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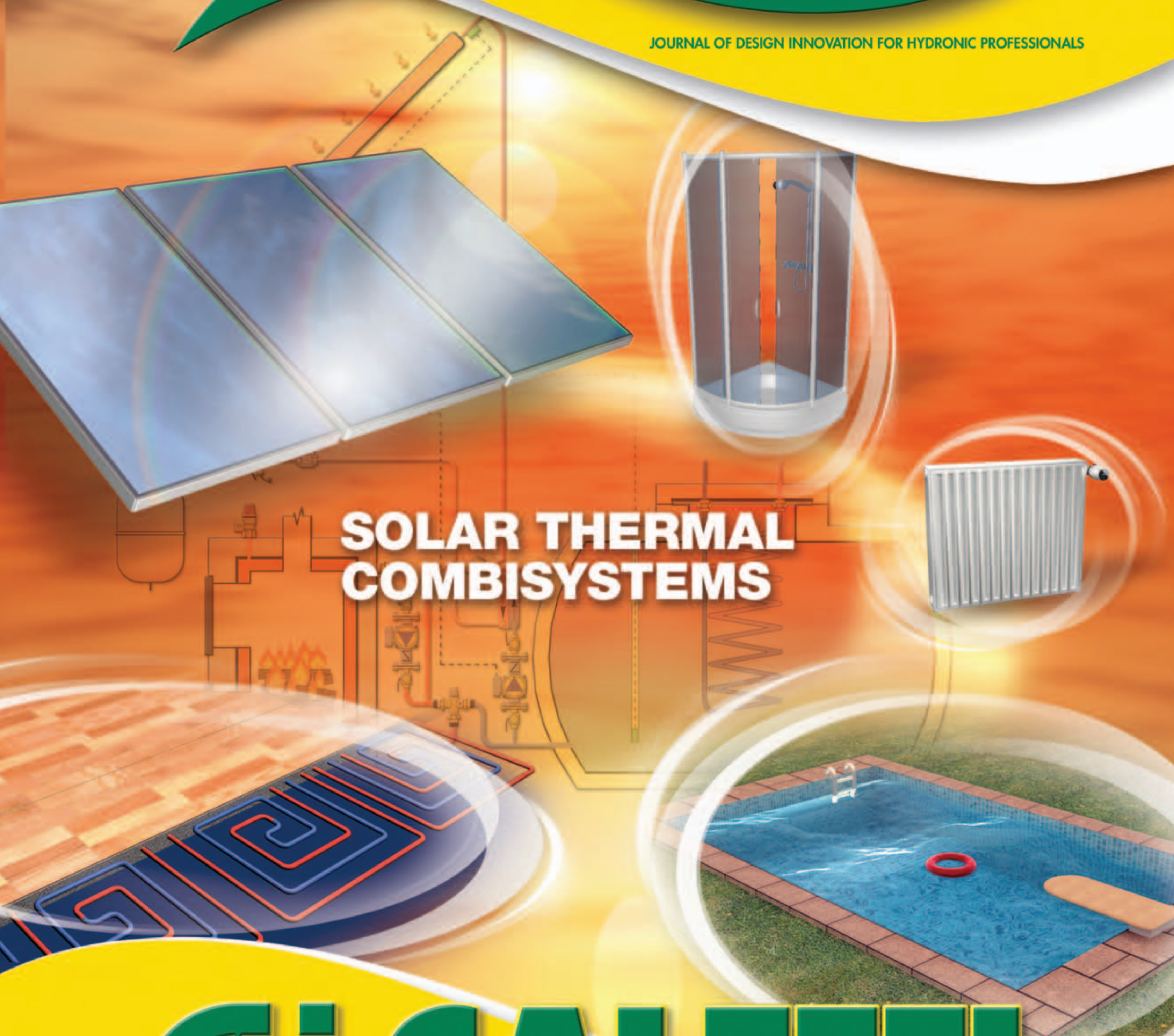
JOURNAL OF DESIGN INNOVATION FOR HYDRONIC PROFESSIONALS



SOLAR THERMAL COMBISYSTEMS

CALEFFI

A Technical Journal
from
Caleffi Hydronic Solutions

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Dear Hydronic Professional,

Welcome to the 6th edition of idronics, Caleffi's semi-annual design journal for hydronic professionals.

The global recession has slowed nearly all industries over the past year. However, despite declines in construction, solar water heater shipments in the US increased 50% during 2008.

As more and more HVAC professionals become familiar with solar water heating, many recognize opportunities to extend solar thermal technology for combined domestic hot water and space heating applications. This is a trend our parent Caleffi SpA identified several years ago in Europe, and is now a topic of growing interest here in North America. For this reason, solar "combisystems" was selected as the topic for this edition of idronics.

Caleffi is pleased to provide the information in this edition to assist those designing solar combisystems. We also stand ready with state-of-the-art hardware to support installation of such systems.

We encourage you to send us feedback on this edition of idronics by e-mailing us at idronics@caleffi.com.

Finally, if you are interested in previous editions of idronics, please go to www.caleffi.us where they can be freely downloaded. You can also register to receive future issues online.

Sincerely,

Mark Olson

Mark Olson
General Manager,
Caleffi North America, Inc.

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SOLAR THERMAL COMBISYSTEMS

1. INTRODUCTION

Most Americans are increasingly aware of rising energy prices and the environmental implications associated with continued use of conventional fuels. “Sustainable living” is one of the most prevalent topics being discussed in a variety of media.

This situation has created growing interest in renewable sources, such as sun, wind and biomass materials. It is also fostering a rapidly expanding market for equipment that harvests this energy.

Hydronics technology is the “glue” that holds most thermally based renewable energy systems together. Although heat sources such as solar collectors, solid-fuel boilers and geothermal heat pumps are indispensable components in such systems, they are not the sole determinants of efficiency, energy yield or financial viability. Without proper heat conveyance, even the best renewable energy heat source will not perform as expected. Thus, the proper application of modern hydronics technology is vital to the continued growth of the thermally based renewable energy systems market.

This issue of idronics focuses on systems that use solar energy, as well as an auxiliary energy source, to supply a portion of the domestic hot water and space heating needs of a building. Such configurations are commonly called solar thermal combisystems. Several design variations will be introduced and discussed in the context of residential and light commercial building applications. In each case, state-of-the-art hydronic technology such as variable flow, manifold-based distribution, hydraulic separation, thermal mass and precisely controlled zoning are used to enhance the system’s energy efficiency, enabling it to deliver the same unsurpassed comfort, reliability and long life as that provided by a well-designed conventional hydronic system.

Both piping and control aspects of solar combisystems are illustrated and described. In many cases, the control techniques are similar to those used in modern “non-solar” hydronic systems. When properly applied, these techniques allow combisystems to smoothly transition between use of solar and auxiliary energy so that occupants experience no difference in comfort.

The energy savings potential of such systems will also be discussed. The goal is for designers to develop reasonable expectations for what typical solar thermal combisystems can provide based on differences in climate, system size and loads.

2. FUNDAMENTALS OF SOLAR COMBISYSTEM DESIGN

The largest sector of the solar thermal market is domestic water heating. This is true both in North America and worldwide. The underlying reason is the capacity to use solar energy on a year-round basis, and in particular, the ability to collect solar energy when it is most abundant — in summer. Solar thermal systems for heating domestic water were discussed in detail in idronics #3 (January 2008).

A natural extension of a solar domestic water heating system is adding capability to offset a portion of the space heating load in the same building, and hence the name “combisystem.”

Most combisystems intended for residential applications treat domestic water heating as the primary load, and thus take advantage of high solar energy availability in summer. Beyond their DHW “base load,” combisystems typically use greater collector area and larger storage tanks to capture and contain additional energy that can offset a portion of the building’s space heating load.

As with solar DHW systems, combisystems require a reliable means of freeze protection, as well as an auxiliary energy device that supplies the energy required for uninterrupted delivery of hot water and space heating when solar heat gains cannot cover the load.

ESSENTIAL DESIGN PRINCIPLES:

The following design concepts are imperative to the success of a solar combisystem. Each will be discussed in the context of specific system designs described later in this issue.

- The cooler the solar collectors can operate, the higher their efficiency, and the greater the amount of solar energy they harvest.

- In an "ideal" solar thermal system, none of the heat produced by the auxiliary heat source would enter the solar storage tank. This prevents the auxiliary heat source from increasing the temperature of the storage tank above what it would be based solely on solar energy input. Such heating, if allowed to occur, delays the startup of the solar collection cycle, and thus reduces the energy collected during that cycle.

Some "single tank" combisystems discussed in this issue do not adhere to this principle. However, they all rely on temperature stratification to direct heat added by the auxiliary heat source to the upper portion of the storage tank. This minimizes heating of the lower portion of the tank, and thus reduces interference with the solar collection control process.

- The collector array and any piping outside of the heated space must be protected against freezing.

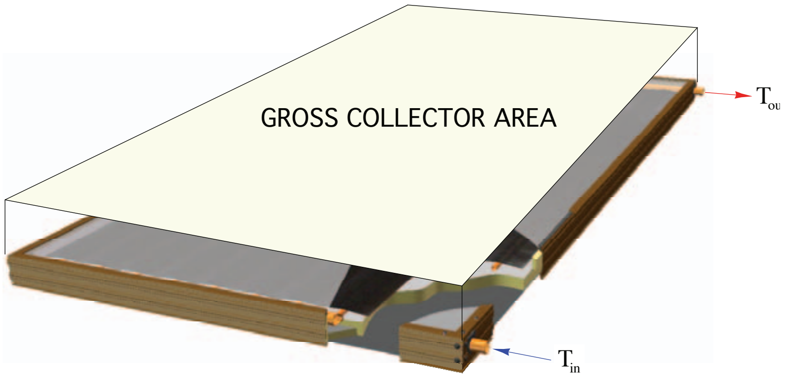
- Almost every solar combisystem gathers more energy on a sunny summer day than can be used by the load (which is typically just domestic water heating). All solar combisystems must have a means of dealing with this surplus energy so it doesn't damage the system.

INSTANTANEOUS COLLECTOR EFFICIENCY:

The performance of any solar combisystem is implicitly linked to the performance of its solar collector array. The best solar combisystems are designed to enhance collector efficiency. Doing so requires a fundamental knowledge of what collector efficiency is and how it is affected by operating conditions imposed by the balance of the system.

Figure 2-1

$$\text{collector efficiency} = \frac{\text{thermal output from collector (Btu/hr)}}{\text{solar radiation striking GROSS collector area (Btu/hr)}}$$



The instantaneous thermal efficiency of a solar collector is defined as the ratio of the heat transferred to the fluid passing through the collector divided by the solar radiation incident on the gross area of the collector, as shown in figure 2-1.

Instantaneous collector efficiency can be measured by recording the flow rate through the collector along with simultaneous measurement of the collector's inlet and outlet temperature. The intensity of the solar radiation striking the collector must also be measured. Formula 2-1 can then be used to calculate the instantaneous thermal efficiency of the collector.

Formula 2-1:

$$\eta_{collector} = \frac{(8.01 \times c \times D) \times f \times \left(T_{out} - T_{in}\right)}{I \times A_{gross}}$$

Where:

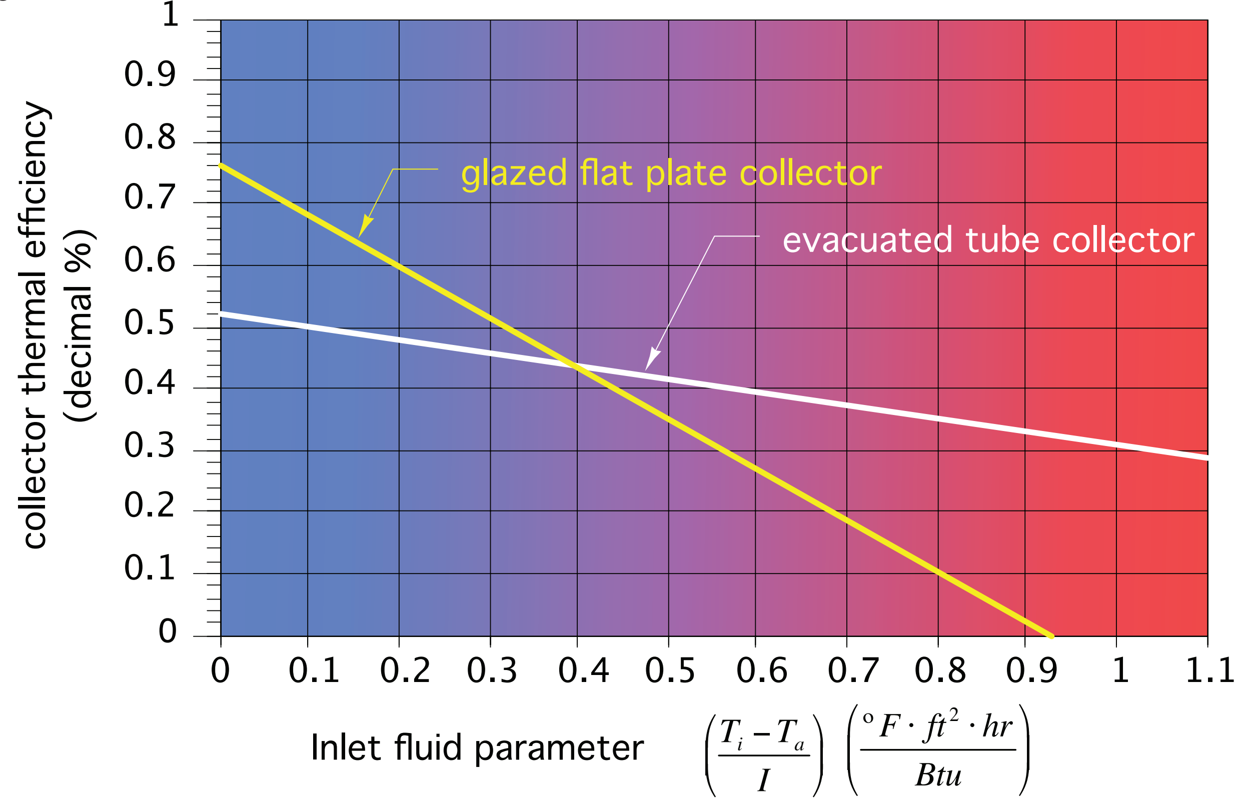
c = specific heat of fluid (Btu/lb/°F)
D = density of fluid (lb/ft^3)
f = flow rate (gallons per minute)
T_{in} = collector inlet temperature (°F)
T_{out} = collector outlet temperature (°F)
I = instantaneous solar radiation intensity (Btu/hr/ft^2)
A_{gross} = gross collector area (ft^2)
8.01 = a unit conversion factor

The phrase *instantaneous collector efficiency* can vary from moment to moment depending on the operating conditions. Do not assume that a given set of operating conditions is "average" or "typical," and thus could be used to determine the collector's efficiency over a longer period of time.

Instantaneous collector efficiency is very dependent on the fluid temperature entering the collector, as well as the temperature surrounding it. It also depends on the intensity of the solar radiation incident upon the collector. This relationship is shown in figure 2-2 for a typical flat plate and evacuated tube collector.

The thermal efficiency of each collector is plotted against the inlet fluid parameter. This parameter combines the effects of inlet fluid temperature, ambient air temperature and solar radiation intensity into a single number.

Figure 2-2



For a given solar radiation intensity and outdoor air temperature, any operating condition that increases the fluid temperature entering the collector causes the inlet fluid parameter to increase. This causes a drop in thermal efficiency for both the flat plate and evacuated tube collectors. Conversely, any operating condition that lowers the inlet fluid temperature also lowers the inlet fluid parameter and increases collector efficiency.

Systems that can operate with relatively low collector inlet temperatures generally allow flat plate collectors to reach thermal efficiencies higher than those attained by evacuated tube collectors. Conversely, systems that require the collector to operate at higher temperatures are usually better suited to evacuated tube collectors. Design tools such as simulation software can be used to determine which type of collector allows a given combisystem to harvest the greatest amount of solar energy.

The value of the inlet fluid parameter often changes from moment to moment depending on the operating conditions of the system and the prevailing weather. For example, if a cloud temporarily shadows the collectors from direct sun, the value of the inlet fluid parameter could easily double, which temporarily decreases efficiency. Designers are cautioned about assuming any given value of the inlet fluid parameter as “representative” of average operating conditions. Instead, the variability of this parameter is accounted for in system simulation software. The latter is essential in determining the net effect of any collector in a solar combisystem.

FREEZE PROTECTION:

All solar combisystems require a means of protecting the collectors and piping outside of the heated space from freezing. Although there are several possible ways to do this, two methods of freeze protection dominate the market worldwide:

- Use of antifreeze fluid in the collector circuit
- Gravity drainback systems

Each of these systems has advantages and limitations, and several options for each approach will be described.

3. SPACE HEATING OPTIONS:

Not every hydronic space heating distribution system is suitable for use with a solar combisystem. Distribution systems that operate at low water temperatures are greatly preferred because they allow for higher solar energy yields.

Space heating distribution systems that provide design heating load output using supply water temperatures no higher than 120ºF will allow the solar subsystem to deliver relatively good performance.

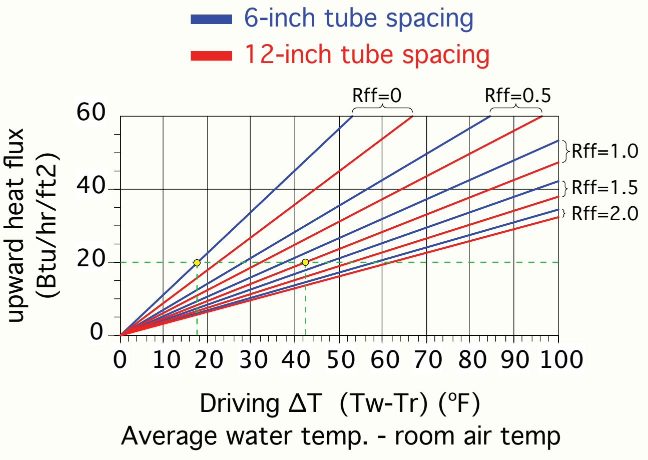
Distribution systems that supply each heat emitter using parallel piping branches rather than series configurations are also preferred because they provide the same supply water temperature to each heat emitter.

Examples of space heating systems that allow the solar subsystem to provide good performance include:

- Heated floor slabs with low-resistance coverings
- Heated thin-slabs over framed floors with low-resistance coverings
- Generously sized panel radiator systems with parallel piping
- Forced-air systems with generously sized water-to-air heat exchangers and carefully placed diffusers that do not create drafts

Each of these will be discussed in more detail.

Figure 3-1 Upward heat output vs. Driving ΔT for 4" concrete slab



Rff = resistance of finish flooring (ºF/hr/ft^2/Btu)

HEATED FLOOR SLABS:

Heated floor slabs with relatively close tube spacing and low finish floor resistances are generally well suited for use with solar combisystems. The graph in figure 3-1 shows upward heat output from a heated slab based on tube spacing of 6 inches and 12 inches, and for finish floor resistances ranging from 0 to 2.0 (ºF•hr•ft2/Btu). The steeper the line, the better-suited the distribution system is for use in a solar combisystem.

For example, achieving an upward heat output of 20 Btu/hr/ft^2 from a slab with no covering (e.g., Rff = 0) and 6-inch tube spacing requires the "driving ΔT" (e.g., the difference between average water temperature in tubing and room air temperature) to be 17.5ºF. Thus, in a room maintained at 70ºF, the average water temperature in the circuit needs to be 87.5ºF. The supply water temperature to the circuit would likely be in the range of 95–98ºF. This is a relatively low supply water temperature, and should allow the collectors to operate at reasonably good efficiency, especially if flat plate collectors are used.

For comparison, consider supplying the same 20 Btu/hr/ft^2 load using a heated floor slab with 12-inch tube spacing and a finish floor resistance of 1.0ºF•hr•ft^2/Btu. The driving ΔT must now be 42.5ºF. The average circuit water temperature required to maintain a room temperature of 70ºF would be 70 + 42.5 = 112.5ºF, and the supply temperature likely in the range of 120–123ºF. This higher temperature would reduce the efficiency of the solar collectors, and decreases the total energy collected by the system during the heating season. Again, the net effect of such a change on a seasonal basis would have to be assessed through computer simulation of a given system.

Figure 3-2

The following guidelines are suggested in applications where a heated floor slab will be used to deliver heat derived from a solar collector array:

- Tube spacing within the slab should not exceed 12 inches
- Slab should have minimum of R-10 underside insulation
- Tubing should be placed at approximately 1/2 the slab depth below the surface, as shown in figure 3-2
- Bare, painted or stained slab surfaces are ideal because the finish floor resistance is essentially zero
- Other floor finishes should have a Total R-value of 1.0 or less

HEATED THIN-SLABS:

Another common method of installing floor heating uses a “thin slab” (1.5-inch to 2-inch thickness) poured over a wooden floor deck. Figure 3-3 shows an example of such an installation, awaiting placement of the slab material.

Figure 3-3

Courtesy of H. Youker

Because the slab is thinner than with slab-on-grade floors, it has slightly lower lateral heat dispersal characteristics. This translates into a slightly higher water temperature requirement for a given rate of heat output relative to that required for a slab-on-grade. This difference is slight. A 1.5-inch-thick concrete thin slab with 12-inch tube spacing and covered with a finish flooring resistance of 0.5ºF•hr•ft^2/Btu yields about 8% less heat output than a 4-inch-thick slab with the same tube spacing and finishing flooring. This can be easily compensated for by using 9-inch rather than 12-inch tube spacing.
The following guidelines are suggested:

- Tube spacing within the thin slab should not exceed 9 inches
- Slab should have minimum of R-19 underside insulation
- Floor finishes should have a total R-value of 1.0 or less
- Never use “lightweight” concrete for heated thin slabs

OTHER SITE-BUILT RADIANT PANELS:

Radiant panels can be integrated into walls and ceilings as well as floors. Several of these configurations may be suitable for use with solar combisystems. The key is ensuring the radiant panel can deliver design load output while operating at a relatively low water temperature. This helps ensure the solar collectors will also operate at a relatively low fluid temperature and reasonably good efficiency.

This criterion favors radiant panels that provide high surface areas relative to the rate of heat delivery. It also favors panels that have relatively low internal resistance between the tubing and the surface area releasing heat to the room.

One example is a radiant wall panel constructed as shown in figure 3-4.

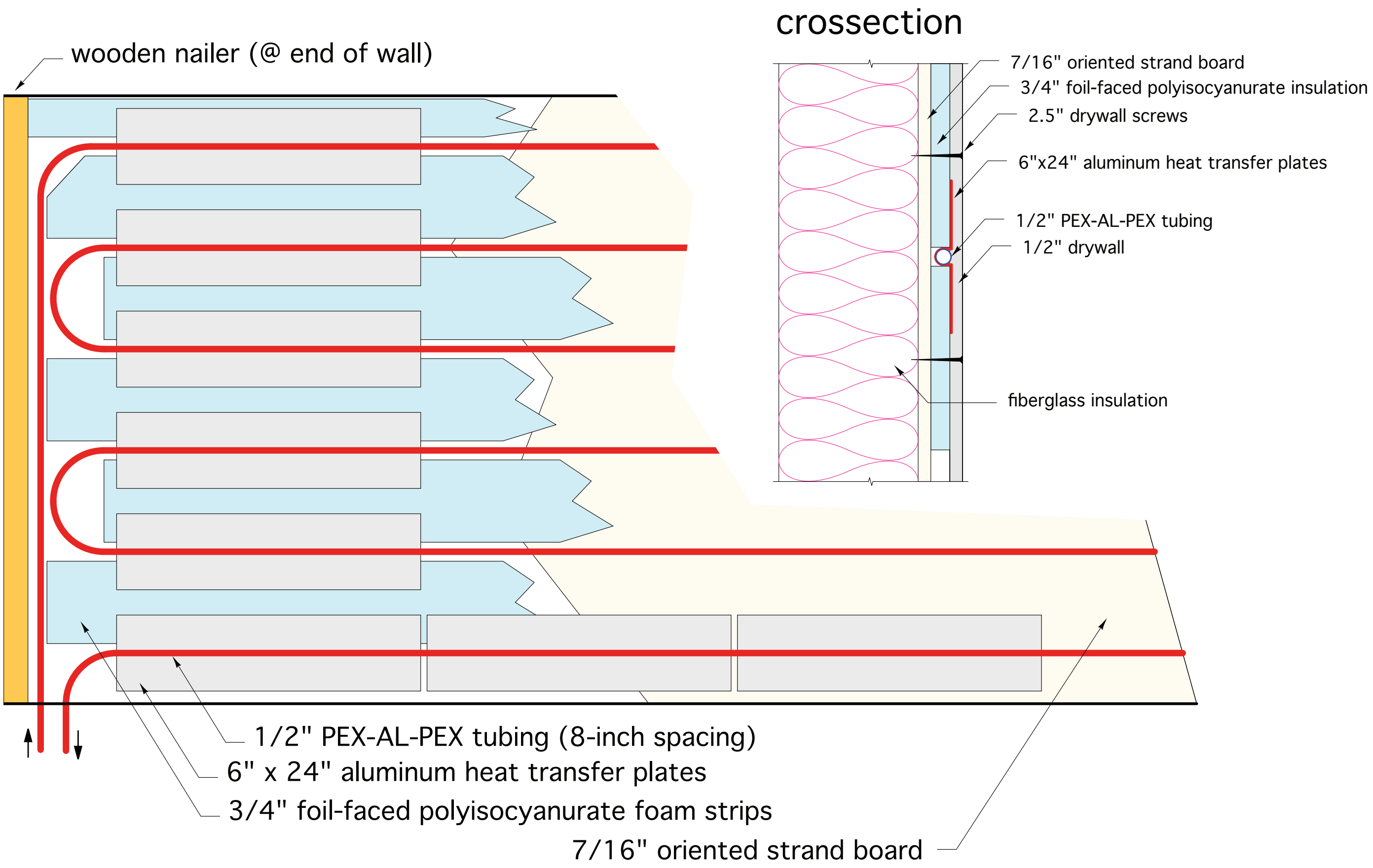
When finished, this “radiant wall” is indistinguishable from a standard interior wall. Its low thermal mass allows it to respond quickly to changing internal load conditions or zone setback schedules. The rate of heat emission to the room is approximately 0.8 Btu/hr/ft^2 for each degree Fahrenheit the average water temperature in the tubing exceeds room air temperature. Thus, if the wall operates with an average water temperature of 110ºF in a room with 70ºF air temperature, each square foot of wall would release about 0.8 x (110 - 70) = 32 Btu/hr/ft^2. This performance makes it well suited for use with a solar combisystem.

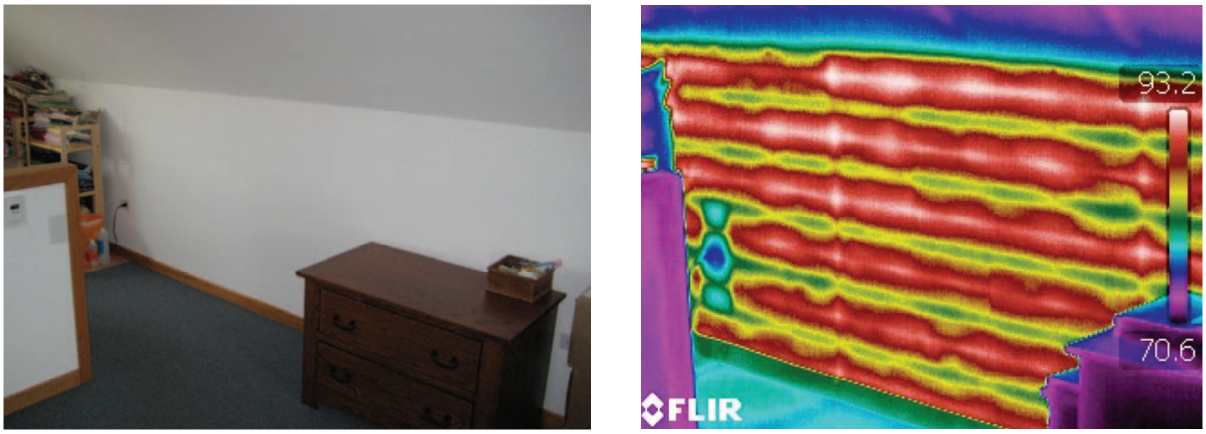
Another possibility is a radiant ceiling using the same type of construction as the radiant wall, as shown in figure 3-5.

As with the radiant wall system, this radiant ceiling has low thermal mass and responds quickly to interior temperature changes. Heated ceilings also have the advantage of not being covered or blocked by coverings or furniture, and thus are likely to retain good performance over the life of the building.

For the construction shown, the rate of heat emission is approximately 0.71 Btu/hr/ft^2 for each degree Fahrenheit

Figure 3-4



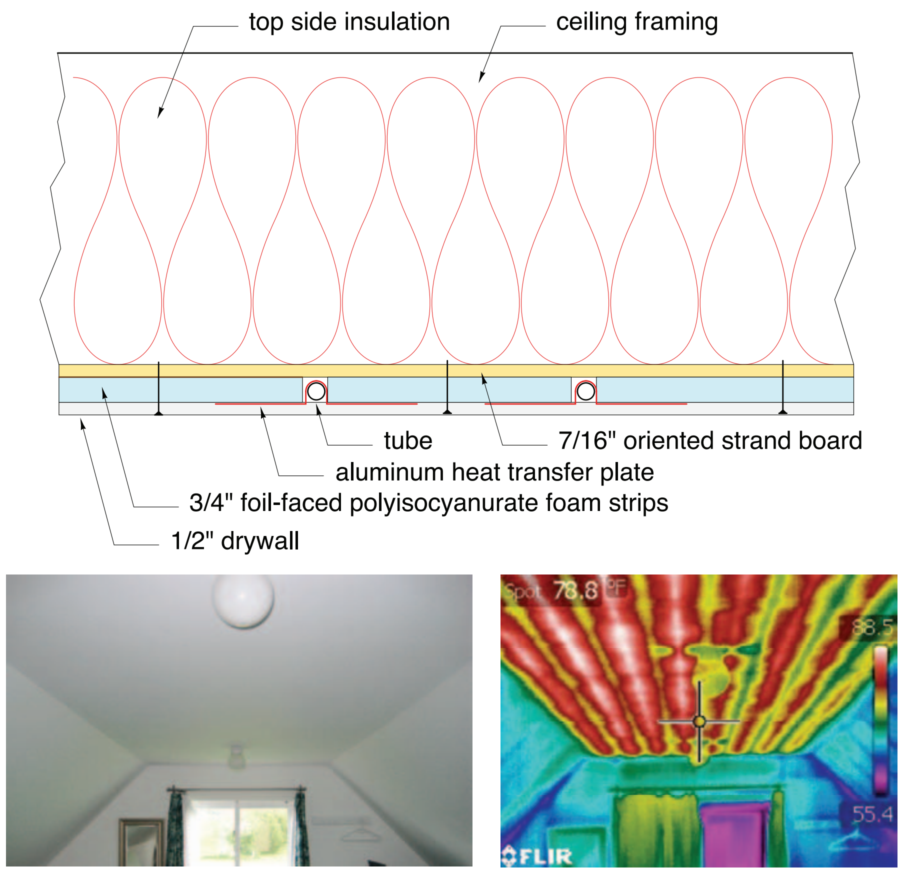


finished radiant wall

thermal image of wall in operation

$$\frac{Btu}{hr \bullet ft^2} = (0.8) \times (T_{water} - T_{room})$$

Figure 3-5



finished radiant wall

thermal image of ceiling in operation

$$\frac{Btu}{hr \bullet ft^2} = (0.71) \times (T_{water} - T_{room})$$

the average water temperature in the tubing exceeds room air temperature. Thus, if the ceiling operated with an average water temperature of 110°F in a room with 70°F air temperature, each square foot of wall would release about 0.71 x (110 - 70) = 28.4 Btu/hr/ft^2. This performance makes the radiant ceiling well suited for use in a solar combisystem.

PANEL RADIATORS:

Generously sized panel radiators can also provide good performance when used as part of a solar combisystem. Again, the suggested guideline is to size panels so they can deliver design space heating output using a supply water temperature no higher than 120°F.

Manufacturers provide output ratings for their panel radiators in either graphical or tabular form. In many cases, “reference” heat output ratings for a given size panel are stated along with corresponding water temperature and room air temperatures. Correction factors are then given, which, when multiplied by the reference heat output, give the actual heat output for specific water and room air temperatures.

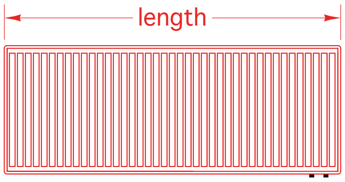
Figure 3-6 shows a typical fluted water panel radiator. Figure 3-7 gives reference heat output ratings for this type of panel based on an average panel water temperature of 180°F and room air temperature of 68°F. Figure 3-8 gives correction factor to modify the reference heat output ratings based on different average water temperatures and room air temperatures. The formula on the graph in figure 3-8 can also be used to calculate these correction factors.

For example: Figure 3-7 indicates that a panel with a

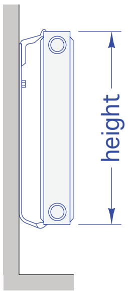
Figure 3-6

Courtesy H. Youker

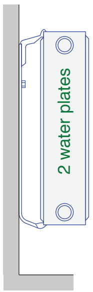
Figure 3-7



Heat output ratings (Btu/hr)
at reference conditions:
Average water temperature in panel = 180°F
Room temperature = 68°F
temperature drop across panel = 20°F



	1 water plate panel thickness					
	16" long	24" long	36" long	48" long	64" long	72" long
24" high	1870	2817	4222	5630	7509	8447
20" high	1607	2421	3632	4842	6455	7260
16" high	1352	2032	3046	4060	5415	6091



	2 water plate panel thickness					
	16" long	24" long	36" long	48" long	64" long	72" long
24" high	3153	4750	7127	9500	12668	14254
20" high	2733	4123	6186	8245	10994	12368
16" high	2301	3455	5180	6907	9212	10363
10" high	1491	2247	3373	4498	5995	6745

	3 water plate panel thickness					
	16" long	24" long	36" long	48" long	64" long	72" long
24" high	4531	6830	10247	13664	18216	20494
20" high	3934	5937	9586	11870	15829	17807
16" high	3320	4978	7469	9957	13277	14938
10" high	2191	3304	4958	6609	8811	9913

single water plate, measuring 24 inches high and 72 inches long, has a heat output of 8447 Btu/hr based on the reference conditions of 180°F average water temperature and 68°F room air temperature. Using the formula in figure 3-8, the correction factor with an average panel water temperature of 110°F and room temperature of 68°F is:

$$CF = 0.001882\left(110-68\right)^{1.33} = 0.271$$

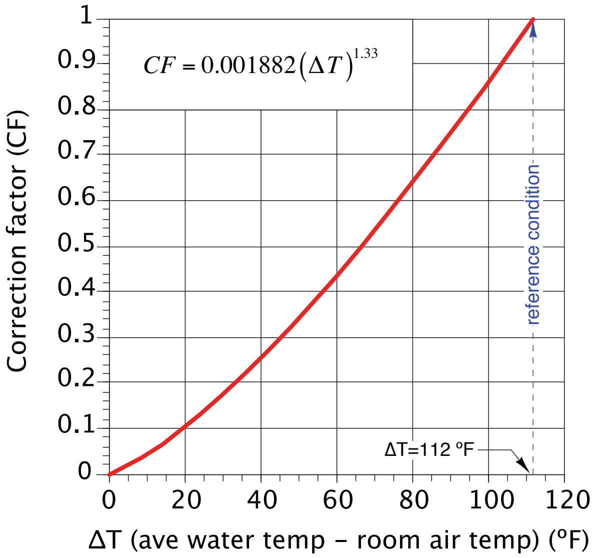
The estimated heat output at the lower water temperature is thus:

$$Output = \left(0.271\right) \times 8447 = 2289\,Btu/hr$$

This example demonstrates that systems limiting the supply water temperature to 120°F to retain good performance of the solar collectors often require substantially larger panel radiators compared to systems with conventional heat sources that often supply much higher water temperatures.

When panel radiators are used in a solar combisystem, they should be piped in parallel. Ideally, each panel radiator is served by its own supply and return piping. A manifold-based distribution system, as shown in figure 3-9, uses small diameter PEX or PEX-AL-PEX tubing to supply each radiator. Tube sizes in such systems varies from 3/8-inch to 5/8-inch depend on flow rate and head loss allowances. This type of distribution system is well suited for solar combisystems and is shown in several subsequent schematics.

Figure 3-8



Reference condition:
Ave water temperature in panel = 180°F
Room air temperature = 68°F

FORCED-AIR DISTRIBUTION SYSTEMS:

Although most solar combisystems use hydronics technology, it is possible to use a forced-air system to deliver both the solar-derived heat and any necessary auxiliary heat to the building. This is usually done using a hot water coil mounted in the plenum of the air handling device (furnace, heat pump indoor unit, etc.), as shown in figure 3-10.

The coil is mounted on the discharge plenum to avoid heating the components inside the air handler. Although this may not be an issue with devices such as furnaces, it could void warranties on other types of air handlers containing refrigeration components.

The check valve installed in the pipe supplying the plenum coil prevents reverse heat migration from the furnace to the solar storage tank when the latter is too cool for use.

An air temperature sensor is located in the discharge plenum, downstream of the coil. This is used in

Figure 3-9

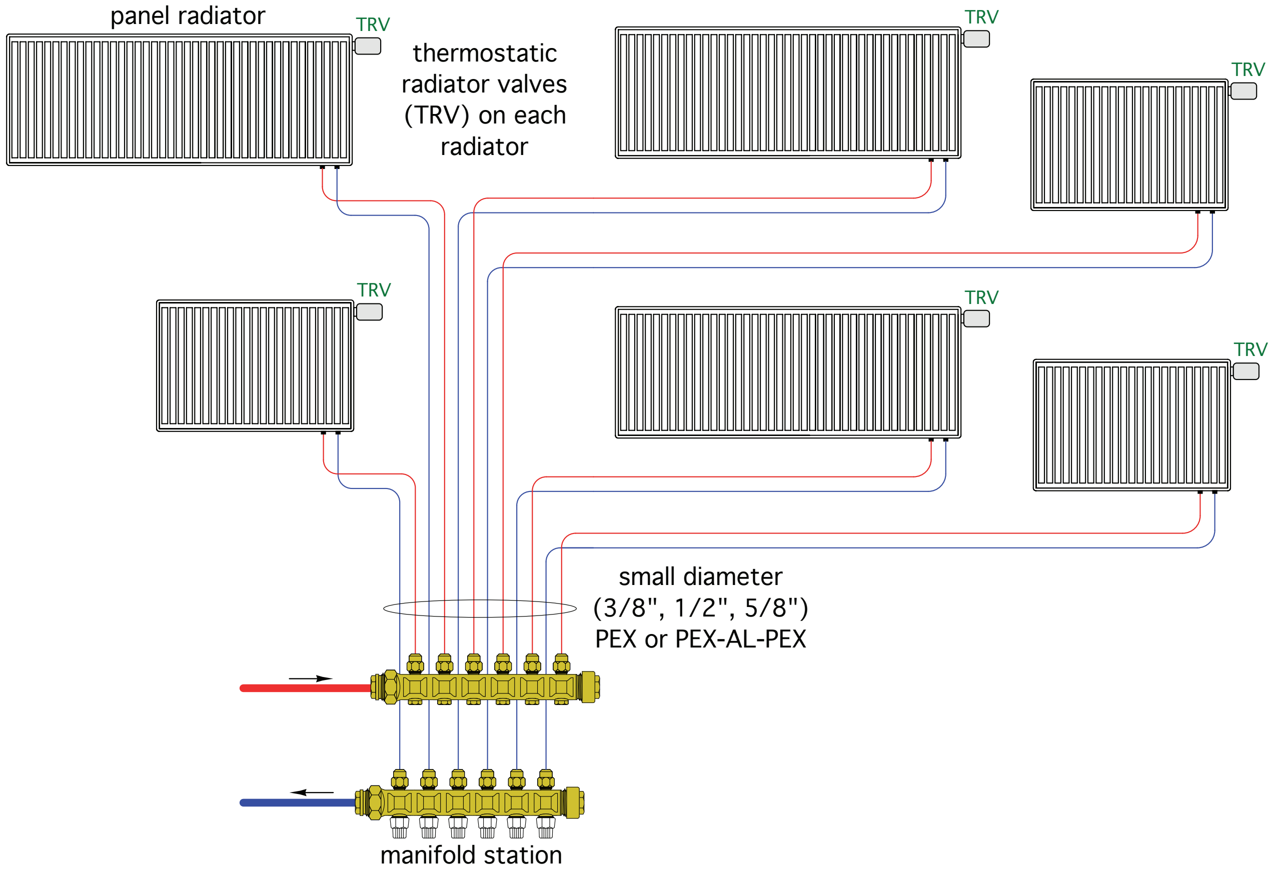


Figure 3-10

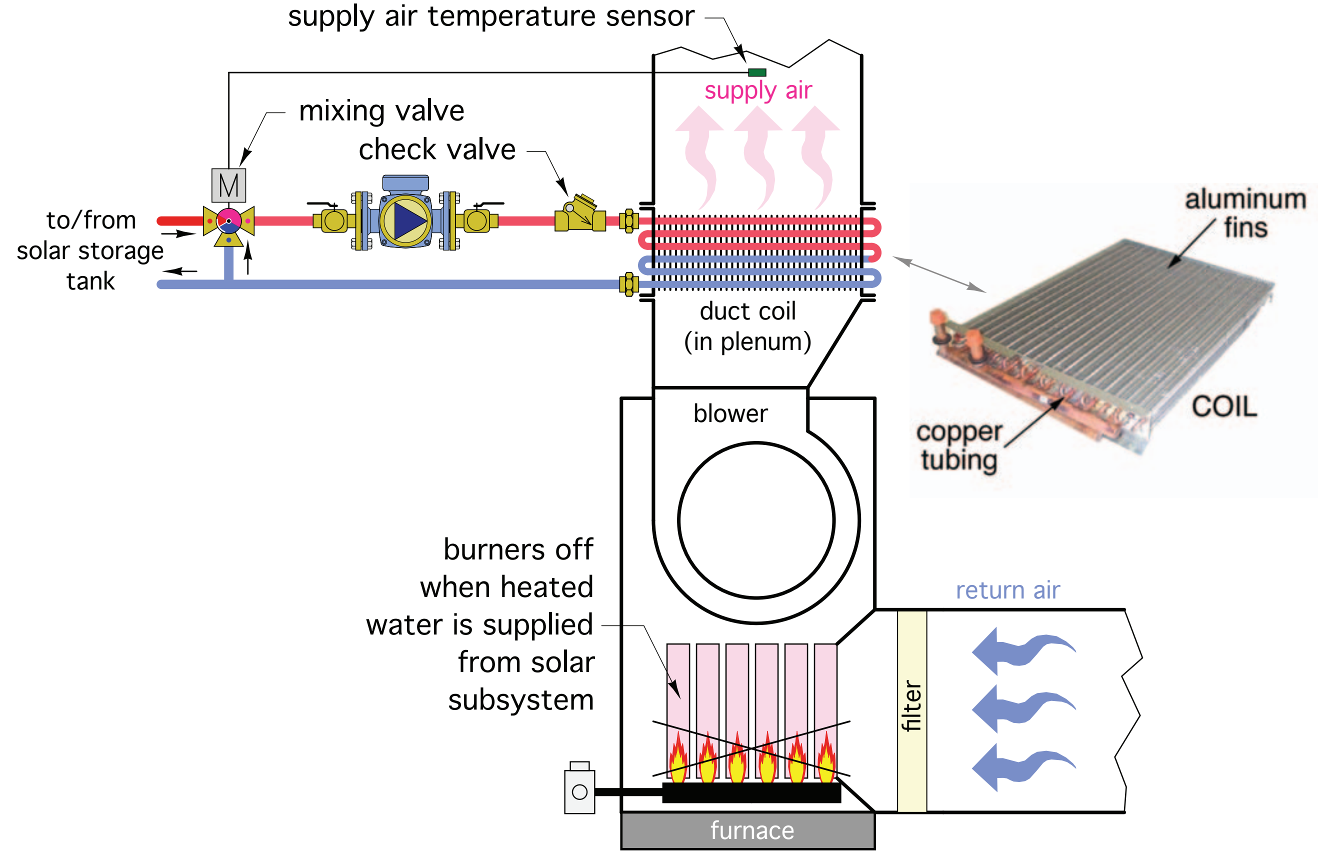
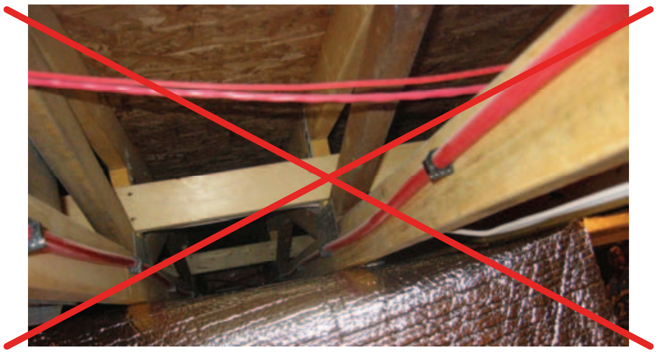


Figure 3-11



combination with a mixing device to regulate the temperature of the supply air stream. Such regulation prevents very hot water in the solar storage tank from creating a burst of very warm air to the heated space.

The size of the plenum coil should allow relatively low water temperatures in the solar storage tank to meet the heating load. Coils with multiple tubing rows and large aluminum fins improve heat transfer at low water temperatures, and as such are preferred. Coil manufacturers can size coils for the required rates of heat transfer at specified entering water and air temperatures.

This type of system may not always create supply air temperatures as high as those created by a furnace, especially if the water temperature supplied to the coil is regulated by outdoor reset control. The registers and diffusers used for such a system should be carefully sized and placed to avoid creating drafts within the heated space. Ideally, supply air from the diffusers should be mixed with room air above the occupied zone. Vertical air velocities into the occupied zones should be minimized to avoid drafts.

Fin-tube baseboards, although commonly used in conventional hydronic systems, generally do not provide good performance in solar combisystems. Most systems using fin-tube baseboard are designed around relatively high water temperatures (180ºF or higher). While it is possible to lower the supply water temperature by adding fin-tube baseboard to the system, lowering it from 180ºF to 120ºF typically requires about 3.5 times as much fin-tube length for the same heat output. Few rooms can physically accommodate this, and few occupants would accept the associated aesthetics.

Some radiant floor panels require water temperatures well above 120ºF at design load conditions. Such panels will not allow a solar thermal subsystem to perform as well as the previously discussed radiant panels. Careful analysis using solar simulation software can quantify the differences in expected solar subsystem performance.

Cast iron radiators sized for steam heating but converted for use with higher temperature water are also unlikely to be suitable. The possible exception would be a building that has undergone extensive weatherization since the steam radiators were installed. In some cases, the significant reduction in heating load relative to the surface area of the original radiators might allow operation at water temperatures within the range that can be consistently supplied by solar collectors. In such cases, the original radiator system should also be internally cleaned and flushed to remove any accumulated residue associated with steam heating.

4. ANTIFREEZE-BASED SOLAR COMBISYSTEMS

The use of antifreeze fluids to protect solar collectors and exposed piping against freezing is very similar to its use in other hydronic systems. The piping circuits containing the antifreeze solution are closed loops. When the system is commissioned, these loops are purged of air and slightly pressurized. In a closed, fluid-filled piping circuit, the weight of the upward flowing fluid is exactly balanced by that of the downward flowing fluid.

ADVANTAGES OF ANTIFREEZE-BASED SYSTEMS:

In a properly purged closed piping circuit, the circulator is only responsible for overcoming the head loss due to friction between the piping components and the fluid. It is not responsible for "lifting" fluid into unfilled piping. That task is handled by a separate filling/purging pump. Thus, the circulator in a closed, fluid-filled piping loop can be relatively small. In residential combisystems, the collector loop circulator might only require 25 watts or less of electrical input energy. This keeps the operating cost of the solar collection subsystem low.

Another advantage of antifreeze-based systems is that tubing to and from the collector array can be installed in any orientation. This allows flexible stainless steel or other types of coiled metal tubing to be installed in spaces where it would be difficult or impossible to install rigid tubing, or to maintain a minimum slope on that tubing.

DISADVANTAGE OF ANTIFREEZE-BASED SYSTEMS:

One disadvantage of antifreeze-based systems is that a heat exchanger is required between the antifreeze solution in the collector circuit and the water in the remainder of the system. Any heat exchanger imposes a performance penalty on the system because it forces the collector circuit to operate at a temperature higher than that of the water near the bottom of the storage tank. The magnitude of this temperature difference depends on the sizing of the heat exchanger. The greater the internal surface of the heat exchanger is relative to the rate of heat transfer, the less the performance penalty. The performance of heat exchangers and the penalty factor they impose on solar combisystems are discussed in Appendix B.

Another disadvantage of antifreeze-based systems is that glycol-based antifreeze will chemically degrade and become acidic over time. In such a state, the fluid can cause internal corrosion of both piping and collectors, eventually leading to failure. This degradation is accelerated at higher temperatures. It is not good for glycol-based fluids to be maintained at high temperatures over long periods of time. This can happen in solar combisystems that generate far more heat in summer than is required by the load. It also implies that annual testing of the pH and reserve alkalinity of glycol-based antifreeze solutions is imperative.

HEAT DUMP PROVISIONS:

The potential for thermal degradation of glycol-based antifreeze solutions justifies the need for a "heat dump" provision on antifreeze-based solar combisystems. The heat dump provides a way for the system to shed excess heat when the solar storage tank has reached a user-set upper temperature limit and there is no immediate need for further heat in the system. Heat dumps can take the form of:

- Additional storage tanks.

- Passive or fan-forced convectors through which the hot antifreeze solution is diverted when necessary. These convectors are typically located outside the building and dissipate heat directly to outdoor air.

- Heat exchangers that dissipate surplus heat to high thermal capacity loads, such as swimming pools, spas or buried earth loops. The latter is well-suited for geothermal heat pump systems in climates with relatively small cooling loads.

- Nocturnal cooling — the antifreeze solution is circulated between the tank heat exchanger and the collector array at night to dissipate heat back to the atmosphere. In some systems, the check valve in the collector loop can be manually opened to allow nocturnal cooling without operation of the circulator. Note: Nocturnal cooling can only be used with flat plate collectors.

Heat dumps (other than nocturnal cooling) are usually brought online using an electrically operated diverting valve. In its unpowered state, this valve allows the antifreeze solution to flow between the collector array and the normal load — such as a heat exchanger in the solar storage tank.

When the solar tank reaches a user-specified temperature limit, the solar system controller powers up the diverting valve. The heated antifreeze solution returning from the collector array is then routed to the heat dump. If, during the heat dump mode, the solar storage tank temperature drops, the solar system controller discontinues the heat dump mode and redirects the heated antifreeze to the normal load.

Power outages are one of the chief causes of collector stagnation. For a heat dump to be effective during such times, it must be able to operate in the absence of utility-supplied power. DC circulators operated from batteries are one possibility. Passive heat dissipation devices that operate based on buoyancy-driven flow are another.

Heat dump subsystems should be sized to dissipate the entire heat gain of the collector array during a warm and sunny summer day and with no load assumed on the system. This is based on the premise that two or more such days could occur in sequence, and that the first could bring the solar storage tank to its upper temperature limit. The absence of load during this scenario is based on the occupants being away from the building.

ANTIFREEZE-BASED COMBISYSTEM DESIGNS:

Solar combisystems can be designed many ways depending on project requirements and constraints. For example, a narrow doorway might require that a system needing several hundred gallons of storage is designed around multiple smaller tanks rather than a single large tank. A ground-mounted collector array may not provide the elevation change required for a drainback system, and thus the only choice would be an antifreeze-based system. The size of the space heating load and the type of auxiliary heat used will certainly influence overall system design. In short, there is no “universal” design concept for a solar combisystem that suits all situations.

The remainder of this section discusses several “templates” for solar combisystems that can work for many residential or light commercial applications. All these systems use antifreeze-based closed collector circuits. Section 5 will present several additional templates for drainback combisystems.

ANTIFREEZE-BASED COMBISYSTEM #1:

The first design presented is a natural extension of a solar domestic water heating system. It adds an auxiliary storage tank to accept heat from the collector array whenever it’s available, and the domestic hot water storage tank has reached a user-set maximum temperature. A piping schematic for the system is shown in figure 4-1.

A standard solar circulation station like that used in a solar DHW system controls flow through the collector array. Whenever the temperature sensor (S2) on the domestic water tank is below a user-selectable maximum setting, flow returning from the collectors is routed to the left, through the internal heat exchanger in the DHW storage tank. It then passes into the “B” port of the 3-way diverter valve (D1), out through the “AB” port and back to the supply side of the solar circulation station. The diverter valve is not energized in this mode. There is no flow through the coil in the auxiliary storage tank. A spring-loaded check valve helps prevent heat migration into the auxiliary storage tank during this mode.

If the solar controller detects that temperature sensor (S2) has reached the maximum temperature setting, it applies line voltage to the diverter valve (D1). Hot antifreeze solution returning from the collectors is now routed through the coil of the auxiliary storage tank.

As heat is diverted to the auxiliary storage tank, the solar controller continues to monitor the temperature of the DHW tank sensor (S2). If its temperature drops a preset amount, the diverter valve (D1) reverses position to route the antifreeze solution returning from the collectors through the coil in the DHW tank. The solar controller always treats the DHW storage tank as the “priority” load, directing heat to it whenever its temperature is under a user-specified maximum value.

Figure 4-1

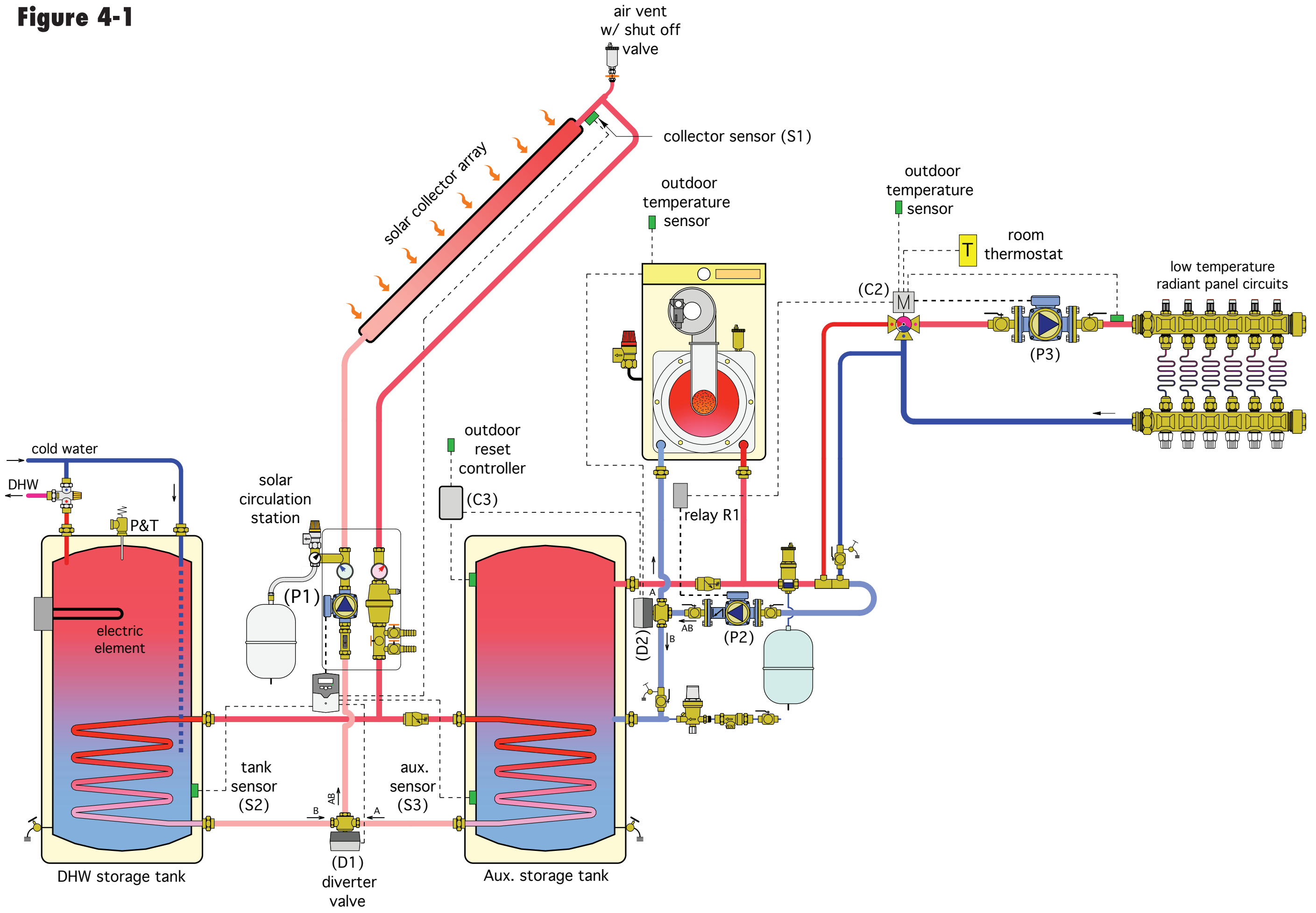
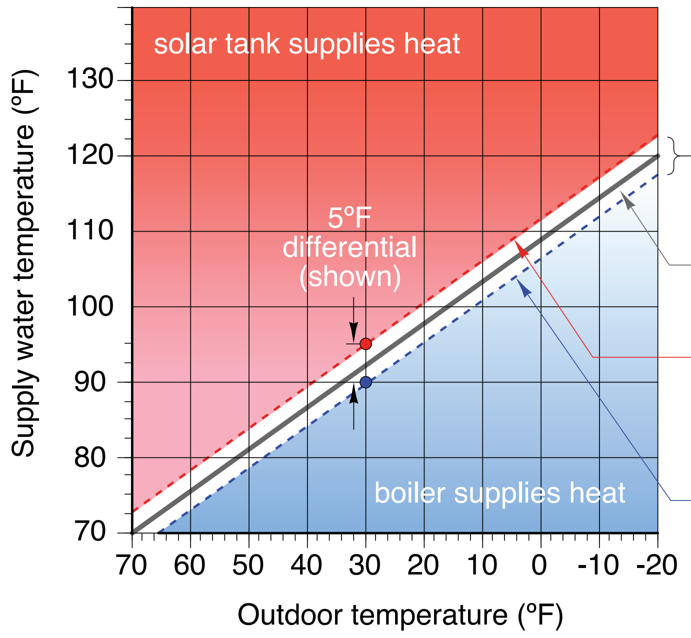


Figure 4-2



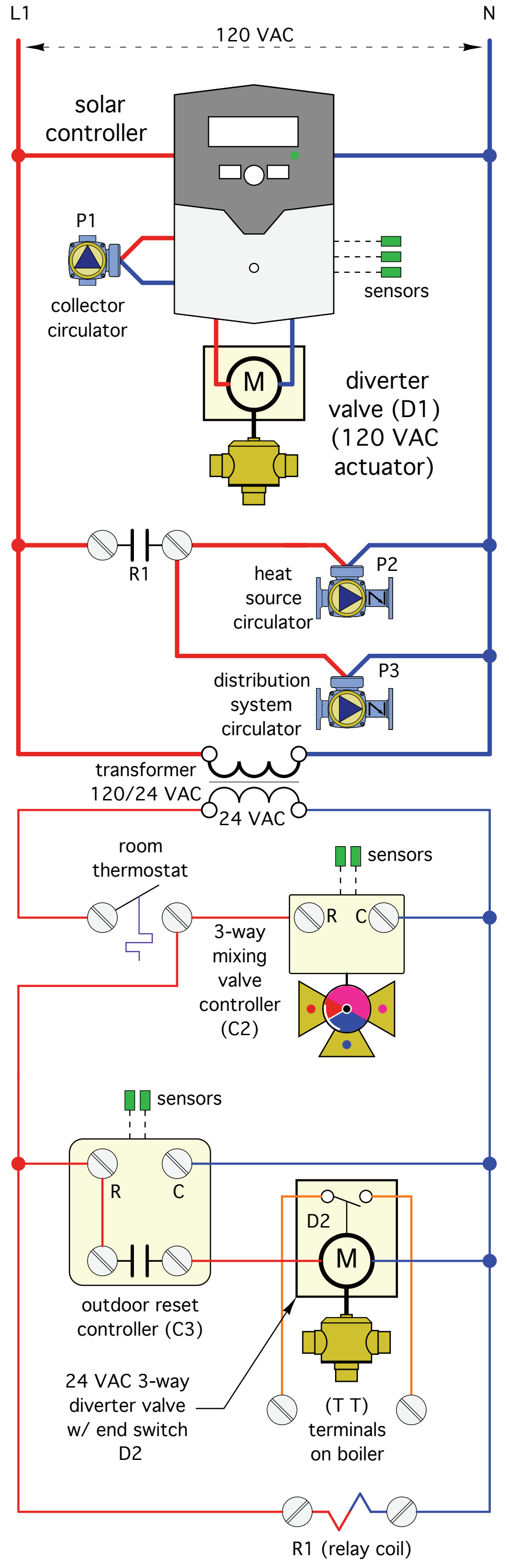
boiler supplies heat when temperature is climbing. Solar storage supplies heat when temperature is dropping

calculated target temperature

contacts on reset controller open to allow solar tank to serve as heat source

contacts on reset controller close to enable boiler as heat source

Figure 4-3



The temperature the auxiliary storage tank reaches depends on the load and solar availability. During a sustained sunny period, it is possible for the auxiliary tank to reach a temperature well above that needed by the space heating distribution system.

In this system, a call for space heating comes from a thermostat, which switches 24 VAC power to the 3-way motorized mixing valve, allowing it to begin operation. 24 VAC power also powers up the coil of relay (R1), which switches line voltage to operate circulators (P2) and (P3). 24 VAC power also energizes the outdoor reset controller (C3), which calculates the required supply water temperature for the space heating based on its settings and the outdoor temperature. An example of the logic used by the outdoor reset controller is shown in figure 4-2.

The sloping gray line represents the "target" temperature, which is the ideal supply water temperature (read from the vertical axis) for a corresponding outdoor temperature (read from the horizontal axis). The slope of the gray line can be adjusted by changing the settings on the controller. The dashed blue line below the gray line indicates the temperature at the supply sensor at which the output contacts on the outdoor reset controller close. The dashed red line above the gray line indicates the temperature at the supply sensor where these contacts open.

If, for example, the outdoor temperature is 30ºF, the calculated target temperature shown in figure 4-2 is 92.5ºF. The lower dashed line indicates the output contacts close if the temperature at the supply sensor is 90ºF or less. The upper dashed line indicates these contacts open if the temperature at the supply sensor is 95ºF or more.

The controller's supply sensor measures the temperature near the top of the auxiliary storage tank. Thus, with these settings, if the outdoor temperature is 30ºF, and the temperature near the top of the auxiliary storage tank is 90ºF or less, the controller determines that the auxiliary storage tank is too cool to supply the space heating distribution system. It closes its output contacts to power on the diverter valve (D2), allowing it to change position so flow passes through the boiler. When the diverter valve completes its rotation, an end switch in its actuator closes to fire the boiler.

When there is a call for space heating, and the temperature at the top of the auxiliary tank is 95ºF or higher, the outdoor reset controller allows the auxiliary storage tank to serve as the heat source for the distribution system.

If the storage tank is serving as the heat source, it continues to do so until the tank sensor temperature drops to 90ºF, at which point the system automatically switches to the boiler as the heat source. If the boiler is serving as the heat source, it continues to do so until the tank temperature climbs above 95ºF, at which point the auxiliary tank becomes the heat source.

Keep in mind that these temperatures change based on the current outdoor temperature. The slope of the reset line and the differential of the outdoor reset controller can also be adjusted to suit the type of heat emitters and auxiliary heat source used in the system.

This simple logic for switching between heat sources allows the solar storage tank to be utilized to the lowest possible temperature that can still satisfy the space heating load. This improves collector efficiency, and increases total solar energy collection over the heating season.

A wiring schematic for this system using the control method described above is shown in figure 4-3.

ANTIFREEZE-BASED COMBISYSTEM #2:

Some combisystems are designed around a single storage tank. The energy in this tank supplies both domestic hot water and space heating. One example of such a system is shown in figure 4-4.

Solar energy is added to this tank through the lower heat exchanger coil. In smaller combisystems, a solar circulation station (as shown) could likely handle flow through the collector array.

The storage tank contains potable water. The upper heat exchanger coil is used to extract heat from this water for use by the space heating system. It is also used to *add* heat produced by the boiler to the water at the top of the tank. The latter mode ensures that domestic hot water is always available at a suitable supply temperature regardless of solar energy input.

Figure 4-4

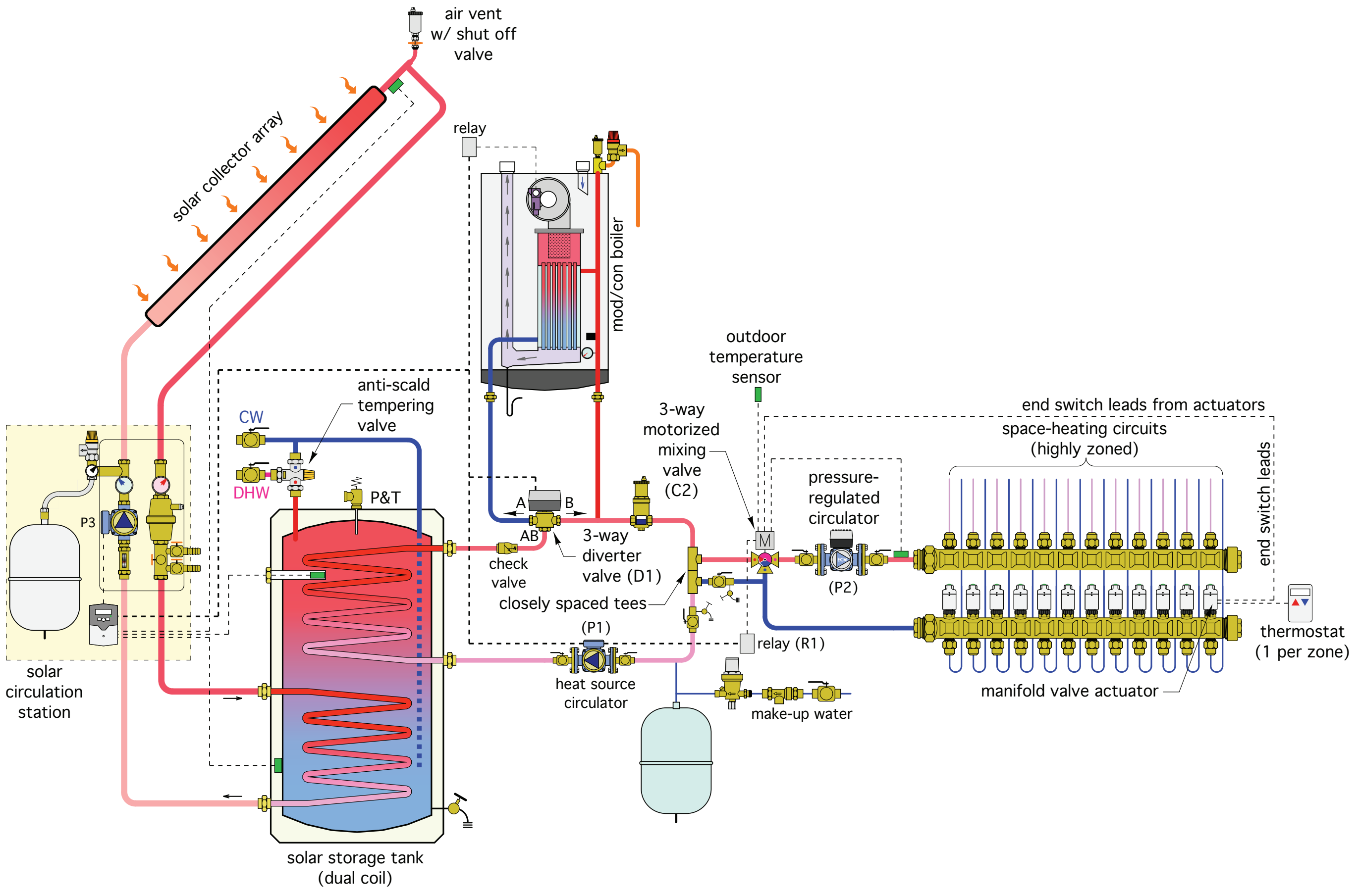
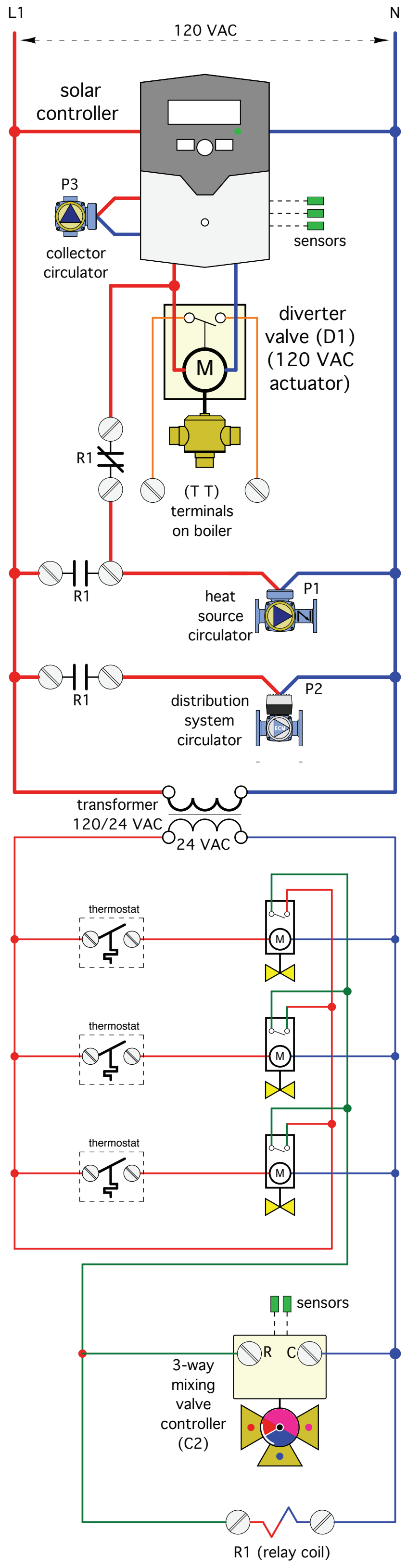


Figure 4-5



Temperature stratification helps keep this heat at the top of the tank. The bottom of the tank remains as cool as possible to maximize collector efficiency. The spring-loaded check valve at the upper outlet of the tank reduces heat migration through the attached piping. Its function is especially important in warm weather when no space heating is required.

A wiring diagram for this system is shown in figure 4-5.

In this system, the solar controller determines when the top of the tank requires heating, and if so, turns on the boiler, the heat source circulator (P1) and powers up the 3-way diverter valve (D1) so flow passes through the boiler and eventually the upper tank coil. In systems where the solar controller does not provide this logic, it can be created using standard hydronic control hardware as described for the previous system.

A call for heating is initiated by any zone thermostat, which powers up one of the manifold valve actuators. When the associated manifold valve is fully open, an end switch within the actuator closes. This provides 24 VAC power to operate the 3-way motorized mixing valve (C2), which then regulates supply temperature to the distribution system based on outdoor temperature. Relay (R1) is also energized to turn on the heat source circulator (P1), and the distribution circulator (P2).

If the boiler is NOT operating, there is no power to the 3-way diverter valve (D1). Flow passes from the tank's upper coil into the "AB" port of the diverter valve, and then out through the valve's "B" port. It moves on through the air separator to a pair of closely spaced tees. The latter provide hydraulic separation between circulators (P1) and (P2). Hot water passes from the side port of the upper tee to the hot port of the motorized mixing valve as required to achieve the necessary supply temperature. The distribution system could supply any of the lower temperature heat emitters discussed earlier, and it could be extensively zoned. In the latter case, a variable-speed pressure-regulated circulator (P2) provides differential pressure control in response to operation of the zone valves. A normally closed contact on relay (R1) is now open to prevent line voltage from energizing the diverter valve (D1).

When the temperature in the upper portion of the storage tank drops to a lower limit, (based on the system's ability to supply adequate domestic hot water), the diverter valve (D1) is powered on by the solar controller. Flow now passes from this valve's "AB" port out through its "A" port and onward through the boiler. When the diverter valve (D1) reaches the end of its travel, an end switch within the valve's actuator closes to fire the boiler.

If the space heating distribution system is also operating while the boiler is firing, some of the boiler's heat output is used for space heating. Any remaining heat output is transferred to the upper portion of the storage tank by the upper heat exchanger coil. If the space heating distribution system is not operating, line voltage from the solar controller passes through the normally closed relay contact (R1) to operate the heat source circulator (P1).

This configuration allows the thermal mass of the water in the upper portion of the tank to buffer the space heating load, and thus helps prevent boiler short cycling. This is especially beneficial when the distribution system is extensively zoned.

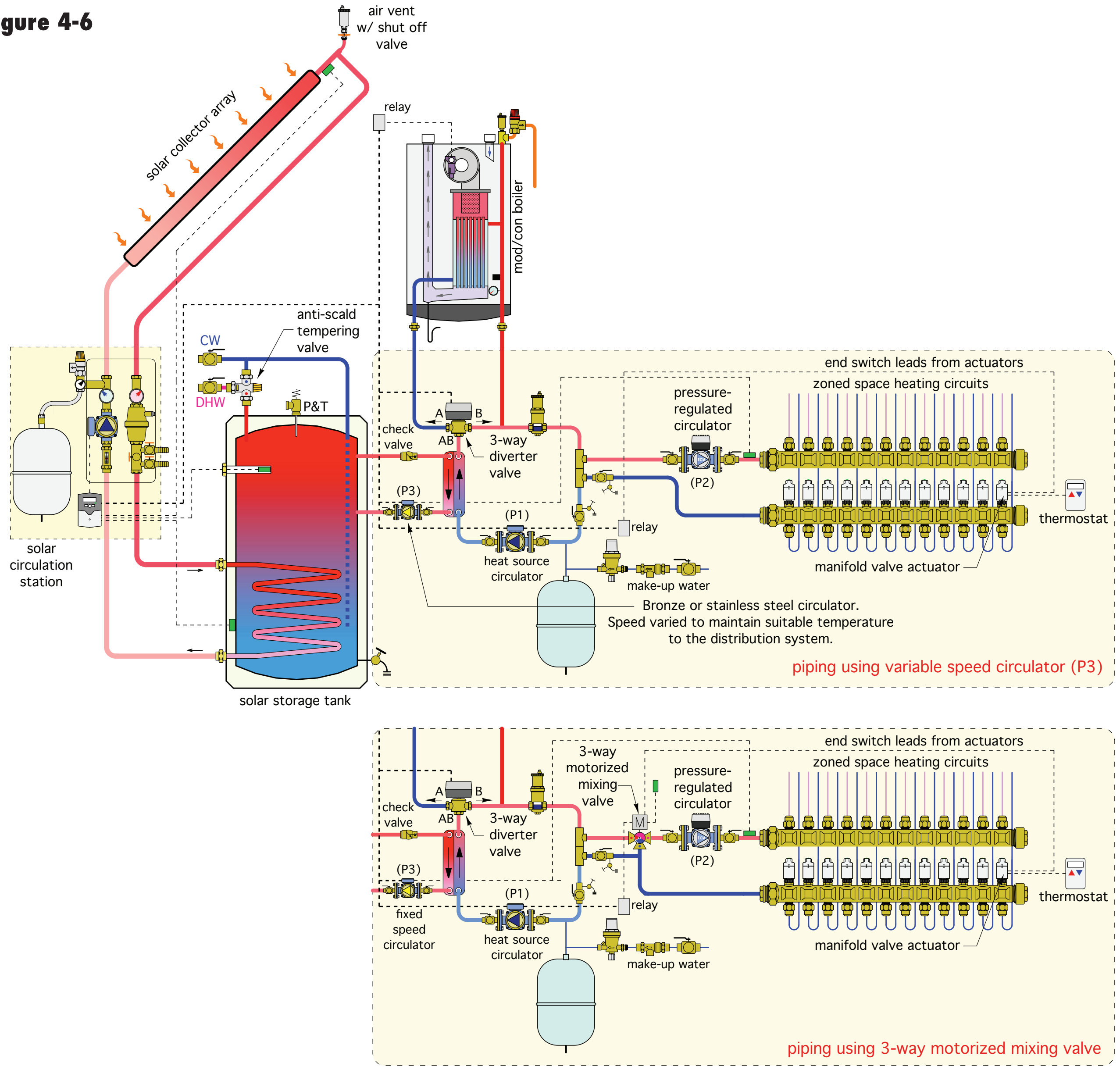
ANTIFREEZE-BASED COMBISYSTEM #3:

The functionality of antifreeze-based system #2 can also be achieved using slightly different hardware. Figure 4-6 shows a very similar solar subsystem to that used in figure 4-4. The difference is an external stainless steel brazed plate heat exchanger rather than an upper coil in the storage tank.

Domestic hot water from the storage tank flows through the external heat exchanger based on the operation of a small bronze or stainless steel circulator (P3). This pump can be configured for either constant-speed or variable-speed operation. Figure 4-6 shows two different piping arrangements based on how circulator (P3) is controlled.

If the speed of circulator (P3) is varied (as shown in the upper portion of figure 4-6), it can meter domestic hot water through the external heat exchanger such that the water temperature supplied to the space heating distribution system also varies. The higher the speed of circulator (P3), the faster heat transfers across the heat exchanger and the warmer the distribution system becomes.

Figure 4-6



The speed of circulator (P3) could be varied based on maintaining a fixed supply temperature to the distribution system. It could also be varied based on outdoor reset logic.

The ability to control the speed of circulator (P3) also prevents what could be very hot water in the solar storage tank from flowing directly to a low-temperature distribution. As such, it eliminates the need for a motorized mixing valve in most applications. However, if the distribution system operates at very low water temperatures relative to the minimum temperature maintained in the top of the storage tank (for delivery of domestic hot water), the space heating distribution circulator (P2) should be temporarily turned off while the boiler is heating the top of the storage tank. Circulator (P3) should also operate at full speed during this mode to maximize heat transfer across the heat exchanger. When the top of the storage tank has reached the preset water temperature, variable-speed operation of circulator (P3) can resume.

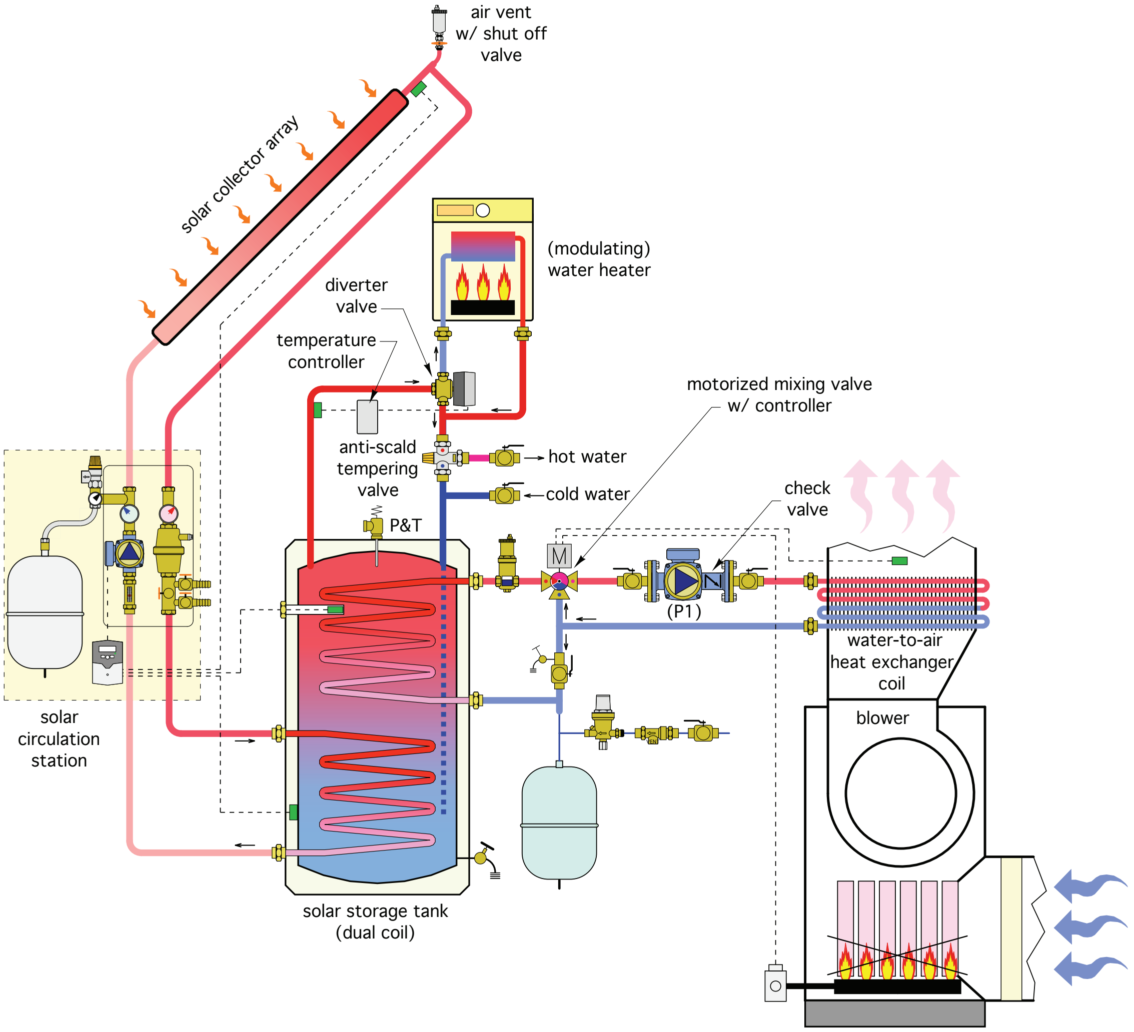
If circulator (P3) is operated in an on/off manner, a mixing valve is required in the distribution system. Circulator (P3) would turn on whenever the boiler is operating as well as when there is a call for space heating.

One advantage of either of these approaches is that the external heat exchanger is serviceable or replaceable if ever necessary. Another advantage is that the thermal mass of the water in the storage tank will buffer a highly zoned space heating distribution system, and thus reduce the potential for boiler short cycling.

ANTIFREEZE-BASED COMBISYSTEM #4:

There are many homes and commercial buildings with forced-air distribution systems for heating. It is possible to build a solar combisystem using hydronic hardware to collect and convey solar energy, and then pass this energy to a forced-air distribution system. One approach is shown in figure 4-7.

Figure 4-7



The solar collection subsystem is essentially the same as in previous systems.

The storage tank contains domestic water and absorbs solar-derived heat through the lower coil.

If the domestic water leaving the tank needs a further temperature boost, it is routed through the modulating instantaneous water heater via a 3-way diverter valve, which is operated by a setpoint temperature controller. If this controller determines that domestic water leaving the tank does not need further heating, the diverter valve routes flow directly to the hot port of an anti-scald tempering valve. This configuration eliminates the heat loss associated with passing heated water through the unfired water heater.

Any instantaneous water heater used in this type of system must modulate its firing rate to adjust for preheated incoming water. Verify that any instantaneous water heater being considered for such an application is warranted for use with solar combisystems that supply preheated domestic water.

Upon a call for space heating, a controller determines if the temperature at the top of the storage tank is sufficient to supply the water-to-air heat exchanger coil mounted in the supply plenum of the forced-air distribution system. This decision can be based on outdoor reset control. However, designers are cautioned that low-temperature supply air must be carefully introduced into heated spaces to avoid drafts. This may require a lower temperature limit on the reset controller.

A motorized mixing valve monitors the temperature of the supply air downstream of the plenum coil. The mixing valve adjusts itself as required to prevent potentially high-temperature water in the storage tank from creating overly hot supply air to the building.

If the tank's temperature is too low to properly supply the plenum coil, the furnace's burner (or the compressor in a forced-air heat pump system), would operate as normal. The space heating circulator (P1) would be off. A check valve in this circulator, or mounted as a separate component, prevents heat in the plenum from migrating backward into the hydronic system.

ANTIFREEZE-BASED COMBISYSTEM #5:

Another possible system configuration uses a storage tank with an integral gas-fired heat source, as shown in figure 4-8. This eliminates the boiler as a separate component. It also eliminates the diverter valve and the piping associated with connecting the boiler and diverter valve to the system.

As with the other antifreeze-based systems, solar energy is added to the storage tank through the lower heat exchanger coil.

The modulating/condensing burner and heat exchanger assembly operate as necessary to maintain the top of the storage tank at an adequate temperature to supply domestic hot water whenever required (not necessarily 24/7). At other times, such as night setback periods, the temperature at the top of the storage tank may be allowed to drop based on outdoor reset control logic.

The position of the burner/heat exchanger assembly within the tank encourages temperature stratification and minimizes heating of the lower portion of the tank to minimize losses in collector efficiency.

The water in the storage tank is not potable water. It's the same water that circulates through the panel radiators during space heating. This allows the tank to be constructed of standard steel (rather than stainless steel or standard steel with glass lining to hold potable water).

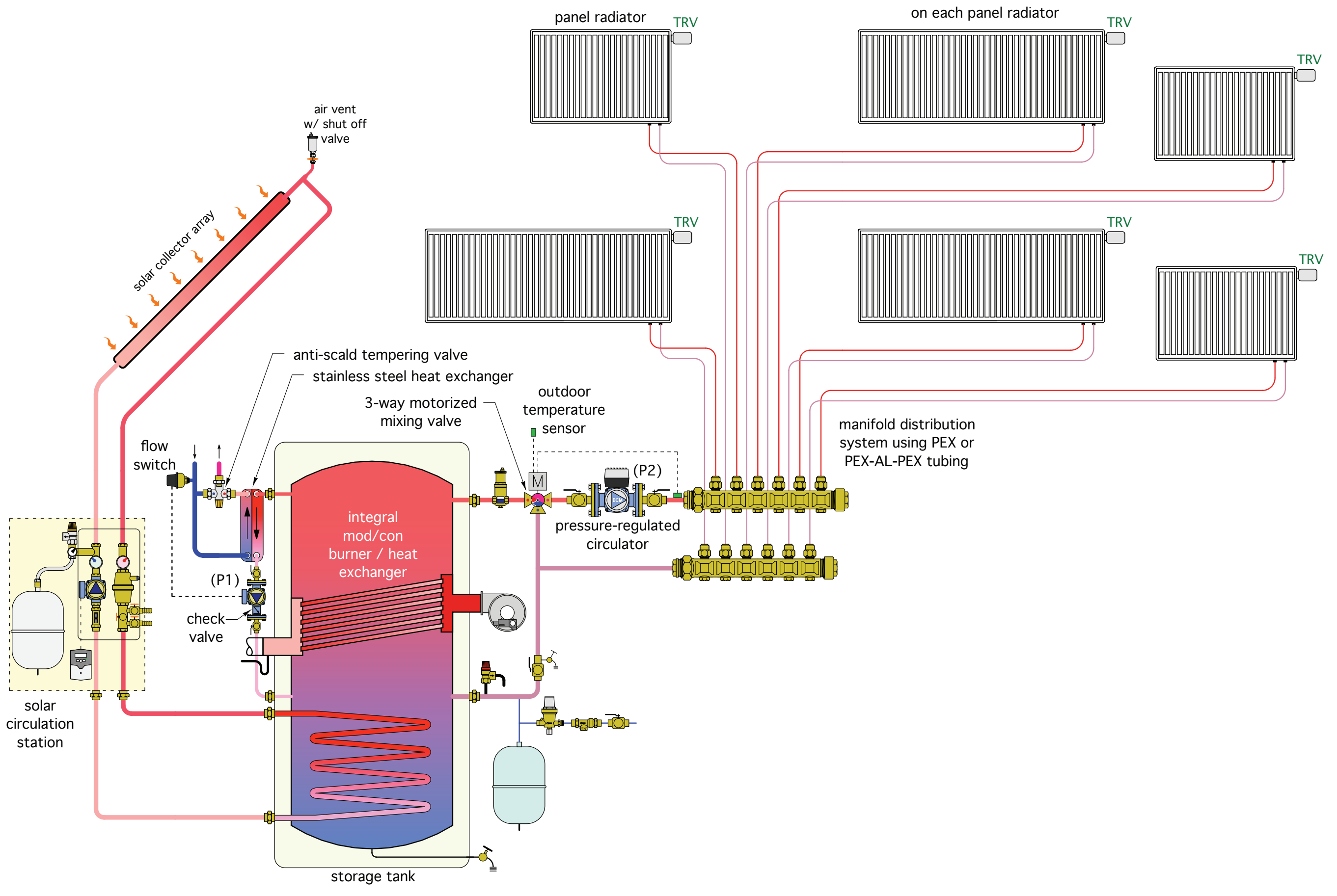
Domestic water is instantaneously heated as it is drawn through the system. A flow switch closes it contacts whenever cold domestic water is drawn into the external brazed plated heat exchanger. These contacts turn on a small circulator (P1), which creates flow through the tank side of this heat exchanger.

Brazed plate heat exchangers have very small volume and low thermal mass relative to their heat transfer surface area. They can begin heating potable water in one or two seconds after flow is initiated. An anti-scald mixing valve protects against high water temperatures being sent to the fixtures. As soon as hot water flow stops, so does circulator (P1).

Very little domestic hot water is held in the heat exchanger. This reduces the potential for legionella. The heat exchanger can also be removed and serviced if ever necessary.

The heated water at the top of the tank provides thermal mass for a stable supply of heat to the heat exchanger.

Figure 4-8



As the tank's temperature begins to drop, the burner fires to maintain a suitable temperature at the top of the tank for sustained domestic hot water delivery.

The thermal mass at the top of the tank also stabilizes a highly zoned space heating distribution system. In figure 4-8, this distribution system consists of a manifold station supplying individually controlled panel radiators. Each radiator has its own thermostatic valve to control heat output. This allows for room-by-room zone control. A variable-speed, pressure-regulated circulator (P2) automatically varies its speed in response to radiator valve modulation.

USING A POOL AS A HEAT DUMP:

The system shown in figure 4-9 is an extension of antifreeze-based system #2, and includes a provision to dump excess heat from the storage tank to a swimming pool.

The extremely large thermal mass represented by the pool can accept a significant amount of heat while only raising a few degrees Fahrenheit in temperature.

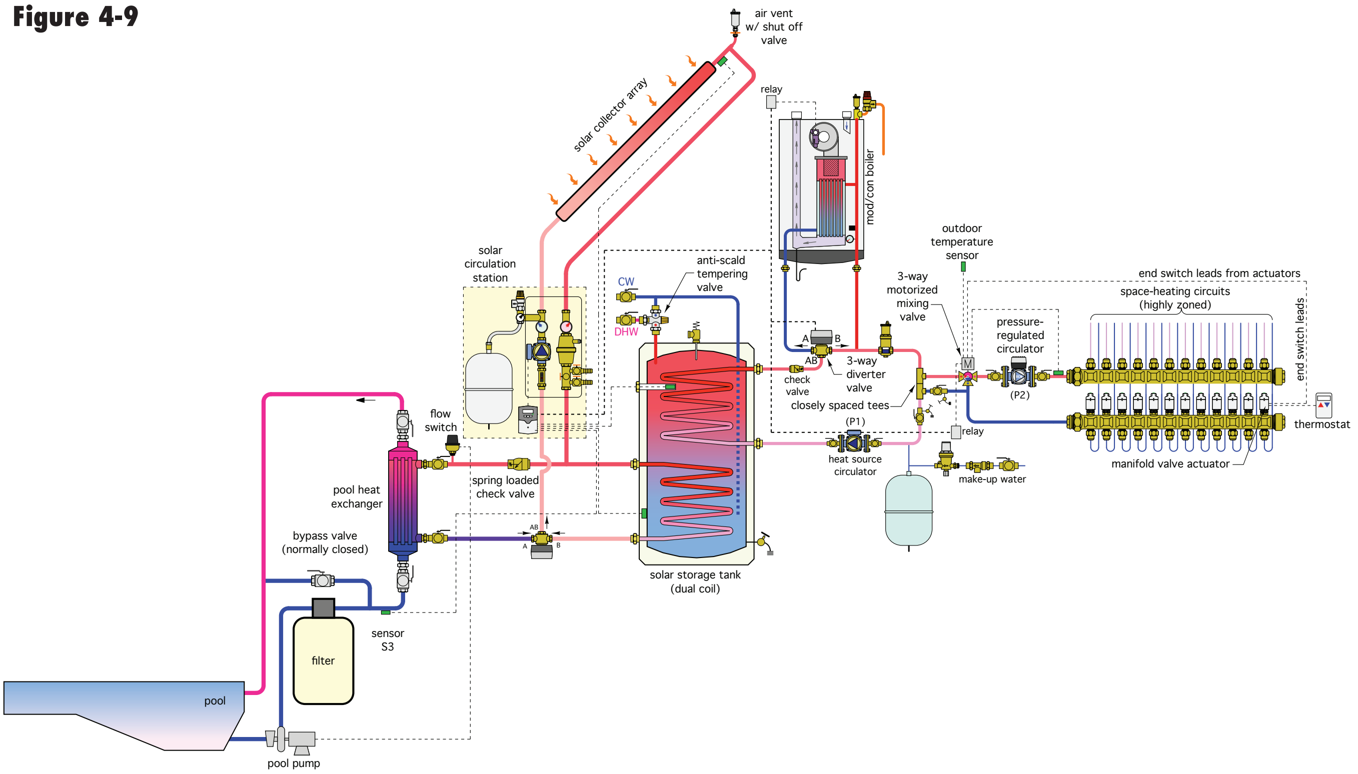
This system would treat domestic water as its priority load, routing solar-derived heat to the tank whenever possible. The space heating portion of the system would operate as described for antifreeze-based system #2.

If the temperature at the top of the storage tank reached a user-selected maximum limit, the heat dump subsystem would come into operation. In this system, the following sequence takes place: 1) The diverter valve routes the hot antifreeze solution returning from the collectors to the pool heat exchanger. 2) The flow switch detects this flow and turns on the pool filter pump (if it is not already operating). 3) Heat is now transferred to the pool.

Since the space heating portion of this system is unlikely to operate during warm weather, a significant percentage of the collected solar energy will likely be routed to the pool.

For outdoor pools not used in winter, designers must provide a means of disabling the pool heating mode, and direct any excess energy to an alternative heat dump.

Figure 4-9



5. DRAINBACK SOLAR COMBISYSTEMS

Drainback systems are the most common alternative to antifreeze-based solar thermal systems. There are many ways to configure drainback combisystems, depending on the heating distribution system used, the percentage of the load to be supplied by solar energy and the type of auxiliary heat source used.

Whenever they are not operating, drainback systems allow water from the collector array and piping outside heated space to drain back to a tank located within heated space. This action requires only gravity and properly sloping piping components. It does not rely on devices such as solenoid valves or vacuum breakers, and as such is highly reliable.

This section discusses several systems that show a wide variety of concepts. The systems are assumed to be for residential applications. However, most can bescaled up for commercial installations.

ADVANTAGES OF DRAINBACK SYSTEMS:

Perhaps the most apparent advantage of a drainback system is the elimination of antifreeze fluids. This, in turn, implies several other benefits, including:

- Antifreeze solutions require a heat exchanger between the collector subsystem and the water in the remainder of the system. Beside the fact that heat exchangers can add significant cost to the system, they also induce a performance penalty. All heat exchangers require a temperature differential to drive heat from their "hot" side to their "cool" side. In solar collection subsystems, the temperature differential shows up as an increase in collector inlet temperature relative to the water temperature near the bottom of the storage tank. This decreases collector efficiency. The magnitude of this performance penalty depends on the size of the heat exchanger. Larger, more expensive heat exchangers reduce the penalty, but never completely eliminate it. Appendix B gives information for estimating the thermal performance penalty associated with a heat exchanger between the collector array and storage tank.

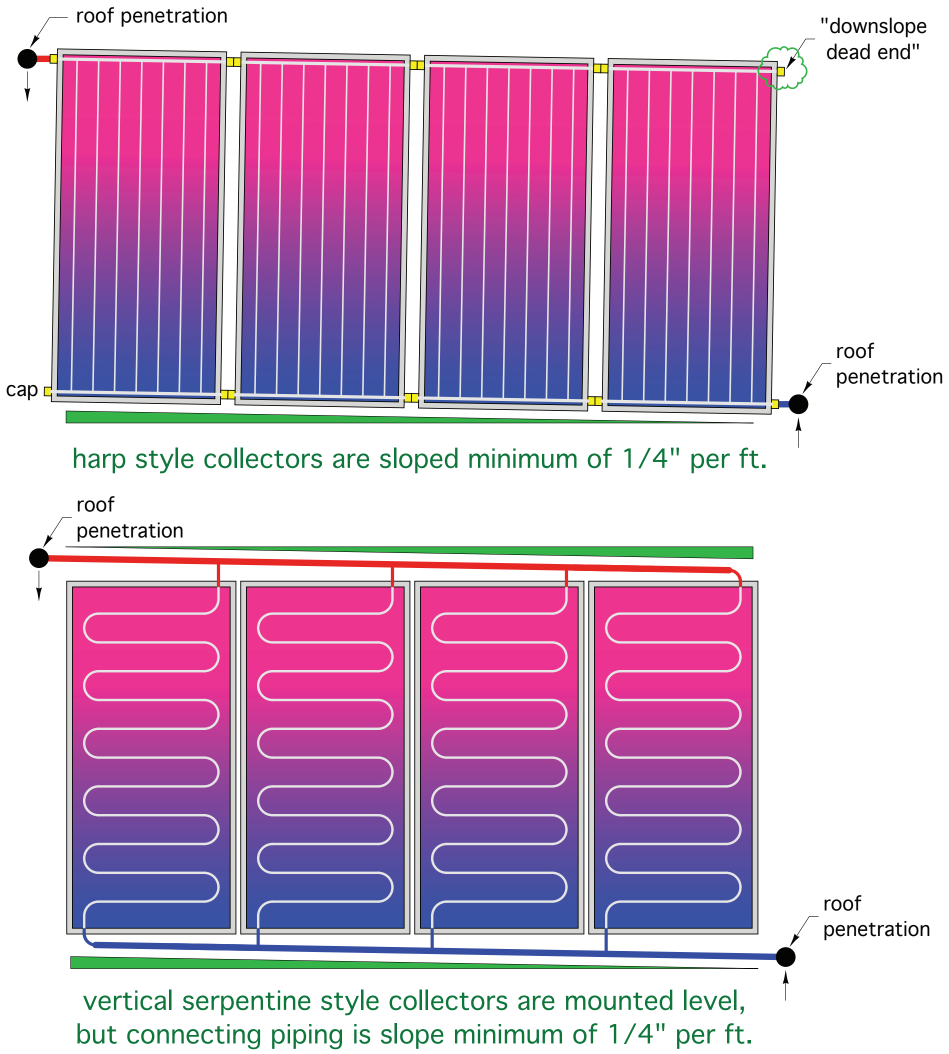
- Eliminating antifreeze also eliminates the annual fluid testing, and thus reduces system owning cost.

- The collectors in a drainback combisystem do not contain fluid when they stagnate. A power outage, control failure or other condition that stops the collector loop circulator results in the water draining back from the collectors and exposed piping. This minimizes internal stresses on the collector relative to systems in which the fluid remains in the collector or flashes to vapor during stagnation.

- Because the collectors in a drainback system "dry stagnate," there is no need for a heat dump provision. This is especially relevant to combisystems, which often have larger collector arrays compared to DHW-only systems, and thus have increased potential for warm weather stagnation due to the storage tank reaching a maximum temperature setting.

- Many drainback systems eliminate the need for an expansion tank in the system. The air volume that accommodates drainback water, if properly sized, can serve as the expansion tank for the system.

Figure 5-1



DISADVANTAGES OF DRAINBACK SYSTEMS:

- All piping to and from the collector array, and in some cases the collectors themselves, must be sloped to ensure proper drainage. A minimum pitch of 1/4-inch vertical drop per foot of horizontal run is recommended. The absorber plates used in some collectors ensure that they will drain completely. Other collector designs may require that the entire collector array be sloped to ensure complete drainage (see figure 5-1). Verify that any collectors being considered for a drainback system are approved and warranted for this application.

It's also possible to slope half the collectors in one direction and half in the other as shown in figure 5-2. In this case, the supply piping penetrates the roof at the midpoint between the two banks of collectors. Return piping penetrates the roof at the upper outside corners of each bank and is joined together under the roof deck.

There can be no low points in any piping connecting the collector array with the storage tank. Any low points can interfere with air reentering the collectors, or create a "trap" that could eventually freeze and burst the pipe.

Designers should also ensure that any "downslope dead ends" (see figure 5-1) are detailed so that water will not puddle across the diameter of the piping. In general, such dead ends should be kept as short as possible.

Collectors with an integral sensor well are preferred for drainback applications. This detail allows the sensor to closely track absorber plate temperature without relying on convection of fluid within the collector. Strapping a sensor to outlet piping, as is commonly done with systems using antifreeze solutions, will delay the control response. Figure 5-3 shows an example of an absorber plate with integrated sensor well.

Figure 5-2

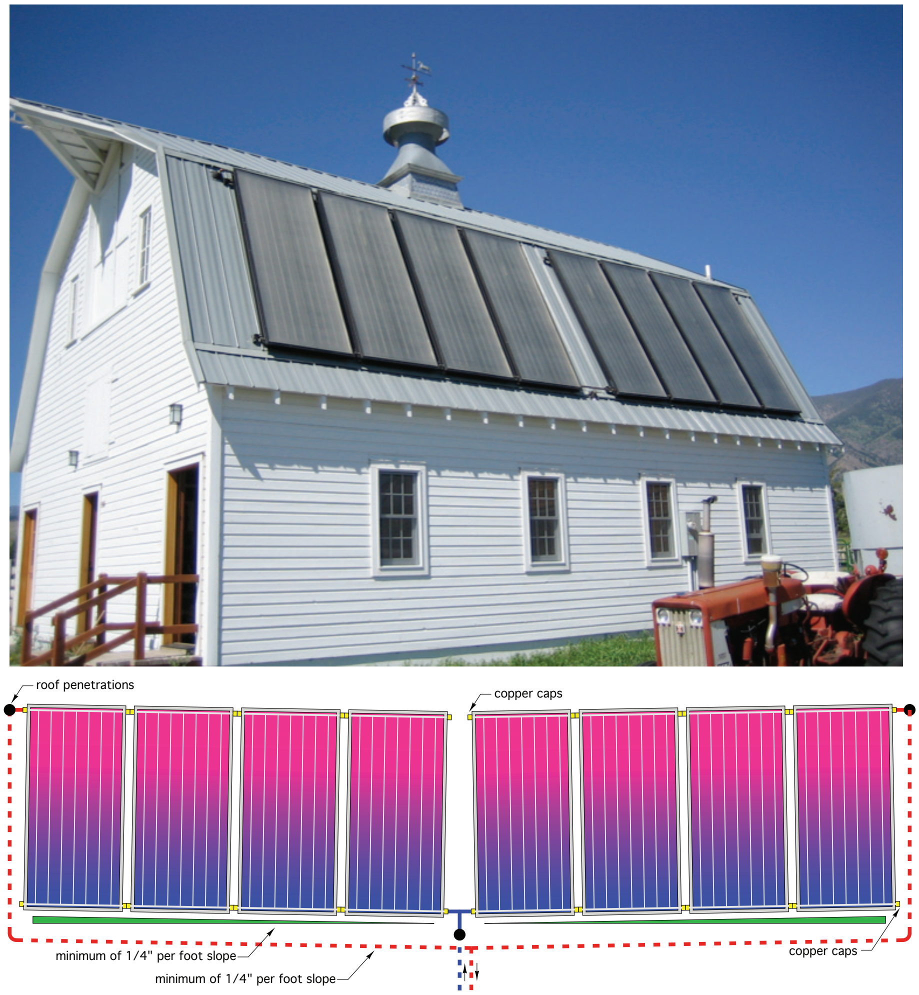
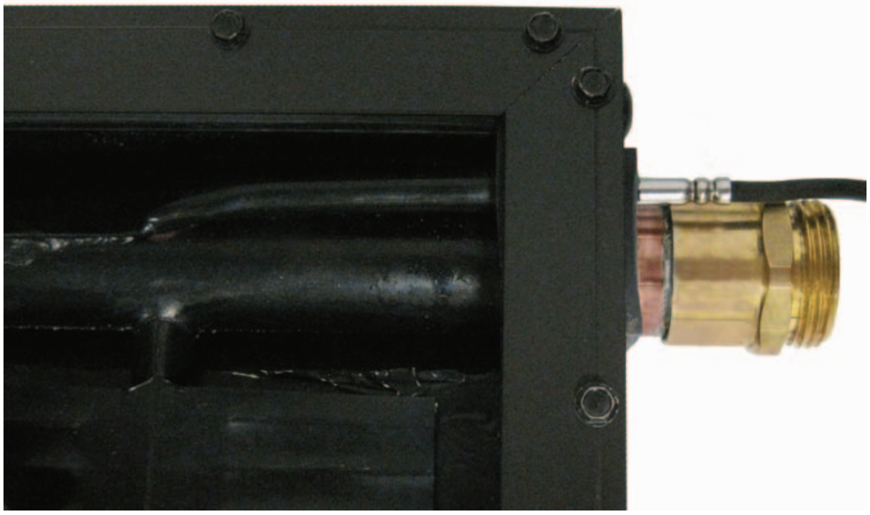


photo courtesy of Radiant Engineering

Figure 5-3



OPEN-LOOP VS. CLOSED-LOOP DRAINBACK SYSTEMS:

As is true with hydronic heating, drainback systems can be designed as either “open-loop” or “closed-loop” systems, as shown in figure 5-4.

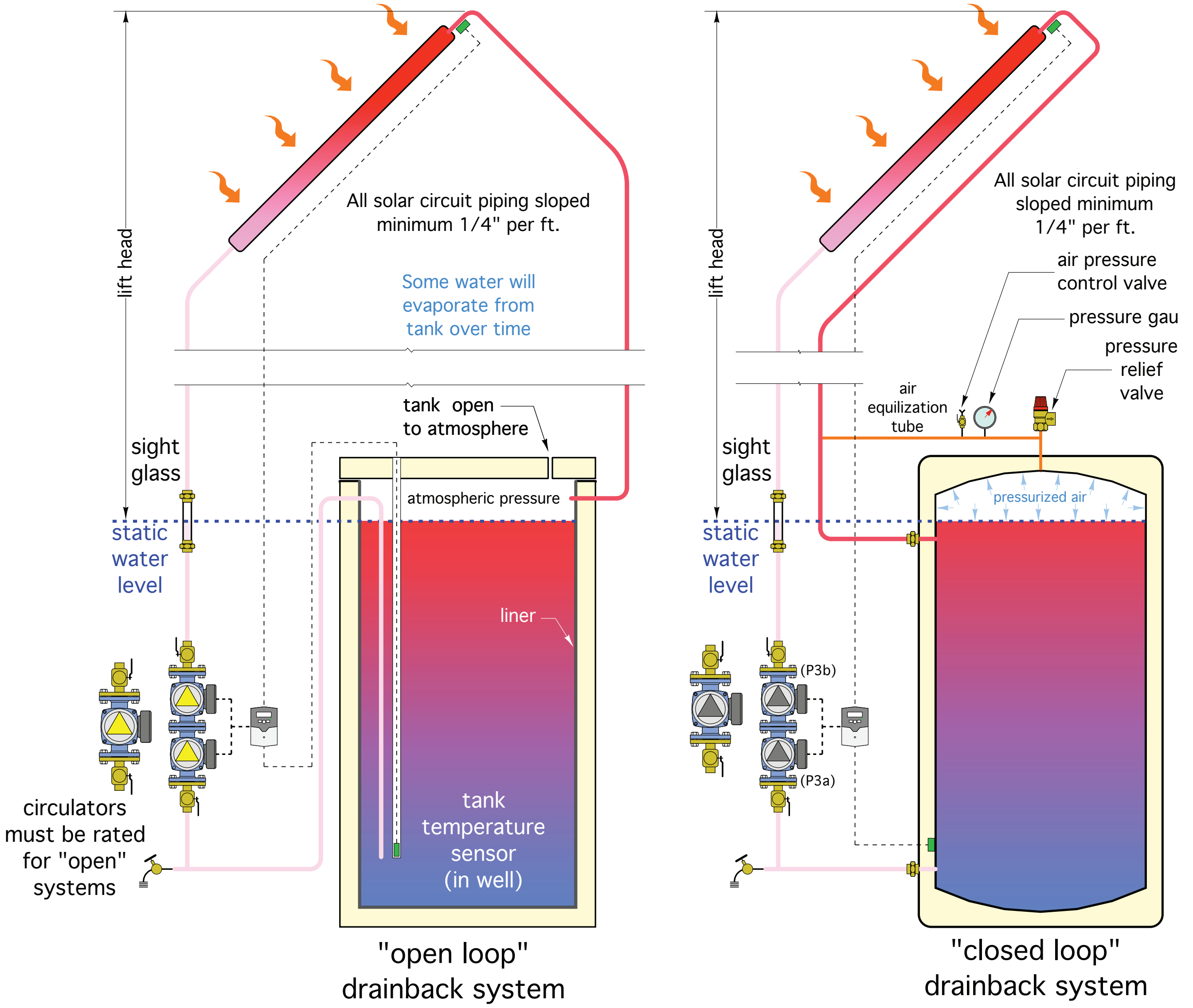
Open-loop drainback systems use a non-pressurized storage tank. The air above the water is always at atmospheric pressure.

Non-pressure rated tanks are usually less expensive per gallon of storage than pressure-rated tanks. They can often be assembled on site. Some use an insulated structural “shell” to support a flexible EPDM rubber liner that contains the water. Others are constructed of molded polypropylene. All piping connections to such tanks usually penetrate the tank wall above the water line to minimize any chance of leakage.

Because the water in an open-loop system is in direct contact with the atmosphere, it will always contain dissolved oxygen molecules. All piping components must therefore be suitable for contact with this “oxygenated” water. Circulators must be of stainless steel, bronze or polymer construction. All piping, fittings and valves must also be corrosion-resistant. Copper piping along with copper or brass fittings and valves are common. Stainless steel and high-temperature composite or polymer materials are also a possibility, provided they are rated to withstand the potentially high temperatures within the solar collector circuit.

Open-loop systems will experience some water loss due to evaporation. The water level in the tank should be checked monthly using the sight glass or dip stick. Water can be easily added to the system through the hose bib valve at the bottom of the collector supply piping.

Figure 5-4

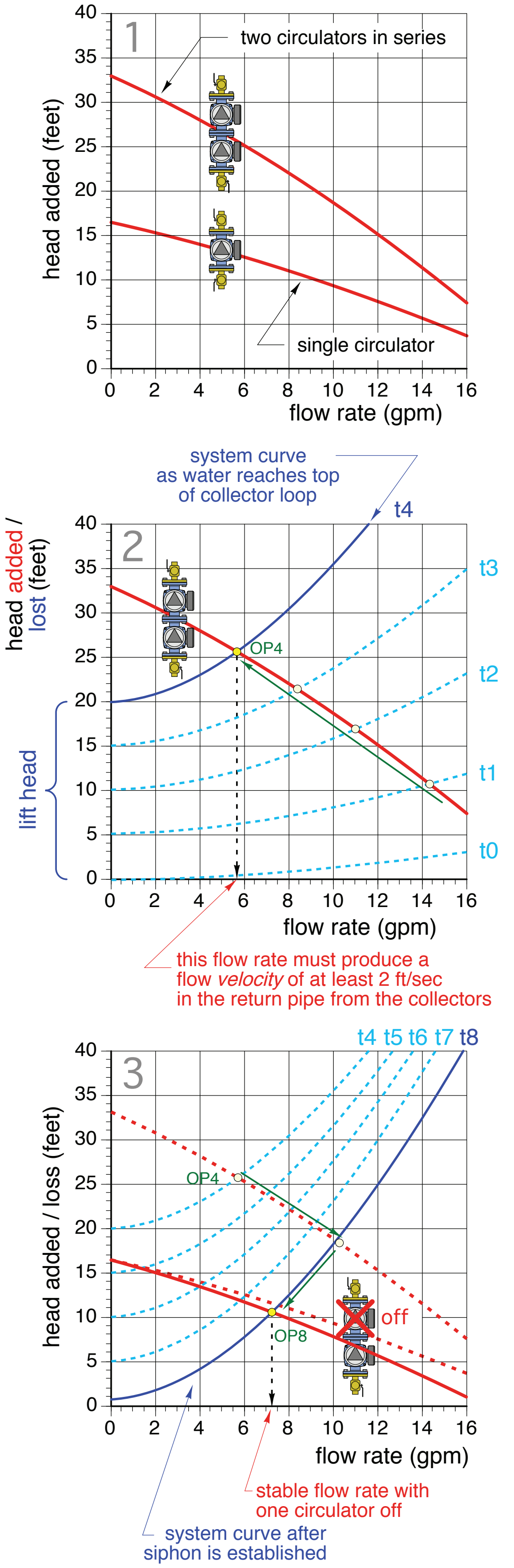


Most of the drainback combisystems to be presented in this section are closed-loop systems. The water and air they contain is, for all practical purposes, sealed into the system. Like other closed-loop hydronic systems, they can use cast iron circulators and contain steel components. The dissolved oxygen in the initial water and air volume will react with any ferrous metal in the system, forming a very light and essentially insignificant oxide film. At that point, the water is neutralized and will not continue to oxidize metals.

Closed-loop systems can also experience very minor water losses over a period of time due to weepage at valve packing or circulator flange gaskets. Some of the dissolved air in the cold water used to fill the system will also be removed and vented over time. These effects will cause a minor drop in the system's static water level over time. Small amounts of water can be manually added to the system through the lower hose bib valve to correct for these losses.

An automatic make-up water assembly should NEVER be connected to this type of system. Doing so, especially in systems with high-performance air separating/venting devices, will eventually replace the air in the system with water. Over time this will eliminate the necessary air space for proper drainage and could eventually lead to freezing of water-filled piping or collectors exposed to outdoor temperatures.

Figure 5-5



OPERATION OF A DRAINBACK SYSTEM:

The solar heat collection cycle in a drainback system is controlled the same way as that in an antifreeze-based system. When the collector sensor reaches a temperature a few degrees above that of the tank sensor, the circulator(s) are turned on.

A drainback system might contain two circulators in series, or a single "high head" circulator. In either case, the circulator(s) push water up through the piping and collector array. Air is pushed ahead of this water and eventually back to the space at the top of the storage tank. The water level within the tank drops slightly during this process. There is no need of either a high-point air vent (as required in an antifreeze-based system) or a vacuum breaker at the top of the collector circuit.

With proper pipe sizing, the flow velocity in the piping returning from the collector array allows air bubbles to be entrained with the water and returned to the top of the storage tank. As this occurs, a siphon is formed within the return piping. This siphon eventually cancels out most of the initial "lift head" associated with filling the collector array.

Once the siphon is established, it is usually possible to turn off the upper of two series-connected circulators, or reduce the speed of a single high-head circulator, and still maintain adequate flow through the collector array.

The sequence of operation of a "dual-pumped" drainback system using two series-connected fixed-speed circulators is depicted in figure 5-5.

The upper graph shows the effective pump curve of two identical fixed-speed circulators connected in series. It is constructed by doubling the head of the single circulator at each flow rate.

Both circulators are turned on each time the solar energy collection process begins. During the first few seconds of operation, water is lifted upward through the collector supply piping. This causes the system curve to migrate upward along the graph as depicted by the light blue dashed lines labeled t1, t2 and t3 in the upper graph. Notice that these curves steepen as they rise. This is due to the frictional resistance of water flowing through more piping and the collector array as flow approaches the top of the collector circuit.

The dark blue system curve labeled t4 represents the situation as water "rounds the turn" at the top of the collector circuit. The intersection of this system curve and the pump curve for two circulators in series establishes the instantaneous operating point marked as OP4. The flow rate associated with this operating point can be read from the horizontal axis directly below this point. For the example shown in figure 5-5, this flow rate is about 5.7 gallons per minute.

To establish a siphon, the flow rate at operating point OP4 must produce a corresponding flow velocity within the return piping of 2 feet per second or higher. The flow rates necessary for a flow velocity of 2 feet per second in type M copper tubing are shown in figure 5-6.

Water at a flow velocity of 2 feet per second or higher can entrain air bubbles and drag them along. This action eventually rids the return piping of air, displacing it back to the top of the storage tank. At that point, a siphon is established in the return line. Think of the water going down the return pipe as helping "pull" water up the supply pipe. The formation of a siphon causes the system curve to shift downward, as depicted by the light blue curves t4, t5, t6, t7, and finally the dark blue curve t8. In a typical residential drainback system, this sequence may take 30 seconds to perhaps 3 minutes. Depending on the details at the top of the storage tank, the system's pressure and the height of the collector array, much of the initial "lift head" is now recovered by the downward "pull" of the siphon.

Figure 5-6

Tubing	Flow rate to establish 2 ft/sec flow velocity
1/2" type M copper	1.6 gpm
3/4" type M copper	3.2 gpm
1" type M copper	5.5 gpm
1.25" type M copper	8.2 gpm
1.5" type M copper	11.4 gpm
2" type M copper	19.8 gpm
2.5" type M copper	30.5 gpm
3" type M copper	43.6 gpm

When the upstream circulator is turned off, the operating point shifts to a final position marked as OP8. This point determines the flow rate the collector array operates at during the remainder of the solar collection cycle. Notice that the flow rate at the stable operating point OP8 is higher than the flow rate through the collectors when the water first passes over the top of the collector circuit with both circulators operating. For the example given, it is about 7.2 gallons per minute.

The solid red pump curve in graph 3 is shifted slightly below the pump curve for the single circulator. It represents the "net" effect of the lower circulator pumping through the volute of the upstream circulator, which is now off.

A similar solar collection cycle process occurs in systems that use a single speed-controlled high-head circulator. The circulator starts at full speed to quickly push water up through the collector array and establish the siphon. After some period of time, the circulator reduces its speed (based on user programmed settings). The intersection of the circulator's reduced speed pump curve and the system curves after the siphon has formed determines the stabilized flow rate through the collector array for the remainder of the cycle.

SIPHON LIMITATIONS:

Once a siphon is established within a drainback system, it's important to maintain it until no further solar energy collection is possible.

Modern controllers, which vary collector circulator speed in response to the difference between the collector temperature and storage tank temperature, have a minimum speed function intended to maintain the siphon under reduced speed operation. If the siphon does break, the collector temperature would rise rapidly (because there is no flow through it). The controller would detect this, and increase circulator speed to reestablish the siphon.

In addition to adequate flow velocity in the collector retun piping, siphon stability depends on a relationship between the water's temperature, its corresponding vapor pressure, and the vertical distance between the top of the collector circuit and the water level in the storage tank.

A conservative estimate for the maximum siphon height that can exist can be made using formula 5-1:

Formula 5-1

$$H_{max} = \left(\frac{144}{D}\right)\left(P_a + P_{top} - P_v\right)$$

Where:

Hmax = maximum siphon height

D = density of water at maximum anticipated temperature (lb/ft^3)

P_a = atmospheric pressure (psia)

P_{top} = extra pressurization (above atmospheric) at the top of the collector circuit (psi)

P_v = vapor pressure of water at maximum anticipated temperature (psia)

The vapor pressure and density of water needed for formula 5-1 can be calculated using the following formulas:

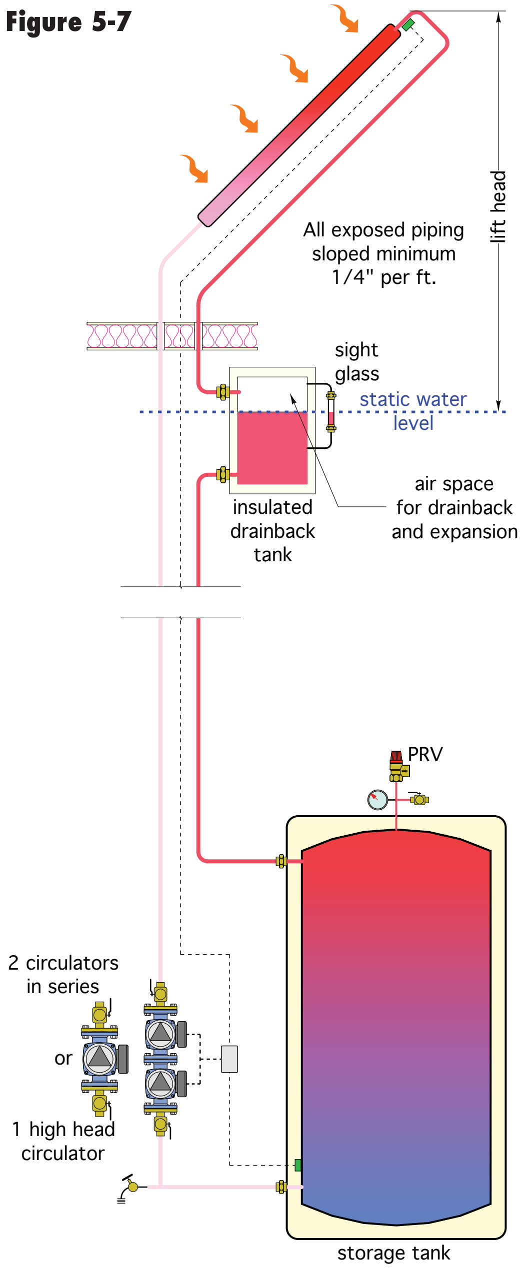
$$P_v = 0.771 - 0.0326 \times T + \left(5.75 \times 10^{-4}\right) \times T^2 - \left(3.9 \times 10^{-6}\right) \times T^3 + \left(1.59 \times 10^{-8}\right) \times T^4$$

$$D = 62.56 + \left(3.413 \times 10^{-4}\right)T - \left(6.255 \times 10^{-5}\right)T^2$$

Where:

P_V = vapor pressure of water (psia)
D = density of water (lb/ft^3)
T = temperature of water (°F)

Figure 5-7



For example: Determine the maximum siphon height based for water at 200°F in a system at sea level (where Pa = 14.7 psia), and where the pressure at the top of the collector circuit is 10 psi above atmospheric pressure.

Solution: The density and vapor pressure of water at 200°F is:

$$D = 62.56 + \left(3.413 \times 10^{-4}\right)200 - \left(6.255 \times 10^{-5}\right)200^2 = 60.1 lb / ft^3$$

$$P_v = 0.771 - 0.0326 \times 200 + \left(5.75 \times 10^{-4}\right) \times 200^2 - \left(3.9 \times 10^{-6}\right) \times 200^3 + \left(1.59 \times 10^{-8}\right) \times 200^4 = 11.49 psia$$

The maximum siphon height is then calculated:

$$H_{max} = \left(\frac{144}{D}\right)\left(P_a - P_v + P_{top}\right) = \left(\frac{144}{60.1}\right)\left(14.7 - 11.49 + 10\right) = 31.7 ft$$

If the system were installed with a greater vertical drop from the top of the collector circuit to the water level in the storage tank, the water in the return piping would flash to vapor (e.g., boil) and break the siphon.

The maximum siphon height decreases with increasing water temperature, because as temperature increases, the water comes closer to its vapor flash point.

The maximum siphon height can be increased by raising the pressure within a closed-loop drainback system. Increased pressure helps "suppress" water from boiling. This is a significant advantage of a closed-loop pressurized drainback system relative to an open-loop system where no pressurization is possible.

This analysis does not include the effect of frictional pressure drop in the return piping, or the potential effect of adding a flow-restricting device near the end of the return piping to increases pressure in that pipe and thus help suppress vapor flash.

If the height of the building is such that the collector circuit must be taller than the maximum siphon height, a separate drainback tank may be located high in the building to limit the lift head, as shown in figure 5-7.

The lift head is now from the static water level in the elevated drainback tank to the top of the collector circuit. The vertical height of the piping circuit below this water level does not affect lift head.

SIGHT GLASSES:

All drainback systems require a means of verifying the proper water level in the drainback reservoir. This is true when the top of the storage tank serves as the drainback reservoir or if a separate drainback tank is used.

Figure 5-8

Image courtesy of Hot Water Products, Inc.

In some systems, particularly open-loop systems using translucent polymer storage tanks, it may be possible to see the water level as a shadow line on the tank wall or by looking into the tank through a small opening at the top. A “dip stick” is another possibility for checking water level in such systems.

In a closed-loop pressurized system, a “sight glass” is the common solution for checking water level (see figure 5-8). The sight glass can be mounted within the upgoing collector supply piping, directly to the storage tank, or to two other piping locations on the same side of the collector circuit — one above and one below the static water level. In all cases, the water in the system seeks a single level when the collector circulators are off. It is advisable to place the sight glass where it can be easily accessed. Some sight glasses are made of temperature resistant glass, others may use temperature resistant translucent polymers. It is even possible to use a piece of translucent PEX tubing as a sight “glass” provided it is operated within its rated temperature/pressure range.

It is suggested that the sight glass tube be a minimum of 12 inches long and centered on the desired static water level in the tank. Longer sight glasses will obviously allow more variations in water level to be detected. Sight glasses should also be serviceable. The transparent or translucent tube itself may accumulate a film over time and require removal for cleaning or replacement. Install isolating ball valves to ensure such service is possible without need of draining the storage tank.

TANK PIPING CONNECTIONS:

There are several ways to detail the piping at the top and bottom of a drainback tank. As previously mentioned, most open-loop drainback systems bring all piping connections through the top or high side wall of the tank, and above the static water level. This reduces the possibility of leakage as gaskets at such connecting points age.

In open-loop systems, an inverted U-tube is used to draw water from the lower portion of the tank to the collector circulator(s) (see figure 5-4). The top of this U-tube should be kept as close to the top of the tank as possible. It should also use generously sized piping to minimize frictional head loss. The inverted U-tube is “primed” with water by closing an isolation flange on the collector circulator and adding water at a high flow rate through the hose bib valve below the collector circulator. The objective is to displace air within the upper portion of the U-tube. Once this is accomplished, the water will remain in place when the circulators are off. A valve can be added to the top of the U-tube to minimize the amount of air needing to be displaced at priming; however, be sure this valve is tightly sealed at all other times to maintain the priming water in place. Do not place a float-type air vent or vacuum breaker at the top of the inverted U-tube. Since this portion of the piping is under negative pressure relative to the atmosphere, either of these devices will allow air into the system.

There are also numerous variations in how the return piping from the collector array attaches to the tank. It is crucial that all such connections allow air to flow backward into the return piping at the onset of the drainback process. It is also preferable that the water enters the storage tank horizontally. This minimizes disruption of the vertical temperature stratification within the tank.

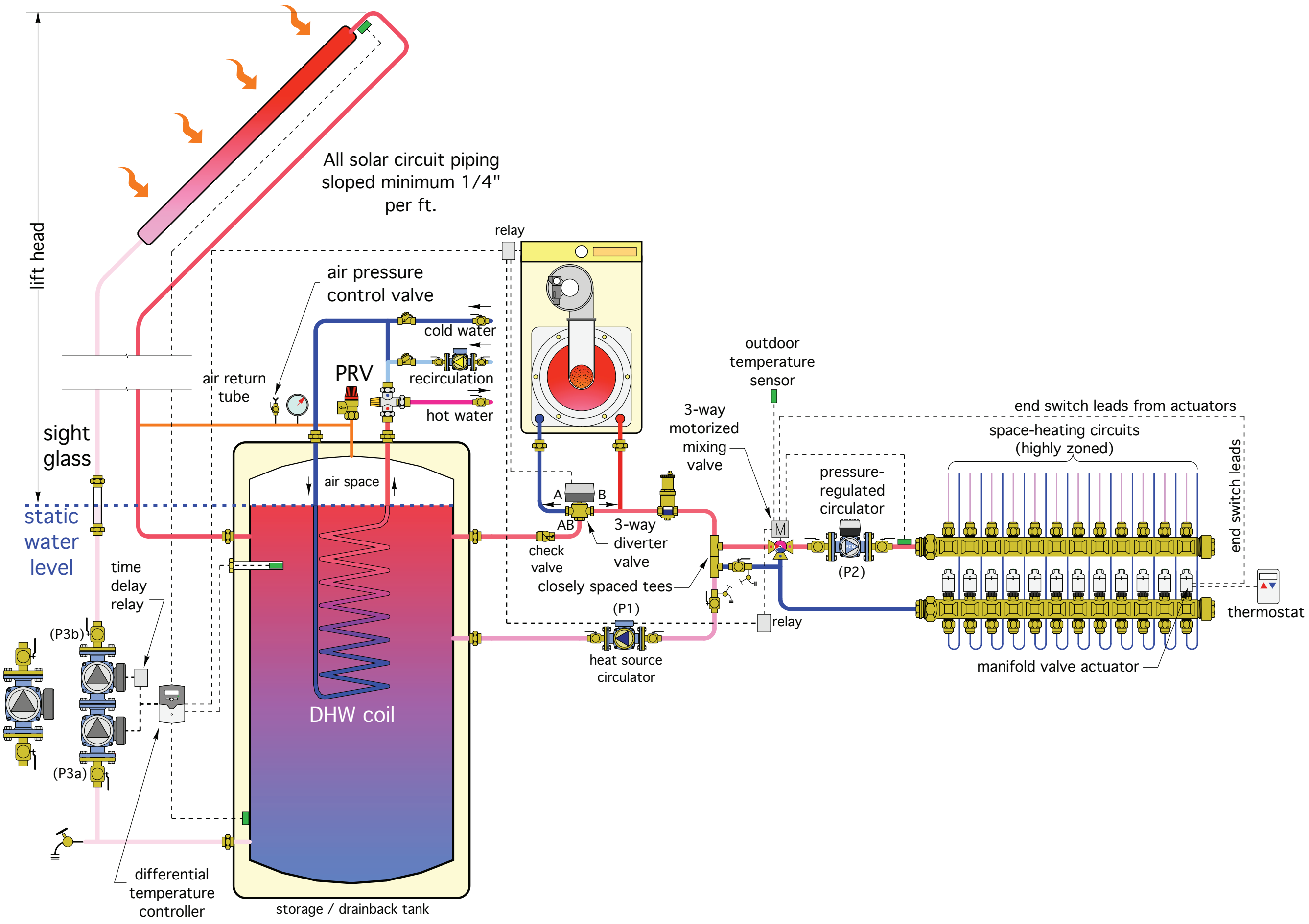
If the return piping enters the drainback tank above the operating water level, there will be a slight “water fall” sound created by the water falling from the end of the pipe to the water level in the tank. Although a matter of opinion, a drop of perhaps a few inches within a well insulated tank, located in a mechanical room away from primary living space, should not create objectionable sounds.

If the return pipe enters the tank below the operating water level, a separate air equalization tube must be used as shown in some schematics within this section. Some of the flow returning from the collectors may pass into this tube as the system operates. However, momentum will carry most of the flow past the tee where the air equalization tube connects to the collector return piping, and thus most of the water will enter below the water level in the tank.

DRAINBACK COMBISYSTEM #1:

The first complete drainback combisystem we’ll discuss is shown in figure 5-9. This system may look familiar to those who have read section 4. It uses the same boiler, near-boiler piping and distribution system concept as shown with antifreeze-based system #2. The only difference is that a drainback solar subsystem is now in place.

Figure 5-9



This is a slightly pressurized closed-loop drainback system. The same water that flows through the collector array can also flow through the space heating distribution system, as well as through the boiler when necessary. No heat exchangers are required between these parts of the system.

The suspended coil near the top of the tank is for heating domestic hot water. It is constructed of either stainless steel or copper, and in some tanks, can be removed through a large flanged opening at the top of the tank.

The boiler operates as necessary to maintain a suitable minimum temperature at the top of the storage tank. This ensures that domestic hot water is always available upon demand. Temperature stratification within the tank minimizes heat migration to the lower portion of the tank.

The solar system controller used in this system provides two outputs. One operates the collector circulator(s). The other is used to operate the boiler and 3-way diverter valve as necessary to maintain a suitable minimum temperature at the top of the storage tank.

If two series-connected circulators are used for the collector circuit, a separate time delay relay can be used to turn the upper circulator off once the siphon is established in the return piping.

Whenever the solar system controller determines the top of the tank requires heating, it fires the boiler and powers on the 3-way diverter valve so flow passes from the valve's "AB" port through its "A" port, and on through the boiler. The same signal also turns on the heat source circulator (P1).

A call for space heating comes from any zone thermostat, which powers up a manifold valve actuator. When the actuator reaches the end of its travel, an internal end switch closes to send 24 VAC power to the mixing valve controller. This 24 VAC signal also powers the coil of a relay (R1), which applies 120 VAC to operate circulator

(P1) and (P2). The mixing valve controller operates on outdoor reset logic to maintain the ideal supply temperature to the distribution manifold.

If the boiler is operating during the call for space heating, some of its heat output will be extracted at the closely spaced tees that provide hydraulic separation between circulators (P1) and (P2). The remainder of its output will be absorbed into the water at the top of the storage tank.

If the boiler is not operating during the call for heat (which is the expected situation after a significant period of solar energy collection), the 3-way diverter valve routes flow through its "B" port, bypassing the boiler. Heated water is supplied directly from the storage tank to the closely spaced tees. The motorized mixing valve draws in the hot water it needs to control the supply temperature to the space heating distribution system.

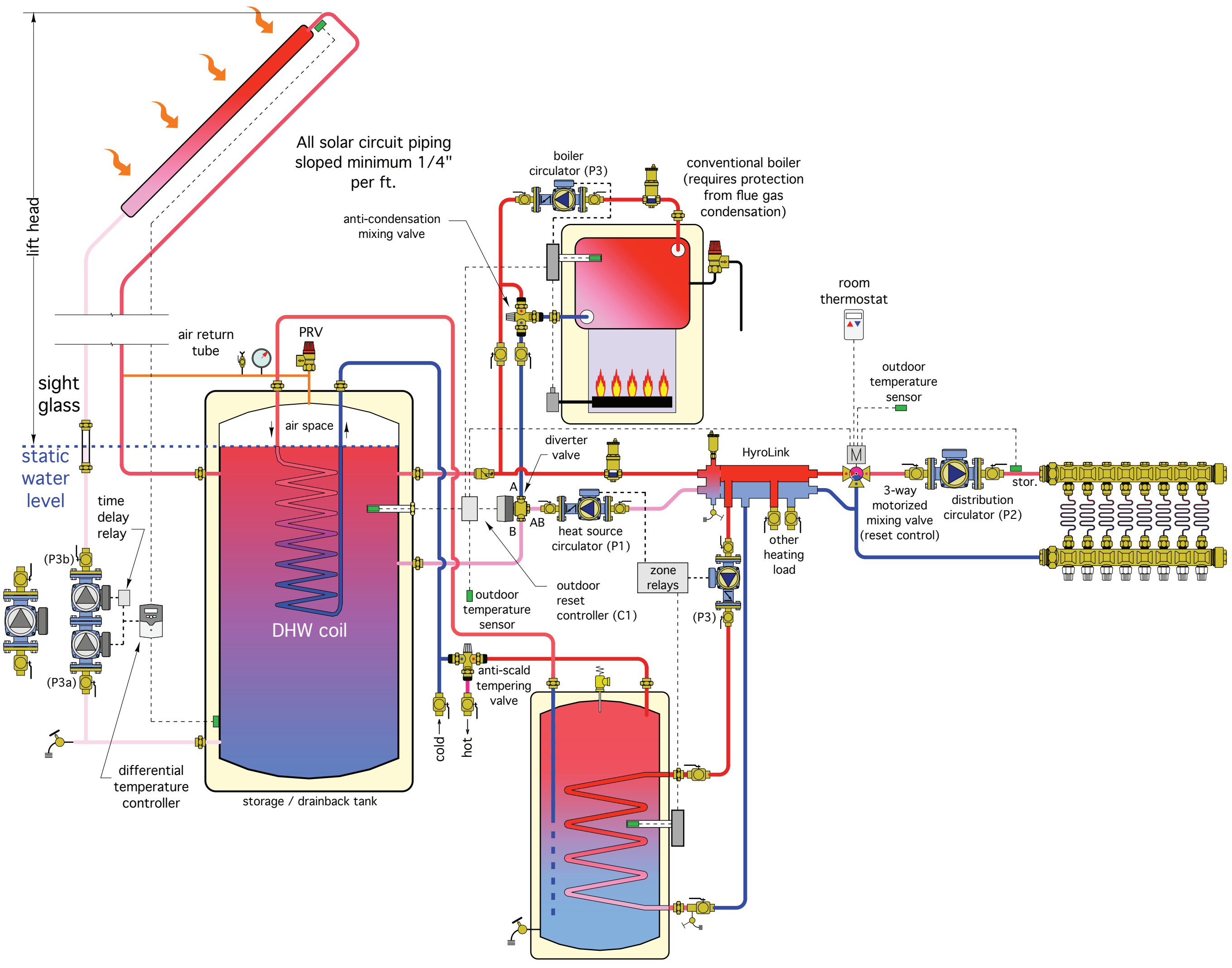
Notice that there is no automatic make-up water assembly used on this system. Likewise, there is no separate expansion tank. Minor water losses over time can be monitored at the sight glass, and "made up" by manually adding water through a low-point hose bib valve. The air reservoir at the top of the storage tank, if properly sized, can serve as the system's expansion tank.

This system uses the thermal mass at the top of the storage tank to "buffer" the space heating distribution system. This is especially desirable if the distribution system is highly zoned.

DRAINBACK COMBISYSTEM #2:

Another combination of subassemblies has been used to build the combisystem shown in figure 5-10.

Figure 5-10



The solar collection process operates the same way as in drainback combisystem #1. However, in this system, the differential temperature controller only handles the solar collection function. Other control devices manage the heat source selection, distribution of heat and domestic water heating. Many of these other controls are common to other types of hydronic systems.

This system uses two tanks: solar storage and a conventional indirect water heater. No auxiliary heat from the boiler is ever sent to the solar storage tank. This allows that tank to remain as cool as possible, and thus maximizes solar collector efficiency.

Heat in the solar storage tank is transferred to cold domestic water through the suspended coil heat exchanger. This allows the solar storage tank to provide some domestic water preheating even when it is relatively cool. However, during or after a period of solar energy collection, this coil may provide the full temperature rise required. If not, supplemental heat is supplied by the boiler through the HydroLink and then through the heat exchanger of the indirect water heater.

For the system shown, a call for spacing heating comes from the room thermostat, which supplies 24 VAC power to the 3-way motorized mixing valve, as well as the outdoor reset controller (C1). The mixing valve begins regulating the supply temperature to the distribution system based on its settings.

The outdoor reset controller (C1) compares the temperature at the top of the storage tank to a calculated "ideal" supply water temperature for the space heating subsystem.

An example of the outdoor reset control function is shown in figure 5-11. The "target" temperature is represented by the solid gray sloping line on this graph, and is a function of outdoor temperature and the current controller settings. The blue dashed line below the target temperature line indicates the temperature at which the contacts on the outdoor reset controller close. The red dashed line above the target temperature line indicates the temperature where these contacts open.

For example, if the outdoor temperature is 30ºF, the calculated target temperature shown in figure 5-1 is 92.5ºF. The lower dashed line indicates that the contacts close if the temperature at the tank top sensor is 90ºF or less. The upper dashed line indicates that the contacts open if that temperature is 95ºF or more.

With these settings, if the outdoor temperature equals 30ºF and the temperature at the top of the solar storage tank is 90ºF or less, the controller determines that the solar storage tank is too cool to supply the heating distribution system. It then closes its contacts to power on the diverter valve, allowing it to change position and route flow through the boiler. When the diverter valve has completed its movement, an end switch within the valve's

Figure 5-11

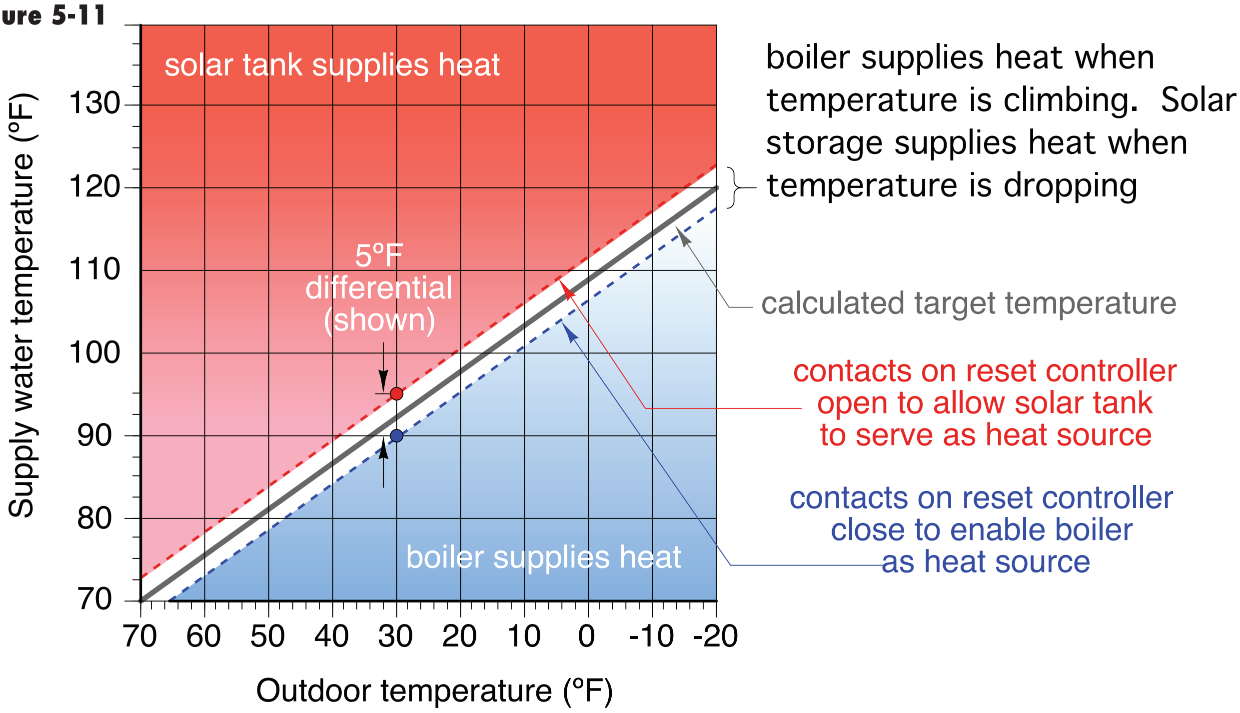
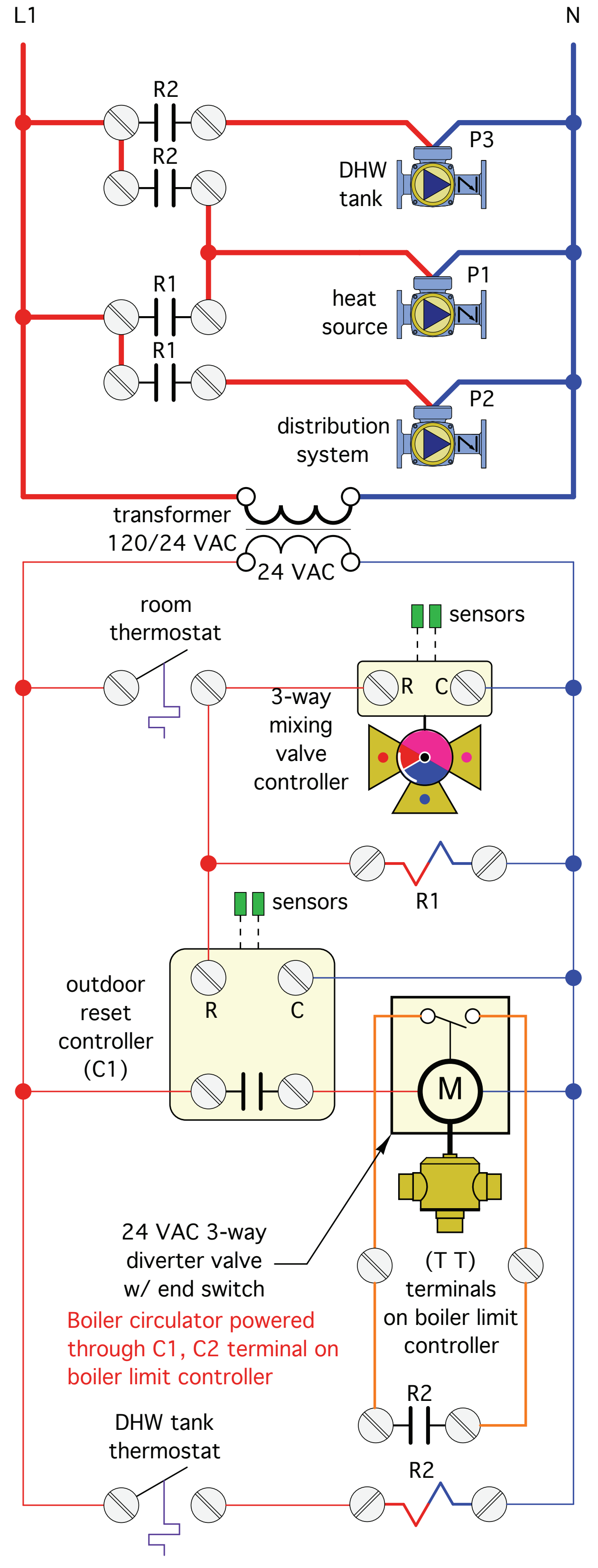


Figure 5-12



Boiler circulator powered through C1, C2 terminal on boiler limit controller

actuator closes to operate the boiler and the boiler circulator. Hot water is then supplied to space heating through the HydroLink, and eventually the 3-way mixing valve.

If the temperature at the top of the auxiliary tank is 95ºF or higher, the outdoor reset controller (C1) allows the solar storage tank to serve as the heat source for the distribution system.

If the solar storage tank is serving as the heat source, it continues to do so until the tank sensor temperature drops to 90ºF, at which point the system automatically switches to the boiler as the heat source.

If the boiler is serving as the heat source, it continues to do so until the tank temperature climbs above 95ºF (from additional solar gain). At this point, the solar storage tank again becomes the heat source.

Keep in mind that these temperatures change based on the current outdoor temperature. The slope of the reset line, as well as the differential of the outdoor reset controller, can be adjusted to suit the type of heat emitters and auxiliary heat source used in the system. This simple method of switching between heat sources allows the solar storage to be utilized to the lowest possible temperature compatible with the heat emitters. This improves collector efficiency and increases the total solar energy gathered over the heating season.

A conventional boiler is shown in this system. As in other hydronic systems serving low-temperature distribution systems, such boilers require protection against sustained flue gas condensation. This is accomplished using a thermostatic mixing valve to monitor the inlet temperature to the boiler and boost it when necessary by blending in hot water from the supply side of the boiler.

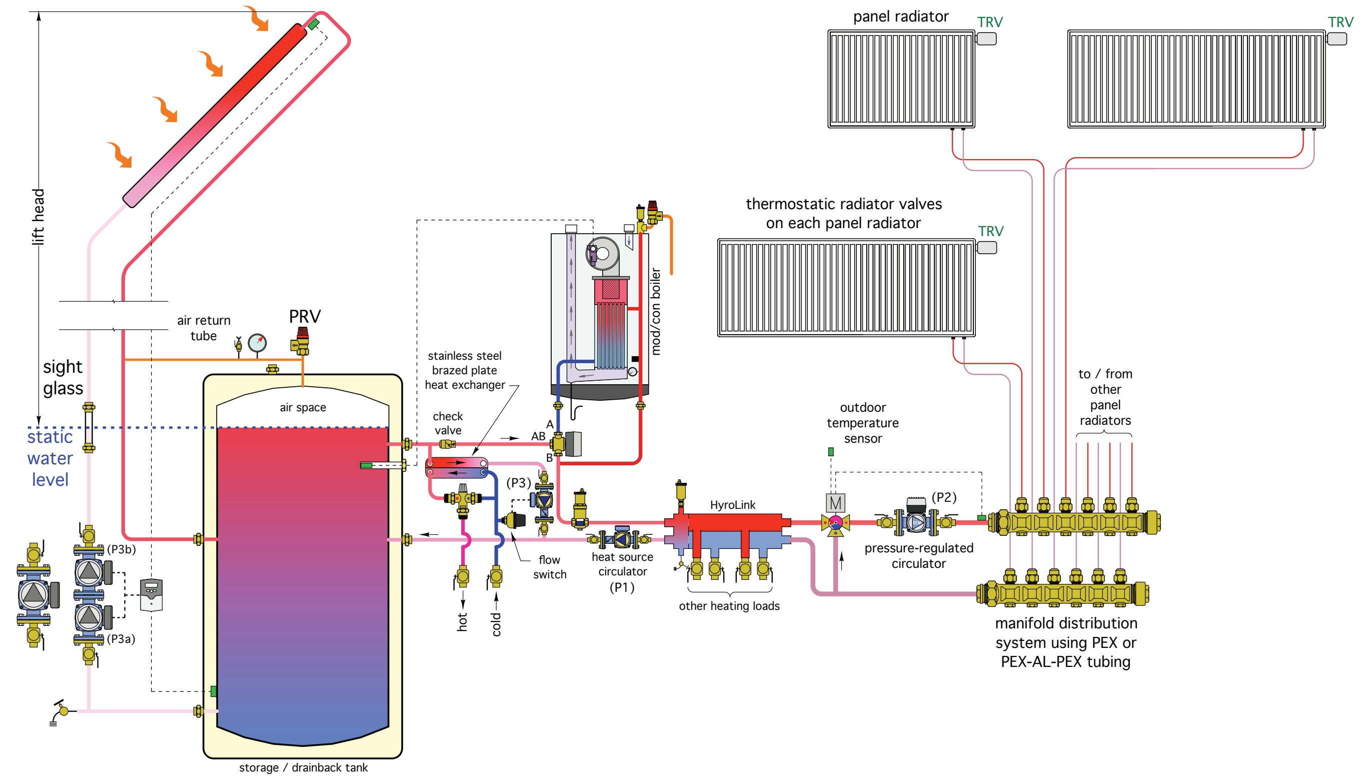
A partial wiring schematic showing how the system operates (other than solar energy collection function) is shown in figure 5-12.

DRAINBACK COMBISYSTEM #3:

Both of the previous drainback designs use a suspended coil heat exchanger in the solar storage tank for domestic water preheating. While certainly plausible, this approach limits potential tank suppliers, especially if the size of the tank or its internal heat exchanger is “non-standard.”

The serviceability of an internal heat exchanger over the life of the system is also a consideration. Some tanks allow the internal heat exchanger to be lifted out through a large flange at the top of the tank if ever necessary. Others do not allow any access to the internal heat exchanger. The

Figure 5-13



latter present few options if a leak, corrosion or scaling ever develop to the point where the coil can no longer function.

The approach used in figure 5-13 eliminates the need for this internal heat exchanger.

Solar collection is handled by a closed-loop, slightly pressurized drainback subsystem. The storage tank is a simple, carbon steel vessel with no internal components or special detailing.

The boiler operates as necessary to maintain the top of the storage tank at a suitable minimum temperature for domestic hot water delivery. When a hot water fixture opens, a flow switch detects the flow of cold domestic water and turns on the small circulators (P3). This moves heated water from the top of the storage tank through one side of a stainless steel brazed plate heat exchanger. Cold domestic water flows through the other side of this heat exchanger.

Because the plate heat exchanger has very little water content relative to its plate area, it warms and transfers heat within a second or two after the flow of hot water begins. Thus, domestic hot water is produced “instantaneously” upon demand. The thermal mass of hot water in the storage tank allows for stable DHW delivery. This approach also minimizes the quantity of domestic hot water held in the system at any time reducing the potential for legionella.

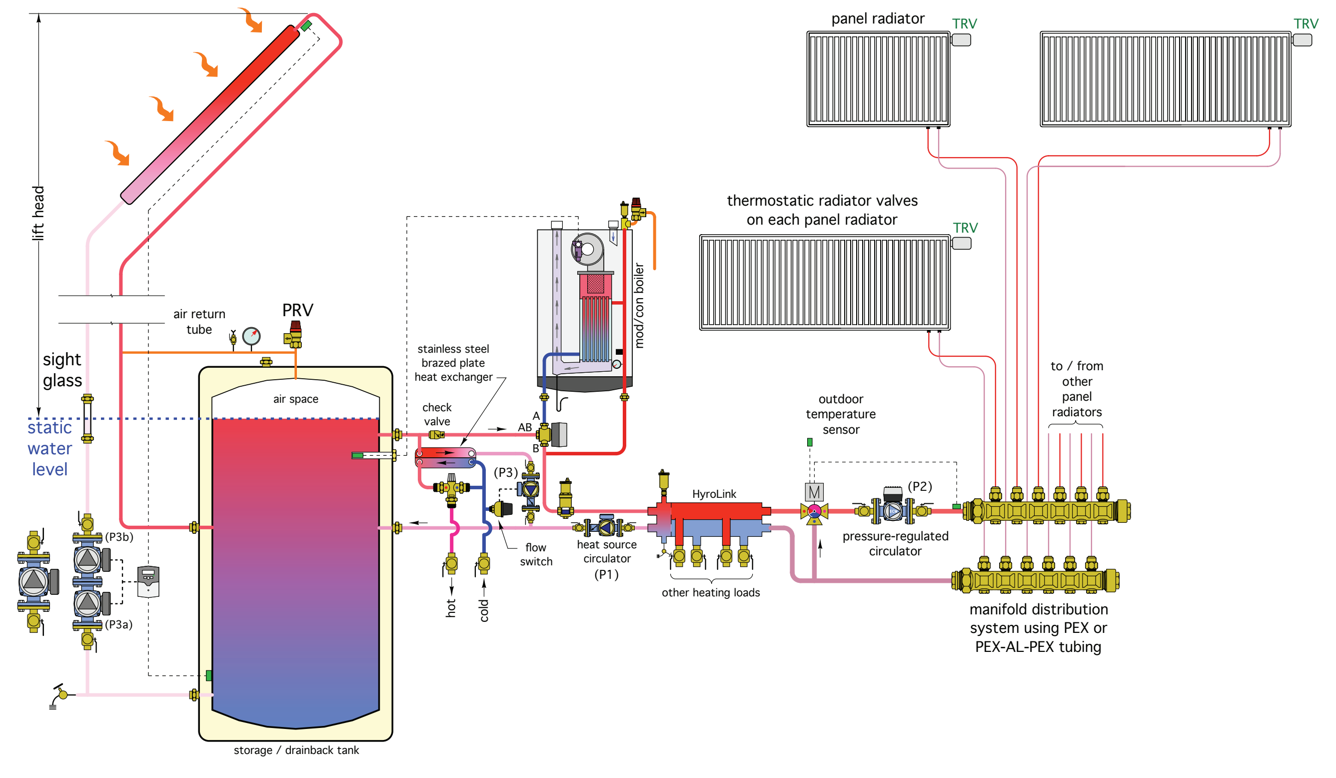
Space heating is provided from a manifold station serving panel radiators (sized for operation at low supply water temperature). Each panel radiator is controlled by its own thermostatic radiator valve. A variable-speed pressure-regulated circulator (P2) modulates its speed as necessary to maintain a constant differential pressure across the manifolds as zone circuits open and close.

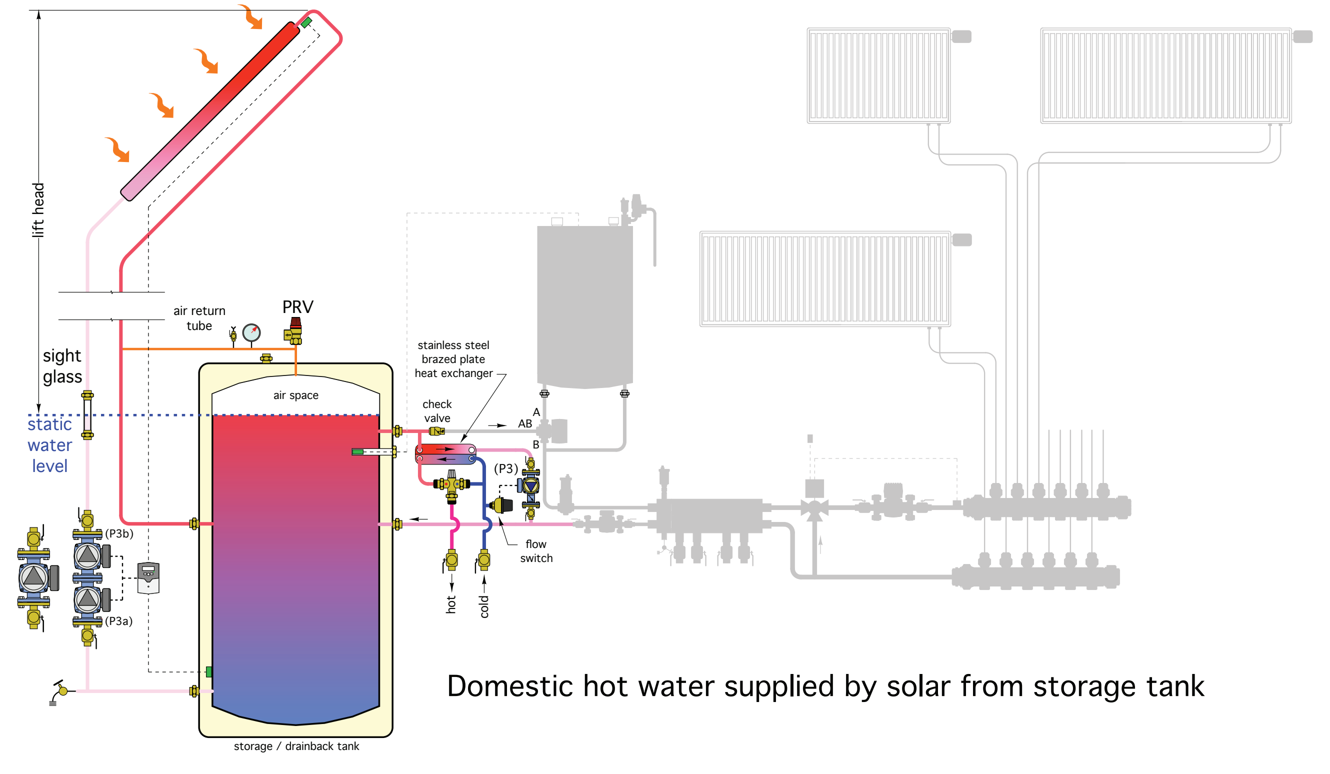
A HydroLink serves to hydraulically isolate the space heating distribution system and two other potential heating zones (served from the bottom connections of the HydroLink) from the heat source circulator (P1).

This system provides the benefits of a single storage tank, elimination of heat exchangers between the solar subsystem and space heating circuits, buffering for a highly zoned distribution system, instantaneous domestic water heating and an easily serviced external heat exchanger for domestic water heating.

Figure 5-14 shows the original system schematic at the top, and its operating mode while supplying domestic hot

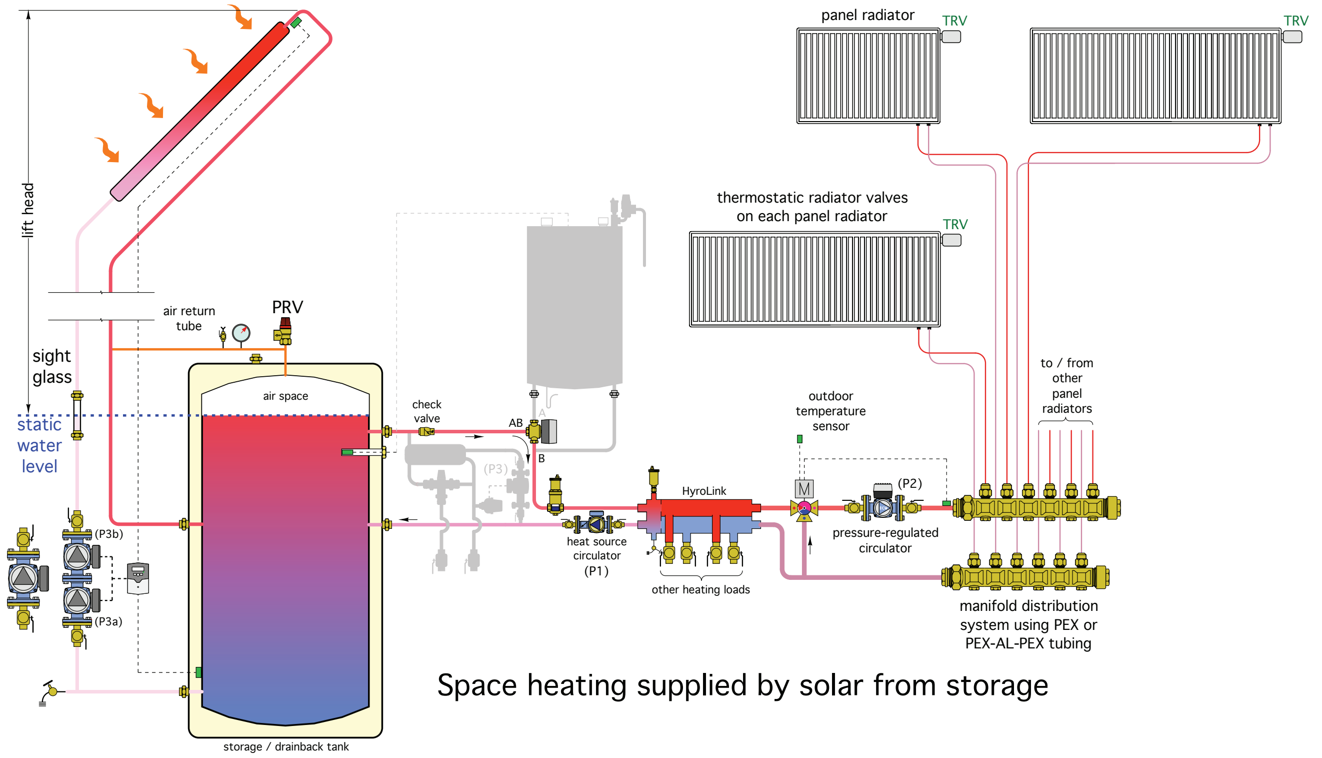
Figure 5-14



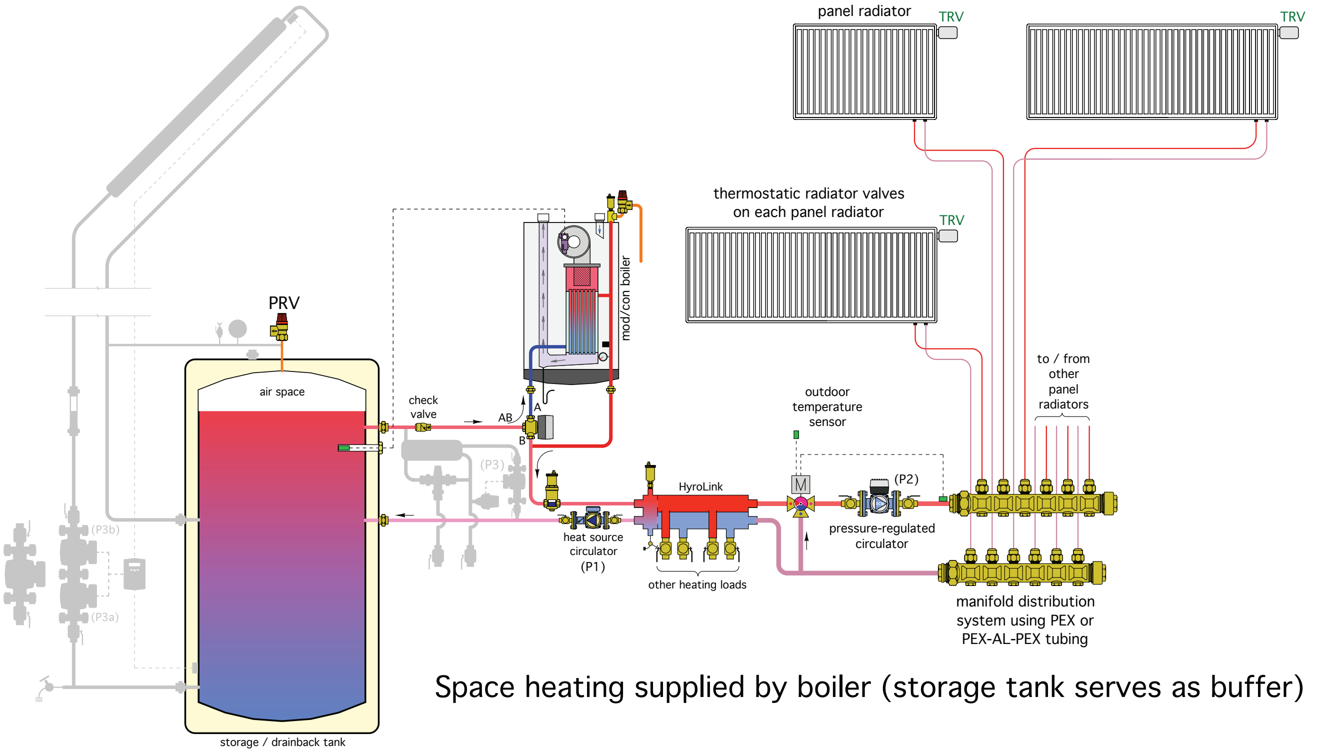


Domestic hot water supplied by solar from storage tank

Figure 5-15



Space heating supplied by solar from storage



Space heating supplied by boiler (storage tank serves as buffer) water from solar storage tank. Inactive components in the lower schematic are shown in gray.

The upper schematic in 5-15 shows the system supplying space heating from the solar storage tank. The lower schematic shows the system supplying space heating from using the boiler as the heat source and the storage tank as a buffer. Inactive components are shown in gray.

DRAINBACK COMBISYSTEM #4:

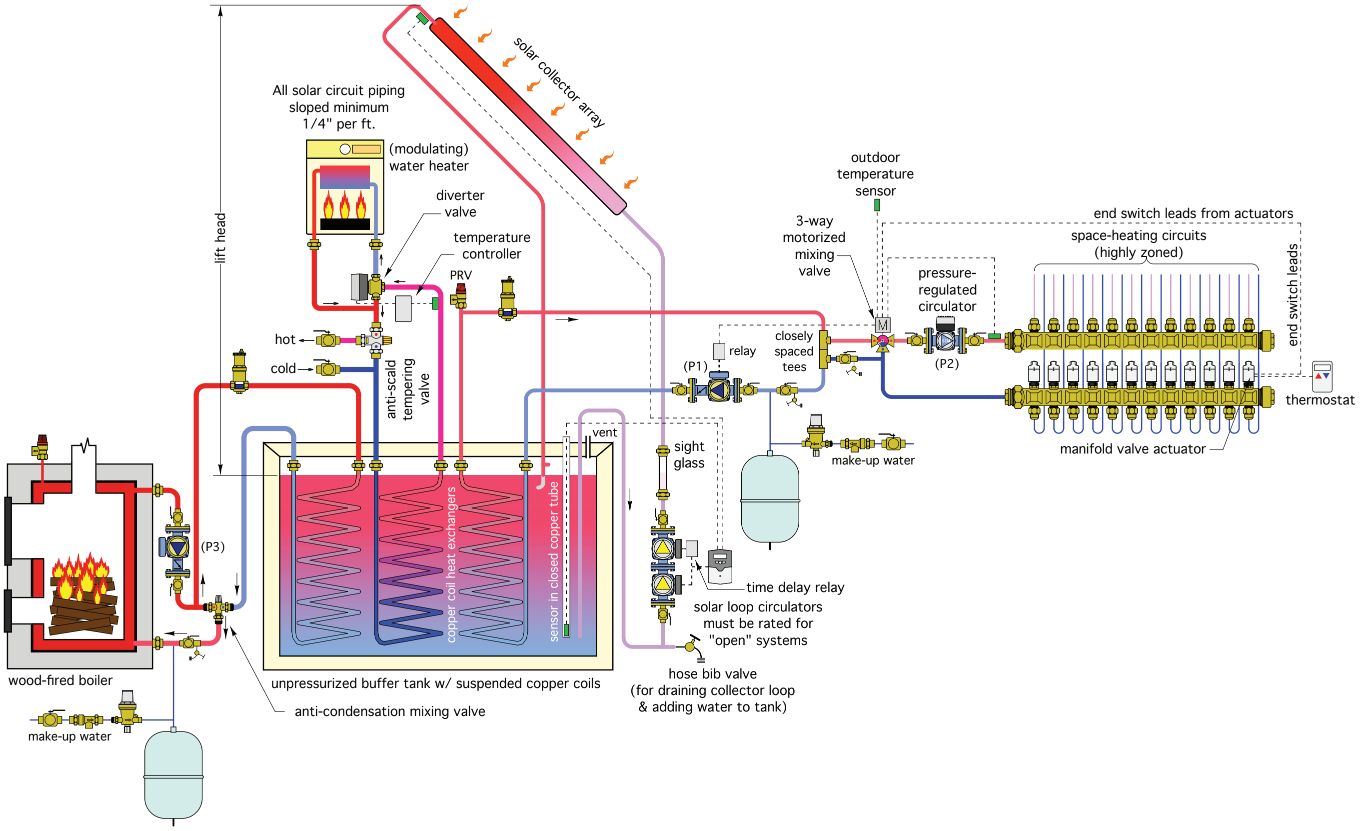
Some solar combisystems may include auxiliary heat sources that also require a storage tank. One example is a system using a wood-fired boiler. In these cases, it's often possible to combine the storage requirements into a single tank, as shown in figure 5-16.

This system is built around an unpressurized storage tank. Such tanks typically have an insulated structural shell supporting a flexible waterproof liner. They are vented to the atmosphere and thus not capable of operating under pressure. The air space above the water is sufficient to accommodate thermal expansion of the water. All piping connections are usually made above the water level to minimize any potential leakage with age. An example of a large (550-gallon) unpressurized storage tank (partially assembled) is shown in figure 5-17.

Figure 5-17

Image courtesy of American Solartechnics

Figure 5-16



All hydronic subsystems connected to this tank are pressurized. They include the boiler circuit, domestic water preheating subsystem and the space heating distribution system. These subsystems absorb or dissipate heat to the water in the tank through large, coiled, copper heat exchangers, such as the one shown in figure 5-18.

Figure 5-18

Image courtesy of American Solartechnics

This heat exchanger consists of four parallel "windings" of copper tube manifolded together at each end. This configuration produces far less pressure drop than would a single tube coil of the same total length.

The wood-fired boiler heats the tank through a copper coil heat exchanger suspended from the top or side of the tank. This coil and remaining boiler piping constitute a closed hydronic circuit, and therefore require a pressure relief valve and expansion tank. Depending on local codes, the boiler circuit may also require safety devices such as a low-water cut off or manual reset high limit. A 3-way thermostatic mixing valve is used to boost boiler inlet temperature to prevent flue gas condensation within the boiler. This is essential for minimizing creosote formation within the boiler and its venting system.

Domestic water is preheated through another suspended copper coil in the tank. A controller measures the temperature of the water leaving this coil. If it's hot enough to supply the fixtures, the diverter valve directs it to the anti-scald tempering valve. As in other combisystems, this valve prevents excessively hot water from flowing directly to the fixtures. If the water needs further heating, the diverter valve directs it through the modulating instantaneous water heater. After this, it again passes through the anti-scald mixing valve before going to the fixtures.

Energy for space heating is also extracted from the tank through a third suspended coil. This coil and the remaining space heating piping constitute another closed-loop pressurized subsystem, and thus require a pressure relief valve and expansion tank.

Heat from the collector array is added to the tank through the drainback subsystem. The tank water passes directly through the collector circuit. No heat exchangers are required. The absence of a heat exchanger improves the efficiency of the collectors.

Because this is an open-loop drainback system, the circulators must be bronze, stainless steel or a high-temperature polymer to avoid corrosion. A "dual-pumped" circulator is shown with a time delay relay used to turn off the upper circulator when the siphon is established in the collector return piping.

An elbow located just below the operating water level deflects flow returning from the collectors so it enters the tank horizontally rather than vertically. This helps preserve temperature stratification within the tank. A tee is installed a few inches above the water level to allow air to reenter the return piping fro drainback.

The water level in the tank is indicated by a sight glass installed at a suitable height. Water can be added to the tank through the hose bib valve at the bottom of the collector loop.

An "inverted-U" piping configuration is used to supply the collector circulators. This eliminates the need for piping to penetrate the tank below the water level. This piping should be kept as short and low to the tank top as possible. The collector loop circulators should be mounted as low as possible to maintain some slight positive pressure at their inlet. The inverted U is primed by closing an isolation valve on the solar loop circulators and adding water to the tank at a high flow rate through the hose bib valve. Once filled, the inverted U should remain full of water.

The combination of a solar collector array and wood-fired boiler is synergistic. The boiler will likely be used more during cold and cloudy winter weather. The solar array will produce greater outputs in spring and fall, and may even eliminate the need to operate the wood-fired boiler for domestic water heating during warm weather.

6. PERFORMANCE ESTIMATION:

The performance of any solar energy system obviously depends on weather. As such, it cannot be precisely predicted from one day to the next. In the case of a solar combisystem, performance also depends on both the space heating and domestic hot water loads of the building it serves. Both loads are highly variable depending on personal preferences, energy saving efforts and habits of the building occupants. Compounding this situation are issues such as collector shading at specific times or the possibility of snow on the collectors — even when the sun is out.

Because of the highly variable nature of the source as well as the demand for energy, the performance of solar thermal systems is often estimated through computer simulation. In some cases, these simulations take place on an hour-by-hour basis, or possibly even on a 15-minute basis. Because there are 8760 hours in a year, these calculations are laborious and only capable of being done using a computer.

EXPECTATIONS:

Many people with little more than a philosophical interest in solar heating tend to overestimate the performance of solar energy systems. Upon seeing a typical three- to eight-collector array on a roof, a common question to the building's owner might be: "Can those heat your entire house?" Implicit in this question is optimism that solar collectors might eliminate the need for heat from conventional fuels, such as oil, gas or electricity. Although a lofty goal, this is almost never the case.

Constructing a very large solar thermal system that could approach the ideal of 100% solar heating would be very expensive, and unable to pay for itself in savings over the useful life of the system. Such a system would also generate much more heat than could be used during warmer weather. In short, such a system would be far from economically justifiable. Without economic justification, such systems would have very limited acceptance and contribute very little to widespread use of renewable energy.

The most economical solar combisystems always use a combination of solar and auxiliary energy.

Increasing the size of the solar portion of a combisystem (e.g., more collector area and a larger storage tank) demonstrates the law of diminishing returns. Each time the collector area is increased by a fixed amount, say by adding 100 square feet of collector area to the array, the resulting savings will be less than that associated with adding the previous 100 square feet. The total savings goes up, but at a constantly diminishing rate.

From an economic standpoint, the goal is to find the best combination of solar-derived and auxiliary heat that produces the lowest life-cycle cost for a given project. This requires knowledge of or accurate estimates for many factors, such as the cost of various-size systems, the thermal performance of the same, the cost of auxiliary heating and its likely rate of inflation several years into the future, the expected cost of system maintenance and insurance, and how the system's economics are influenced by current incentives, such as tax credits and subsidized loans. Having detailed and reliable information on all these considerations during the design process is virtually impossible. The best that can be done is to make estimates, then use a software tool to gauge the sensitivity of the design to variations in these estimates.

f-CHART ANALYSIS:

One established method of predicting the monthly and annual performance of solar combisystems was developed at the University of Wisconsin, Madison during the mid-1970s. It is called f-chart. The letter f stands for fraction—specifically, the fraction of the combined space heating and domestic hot water load that is supplied by solar energy.

f-chart was originally developed as a simplified method for predicting the performance of solar thermal systems for residential-scale applications at a time when the computational performance needed for hour-by-hour simulations was only available on mainframe computers, and thus unavailable to most individuals. f-chart is based on empirical correlations of the results of thousands of hour-by-hour simulations done with a specialized solar simulation program called TRNSYS. In its initial form, the f-chart methodology could be completed using a scientific calculator. Although this is still possible, the methodology has been translated to software and is now available from at least two sources.

Like other solar design tools, f-chart requires several variables to describe the system being modeled. These include:

- Location of installation (weather database)
- Collector area
- Collector efficiency intercept (FRta)
- Collector efficiency slope (F_RU_L)
- Collector slope
- Collector azimuth

- Collector flow rate
- Storage tank volume
- Effectiveness of collector/storage heat exchanger
- Specific heat of collector circuit fluid
- Space heating load
- Domestic hot water load

Once a specific system is defined by these inputs, f-chart calculates several outputs on a monthly and annual basis. These include:

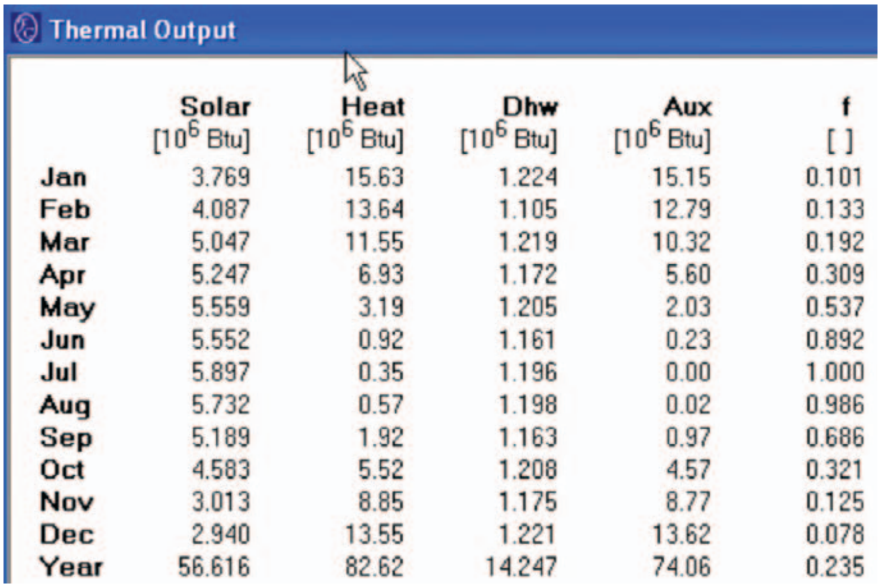
- Total solar radiation incident on the collector area
- Space heating load of the building
- Domestic water heating load of the building
- Auxiliary energy needed for space heating and DHW
- Percentage of the monthly (space heating + DHW) load supplied by solar

An output screen listing these outputs for a specific combisystem is shown in figure 6-1. The lowest line is the annual total of the monthly quantities listed above it, except for the solar fraction (f), in which case the lower line gives the annual solar fraction. For the results given in figure 6-1, solar energy supplied 0.235 (e.g., 23.5%) of the annual total space heating plus domestic water heating load.

CASE STUDIES:

The performance of some representative solar combisystems will now be discussed. These combisystems have been designed for two different houses: one with a design heating load of 35,000 Btu/hr and the other with a design heating load of 100,000 Btu/hr.

Figure 6-1



	Solar [10^6 Btu]	Heat [10^6 Btu]	Dhw [10^6 Btu]	Aux [10^6 Btu]	f [ ]
Jan	3.769	15.63	1.224	15.15	0.101
Feb	4.087	13.64	1.105	12.79	0.133
Mar	5.047	11.55	1.219	10.32	0.192
Apr	5.247	6.93	1.172	5.60	0.309
May	5.559	3.19	1.205	2.03	0.537
Jun	5.552	0.92	1.161	0.23	0.892
Jul	5.897	0.35	1.196	0.00	1.000
Aug	5.732	0.57	1.198	0.02	0.986
Sep	5.189	1.92	1.163	0.97	0.686
Oct	4.583	5.52	1.208	4.57	0.321
Nov	3.013	8.85	1.175	8.77	0.125
Dec	2.940	13.55	1.221	13.62	0.078
Year	56.616	82.62	14.247	74.06	0.235

Each house is assumed to be located in Syracuse, New York (a cold and relatively cloudy winter climate), as well as in Colorado Springs, Colorado (a cold but relatively sunny winter climate).

Each house has been analyzed with two different combisystems: One built around four 4-foot by 8-foot flatplate collectors with 256 gallons of water storage, and the other built around eight of the same collectors and 512 gallons of storage.

Other specific data for each system is as follows:

For the smaller house:
- Design heating load = 35,000 Btu/hr, with outdoor temperature = 0ºF and indoor temperature is 70ºF
- Domestic water heating load = 60 gallons per day heated from the local cold water temperature to 125ºF.

For the larger house:
- Design heating load = 100,000 Btu/hr, with outdoor temperature = 0ºF and indoor temperature is 70ºF
- Domestic water heating load = 100 gallons per day heated from the local cold water temperature to 125ºF.
- Each system uses drainback freeze protection with no collector-to-storage heat exchanger
- Collectors are 4-foot by 8-foot, with a gross area of 32 square feet each
- Collector efficiency intercept is 0.76, and the efficiency slope is 0.865 (Btu/hr/ft^2/ºF)
- Collector arrays are sloped at local latitude +15º
- Collector arrays face directly south
- Storage volume is 2 gallons per square foot of collector area

The performance estimates that follow were all determined using f-chart software.

Figure 6-2 shows the monthly solar fractions for both combisystems in the smaller house located in Syracuse, NY.

Notice that several bars representing the solar fraction in mid-year reach 100%, even for the smaller combisystem. This happens because the collector array can generate more heat than the load requires at this time of year. During the colder months, the larger system has approximately double the solar fraction of the small system. However, on an annual basis, the four-collector system meets 23.5% of the total load of the smaller house, whereas the 8-collector

Figure 6-2

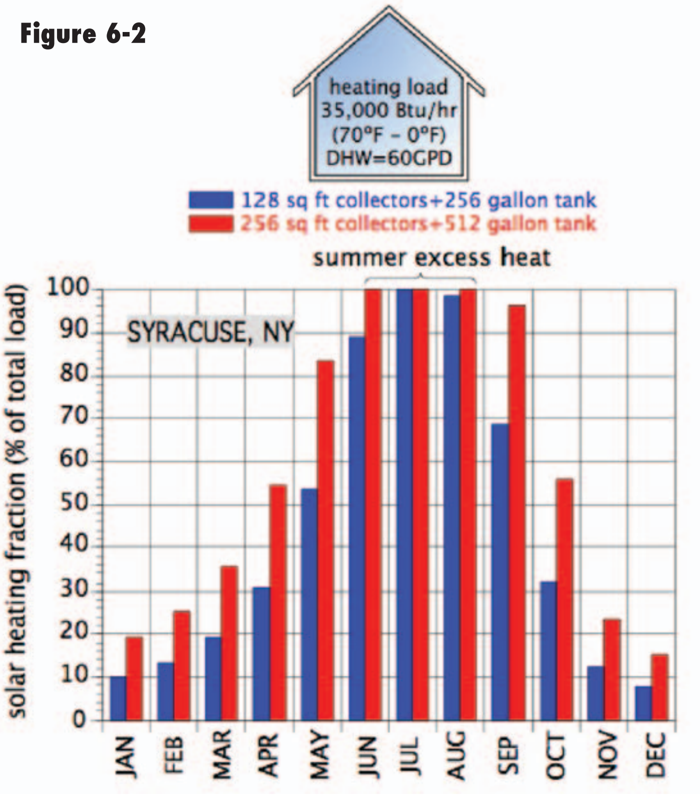
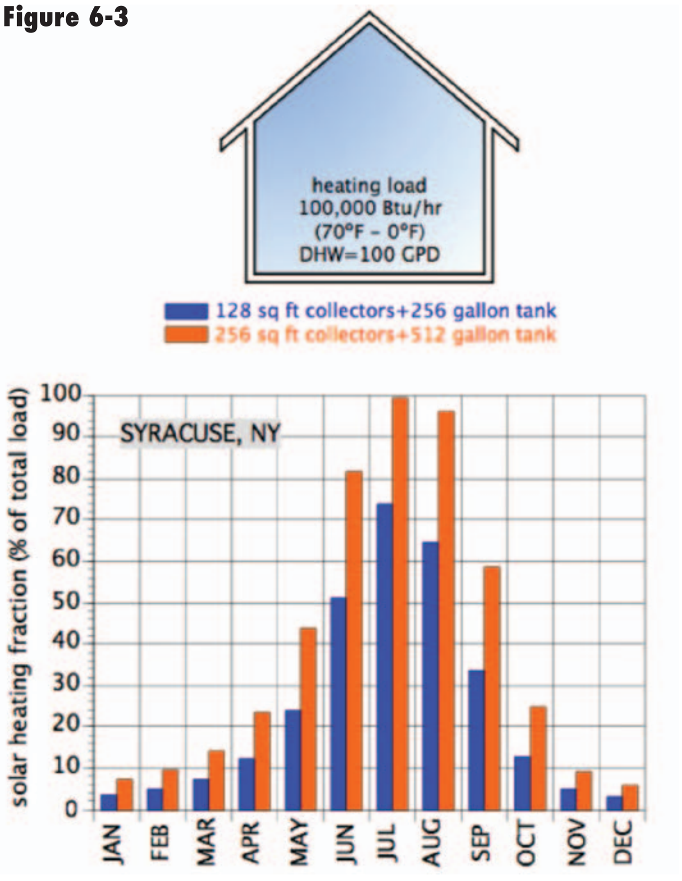


Figure 6-3



system meets 37.4% of the total load. Thus, the smaller system produced about 63%of the savings associated with the larger system. Although double in size, the larger system did not double the energy savings. This is largely because of the lack of load in warmer weather, where the higher potential output of the larger system is of essentially no use.

It follows that the economic return on investment of the smaller system, per square foot of collector area, is greater than that of the larger system. The choice of which system to install should consider this, as well as the goals of the owners and the available space required for each system. If the choice is largely driven by economic considerations, the smaller system is the better choice. However, if the owner's desire is to cover a greater percentage of the load, and both the space and funds are available, the larger system may be selected. Ultimately, most combisystem sizes are selected based on the owner's weighted preferences for performance, economic return and philosophical commitment to renewable energy use.

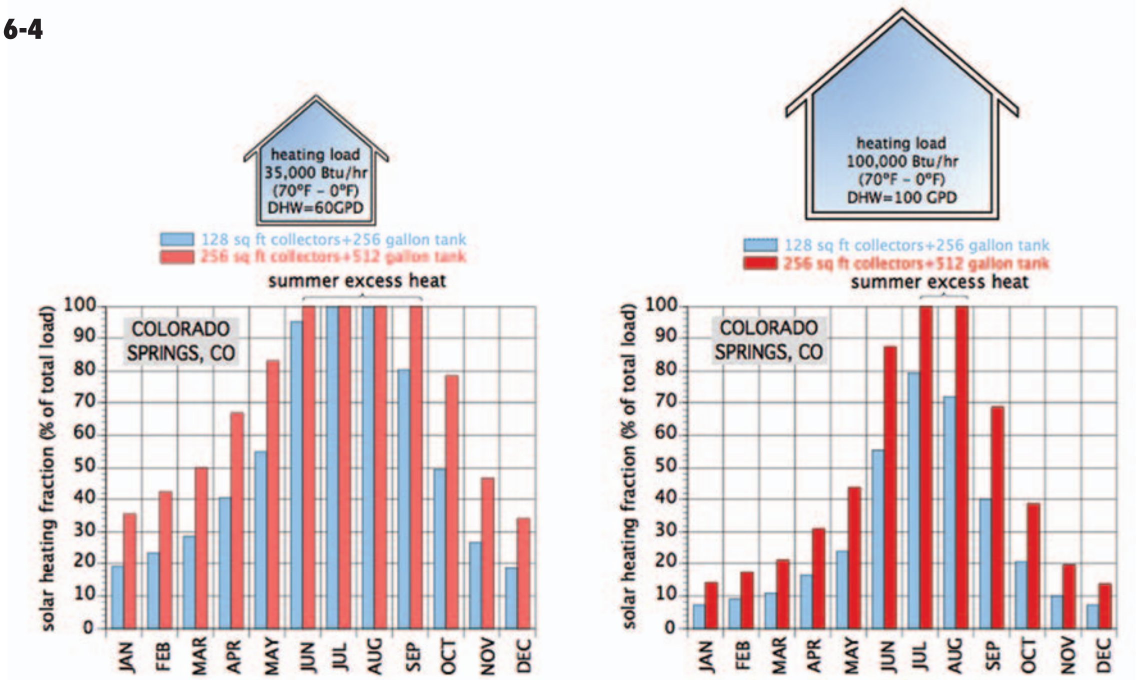
Figure 6-3 shows the performance prediction for the larger house in Syracuse, NY, with the same two combisystems.

Notice that only one bar — that associated with the larger (8 collector) system — reaches the 100% mark in July. The larger load — especially that associated with 100 gallons per day of domestic hot water — makes better use of the collected energy. The eight-collector system still approximately doubles the monthly fraction of the four-collector system from November through March. The annual solar fraction of the smaller system is 10.1% versus 18% for the larger system. Again, having twice the collector and storage size does not double the annual solar yield. However, the difference is more significant in this application relative to the small-house application because there is less wasted solar energy during warmer weather (e.g., the larger domestic water heating load makes better use of the available solar energy).

Moving both of these systems to Colorado Springs, Colorado, increases both the monthly and annual solar fractions, as shown in figure 6-4.

Given the more favorable solar climate, the system on the smaller house experiences even more excess energy in warmer weather, especially if the larger collector array is used. The annual solar fraction for the four-collector system is now 34.8% versus 54.6% for the eight-collector system. Using twice the collector area and storage yields about 57% more collected energy on an

Figure 6-4



annual basis. The diminishing return on the larger system is again attributable to lack of load in warmer weather.

The larger house, with its larger load reduces this excess, but doesn't eliminate it for the eight-collector system in either July or August. The annual solar fraction for the four-collector system on the larger house is now 15.1% versus 26.9% for the eight-collector system.

The most important point to be taken from these comparisons is that large solar combisystems in typical residential applications do not offer the same economic advantages of smaller combisystems. This is due to loads being far less than the potential amount of heat collection from a large collector array.

In some installations, the greater summertime energy delivery of a solar combisystem could be used to heat to a swimming pool. Heated fluid from the collector array would be sent through a stainless steel heat exchanger connected to the pool's filter system. Assuming this energy displaced other conventional energy for pool heating, the economic viability of the system would definitely improve.

Another way to add load to the system in summer is to dissipate heat into the loop field used for a geothermal heat pump system. This could allow some quantity of solar-derived heat to be stored in the earth—heat that could later be recovered and used during the heating season. However, the feasibility of this concept precludes situations where the geothermal loop field is also being used to dissipate heat from a building cooling system. It also requires assurance that underground aquifers will not be carrying away that heat prior to its recovery.

The potential for excess heat production in summer also favors the use of drainback freeze protection versus antifreeze in combisystem applications. When no more energy can be delivered to storage, the drainback system drains and the collector array "dry stagnates." In an antifreeze-based system, a heat-dumping subsystem must be operational to prevent rapid thermal deterioration of the antifreeze solution.

COLLECTOR ORIENTATION IN COMBISYSTEMS:

The theoretical optimum collector orientation for a combisystem is true (polar) south. However, site conditions that create shading may justify different orientations. Variations up to 30 degrees East or West of true South typically result in less than 10% loss of annual solar energy collection.

An accepted rule of thumb for collector slope in combisystem applications is latitude plus 15 degrees. The steeper slope, relative to collectors used solely for domestic water heating, favors winter sun angles, and improves performance when heating loads are greatest. Steeper collector slopes also reduces solar radiation on collectors during warmer weather when loads are small, and thus reduce the potential for overheating. Collectors mounted to a vertical, south-facing, unshaded wall (slope angle = 90 degrees) yield approximately 20% less energy gain than collectors mounted at an optimal slope.

STORAGE TANK SIZE IN COMBISYSTEMS:

The size of the combisystems's storage tank affects its annual performance. A rule of thumb is to size storage tanks in combisystems within the range of 1.25 to 2.5 gallons per square foot of collector area. Tanks larger than the upper end of this range usually show little return on the extra investment. Research has even shown that tanks larger than about 3.7 gallons per square foot of collector can decrease annual system performance due to increased heat losses.

Figure 6-5

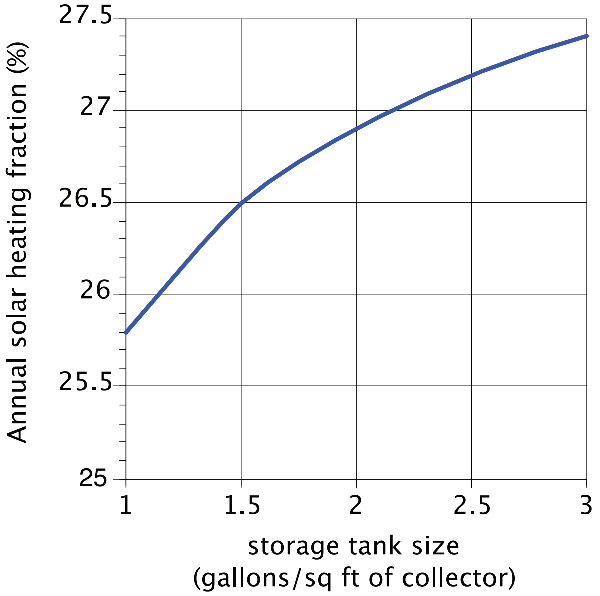


Figure 6-5 shows the affect of storage tank size on the annual solar heating fraction for the 8-collector system on the larger house in Colorado Springs, as discussed earlier in this section. There is an increase in annual solar heating fraction as tank volume increases, but the rate of increase goes down as the size of the tank increases.

SUMMARY:

Solar thermal combisystems are a natural extension of solar domestic water heating. Their objective is to provide a high percentage of the building's domestic hot water and some percentage of its space heating energy.

There are countless variations in how solar combisystems can be designed. A system that's "perfect" for one situation may not be suitable for the next. However, all combisystems should address the following considerations.

- For best performance, solar subsystems should be interfaced with space heating delivery systems that operate at low water temperatures. Do not simply assume that a solar subsystem can interface directly to any existing space heat distribution system. A suggested maximum operating temperature for a space heating distribution system that will interface to solar collectors is 120ºF.

- All combisystems must include mixing assemblies that prevent potentially high-temperature water generated by the solar subsystem from reaching low-temperature heat emitters. This mixing device can be operated based on outdoor reset control logic to allow the lowest possible water temperatures to satisfy the load.

- All systems should include a simple and automatic means of switching the distribution system from using the storage tank as the heat source to some form of auxiliary heating when necessary. Building occupants should not experience any loss of comfort as the system transitions between these heat sources. An outdoor reset controller that calculates the lowest possible temperature at which the solar storage tank can supply the load is ideal for selecting which heat source supplies the distribution system.

- All solar combisystems benefit from the same state-of-the-art hydronics technology used in non-solar hydronic systems. These technologies include pressure-regulated circulators in combination with valve-based zoning, hydraulic separation, manifold-based distribution systems and high-performance air separation.

- All combisystems should provide year-round preheating of domestic water, and thus utilize solar-supplied heat at its lowest possible temperature.

- For good performance, the effectiveness of the collector-to-storage heat exchangers in antifreeze-based systems should be at least 0.55 (see appendix B for information on calculating heat exchanger effectiveness).

- Systems should be designed with the assistance of software. The latter can be used to estimate the combined effects of many variables that vary from one system to the next.

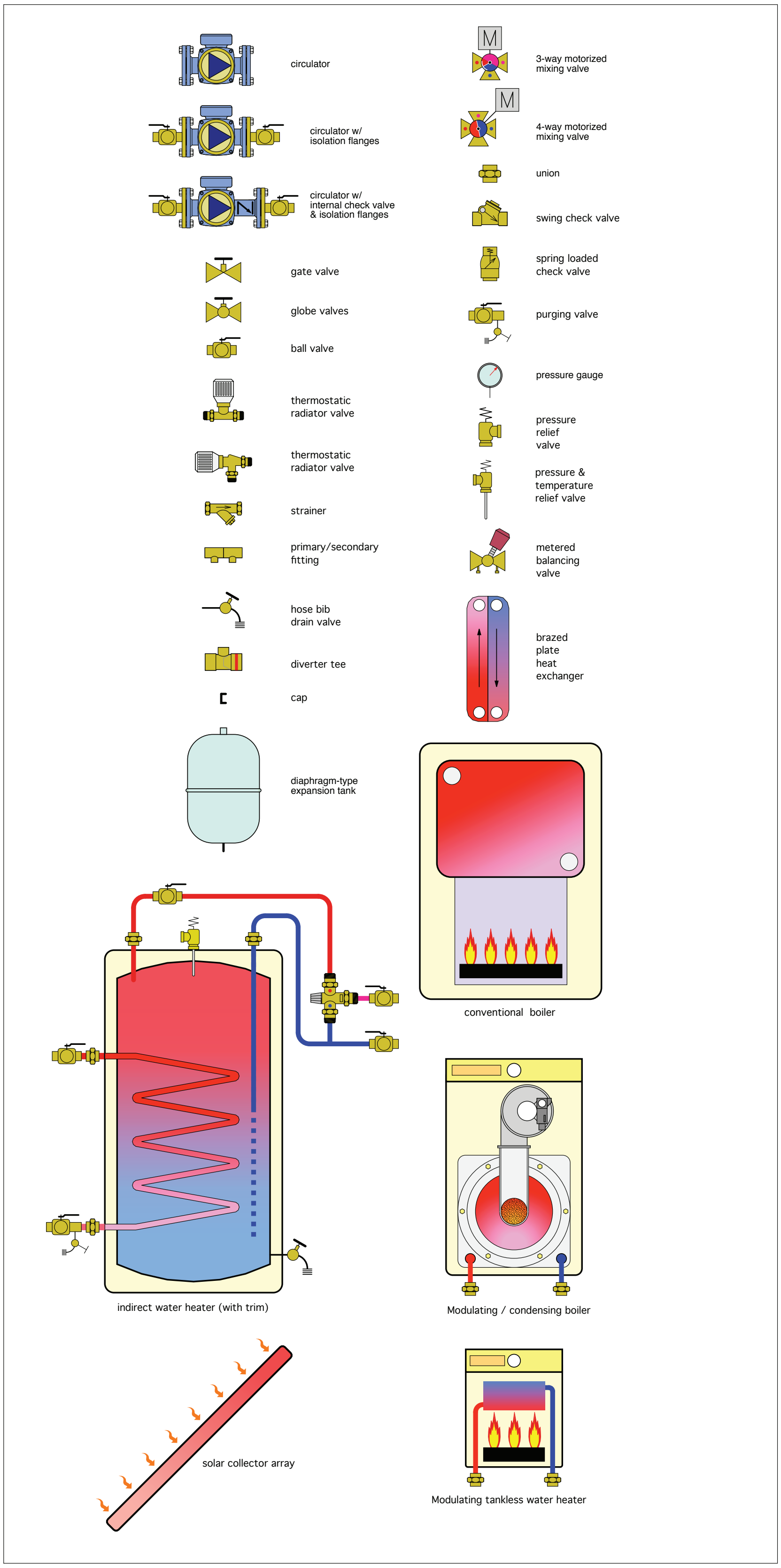
- All piping components should be well insulated to minimize extraneous heat loss and optimize the delivery of heat precisely where and when it's needed.

- Optimum collector orientation in combisystem applications is generally due south, with a slope angle of latitude plus 15 degrees.

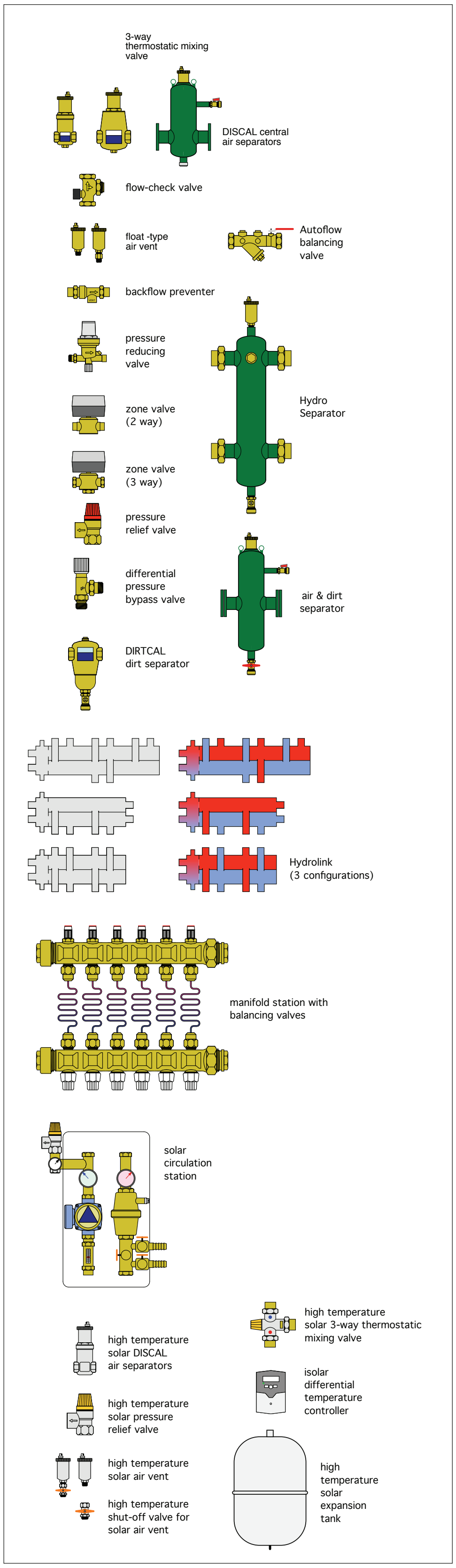
- Storage tanks in combisystem applications should be sized between 1.25 and 2.5 gallons per square foot of collector area. Tanks larger than this add very little to annual system performance.

APPENDIX A: Piping Symbol Legend

GENERIC COMPONENTS



CALEFFI COMPONENTS



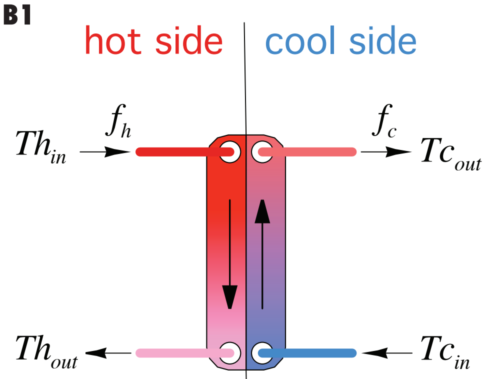
APPENDIX B:
Heat Exchanger Performance:

Heat exchanger performance is often expressed as “effectiveness,” which is defined as follows:

$$\text{e=effectiveness} = \text{e} = \frac{\text{actual heat transfer rate}}{\text{maximum possible heat transfer rate}}$$

The actual rate of heat transfer can be determined based on the flow rate, specific heat and temperature change of either fluid, as shown in figure B-1.

Figure B1



$$Q_{actual} = (8.01 \times D_h \times c_h) \times f_h \times (Th_{in} - Th_{out})$$

or

$$Q_{actual} = (8.01 \times D_c \times c_c) \times f_c \times (Tc_{out} - Tc_{in})$$

Where:

Q_{actual} = actual rate of heat transfer across heat exchanger (Btu/hr)
8.01 = unit conversion factor
D_h = density of fluid through hot side of heat exchanger (lb/ft^3)
D_c = density of fluid through cool side of heat exchanger (lb/ft^3)
c_h = specific heat of fluid through hot side of heat exchanger (Btu/lb/°F)
c_h = specific heat of fluid through cool side of heat exchanger (Btu/lb/°F)
f_h = flow rate of fluid through hot side of heat exchanger (gpm)
f_c = flow rate of fluid through cool side of heat exchanger (gpm)
T = temperatures at locations shown in figure (°F)

The maximum possible rate of heat transfer through the heat exchanger can be calculated as follows:

$$Q_{max} = \left[8.01 \times D \times c \times f\right]_{min} \times (Th_{in} - Tc_{in})$$

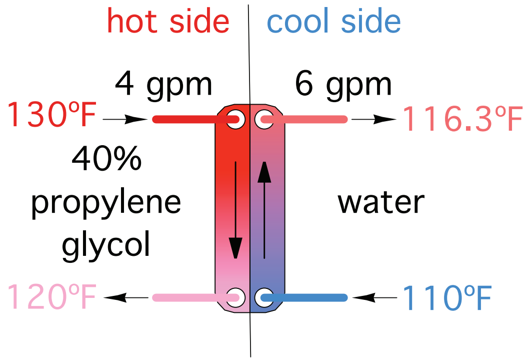
Where:

$(8.01 \times D \times c \times f)_{min}$ = the smaller of the two fluid capacitance rates. Found by calculating the product (8.01 x D x c x f) for both the hot and cool side of the heat exchanger and then selecting the smaller of the two.
Th_{in} = inlet temperature of the hot fluid (°F)
Tc_{in} = inlet temperature of the cool fluid (°F)

As the size of the heat exchanger increases relative to the required rate of heat transfer, its effectiveness approaches the theoretical limiting value of 1.0.

Example: A heat exchanger in a solar combisystem operates at the conditions shown in figure B-2. The fluid in the collector loop is a 40% solution of propylene glycol. The fluid on the cool side of the heat exchanger is water. Determine the rate of heat transfer across the heat exchanger and its effectiveness under these operating conditions.

Figure B2



Start by finding the fluid properties of both the 40% propylene glycol solution and water at the average temperature of each fluid as it passes through the heat exchanger.

For the 40% propylene glycol solution:
D = 64.0 lb/ft^3
c = 0.91 Btu/lb/ºF

For water:
D = 61.8 lb/ft^3
c = 1.00 Btu/lb/ºF

Next, calculate the actual rate of heat transfer across the heat exchanger. This can be done using data from either flow stream. In this case, the data from the flow stream through the hot side of the heat exchanger (using the 40% propylene glycol solution) is used:

$$Q_{actual} = (8.01 \times D_h \times c_h) \times f_h \times (Th_{in} - Th_{out}) = (8.01 \times 64.0 \times 0.91) \times 4 \times (130 - 120) = 18,660\,Btu/hr$$

Next determine which side of the heat exchanger has the minimum fluid capacitance rate (e.g., calculate the product (8.01 x D x c x f) for each flow stream and determine which is smaller).

For the hot side of the heat exchanger:

$$(8.01 \times D \times c \times f)_{40\% PG} = (8.01 \times 64.0 \times 0.91 \times 4) = 1866 \frac{Btu}{hr \bullet {}^{\circ} F}$$

For the cool side of the heat exchanger:

$$(8.01 \times D \times c \times f)_{water} = (8.01 \times 61.8 \times 1.00 \times 6) = 2970 \frac{Btu}{hr \bullet {}^{\circ} F}$$

The fluid capacitance rate on the hot side of the heat exchanger is the smallest.

Determine the maximum possible heat transfer across the heat exchanger. This corresponds to a thermodynamic limit in which the outlet temperature of the fluid with the lower fluid capacitance rate approaches the inlet temperature of the other fluid stream. It is determined by multiplying the minimum fluid capacitance rate by the difference in temperature between the entering hot fluid and the entering cool fluid. This difference is often called the “approach” temperature difference.

$$Q_{max} = \left[8.01 \times D \times c \times f\right]_{min} \times \left(Th_{in} - Tc_{in}\right) = [8.01 \times 64.0 \times 0.91 \times 4] \times \left(130 - 110\right) = 37,320 Btu / hr$$

Finally, determine the effectiveness of the heat exchanger under these conditions.

$$e = \frac{Q_{actual}}{Q_{max}} = \frac{18,660}{37,320} = 0.50$$

COLLECTOR HEAT EXCHANGER PERFORMANCE PENALTY:

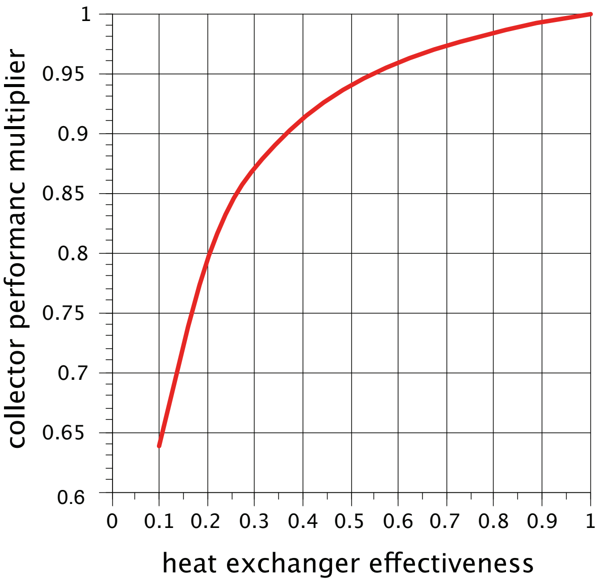
The decrease in solar energy collected as a result of having a heat exchanger between the collector loop fluid and the storage tank can be estimated using the following formula.

$$CF = \frac{1}{1 + \left[\left(\frac{(F_R U_L) \times A_{ca}}{8.01 \times D \times c \times f_{ca}}\right) \times \left(\frac{1}{\varepsilon} - 1\right)\right]}$$

Where:
CF = correction factor (derating multiplier)
$F_R U_L$ = slope of collector efficiency line (Btu/hr/ft^2/°F)
A_{CA} = area of collector array (ft^2)
D = density of collector loop fluid (lb/ft^3)
c = specific heat of collector loop fluid (Btu/lb/°F)
f_{ca} = fluid flow rate through collector array (gpm)
e = effectiveness of collector/storage heat exchanger.

The correction factor is a derating multiplier. For example, if the correction factor were 0.95, the collector array and heat exchanger used as a system, would gather 95% of the amount of solar energy compared to the same collector array without the heat exchanger. This could also be viewed as a 5% performance penalty due to the presence of the heat exchanger.

Figure B-3 shows how the correction factor varies as a function of the heat exchanger’s effectiveness. This graph is for a small combisystem using four 4-foot by 8-foot flat plate collectors, a 50% solution of propylene glycol as the collector fluid and a flow rate of 1 gallon per minute per collector. The collector’s efficiency line has a slope ($F_R U_L$) of 0.865 Btu/hr/ft^2/°F.

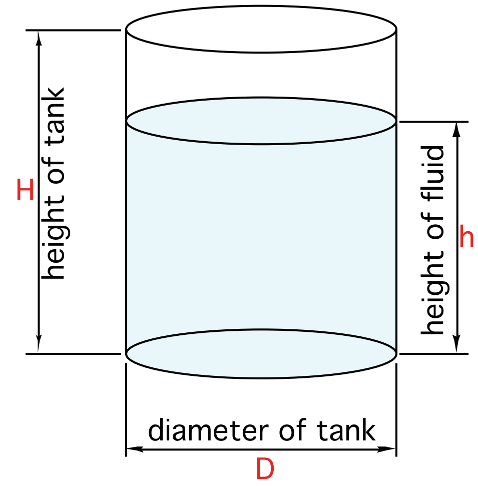


The graph shows that heat exchangers with low effectiveness numbers (less than 0.55) create significant performance penalties (over 5% reduction in energy gain). It is suggested that all collector-to-storage heat exchangers used in solar combisystems have effectiveness ratings of 0.55 or higher, and thus impose losses of not more than 5% on solar energy collection.

APPENDIX C: TANK AND PIPING VOLUME FORMULAS:

This section provides data and formulas for calculating the volumes of tanks and piping. This is useful for tasks such as determining the drop in water level of a specific size storage tank when a given volume of water is extracted (such as when a drainback system begins the collection cycle).

Formula C-1 can be used to calculate the volume of a cylindrical storage tank of known diameter and height:



Formula C-1:

$$V_{tank} = \frac{\pi\left(D^2\right)H}{924}$$

Where:
V_{tank} = volume of tank (US gallons)
D = diameter of tank (inches)
H = height of tank (inches)

Formula C-2 can be used to calculate the volume of liquid of known height h with a cylindrical storage tank of known diameter and height:

Formula C-2:

$$V_{fluid} = \frac{\pi\left(D^2\right)h}{924}$$

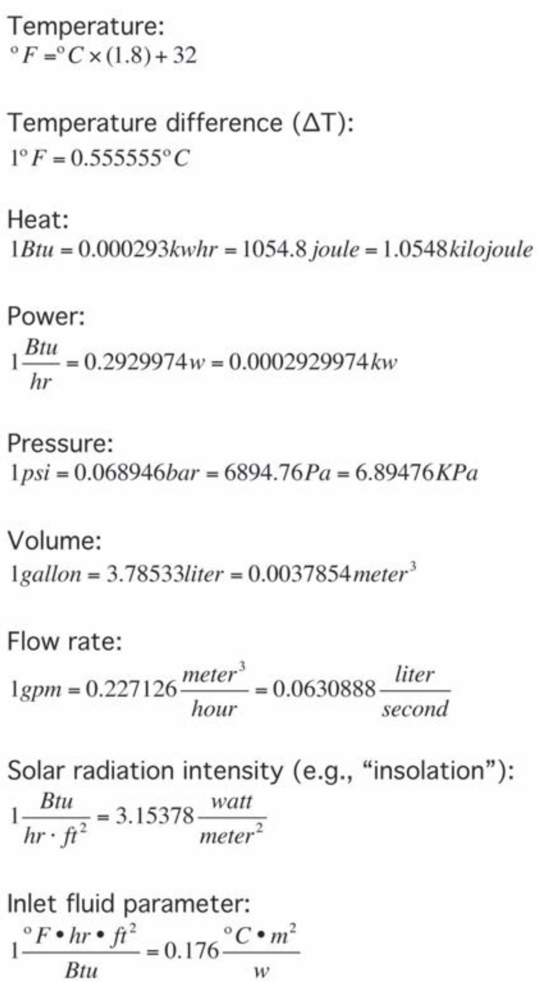
Where:
V_{fluid} = volume of fluid in tank (U.S. gallons)
D = diameter of tank (inches)
h = height fluid in tank (inches)

PIPE VOLUME DATA:

The following table can be used to calculate the volume of piping in solar as well as other types of hydronic systems.

Tube type / size	Gallons /foot
3/8" type M copper:	0.008272
1/2" type M copper:	0.0132
3/4" type M copper:	0.0269
1" type M copper:	0.0454
1.25" type M copper:	0.068
1.5" type M copper:	0.095
2" type M copper:	0.165
2.5" type M copper:	0.2543
3" type M copper:	0.3630
3/8" PEX	0.005294
1/2" PEX	0.009609
5/8" PEX	0.01393
3/4" PEX	0.01894
1" PEX	0.03128
1.25" PEX	0.04668
1.5" PEX	0.06516
2" PEX	0.1116
3/8" PEX-AL-PEX	0.00489
1/2" PEX-AL-PEX	0.01038
5/8" PEX-AL-PEX	0.01658
3/4" PEX-AL-PEX	0.02654
1" PEX-AL-PEX	0.04351

APPENDIX D: UNIT CONVERSION FACTORS:



Temperature:

$$^{\circ}F = {}^{\circ}C \times (1.8) + 32$$

Temperature difference (ΔT):

$$1^{\circ}F = 0.555555^{\circ}C$$

Heat:

$$1Btu = 0.000293kwhr = 1054.8\,joule = 1.0548\,kilojoule$$

Power:

$$1\frac{Btu}{hr} = 0.2929974w = 0.0002929974kw$$

Pressure:

$$1psi = 0.068946bar = 6894.76Pa = 6.89476KPa$$

Volume:

$$1gallon = 3.78533liter = 0.0037854meter^3$$

Flow rate:

$$1gpm = 0.227126\frac{meter^3}{hour} = 0.0630888\frac{liter}{second}$$

Solar radiation intensity (e.g., “insolation”):

$$1\frac{Btu}{hr \cdot ft^2} = 3.15378\frac{watt}{meter^2}$$

Inlet fluid parameter:

$$1\frac{^{\circ}F \bullet hr \bullet ft^2}{Btu} = 0.176\frac{^{\circ}C \bullet m^2}{w}$$