Figure 3

Control System Strategy

Figure 4

Control System for Space Conditioning and Domestic Hot Water (DHW)

auxiliary heat comes on. Some manufacturers supply combination thermostat and solar system controls.

8. PIPING, PUMPS, VALVES

8.1 PIPE AND HEADER SIZING. Piping should be designed for low pressure drop. All exposed piping should be well insulated with approved weather-resistant insulation. Dielectric unions should be used at connections between dissimilar metals. Rubber or silicone hose used for connections must be of a high temperature type. The pipe ends should have ferrules to provide a good seal with the hose. In low pressure systems, spring type clamps are preferred because they compensate for thermal expansion. Copper pipe is preferred to galvanized steel due to its longer life expectancy and relative ease of installation. Thermal expansion should be provided for all piping or hard tubing. Pipe sizing should be in accordance with recognized methods, but for most installations the following estimates are reasonable:

8.1.1 FOR A SINGLE ROW OF PARALLEL COLLECTORS WITH "X" NUMBER OF BRANCHES

- 0.5 gpm flow per collector, water or 50% glycol as heat transfer fluid.
- Up to 3 collectors - 1/2-inch headers
- 4 to 7 collectors - 3/4-inch headers
- 8 to 12 collectors - 1-inch headers
- 13 to 18 collectors - 1-1/4-inch headers
- More than 19 collectors - 1-1/2-inch or larger (size for each design)

8.1.2 SAME AS ABOVE EXCEPT COLLECTORS IN A DOUBLE ROW SERIES-PARALLEL ARRANGEMENT

- Up to 5 collector branches - 1/2-inch headers
- 6 to 10 collector branches - 3/4-inch headers
- 11 to 15 collector branches - 1-inch headers

- 16 to 22 collector branches - 1-1/4-inch headers
- More than 23 collectors - 1-1/2-inch or larger (size for each design)

8.2 PUMPS AND COLLECTOR FLOWRATE. Pumps are sized in accordance with recognized practices also. Since solar systems are nothing more than a combination of pipes, valves, and fittings it is possible to do a heat loss calculation to determine the system head. Charts are available in standard fluid flow handbooks that give the friction losses or "equivalent length of feet in pipe" for various fittings and valves. These are merely summed for the entire system. The flowrate through the collector loop is determined by the maximum amount of energy which must be removed from the collector. This maximum is about 225 Btu/ft^2/hr. Often a manufacturer will specify the flowrate through his collector and this value should be used. If not, an estimate can be made by determining the flowrate necessary to remove the maximum amount of energy while minimizing the collector inlet temperature (to maintain high collector efficiency). The rule of thumb for this calculation is 0.015 to 0.020 gpm for each square foot of collector area for water. For other fluids this can be scaled by the value of the specific heat of the fluid as compared to water (C_p= 1 Btu/lbm-deg. F). Now that head loss and flowrate are determined, a pump can be selected by using the manufacturers' standard tables and graphs. For typical domestic hot water systems and space heating systems for a house for a family of four, the pumps are quite small, averaging 1/12 to 1/20 hp. In some systems, like a drain down system, pump sizes can be much larger due to the higher vertical "head" requirements. If the water in the system is open to the atmosphere or if the water is to be used for drinking the pump should be made of bronze or stainless steel on all water-wetted surfaces to minimize corrosion. Pumps will have longer life if they are placed in low temperature parts of the water circuits. Pumps can be "staged" to give more flow or head. Two pumps in series will give the same flow against twice the head. Two pumps in parallel will give twice the flow at the same head. Two or more small circulator-type pumps are often cheaper than a single larger pump.

8.3 VALVES. Valves, other than seasonal or emergency shut-off valves, should be electrically operated and located out of the weather or well protected. A vent must be

provided at the high point in liquid systems to eliminate entrapped air and it should also serve as a vacuum breaker to allow draining of the system. To avoid multiple venting, systems should be piped to avoid having more than one high point. Pressure relief must be provided at some point in each flow circuit. Check valves can be added to prevent thermally induced gravity circulation. A flow-check valve (used in the hydronic heating industry) will also accomplish the same purpose. Mixing valves should be used to protect DHW systems from delivering water hotter than specified (usually 120 deg. - 140 deg. F). Consideration should be given to energy conservation by lowering DHW temperature whenever possible. Often 105 deg.-115 deg. F will suffice if water is used only for showers and washing hands.

9. COLLECTORS. The collector is the most important and one of the most expensive parts of a solar system. It must be long-lived and well insulated, yet its cost must be minimized. Collectors of primary interest are of two basic types: liquid and air. Liquids may be water, an antifreeze mixture, or various hydrocarbon and silicone heat transfer oils. Air-type collectors use air as the collector fluid. The absorber plate is that part of the collector which absorbs the solar energy and converts it to thermal energy. A portion of the thermal energy is carried to the building or thermal storage unit by the fluid which circulates through passages in the absorber plate. The absorber plates can be made of metal, plastic, or rubber compounds. The metals commonly used in order of decreasing thermal conductivity are copper, aluminum, and steel. Plastics (polyolefins) and rubbers (ethylene propylene compounds) are relatively inexpensive, but due to their low thermal conductivity and their temperature limitations, they are suitable only for low temperature applications, such as heating swimming pool water or for use with water source heat pumps. Other major components of a solar collector include:

- **Absorber plate coating** - To enhance the heat transfer and protect the absorber plate.
- **One or more transparent covers** - To reduce thermal losses by radiation (using the "greenhouse effect") and by convection (wind, etc.). Spacings are nominally 1/2 inch or more.

- **Insulation** - One to three inches are used to reduce heat loss through the side and back of the absorber plate.

- **Collector box or housing** - To provide a rigid mounting to hold the components. Must be weatherproofed.

- **Gaskets and seals** - To insure a weathertight seal between components while allowing thermal expansion of the components. Normally these seals remain ductile to accomplish their purpose.

Flat-plate collectors are most suitable for low temperature applications such as domestic hot water and space heating. They collect both direct and diffuse radiation. It is not required that they track the sun, thus initial cost and maintenance are minimized. A properly designed flat-plate collector has a life expectancy of 10 to 25 years, or sometimes longer. All copper and glass systems currently exhibit the longest lives. Using softened water will help. Tubes should be 1/2 inch in diameter or greater for low pressure drop and longer life. The better the attachment of tube-to-plate (such as by soldering), the better the heat transfer, but the greater the manufacturing cost. Advances in collector cost reduction will probably be made in the direction of cheaper manufacturing processes. Some collectors not made from tube and sheet may not tolerate DHW line pressures. Specifications for pressurized collector circuits should require collectors which will take proof test pressure equal to 150% of expected circuit pressure. In hot climates, it is important to reduce roof heat load due to collector heat gain in summer; this can be accomplished by venting the space between collector plate and glazes with dampers or by covering the collectors. A normal amount of dirt and dust on the glass cover will reduce heat collected by about 5%. Normal rainfall is usually sufficient to relieve this problem. Except for warm climates with high insolation (I > / - 1400 Btu/ft^2-Day), two cover glasses may be optimum. In warm climates, one glass is optimum. Many plastics have an undesirable transparency to infrared radiation, to which glass is nearly opaque, so the desired "greenhouse effect" is not so pronounced with plastic materials as with glass. However, losses by radiation from the collector are small compared with convective losses due to wind; thus plastics can be employed to reduce breakage and cost, but with some loss in collector performance. Plastics with maximum

opaqueness to infrared and maximum transparency to ultraviolet (UV) and visible radiation and with high resistance to UV degradation should be specified. The following sections give more detailed information on collector designs and components.

9.1 LIQUID AND AIR-TYPE COLLECTORS.   Liquid types are more suited to domestic hot water (DHW), the collector area is usually smaller, and more information is available about liquid systems. Collectors for heating air do not require protection from freezing and have minimal corrosion problems, leaks do not cause serious damage, they may cost less per unit area, and are better suited to direct space heating for residences where duct-work is already present. However, since leaks in air systems are less easily detected, they can degrade system performance if not corrected. Wherever this manual discusses liquid collectors, air collectors are included, and cost analyses apply equally to both. The design procedure for air collectors differs, however. Heat transfer oils used in liquid systems offer freeze protection and some corrosion protection, but they also require heat exchangers for heating domestic hot water, as do antifreeze-water mixtures.

9.2 SELECTIVE SURFACES. Some collectors are manufactured with a black coating which absorbs the high frequency incoming solar radiation very well and which emits low frequency infrared radiation poorly. This is a highly desirable combination of properties for a collector. The absorptance should be 0.9 or higher and emittance may be 0.1 or lower. Such coatings are approximately equal in effect to one cover glass. Thus, a selective coating plus one cover glass may be expected to be about equal in efficiency to a collector with two cover glasses and a flat black painted surface. Electroplated black nickel, black chrome, copper oxide and anodized aluminum are common types of selective coatings. Cost of selective surface coatings may be greater than an extra sheet of glass, but much research is being done to produce low cost, easily applied coatings. The stability of black nickel, chrome and aluminum in the presence of moisture has not yet been proven. Long-term stability in the presence of moisture or other expected environmental factors (salt air, etc.) must be included in specifications for selective surfaces.

9.3 COLLECTOR COVERS (GLAZES). The transparent covers serve to admit solar radiation to the absorber while reducing convection and radiation heat losses from the collector. The covers also protect the absorber from dirt, rain, and other environmental contaminants. The material used for covers include glass and/or plastic sheets. Glass is most commonly used because of its superior optical properties and durability. Standard plate glass reflects about 8% and absorbs about 6% of normal incident solar radiation, resulting in a transmissivity of about 86%. Yet it is essentially opaque to long-wave thermal radiation from the absorber. Transmission of solar radiation into the collector can be increased by minimizing the reflectance and the absorptance of the glass covers. Absorptance of solar radiation by the collector can be increased with the use of thinner tempered glass and by using glass that has a low iron content. Although glass is subject to impact damage and is more expensive than plastic, it does not degrade in sunlight or at high collector temperatures, and is generally considered to be more durable than plastic. Impact damage may be reduced with the use of tempered glass and small collector widths. Also 1/2-inch wire mesh may be hung over glass covers for protection, but the effective absorber area will be reduced by approximately 15%. In general, screens are not recommended. Most plastic covers transmit the solar spectrum as well or better than glass glazing. Unfortunately, they transmit infrared radiation well also, increasing radiation losses from the collector.   Although resistant to impact damage, plastics generally degrade in sunlight and are limited as to the temperatures they can sustain without undergoing serious deformation. Often they do not lie flat, resulting in a wavy appearance. In general, acrylic is the most UV resistant and FRP Plastics offer good impact and high temperature properties. Teflon FEP film has good transmittance and high temperature properties, but is limited in strength. Some collectors using plastic covers are designed to have stagnation temperatures no higher than 200 deg. - 275 deg. F. However, plastic covers have been developed to withstand 400 deg. F. The manufacturer should be consulted.   Each additional cover, whether it is glass or plastic, reduces convection heat losses but results in added expense and less solar radiation transmitted to the absorber. Most commercially available collectors come with one or two covers. The decision to use one or two covers

depends on the type of absorber coating, the required collection temperatures, average ambient air temperature, the local wind conditions, and of course, the cost of the covers. The use of a selective surface is about equal to using one additional cover. Thus for most cases, only one glass cover is needed if the absorber has a selective coating. In fact, one study indicated that winter performance was actually reduced by the use of two glass covers with a selective surface compared to one cover with the selective surface. Two covers are generally recommended for use in Northern climates where winter ambient air temperatures are low. For flat-plate collectors used mostly for winter heating, one rule of thumb is to use one glass cover where average winter air is greater than, 45 deg. F, and two glass covers in colder climates.

9.4 COLLECTOR INSULATION. Insulation behind and to the side of the absorber serves to reduce conduction losses. Usually, this insulation consists of 1-6 inches of high-temperature fiberglass batting or semi-rigid board or even mineral wool. Styrofoam and urethane foams are usually not used because they may deform at high temperatures or give off gases (which may be toxic). The insulation should be separated from the absorber plate by 1/2 to 3/4 inch and have a reflective foil facing the absorber plate. If fiberglass insulation is used, it should not be typical construction grade which contains phenolic binders that may "outgas" at the stagnation temperature of the collector. In all cases, specifications should call for insulations that are not flammable, have a low thermal expansion coefficient, do not melt or outgas at collector stagnation temperatures (300 deg. – 400 deg. F), and (whenever possible) contain reflective foil to reflect thermal radiation back to the absorber.

9.5 COLLECTOR HOUSINGS. The housing or collector box serves to:

- Support the collector components.
- Protect the absorber and insulation from the environment.
- Reduce convection and conduction losses from the absorber.

Many housing designs are available on the market. They are constructed of metals, wood, plastics, concrete, and other materials. The most commonly used materials are aluminum, galvanized sheet metal, fiberglass laminates, high temperature thermoplastics, and wood. It is recommended that wood be avoided for use as a structural member, spacer, or anchor for panels due to its susceptibility to deterioration and flammability. All structural materials are suitable if properly used. However, most commercially available housings consist of a galvanized sheet metal box with an anodized aluminum frame which fits on top of the box. Some housings are designed to be integrated directly into the roof or wall structure, thus reducing construction costs. Since field labor is expensive, the collector housing should be designed such that the collector units can be quickly secured in place and connected to the external piping. Provisions should also be made for easy replacement of broken glass covers. The absorber plate should be mounted so as to be thermally isolated as much as possible from the housing.

9.6 COLLECTOR GASKETS AND SEALANTS. Gaskets and sealants must be carefully selected if a collector is to have a long life. Generally, the housing and the glazing have different rates of thermal expansion. Gaskets and sealants form the flexible interface between the two components and seal out moisture and other contaminants; if they fail, moisture will fog the glazing and may possibly damage the absorber coating and the insulation. These problems can drastically reduce the thermal performance of the collector.   Gaskets provide flexible support and the primary weather sealant insures against moisture leakage. Desiccants are sometimes placed between the two glazings to absorb any moisture that may remain after cover installation. When selecting collector gaskets and sealants, certain material requirements must be kept in mind. The gaskets and seals must:

- Withstand significant expansion and contraction without destruction.
- Adhere effectively to all surfaces.
- Resist ultraviolet degradation.
- Resist outdoor weathering.

- Not harden or become brittle.

- Withstand temperature cycling from -30 deg. to 400 deg. F.

- Not outgas at high temperatures.

Silicone sealants have exceptional weathering resistance and have received widespread use for many years.

9.7 COLLECTOR FLUIDS - CORROSION AND FREEZE PROTECTION. The choice of which collector fluid to use is important because this is the life-blood of the system. The cheapest, most readily obtainable, and thermally efficient fluid to use is ordinary water. However, water suffers from two serious drawbacks - it freezes and it can cause corrosion. Therefore, the choice of collector fluid is closely linked to the type of solar system, the choice of components, future maintenance, and several other factors which will be discussed in this section. Implicit in this discussion is the use of a fluid other than air as the collector fluid. An air solar system does not suffer from corrosion or freezing effects, but its low density and heat capacity require the use of fans and large ducts, large storage volumes, and is generally not suitable for domestic water heating. The remainder of this section applies to liquid solar systems. Generally the heat transfer fluid must be nonionic, high dielectric, nonreactive, noncorrosive, nonflammable and stable with temperature and time. If the fluid is toxic it may be used only in systems specially designed for it. The National Bureau of Standards (1980), Ref - DOE Solar Heating Materials Handbook, has proposed the following criteria to reduce the risk of fire in the use of solar heat transfer fluids: The flash point of the liquid heat transfer fluid shall equal or exceed the highest temperature determined from below:

- A temperature of 50 deg. above the design maximum flow temperature of the fluid in the solar system; or (1) A temperature 200 deg. F below the design maximum no-flow temperature of the fluid attained in the collector provided the collector manifold assembly is located outside of the building and exposed to the weather and provided that relief valves located adjacent to the collector or

collector manifold do not discharge directly or indirectly into the building and such discharge is directed away from flames and ignition sources; or,

- The design maximum no-flow temperature of the fluid in all other manifold and relief valve configurations;

- 100 deg. F.

If there is no danger of freezing and the collector loop consists of all copper flow passages, then ordinary water would be the choice for collector fluid. If freezing conditions are encountered, there are a number of designs that should be considered before it is decided to use a heat transfer oil or antifreeze mixture. These freeze protection schemes are summarized:

9.7.1 DRAIN DOWN OR DRAIN BACK METHOD - The water in the collector is drained out of the system, or into a tank near the collector, or into the main storage tank when temperatures in the collector approach freezing. This scheme requires automatic valves to dump the water and purge air from the system. Often a larger pump will be required to overcome the system head and re-prime the collectors. A way to avoid automatic (solenoid) valves is to drain the collectors whenever the pump shuts off. This still requires a larger pump. Three-way valves exist that can use city water pressure to reprime the system; otherwise pumps must be used. Some drainback systems only drain the water to a small tank near the collectors thus requiring only a small additional pump. Heat exchangers may be required to separate potable water from nonpotable water.

9.7.2 HEAT TAPES - Electric resistance heat tapes are thermostatically activated to heat the water. This scheme requires extra energy and is not completely reliable. Insertion of heat tapes into preconstructed collectors may be difficult.

9.7.3 RECIRCULATION METHOD - In this method the control system merely turns on the pump if freezing approaches. In this way, warm water from storage circulates through the collectors until the freezing condition is over. The only extra component

needed is a freeze sensor on the collector. However, by circulating heated water, the capacity of storage decreases and less is available the following day. This method is probably the most reliable of the three since it does not depend on additional electrical valves or heating tape, provided that back up power is available to operate pumps in the event of power failure. If the preceding methods are not acceptable or if the choice of water is not acceptable due to concern about corrosion, then a heat transfer fluid must be used. The heat transfer fluid must be used with a heat exchanger in a "closed--loop" configuration. If the heat transfer fluid is toxic or non-potable (such as antifreeze) then a double-walled heat exchanger must be used for protection.   It is difficult to estimate the most cost effective freeze protection method. Some studies have shown that for many areas in the U.S., the recirculation method is best particularly where freezing days are few in number. It tends to have the lowest capital cost and energy use cost. However, all the methods except heat transfer fluids rely on the presence of electricity to operate. A simultaneous electrical failure and freezing condition would result in potential failure of the systems. An exception is that new thermally actuated draindown valves are becoming available to replace the sometimes troublesome solenoid valves. Therefore, the absolute safest system would be the nonfreezing heat transfer fluids and these might be considered for the very cold parts of the country (Boston, Chicago, etc.). Each potential project should be considered individually using local weather criteria, freeze protection capital costs, additional energy to run the system, reliability, maintenance, and type of system as the criteria. Often a detailed computer simulation would be required to choose. However, any of the methods will provide some degree of protection. If heat transfer fluids are selected for corrosion or freeze protection, the following paragraphs discuss pertinent criteria.

Most heat transfer fluids contain some degree of toxicity. To minimize the probability of contamination of potable water systems the following items should be addressed:

- Assurances to preclude the possibility of cross connection of potable water piping with heat transfer fluid piping. The use of tags, color coding, different pipe connections, etc, are suggestions.

- Hydrostatic testing of system to find leaks.

- Color indicators in heat transfer fluid to find leaks.

- Safe designs for heat exchangers.

- Determine toxicity classification of heat transfer fluids.

9.7.4 CORROSION. Before heat transfer fluids are discussed, a review of basic corrosion theory is in order. The two types of corrosion which cause the most damage in solar systems are galvanic and pitting corrosion.

Galvanic corrosion is a type of corrosion which is caused by an electrochemical reaction between two or more different metals in contact with each other. A chemical reaction between the metals causes a small electrical current which erodes material from one of the metals. Solar energy systems generally contain a number of different metals such as aluminum, copper, brass, tin, and steel. This makes the solar system a prime candidate for galvanic corrosion. If the dissimilar metals are physically joined or if they are contacted by a common storage or heat-transfer fluid, the possibility of galvanic corrosion becomes much greater.

Pitting corrosion is a highly localized form of corrosion resulting in deep penetration at only a few spots. It is one of the most destructive forms of corrosion because it causes equipment to fail by perforation with only a very small weight loss. When heavy metal ions such as iron or copper plate on a more anodic metal such as aluminum, a small local galvanic cell can be formed. This corrosion spot or "pit" usually grows downward in the direction of gravity. Pits can occur on vertical surfaces, although this is not as frequent. The corrosion pits may require an extended period (months to years) to form, but once started they may penetrate the metal quite rapidly. Heavy metal ions can either come as a natural impurity in a water mixture heat transfer fluid or from corrosion of other metal parts of the solar system. Pitting corrosion has the same mechanism (concentration cell) as crevice corrosion thus it can also be aggravated by the presence of chloride or other chemicals which can be part of the water mixture or a contaminant

from solder fluxes. Aluminum is very susceptible to pitting corrosion, while copper generally is not.

There are several preventive measures which will eliminate or at least minimize galvanic and pitting corrosion in collector systems which use an aqueous collector fluid. The best method to prevent galvanic corrosion is to avoid using dissimilar metals. Where this is not possible or practical, the corrosion can be greatly reduced by using nonmetallic connections between the dissimilar metals, thus isolating them. Galvanic protection in the form of a sacrificial anode is another method of protecting the parent metals. Also, use of similar metals reduces the problems of fatigue failure caused by thermal expansion. Pitting corrosion is essentially eliminated if copper absorber plates are used. Corrosion inhibitors can minimize pitting corrosion in aluminum absorbers. The types of heat transfer fluids available may be divided into two categories, nonaqueous and aqueous. Silicones and hydrocarbon oils make up the nonaqueous group, while the aqueous heat transfer fluids include untreated potable (tap) water, inhibited-distilled water, and inhibited glycol/water mixtures. The potable tap water and inhibited distilled water do not, of course, offer freeze protection.

9.7.5 SILICONE FLUIDS. Silicone heat transfer fluids have many favorable properties which make them prime candidates for collector fluids. They do not freeze, boil, or degrade. They do not corrode common metals, including aluminum. They have excellent stability in solar systems stagnating under 400 deg. F. Silicone fluids are also virtually nontoxic and have high flash and fire points. Current evidence indicates that silicone fluids should last the life of a closed-loop collector system with stagnation temperatures under 350 deg. - 400 deg. F. The flash point is fairly high, 450 deg. F, but since the HUD standards state that heat transfer fluids must not be used in systems whose maximum stagnation temperature is less than 100 deg. F lower than the fluid's flash point, this limits most silicone oils to systems with a maximum temperature of 350 deg. F or less. Also silicones do not form sludge or scale, so system performance does not decrease with time. The main drawback of silicone fluids is their cost.   As with hydrocarbon oils, the lower heat capacity and higher viscosity of silicone fluid requires

larger diameter and more expensive piping. Due to the higher viscosity, larger pumps will be required and subsequent higher pumping costs. One other problem with silicone fluids is the seepage of fluid at pipe joints. This problem can be prevented by proper piping installation and by pressurizing the system with air to test for leaks. There have also been reports of seepage past the mechanical seals of circulating pumps. The use of magnetic drive or canned wet rotor pumps when available in the proper size is a method of avoiding mechanical seal leakage. Silicones have the advantage of lasting the life of the system with little maintenance. While this helps minimize operating expenses, the initial cost of silicones is markedly higher than that of other available heat transfer fluids. However, the high initial cost of silicone heat transfer fluid may be less than the savings that result from minimum maintenance and no replacement of collector fluid. The use of silicone fluid allows absorbers with aluminum fluid passages to be used without fear of corrosion. The savings gained from the use of aluminum absorbers as opposed to copper absorbers could be substantial.

9.7.6 HYDROCARBONS. Hydrocarbon oils, like silicones, also give a long service life, but cost less. They are relatively noncorrosive, nonvolatile, environmentally safe, and most are nontoxic. They are designed for use in systems with lower operating temperatures, since some brands break down at higher temperatures to form sludge and corrosive organic acids. Typical closed-cup flashpoints run from 300 deg. F to 420 deg. F, but the fluids with higher flashpoints have a higher viscosity. The HUD bulletin on minimum property standards for solar heating systems recommends a closed-cup flashpoint 100 deg. F higher than maximum expected collector temperatures. Unsaturated hydrocarbons are also subject to rapid oxidation if exposed to air, necessitating the use of oxygen scavengers. Some hydrocarbons thicken at low temperatures and the resultant higher viscosity can cause pumping problems.

Newer hydrocarbons are being developed which do not harm rubber or materials of construction, since this has been a problem with hydrocarbons. In general, they cannot be used with copper, as it serves as a catalyst to fluid decomposition. The thermal conductivity of hydrocarbons is lower than that of water, although the performance of

some brands is much better than others. A typical liquid collector of 500 ft^2 plus the piping to and from storage will require from 20 to 30 gallons of collector fluid. The lower heat capacity and higher viscosity of these oils will also require larger diameter pipe, increasing materials costs further. If hydrocarbon fluids are used, the additional capital cost should be compared with expected savings due to lower maintenance costs. The use of aluminum absorbers rather than copper absorbers will also result in substantial savings.

9.7.7 DISTILLED WATER. Distilled water has been suggested for use in solar collectors since it avoids some of the problems of untreated potable water. First, since the distillation process removes contaminants such as chlorides and heavy metal ions, the problem of galvanic corrosion, though not completely eliminated, should be alleviated. However, distilled water is still subject to freezing and boiling. For this reason, an antifreeze/anti-boil agent such as ethylene glycol is often added.

9.7.8 WATER-ANTIFREEZE. Nonfreezing liquids can also be used to provide freeze protection. These fluids are circulated in a closed loop with a double wall heat exchanger between the collector loop and the storage tank. Water/antifreeze solutions are most commonly used because they are not overly expensive. Ethylene and propylene glycol are the two most commonly used antifreezes. A 50-50 water/glycol solution will provide freeze protection down to about -30 deg. F, and will also raise the boiling point to about 230 deg. F. The use of water/glycol solution presents an additional corrosion problem. Water glycol systems will corrode galvanized pipe. At high temperatures glycols may break down to form glycolic acid. This breakdown may occur as low as 180 deg. F and accelerate at 200 deg. F. This acid corrodes most all metals including copper, aluminum, and steel. The rate of glycol decomposition at different temperatures is still a subject of uncertainty. The decomposition rate of glycol varies according to the degree of aeration and the service life of the solution. Most water/glycol solutions require periodic monitoring of the pH level and the corrosion inhibitors. The Ph should be maintained between 6.5 and 8.0. Replacement of the water/glycol solution may be as often as every 12-24 months or even sooner in high temperature systems. If

these solutions are used in the collector loop, the seller should specify the expected life of the solution and the amount of monitoring required. The cost of periodic fluid replacement and monitoring should be considered in the economic analysis. Since glycol-water mixtures do require a lot of maintenance (and since users can be quite negligent) it is recommended that glycols not be used in family housing solar heating and DHW systems, and that glycol-water solutions be reserved for use in large-scale installations which have regular maintenance schedules and where the high cost of silicone oils would be prohibitive.

9.8 COLLECTOR CONNECTIONS. Water flow through non-horizontal collectors should always be against gravity, except in trickle-type collectors. Usually this means water inlet to the collector at the bottom, and outlet at the top. Care must be taken so that equal flow goes to all collectors. If the pipe manifold pressure drop is large, then end collectors will get little flow. The design most usually used is one in which the collectors are connected in parallel. This results in low pressure drop and high efficiency of each collector. A series hookup results in the highest temperature and the highest pressure drop but lowest collector efficiency. Higher temperatures than in the parallel arrangement may be obtained with parallel-series connections, but at the expense of reduced efficiency and greater cost. These high temperatures are not usually required for hot water and space heating.

10. OTHER CONSIDERATIONS

10.1 ARCHITECTURAL. Solar collector arrangements should be studied to facilitate blending collector panels into the architecture of new or existing buildings. Shade trees must be so located as not to cast shadows on the collector. Other structures such as chimneys which can cast shadows should be carefully located to avoid shading of the collector. Experience of Florida installers indicates that if collectors are placed directly on the roof, the life of asphalt shingles under the collector may be reduced by up to 50%. This suggests that a small space should be left between the collector and the roof, or the collector should be built into the roof. In the latter case, the design must provide

for simple glass replacement. A space between collector and roof allows for snow to fall through rather than accumulate.

10.2 REDUCTION OF HEAT LOSSES. Reduction of heat losses is usually one of the most important steps in the design of a solar space conditioning system. It almost always costs less to super-insulate a building to reduce losses than to provide additional solar collector area to provide the extra heat. Installing 12 or more inches of insulation in the attic, insulating existing walls by injecting nonflammable foam (one manufacturer claims 30% reduction in total heat loss at cost $1.00/ft^2 floor area), multiple glazing, and weatherstripping should all be evaluated for cost effectiveness versus a larger solar system. If the solar-augmented system is found to be cost competitive with a conventional system on a life cycle cost basis, then the cost effective amount of insulation will be the same for both the solar and conventional systems. Thus the solar system should not be charged for the cost of insulating the house.

10.3 MAINTENANCE AND ACCESSIBILITY. Systems should be designed for minimum maintenance. Maintenance of glass will be minimized if vandalism can be reduced. Collectors of flat-roofed buildings may be shielded from the ground by a skirt around the roof perimeter. Locating the collector in the backyard area of residences rather than on a street-facing roof reduces probability of vandalism. Double strength glass for top surface can be used in hail areas, and also provides protection from small stones. Still more protection is offered by a screen of 0.5-inch mesh stretched several inches above the collectors, but with some loss in collector efficiency (15%). Generally mesh screens are not recommended. Collectors and mounts must withstand expected wind and snow loads. Collector design should allow for rapid replacement of glass covers. Pumps, pipes, and controls should be reasonably accessible to allow repair or replacement. Water pumps should be located so that leakage does not cause serious damage. As solar designs move from theory to practice, knowledge of reliability, durability, and maintainability is desired to achieve maximum system performance. The list of "lessons learned" can be used as a pre-design checklist as well as a guide for a preventative maintenance program.