

AN INTRODUCTION TO DESIGN OF SOLAR WATER HEATING SYSTEMS

By:

J. Paul Guyer, P.E., R.A.

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3 PDH HOURS



J. Paul Guyer, P.E., R.A.

Paul Guyer is a registered civil engineer, mechanical engineer, fire protection engineer and architect with 35 years experience designing buildings and related infrastructure. For an additional 9 years he was a principal staff advisor to the California Legislature on capital outlay and infrastructure issues. He is a graduate of Stanford University and has held numerous national, state and local offices with the American Society of Civil Engineers, Architectural Engineering Institute and National Society of Professional Engineers.

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1. **INTRODUCTION.** This course presents the information required to design a solar energy water heating system, after planning and system selection have been completed.

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2. COLLECTOR SUB-SYSTEM

2.1 COLLECTOR SPECIFICATION

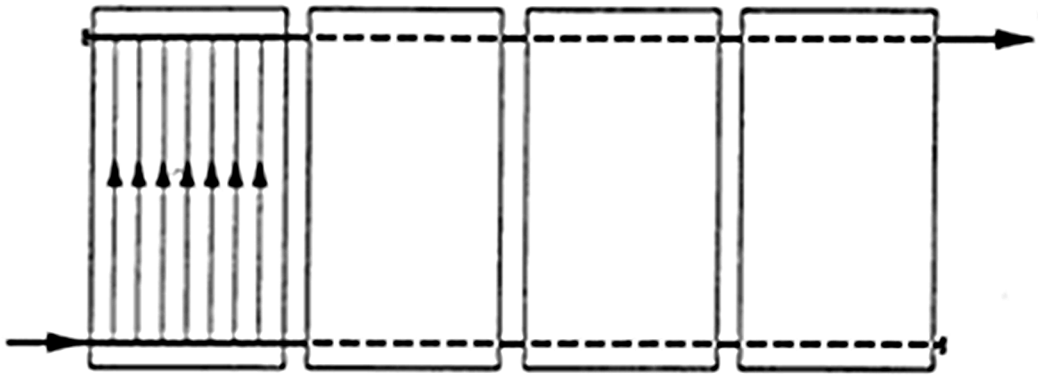
2.1.1 COLLECTOR CONSTRUCTION

2.1.1.1 ABSORBER CONSTRUCTION AND COMPONENTS. The solar collector absorber surface normally has two separate components: the absorber plate and fluid passageways. Many types of absorber designs have been used, such as parallel or serpentine tubes bonded to the absorber plate and double plates rolled together and bonded with hydrostatically expanded fluid passages. The method for bonding the tubes, the circuit flow path, and the absorber surface properties are each critically important to collector performance. The flow path geometry, cross-sectional area, and flow rate determine the fluid pressure drop across the collector. This pressure drop affects the flow distribution throughout the array. Methods used to bond the flow tubes to the absorber plate include mechanical bonds (soldered, brazed, or welded), adhesives, and mechanical encirclement. Flow tubes that have separated from the absorber plates are a leading cause of poor performance for flat-plate collectors. It is imperative that the bond be able to withstand the expected stagnation temperature of the collector and the daily temperature variations to which the collectors are exposed. Serpentine flow tubes and roll-bonded absorber plates can trap the heat transfer fluid in the collector, which can freeze and burst the tubes or absorber plate. Some rollbonded absorbers have also been found to separate with time and cause flow problems or short-circuiting within the fluid passageway.

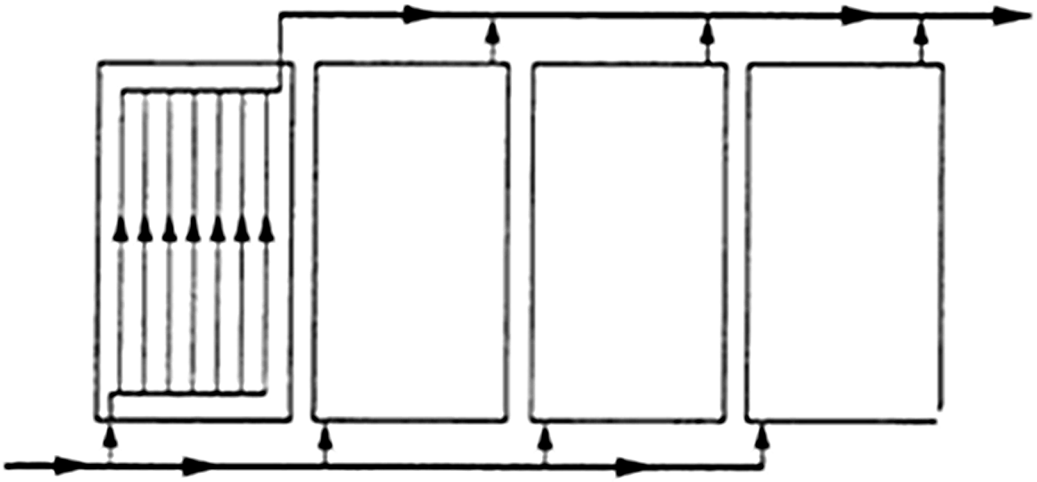
2.1.1.2 ABSORBER SURFACE. The absorber plate surface is also an important factor in the performance of the collector. There are two basic surface finishes, selective and non-selective. Selective surfaces are typically finished with black chrome or black nickel deposited film. Non-selective surfaces are usually finished with flat black paint and can have as large a value of emissivity as they do absorptivity. Selective surfaces have the advantage of absorbing the same amount of energy as the painted surface, but they emit

much less radiation back to the cover. Non-selective painted surfaces have had numerous problems with fading, peeling, and outgassing. In contrast, deposited metallic surface coatings have an excellent history for retaining their properties with time. The most common absorber plate materials are copper, although aluminum absorbers can still be found. Copper has shown the best success due to the lack of thermal expansion problems with the attached copper flow tubes.

2.1.1.3 COLLECTOR MANIFOLD. The collector manifold is the piping that branches from the array supply to each of the individual collectors. There are two main types of collector manifolds: external and internal. External-manifold collectors have small diameter inlets and outlets that are meant to carry the flow for only one collector. The manifold piping to each inlet and from each outlet remains external to the collector. Today, external-manifold collectors are being replaced by those with internal manifolds. Internal-manifold collectors have larger manifolds designed to carry the flow for many collectors connected together, with the manifolds built into the collector unit. Figure 2-1 shows an example of both types of manifold collectors. The internal-manifold collector has many advantages, particularly when used in large systems. Benefits include reduced costs for piping materials, pipe supports, insulation, and labor; more effective flow balancing, which improves thermal performance; and the reduced heat losses to ambient air. Use internally manifolded collectors for all new design projects (externally manifolded collectors will not be used).



(a) Internally Manifolded Collectors (Required)



(b) Externally Manifolded Collectors

Figure 2-1
Collector manifold types

2.1.1.4 COLLECTOR GLAZINGS. Collector covers, or glazings, are required to let radiant energy from the sun through to the absorber and to prevent convection from the hot absorber plate to the ambient air. Some properties to consider when choosing glazings are

structural integrity and strength, durability, performance and safety. Tempered, low-iron glass is by far the most common glazing used because of its excellent optical properties and durability. Clear plastics, such as acrylics and polycarbonates, have a history of problems with clarity over time due to ultraviolet degradation and are not recommended. Double-glazing reduces the thermal losses from the collector, but also decreases optical efficiency and increases weight and cost. This fact can be seen on a collector efficiency plot as a decrease in the F_R value and a decrease in the slope F_RU_L. For certain higher temperature applications, the increase in efficiency at larger values of $(T_i - T_a)/I$ may warrant the extra expense of double glazing, but for service water heating applications, single-glaze collectors will suffice.

2.1.1.5 INSULATION. An insulating material is required behind the absorber plate and on the sides of the collector to reduce conduction losses. Insulation types currently in use include fibrous glass, mineral insulation, and insulating foams. The primary considerations of the insulating materials are their thermal conductivity, ability to withstand stagnation temperatures and moisture, dimensional stability, flammability, and outgassing characteristics. Fibrous glass, closed cell polyisocyanurate foam, and polyurethane foams are currently used in most solar systems. Polyurethane foam is especially well suited because of its ability to retain its shape and to resist moisture that may be present from condensation. Often, a layer of fibrous glass will be sandwiched between polyisocyanurate insulation and the absorber plate, since this material is better suited to withstand the high stagnation temperatures, which can exceed 350 degrees F (177 degrees C) in that part of the collector.

2.1.2 COLLECTOR SELECTION. Required information on the chosen collector includes the net aperture area (A_c); overall dimensions of length or height (L) and width (W); the manufacturer's recommended collector flow rates (CFR) and the pressure drop across the collector at that flow rate; the internal manifold tube diameter; and the collector weight when filled. The designer should note whether the manufacturer recommends a maximum number of collectors per bank less than seven. Of special importance are the values for A_c and CFR. While collector areas range from approximately 16 to 47 ft^2, it is recommended

that collectors with net areas of 28 ft^2 or more be specified whenever possible. For large commercially-sized arrays, smaller collectors result in higher installation costs due to increased materials and labor required to achieve a given array area. The pressure drop is often reported in units of "ft of water". The following range of values could apply to typical flat-plate collectors: A_c = 28 to 40 ft_2 (2.6 to 3.7 m_2), Length = 8 to 10 ft (2438 to 3048 mm), Width = 4 to 5 ft (1219 to 1524 mm), CFR = 0.01 to 0.05 gals/min-ft^2, pressure drop = 0.1 to 0.5 psi (690 to 3447 Pa), internal manifold diameter = 1 to 1.5 inches (25 to 38 mm), and collector filled weight = 100 to 160 lbs (45 to 73 kg). When the designer has this information, the final array layout can be completed.

2.2.2 COLLECTOR SUB-SYSTEM PIPING AND LAYOUT

2.2.2.1 LAYOUT AND TERMINOLOGY. Figure 2-2 provides an example of a collector array layout with the appropriate terminology.

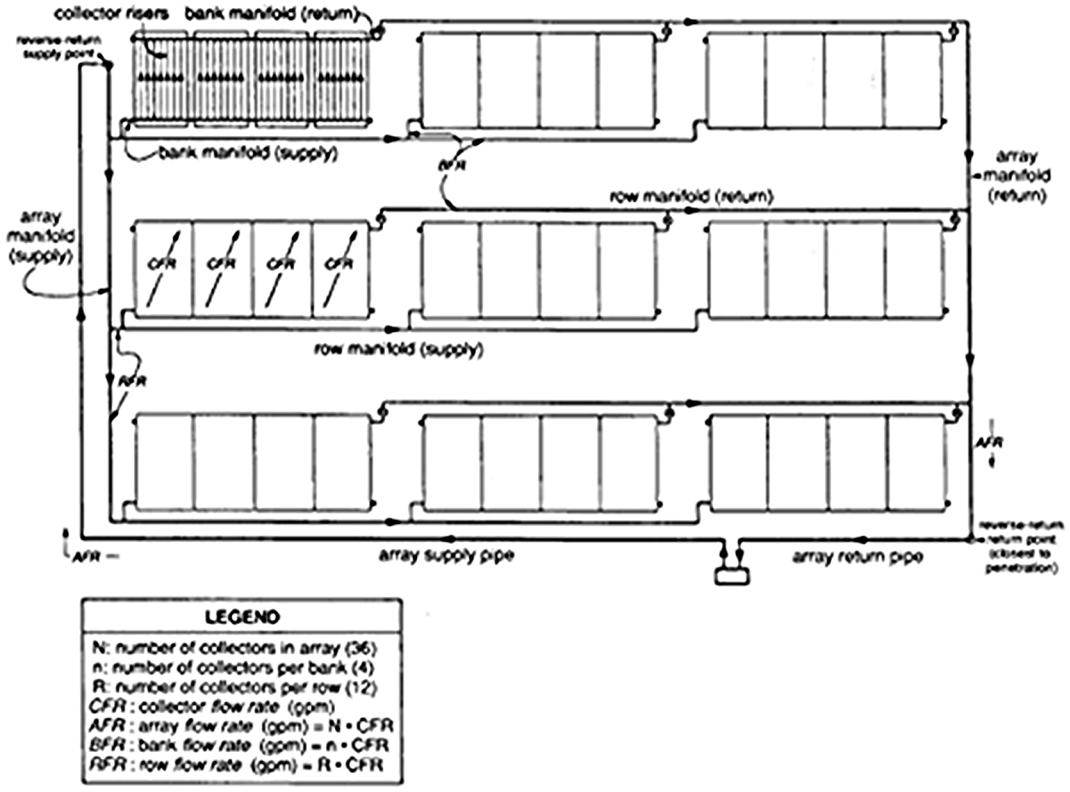


Figure 2-2

Collector array terminology

2.2.1.1 COLLECTOR ARRAY. The collector is one internal-manifold, flat-plate collector unit. The collector array is the entire set of collectors necessary to satisfy the collector area specified by the thermal analysis. These collectors are often connected together into smaller sub-arrays, or banks. These banks can be arranged in different ways (rows and columns) to provide the required area, allowing the roof shape to vary depending on the building plan. "Supply" piping provides unheated fluid to the array and "return" piping carries heated fluid away from the array.

2.2.1.2 MANIFOLDS. The piping used to carry the heat transfer fluid through the array can act as either manifold (also called header) piping or riser piping. Simply stated, the

pipes that act as risers branch off of a main supply pipe, or manifold. Manifold piping typically serves two functions, as an array manifold (supply or return) or as a bank manifold (supply or return). As the name implies, the array supply manifold is the supply for the entire array, whereas a bank supply manifold is the pipe run consisting of all of the collector internal manifolds, after the bank is connected together. The bank manifold acts as a riser off of the array manifold. For the case of a small system that has only one bank, the array supply manifold is the same as the bank manifold. When more than one bank exists, the array supply manifold branches to separate row and/or bank manifolds. The diameter of the array supply manifold will be larger than the bank manifold, and the bank manifold diameter will be larger than the collector riser diameter. This design is required to maintain balanced flow through the array. The actual pipe sizes and layouts to be used depend on many factors, as will be discussed in the following sections.

2.2.2 FLOW BALANCING. Flow can be balanced by active flow control or by "passive" piping strategies. For active flow balancing, automatic or manual valves are installed on manifolds and risers to regulate the fluid flow. In passive flow balancing, the array plumbing is designed so that uniform flow will occur as naturally as possible in the array. The most successful passive flow balancing method requires the designer to consider the fluid path length and the pressure drop along this path. The solar systems described rely mainly on the passive flow balancing method discussed below. In addition, manually calibrated balancing valves are included on the outlet of each bank to adjust for any flow imbalances after construction. Automatic flow control strategies have been a cause of system failure and are not recommended.

2.2.3 REVERSE-RETURN-PIPING LAYOUT - THE DIAGONAL ATTACHMENT RULE. The pipe run configuration is important for balancing flow, especially with regard to fluid path length. The reverse-return piping layout provides almost equal path lengths for any possible flow path that the fluid may take. This design is in contrast to the "direct-return" system, which results in non-uniform flow through the collector bank due to unequal path lengths. These two strategies are illustrated for collector banks in Figure 2-3, with vectors on the collector risers to indicate relative fluid velocities. Note that even for the reverse-

return system, the flow is not shown to be perfectly balanced since pipe resistance is a function of flow rate. The reverse-return strategy of providing approximately equal length flow paths can be applied to any bank layout or complete collector array layout by insuring that the supply and return pipes attach to the array at any two opposite diagonal corners of the array (See Figure 2-3). Use reverse-return piping strategies for all new design projects (direct return piping strategies will not be used).

2.2.3.1 REVERSE-RETURN PIPING SCHEMATICS. Figure 2-4 illustrates the steps in the development of a reverse-return piping schematic, and Figure 2-5 shows some examples of proper reverse-return piping schematics. Small circles show the attachment points on opposite sides of the bank in Figure 2-3 and opposite sides of the array in Figure 2-4 and Figure 2-5. The corner closest to the pipe roof penetrations will be used as the return point, since this results in the shortest pipe length for the heated fluid. A slight variation of the diagonal attachment rule is needed if the pipe roof penetrations are near the centerline of a multiple row, multiple column array with an even number of columns. For this case, some pipe length can be saved by feeding the array on the outside and returning the heated fluid from the center of the array. This case is shown in Figure 2-5(c).

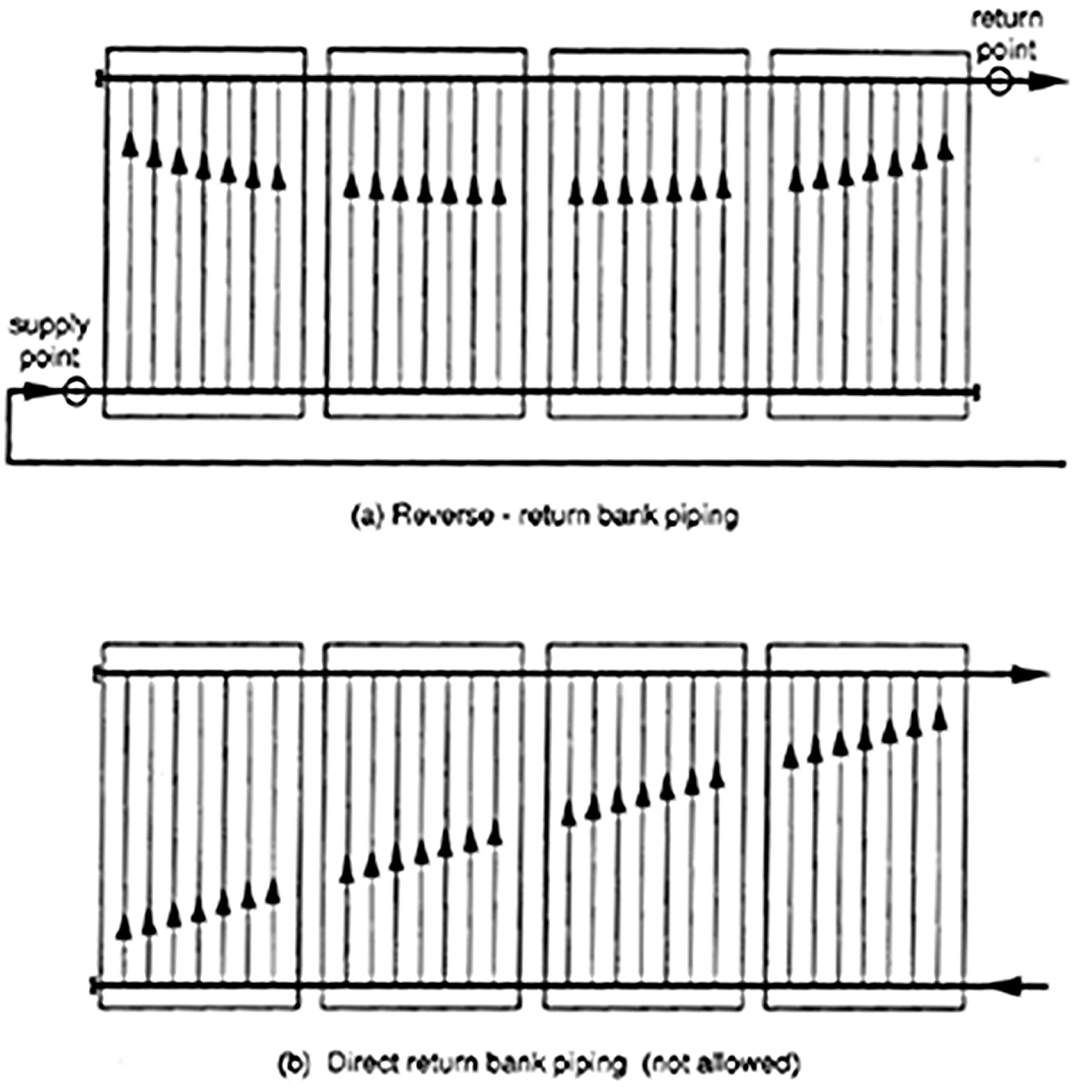


Figure 2-3

Reverse-return versus direct-return return piping strategies

2.2.3.2 STEPPED COLLECTOR ROWS. Note that true reverse-return is not possible for stepped collector rows. The reason is that extra pipe length is required to reach the roof level supply and return manifolds up to and back from the elevated bank inlets and outlets. However, the same diagonal attachment strategy should be used and the extra pipe length for each elevation should be accounted for in the pressure drop/pump sizing calculation.

2.2.4 ARRAY LAYOUT AND PIPING SCHEMATIC. The final array layout should be determined using the methodology discussed under paragraph 3-4. If the dimensions of the collector to be specified differ from those used to perform the estimated roof area calculations, the array layout will need to be performed based on the collector specification and the unshaded roof area available. The designer has the option to decide which collector grouping is best within the guidelines requiring that the actual collector area be plus or minus 10 percent of the calculated area from the thermal analysis. For the example, the deviation is a 6 percent area increase from the 26 to 28-collector case. The next smallest collector areas would have required 25 or 24 collectors, representing 5 and 9 percent decreases, respectively. The 24-collector case may be preferred over the 25-collector option since more variations are possible for the array layout. With this array layout and using the reverse-return piping strategy discussed earlier, piping schematics similar to those shown in Figure 2-4 and Figure 2-5 can be determined. The array layout and piping schematic should be noted in the construction drawings to alert the contractor to pipe the array exactly as that shown to ensure flow balance.

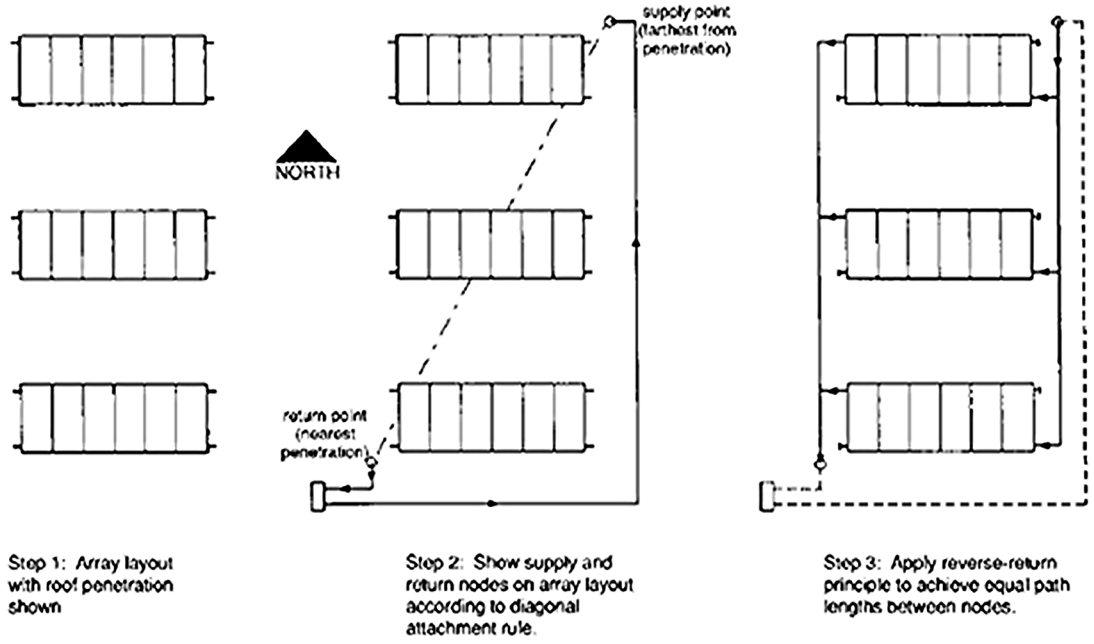


Figure 2-4

Steps in developing a reverse return piping layout

2.2.5 PRESSURE DROP

2.2.5.1 THE 30 PERCENT RULE. Flow balance through the collector array depends on the relative pressure drop associated with the different piping branches of the array. The change in pressure along any flow path is a measure of the resistance to flow. Of interest to the solar system designer are the pressure losses across the collector risers, along a manifold, and along linear uninterrupted pipe. As the ratio of a manifold's pressure drop to its riser pressure drop becomes smaller, the flow becomes more uniform. To ensure uniform flow through the collector bank, this ratio should be around 10 percent, and under no circumstances should it exceed 30 percent (for a pressure drop ratio of 30 percent, the

flow in any riser does not deviate from the average riser flow rate by more than plus or minus 5 percent). It is thus an advantage to choose a collector with a relatively large pressure drop and to ensure that the pipe diameters throughout the system are sized correctly to maintain adequate riser to manifold pressure drop while allowing enough cross-sectional area for the calculated flow rate and keeping the flow velocity below the 5 ft/s (1.5 m/s) limit for copper pipe.

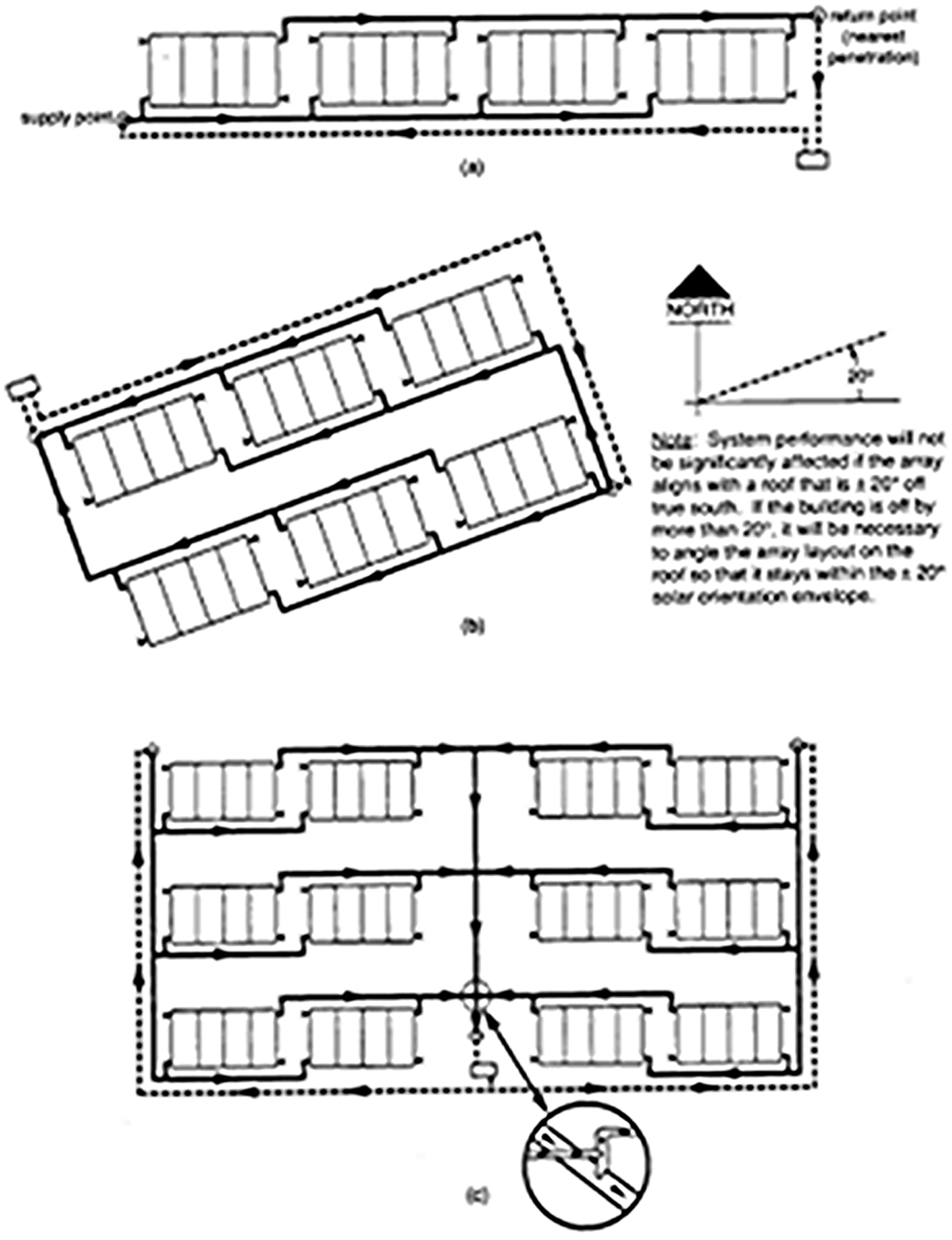


Figure 2-5

Examples of reverse return piping

2.2.5.2 PRESSURE DROP ACROSS BANKS AND ROWS. The pressure drop across a bank of collectors must be determined in order to calculate the pipe sizes necessary to achieve balanced flow in the array. Once the array layout is determined and assuming that the pressure drop across each collector unit at the recommended flow rate is known, the pressure drop associated with each branch extending from a manifold can be determined. When internal-manifold collectors are banked together in groups of seven or less, it can be assumed that the pressure drop across the entire bank is equal to the pressure drop across a single collector. This information will be used in sizing the pipe, as described below.

2.2.6 PIPE SIZING. Sizing of the piping in the solar array is critical to system performance. Flow throughout the array should be in balance at the proper flow rates, while maintaining a maximum velocity limit of about 5 ft/s (1.5 m/s). These two criteria impose constraints on the minimum pipe diameter possible, while material and labor costs pose a constraint on excessively large piping. Another consideration is pumping power. Specifying pipe diameters that are larger than the minimum can sometimes lower the system life-cycle cost. By doing so, pumping power requirements are reduced and the savings over the system lifetime can exceed the initial material and labor costs of the larger pipe. This situation however is not important for the sizes and types of solar systems discussed in this guidance.

2.2.6.1 VOLUMETRIC FLOW RATES. The manufacturer's recommended collector flow rate, CFR, and the piping schematic should be used to determine the design flow rates throughout the collector sub-system. The total array flow rate, AFR, is determined by multiplying the CFR by the actual number of collectors, N. Bank flow rates (BFR) and row or other branch flow rates are determined by multiplying the CFR by the number of collectors per bank (n) or per row. These flow rates were previously illustrated in Figure 2-2.

2.2.6.2 PRESSURE DROP MODELS AND THE FLUID VELOCITY CONSTRAINTS. The fluid velocities in the various pipe branches should be kept below 5 ft/s (1.5 m/s) to prevent

erosion of the copper piping. Below this value, fluid velocity is of no great concern. The fluid velocity for a given flow rate is dependent on the fluid properties, internal pipe diameter, the pipe material, and its internal surface characteristics. Empirical expressions have been developed to model the flow rate, pressure loss, and velocity behavior of different liquids flowing through various types of pipe. These expressions are widely available in graphical form for water (usually at 60 degrees F (15 degrees C) and for turbulent flow) and standard practice dictates their use. For this reason, they are not presented in this guidance. Although more precise methods can be considered, the designer can easily correct the pressure drop for water to account for propylene glycol solutions by the use of Table 2-1. The pressure drop correction is more important than the velocity correction since there is an increasing effect on the pressure drop. Use of the velocity result for water is conservative and as such requires no correction. This velocity correction calculation assumes similar turbulent flow characteristics for water and propylene glycol solutions (an incorrect assumption in many cases). Due to the viscosity differences of water and propylene glycol solutions, flow of the solution is often laminar. This fact can be neglected and the turbulent water model can still be used with a correction for propylene glycol, since such use will be conservative. In addition, although these flows are often laminar, they are usually near the laminar/turbulent transition point where pipe bends and flow restrictions can easily trip laminar flow to turbulent. The design operating temperature of the collector loop should be between 60 and 90 degrees F (15 and 32 degrees C), with the 60 degree F (15 degrees C) value preferred because it is the lowest temperature (thus highest viscosity and pressure drop) that steady-state operation could be expected. If a higher temperature is to be used, the designer should apply the standard temperature corrections for water before correcting for the use of propylene glycol.

Heat Transfer Fluid (Percent Propylene-Glycol)	Pressure Drop Correction	Velocity Correction (Estimated)
50 (closed loop)	x 1.4	x 0.8
30 (closed-loop)	x 1.2	x 0.9
0 (direct circulation)	(x 1.0)	(x 1.0)

Table 2-1

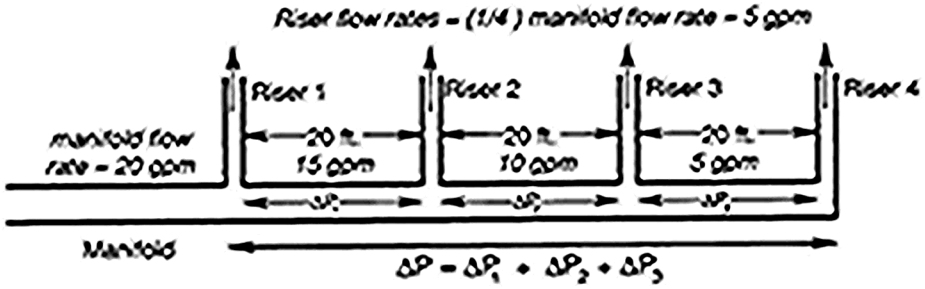
Pressure drop correction

2.2.6.3 FLOW BALANCING. Flow balancing of the main array supply manifold and its associated risers can be accomplished using the "30 percent rule" cited earlier. To begin, the pressure drop in the risers must be known - this usually means that the flow balancing calculations start with the collector banks since the pressure drop across a collector bank can be considered to be the same as the pressure drop across a single collector. The flow rates required in all branches must also be known. A first guess of the manifold internal diameter should be made. Each section of manifold between the risers will have a different flow rate, and the pressure drop associated with each flow rate and pipe length must be determined. The sum of each of these pressure losses will be the pressure drop along the entire manifold. This pressure loss is compared to the pressure drop across the riser (in this case, the row or bank manifold), and if it is less than 0.3 (around 0.1 is preferred) of the bank manifold pressure drop, the proposed diameter is acceptable from a flow balancing point of view. This assumption neglects the additional pressure loss associated with the bank manifold and its connections, and is thus conservative. If the proposed diameter is too small (or too large), another guess should be made. Figure 2-6 and Figure 2-7 provide an

example of sizing a manifold to provide balanced flow while satisfying both the 30 percent rule and the 5 ft/s (1.5 m/s) velocity restriction.

Example: Manifold with 4 Risers

- Riser pressure drop: $\Delta P_R = 0.7$ psi
- Manifold flow rate = 20 gpm
- 50% propylene-glycol solution



Note: Bank pressure drop = single collector unit pressure drop

From pressure drop tables: ΔP_1 = f(Flow rate in section 1, Manifold diameter)

ΔP_2 = f(Flow rate in section 2, Manifold diameter)

ΔP_3 = f(Flow rate in section 3, Manifold diameter)

		Guess A: 1.25 in.		Guess B: 1.5 in.		Guess C: 2 in.	
Manifold Position	Flow Rate	ΔP	Velocity < 10 ft/s?	ΔP	Velocity < 10 ft/s?	ΔP	Velocity < 10 ft/s?
after riser 1	15	0.4	yes	0.18	yes	0.05	yes
after riser 2	10	0.2	yes	0.1	yes	0.03	yes
after riser 3	5	0.06	yes	0.03	yes	0.01	yes

Total manifold pressure drop (corrected for 50%): $\Delta P_A = 0.66 \times 1.4 = 0.92$ psi; $\Delta P_B = 0.31 \times 1.4 = 0.43$ psi; $\Delta P_C = 0.09 \times 1.4 = 0.13$ psi

Ratio (must be less than 0.3): $\frac{\Delta P_A}{\Delta P_R} = 1.3$; $\frac{\Delta P_B}{\Delta P_R} = 0.61$; $\frac{\Delta P_C}{\Delta P_R} = 0.19$

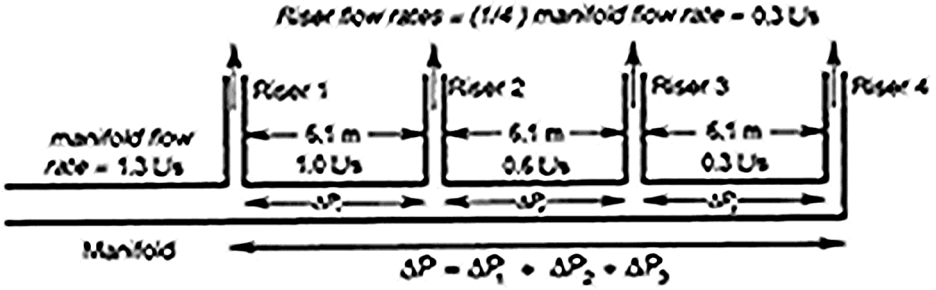
Result: 2 in. manifold or greater

Figure 2-6

Manifold sizing example

Example: Manifold with 4 Risers

- Riser pressure drop: ΔP_R = 4826 Pa
- Manifold flow rate = 1.3 L/s
- 50% propylene-glycol solution



Note: Bank pressure drop = single collector unit pressure drop

From pressure drop tables: ΔP_1 = f (Flow rate in section 1, Manifold diameter)

ΔP_2 = f (Flow rate in section 2, Manifold diameter)

ΔP_3 = f (Flow rate in section 3, Manifold diameter)

Manifold Section	Flow Rate	Guess A: 32 mm ΔP	Guess A: 32 mm Velocity <1.5 m/s?	Guess B: 40 mm ΔP	Guess B: 40 mm Velocity <1.5 m/s?	Guess C: 50 mm ΔP	Guess C: 50 mm Velocity <1.5 m/s?
after riser 1	1.0	2758	yes	1241	yes	345	yes
after riser 2	0.6	1379	yes	690	yes	207	yes
after riser 3	0.3	414	yes	207	yes	69	yes

Total manifold pressure drop (corrected for 50%): ΔP_A = 4551 x 1.4 = 6371 Pa; ΔP_B = 2138 x 1.4 = 2993 Pa; ΔP_C = 621 x 1.4 = 869 Pa

Ratio (must be less than 0.3): $\frac{\Delta P_A}{\Delta P_R}$ = 1.3; $\frac{\Delta P_B}{\Delta P_R}$ = 0.61; $\frac{\Delta P_C}{\Delta P_R}$ = 0.19

Result: 50 mm manifold or greater

Figure 2-7

Manifold sizing example (metric)

2.2.7 COLLECTOR SUB-SYSTEM PLUMBING DETAILS. The collector banks must be able to be valved off for maintenance, repair, or replacement. It is recommended that ball valves be used in this capacity instead of gate or globe valves. Manually operated, calibrated balancing valves are also to be located at the outlet to each collector bank to adjust for any flow imbalances present after construction. Drain valves should be located at all low points in the collector sub-system to allow the collectors to be drained if necessary. Pressure relief valves should be located on each collector bank that could be valved off accidentally and allowed to stagnate. Finally, manual air vents should be located at the high points of the collector loop to allow air to escape during the filling process. Ensure that adequate room is provided for expansion of the internal manifold and absorber plate assembly within the collector casing. The differential expansion between the system flow paths and the system and the support structure must be considered in the design.

2.2.8 THERMAL EXPANSION. Thermal expansion control becomes important when long lengths of pipe are present or when pipes must be secured at a given location. Other locations for which pipe movement can be critical are in pipe chases and near pumps, where expanding pipe could cause shifts in pump alignment. The preferred method of accounting for thermal expansion is to construct a U-shaped bend in the pipe run that can absorb the anticipated movement at a given location. When necessary, these loops should be located horizontally and supported properly so that the fluid contained within can be drained. Figure 2-8 shows the change in length of copper pipe with temperature change. When long pipe runs are required, the designer will ensure that the resulting expansion or contraction will not harm system components or cause undue stress on the system or the building. If the plumbing geometry cannot withstand the length changes or if the plumbing must be anchored at certain locations, pipe supports and guides must be designed to allow freedom of movement in the direction of motion.

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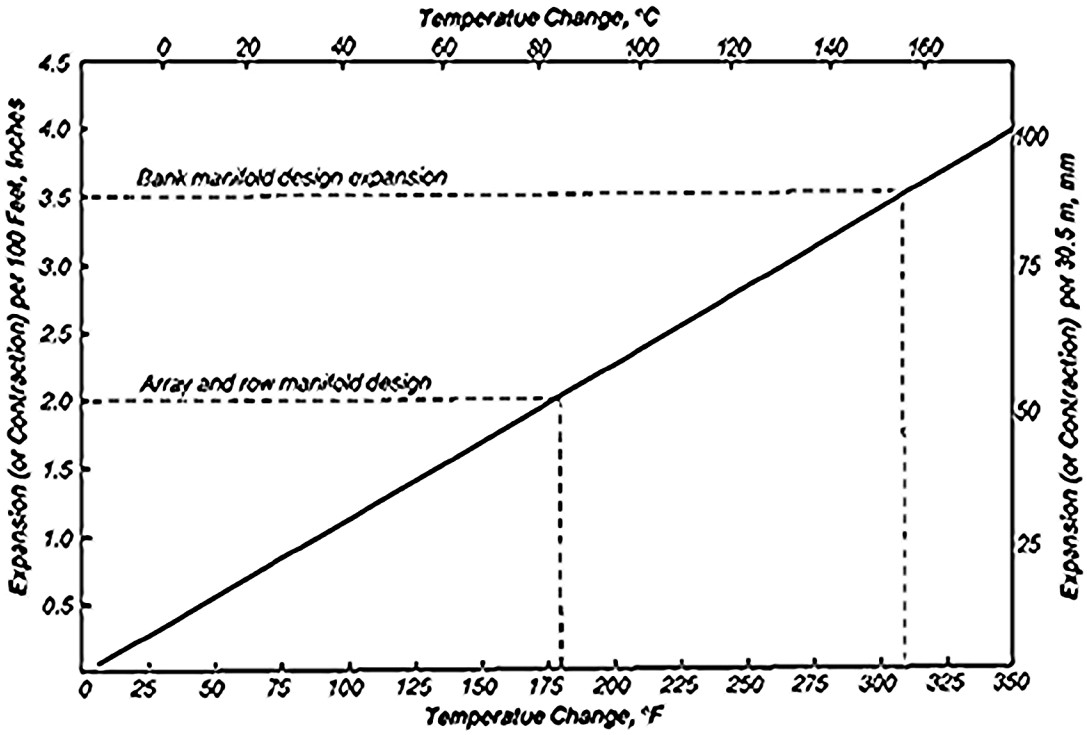


Figure 2-8

Thermal expansion versus temperature differential for copper pipe

3 STORAGE SUB-SYSTEM

3.1 STORAGE TANK CONSTRUCTION. Solar storage tanks must be insulated to a value of R-30 or better, to minimize loss of collected solar energy. The storage tank should be equipped with a minimum of four pipe connections, two located near the top of the tank and two located near the bottom. To take advantage of storage tank stratification, pipes supplying the collector array and the cold-water inlet should be connected to the bottom penetrations, and the pipes returning to the tank from the collector array and hot water supplied to the load should be connected to the penetrations near the top. Instrumentation openings will be required as well as openings for relief valves, drains, and the like. Since copper is to be used for all system plumbing, the designer should ensure that a dielectric coupling is included in the design of any necessary penetrations of the storage tank**.**

3.2 STORAGE TANK SIZING. The solar storage tank should be specified based on the sizing criteria that the volume be between 1.5 to 2 gals per square foot (61.1 to 81.5 L per square meter) of total array collector area. This allows considerable flexibility for finding an off-the-shelf, standard-sized tank that will meet all specifications. Tank dimensions for the given storage volume and expected floor loads should be noted.

3.3 STORAGE SUB-SYSTEM FLOW RATE. The flow rate in the storage loop depends on the collector loop flow rate. To ensure that the storage loop can accept the energy available, the thermal capacity on the storage side of the heat exchanger (the product of the mass flow rate and constant pressure specific heat) must be greater than or equal to the thermal capacity on the collector side of the heat exchanger. An expression relating the volumetric flow rates in the two loops can be determined by noting that the constant pressure specific heat for propylene glycol is as low as 85 percent of that for water and that the density of water is as low as 95 percent of that for propylene glycol. Substituting these relationships into the thermal capacities yields the result that the storage sub-system volumetric flow rate should be at least 0.9 times that of the total array volumetric flow rate. To be conservative, the flow rate relationship across the heat exchanger should be determined using Equation 3-1.

Storage Sub-System Flow Rate = 1.25 x AFR (eq. 3-1)

3.4 TRANSPORT SUB-SYSTEM

3.4.1 TRANSPORT SUB-SYSTEM DESIGN. Although the collector array layout may differ for each building, the design of the transport sub-system should be similar for all solar energy systems.

3.4.1.1 HEAT TRANSFER FLUID. A solution of 30 percent or 50 percent food-grade, uninhibited propylene glycol and distilled water is required as the heat transfer fluid for closed-loop solar energy systems. Ethylene glycol is highly toxic and should never be used.

3.4.1.2 HEAT EXCHANGER

3.4.1.2.1 HEAT EXCHANGER ANALYSIS. Two methods of heat exchanger analysis are used in design: the log mean temperature difference (LMTD) method and the effectiveness-number of transfer units (e-NTU) method. The LMTD method is used most often for conventional HVAC systems and requires knowledge of three of the four inlet and outlet temperatures. This method cannot be applied directly to solar systems because the inlet temperatures to the heat exchangers from both the collectors and storage are not constant. Since the goal of the solar system heat exchanger is to transfer as much energy as possible, regardless of inlet and outlet temperatures, the e-NTU method should be used. However, a complete e-NTU analysis can be avoided by considering the impact of the heat exchanger on the overall system performance. The annual system solar fraction is decreased by less than 10 percent as heat exchanger effectiveness is decreased from 1.0 to 0.3. By setting a minimum acceptable effectiveness of 0.5, the e-NTU method can be used to generate the temperatures required by the LMTD method. These temperatures and the corresponding flow rates can then be used to size the heat exchanger according to the LMTD method, with the resulting heat exchanger satisfying the minimum effectiveness of 0.5.

3.4.1.2.2 SIZING. For proprietary reasons, manufacturer's representatives, through the use of computer codes, typically size heat exchangers. These codes are usually based on the LMTD method and require the designer to provide three temperatures and the flow rates of both streams. To ensure that an effectiveness greater than 0.5 is achieved, the following temperatures and flow rates should be used for sizing the heat exchanger:

Temperatures:

Solar loop inlet = 140 degrees F (60 degrees C)

Solar loop exit = 120 degrees F (49 degrees C) or less

Storage side inlet = 100 degrees F (38 degrees C)

Flow rates:

Solar loop = AFR (see Figure 2-2 legend)

Storage loop = 1.25 x AFR

The 120 degrees F (49 degrees C) solar loop exit temperature corresponds to an effectiveness of 0.5. Raising the required solar loop exit temperature to 125 degrees F (52 degrees C) decreases the effectiveness to about 0.4. The cost difference at these levels of effectiveness is not significant for either plate or shell-and-tube heat exchangers. As the heat exchanger effectiveness is further increased (or as the required solar loop exit temperature is decreased), heat exchanger costs are affected more. The designer should use judgment to determine if the cost of increasing effectiveness is justified. For plate-and-frame heat exchangers, gains in effectiveness can often be achieved with low additional cost.

3.4.1.2.3 SPECIFICATION. The heat exchanger area should be available from the manufacturer, along with the pressure drop across each side at various flow rates. A single-isolation heat exchanger can be used, since non-toxic USP propylene glycol is required as the heat transfer fluid. All materials used in the heat exchanger must be compatible with the fluids used. The plate or plate-and-frame types of heat exchangers are becoming increasingly popular, due to their compact size and excellent performance, availability in a wide range of materials, and ease of cleaning and servicing. If a shell-and-tube heat exchanger is used, it should be installed such that the shell side is exposed to the heat transfer fluid, with the tube side containing potable water. This design is required because potable water tends to foul the tube bundle, so it must be possible to remove and clean the bundle.

3.4.1.3 PIPING

3.4.1.3.1 SIZING. The collector loop piping to the manifold should be sized small enough to reduce material costs but large enough to reduce excess pressure drop (and associated pump and energy costs) and to maintain the fluid velocity below 5 ft/s (1.5 m/s). The upper limit is the size of the array supply and return manifold, while the lower side is that defined by the 5 ft/s (1.5 m/s) velocity limit. Although an optimization procedure could be performed to determine the pipe size providing the lowest life-cycle cost (LCC), experience shows that the supply piping can be sized at least one size smaller than the supply manifold as long as the fluid velocity restriction is not exceeded. The pipe size on the storage side of the heat exchanger can also be calculated based on the storage loop flow rate, pump costs, and the 5 ft/s (1.5 m/s) fluid velocity limit.

3.4.1.3.2 MATERIALS. Piping materials are limited to copper. To ensure materials compatibility, only tin-antimony (Sn-Sb) solders are allowed (Sb5, Sn94, Sn95, and Sn96).

3.4.1.3.3 INSULATION. Insulation should withstand temperatures up to 400 degrees F (204 degrees C) within 1.5 ft (457 mm) of the collector absorber surface, and 250 degrees F (121 degrees C) at all other locations. Insulation exposed to the outside environment should be weatherproof and protected against ultraviolet degradation. Pre-formed, closed-cell polyisocyanurate insulation has an excellent history of withstanding the temperatures and environmental conditions required, and its use is recommended when possible. The amount of insulation to be used is dependent on the operating temperature of the pipe; however, a minimum of R-4 should be specified on all piping.

3.4.1.4 EXPANSION TANK

3.4.1.4.1 OPERATION. An expansion tank is required in the collector circulation loop. In a closed-loop system, the expansion tank must serve two purposes: to protect the system from overpressure due to thermal expansion of the fluid at high temperatures and to maintain the required minimum pressure when the fluid in the loop is cold. Expansion tanks are closed and initially charged with a gas (usually air) at some given minimum pressure. As the temperature increases in the loop and thermal expansion takes place,

increasing amounts of displaced fluid enter the expansion tank and compress the air within it. There are three common types of closed expansion tanks: non-bladder, bladder, and diaphragm. In the non-bladder expansion tank, the expanding fluid is in direct contact with the air charge. Bladder tanks are fitted with a flexible balloon-like surface that separates the air from the expanding fluid. Usually, bladder tanks require an initial fluid volume and air pressure, and do not permit the fluid to come in contact with the metal tank surface. Diaphragm tanks are initially charged with air also, but allow some fluid-metal contact as they fill. These mechanisms prevent the air charge from being absorbed into the expanding fluid, with a resulting decrease of corrosion problems and periodic venting maintenance. Because bladder tanks are widely available and they prevent any metal-fluid contact, their use is required for solar preheat systems. The expansion tank should be located in the equipment room on the suction side of the pump.

3.4.1.4.2 DETERMINATION OF ACCEPTANCE VOLUME. Determination of the collector loop expansion tank acceptance volume is similar to that for a conventional hydronic or boiler system tank sizing, with one important variation. Typical expansion tank sizing routines account only for the variation of fluid volume with temperature change in the liquid phase. While this is the condition existing within the solar collector loop during normal operation, a more critical condition exists in the event of system stagnation that requires a much larger volume than the conventional sizing routines. Solar energy systems are quite capable of boiling during stagnation, and the expansion tank must be sized to account for the displacement of all of the fluid contained in the collector array that is subject to vaporization. Since the stagnation condition requires far greater volume than that needed for the conventional liquid-phase expansion case and these two situations will never occur at the same time, the conventional temperature-based expansion term is not needed. Experience shows that during stagnation conditions, only the volume of fluid located in the collector array and associated piping above the lowest point of the collectors is subject to vaporization. Thermal stratification prevents fluid below this point from vaporizing to any significant degree. The required acceptance volume of the collector loop expansion tank is thus determined by adding the total volume of all collectors plus the volume of any piping at or above the elevation of the collector inlets. When properly applied, this procedure

provides fail-safe pressure protection of the system, and prevents the loss of the propylene glycol solution from the pressure relief valves. The result is a large decrease in the number of failures and resulting maintenance calls.

3.4.1.4.3 DETERMINATION OF DESIGN PRESSURES. The air-side of closed expansion tanks are normally required by the manufacturer to be precharged to some pressure above atmospheric. This initial or precharged pressure (P_i) must be determined, along with the collector loop fill pressure (P_f) and the maximum relief pressure allowed in the system (P_r). As discussed previously, the maximum pressure in the collector loop should be 125 psi (862 kPa). The system fill pressure should result in a +10 to +15 psi (+69 to +103 kPa) pressure at the highest point of the system. The expansion tank precharge pressure should be equal to the fill pressure at the expansion tank inlet, minus 5 to 10 psi (35 to 69 kPa). This initial condition allows fluid to be contained within the expansion tank at the time of filling and will provide positive pressure in the event of the system operating at temperatures below that occurring when the system is filled.

3.4.1.4.4 SIZING AND SPECIFICATION. Once the acceptance volume and the design pressures have been determined, the total (fluid plus air) expansion tank volume V_T can be calculated by using Equation 3-2.

$$V_T = \frac{V_{coll}}{\left(\frac{P_i}{P_f} - \frac{P_i}{P_r}\right)} \qquad \text{(eq. 3-2)}$$

where V_{coll} is the total volume of the collectors and piping above the collectors. This equation is plotted graphically in Figure 3-1. Manufacturers provide expansion tank sizes by either the total volume of both the air and fluid, or by separate specification of the acceptance volume and design pressures. When the manufacturer supplies both the acceptance and total tank volumes, the designer should specify the tank that satisfies both

conditions. The volume data given by the manufacturer in these cases may not coincide exactly with those calculated by the methods shown above. The values should be close, however, since variations should only be due to slightly different types of fluid/air separation mechanisms. The manufacturer should supply literature on their particular requirements for initial charge (if any) and temperature and pressure limits. Careful attention should be given to the bladder materials. EPDM rubber is the recommended material for use with propylene glycol. As in other parts of the system, the propylene glycol based heat transfer fluid should not be allowed to come in contact with ferrous materials, especially galvanized steel.

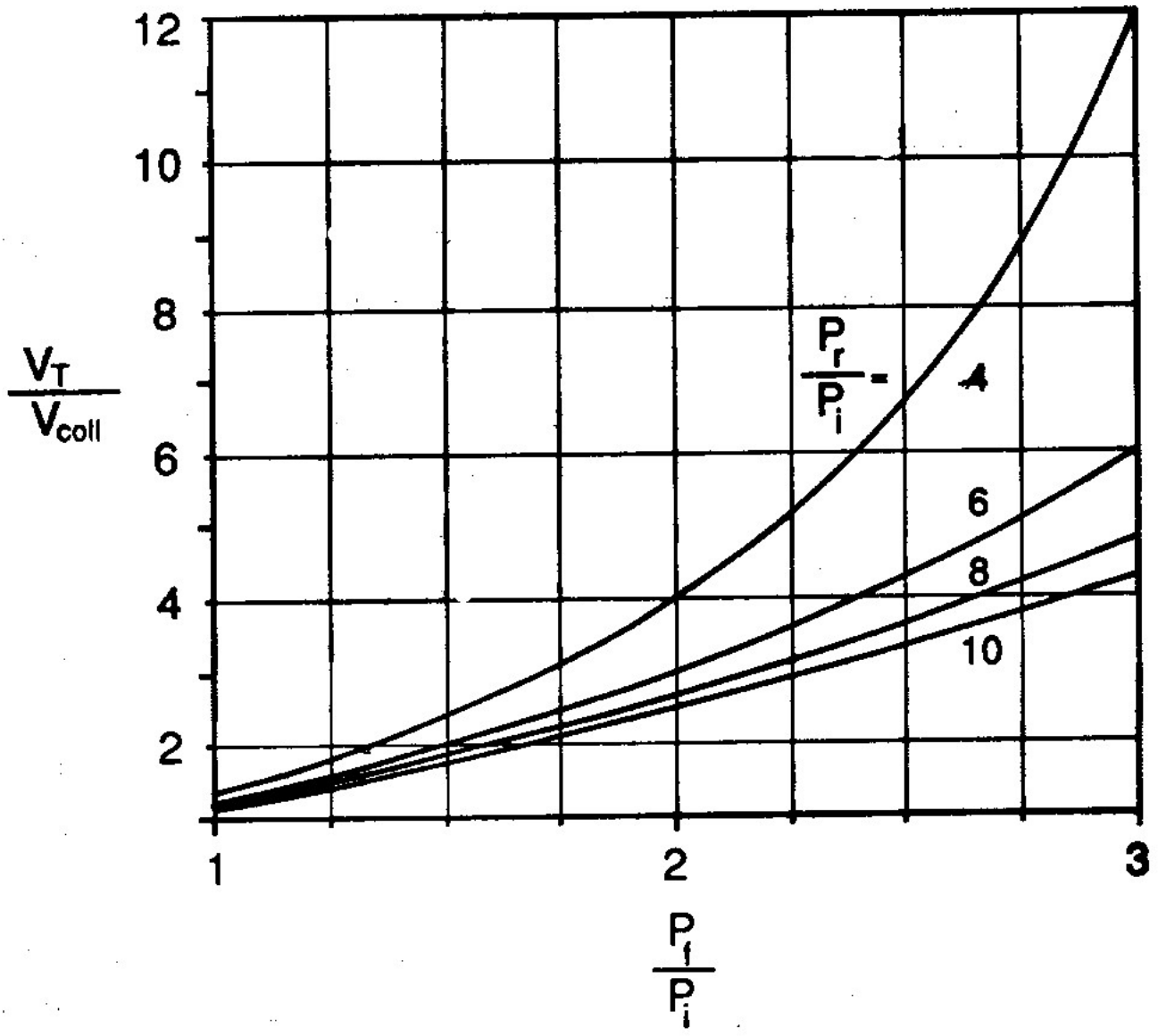


Figure 3-1

Calculation of Total Expansion Tank Volume

3.4.1.5 FITTINGS

3.4.1.5.1 ISOLATION VALVES. Gate and ball valves are installed to allow component or sections of the system to be isolated without draining the entire system. Gate valves are

less expensive than ball valves and will be used in locations where only on/off operation is required. Ball valves are recommended at locations where partial flow may be required, such as on the outlet side of the collector banks. These valves are manually operated and may have a key or special tool to prevent unauthorized tampering. Care should be taken when locating isolation valves to ensure that system pressure relief cannot be valved off accidentally. Globe-type valves are not recommended because they can reduce flow (even when fully open), cause excessive pressure drop, and reduce system efficiency.

3.4.1.5.2 THUMB VALVES. Thumb valves also function as on/off valves for smaller sized tubing (typically 1/4 inch (6 mm) or less). They are used to manually open pressure gauges or flow indicators to local flow and are not meant for constant use.

3.4.1.5.3 DRAIN VALVES. Drain valves are required at all system low points. Specifically, these locations include the low points of the collector banks, the bottom of the storage tank, and two at the bottom of the collector loop between the expansion tank and the pump. These latter two drain valves are used for filling and draining and should be separated by a gate valve. When the system is to be filled, the gate is closed and a pump is connected to one of the drains. As the propylene glycol solution is pumped into the system, the other open drain allows air to escape. When filling is complete, both drains are closed and the gate between them is opened.

3.4.1.5.4 CHECK VALVES. A spring-type check valve should be located in the system between the pump and the collector array, on the supply side. This check valve prevents reverse thermosiphoning, which can occur when the system is off and warm fluid in the collector loop rises from the heat exchanger to the collector array and is cooled.

3.4.1.5.5 PRESSURE RELIEF VALVES. A pressure relief valve is required in any line containing a heat source that can be isolated (such as a collector row) and is also typically provided between the heat exchanger and the suction side of the collector loop pump. The latter pressure relief valve is provided in case of stagnation in the fully open collector loop. This relief valve should open before those at the top of the loop due to the elevation head

experienced at the bottom of the loop. Pressure relief for solar systems should be set at 125 psi (862 kPa) (maximum system design pressure). The discharge from pressure relief valves will be either routed to an appropriate floor drain or captured as required by either local or state regulatory requirements. The discharge should be piped to avoid personnel injury from the hot fluid. Some means for determining if fluid has discharged may be provided.

3.4.1.5.6 TEMPERATURE-PRESSURE RELIEF VALVES. Temperature/pressure relief valves are similar in operation to pressure relief valves, except they also contain a temperature sensor to detect and relieve any temperature exceeding the design temperature. They should be installed on the solar storage tank and set for 125 psi (862 kPa) or 210 degrees F (99 degrees C).

3.4.1.5.7 MANUAL AIR VENTS. Manual air vents are recommended to purge trapped air within the system. They should be located at the high point(s) of the system where air will accumulate. Air can be present in the system from the initial charge or can be drawn in at leaks in the system piping or components. Automatic air vents with air separators have a tendency to fail when moisture condenses and freezes near the relief port, and should thus be avoided.

3.4.1.5.8 STRAINERS. Standard plumbing practice recommends that a strainer be located before the pump to test for system flush.

3.4.1.6 PUMPS

3.4.1.6.1 OPERATION. Circulation pumps are required in both the collector and storage loops. Both pumps are activated simultaneously by the control sub-system when it has been determined that net energy collection can occur.

3.4.1.6.2 FLOW PATH PRESSURE DROP. The pump size is based on the required flow rate and the resistance to flow in the loop (at that flow rate). The total pressure loss to be

overcome by the pump is the sum of the individual component and piping pressure losses around the loop. To calculate the pressure drop around the loop, the piping layout must be determined, certain major components specified, and approximate pipe lengths, fittings and diameters known. The pressure drop in the plumbing is calculated by first determining a flow path length, which is equal to the length of all linear piping plus the "equivalent lengths" of all valves and fittings. These equivalent lengths can be found in most plumbing handbooks; or accounted for by multiplying the linear pipe length by an appropriate factor (usually between 1.2 and 2, depending on the complexity of the plumbing circuit). Manufacturers should supply the pressure drops associated with the heat exchanger, solar collectors (or collector array), and other components at the respective loop flow rates. The pressure drops listed for these components will most likely assume water as the working fluid. The designer should be slightly conservative to account for the difference between pure water and the propylene glycol solution in these components. The correct values for the system piping should be available, since Table 3-1 provides corrections for pressure losses with propylene glycol solutions.

3.4.1.6.3 PUMP SIZING AND SPECIFICATION. Pump performance is usually plotted as pressure rise versus flow rate. The pressure drop in the loop at a given flow rate is represented by a point on this plot (or a line if the pressure drops for a variety of flow rates are known). Figure 4-10 shows an example of these curves. If this operating point is inside, or to the left of a given pump curve, that pump can be used. In Figure 2-10, pump "B" can be used. It should be noted that the pump could only operate at points along its curve. For this reason, the designer should try to find a pump curve lying as near the recommended system operating point as possible (unless this point lies on the pump curve, the pump will be slightly oversized). After the selected pump is installed and the system is started, the flow at the pump outlet must be throttled slightly to increase the pressure drop (or resistance) of the loop (refer to the system performance curve “D”). This procedure is normally done using a ball valve at the pump outlet (cavitation is possible if the throttling is done on the suction side). Many pump manufacturers supply pumps with built-in throttling valves. Refer to Figure 3-2.

3.4.2 TRANSPORT SUB-SYSTEM CHECKLIST

3.4.2.1 SCHEMATIC. Based on the topics discussed thus far, the complete closedloop system schematic can be completed. Except for the collector array and piping layout, the system schematic is not specific to any given building. For this reason, the system schematic need not be to scale and thermal expansion loops need not be shown. Information should be provided on the drawings wherever possible to ensure that construction is completed according to design.

3.4.2.2 CONSTRUCTION DETAILS. This section provides information on various system details that commonly cause problems. These details are not necessarily solar-specific issues, but are important to ensure a quality solar energy system.

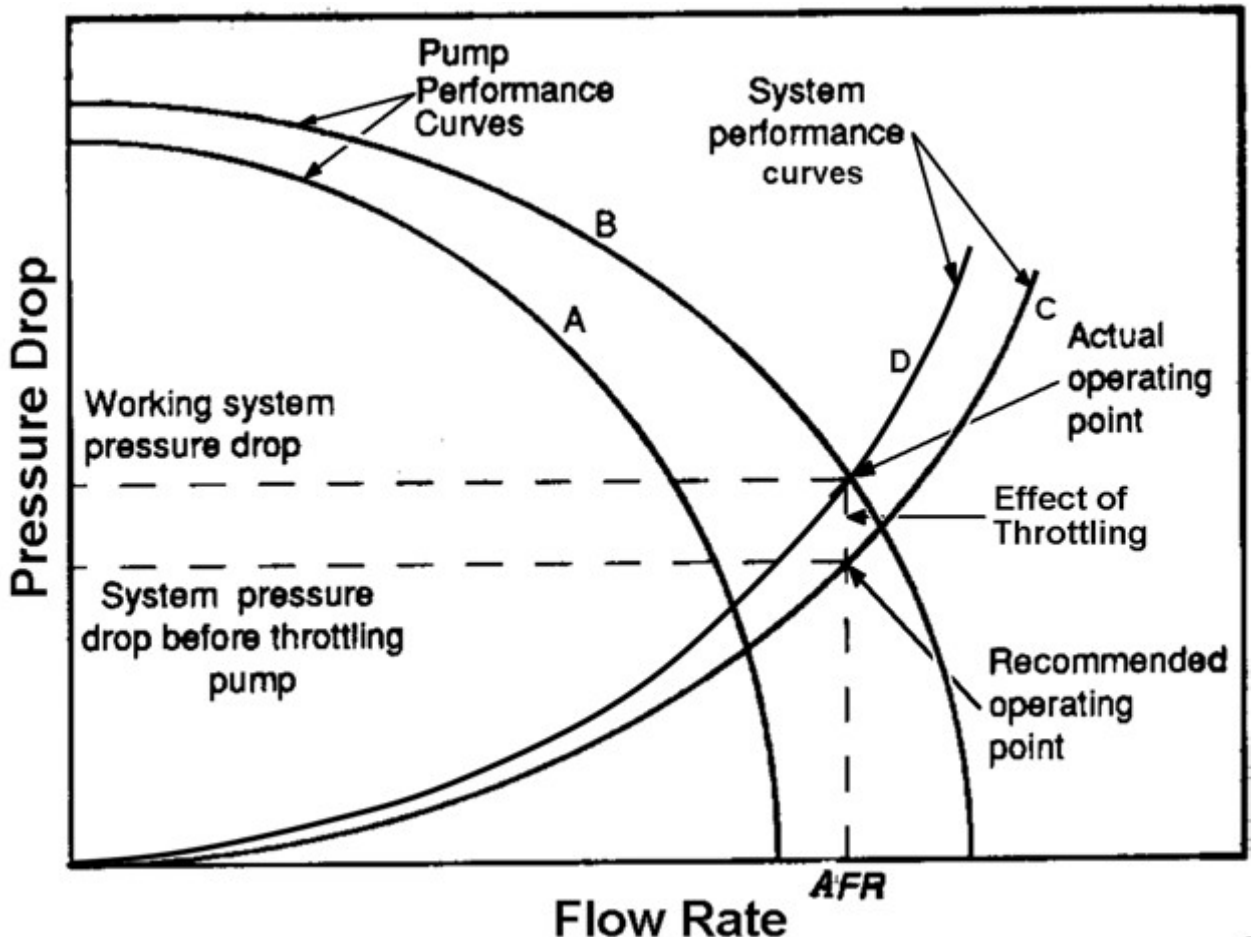


Figure 3-2

Typical Pump and System Operation Curves

3.4.2.2.1 COMPONENT CONNECTIONS. Major system components, such as the collector banks, storage tank, heat exchanger, and circulation pumps, should be able to be valved off and removed for cleaning, repair, or replacement. Installing valves on both sides of the component usually provides this feature.

3.4.2.2.2 ROOF PENETRATIONS. Roof penetrations for the array supply and return piping and sensor wiring conduit should be designed carefully to prevent leaking and to account for movement due to thermal expansion. Standard penetration schemes (such as those

used for plumbing system vents) can fail because of the increased temperature extremes to which solar system piping is subjected.

4. CONTROL SUB-SYSTEM. There are four areas concerning the control subsystem that needs to be addressed during the final design stage. These include specification of a control unit, location of control sensors, the location of local monitoring equipment, and measurement of thermal energy delivered by the system.

4.1 DIFFERENTIAL TEMPERATURE CONTROL UNIT (DTC). The proper specification of the differential temperature control unit is important to ensure reliable system performance. Because the cost of a simple solar system controller is small relative to the total system cost, a high quality, commercially available unit is recommended. The controller should include solid-state design with an integral transformer. The designer should also ensure that the switching relay or other solid state output device is capable of handling the starting current imposed by the system pump(s). The control unit should allow the on and off set-points to be variable, and should allow the instantaneous temperatures of the collector and storage tank to be displayed by the system operator or maintenance personnel. Faulty sensors are a common cause of system failure, so it is desirable to choose a control unit that will diagnose and flag open or short circuits. Since a non-functioning solar system can go undetected by maintenance personnel due to the presence of the backup heating system, some means for determining if the system is not operating or has not functioned for a given amount of time is helpful. The most commonly used method provides a visual indication at the control panel when the pump(s) are energized, although this indication is only instantaneous and does not provide any history. Some controllers indicate the elapsed time that the controller has signaled the pumps to switch on, but this is not necessarily an indication of whether the pumps have in fact been operational. The elapsed time indicator required on the pump showing cumulative running time of the system provides a check of system operation, if maintenance personnel choose to inspect and record it.

4.2 TEMPERATURE SENSORS AND LOCATIONS. There are two temperature sensors that the DTC relies upon to determine when to activate the collector loop pump and storage

loop pump. It is important that these sensors be reliable and accurate, as they can have a significant impact on system performance. Platinum resistance temperature detectors (RTD's) are most commonly used and are recommended, although 10 K-ohm thermistors are also sometimes used for this application.

4.2.1 COLLECTOR TEMPERATURE SENSOR. One sensor is required on the collector array to determine when sufficient energy is available for collection. This sensor is typically located in the fluid stream or is fastened directly to the absorber plate. When specifying a location in the fluid stream, the sensor should be located on a nearby collector bank and in the top internal manifold piping between two collectors. This location allows the sensor to be heated by the heat transfer fluid by natural convection. To minimize the length of sensor wiring, mount the sensor between two collectors on the bank closest to the roof penetration whenever possible. Most sensor manufacturers provide threaded wells to allow insertion of sensors into pipe flows. These wells should not consist of ferrous materials due to material compatibility with the propylene glycol heat transfer fluid. The sensor assembly should also be covered with a weatherproof junction box to shield connections from moisture while allowing room for the insulation around the manifold. The collector temperature sensor may be attached to the absorber plate of a collector only if the collector manufacturer provides this service at the factory. Sensors located in wells are easy to replace but may leak, whereas those located on the absorber plate are usually quite difficult to repair.

4.2.2 STORAGE TANK SENSOR. The storage tank temperature sensor is intended to measure the temperature of the coolest part of the storage tank. This is the fluid that will be delivered to the heat exchanger. Ideally, this sensor should be located within a well protruding into the storage tank near the outlet to the heat exchanger. If desired, auxiliary sensors may be added in the top half of the tank to check for stratification and in the bottom of the tank to provide backup.

4..2.3 SENSOR WIRING. Wiring from the controller to the collector and storage sensors should be located within metal conduit. It is recommended that spare conductors be provided in the conduit for future maintenance or expansion needs. Color-coding should be

consistent from the controller to the sensor, and junctions or pull boxes should not be located in concealed areas.

4.3 MONITORING EQUIPMENT. Monitoring devices are provided at various points in the system to enable inspection and maintenance personnel to visually check system operation.

4.3.1 PRESSURE INDICATORS. Pressure gauges should be installed on the supply and discharge sides of both pumps, on all inlets and outlets of the heat exchanger, and on the storage tank. Duplex gauges can be used or single pressure gauges can be connected to supply and discharge pipe with small plug valves installed in the gage lines. This arrangement allows the pressure to be monitored on either side of the pump by closing the opposite valve. A decrease in the pressure rise across the pump indicates a potential problem with the pump, whereas an increase may mean flow restrictions are developing in the loop. Monitoring the pressure drop across the heat exchanger can also alert system operators to heat exchanger fouling. Pressure gauges should be rated for 125 psi (862 kPa) and 210 degrees F (99 degrees C) operation.

4.3.2 TEMPERATURE INDICATORS. Thermometers should be provided at the heat exchanger inlets and outlets (hot and cold sides) and at the top and bottom of the solar storage tank. These can be used to monitor both heat exchanger performance and the fluid temperature being supplied by the collector array. Although some differential temperature control units are capable of monitoring all of these temperatures remotely, it is recommended that local fluid-in-glass or bi-metal thermometers be retained in the system as a backup.

4.3.3 FLOW INDICATORS. Show and specify a flow indicator in the collector loop, and in the storage loop, after the pump(s) to verify that flow exists. Venturi-type flow meters are recommended when quantified flow measurement is deemed necessary, whereas rotary or impeller-type flow indicators suffice to visually confirm flow in the collector loop. Since the flow indicator is wetted by the propylene glycol solution, components within it should be

brass, bronze, or other compatible non-ferrous material. Flow devices should be installed at least five pipe diameters downstream of any other fittings.

4.3.4 ELAPSED TIME MONITOR. An elapsed time monitor is required to record the operating time of each circulation pump. This time recorder is used to alert maintenance personnel to problems with pump operation.

4.3.5 BTU METER. An optional Btu meter may be specified for cases when the solar energy system performance is monitored. Btu meters are not required for control of the system. Therefore, if it is not essential to monitor performance, the cost of a Btu meter is not justified. When used, this device is installed in the storage loop to measure the total thermal energy that is delivered to the storage tank. It consists of a flow meter, temperature sensors for the heat exchanger inlet and outlet, and electronics to calculate the amount of energy (in Btu) delivered from the measured temperature change and flow. These units are available commercially and should be installed according to the manufacturer's recommendation.

5. FALL PROTECTION. Design equipment so that fall hazards are minimized during maintenance, repair, and inspection or cleaning. Consider future degradation of installed fall prevention components in maintenance and inspection activities. Design should minimize work at heights. Include in a design prevention systems such as guardrails, catwalks, and platforms. Provide anchorage points compatible with the job tasks and work environment. Design horizontal cable, vertical rail, cage or I-beam trolley systems in areas where employees require continuous mobility and where platforms, handrails, or guardrails are not feasible. Ensure proper test methods are used to ensure systems are capable of fall prevention functions. References applicable to fall protection include OSHA 29 CFR 1910 (Subpart F), ANSI Z359.1, and NFPA 101.

5.1 EQUIPMENT LOCKOUT AND DISCONNECT. Specify or design energy isolation devices capable of being locked out. Layout machinery and equipment to ensure safe access to lockout devices and provide each machine/equipment with independent disconnects. Specify lockout devices that will hold the energy isolating devices in a "safe" or "off" position. Ensure equipment and utilities have lockout capability and that any replacement, major repair, renovation, or modification of equipment will still accept lockout devices. Design emergency and non-emergency shutoff controls for easy access and usability. Integrate actuation controls with warning lights and alarms to prevent personnel exposure to hazards. References applicable to equipment lockout and disconnect include OSHA 29 CFR 1910.147, ANSI Z244.1, and NFPA 70.

QUIZ

AN INTRODUCTION TO DESIGN OF SOLAR WATER HEATING SYSTEMS

1. The solar collector absorber surface normally has two separate components: the absorber plate and _____ .

a. backflow baffles
b. the intercooler
c. fluid passageways
d. opaque glazing

2. The absorber plate surface is an important factor in the performance of the collector. There are two basic surface finishes, selective and _____ .

a. adsorptive
b. non-selective
c. opaque
d. reflective

3. The _____ is the piping that branches from the array supply to each of the individual collectors. There are two main types: external and internal.

a. exhaust manifold
b. supply intake
c. distributor
d. collector manifold

4. Collector covers, or glazings, are required to let radiant energy from the sun through to the absorber and to prevent _____ from the hot absorber plate to the ambient air.

a. convection
b. conduction
c. transmission
d. irradiation

5. An insulating material is required behind the absorber plate and on the sides of the collector to reduce _____ losses.

a. radiation

b. transmission
c. convection
d. conduction

6. The collector is one internal-manifold, flat-plate collector unit. The collector array is the entire set of collectors necessary to satisfy the collector area specified by the _____ .

a. ASHRAE Handbook, Vol. 3
b. supplier
c. general contractor
d. thermal analysis

7. The piping used to carry the heat transfer fluid through the array can act as either manifold (also called header) piping or _____ .

a. fluid isolator
b. a collector
c. riser piping
d. cross-connector

8. Flow can be balanced by active flow control or by _____ piping strategies.

a. multi-collector
b. makeup water
c. counterflow
d. passive

9. The _____ provides almost equal path lengths for any possible flow path that the fluid may take.

a. reverse-return piping layout
b. collector array
c. manifold piping layout
d. intercooler

10. Flow balance through the collector array depends on the relative pressure drop associated with the different piping branches of the array. The change in pressure along any flow path is a measure of the resistance to flow. Of interest to the solar system designer are the pressure losses across the collector risers, along a manifold, and along linear uninterrupted pipe. As the ratio of a manifold's pressure drop to its riser pressure drop becomes smaller, the flow becomes more uniform. To ensure uniform flow through the collector bank, this ratio should be around 10 percent, and under no circumstances should it exceed _____ percent.

a. 50
b. 40
c. 30
d. 20

11. Sizing of the piping in the solar array is critical to system performance. Flow throughout the array should be in balance at the proper flow rates, while maintaining a maximum velocity limit of about _____ feet/second.

a. 20
b. 15
c. 10
d. 5

12. The collector banks must be able to be valved off for maintenance, repair, or replacement. It is recommended that _____ valves be used in this capacity.

a. plug
b. globe
c. ball
d. gate

13. Thermal expansion control becomes important when long lengths of pipe are present or when pipes must be secured at a given location. The preferred method of accounting for thermal expansion is to _____ in the pipe run that can absorb the anticipated movement at a given location.

a. construct a U-shaped bend
b. provide expansion compensators
c. stress belief bellows
d. construct spiral segments

14. Solar storage tanks must be insulated to a value of R-_____ or better, to minimize loss of collected solar energy

a. 9
b. 15
c. 20
d. 30

15. The solar storage tank should be specified based on the sizing criteria that the volume be between _____ gallons per square foot of total array collector area.

a. 12 to 15

b. 7 to 10
c. 3 to 5
d. 1.5 to 2