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Final Reliability and Materials Design Guidelines for Solar Domestic Hot-Water Systems

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FINAL RELIABILITY AND MATERIALS DESIGN GUIDELINES FOR SOLAR DOMESTIC HOT-WATER SYSTEMS

prepared by

Energy and Environmental Systems Division
Energy Supply and Utilization Section

September 1981

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FOREWORD

The first edition of these domestic hot-water (DHW) system reliability and materials-design guidelines was published, after an extensive review by members of the solar-energy and reliability communities, as an Argonne National Laboratory (ANL) report in September 1980 and made available through the National Technical Information Service. Prepublication copies were sent to over 200 members of the solar-energy community, and their review comments were obtained during a series of four seminars sponsored by the Solar Energy Research Institute (SERI) and hosted by the Regional Solar Energy Centers. We acknowledge the constructive comments received from the seminar participants and their suggestions for improving the guidelines. In addition, we acknowledge the assistance of R. Ancis of Solahart Corporation, J. Meeker, formerly of Solaron Corporation, and J. Meeker of the Northeast Solar Energy Center, who provided detailed system recommendations.

This final version of these guidelines contains an expanded reliability section, as well as an appendix on reliability modeling and failure-rate estimation. The failure rates used in this document have been obtained from various non-solar sources, because consistent reliability data from in-place DHW systems do not exist. The available failure-rate information has been modified to account for system duty cycles as well as component degradation during nonoperational periods. Engineering judgment, in conjunction with recommendations from military standards, was used to bracket the range of values for the degradation parameter. This approach was adopted because consistent field data are not available.

An appendix has been added that contains a Fortran computer program for estimating the scaling potential of local water supplies. Although this program is written for a large-scale computer, the equations can be programmed for use on hand-held calculators. The computer program is easy to use and should assist solar contractors in evaluating the scaling potential of local water supplies. If scaling is predicted, water-treatment techniques should be investigated and implemented.

The principal authors, J. Vresk, R.M. Wolosewicz, and P.Y. Wang of Argonne National Laboratory (ANL) and C.F. Cheng of ECA, Inc., acknowledge the assistance of the other contributors: E. Waite, P.S. Chopra, and J. Mavec of ANL, and I. Singh of ECA, Inc. General guidance and assistance was provided by W.W. Schertz and N.F. Sather of ANL.

The Solar Reliability and Materials Program (SRMP), a major activity of the Energy Supply and Utilization Section of the Energy and Environmental Systems Division, is managed by H. Singh and staffed by several divisions of the laboratory. The SRMP is sponsored by DOE's Assistant Secretary for Conservation and Solar Energy, Office of Solar Applications for Buildings, Active Heating and Cooling Division, Field Applications Branch, and is administered by R. Hassett, Program Manager. Program guidance is provided by A. Eden of the Solar Energy Research Institute.

P.S. Chopra, Director
Energy Supply and Utilization Section

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ABSTRACT

This document provides solar-energy-system engineers, designers, and manufacturers with a stand-alone publication containing the concepts and techniques for developing reliable solar domestic hot-water systems. We discuss the minimum instrumentation required to determine if a domestic hot-water system is operating properly, and we supply system start-up and trouble-shooting information. We do not provide detailed sizing, design, or installation information. This document includes an evaluation of the reliability of six generic solar domestic hot-water systems -- drain-down, drain-back, circulating-water, thermosiphon, antifreeze, and air systems. Failure-rate data for these evaluations were obtained from the open literature. Reliability block diagrams are used to analyze collector panels as well as the generic systems. System reliability results are shown as estimated mean time between failures, based on 6-hr/d operation. For other operating times, the duty-cycle concept may be applied similarly. Materials considerations are covered for common components in solar domestic hot-water systems. Information is also presented on glycol-testing and water-scaling predictions.

1 INTRODUCTION

1.1 PURPOSE

The purpose of this report is to provide solar-energy-system engineers, designers, and manufacturers with concepts and techniques needed to develop reliable solar domestic hot-water (DHW) systems. These guidelines do not provide detailed sizing, design, or installation information for such systems.*

This document is intended to fill the gaps left by the footnoted publications and to consolidate much of the available information on solar DHW systems into one publication. It is intended to be a stand-alone document dealing with the following generic types of DHW systems:

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*System-sizing criteria are specified by various solar-energy-system simulation codes, such as SOLCOST; TRNSYS and f-chart, developed by the University of Wisconsin's Solar Energy Laboratory; and DOE's building simulation code, DOE.1. Design information is available in the DOE publication, *Active Solar Energy Design Practice Manual*. Installation criteria are provided in a Department of Housing and Urban Development document, *Installation Guideline for Solar DHW Systems*.

- Direct Systems
  - Drain-Down
  - Circulating-Water
  - Thermosiphon
- Indirect Systems
  - Drain-Back
  - Antifreeze
  - Air

These systems are similar to systems in the field from which thermal performance and some reliability data have been obtained.

If we have not mentioned some particular material or component this should not be taken to mean that the material or component is not a suitable one. Owing to the dynamic nature of the solar DHW industry, improvements are being made continually. Components, materials, and systems rapidly become obsolete and are replaced with improved versions.

Although this document is intended primarily for the solar-energy-system design and manufacturing industry, do-it-yourselfers may find it useful for selecting reliable components and in starting up, troubleshooting, and maintaining their systems.

1.2 SCOPE AND ORGANIZATION

This report provides a detailed discussion of components used in residential solar DHW systems. These systems are similar to systems that have been funded and installed under various federal solar DHW programs. Estimates for the mean time between failures for six generic systems are presented, and maintenance and troubleshooting information is included. The use of equations is limited.

Chapter 2 deals with the components in most solar DHW systems. The data presented can be used to select components or the materials from which components should be fabricated. Failure information is based on field experience from federally funded solar-energy demonstration programs. The component mean-life estimates are based on data from the chemical, electric-power, and nuclear-power industries. These data sources have been used because solar-energy systems have not been operating long enough to accumulate appropriate failure-rate statistics.

The six generic system types are illustrated schematically and discussed in Chapter 3, which also contains information on system start-up, maintenance, and estimated mean maintenance-free time or mean time between failures. The estimates of mean maintenance-free time are based on a system-reliability block diagram, component-failure rates from nonsolar sources, and a six-hour operating day. This operating time was chosen using data from several residential systems being monitored by the National Solar Data Network.

Chapter 4 summarizes the reliability estimates for the six generic systems. Reliability estimates for freeze-protection and overheat-protection modes also are provided. This concluding chapter presents recommendations for DHW systems.

The six appendices include information on the performance of reliability assessments, selection of low-temperature differential set-points, and estimation of water-scaling potential. Thermal design equations for interconnections, HUD heat-exchanger standards, and background information on refrigerant-charged systems also are provided in the appendices.

In this report, we have used both English and metric units, with the English units appearing first, followed by the metric equivalents in parentheses.

1.3 RELIABILITY ENGINEERING ASSESSMENT

Although the application of reliability-engineering techniques for estimating the consistency of service of solar DHW systems is new, the techniques are used daily in various industries. The aerospace and nuclear industries use them to insure system safety; the electric-power industry, to obtain consistent system operations; and consumer-products industries, to reduce warranty costs or to anticipate potential manufacturing problems.

The accepted definition of reliability, regardless of the system application, is:

> Reliability is the probability that a component or a system will perform its required function under the specified conditions for a specified time.

Figure 1.1 illustrates schematically a typical failure-rate curve for a system that is assembled from components. When the system is put on-line initially (the break-in period), the failure rate is high because of design errors, omissions, or operator errors.

After the break-in period, the useful portion of the system's life cycle begins. The failure rate drops and then remains virtually constant. Any malfunctions or failures that occur are random and result primarily from the degradation of material structures by fatigue, creep, or poor maintenance.

After the system has been in service for a certain amount of time, wear begins to affect its performance, and the failure rate increases (the wear-out period). At this point, the decision must be made either to overhaul the system or to abandon it.

Generally speaking, the application of reliability techniques meets some or all of the following objectives:

- Assess the reliability of existing systems or proposed design configurations.

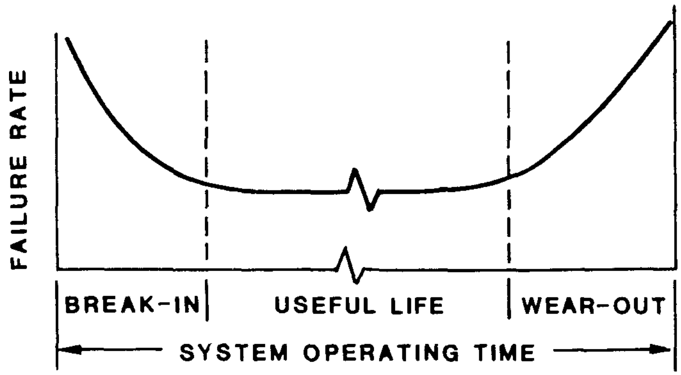


Fig. 1.1 Typical System Failure-Rate Curve

- Minimize failures during break-in period by development and testing.
- Develop recommendations for improving system reliability and achieving low frequency of failures.
- Ensure that reliability is as important as performance and cost.

Solar-energy-system designs depend on the service to be provided. While solar DHW systems are similar, they are seldom identical. Each system has specific features, and a system designed and installed in New England may not resemble a system intended for use in Florida. Although each system will probably be unique, reliability engineering can be applied to any system to reduce downtime and to increase productivity.

1.3.1 Component Reliability

As illustrated in Fig. 1.1, the useful life of a component generally is characterized by a virtually constant failure rate. As a result, component reliability is characterized by an exponential distribution function and can be expressed as:

$$R = \exp(-\lambda t) \tag{1.1}$$

where:

R = Probability that a component will operate without malfunction or failure for a specified period of time under the stated operating conditions

λ = Component failure rate, usually expressed as the number of malfunctions or failures per unit of time

t = Time during which a component is subjected to operating conditions

To obtain the component reliability from Eq. 1.1, the component failure rate must be known. The best sources for component failure rates are field data or accelerated-testing results. If failure-rate data are not available, component failure rates may be estimated from the failure rates of the elements that make up the component or subsystem. Appendix A presents examples of this technique.

Another technique for estimating component failure rates is to use published warranty data. Warranties are generally written to cover the component from date of installation. In some situations, operating time and calendar time on which the warranty is based are identical. However, these two time periods can differ, because the component operates only for a portion of each day.

Assume a component is warranted for 15 months and the manufacturer knows the component operates, on the average, for five hours per day. With this information, an upper bound for the failure rate can be estimated.

$$\text{Operating Time} = 365 \frac{d}{yr} \times 5 \frac{hr}{d} \times 1.25 \text{ yr}$$

$$= 2281 \text{ hr}$$

$$\text{and } \lambda_{up} = 1/2281 = 4.4 \times 10^{-4} \text{ failures/hr}$$

A lower-bound estimate for the failure rate can be obtained by assuming the component operates continuously for twice the warranty period. In this case,

$$\text{Operating Time} = 21{,}900 \text{ hr}$$

$$\text{and } \lambda_{lw} = 4.6 \times 10^{-5} \text{ failures/hr}$$

Table 1.1 summarizes this information and indicates the difference between operating and calendar time.

For components with constant failure rates, Eq. 1.1 applies. Here, several reliability measures -- such as Mean-Life (ML), Mean-Time-Between-Failures (MTBF), and Mean-Time-To-Failure (MTTF) -- are used interchangeably.

Table 1.1 Comparison of Calendar Time, Operating Time, and Failure Rates

Calendar Time		Operating Time	Estimated Failure Rates
Years	Hours	(hr)	(No. of failures/hr)
1.25[a]	10,950	2,281[b]	4.4×10^{-4}
2.50	21,900	21,900	4.6×10^{-5}

[a]Assumed warranty period.

[b]Component operates five hours daily.

Although each of these reliability measures has a slightly different meaning, an accepted definition for ML, MTBF, and MTTF is:

> The total operating time of a number of identical components, divided by the number of failures during the measured time period.

In reliability testing, ML and MTBF are used interchangeably and indicate the average life of the components being tested. In these DHW guidelines, ML, MTBF, or MTTF will also indicate the average life of the components or systems. Because of the assumption of constant failure rates,

$$ML = MTBF = MTTF = 1/\lambda \tag{1.2}$$

The time t used to compute component reliability in Eq. 1.1 is the continuous operating time. When components such as pumps or powered valves in solar DHW systems do not operate continuously, the time t has to be modified and replaced by td, where d is the period-of-operation (duty-cycle) factor expressed as the ratio of operating time to total mission time. The component mean-life estimate MTBF should be adjusted accordingly by increasing its value by a factor of 1/d.[1]

1.3.2 System Reliability

In developing a reliability model for a specific system, the main concern is to include a degree of complexity that is appropriate for the accuracy required and the data available. An overly complex model results in analytic difficulties and insufficient data. A simplified model can lead to inaccurate conclusions and difficulties in substantiating the assumptions.

One of the tasks in deriving a reliability formula is to prepare a functional diagram of the system showing how the input and output elements are related. System reliability is, therefore, a reflection of the successful operation of one or more of the component parts. Conversely, system malfunction is represented by one or more component malfunctions. The failures or successes of the components can combine in series so that if any one fails, the system fails. On the other hand, components can be combined in parallel, so that when one component fails, another is available to perform the same function.

To evaluate the reliability of a system, consider the block diagram in Fig. 1.2. In this system, all seven components must operate for the system to function.

The reliability of this system is given by:

$$R_s = \exp(-\lambda_s t)$$

where:

$$\lambda_s = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7$$

t = time

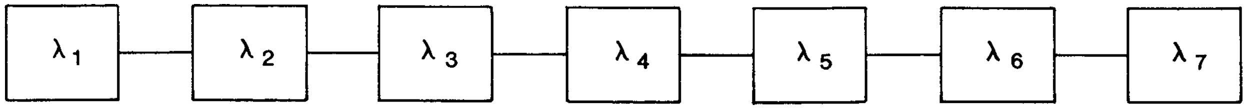


Fig. 1.2 Block Diagram of a System with Seven Series-Connected Components

The failure rates for the components are presented in Table 1.2.

The system failure rate, which is the sum of the individual failure rates, is 8.06×10^{-5}. Component 4 has the highest failure rate and accounts for 43% of the system failure rate.

The effect of component 4 can be reduced by using a higher-quality component. If that is not possible, then a parallel combination, as shown in Fig. 1.3, could be considered.

Table 1.2 Component Failure-Rate Data

Component	Assumed Failure Rate (Failures/10^5 hr)
1	1.2
2	1.06
3	1.4
4	3.5
5	0.3
6	0.3
7	0.3

For the parallel (redundant) combination, the system reliability is now:

$$R_{sp} = [2 - \exp(-\lambda_4 t)]R_s$$

where:

R_{sp} = System reliability with the parallel component

R_s = Original system reliability

The MTBFs of these systems are:

$$MTBF_s = 1/\lambda_s$$
$$MTBF_{sp} = (2/\lambda_s) - [1/(\lambda_4 + \lambda_s)]$$

Using data in Table 1.2, one finds that

$$MTBF_s = 12{,}407 \text{ hr}$$
$$MTBF_{sp} = 16{,}163 \text{ hr}$$

By using a parallel combination, the effect of the component with the highest failure rate is reduced. The system with the redundant component has a MTBF that is 1.3 times greater than that of the original system.

A balance must be struck between calculated reliability values and system or component data obtained from the field or by accelerated testing. Until these experimental data are available, reliability modeling generates a

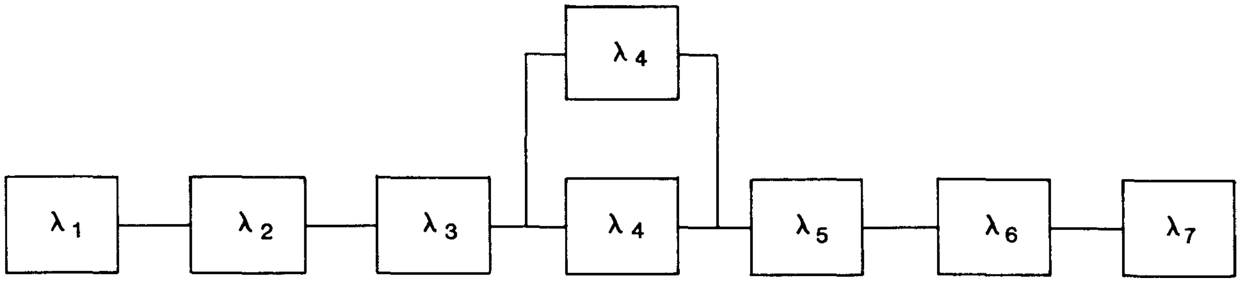


Fig. 1.3 Block Diagram of a System with a Redundant Component

set of values and can identify the critical components that trigger system failure. To improve system reliability, the critical components must be removed, redundancy provided, or improved components developed.

Appendix A contains additional examples of this reliability technique, together with the equations used to characterize the reliability of solar DHW systems.

2 COMMON SYSTEM COMPONENTS

Each solar DHW system has common generic components. The requirements for each generic component are described in this chapter, including heat-transfer fluids, materials of construction, mean-life estimates, and failure modes. The component mean-life estimates are used in Chapter 3 to determine the mean maintenance-free time of particular generic solar DHW systems.

2.1 SOLAR COLLECTORS

Solar collectors for DHW applications are either flat-plate, evacuated-tube, or concentrating collectors. The single-glazed, flat-plate type predominates, and only this type of collector is discussed here. In this section, we describe the flow patterns used in residential systems, the problems that occur during stagnation, materials used in flat-plate collectors, collector failure modes, and mean-life estimates.

2.1.1 Collector-Array Flow Distribution

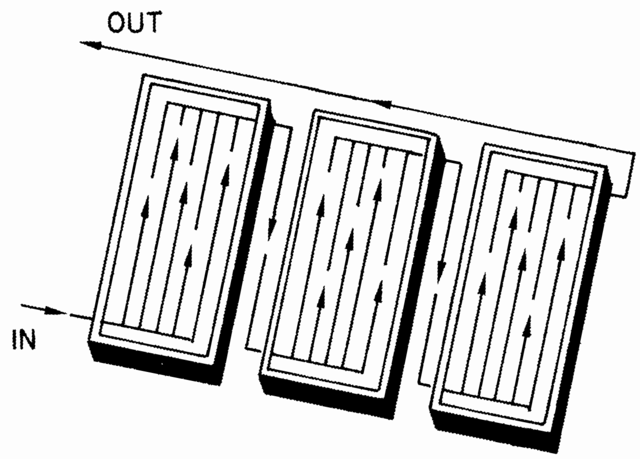
Collector arrays in residential use usually have two to six collector panels, connected in series or parallel. Figure 2.1 illustrates three ways to interconnect three panels. For two to four panels, the choice of series or parallel connection depends on designer preference.

Although the series design (Fig. 2.1a) is slightly less thermally efficient because of higher operating temperatures, it has the advantage of providing hotter water faster than the parallel configuration. Three disadvantages of the series design are the higher pressure drop across the panel array, the necessity of shutting down the entire array to service any single panel, and the difficulty involved in draining the system down.

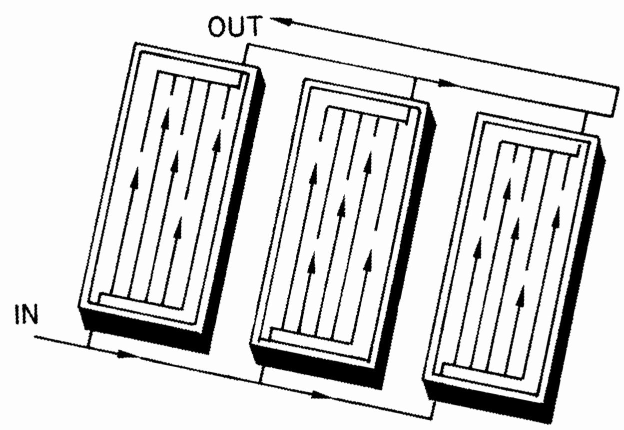
The parallel designs (Figs. 2.1b and 2.1c) are more thermally efficient than the series design (Fig. 2.1a), as long as the flow through each collector is sufficient and balanced. In addition, the pressure drop across a parallel collector array is less than that across a series array. Disadvantages of parallel designs are that flows through the panels may not be equal unless balancing valves are used, and the entire area must be shut down to service a single panel unless isolation valves are installed.

The reverse-return system (Fig. 2.1b) has an advantage over the direct-return system in that, in the former, all flow paths are the same length. Thus, flow distribution in each panel of the reverse-return system is approximately the same, and the panels operate at uniform temperature.

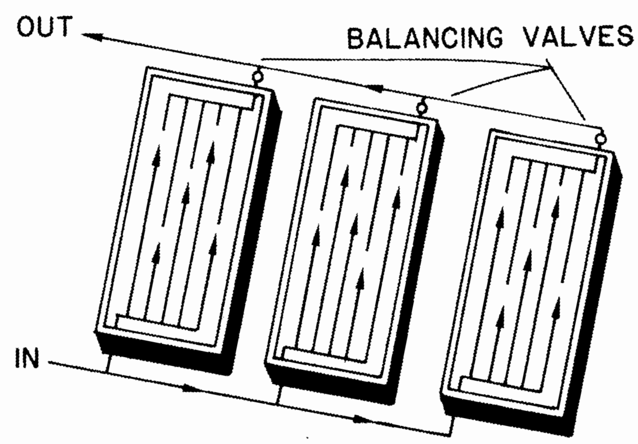
The direct-return system can be used if balancing valves are installed to compensate for flow variations. These valves also equalize pressure drops in the supply and return manifolds. Balancing valves can be eliminated if manifold diameters are varied to maintain constant-velocity flows in the manifolds.



a. SERIES FLOW (LESS EFFICIENT THAN PARALLEL FLOW)



b. PARALLEL FLOW (REVERSE RETURN)



c. PARALLEL FLOW (DIRECT, BALANCED)

Fig. 2.1 Piping Arrangements for Connecting Three Collectors

2.1.2 Stagnation

It is inevitable that collector panels will experience either dry or wet stagnation for varying periods of time during their operating life, if overheat protection is not provided. Because collectors are designed to optimize energy collection and minimize energy loss, absorber-plate surface temperatures easily exceed 350°F (177°C) if the collector is inactive in hot, sunny weather.[2] In most cases, the allowable surface temperatures specified by manufacturers are exceeded. Overheating for extended periods of time may cause the following adverse effects:

- Tin-lead (95/5) solder that bonds the absorber tubes to the absorber plate melts, allowing plate and tubes to separate.
- Foam insulation begins to degrade at 350°F (177°C) or above.
- Freon-blown insulation liberates hydrogen fluoride or hydrogen chloride at 350°F (177°C).
- Sealants and binders of thermal insulation in collectors begin to outgas and fog the glazing at 400°F (204°C).
- System pressure increases rapidly, unless provisions exist to accommodate the increased liquid volume.
- Glycol-water coolant boils, causing a vapor lock that could prevent flow through the collectors.
- Inhibitors in glycol-water coolants deteriorate on repeated exposure to the high temperatures associated with stagnation.

If the collector has stagnated and a relatively cool fluid at about 100°F (40°C) flows through the collector tubes, thermal shock occurs and the absorber plate may undergo large deformations.[3] Thermal shock can cause the cooling tubes to separate from the absorber plate in some configurations.

Hwang et al. investigated thermal shock for a range of materials, absorber-plate thicknesses, and coatings. They also studied the times required for collectors to cool down to thermal equilibrium (Fig. 2.2).[3]

Figure 2.2 compares temperatures at the center of copper, aluminum, and steel absorber plates that are approximately 0.031 in. (0.75 mm) thick. Because the thermal properties of copper and aluminum are similar, the temperature profiles in Fig. 2.2 are similar. However, the equilibrium temperature of the aluminum plate is slightly greater than that of the copper plate.

Steel has relatively poor thermal conductivity, compared with that for aluminum and copper. As a result, temperature response is different for steel, and time to reach equilibrium is greater than 10 min. In addition, the temperature variation across the steel plate is seven times greater than for the copper plate and four times greater than for the aluminum plate.[2]

Several designs can be used to protect the collector from thermal shock. In one design, a temperature sensor on the back of the absorber plate energizes a relay controlling power to the circulating pump. If the collector plate reaches a preselected high temperature, power to the pump is

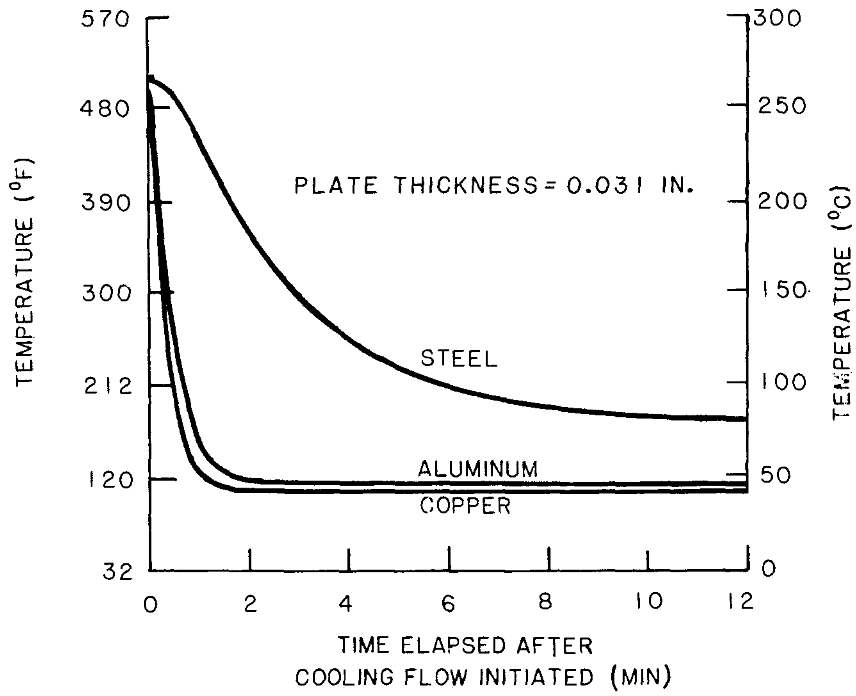


Fig. 2.2 Time for Three Absorber Plates to Reach Equilibrium Temperature[3]

interrupted, preventing circulation of cool collector fluid until the collector cools off. Another design uses a temperature sensor to shut down the circulating pump when a preset temperature differential occurs between absorber plate and circulating fluid. A third design has a temperature sensor that prevents restarting the circulating pump, in case of a power failure, until the collector cools off.

2.1.3 Collector Materials

More than 100 manufacturers produce flat plate collectors from a wide variety of materials. Absorber plates may be made of plastic, aluminum, steel, or copper. The plate surface may be coated with inexpensive flat-black paint, which is easy to apply and lasts more than five years if applied in accordance with manufacturers' recommendations. To increase thermal performance, a more expensive coating with high absorptivity to solar radiation and low emissivity to thermal radiation may be electroplated on the absorber surface. Collector-cover materials include tempered glass, ordinary glass, acrylics, and polycarbonates. The cover also may have an antireflection coating to improve transmission of solar radiation. To minimize energy loss through the back and edge of the collector, one or more layers of thermal insulation, such as fiberglass, foam glass, or polystyrene or isocyanurate foam, is installed. Figure 2.3 illustrates the main components of a typical single-glazed flat-plate solar collector.

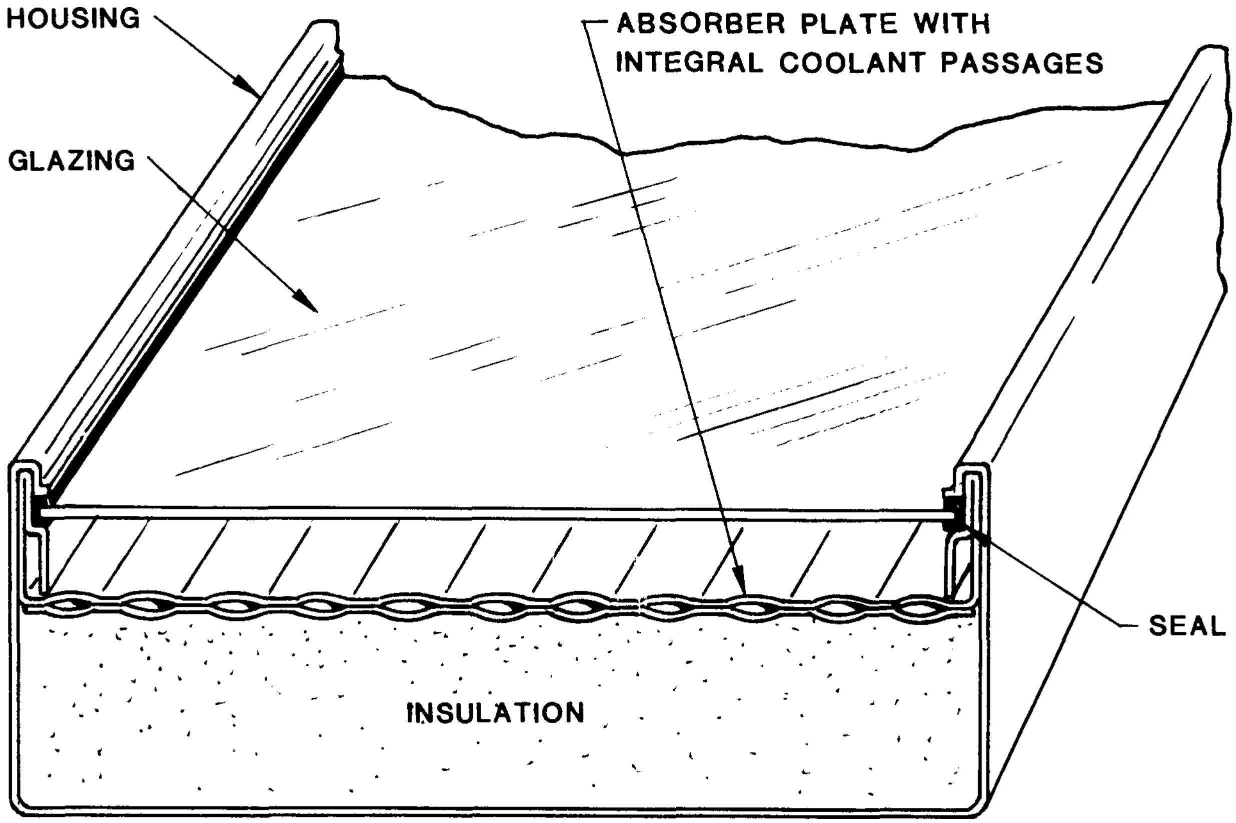


Fig. 2.3 Cross-Section of a Typical Single-Glazed, Flat-Plate Solar Collector

2.1.3.1 Glazings

Solar collectors for DHW systems usually are single-glazed to reduce absorber-plate convection and radiation losses. However, some manufacturers provide double-glazed collectors in which the second glazing is plastic. The decision to use single- or double-glazed collectors should be based on a comparison of the thermal efficiencies over time versus the increased cost of the second cover.

In addition to minimizing convection and radiation losses from the absorber plate, glazings must:

- Transmit a maximum amount of incident solar radiation
- Withstand temperatures in excess of 300°F (150°C)
- Support their own weight
- Withstand impact loads

The materials for collector glazings are sheet glass, plastic, and plastic film. The first two materials are used on single-glazed collectors or as the outer cover on double-glazed units. Plastic films, which cannot withstand impact loads, are recommended only for inner glazings.

Glass is not affected by ultraviolet radiation and absorbs the long-wavelength thermal radiation emitted by the absorber coating. Untempered glass can withstand wind, rain, and snow loads but is susceptible to shattering. Tempering improves impact and heat resistance.[4] Tempered, low-iron glass covers have solar-transmission ratings of 86%. With acid etching, this transmission rating can be increased to 90%.[5]

Dirt and grime reduce the optical transmission of collector covers. However, experiments show that dirt and grime are no worse on etched than unetched glass.[5] For a glass panel exposed to an outdoor urban environment for six months, transmission degradation was 4% from dirt and grime. Washing the glass with a mild detergent restored the original transmission level. If dirt accumulates on a glass cover, washing is required at least twice yearly.

Deposits on the underside of cover plates can result from moisture condensation or from outgassing from an internal source, such as sealants or insulation.[6] The effect of such deposits may be to reduce transmission by 10% or more, but cleaning the inside of cover plates is a relatively costly matter. Some collectors use weep holes or desiccants to alleviate these problems.

Self-supporting Lexan* polycarbonate sheets are lighter than glass and not as brittle, but they are more susceptible to dirt. Lexan* is fairly soft, and warpage was observed in systems with this collector glazing. Stress cracking of polycarbonate cover plates was observed at the edge of stiffening ribs.[6] Furthermore, although Lexan* has an initial transmittance of 83.3%, yellowing from surface weathering and ultraviolet degradation reduced transmittance to 78.7% over a five-year period.[4,7,8]

Plastic films are attractive because of their low cost. However, supplementary support systems, needed to stretch and hold them in position, increase their cost. Plastic films generally are not very durable when exposed to radiation; if a film is used as an inner cover, ultraviolet durability may not be required. The following plastic films are ranked in order of preference according to transmission rate and durability: Teflon** FEP, Tedlar,** Sunlite Premium,† and Mylar.**[8]

The mechanical, thermal, and radiative properties of cover-plate materials have been reviewed by several authors.[4,7,9] Table 2.1 summarizes data extracted from Ref. 10, issued by Illinois Institute of Technology Research Institute. Mean life is determined by estimating the exposure required to decrease solar transmittance to 70% of its initial value or to produce mechanical failure.

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*Trademark of General Electric Co.

**Trademark of E.I. DuPont de Nemours & Co.

†Trademark of Kalwall Corp.

Table 2.1 Properties of Solar-Collector Glazing Materials

Material	Solar Transmittance (%)[a] Initial	Value After Exposure at Chicago	Miami	Phoenix	Exposure Time (months)	Estimated Life (years)	Remarks
Glass[b]							
Libby-Owens-Ford 1/8 in. Regular Float	82.6	83.8	84.0	85.1	32	Indefinite	Estimated life depends primarily on avoiding induced mechanical loads. Exposure increases transmittance.
Libby-Owens-Ford 1/8 in. Regular Soda Lime	82.5	77.9	82.9	82.7	24	Indefinite	Estimated life depends primarily on avoiding induced mechanical loads.
Heliolite 1/8 in. Low Iron Tempered	90	NT[c]	NT	NT	NT	Indefinite	Estimated life depends primarily on avoiding induced mechanical loads.
Sunadex 1/8 in. Rolled, 0.01% Iron Oxide	91	NT[c]	NT	NT	NT	Indefinite	Estimated life depends primarily on avoiding induced mechanical loads.
A F G 1/8 in. Low-Iron (0.05% Iron) Oxide Tempered	89	NT[c]	NT	NT	NT	Indefinite	Estimated life depends primarily on avoiding induced mechanical loads.
Self-Supporting Plastic Sheet							
Rohm and Hass Plexiglass V-100 (Type 045) 1/8 in. Thick Molded Acrylic	87.4	86.4	87.7	88.0	35	5-10	

Table 2.1 (Cont'd)

Material	Solar Transmittance (%)[a] Initial	Value After Exposure at Chicago	Miami	Phoenix	Exposure Time (months)	Estimated Life (years)	Remarks
Self-Supporting Plastic Sheet (Cont'd)							
Rohm and Hass Plexiglass "G" 1/4 in. Thick Cast Acrylic	85.8	83.4	83.7	83.3	33	5-10	
USS Novamont, Inc. S-300 3/16 in. Thick Cast Acrylic	85.2	84.7	86.2	85.3	24	5-10	
USS Novamont, Inc. S-GPA 3/16 in. Cast Acrylic	84.6	82.4	84.9	85.1	24	5-10	
Rohm and Haas "Tuffak" 1/4 in. Extruded Polycarbonate	77.5	66.3	72.5	69.1	12	2-5	
Mobay "Merlon" 1/8 in. Polycarbonate	81.8	NA[d]	42.6	73.1	33	Less than 4	
Mobay "Merlon" 1/8 in. Polycarbonate with Clear Protective Coating	82.8	NA[d]	78.6	73.3	33	Less than 8	

Table 2.1 (Cont'd)

Material	Solar Transmittance (%)[a] Initial	Value After Exposure at Chicago	Miami	Phoenix	Exposure Time (months)	Estimated Life (years)	Remarks
Self-Supporting Plastic Sheet (Cont'd)							
Eastman Chemical UVEX 3/16 in. Cellulose Acetate Butyrate with Ultraviolet Inhibitor	80.3	80.1	81.5	80.9	6	4-8	Limited data; strong temperature dependence.
Plastic Films							
Kalwall "Sunlite Regular" 0.04 in. Acrylic-Fortified Fiberglass-Reinforced, Polyester Sheet[f]	79.9[e]	80.5[e]	65.9[e]	74.5[e]	32	4-6	
Kalwall "Sunlite Premium" 0.04 in. Fiberglass-Reinforced, Modified, Polyester Sheet[f]	87.5[e]	NA[d]	67.3[e]	76.9[e]	32	2-7	Degrades rapidly in moist, sunny climates.
Elion Type 548 0.03 in. Acrylic-Fortified, Fiberglass-Reinforced Tedlar[g]-Coated Polyester Sheet	58	43.1	36.5	35.4	32	2-4	

Table 2.1 (Cont'd)

Material	Solar Transmittance (%)[a] Initial	Value After Exposure at Chicago	Miami	Phoenix	Exposure Time (months)	Estimated Life (years)	Remarks
Plastic Films (Cont'd)							
American Acrylic Corp. "Antique Glass" 0.06 in. Fiberglass-Reinforced Acrylic-Alkyd Copolymer	54.7	48.3	39.0	30.6	32	3-10	
American Acrylic Corp. "Crystal" 0.06 in. Fiberglass-Reinforced Acrylic Sheet	29.5	NA[d]	9.2	11.5	32	1.5-3	
Thin Film Plastics							
DuPont Tedlar[g] 0.004 in. SE Poly-Vinyl-Fluoride	90.7	78.8	86.0	88.7	24	2-5	
3-M Scotchpar #10 0.002 in. Polyester	86.9	86.0	83.4	MF[h]	12	1.5-2	

Table 2.1 (Cont'd)

Material	Solar Transmittance (%)[a] Initial	Value After Exposure at Chicago	Miami	Phoenix	Exposure Time (months)	Estimated Life (years)	Remarks
<u>Thin Film Plastics</u> (Cont'd)							
Penwalt Corp. Kynar 450 0.0038 in. Vinylidene Fluoride Homo-Polymer (unless noted)	82.5	78.6	81.1	81.6	33	1-5	

[a]Normal solar transmittance values shown unless noted. These are a conservative estimate for solar hemispherical transmittance.

[b]Glass is an excellent glazing material, so only a few types are presented.

[c]NT - not tested; data from manufacturer.

[d]NA - data not available.

[e]Hemispherical solar transmittance.

[f]Material replaced with "Sunlite Premium II." Additional data not available.

[g]Trademark of E.I. DuPont de Nemours and Co.

[h]Material failed.

2.1.3.2 Seals and Sealing Compounds

Preformed seals (gaskets) and sealing compounds used to support the glazing and to isolate the absorber plate from its support must withstand high humidity and air temperatures as high as 300°F (150°C) during normal operation. If stagnation occurs, seals and sealing compounds may have to withstand temperatures as high as 400°F (204°C).

The most hostile environmental condition affecting seals and sealing compounds in solar collectors is long-term exposure to air at elevated temperatures. As temperatures increase, gasket and seal materials give off stabilizers, such as antioxidants, antiozonants, and ultraviolet absorbers, and the materials degrade, taking a permanent compression set. Recently, Mendelsohn et al. completed an extensive literature search and performed accelerated testing of elastomers used for preformed seals and sealing compounds in solar collectors.[11] Elastomers evaluated in the Mendelsohn study are listed in Table 2.2.

For materials used in fabricating preformed seals or gaskets, compression set is one of the important properties for flat-plate-collector applications. If the gasket takes a compression set, the seal between collector frame and glazing is lost. As a result, dirt and moisture enter the absorber-plate enclosure and collect on the underside of the glazing. Table 2.3 summarizes Mendelsohn's compression-set data at three operating temperatures and presents the estimated mean life of the compounds under system operating conditions.

Outgassing of seals and sealing compounds at elevated temperatures is a major problem in solar collectors. Volatile organic components of seal materials are released, usually as gases, liquids, or low-melting-point solids. The gaseous forms condense on the underside of the glazing. Once deposited, these condensates do not evaporate cleanly if reheated. As a result, a colored oily residue, white powdery deposit, or solid film remains on the underside of the collector glazing, reducing solar transmittance.

Results of outgassing experiments show that elastomeric sealing compounds generate more volatiles and condensates during thermal aging than do elastomeric preformed seals. Fluorocarbon elastomers show the least outgassing, followed by silicones, acrylics, and EPDM.[11]

Sealing compounds or caulks of Mono* (acrylic), Hypalon** (chlorosulfonated polyethylene), and butyl released unacceptably high quantities of condensable gases and, therefore, should not be used in direct communication with the solar-collector interior. This ban also applies to preformed seals fabricated from butyl and ethylene-propylene-diene monomer (EPDM). A similar problem exists with silicone caulks. When heated, these compounds give off large quantities of low-molecular-weight cyclic polysiloxanes that condense on glazing, ultimately forming an opaque white deposit of silica. The effects of various condensates on transmittance are shown in Table 2.4.

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*Trademark of Tremco Corp.

**Trademark of E.I. DuPont de Nemours & Co.

Table 2.2 Elastomers Evaluated for Solar Collectors

Code	Supplier Designation	Class[a]	Type	Supplier
A	Silicone rubber sealant, known as DC 732	SC	Silicone	Dow Corning
B	790 building sealant, known as DC 790	SC	Silicone	Dow Corning
C	RTV 103	SC	Silicone	General Electric
D	Mono	SC	Acrylic ter-polymer	Tremco
E	External flex Hypalon sealant	SC	Chlorosulfo-nated poly-ethylene	Gibson-Homans
F	Butyl sealant	SC	Butyl	Tremco
G	SE-7550	PS	Silicone	General Electric
H	Silastic 747	PS	Silicone	Dow Corning
I	HS-70	PS	Silicone	Dow Corning (polymer com-pounded by North American Reiss)
J	3300-12A	PS	Ethylene/acrylic	DuPont
K	210-108-35-1, Hycar 4054	PS	Acrylic	Goodrich
L	31-323-0731A, Viton	PS	Fluorocarbon	DuPont
M	PLV 1008, Viton	PS	Fluorocarbon	DuPont (polymer com-pounded by Pelmor)
N	3300-11, Norel	PS	Ethylene-propylene terpolymer (EPDM)	DuPont
O	SR 35020	PS	Butyl	Stalwart
P	BEX-123 (Butyl 100)	PS	Butyl	Polysar
Q	NPC 80/40	PS	Silicone	Dow Corning (polymer com-pounded by North American Reiss)
R		PS	Butyl	Obtained from a collector of used Pittsburgh Plate Glass

[a]SC, sealing compound; PS, preformed seal.

Table 2.3 Summary of Compression-Set Thermal-Aging Data

Material	Code[a]	Days to Reach 50% Compression Set			Estimated Life[b] (years)
		257°F (125°C)	302°F (150°C)	347°F (175°C)	
Fluorocarbon	L	7400[b]	510[b]	135[c]	16
Silicone	Q	100	21	5	2/3
Silicone	G	50	7	2	1/4
Silicone	I	33	8	2	1/4
EPDM	N	103	50	27.5	1-2/3
Acrylic	K	105	28	10.5	1
Ethylene-acrylic	J	35	8	4	1/4
Butyl	P	23	8	4.5	1/4

[a]See Table 2.2 for letter code list.

[b]Based on the 302°F (150°C) data.

[c]Based on an Arrhenius-plot extrapolation.

Table 2.4 Effect of Glaze Deposits on Relative Light Transmittance

Deposit	Amount		Reduction of Relative Light Transmittance (%)
	10^{-5} lb/ft^2	g/m^2	
Water leaching of glass			
Salts	3.09-4.85	0.15-0.24	20-34
Silicone rubber fragments			
Oil	8.19	0.4	1
Powder	2.64	0.13	18
Butyl rubber fragments			
Oxidized	0.68	0.03	4
Acrylate rubber fragments			
Oxidized	0.41	0.02	1
Stearic acid from rubber			
Liquid	8.19	0.4	1
Solid	8.19	0.4	5-6
Processing oil from rubber			
Liquid	8.19	0.4	1
Oxidized	4.1	0.2	10

Substrate corrosion, hydrolytic instability, weather resistance, resistance to fungi, and ozone resistance were not, in general, found to be major problems. Corrosion is not a problem if either anodized aluminum or mill-finish aluminum is used for frames instead of galvanized steel. Although fungicides should be incorporated into fluorocarbon or butyl formulations, most other elastomers have adequate resistance to fungi. Only butyl had inadequate resistance to ozone, and only acrylic caulking compounds appeared to be affected appreciably by accelerated weathering.

On the basis of physical properties, availability, and economics, the preformed seals and sealing compounds recommended by Mendelsohn et al. are as follows: (1) High temperature (approximately 380°F or 195°C) -- fluorocarbons; (2) Intermediate temperature (approximately 350°F or 175°C) -- silicones, acrylics, acrylic copolymers, and EPDMs.[11]

Because organic caulks, such as acrylic or butyl, lose their elastomeric properties rapidly on exposure to elevated temperatures, their use in solar collectors is not recommended. Silicone sealing compounds retain their properties but are mechanically weaker than silicone preformed seals. Silicone sealing compounds, therefore, should be used where they are not subject to mechanical stress. Furthermore, they should have no direct communication with the interior of the solar collector, or volatile cyclic-polysiloxane decomposition products will be deposited on the glazing or absorber plate.

2.1.3.3 Absorber Plates, Tubes, and Coatings

Absorber plates and tubes for flat-plate collectors must withstand the following:

- Operating temperatures to 200°F (93°C)
- Maximum stagnation temperatures to 400°F (200°C)
- Operating flows of 0.3 gal/(min·ft^2)[0.2 L/(min·m^2)]
- Operating air flows of 2 ft^3/(min·ft^2)[10 L/(s·m^2)]
- Operating pressures of 25 to 100 psi (172 to 688 kPa) or 160 psi (1104 kPa) for systems operating on line pressure
- Operating air pressures of 0.2 to 3.0 in. of water (50 to 747 Pa)
- Temperature cycling ranges of -20°F to 400°F (-29°C to 204°C)

Materials for absorber panels and tubes in collector panels are usually highly conductive metals, such as copper, aluminum, and steel. Premature failure of these materials is not anticipated except from corrosion caused by the heat-transfer liquid at the interval passage (see Sec. 2.3), or from poor absorber-panel-to-tube bonds, although in the latter case both extrusion- and roll-bonding have been satisfactory. However, low-temperature solder that has a melting point below 450°F (230°C) must not be used to join absorber plates to the panel and tubes or physical separation may occur at elevated temperatures.

Coatings are applied to absorber plates of solar collectors in order to improve their efficiency in gathering and retaining incident solar energy. The ideal coating would have the following characteristics:

- High absorptivity
- High thermal conduction
- Low thermal emissivity
- Endurance of temperature cycling between -20°F and 400°F (-29°C and 204°C)

Two general types of coatings are used for solar-collector applications, selective and nonselective. Unless collectors are designed to work at temperatures in excess of 200°F (93°C), either coating type gives satisfactory thermal performance. Although nonselective coatings are less expensive than selective coatings, the former are less durable and require periodic maintenance. Selective coatings are more expensive, but they are also slightly more efficient than nonselective coatings and require little or no maintenance for periods of up to 20 years.

Optical parameters for absorber-plate coatings are absorptivity (α), emissivity (ε), transmittance (τ), and reflectance (ρ). Values reported for α or ϵ are usually integrated values derived from reflectance data. In general, many discrepancies and inaccuracies exist among reported values, because different analytical equipment and test procedures are employed. Applied research on coatings for enhanced solar-energy collection is being conducted at Lawrence Berkeley Laboratory.[12]

There are three types of black, nonselective coatings: paints, fused vitreous porcelain enamels, and metal conversion coatings. Of about 80 organic and inorganic pigments evaluted at the Honeywell System and Research Center, Ferro F-6331 had the best optical properties.[13] Paint coatings with this metal oxide in an aliphatic urethane binder have 0.92 absorptivity and 0.13 emissivity. The paint coatings have good environmental stability, but their mechanical durability is poor. Adhesion to substrates and abrasion resistance needs improvement. In normal service, peeling and cracking of paint coatings seem to occur within 2 to 3 in. (5 to 7 cm) of absorber-plate edges and on lower areas of the absorber plate.[6] Table 2.5 summarizes these data.

Fused vitreous porcelains resist high temperatures and have long-term durability, but nonglossy or flat coatings are difficult to formulate and require firing at moderate to high furnace temperatures.

Among chemically blackened coatings evaluated by NASA, only copper treated with Ebonol C* and steel treated with Ebonon S-34* appear satisfactory.[14] Other combinations, such as zinc and Ebonol Z,* aluminum and Electroless Black Magic,** and anodized coatings of aluminum and titanium, lack desired optical properties. Table 2.6 summarizes these data.

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*Trademark of Euthone, Inc.

**Trademark of Michell-Bradford Co.

Table 2.5 Paints Used for Absorber Coatings

Material	Substrate	Plating or Coating Data	Solar[a] Absorptivity (%)	Thermal[b] Emissivity (%)	$\frac{\alpha_S}{\epsilon_{IR}}$	Temperature Limits (°F)	Durability[c]	Estimated Life	Producer
Black acrylic paint - Non-selective	Steel Aluminum	Thoroughly clean the aluminum surface. Spray duracron super 600 L/G and bake at 375°F for 15 min.	95	95	1	325-375	Humidity tests showed no degradation. Temperatures above 325°F cause surface dulling. Surface hardness better on thermosetting acrylic.	Less than 2 yr. Needs repainting of localized hot spots.	Duracon paint producer: P.P.G. Industries
		Similar process, except Nextel black paint is used.	96.7	96.7	1				Applicator, Howmet Corp.
Selective Paint: PbS pigment, Silicon binder	Steel Aluminum	0.1 micron thickness, silicon weight 0.5 mg/cm^2, PbS weight 0.17 mg/cm^2.	84	19	4.4	Above 350	Anticipated durability equal to black acrylic, with better temperature limitations.	Less than 2 yr. Needs repainting of localized hot spots.	Experimental work
		Silicon weight 0.17 mg/cm^2, PbS weight 0.55 mg/cm^2.	90	37	2.4				
Selective Paint: Meteor 7890, Cu-CrO pigment; EPD[d] binder	Steel Aluminum	0.21-mil-thick coating, 30% pigment-volume concentration.	95	47 H = 61[e]	2.02	No data.	Formal durability tests not performed. Anticipated to be equal to that of acrylic paint.	Less than 2 yr. Needs repainting of localized hot spots.	Pigment producer, Harshaw Chemical; Binder producer, EXXON
Selective Paint: CdTe pigment, EPD[d] binder	Steel Aluminum	0.20-mil-thick coating, 30% pigment-volume concentration.	90	48 H = 49[e]	1.9	No data.	Formal durability tests not perfomed. Anticipated to be equal to acrylic paint.	Less than 2 yr. Needs repainting of localized hot spots.	No data provided
Selective Paint: Meteor 7890, Cu-CrO pigment; EPDM[f] binder	Steel Aluminum	30% pigment-volume concentration.				No data. Binder has excellent temperature resistance.	Formal durability tests not performed. Expected to be equal to or better than acrylic paint.	Less than 5 yr.	Pigment producer, Harshaw Chemical; Binder producer, EXXON
		0.5 mil coating.	92	30	2.1				
		0.13 mil coating.	94	45	2.1				

[a]Solar absorptivity data obtained by integrating reflectivity data over solar spectrum, assuming $\alpha_s = 1 - \rho_s$. (Hemispheric values shown.)

[b]Thermal emissivity data based on absorber emitting energy from 200-500°F. Data numerically attained through analysis of reflectivity data using $\epsilon_{IR} = 1 - \rho_{IR}$. (Hemispheric values shown.)

[c]Durability data based on temperature limitations, and on humidity tests conducted by Honeywell, Inc. Principal humidity test (MIL-STD-810B) employed temperature cycling of 90 to 160°F at 95% relative humidity for 24 hours.

[d]EPD is ethylene-propylene-diene.

[e]Total hemispherical thermal emissivity measured calorimetrically at 200°F.

[f]EDPM is ethylene-propylene-diene monomer.

Table 2.6 Dip or Chemical-Conversion Selective Absorber Coatings

Dip or Chemical-Conversion Coatings: Material	Substrate	Plating or Coating Data	Solar[a] Absorptivity (%)	Thermal[b] Emissivity (%)	α_S / ϵ_{IR}	Temperature Limits (°F)	Durability[c]	Estimated Life	Producer
Black copper (copper oxide)	Copper	Proprietary data of Ethone, Inc.	90	12	7.5	375 (continuous use) 400 (short term)	Ethone, Inc., guarantees absorber to be 80% effective after five years. Durability questionable in humid atmospheres and at temperatures above 300°F.	Greater than 10 yr.	Ethone, Inc.
		Bath time: 5 min Bath temperature: 219°F	91	16	5.7				
		Bath time: 10 min Bath temperature: 140°F	90	20	4.5				
		Bath time: 4.5 min Bath temperature: 150°F	88	16	5.5				
Black iron (iron oxide)	Steel	Bath time: 2 min Bath temperature: 295°F	84	8	10.5	600-700[d]	One-micron-thick coating withstood humidity test, with minor rust-spots occurring. Thinner coatings may break down or rust through in humid environments.	Greater than 10 yr.	Ethone, Inc.
		Bath time: 9 min Bath temperature: 295°F	89	35	2.5				
		Bath time: 15 min Bath temperature: 286°F	85	10	8.5				
		Bath time: 3 min Bath temperature: 300°F	90	7	12.9				
Iron oxide	Steel	Heat carbon steel in air to 550-600°F. Quench in water once steel attains dark blue color.	88	12[e]	7.3	Above 600	Coating may break down in humid environments, promoting rust. Difficult to attain uniform properties.	Less than 5 yr.	Industrial Process Data
Alcoa black	Aluminum	Chemical conversion process known as Alcoa process 655 (Alcoa proprietary data).	90	30	3.0	350	Extremely durable in controlled-humidity environment near 200°F. Coating destroyed by impinging water.	Greater than 10 yr.	Aluminum Company of America
			90	40	2.2				

[a]Solar absorptivity data obtained by integrating reflectivity data over the solar spectrum, assuming $\alpha_s = 1 - \rho_s$. (Values are hemispheric.)

[b]Thermal emissivity data based on absorber emitting energy from 100-300°F. Data numerically attained through analysis of reflectivity versus wavelength curves, assuming $\epsilon_{IR} = 1 - \rho_{IR}$. (Values are hemispheric.)

[c]Durability data based on temperature limitations, and on humidity tests conducted by Honeywell, Inc. Principal humidity test (MIL-STD-810B) employed temperature cycling of 90 to 160°F at 95% relative humidity for 24 hours.

[d]Estimated by Ethone.

[e]Estimated by Honeywell.

Among selective coatings, black-iron plate costs less than either chrome or nickel plate, is optically efficient (with an absorptivity of 0.90 and an emissivity of 0.07), and can be made more durable with little increase in cost by applying a silicone overcoat. Black-iron plate uses nonstrategic materials and is satisfactory for low-cost collectors.[14]

Black-chrome plate (Harshaw Process*) and black-iron plate (Ebonol S Process**) are the most promising selective coatings for flat-plate solar collectors. Black-chrome plate has good optical properties (α = 0.95, ε = 0.09) and is the more durable. Coating life is estimated to be more than 30 years when 0.5-mil nickel (Harshaw NUSAT*) and an undercoat is used. One-quarter-mil nickel provides adequate protection for a steel substrate.[14]

Double-layer black nickel on nickel-plated steel exhibits an α of 0.95 and an ε of 0.07. However, this coating is expensive and has been shown to be susceptible to degradation from humidity in laboratory tests and in service.[6,15] Table 2.7 summarizes these data.

2.1.3.4 Insulation

Collector enclosures must be well insulated to minimize heat losses. Insulation should be selected for the following conditions:

- Maximum temperature of 400°F (204°C)
- Temperature cycling range of -20°F to 250°F (-29° to 120°C)
- Thermal conductance of less than 0.1 Btu/(hr-ft^2-°F) [0.57 W/(m^2-°C)]

Many insulation materials designed for construction-industry applications are not suitable for solar collectors, primarily because the insulation binders outgas at normal collector operating temperatures. Also, at temperatures over 350°F (177°C), freon-blown foams liberate hydrofluoric and hydrochloric acids that corrode selective absorber coatings.[16]

Solar-collector insulation types are mineral fiber, ceramic fiber, foamed glass and plastic foam, and fiberglass. Thermal and physical properties of these materials are summarized in Table 2.8.[4,8] Estimated life of these materials is 10 to 30 years.

Mineral and ceramic fibers are comparable with fiberglass in thermal conductivity. Mineral fibers generally are used for high temperatures and cost much more than ceramic fibers; an exception is mineral wool, a loose fill material with relatively low thermal conductivity. Mineral wool tends to settle under its own weight, eventually leaving an air gap behind the absorber panel. This decreases collector efficiency by increasing absorber-plate heat loss. Mineral wool also loses its insulating qualities when subjected to humidity cycling.

Fiberglass is the lowest-cost insulation available today. It is produced in a range of densities (density affects thermal conductance) and a

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*Trademark of Harshaw Chemical Co.

**Trademark of Euthone, Inc.

Table 2.7 Electroplated Selective Absorber Coatings

Electroplated Surfaces: Material	Substrate	Plating or Coating Data	Solar[a] Absorptivity (%)	Thermal[b] Emissivity (%)	α_S / ϵ_{IR}	Temperature Limits (°F)	Durability[c]	Estimated Life	Producer
Black chrome over dull nickel	Steel	Plating density: 180 A/ft^2 Plating time: 30 sec	87	6	14.5	Above 700	Excellent durability in humid environment. Five days humidity testing yielded 1% loss in α_s and 5% gain in ϵ_{IR}.	Greater than 30 yr.	Olympic Plating Industries
	Copper	Plating density: 180 A/ft^2 Plating time: 1 min	96	10	9.6				
	Aluminum	Plating density: 180 A/ft^2 Plating Time: 2 min	96	12	8				
Black chrome	Steel and galvanized steel	Plating density: 300 A/ft^2 Plating time: 2 min	95	15	6.3	Above 800	Humidity tests on galvanized-steel absorber produced minor rusting. Major rusting occurred on steel absorbers. Oxidation developed on copper absorber.	Greater than 30 yr.	Olympic Plating Industries
	Copper	Copper cleaned and buffed Plating density: 180 A/ft^2	90-95[d]	20-25[d]	4.75-3.6				
Black nickel over nickel	Steel copper aluminum	Plating density 1: 93 A/ft^2 Plating time 1: 1-2 min[e]	87.7	6.6	13.3	Above 550	Destroyed by moisture as indicated by humidity tests.	Greater than 2 yr.	Olympic Plating Industries
		Plating density 2: 1.86 A/ft^2 Plating time 2: 1-2 min	96	7	13.7				
Black nickel	Steel and galvanized steel	Plating density: 1.86 A/ft^2 Plating time: 2-4 min	88.6	12.2	7.3	Above 400	Humidity test produced rust on steel absorbers. Copper absorber oxidizes and nickel plating breaks down under moisture and acid.	Greater than 15 yr.	Solar Equipment Corporation
	Copper	Proprietary data of Solar Equipment Corporation	87 91.4	10 11.6	8.7 7.9				

[a]Solar absorptivity data obtained by integrating reflectivity data over the solar spectrum, assuming $\alpha_s = 1 - \rho_s$. (Hemispheric values shown.)

[b]Thermal emissivity data based on the absorber emitting energy from 100 to 300°F. Data attained through analysis of reflectivity versus wavelength curves, assuming $\epsilon_{IR} = 1 - \rho_{IR}$. (Hemispheric values shown.)

[c]Durability data based on temperature limitations and on humidity tests conducted by Honeywell, Inc. Principal humidity test (MIL-STD-810B) employed cycle of 90 to 160°F at 95% relative humidity for 24 hours.

[d]Estimate by Olympic Plating Industries.

[e]Data on electroplating two layers of nickel on substrate metal. Plating data provided yields with varying α_s/ϵ_{IR} ratios depending on lengths of plating time. Two sets of radiative data provide examples of variance in possible results.

Table 2.8 Physical Properties of Collector-Housing Insulation[a]

Type	Name or Code Designation	Manufacturers[b]	Thermal Conductance [Btu/(ft^2-hr-°F)]	Thermal Conductance [W/(m^2-°C)]	Max. Temp. (°C)	Form
Fiberglass	K-295	CTP	0.0102	0.0577	232	Blanket
	K-231	CTP	0.0074	0.0418	232	Blanket
	730	OC	0.0094	0.0533	232	Semirigid
	735	OC	0.0069	0.0389	232	Semirigid
Glass foam	Glass foam	PC	0.0097	0.0548	492	Rigid block or board
Mineral fibers	Mineral fiber	EP	0.0068	0.0386	760	Blanket
	Super Cal-temp	Pabco	0.0087	0.0494	649	Rigid block or board
	Mineral wool	Conwed	0.0081	0.0461	649	Loose fill

[a]Estimated life is 10 to 30 years.

[b]Manufacturers: CTP, Certain-Teed Products; OC, Owens Corning; PC, Pittsburgh Corning; EP, Eagle-Picher.

variety of binders. For high-temperature applications, semirigid fiberglass board with a minimum of binder is recommended. Furthermore, this insulation should be preheated above 350° (177°C) to drive off what little volatile binder is present before placing the cover plate on the collector housing. With this preparation, semirigid fiberglass-board insulation can be used to 700°F (370°C), provided it is not compressed.

Exposed polyurethane foam is not recommended as a collector-insulation material. Field exposure resulted in degradation of the foam from ultraviolet radiation, followed by swelling.[6] A new polyurethane foam impregnated with special resins or binders is said to be resistant to ultraviolet radiation.

2.1.3.5 Collector Housing

Physical and mechanical requirements for collector housings are met by several materials. Maximum anticipated operating temperature is about 250°F (120°C). The housing must be structurally sound, weathertight, fire resistant, and capable of being mechanically connected to a substructure to form an array.

External-housing surfaces may be exposed to a variety of climates that will significantly affect their durability. Factors that are important in microclimatic effects include:

- Chlorides in coastal regions, sulfur dioxide in industrial areas, or other atmospheric pollutants.

- High atmospheric humidity. Corrosion becomes significant when atmospheric relative humidity exceeds 70%. When hygroscopic contaminants are deposited on metal surfaces, critical relative humidity for corrosion may be lowered from 70% to 50%.
- Ultraviolet radiation from the sun breaks down organic materials, such as paint, coatings, mastics, rubbers, and plastics. This radiation affects the durability of many components, including heat-absorber surface.
- Diurnal temperature fluctuations often are as much as 85°F (47°C), which can cause moisture to condense on cool metal surfaces. Water retention on metal surfaces is important in subsequent corrosion. Temperature fluctuations, combined with condensed moisture, are detrimental to metal and to protective coatings on metals.

Collector-housing fabrication materials include:

- Galvanized or painted steel
- Aluminum, folded sheet stock, and extruded wall materials
- Various plastics, either molded or extruded
- Composite wood products, including molded or pieced paper products
- Concrete

Battens and enclosures made of aluminum, galvanized steel, or epoxy-coated steel have resisted atmospheric corrosion successfully at solar demonstration sites for short time periods in some climates. However, severe salt-air corrosion of unprotected surfaces (mechanically cut edges) of galvanized steel battens and enclosures is already being reported.[17] Recent data indicate that corrosion rates of zinc and zinc coatings are much higher than values cited in the literature for temperate zones.[18] At a North Sea offshore-drilling site, a number of dramatic premature failures of a structural steel platform painted with a zinc-silicate primer and vinyl topcoats have been reported, but a similarly treated platform has functioned satisfactorily in the Gulf of Mexico.[19] These examples indicate that microclimatic conditions and exposure times are important factors in selecting collector-housing materials.

2.1.4 Collector Failure Modes

Field data from operational solar-energy systems[15,20] indicate the primary failure modes for flat-plate collectors are:

- Freezing
- Seal or gasket leaks
- Absorber-coating degradation
- Outgassing

Freezing of solar collectors is more related to system design than to collector design. In some collectors that froze, water could not drain because the system was air-bound or the collectors were improperly installed. Improper brazing of absorber tubes to internal manifolds can produce an obstruction and cause a properly installed collector system to freeze.

Unlike freezing, which can damage a collector during one cold night, gasket or seal leakage develops over time. This failure mode can be traced to specification of improper gasket and seal materials. Table 2.3 shows the mean lives of common gasket and seal materials.

When gasket or seal failure occurs, moisture usually appears on the underside of the glazing. In addition, dirt can also enter the collector, in which case glazing transmission can be reduced from approximately 90% to practically zero.

Outgassing of seals, gaskets, absorber coatings, or insulation is an important failure mode. In such cases, the underside of the glazing becomes coated with organic condensates. On reheating, these condensates, which do not evaporate cleanly, can leave a variety of residues, reducing glazing transmission.

When outgassing of gaskets and seals occurs, seals usually fail in time, allowing moisture and dirt to enter the collector enclosure. However, available data do not indicate the fraction of seal failures attributable to outgassing or to compression set.

Usually after insulation or absorber coatings have reached a temperature high enough to cause outgassing, these elements are stable. Exceptions are materials that liberate hydrochloric or hydrofluoric acid vapors. These acid vapors can continue to attack metallic parts or even glazings.

Gasket and seal failures can also cause absorber-plate coatings to degrade. For example, as indicated in Tables 2.6 and 2.7, black-chrome, black-nickel, black-nickel-over-nickel, and iron-oxide coatings are affected by moisture.

Absorber plates also degrade because either improper material was applied or the surface was improperly prepared. In both cases, coatings can peel or flake off the absorber plate. In addition, absorber-plate coatings outgas. The outgassing products accumulate on the underside of glazings.

2.1.5 Single-Collector-Panel Failure-Rate Estimates

The mean life of a single collector panel is estimated from Eq. A.6 in Appendix A. This equation is derived from the reliability block diagram in Fig. A.2.

Based on available component data summarized in Table 2.9, the calculated mean-life range of a single collector panel is from 6 mo to 5 yr. This calculated value is conservative, because the reliability block diagram in Fig. A.2 places all the collector elements in series. If any one element fails, the collector panel requires maintenance and must be repaired.

Table 2.9 Mean Life of Major Elements in Flat-Plate Collectors

Elements	Mean-Life Range (years)
Glazing	
Glass	>50
Polymeric sheets	5-10
Polymeric films	2-5
Seals	1-10
Insulation	10-30
Absorber plate	20-25
Absorber coatings	
Paints	1-5
Black chrome	5-10
Black chrome over dull nickel	15-30

Although calculated values based on Eq. A.6 are low, they are consistent with manufacturers' warranty data.[2] Some of these data indicate that a few collector manufacturers provide limited warranties on their panels for up to 15 yr. Therefore, the failure rate of the collector under full-load operating conditions will be assigned a value that ranges from 11.4×10^{-6} to 114×10^{-6} failures/hr. These failure rates imply a collector mean-life or MTBF of from one to ten years under full-load operating conditions.

2.2 CONTROLS

Control systems initiate the solar collection cycle, activate auxiliary heaters, and activate automatic freeze-protection systems. All these functions must be considered in designing a control system and control sequence so that hot water is available on demand. However, a control system can fail to perform these functions because of improper sensor location and sensor calibration. Section 2.2 describes these problems, reviews control-system failure modes, and provides control-system mean-life estimates.

2.2.1 Operating Modes

2.2.1.1 Solar-Energy Collection

The solar DHW system in Fig. 2.4 is used to describe system operation and typical sensor-location problems. Temperature sensors S_1 and S_2 measure the temperature of the liquid at the top of the solar collectors and at the bottom of the storage tank, respectively. The sensor signals are transmitted to differential-temperature thermostat T-1 for further processing.

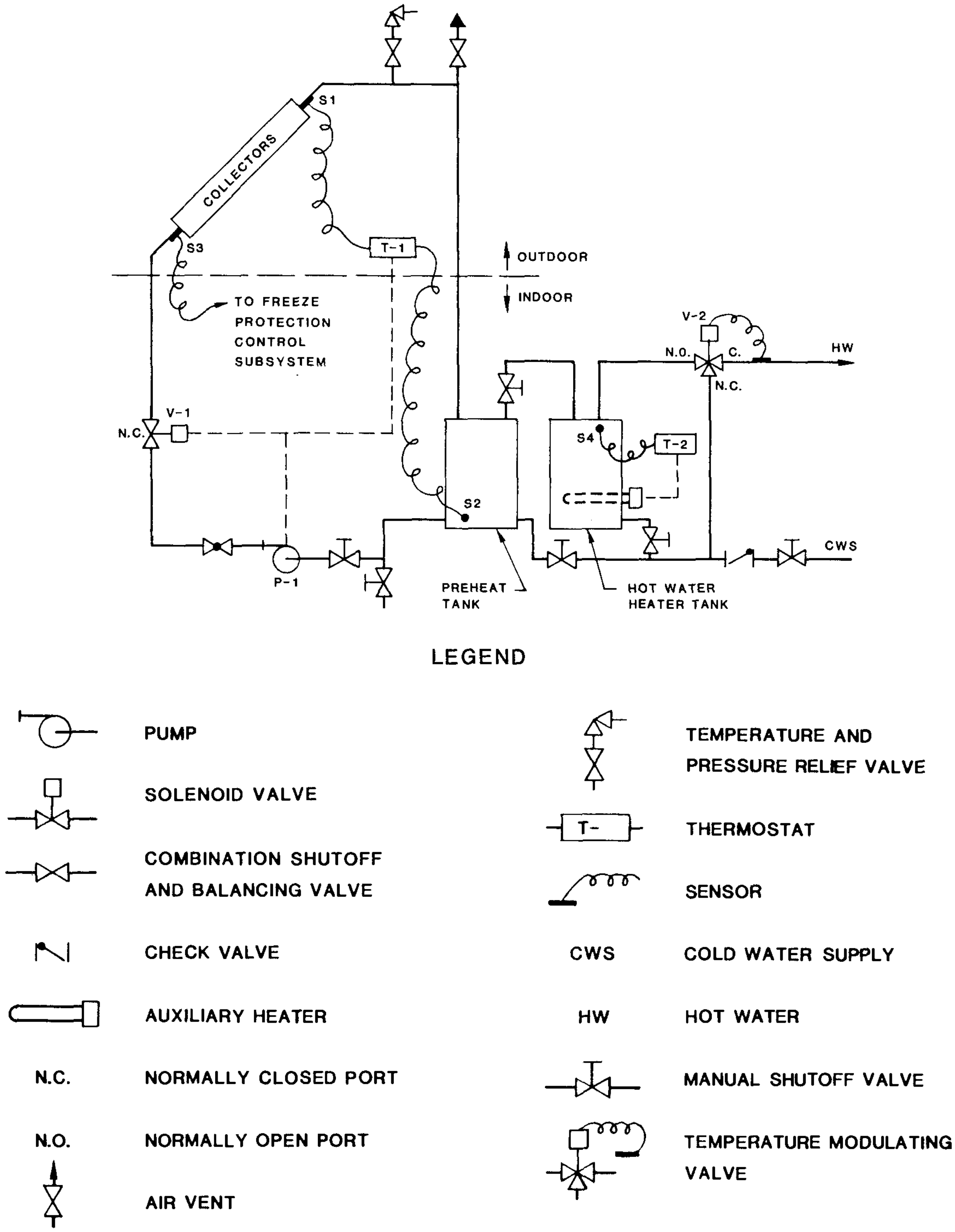

Fig. 2.4 Solar DHW System

Differential thermostat T-1 compares signals from S_1 and S_2 to its adjustable set points for high-temperature differential and low-temperature differential and performs different functions, depending on which set point is met. For example, when the difference between S_1 and S_2 reaches the high set point, which usually is 20°F (11°C), thermostat T-1 closes the electrical circuit and starts collector-loop pump P-1. At the same time, T-1 energizes the actuator of solenoid valve V-1 (normally closed), and the valve opens.*

With V-1 open, P-1 circulates liquid from the bottom of the storage tank through the collectors to the top of the tank. Solar-energy collection continues as long as the temperature differential between the top of the collectors and the bottom of the storage tank is maintained above the low-temperature differential set point.

When the temperature differential between the collectors and the storage tank decreases to the low set point, T-1 opens the control circuits, shutting off P-1 and closing V-1. To restart the system, the temperature differential between the collectors and the storage tank must again exceed the high set point.

2.2.1.2 Operation of Auxiliary Heater

Sensor S_4 (see Fig. 2.4) senses the hot-water temperature in the storage tank and sends a corresponding signal to thermostat T-2. If the temperature in the tank is below the low set point selected by the user, the auxiliary heater is actuated. The heater remains on until the water temperature reaches the selected high set point. When this occurs, T-2 shuts off the heater. Sensor S_4 and thermostat T-2 are usually supplied by the auxiliary-heater manufacturer.

2.2.1.3 Operation of Temperature-Modulating Valve

When the hot water leaving the auxiliary-heater tank exceeds the set-point temperature, temperature-modulating valve V-2 begins mixing hot water and cold make-up water to maintain the set-point temperature.

A temperature-modulating valve is described in Sec. 2.8. Local codes specify the installation and setting of this valve, because it serves as a safety device, protecting the user from excessively hot water.

2.2.2 Temperature Sensors

Without proper inputs from temperature sensors, the control system cannot function, and system performance and reliability are adversely affected.

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*V-1 prevents thermosiphoning. It can be replaced by a check valve, in which case the control schematic is simpler and should be less expensive. However, the check valve must be either spring- or weight-loaded. (Improper check valves have caused some systems to freeze.) Designer must verify that if thermosiphoning occurs in the collector loop, the resulting fluid pressure cannot overcome the resistive force of the check-valve spring or weight.

Temperature sensors must be selected for accuracy and reliability over the operating temperature range and must be located to detect actual fluid temperatures. Temperature-sensor locations will be discussed in terms of the schematic in Fig. 2.4. This information applies to all generic DHW systems.

2.2.2.1 Collector-Loop Temperature Sensors

Temperature-Sensor S_1 - Locations

Temperature-sensor S_1 detects the temperature of the fluid leaving the collector. There are several possible locations for S_1. The following pages describe the advantages and disadvantages of each location for liquid systems. Locations for air systems are described in Sec. 3.2.3.

Sensor S_1 Location in a Pipe above Collector Array

One location for sensor S_1 is in the outlet pipe directly above the collector array, as in Fig. 2.5. In this location, S_1 measures the temperature of the fluid leaving the collector, so the system should operate at maximum efficiency if temperature-differential set points are properly selected.

Although this location for S_1 appears ideal, operating problems may occur. For example, during a cold night or a cold, cloudy day, the system shuts down; valve V-1 is closed. When insolation is again available, collector heat losses are overcome and collector temperature rises. With valve

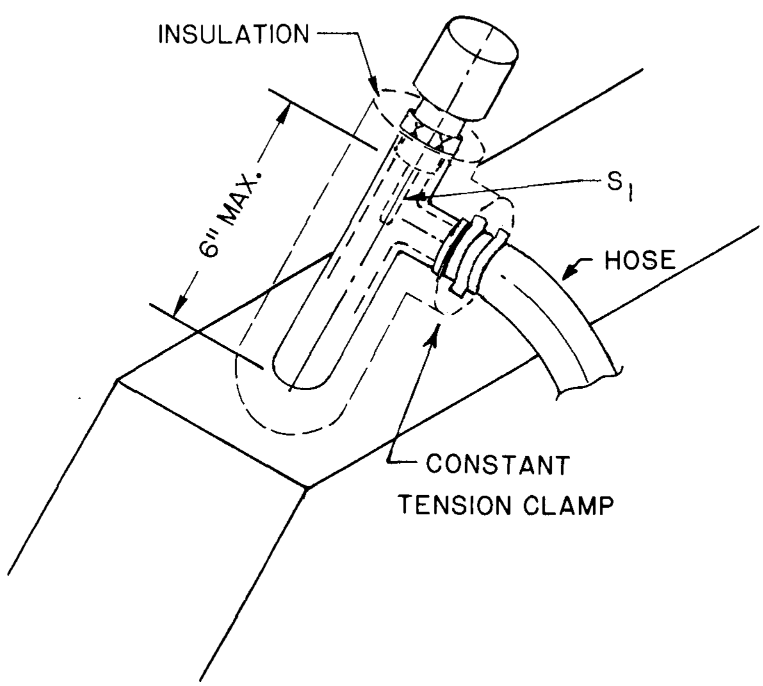

Fig. 2.5 Sensor S_1 in Pipe above Collector Array

V-1 closed, thermal inertia of the outdoor piping, which is approximately at ambient temperature, reduces the rate at which S_1 heats up. As a result, system start-up may be delayed or the system may not start up at all, although there is adequate insolation. Such a delayed start-up has been reported from the field.

According to the field report, on a sunny morning after a cold winter night, the absorber-plate temperature reached 220°F (104°C). However, collector coolant temperature was sensed as being only 55°F (13°C), because the sensor was installed in a pipe one foot away from the collector. Storage-tank temperature was 52°F (11°C), so the temperature differential was insufficient to start the system. The system was started manually. When switched to automatic mode, the system continued to collect solar energy. This field experience emphasizes the need to have sensor S_1 located as close as possible to the collector outlet.

Solar DHW systems that either drain down or drain back to prevent freezing, as described in Secs. 3.1 and 3.2, also may experience start-up difficulties on cold, sunny mornings, because air has replaced the drained water. Air has a lower thermal conductivity than water, so the system may not start even though there is adequate insolation.

Sensor S_1 Located on Pipe near Collector

A temperature sensor attached to the outlet pipe near the collector, as in Fig. 2.6, is more affected by ambient conditions than a sensor installed in the pipe, as in Fig. 2.5. In addition, temperature sensed by S_1 lags behind the temperature of liquid leaving the collector. Also, if the sensor is not firmly attached to the pipe, it may not read properly and the system may not start. Such a starting problem is documented in Ref. 21. Therefore, this S_1 location is not recommended.

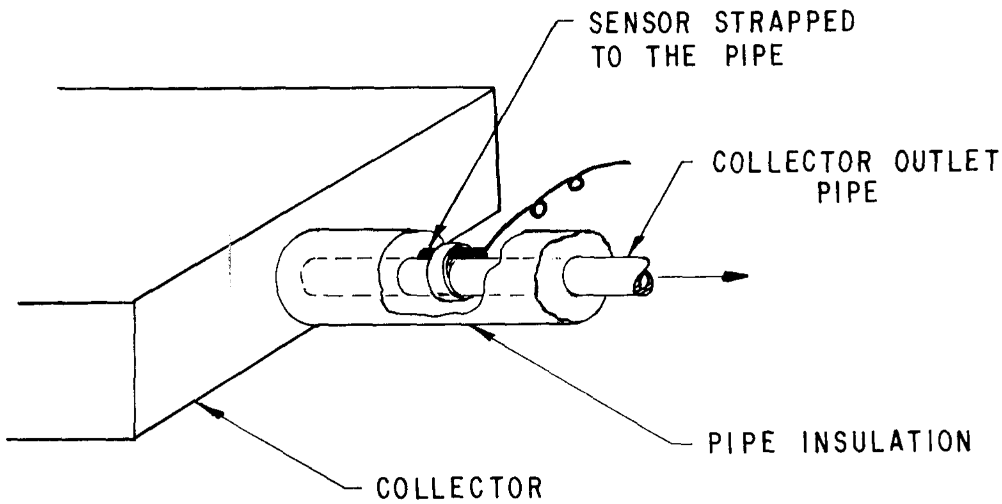

Fig. 2.6 Sensor S_1 Attached to Pipe near Collector

Sensor S_1 Located on Absorber Plate

Sensor S_1 can be located on the absorber plate, as in Fig. 2.7. In this location, the sensor can be used with some differential temperature controllers not only to turn the system on or off, but also for protection against freezing.

Installed on the absorber plate, S_1 detects temperatures 3° to 4°F (2°C) higher than the temperature of fluid leaving the collector. However, such temperature discrepancies can be compensated for in the differential thermostat settings.

If such offsets in temperature readings are not compensated for, the system operates uneconomically during marginal insolation conditions. For example, if the temperature differential between storage water and water leaving the collector is too small, the electrical energy required to operate the collector-loop pump cannot be justified. However, if thermostat differential set points compensate for sensor error, the system should operate economically.

Sensor S_1 must be attached firmly to the absorber plate; the attaching method -- brazing, screws, or spring clips -- depends on the plate and sensor materials. If a sensor access cover is provided on the enclosure, it must be gasketed for a water-tight fit. Adhesives and adhesive tapes should not be used to attach S_1 to the absorber plate. Unless S_1 is attached firmly, absorber-plate temperature is not detected accurately and system reliability is decreased.

Sensor S_1 Located in Collector Outlet Passage

The ideal location for sensor S_1 is in the collector inlet and outlet passages, as in Fig. 2.8. This location provides accurate information on the temperatures of fluid entering or leaving the collector and avoids start-up problems associated with low ambient temperatures.

Although this location for sensor S_1 is ideal, the majority of commercially available solar collectors cannot accommodate installation of temperature sensors in this manner. To overcome this problem, multiple temperature sensors can be used.

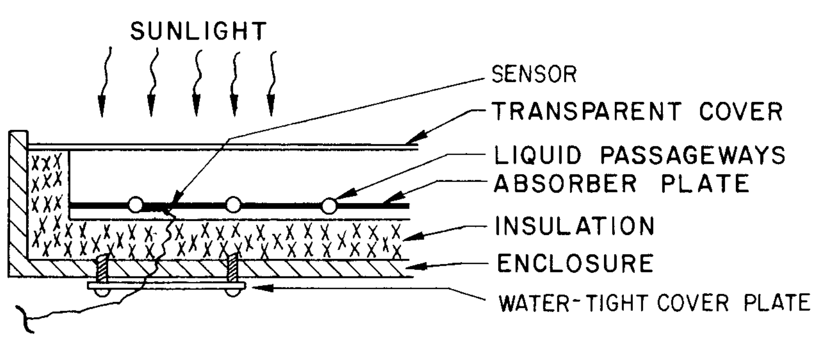

Fig. 2.7 Sensor S_1 Attached to Absorber Plate

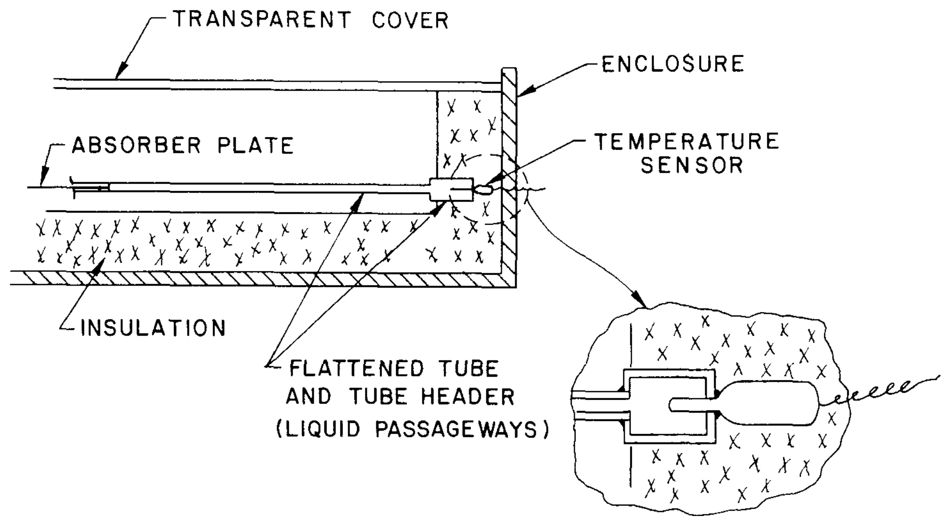

Fig. 2.8 Sensor S_1 in Collector Outlet Passage

Multiple-Sensor Configuration

When multiple temperature sensors are used, the control schematic must be modified to include the components in Fig. 2.9. These additional sensors and components make the control system more expensive but eliminate the start-up problems associated with low ambient temperatures.

In the multiple-sensor configuration, S_1, which is attached to the absorber plate, initiates the solar-energy collection cycle. A second sensor, S_1*, which terminates the collection cycle, is located in the pipe between the collectors and storage. The preferred location for S_1* is as close as possible to storage, so that piping heat-loss effects are eliminated. The third sensor, S_2, is located in the storage tank and acts as a reference for S_1 and S_1*. This control option also employs two differential thermostats, T-1 and T-1*, and a time-delay relay.

Differential thermostat T-1, which initiates energy collection, receives signals from sensors S_1 and S_2. When the high-temperature differential set point is reached, normally open contacts in T-1 close, activating pump P-1 and starting solar-energy collection. The time-delay relay also is activated. This relay is needed to compensate for the thermal inertia of the piping where S_1* is located. A time delay of 2 to 3 min is usually sufficient, but the actual setting depends on the distance between the collectors and S_1*.

After the adjustable time delay has run out (and S_1* has warmed up), the time-delay-relay contacts open, and system control is transferred to differential thermostat T-1*. This thermostat has normally open contacts that close when the temperature difference between S_1* and S_2 exceeds the high-temperature differential set point. With S_1* warmed up by hot liquid leaving the collectors, temperature difference between S_1* and S_2 exceeds the high-temperature differential set point of T-1*. Thus, the contacts are closed, and pump P-1 continues to operate. Solar-energy collection continues until the temperature difference between S_1* and S_2 decreases below the

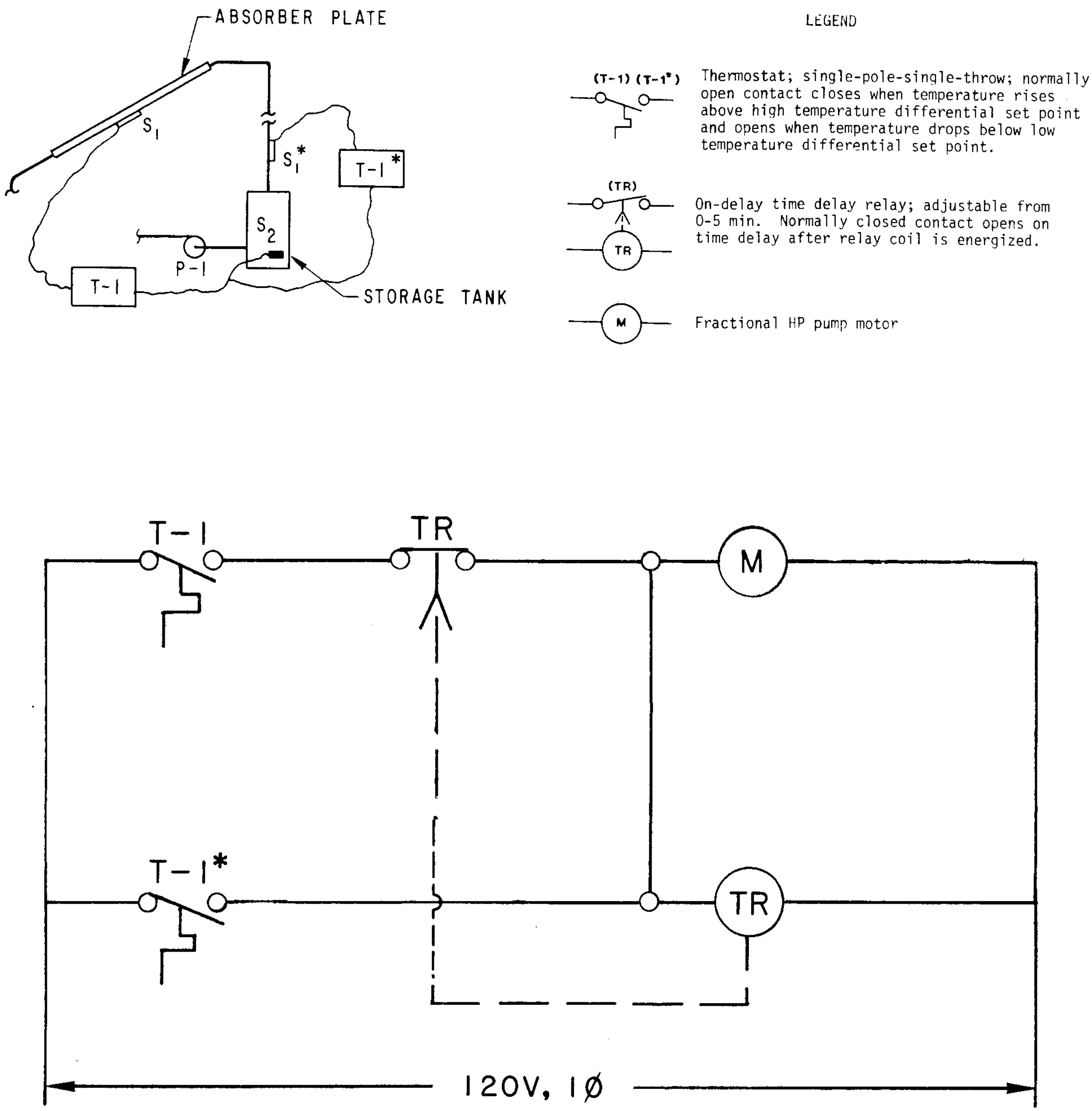

Fig. 2.9 Schematic of Multiple-Sensor Installation

low-temperature differential set point, at which time the T-1* contacts open and pump P-1 shuts down.

For reliable operation of the multiple-sensor circuit in Fig. 2.9, thermostats T-1 and T-1* must be high-quality single-pole/single-throw units. In addition, cutoff temperatures for these thermostats must be selected carefully.

As a guide to setting T-1 and T-1*, assume the system is designed to turn on when the temperature difference between collectors and storage is 20°F (11°C) and to turn off when the differential is 5°F (3°C). For these differences, the normally open contacts in T-1 should be set to close when the temperature difference exceeds 20°F (11°C), the high set point, and to open when the difference is 8°F (4°C), the low set point. The second thermostat, T-1*, should have its normally open contacts set to close when the temperature difference is greater than 10°F (5°C) and to open when the difference drops below 5°F (3°C).

2.2.2.2 Preheat-Tank Temperature-Sensor Location

Sensor S_2 detects the average temperature of the liquid at the bottom of the preheat tank. This temperature is affected by the tank flow distribution described in Sec. 2.3, so S_2 must be located as shown in Fig. 2.10 in order to sense the temperature of the liquid as it is pumped to the collectors. Any other location may cause the system to start up too early or run too late. Sensor S_2 must not be located near the incoming cold-water supply lines, because the sensor would detect a drop in the collector inlet temperature after only a few minutes of drawing water from the tank.

The ideal way of installing sensor S_2 is illustrated in Fig. 2.10. However, only a few commercially available DHW tanks for residential systems contain thermowells. The majority of tanks have this sensor attached to the tank wall. As a result, the temperature detected by sensor S_2 lags the water temperature, and this lag must be accounted for when setting thermostat T-1.

In large solar DHW systems, such as would be installed on apartment complexes, the inlet to the collector loop should be flared into a bell. This funnel-type opening provides a smooth transition from the storage tank to the piping system and reduces pumping losses.

2.2.2.3 Freeze-Protection Temperature-Sensor Location

For systems requiring protection from freezing, sensor S_3 must be located where it will detect the coldest liquid temperature that could occur

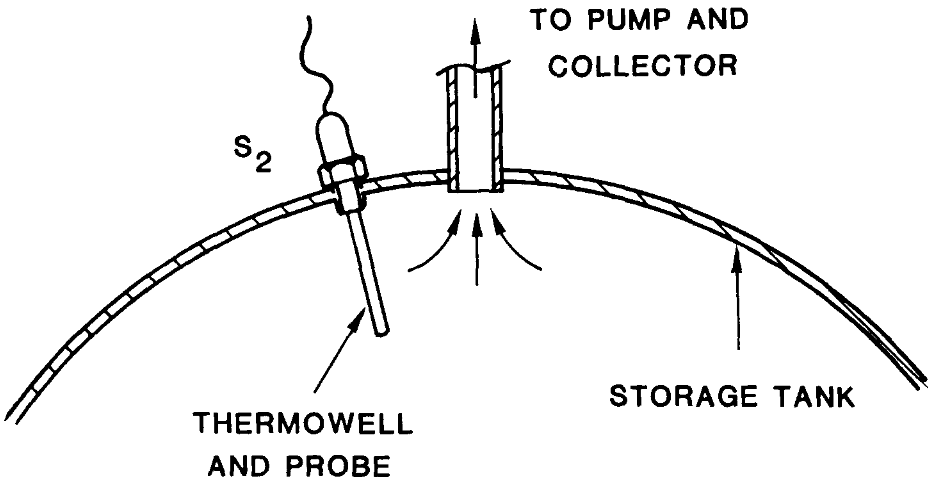

Fig. 2.10 Location of Sensor S_2

when the collector is shut down. The two locations usually selected are at the bottom of the collectors and in the intake manifold.

Recent data indicate that the coldest temperatures in a recirculating system occur at approximately the midpoint of the collector. The exposed portions of the inlet and outlet piping are found to be 3.6 and 4.5°F (2 and 2.5°C) warmer, respectively, than the middle of the collector.[22]

These data may be typical of recirculating systems in the Sunbelt. In northern climates, however, it is possible to have minimum insolation to warm the collector above freezing, while at the same time the fluid temperatures in the insulated manifolds may be below freezing.

If S_3 is strapped to the inlet pipe, as in Fig. 2.11, its readings will be less than actual water temperatures, which lag ambient temperatures. Also, if S_3 is not attached firmly to the pipe, freezing of the collector liquid will not be detected, so the freeze-detection sensor location in Fig. 2.11 is not recommended. A better location for S_3 is shown in Fig. 2.12.

For additional reliability, two freeze-protection sensors can be installed. One sensor would be attached to the absorber plate (Fig. 2.7), and the second sensor would be placed in the inlet manifold (Fig. 2.12).

2.2.2.4 Location of Auxiliary-Heater Temperature Sensor

Sensor S_4 detects the water temperature at the top of the auxiliary-heater tank, sending its signals to thermostat T-2, which controls the auxiliary heater. To be most effective, S_4 must be located as in Fig. 2.13. In this location it detects the temperature of water leaving the auxiliary-heater tank.

Although the location for S_4 in Fig. 2.13 is recommended, temperature sensors in commercially available tanks with electric heaters measure tank surface temperatures. For gas-heater units, the sensor is near the bottom of the heater. Neither of these locations is appropriate for solar DHW systems. (Recently, a manufacturer has introduced a DHW tank with a gas burner in the upper one-third of the tank. Although this location is preferable, these

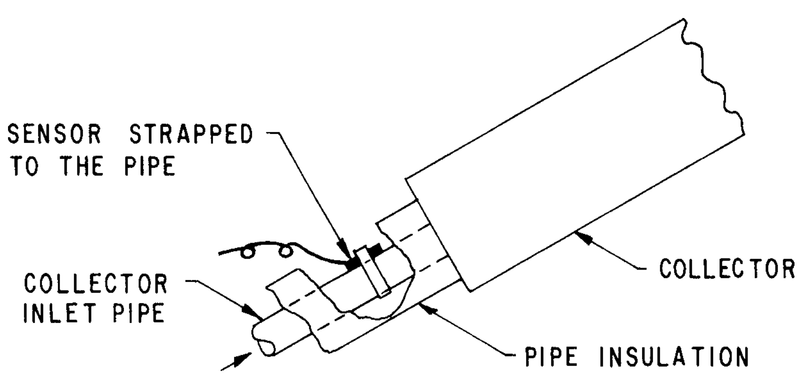

Fig. 2.11 Sensor S_3 at Bottom of Collector

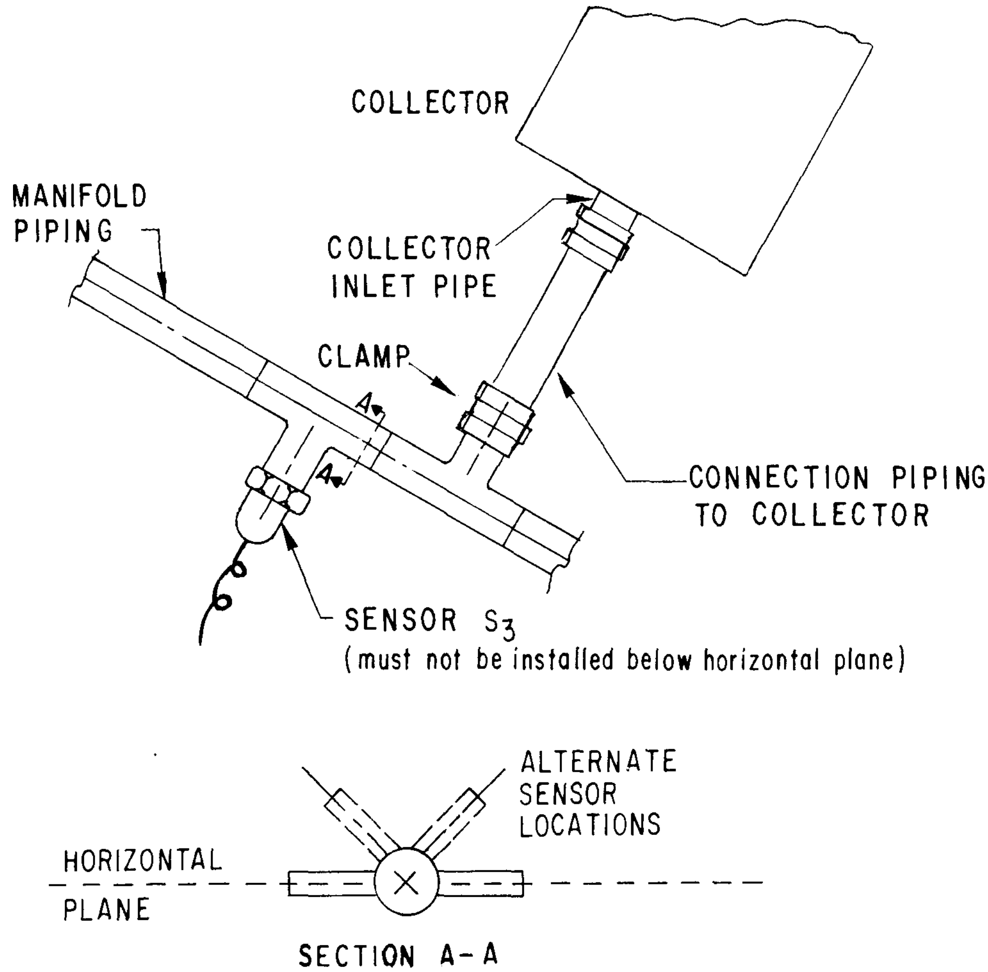

Fig. 2.12 Sensor S_3 in Manifold

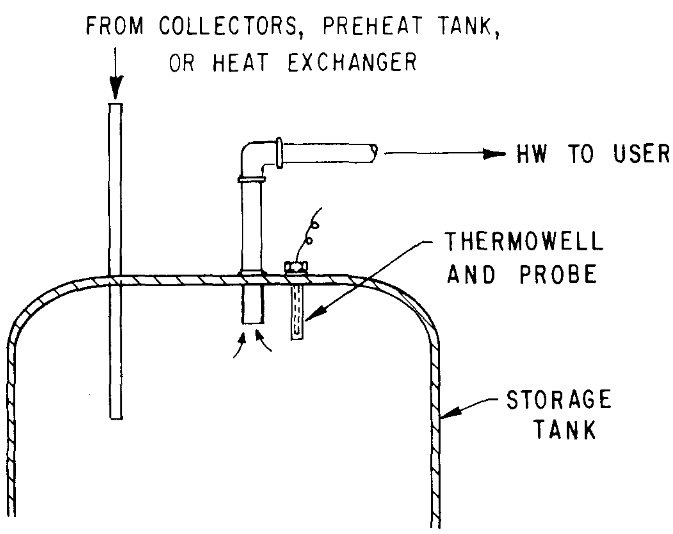

Fig. 2.13 Ideal Location of Sensor S_4 at Top of Auxiliary-Heater Tank

new units are several times more expensive than either conventional gas or electric DHW heaters.)

2.2.3 Control Set-Point Selection

Control set points determine system efficiency and reliability. If set points are too close together, the pump cycles excessively and may fail prematurely. If the set points are too far apart, or otherwise improperly selected, the system may not start, or it may start too late or run too long. Guidelines for set-point selection are discussed in the following sections.

2.2.3.1 Selection of High-Temperature Differential Set Point

Selection of the high-temperature differential set point is not critical from the standpoint of energy collected. In fact, for each operating day, there is a different optimum high-temperature set point. The daily optimum depends on insolation, ambient temperatures, storage temperatures, and wind velocity.

If the high set point is too high, the system starts later than it could. However, a compensating effect occurs, because the collector fluid is at a higher temperature than it would be for an earlier start-up. On the other hand, if the high-temperature set point is too low, the system starts too early and cycles excessively (because the difference between high and low set points is too small). In either of these cases, total energy collected is the same if the collectors are well insulated and heat losses are small, compared to the total energy available. For reliability and low maintenance costs, the high-temperature set point must be far enough from the low-temperature set point to prevent the unnecessary cycling that wears out pump motors.

There is no fixed procedure for selecting the high-temperature differential set point. Although the usual value for liquid systems is 20°F (11°C), set points as low as 15°F (8°C) and as high as 30°F (17°C) have been used. The usual high-temperature differential set point for air systems is 25° to 45°F (14° to 25°C). If in doubt, it is better to be conservative and set the system to start only when adequate insolation is available.

2.2.3.2 Selection of Low-Temperature Differential Set Point

Selecting the low-temperature differential set point is more critical than the high set point. If the low set point is too low, the collector-loop pump runs either continuously or too late in the day. In either case, the electrical energy required for pump P-1 may exceed the available solar energy.

Proper selection of the low-temperature set point requires a comparison between the value of the energy collected and the cost of collecting it. A five-step procedure for estimating the low-temperature set point is provided in Appendix B. This procedure is recommended for custom DHW systems to minimize the possibility of encountering a negative value for the low-temperature differential set point, with a resulting energy loss.

In prepackaged solar DHW systems, manufacturers can compensate for nonlinearities in the control-sensor package, sensor tolerances, and differential-thermostat hysteresis. Through proper testing, the manufacturer can establish the correct low-temperature differential set point for his particular system.

2.2.3.3 Selection of Set Point for Auxiliary-Heater Thermostat

Water at 120°F (49°C) is hot enough for most household purposes, although higher temperatures may be required for laundry and dishwashing. However, the higher the setting of the auxiliary-heater thermostat, the lower the seasonal efficiency of the solar DHW system. In fact, it is more economical to use an electric booster heater with a dishwasher than to maintain 140°F (60°C) or higher water temperatures in an auxiliary-heater/storage tank.

Most commercially available domestic-hot-water heaters have temperature settings marked "medium" and "high." The recommended temperature for the medium setting is 120°F (49°C), and 140°F (60°C) for the high setting.

2.2.3.4 Selection of Set Point for Protection against Freezing

Water temperature in the collector loop varies, depending on ambient temperature, insolation, nocturnal radiation, and the piping insulation. The lowest temperatures in the collector loop occur in either the piping system or the collectors, depending on the ambient temperature.

A conservative estimate of the ambient temperature at which a collector array could freeze, owing to combined impacts of nocturnal radiation and convection, is provided in Fig. 2.14. In developing these curves, it is assumed that the back and sides of the collector array are well insulated, and conductive losses are neglected.

In Fig. 2.14, three values of absorber-plate emissivities are considered. The highest curve characterizes a perfect black body and is shown for reference. Commercially available collectors with nonselective surfaces have emissivities that are approximately 0.8. Theory predicts that collectors of this type can begin to freeze at an air temperature of 47°F (8°C) in a 5 mi/hr (8 km/h) wind. As the wind velocity increases, the ambient temperature at which freezing occurs decreases.

Selectively coated absorber plates have emissivities that are approximately 0.2. As shown in Fig. 2.14, collectors of this type can begin to freeze at 35°F (2°C) in a 5 mi/hr (8 km/h) wind. As a guide, the freeze-detection sensors should be set to detect water temperatures of at least 40°F (4°C). The system designer must evaluate the accuracy of the instrumentation and the suitability of the sensor location before selecting a set point.

The lowest system temperature does not necessarily occur only in the collectors. On a cold, partly cloudy day when water is not circulating through the collectors, marginal insolation may keep water in the collectors from freezing. However, any exposed collector-loop piping may be losing heat to the environment. Thus, a combination of weather, piping insulation, and

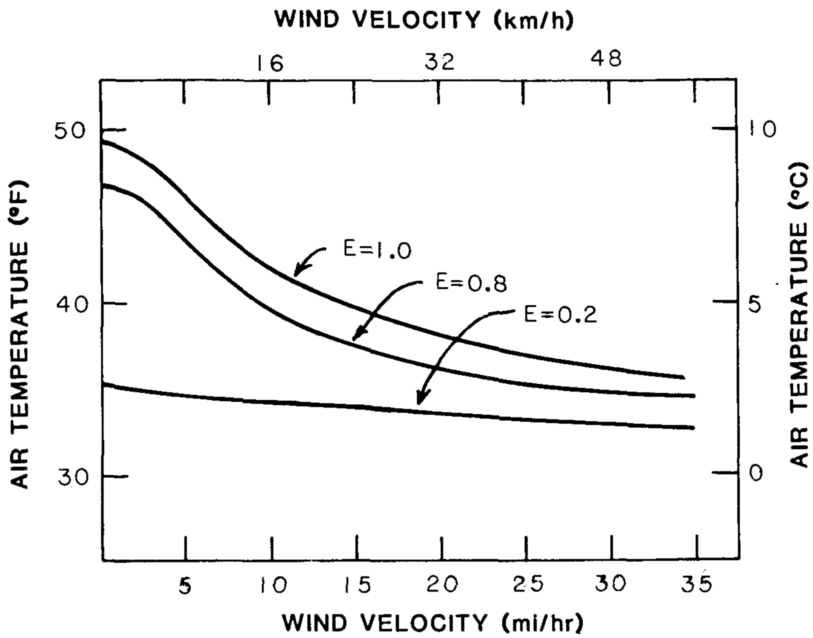

Fig. 2.14 Conservative Estimates for the Air Temperatures That Cause Solar Collectors to Freeze

time can reasonably be assumed to lead to freezing in the piping even though water in the collectors is above the freezing point. Consequently, the freeze-protection-thermostat setting must be high enough to protect cold points in the piping system.

Another consideration in establishing the freeze-protection set point for drain-down or drain-back systems is the time required to drain the system. A system with entirely proper thermostatic protection against freezing may freeze because the pipe and valve sizes are inadequate to drain the system in time.

2.2.4 Sensors

Sensor selection and installation are perhaps the most important and least appreciated aspects of solar DHW control systems. The control cannot produce correct outputs from inaccurate, unreliable sensor inputs. In solar DHW systems, temperature measurement is the important sensor function. A collector-loop sensor is subject to a wide range of temperatures, varying from sub-zero values to stagnation temperatures above 350°F (177°C). Before selecting a sensor, the designer must confirm that it can survive the anticipated operating conditions without physical damage or loss of accuracy. Also, the low-voltage sensor circuits must be located away from 120/240 V ac lines to avoid electromagnetic interference.

Control systems require sensors that detect temperatures and transmit this information from a remote location. Sensors that presently are performing this function in solar-energy systems include platinum resistance devices, thermistors, thermocouples, and thermopiles. There also are electronic temperature-measuring devices that employ integrated-circuit technology.

2.2.4.1 Sensor Calibration

Sensor calibration, often overlooked by installers and maintenance personnel, is critical to system performance. A routine-calibration maintenance schedule is essential. The heating-ventilating-air-conditioning maintenance contractor or trained solar-heating specialist is best qualified to establish and maintain sensor calibration. The average building superintendent or homeowner cannot be expected to have the needed calibration equipment and skills.

Establishing a calibration program requires careful consideration of the following:

- How frequently is calibration needed?
- What is the calibration procedure for each sensor?
- What test instruments are needed to perform adequate calibration?
- What are the benefits from a maintenance service, and how do they compare with those for alternative modes of calibration servicing?

One study shows inadequate sensor calibration is the second-largest cause of control problems in solar heating and cooling systems.[21] Calibration is a problem, because small temperature differences have to be detected to obtain precise control. If sensors are not calibrated, satisfactory control decisions cannot be made. In the majority of cases where solar-energy systems have low energy efficiencies, these result from excessive pump cycling, continuous pump operation, premature pump activation, and pump operation during periods of low solar insolation. All of these problems are traceable to the temperature-sensing system.

Calibration problems also exist in conventional air-conditioning systems. However, these systems use relatively constant energy sources, such as gas or electricity, so the consequences of inadequate sensor calibration are not as severe as in solar-energy systems.

The following example illustrates the importance of proper calibration. Assume a controller with a 5°F low-temperature differential set point is used with uncalibrated or unmatched sensors to interrupt the solar collection cycle. If the sensors are Model A's from Table 2.10, the maximum error of each sensor is ±4.3°F (±2.4°C), so solar collection may be interrupted when the temperature differential is 5°F ±(2 x 4.3°F). At one extreme, the solar collector loop operates even when the storage-tank temperature is 3.6°F (2.0°C) higher than the temperature of the liquid leaving the solar collector, resulting in wasted energy. At the other extreme, the solar loop ceases operating when the temperature differential is as high as 13.6°F (7.6°C).

Table 2.10 Integrated-Circuit Temperature-Sensor Characteristics

Setting	Model[a]		
	A	B	C
Specified maximum calibration error at 77°F (25°C)	±1.8°F (±1°C)	±3.6°F (±2°C)	±9°F (±5°C)
Maximum error through operating-temperature range without calibration	±4.3°F (±2.4°C)	±6.8°F (±3.8°C)	±16.2°F (±9°C)
Maximum error through operating-temperature range with calibration error at 77°F (25°C) set to zero	±1.8°F (±1°C)	±1.8°F (±1°C)	±3.6°F (±2°C)

[a]Operating-temperature range is -67°F to 302°F (-55°C to 150°C) for all three models.

On the other hand, with calibrated sensors, the temperature differential varies between 5°F + (2 x 1.8°F) = 8.6°F (4.8°C) and 5°F - (2 x 1.8°F) = 1.4°F (0.78°C). This comparison emphasizes the importance of sensor calibration in system control. Similar results could be developed for the remaining sensor models.

2.2.5 Control-System Failure Modes

State-of-the-art controls for solar DHW systems are designed around integrated-circuit chips. Other control-system components, each of which is made in several versions by more than 50 manufacturers, are triacs, relays, and transformers. The large number of variations precludes the description of each control-system design. However, common system failures are as follows: pump runs continuously, pump does not start, or pump cycles. In other words, the failures are failures of individual components.

Power-switching triacs, for example, generally have failure rates of 1/100,000,000 hr, so these devices are inherently reliable. However, the triacs' reliability decreases if they are improperly wired, carry large inductive loads, or are exposed to high ambient temperatures.

Integrated-circuit chips fail with power on or off. Depending on how the integrated-circuit chips are used, a no-voltage failure may result in loss of the temperature signal from the storage tank, causing the collector-loop pump to operate continuously. Failure in the voltage-on position also may result in loss of the storage temperature signal but, in this case, the collector-loop pump does not operate.

Relay elements that usually fail are coils and contacts. An open or shorted coil usually means a triggering pulse cannot be sent to activate diodes or other control elements. If relay contacts fail when closed, the collector-loop pump could run continuously.

2.2.6 Control-System Failure-Rate Estimates

Failure rates for electrical components in solar DHW control are given in Refs. 1 and 23. Failure rates in these references are expressed in failures per 1,000,000 hours of operation. A portion of these data, shown in Table 2.11, has been used to estimate overall failure rates of controls in solar DHW systems. Using schematics from several sources and the control schematics in Refs. 21, 24, 25, and 26, one finds that solar DHW control systems have failure rates that range from 5.7×10^{-6}/hr to 28.5×10^{-6}/hr. These failure rates imply that if the control system were installed correctly, it could operate continuously for from four to 20 years.

2.3 HEAT-TRANSFER FLUIDS

Heat-transfer fluids transfer heat from the solar collector to the storage or DHW load. Heat-transfer fluids are water, ethylene-glycol/water, propylene-glycol/water, silicones, hydrocarbon oils, and air. Recently, refrigerants have been used as collector-loop heat-transfer fluids. This section describes heat-transfer-fluid properties, presents recommendations for maintaining those properties, and discusses the scaling tendencies of water. Recommendations for water treatment are provided.

Table 2.11 Failure Rates for Control-System Electrical and Electronic Components

Components	Failure Rate (failures/10^6 hr)
Integrated-circuit chip	0.0028
Carbon resistor	0.003
Diode	0.008
Potentiometer	0.06
12-V relay	0.10
Capacitor	0.11
Transformer	0.5
Rotary switch	0.5

Water. Water is a readily available, inexpensive fluid with high specific heat, high thermal conductivity, and low viscosity. Its major drawbacks are high freezing temperature, expansion on freezing, and corrosion of common engineering materials (with the exception of copper). In addition, the low boiling point of water may cause high pressures within the collector system during stagnation. Water itself causes no adverse biological or environmental effects.

Ethylene-Glycol/Water Solution. A heat-transfer fluid commonly used in flat-plate collectors is an ethylene-glycol/water solution. Relatively inexpensive and available from many manufacturers in a wide range of concentrations and inhibitor levels, these antifreeze solutions are used in many heat-transfer applications. With corrosion inhibitors, ethylene-glycol/water solutions reduce the corrosive action and freezing temperature of water. However, thermal properties of these solutions, namely specific heat, thermal conductivity, and viscosity, are poorer than those for water alone.

The boiling point of an aqueous ethylene-glycol solution is low and can be reached easily under stagnation conditions. Also, glycols oxidize to organic acids, such as glycolic acid, when exposed to air near their boiling temperatures. However, there are inhibitors to neutralize these corrosive acids. Periodic maintenance, and addition of inhibitors, is required with these fluids. Another drawback of ethylene glycol is its high toxicity. Most plumbing codes require that aqueous ethylene-glycol solutions be separated from potable water by double-walled heat exchangers (see Sec. 2.6 and Appendix E).

Propylene-Glycol/Water Solution. Propylene glycol is similar to ethylene glycol, except that propylene glycol is less toxic and has a higher viscosity. With inhibitors, aqueous propylene glycol can be used with most common engineering materials. Periodic solution maintenance is required, because propylene glycol also forms acids at high temperatures in oxygen-rich atmospheres. Because of its low toxicity, propylene glycol has been used widely in the food industry.

Silicone Fluids. Some flat-plate collectors use silicone heat-transfer fluids. Produced by several manufacturers, including Dow Corning and General Electric, these fluids have low freezing and pour points, low vapor pressures, generally low corrosiveness, good long-term stability, and low toxicities. Their major drawbacks are high cost, high viscosity, and low specific heat. Leakage through fittings is a problem, because silicone fluids have lower surface tension than aqueous ethylene- or propylene-glycol solutions. Joints and fittings must be tight to prevent this leakage.

Hydrocarbon Fluids. Hydrocarbon fluids are either manufactured from crude oil or chemically synthesized from base materials. The common petroleum-based fluids are aliphatic hydrocarbons such as Mobiltherm 603* or aromatic

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*Mobiltherm is a trademark of Mobil Oil Corp.

hydrocarbons such as Dowtherm J* and Therminol** 44, 55, and 66. Some of the common synthetic oils are Brayco 888† and Sun-Temp††. All of the hydrocarbon fluids are expensive, have high viscosity and low specific heats, and may not be compatible with some of the sealing materials used in DHW systems. The oil manufacturer should be consulted to verify material compatibilities. Some of the available hydrocarbon oils degrade when used in copper systems. In addition, acids and sludge can form in the presence of oxygen at elevated temperatures.

Air. Air is used as a heat-transfer fluid in solar DHW systems. It is free and functions at all ambient temperatures. A leak in an air system does not cause damage, but it degrades system performance. Because of low volumetric specific heat, air must flow through the system at high rates. Therefore, more energy is required to transfer a given amount of heat with air than with most liquids. Another disadvantage is that air requires large ducts, making retrofitting difficult. Large ducts also mean more area for thermal losses. Finally, air-cooled systems generally are noisier than liquid-cooled systems.

Refrigerants. The least common of the heat-transfer fluids that can be used to cool solar collectors are refrigerants such as R-11 and R-114. These nontoxic fluids do not freeze, are noncorrosive to the metals ordinarily used in solar DHW systems, and are not flammable. Refrigerant fluids are readily available from refrigeration supply houses and are competitively priced. Joints and fittings in refrigerant-cooled systems must be leak-tight, because refrigerants have low surface tension. Fittings usually are silver-brazed. Piping joints should be inspected with a halide leak detector commonly used in the refrigeration trade.

2.3.1 Physical Properties

2.3.1.1 Thermophysical Properties

A comparison of the thermophysical properties of heat-transfer fluids over flat-plate-collector operating-temperature ranges can be made from manufacturers' specifications. Water is the best heat-transfer fluid. It has high specific heat, high thermal conductivity, and low viscosity. The absolute viscosity, heat capacity, thermal conductivity, and density of water are compared with those of other heat-transfer fluids in Figs. 2.15 through 2.18.

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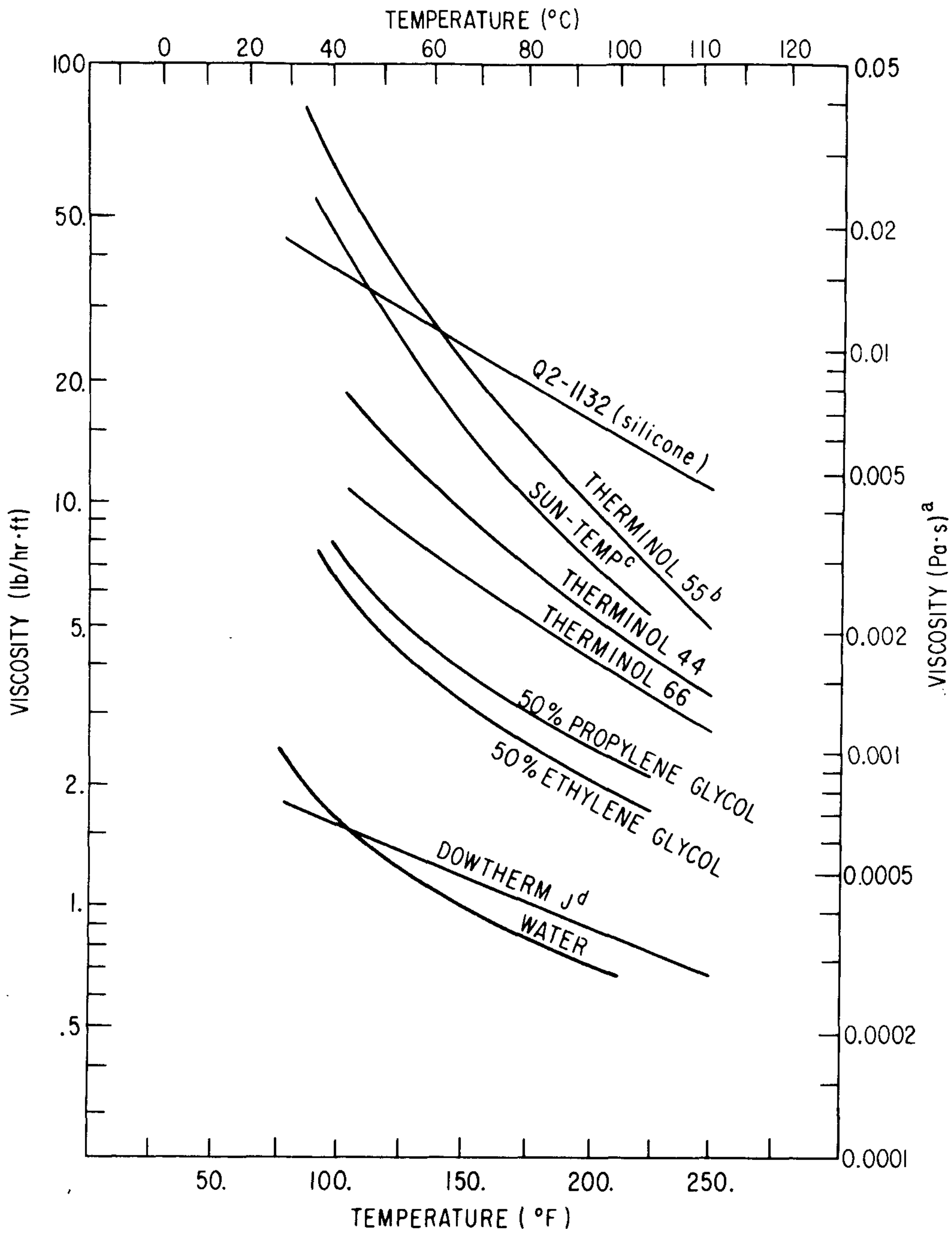
*Dowtherm is a trademark of Dow Chemical Co.

**Therminol is a trademark of Monsanto Corp.

†Brayco is a trademark of Bray Oil Co.

††Sun-Temp is a trademark of Research Technology Corp.



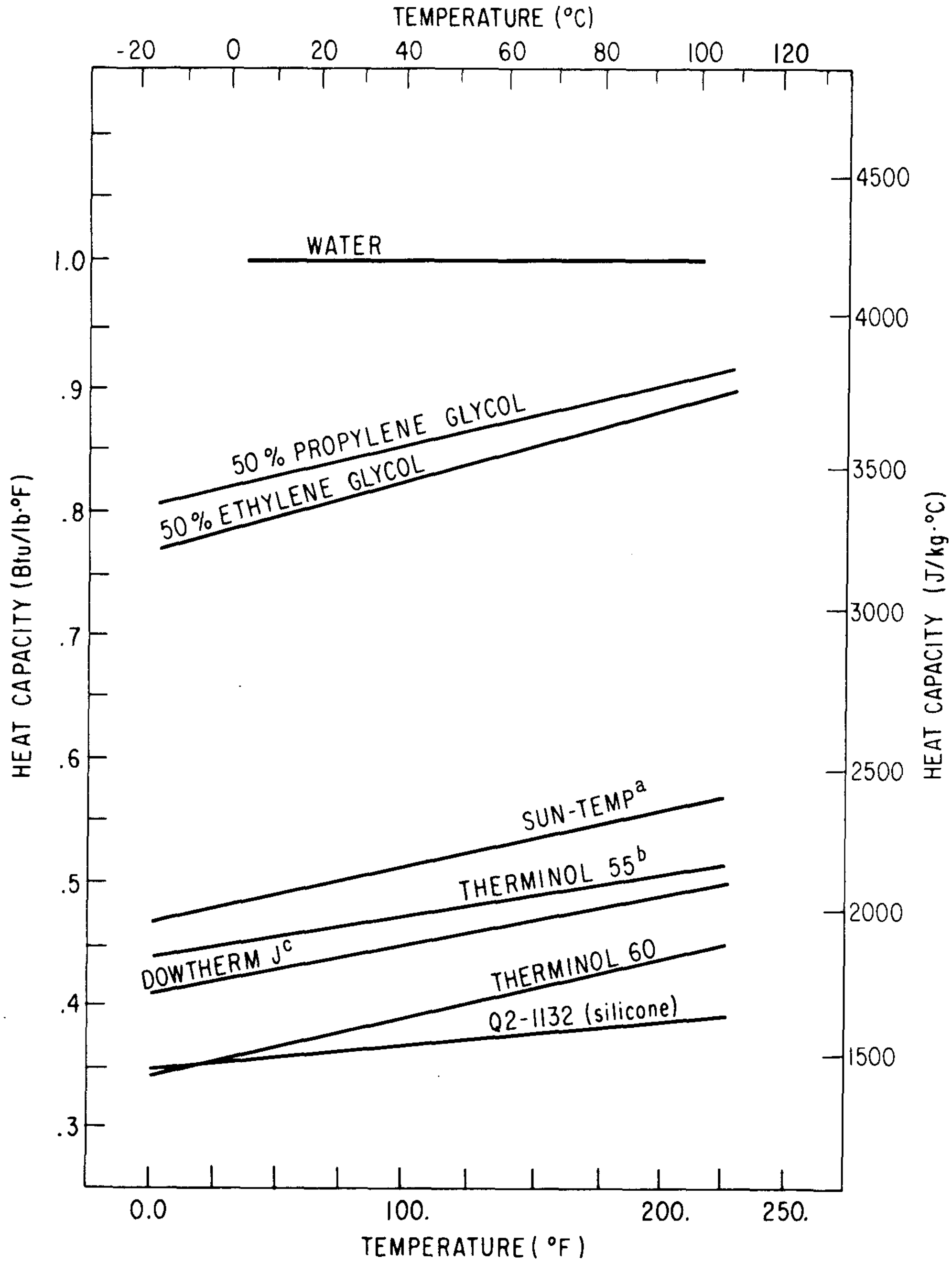
[a]Viscosity in Pa·s times 2419 equals viscosity in lb/(hr-ft).

[b]Therminol, trademark of Monsanto Co.

[c]Sun-Temp, trademark of Resource Technology Corp.

[d]Dowtherm, trademark of Dow Chemical Corp.

Fig. 2.15 Viscosity of Heat-Transfer Fluids versus Temperature

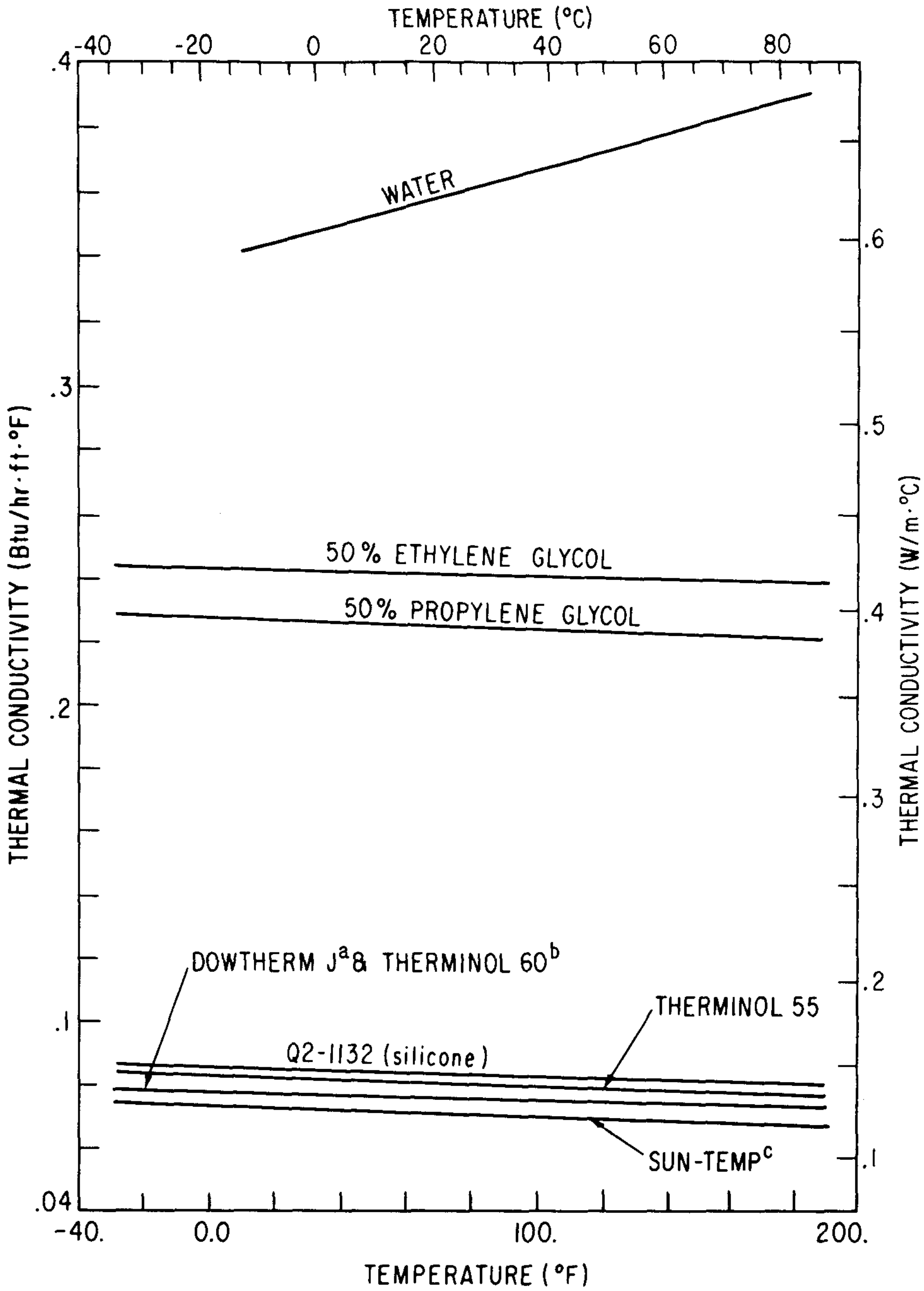


[a]Sun-Temp, trademark of Resource Technology Corp.

[b]Therminol, trademark of Monsanto Co.

[c]Dowtherm, trademark of Dow Chemical Corp.

Fig. 2.16 Specific Heat of Heat-Transfer Fluids versus Temperature

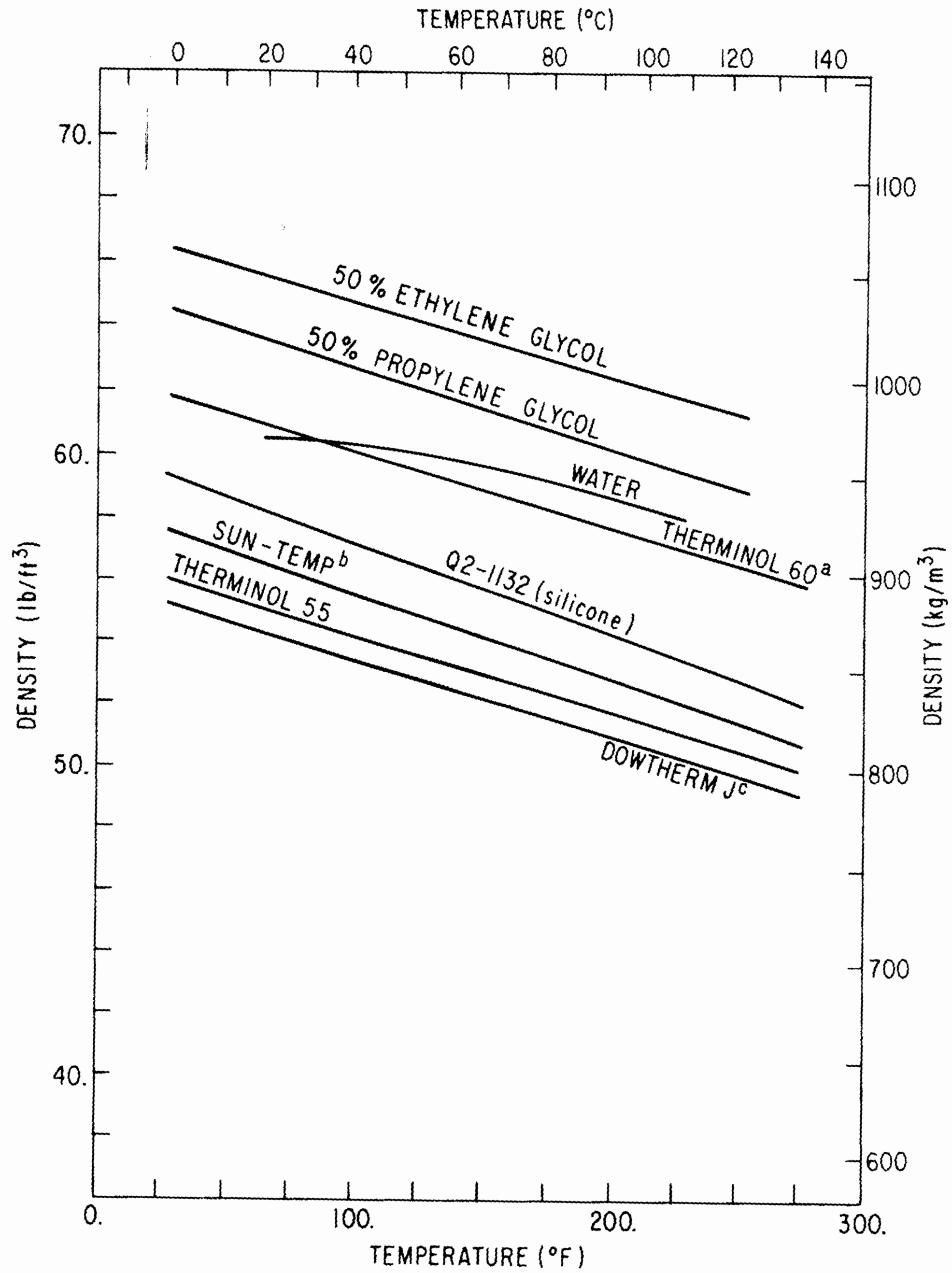


[a]Dowtherm, trademark of Dow Chemical Corp.

[b]Therminol, trademark of Monsanto Co.

[c]Sun-Temp, trademark of Resource Technology Corp.

Fig. 2.17 Thermal Conductivity of Heat-Transfer Fluids versus Temperature



[a]Therminol, trademark of Monsanto Co.

[b]Sun-Temp, trademark of Resource Technology Corp.

[c]Dowtherm, trademark of Dow Chemical Corp.

Fig. 2.18 Density of Heat-Transfer Fluids versus Temperature

2.3.1.2 Toxicity

Heat-transfer fluids -- with the exception of potable water and air -- are toxic and could contaminate potable-water supplies in the event of leakage. Glycol solutions and their degradation products are water-soluble; if a leak occurred, they could be dispersed throughout the DHW system. As for the silicone and hydrocarbon oils, the oils would float on the surface of the water or become dispersed in the water as immiscible droplets.

Heat-transfer fluids might be toxic even when their major constituents were nontoxic. Fluid additives, which are usually technical-grade liquids, could contain toxic residuals from the manufacturing process. Distributors of heat-transfer fluids, unaware of the additives or their grade, might report in good faith that a toxic material was nontoxic.

Table 2.12 presents data from a study by Clark et al.[27] These data indicate that most commercially available heat-transfer fluids are safe for residential DHW applications. However, Marshall notes that these ratings are based on single doses and should not be used in considering toxicities associated with long-term, low-level exposure.[28]

2.3.1.3 Flammability

The flammability of a heat-transfer fluid is specified by the fluid's flash point or the minimum temperature at which sufficient vapor is given off from a liquid to form an ignitable mixture with air. Closed-cup flash points as determined by ASTM Standard D-93 are close to the minimum temperatures at which pools of fluid will support combustion.[29] Manufacturers often report open-cup flash-point data based on ASTM Standard D-92.[30] Both sets of data are presented in Table 2.13.[31]

Flash points of aqueous solutions of organic liquids depend on the percentage of water in the mixture. Lee and Walton indicate that ethylene-glycol solutions will not ignite if they have more than 5% by volume of water.[31]

A 1980 publication from the National Bureau of Standards presents the following criteria to reduce the risk of fire from solar heat-transfer fluids.[32]

The flash point of a liquid heat-transfer fluid shall equal or exceed the higher temperature determined from A and B:

A. A temperature of 50°F (10°C) above the design maximum flow temperature of the fluid in the solar-energy system;

B. (1) A temperature of 200°F (93.5°C) below the design maximum no-flow temperature of the fluid attained in the collector, provided the collector manifold assembly is located outside of the building and exposed to the weather and that relief valves located adjacent to the collector or collector manifold do not discharge directly or indirectly into the building (such discharge is to be directed away from flames and ignition sources); or

Table 2.12 Toxicities of Commercial Heat-Transfer Fluids

Heat-Transfer Fluid	Composition	Skin Irritation[a,b]	LD_{50}[a,c] (g/kg)	Gossein[d] Rating
Dowtherm SR-1[e]	Ethylene glycol	0.3	8.2	2
Ethylene Glycol[g]	Ethylene glycol	0.4	4.2	3
Dowfrost[e]	Propylene glycol	0.1	20.3	1
Freezeproof[h]	Propylene glycol	0.1	>24.0	1
Noteck 835[i]	Propylene glycol	0.1	>24.0	1
Propylene Glycol USP[j]	Propylene glycol	0.1	22.8	1
Solar Winter Ban[k]	Propylene glycol	0.2	>24.0	1
Sunsol 60[l]	Propylene glycol	0.3	>24.0	1
UCAR Food Freeze 35[j]	Propylene glycol	0.1	19.4	1
UCON 50-HB-280-X[j]	Polyalkylene glycol	0	1.9	3
Solargard G[m]	Glycerol/water	0.1	>24.0	1
Caloria H7-43[n]	Parrafinic oil	0.1	>24.0	1
Mobiltherm Light[o]	Aromatic oil	1.2	24.0	1
Mobiltherm 603[o]	Paraffinic oil	0.2	>24.0	1
Process Oil 3029[n]	Naphthenic oil	0.6	>24.0	1
Sun-Temp[p]	Petroleum based	1.1	>24.0	1
Dowtherm A[e,f]	Diphenyl plus diphenyl oxide	0.4	4.1	3
Therminol 66[q]	Modified terphenyl	2.0	>24	1
SF - 96[r]	Silicone	0	>24.0	1
Syltherm 444[s]	Silicone	0	>24.0	1

[a]Data from C.R. Clark et al. (Ref. 27).

[b]>2, mild or no irritation; 2.1 to 5.0, moderately irritating; 5.1 to 8.0, severely irritating.

[c]LD_{50} is the single dose ingested by rats that results in death of 50% of the rats within 24 hr. Because animals react to toxic materials differently, values for animals do not necessarily reflect the response of humans.

[d]Lethal dose for 150-pound person: 6, supertoxic (<7 drops); 5, extremely toxic (7 drops to one teaspoon); 4, very toxic (one teaspoon to one ounce); 3, moderately toxic (one ounce to one pint); 2, slightly toxic (one pint to one quart); 1, practically nontoxic (>one quart).

[e]Trademarks of Dow Chemical U.S.A.

[f]Not recommended for residential solar-energy systems.

[g]Trademark of Aldrich Chemical Co.

[h]Trademark of Commonwealth Chemical.

[i]Trademark of Nuclear Technology Corp.

[j]Trademark of Union Carbide Corp.

[k]Trademark of CAMCO Mfg., Inc.

[l]Trademark of Sunworks, Ethone, Inc.

[m]Trademark of Daystar Corp.

[n]Trademark of Exxon Co., U.S.A.

[o]Trademark of Mobil Oil Co.

[p]Trademark of Resource Technology.

[q]Trademark of Monsanto Chemical Co.

[r]Trademark of General Electric.

[s]Trademark of Dow Corning.

Table 2.13 Flash Points of Heat-Transfer Fluids[31]

Heat-Transfer Fluid	Flash Points (°F) Closed-Cup[a]	Open-Cup[b]
Ethylene Glycol[c]	245	250
Polyalkylene Glycol	480	555
Alkylated Aromatic Oil	135	145
Diphenyl/Diphenyl Oxide	240	265
Extracted Naphthenic Oil	280	325
Paraffinic Oil - Type 1	275	305
Paraffinic Oil - Type 2	325	360
Paraffinic Oil - Type 3	390	455
Paraffinic Oil - Type 4	405	465
Silicone Fluid	545	605

[a]Pensky-Martens Closed-Cup Test, ASTM D93.

[b]Cleveland Open-Cup Test, ASTM D92.

[c]Data for concentrated ethylene-glycol solutions. If aqueous solutions of ethylene glycol contain more than 5% water, the solutions do not have flash points.

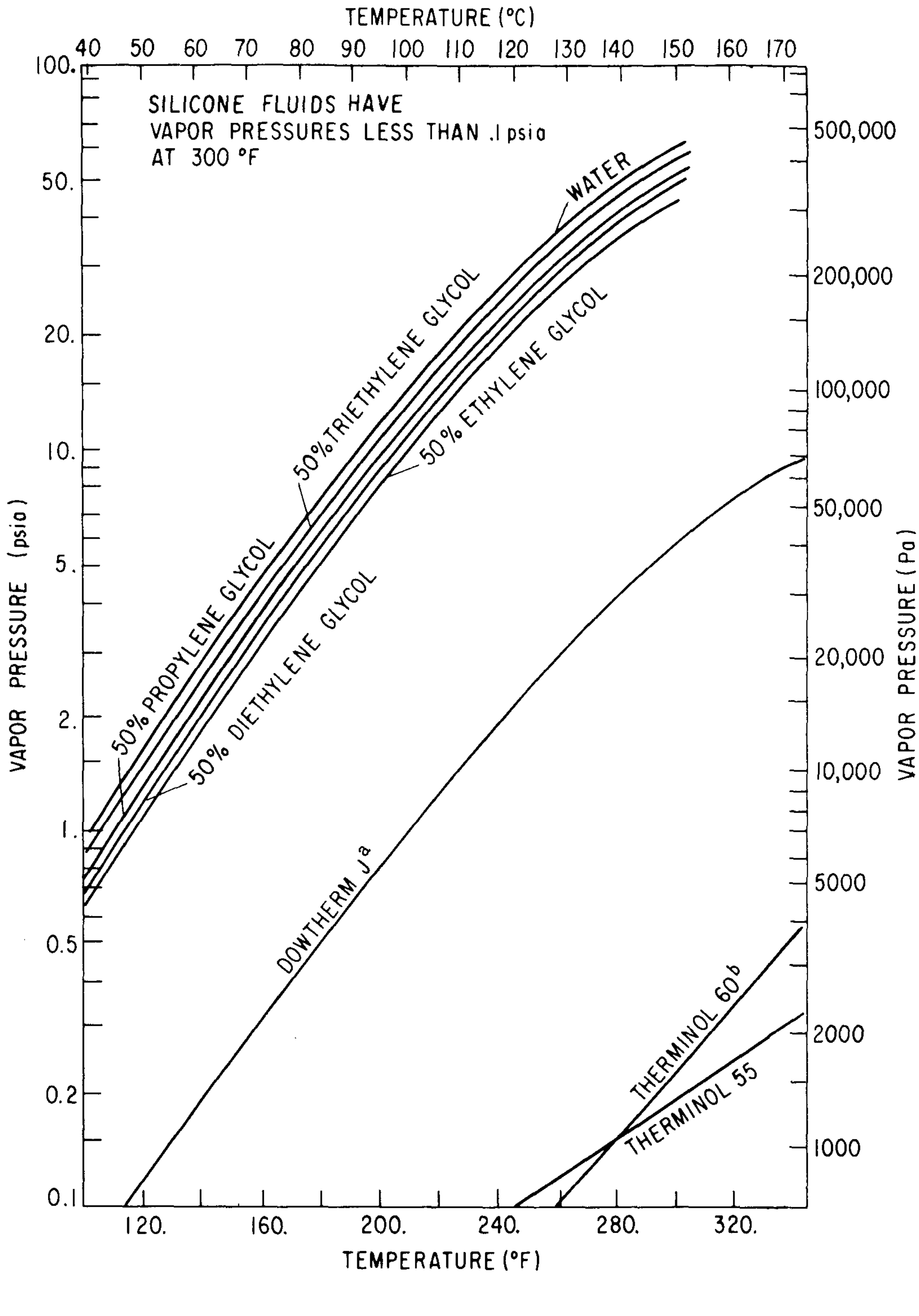
(2) The design maximum no-flow temperature of the fluid in all other manifold and relief-valve configurations.

2.3.1.4 Vapor Pressure

Temperatures may exceed 300°F in collectors during stagnation. As a result, the vapor pressures of the aqueous heat-transfer fluids can reach several atmospheres, forcing the solution into the expansion tank. Figure 2.19 presents absolute vapor pressure versus temperature for several heat-transfer fluids.

2.3.1.5 Freeze Protection

In the continental United States, there are only a few locations where the ambient temperatures do not fall below 32°F (0°C). Table 2.14 indicates that, of the common heat-transfer fluids, water has the highest freezing point. This table also summarizes the data on the boiling points, flash points, fluid stabilities, and life estimates of aqueous fluids.



[a]Dowtherm, trademark of Dow Chemical Corp.

[b]Therminol, trademark of Monsanto Co.

Fig. 2.19 Vapor Pressure of Heat-Transfer Fluids versus Temperature

Table 2.14 Properties of Aqueous Heat-Transfer Liquids

Property	Water	Glycols: 50% Ethylene-Glycol/Water	Glycols: 50% Propylene-Glycol/Water
Freezing point, °F	32	-33	-28
Boiling point at atmospheric pressure, °F[a]	212	230[b]	225[c]
Fluid stability	Requires pH or inhibitor monitoring.		
Flash point, °F[d]	None	None	None
Estimated life, yr	Five or more if inhibitors are maintained.		

[a]Boiling point is the temperature at which the vapor pressure of a liquid equals the absolute external pressure at the liquid-vapor interface.

[b]100% ethylene glycol boils at 387°F (197°C) at atmospheric pressure.

[c]100% propylene glycol boils at 372°F (189°C) at atmospheric pressure.

[d]Flash point is the temperature at which the vapor-air mixture above a liquid ignites and burns.

Because water has a rather high freezing point, either the water must be removed from the collectors to prevent damage from freezing or antifreeze solutions must be added to the water to lower its freezing point. As the ambient temperature drops, the aqueous antifreeze solutions form a slush that does not rupture the collectors or the associated piping. The non-aqueous heat-transfer fluids such as silicone oil and hydrocarbons do not expand on freezing, so the risk of system damage is reduced.

2.3.2 Corrosion

Depending on the type of solar DHW system, there are two approaches to controlling corrosion.[33] In direct systems, potable water is drawn from storage, heated in the collectors, and returned to storage for eventual use. Little can be done to potable water to reduce its corrosive action.

In indirect systems, the heat-transfer fluid, such as treated water, antifreeze solution, silicone oil, or hydrocarbon oil flows in a closed loop through the collector to the heat exchanger and back to the collector. Because the heat-transfer and water-storage systems are separated, the heat-transfer fluid can be conditioned to prevent scaling and corrosion. The danger in this system is that the conditioned water may be toxic as a result of the chemical treatment. There also is the possibility of corrosion from either side of the heat-exchanger surface. Therefore, safeguards are necessary to insure that the toxic fluid on the collector side of the heat exchanger does not contaminate the potable water in the storage vessel. It may be advisable to use double-walled heat exchangers (see Sec. 2.6).

2.3.2.1 Corrosion Characteristics of Aqueous Heat-Transfer Liquids

Proper design of a solar heating system requires a knowledge of the conditions that can affect the rate of metal corrosion. The following factors are important in liquid systems using aqueous solutions.[34]

- pH (acid/alkali content)
- Aeration
- Impurities and corrosion products
- Electrical conductivity of solutions
- Temperature
- Flow rate

Silicone oils and hydrocarbon oils are generally inert to metals in solar DHW systems, except when traces of acids are present.[35]

pH (Acid/Alkali Content). The corrosion rate of a metal is highly dependent on the acid or alkali concentration in the fluid. Metals generally corrode more rapidly in acidic solution; that is, the lower the pH, the greater the corrosion rate. Aluminum is an exception. It is attacked by both very acidic and very alkaline solutions. The optimum pH for aluminum is around 6.5. The optimum pH for copper is near neutrality, or around 7.0.[36]

However, for a three-metal system of aluminum-copper-iron, the overall Pourbaix (corrosion potential vs. pH) diagram in Fig. 2.20 indicates a narrow pH range, between 7.5 and 8.5 for uninhibited aqueous systems at room temperature.[36] This narrow pH range is difficult to maintain, and suitable inhibitors are needed to widen the stability region. These inhibitors must combine a two-fold function: (1) to seal and reinforce the protective films on aluminum and (2) to reduce the deleterious effects of heavy metal ions from the ionic dissolution of copper and steel on aluminum.[37]

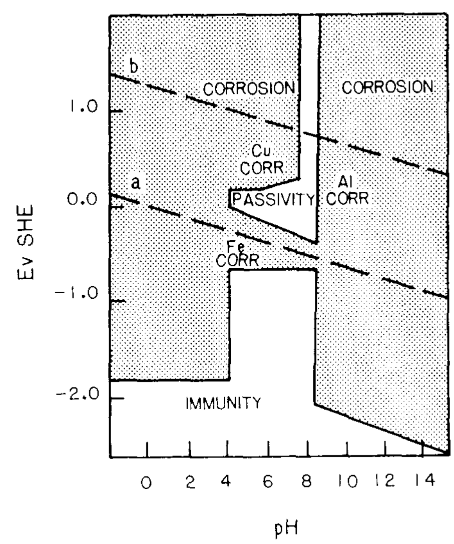


Fig. 2.20 Stability of Aluminum, Copper, and Iron[37]

Aeration. Dissolved oxygen in water is one of the most important contributors to metal corrosion in solar DHW systems, because it is a cathodic stimulant. Chlorine from chlorination of potable water also acts as a cathodic stimulant. Dissolved oxygen in ethylene-glycol/water and propylene-glycol/water solutions accelerates the decomposition of glycol into glycolic and/or formic acid.[38]

If oxygen is excluded from the system, the rate of corrosion is reduced. In closed-loop solar DHW systems, there usually is no problem in excluding oxygen. However, the system should be designed to prevent entrainment of air, which can occur in turbulent areas beneath a dead-air space or by suction at a leaking pump seal.[34]

Impurities and Corrosion Products. Raw tap water contains a number of dissolved impurities that can accelerate the corrosion process. These impurities include chlorides and sulphates, calcium and magnesium carbonates, copper and iron ions, and other dissolved solids. Each impurity causes a different corrosion problem, but the solution to each problem is the same: Use de-ionized water with inhibitors or inhibited glycols.

Aggressive anions, such as chlorides and sulphates, in water or glycol-water solutions increase corrosion rates. These ions lower the electrical resistivity of corrosion cells and penetrate and break down protective films that may form on the metal surface, such as Cu_2O on copper.

Dissolved calcium and magnesium carbonates form deposits on heat-transfer surfaces, because solubility of these salts decreases as water temperature rises (see Sec. 2.3.3).

Traces of copper or iron in the heat-transfer fluid can initiate pitting corrosion of aluminum collectors. Complexing inhibitors can be used to deactivate such noble ions in solution. The addition of a getter tube or column also reduces these ions.

A getter tube (see Fig. 2.21) contains a large area of less noble metal. As the heat-transfer fluid passes through the tube, the noble metal ions are displaced by sacrificing the less noble metal. The material in the tube must be replaced periodically as a result of this ion displacement. Although a getter tube does not eliminate corrosion in the DHW system, the corrosion is reduced and the getter tube provides insurance in the event of inhibitor breakdown.

Iron and manganese compounds in potable water from wells and municipal systems are a common cause of deposit problems. These compounds produce what usually is referred to as "red water." When distribution lines are shut off for repairs, homeowners sometimes experience red or rusty water for short periods after service is restored. The problem is caused by soluble iron and manganese compounds in groundwaters that have oxidized and precipitated in the distribution system. Iron and manganese bacteria sometimes are major factors in deposit formation. In such instances, nontoxic inorganic tri-, mono-, and diammonium phosphates are used in concentrations of 1 to 5 ppm. These phosphates do not prevent oxidation of iron and manganese, but they disperse the oxidized particles, preventing agglomeration. However, at operating temperatures of 176°F (80°C) or higher, polyphosphates decompose by hydrolysis. Sodium silicate has been used for years to limit red-water problems by

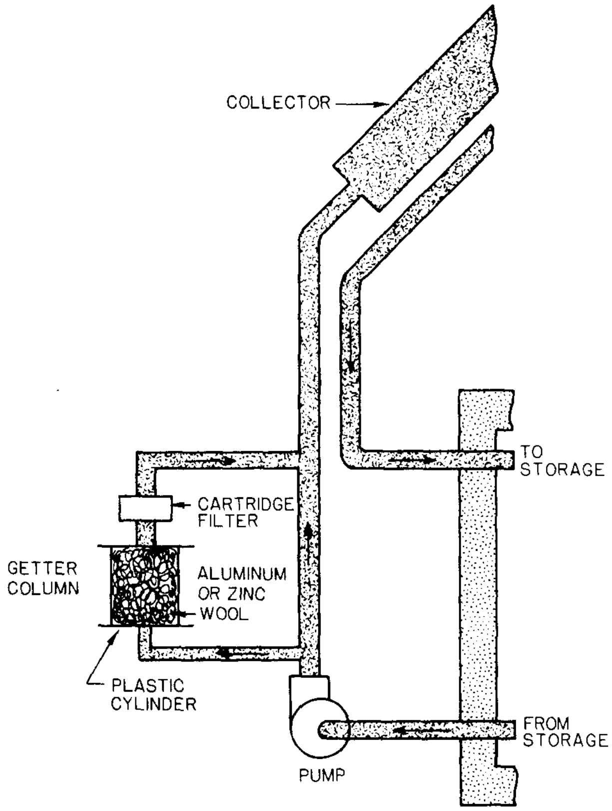


Fig. 2.21 Getter Column in Collector Loop

reducing corrosion. Treatment with silicate, usually recommended for relatively soft waters, involves raising silicate content to 8 ppm, measured as SiO_2.[38]

Precipitates from soluble metal ions in water or system metal dissolution accelerate inhibitor-depletion rates by providing large surfaces for inhibitor absorption. Green et al. found a hundredfold increase in iron corrosion in the presence of hydrated iron oxide and a lesser increase in corrosion of aluminum and solder.[39] Mercer and Wormwell report that suspensions of ferric hydroxide rapidly depleted phosphate inhibitor but had less effect on benzoate and none on borate.[40]

Electrical Conductivity of the Fluid. In multimetal systems, electrical conductivity of the heat-transfer fluid can affect corrosion rates. In general, the greater the fluid conductivity, the higher the corrosion rate. Providing a dielectric separation between dissimilar metal connections prevents local galvanic corrosion. For example, corrosion of the more active aluminum was reported in a case where copper tubing was connected to an aluminum collector without a dielectric separator. Similarly, material incompatibility between threaded copper pipe and a connecting steel flange accelerated local corrosion of the more active steel-flange face, allowing the joint to leak an aqueous fluid. The problem was eliminated by refitting with a brass flange.

Temperature. Temperature affects the rate of metal corrosion. In general, the higher the temperature, the greater the corrosion rate. Temperatures in a flat-plate collector should not exceed 185°F (85°C) when the system is in operation. During shutdown, fluid temperature in a closed-loop system can exceed 212°F (100°C). As a safety measure, a pressure-relief valve should be provided. Ethylene glycol at these temperatures can break down into corrosive acids, especially if oxygen is present. High temperatures also can break down some inhibitor systems, forming precipitates that further aggravate corrosion.

To avoid these problems, fluid overheating must be prevented. One technique is to drain the fluid when the system is shut down for prolonged periods. If this is not possible, the quality of the ethylene-glycol solution should be checked at regular intervals.[34]

Flow Rate. Flow rates through a solar collector must be carefully controlled, and manufacturer recommendations must be followed, in order to avoid turbulence, which removes protective oxide films. Partial restriction of channels by debris can produce high flow velocities locally, causing erosion/corrosion. Heat-transfer-fluid flow velocity should be kept below 4 ft/s (1.2 m/s) to prevent erosion/corrosion in copper pipe and below 6 ft/s (1.8 m/s) in aluminum and steel pipe. However, flow should be sufficient to prevent stagnant areas that increase crevice corrosion, involving differential aeration cells. In addition, the stagnant areas accelerate overall corrosion because inhibitors become exhausted and cannot be renewed fast enough by incoming solution.[34] Crevice corrosion also is aggravated by chloride ions and oxygen level. Aluminum and carbon steel are particularly susceptible to this corrosion. Copper also is susceptible, but to a lesser degree.

2.3.2.2 Glycol-Water Solutions

Antifreeze Ingredients. Commercial antifreeze solutions contain several important ingredients, including corrosion inhibitors, foam suppressants, and dyes. Antifreeze solutions also contain buffers to keep heat-transfer fluids alkaline by neutralizing acids formed by the oxidation of the fluid.

Foam suppressant is included to prevent formation of foam caused by entrainment of air. Foam in a closed system can erode the pump and reduce the heat transfer at the absorber plate, causing hot spots. Hot spots in turn degrade ethylene glycol, shortening heat-transfer-fluid life.

Dyes are added to commercial solar antifreeze so leakage and potable-water contamination can be detected.[34]

Inhibitors. There are three inhibitor categories: (1) pH buffers that neutralize acid decomposition products, providing an optimum pH to minimize corrosion rates; (2) film formers that react with metal to form a protective layer against pitting, and (3) complexing agents that tie up heavy-metal ions in solution.

A review of literature on metallic corrosion inhibitors in glycol antifreeze formulations follows:

- Copper and brass: MBT (2-Mercaptobenzothiazole), BTZ (benzotriazole), and TTZ (tolyltriazole) form insoluble copper complexes on metal surfaces. These copper inhibitors indirectly protect less noble metals in the same system, such as aluminum and steel, by suppressing copper ions in solution. Galvanic corrosion and pitting owing to copper plating on the other metal surface is prevented. TTZ and BTZ are preferable to MBT because of their better thermal stability. Also, MBT converts to insoluble and ineffective disulfide via oxidation reactions and photochemical excitation by the absorption of visible or ultraviolet light.

- Aluminum: At temperatures below 250°F (120°C), silicates in silicone silicate copolymers are used to protect aluminum by forming insoluble metal silicates. Some inhibitors in combination with others act synergistically, whereas singly they produce little or no pitting protection at low concentrations. Examples are molybdate/phosphate, silicate/benzoate, and silicate/molybdate.[33] Sodium nitrate is also used to form or repair protective oxide film on aluminum. This iron inhibitor has to be used with care, because under certain conditions it may have a deleterious effect on solders. Nitrite should be avoided for aluminum heat-exchanger coolants except for cast-iron protection. Nitrate then should be added to protect aluminum.

- Iron and steel: Borates, phosphates, benzoates, arsenites, and silicates function as ferrous-metal inhibitors by forming protective films. Also, borates and phosphates stabilize solution pH. Chromate inhibitor, which is effective in water-only systems, is not recommended for glycol-water solutions. Chromate oxidizes glycol to acid, depleting the inhibitor.

- Solder: There is no generally recognized inhibitor for lead alloys, but corrosion protection is usually achieved by adding a silicate, which forms an insoluble film; by controlling solution pH; or by using a polar-type oil, which is absorbed on metal surfaces.

- Galvanized steel: Trisodium phosphate is said to be a good inhibitor for zinc coating, while benzoates or borates increase corrosion attack on the coating.[41] Recently, ANL reported that the zinc coating on the galvanized-steel tube in flat-plate collectors had started to dissolve in an inhibited propylene-glycol/water solution (Dowfrost* containing 1.5% to 2% phosphate, K_2HPO_4). During operation, K_2HPO_4 inhibitor reacts with zinc

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*Trademark of Dow Chemical Co.

to generate hydrogen gas and to form compounds that increase solution alkalinity. As a result, the inhibitor is depleted to about 1%, and solution pH and reserve alkalinity are raised.[42] To date, inhibited glycol solutions that can be used with galvanized steel in solar applications do not exist. Furthermore, solar antifreeze solutions, such as Dowtherm SR-1,* may cause certain inhibitors to precipitate out of solution and form a scale that can foul collector surfaces.

Antifreeze Life. In time, antifreeze breaks down into corrosive acids, especially if oxygen is present. Because the corrosion potential of tap water varies from region to region, the time required for the glycol-water solution to degrade also varies. Antifreeze in a solar DHW system should last five or more years if recommended inhibitor levels are maintained. Also, manufacturers' recommendations for maintaining antifreeze-solution quality must be followed. Furthermore, antifreeze life can be extended several more years if de-ionized water is used in preparing the coolant. Nevertheless, antifreeze solutions should be tested periodically for:

- Inhibitor level: The recommended standard test method for measuring the inhibitor level is ASTM D 2688.[43] Recently, special indicator papers have been developed to evaluate the level of specific inhibitors; an example is Nalco 2000** test strip, which is used to detect copper-inhibited MBT. Argonne National Laboratory has evaluated an experimental model of a "voltage corrosivity sensor" built by Texas Instruments for monitoring inhibitor breakdown in glycol-water solutions. Preliminary data indicate this probe is satisfactory for detecting breakdown of aluminum, iron, and steel inhibitors, but not copper inhibitors. However, the meter is sensitive to temperature and flow variation.[42]
- pH: The pH level of a heat-transfer fluid should be measured periodically to determine if the fluid is still alkaline. This can be done easily by testing the solution with commercially available pH test papers, such as those available from Sunearth†. The initial pH value of a glycol-water solution can be as high as 10 but must never drop below 7 in systems constructed of metals other than aluminum. (Note the case of increasing pH in Sec. 2.3.2.2.)
- Reserve alkalinity: Reserve alkalinity is a measure of alkaline inhibitor concentration and is defined as number of milliliters of one-tenth-normal solution of hydrochloric acid required to titrate 10 milliliters of concentrated glycol to a pH of 5.5 (ASTM D1l2).[43] (Note the case of increased reserve alkalinity in Sec. 2.3.2.2).

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*Trademark of Dow Chemical Co.

**Trademark of Nalco Co.

†Trademark of Sunearth Co.

For example, in the case of Dowfrost,* propylene antifreeze formulated with 1.75% dipotassium phosphate, Dow recommends that if the reserve alkalinity drops below 9.0, additional inhibitor should be added to raise the reserve alkalinity until it is in a range of 10 to 12. (A Dowfrost* test strip that indicates any reduction in reserve alkalinity with glycol concentration is available from Dow Chemical Co.). Similarly, in the case of Dowtherm* SR-1, an inhibited ethylene glycol, Dow recommends reinhibition back to 11.0 minimum if the reserve alkalinity drops to 8.0 or below.

2.3.3 Calcium-Carbonate Scaling

In waters supplied by some municipalities, temporary hardness caused by calcium and magnesium bicarbonates may degrade solar DHW system performance because of corrosion and scale formation. Permanent hardness may also be important if chlorides and sulphates of calcium and magnesium are present in significant concentrations. Water containing fewer than 50 ppm of total hardness (reported as $CaCO_3$) is considered soft; if the hardness exceeds 250 ppm, the water is considered hard.

Calcium bicarbonate in hard water gives rise to an insoluble calcium-carbonate film. This film or scale may prevent corrosion, but it also reduces pipe diameters, impairs surface heat-exchange properties in absorber tubes and heat exchangers, and blocks collector inlet and outlet passages.

Chemicals likely to form scale in aqueous solutions are calcium carbonate, magnesium hydroxide, calcium silicate, and calcium sulfate. Calcium carbonate has the highest potential for depositing scale, which may be expected mostly on the collector's internal absorber surfaces, because calcium carbonate becomes less soluble as temperature increases.[44] At present, we lack sufficient data to predict if calcium-carbonate scaling will be a problem with water-glycol antifreeze solutions.

2.3.3.1 Assessment of Calcium-Carbonate-Scaling Tendency

To evaluate the $CaCO_3$ scaling tendency, water samples from or for solar DHW systems should be analyzed for the following properties: (1) pH and temperature; (2) alkalinity, as ppm $CaCO_3$; (3) calcium, as ppm $CaCO_3$, and (4) total dissolved solids (TDS). Given these data, the Palin index at the operating temperature is calculated. If the Palin index is greater than 11.6, calculate the scaling potential by the ANL technique given in Appendix C.

Table 2.15 shows the analyses of eight water samples reported in the literature.[45] Prediction of calcium-carbonate scaling by the Palin index and the scaling-potential method is provided also.

Assuming collector temperature to be 176°F (80°C), the scaling predictions for the soft, medium-hard, and hard waters are:

I. Soft Water -- Scaling is not anticipated with this type of water.

*Trademark of Dow Chemical Co.

Table 2.15 Calcium-Carbonate Scaling in Various Waters

	Water Composition				Scaling Prediction				
					Palin Index[a]		$CaCO_3$(ppm)[b]		
Water Type	pH 25°C	Calcium (as ppm $CaCO_3$)	Alkalinity (as ppm $CaCO_3$)	Total Dissolved Solids (ppm)	25°C[c]	80°C[d]	25°C	80°C	Remarks
I. Soft									
Boston, Mass.[45]	6.90	12.5	13.1	43	8.4	9.2	NP[e]	NP	No scaling
Alkaline raw[b]	8.10	40	60	96	10.8	11.5	NP	8.36	No scaling
San Mateo, Calif. (softened)[45]	8.20	27.5	224	786	11.3	12.0	NP	5.67	No scaling
W. Palm Beach, Fla.[45]	9.50	37.5	11.5	91	11.4	11.3	NP	NP	No scaling
II. Medium-Hard									
Grand Rapids, Mich.[45]	8.60	175	77.1	156	12.0	12.5	NP	15.6	Possible scaling in collectors at 80°C or higher
San Francisco, Calif.[45]	7.70	112	148	250	11.3	12.1	NP	20.7	
III. Hard									
Springfield, Ohio[44]	7.47 (27°C)	205	333	376	11.6	12.4	8.36	66.3 (73°C)	Collector scaled in service
Springfield, Ohio (softened)[44]	8.70 (27°C)	29	249	327	11.9	12.5	9.73	17.7 (73°C)	Possible scaling in collectors at 73°C or higher

[a]Palin Index total value: Ideal Balance = 11.0 to 11.2; Acceptable Balance = 11.3 to 11.6; Scaling = 11.7 to 12.6.

[b]See Appendix C for details on the ANL technique used to obtain these values.[44]

[c]25°C = 77°F.

[d]80°C = 176°F.

[e]NP -- no precipitate predicted.

II. Medium-Hard Water -- Scale could form in collectors operating at 176°F (80°C).

III. Hard Water -- In general, hard waters will form scale deposits on the collector water passages. For the case of the Ulery Greenhouse in Springfield, Ohio, the untreated water sample had a calcium-carbonate scaling potential of 66 ppm at 164°F (73°C).[44] After chemical treatment, the water sample still had 18 ppm of calcium carbonate over saturation at 164°F (73°C). However, the scaling potential was reduced by approximately a factor of four.

Because of the complexities of scaling phenomena, the following considerations and practical approaches to minimize scaling are suggested:

- A complete water analysis should be made to provide data for calculating the Palin index (or scaling potential, as in Appendix C). If the scaling potential calculated by the ANL technique in Appendix C ranges from 5 to 10 ppm $CaCO_3$, the water is probably suitable for solar DHW systems. If the scaling potential is high, further investigation is recommended. Water treatment may be necessary.
- Known performance of metals in a particular type of local water should be ascertained from experience and then checked against the likely performance, as predicted from chemical analysis. Design factors, such as open circuits, closed circuits, material choices, crevices, etc. may override factors predicted from water chemistry.
- With waters having high chloride or sulphate content, predictions calculated from a chemical analysis of the water should be treated with caution.

2.3.3.2 Calcium-Carbonate-Scaling Treatment

Any water-treatment chemical selected for direct systems must be suitable for use with potable water. Corrosion and scale are primary problems, because potable water usually contains fewer than 5 ppm suspended matter and 0.3 ppm iron, and has a low bacterial level. If microbiological growth occurs in the system, chlorine is usually the only acceptable toxicant control. If the water's pH drops after the addition of chlorine, scale and corrosion control can be achieved by adding up to 10 ppm of polyphosphate supplemented by up to 5 ppm of zinc. Sodium silicate is also frequently used to reduce corrosion. Softening the water with ion-exchange resins is the most successful solution to the problem.*

*Hardness reduction also can be achieved with a cold-lime softening.

In indirect systems, effective water treatment does not require controlling pH within a range suitable for drinking water. For example, many chromate and nitrite corrosion-inhibitor formulations are buffered to maintain the treated water in a highly alkaline pH range. Under certain circumstances, inhibitors such as phosphates, molybdates, and polymers can be used to control a marginal scaling condition. In other cases, scaling can become even more of a problem when the water supply has a high scaling potential and the system continually loses water. To help minimize scaling, a softened, demineralized make-up supply is preferred.

2.4 STORAGE TANKS

Water storage for single-family solar DHW systems consists of one or two tanks. The storage tanks must be sized to accommodate 1.5-2.0 gal water/ft^2 (60-80 L/m^2) of collector. In single-tank systems, storage water usually is well mixed, and there is little or no stratification. Two-tank systems provide better separation between hot and cold storage water, thereby improving stratification. This section presents several designs for one- and two-tank systems. Construction materials, failure modes, and failure rates of storage tanks are discussed.

2.4.1 Stratification

Temperature stratification occurs in storage tanks because hot water is less dense than cold water. Figure 2.22 illustrates the ideal and typical temperature profiles within a storage tank. If the ideal temperature profile were maintained, thermal efficiency of the collector system would be increased by 5% to 10%.[46]

Although temperature stratification improves solar DHW system performance, such stratification is usually difficult to maintain. Pumping water from the storage tank to the collectors mixes warm and cool water. Natural convection in storage tanks with coil or wraparound heat exchangers upsets thermal stratification. In addition, if water usage is large, the storage tank is charged and discharged frequently, preventing stratification.

2.4.2 One-Tank Storage

The simplest water-storage configuration for a solar DHW system is shown in Fig. 2.23. A single tank is both storage and auxiliary-heater tank. Generally, the hot-water outlet is at the top of the tank. Make-up water enters through a dip tube that extends down to within 4 to 6 in. from the bottom.

The inlet to the collector loop should be within 4 in. of the bottom of the tank. One configuration is shown in Fig. 2.23. Another manufacturer makes the connection to the collector loop through a pipe that extends down from the top of the tank. Either configuration is acceptable and prevents hard-water deposits from being drawn into the collector array.

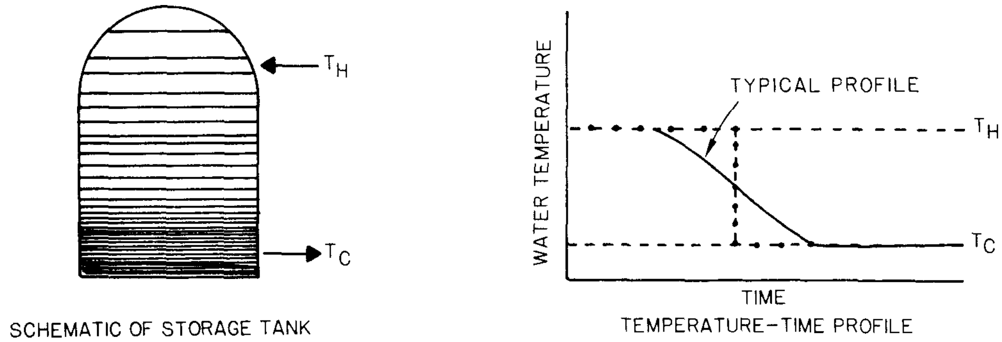


Fig. 2.22 Thermal Stratification in a Storage Tank

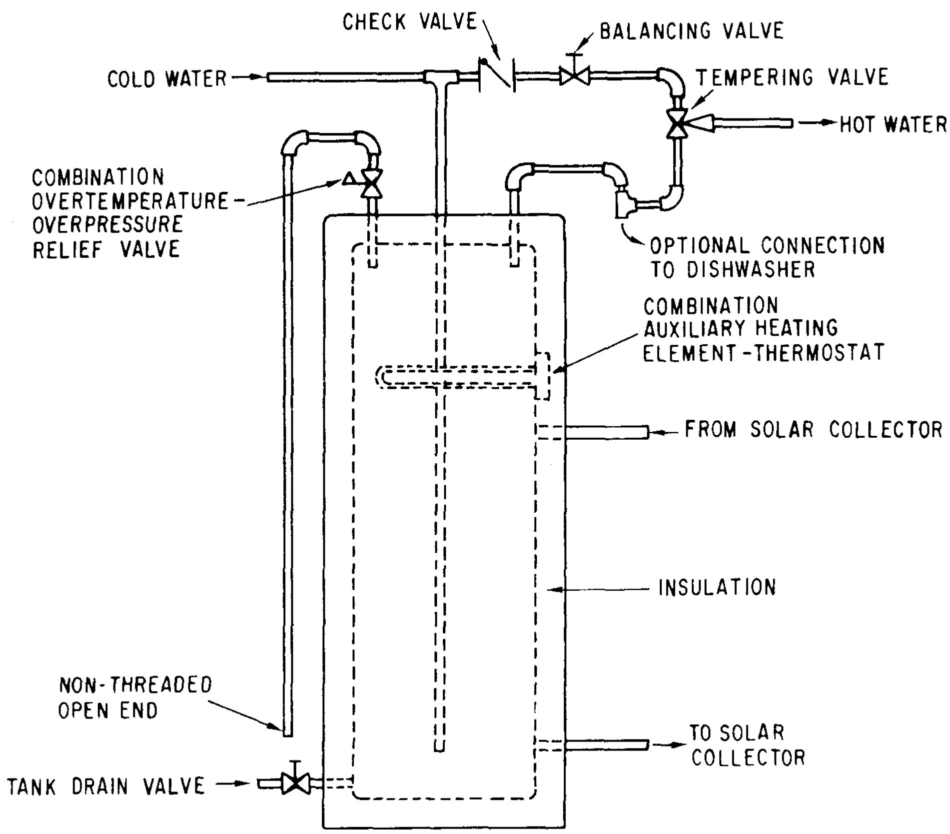


Fig. 2.23 One Configuration for One-Tank Water Storage

The return line from the collector loop can enter the tank just below the auxiliary heating element, as shown in Fig. 2.23. Another possibility is to have the return pipe enter from the top of the tank and terminate below the auxiliary heating elements. With the return line in this position, energy provided by the electric auxiliary heater is added only to the warm water layer in the upper part of the tank, which minimizes auxiliary-heater operating time.

Indirect solar DHW systems do not use potable water as a heat-transfer fluid. If the heat-transfer fluid is toxic, double-walled heat exchangers, such as the types described in Sec. 2.6, are used. A one-tank design with a wraparound heat exchanger is shown in Fig. 2.24. A coil-in-tank design is shown in Fig. 2.35. These designs have all the advantages and disadvantages of single-tank systems. In addition, the heat exchanger reduces collector efficiency.

2.4.3 Two-Tank Storage

When two storage tanks are used in solar DHW systems, one tank acts as a preheater for the auxiliary tank, an arrangement that provides the following advantages:

- With proper inlet and outlet placement, stratification is achieved in the preheat tank.
- Auxiliary heat is in a separate tank.
- Gas, oil, or electric energy can be used for auxiliary heat.
- Temperature of heat-transfer fluid going to collector array is lower, which increases collector efficiency.

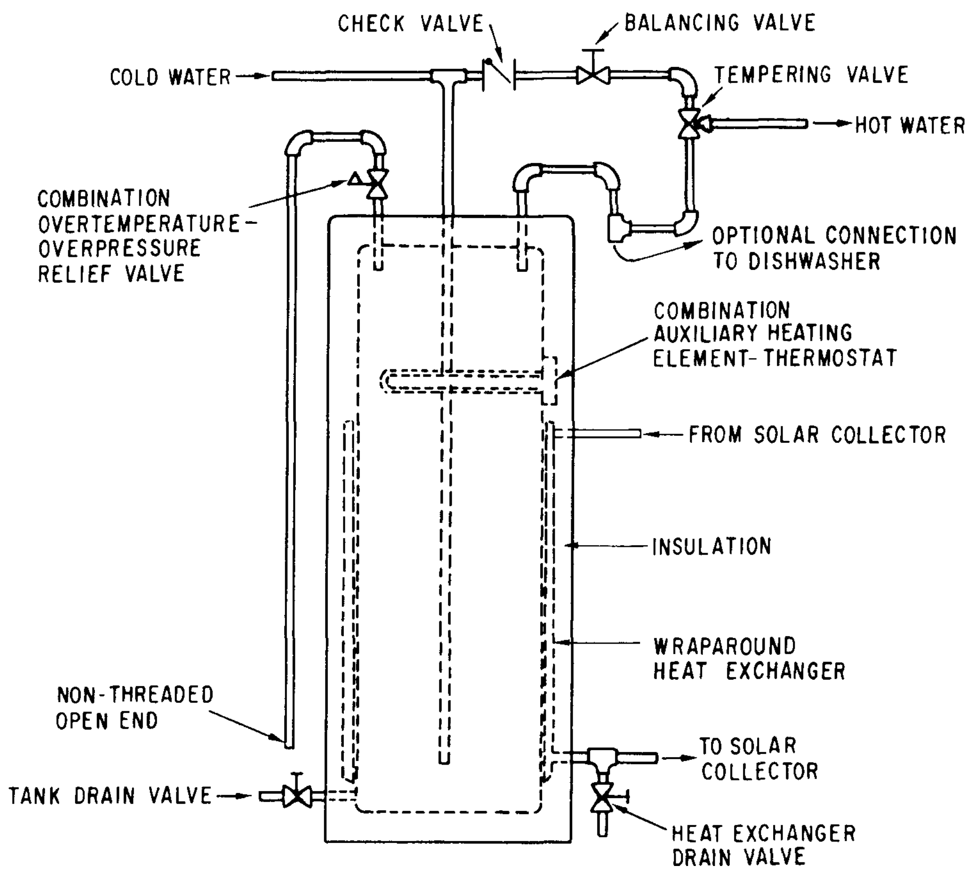


Fig. 2.24 One-Tank System with Wraparound Heat Exchanger

Disadvantages of two-tank systems include the following:

- Heat losses are usually greater than with a single tank because of an increased surface-to-volume ratio.
- Solar heat is employed only when potable water is drawn from the auxiliary tank. During periods of high insolation and low water use, preheat-tank water temperature could exceed the temperature of the auxiliary water tank. In addition, the auxiliary heater will operate to overcome standby losses from the auxiliary tank.
- Larger floor space is required.
- System installation cost is greater because of the two tanks and the necessary plumbing.

A typical two-tank system is illustrated in Fig. 2.25. One tank, a large preheating unit, is connected to the collector. The second, smaller tank contains the auxiliary heater that raises the preheat-tank water to the temperature desired by the user.

Inlet and outlet connections to the collectors should be on the sides of the preheat tank to promote stratification. The cold-water inlet to the collector should be 4 to 6 in. above the bottom of the tank to prevent sediment or scale from being drawn into the collectors.

The outlet of the preheat tank is the cold-water inlet of the auxiliary tank. When there is demand for hot water, make-up water pressure forces heated water from the auxiliary tank to the tap. As water is drawn from the

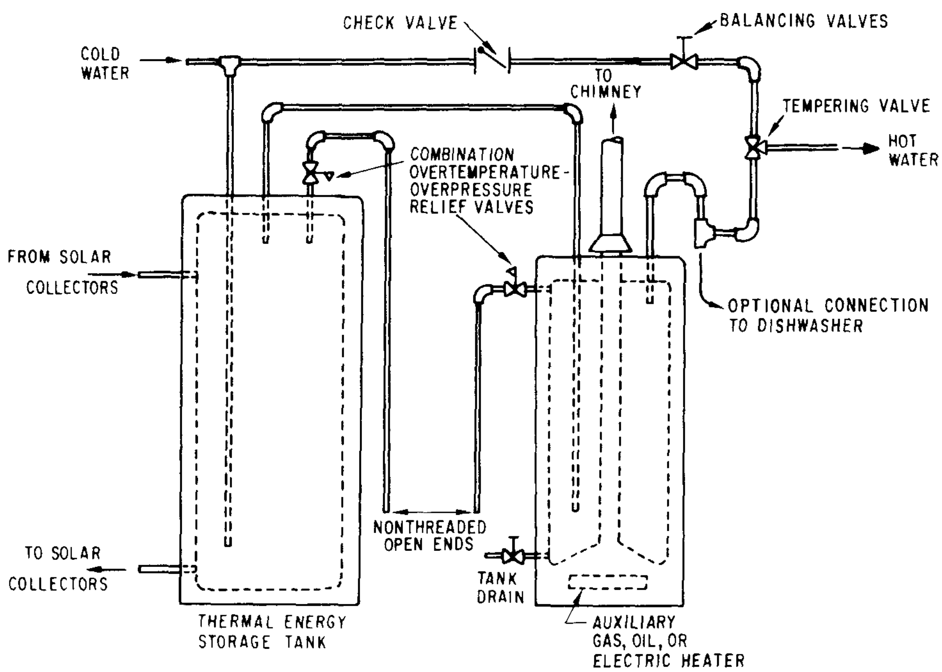


Fig. 2.25 Two-Tank Water Storage

auxiliary tank, cold make-up water enters the preheat tank to replace the water drawn from the system.

Indirect systems are defined in this solar DHW design guide as systems with a heat-transfer fluid and a heat exchanger in the collector loop. The type of heat exchanger used depends on the heat-transfer fluid and on local plumbing codes (see Sec. 2.6).

Except for the heat exchanger and additional pump, the two-tank design in Fig. 2.26 is the same as the design in Fig. 2.25. All the advantages and disadvantages of the design in Fig. 2.25 apply to the design in Fig. 2.26 as well. In addition, the indirect system in Fig. 2.26 costs more than an indirect system with internal heat exchanger (Fig. 2.27), because of the external heat exchanger, additional pump, and need for a more elaborate control system.

The pump between the preheat tank and collector-loop heat exchanger can be eliminated if a double-walled heat exchanger is immersed in the preheat tank as illustrated in Fig. 2.27. This arrangement applies only to liquid-cooled collector systems. The heat exchanger immersed in the preheat tank in Fig. 2.27 must be larger than the heat exchanger in Fig. 2.26. The larger size is needed because convection is a less effective way to transfer heat than forced circulation. Ref. 46 contains additional heat-exchanger information.

2.4.4 Construction Materials

Water tanks in solar DHW systems generally are modifications of tanks used in conventional residential hot-water systems. The tanks are made of rolled sheet steel welded to form a cylindrical body. Steel heads, dished to withstand the water pressure, are welded to the cylindrical body. Fiberglass or foam insulation is installed around the tank to reduce heat loss. A procedure for calculating proper tank-insulation thickness is provided in Sec. 2.10.

The steel shell is protected against corrosion by a lining and an anode. The lining can be a glass coating that is applied wet and then baked at approximately 1500°F (816°C). The anodes are usually magnesium rods, which are more active electrochemically than steel; thus, the rods corrode instead of the steel tank.

Porous concrete, also known as hydraulic stone, can be used as a tank lining. This concrete lining is approximately 0.5 in. (1.27 cm) thick. When the tank is first filled, the porous concrete absorbs water. This trapped water soon loses its oxygen. Without oxygen, the corrosion rate of the steel shell is drastically reduced. Sacrifical magnesium anodes are not required.

2.4.5 Storage-Tank Failure Modes

Corrosion is the primary cause of failure in solar DHW tanks. The corrosive attack of water usually starts around openings, irregularities, or

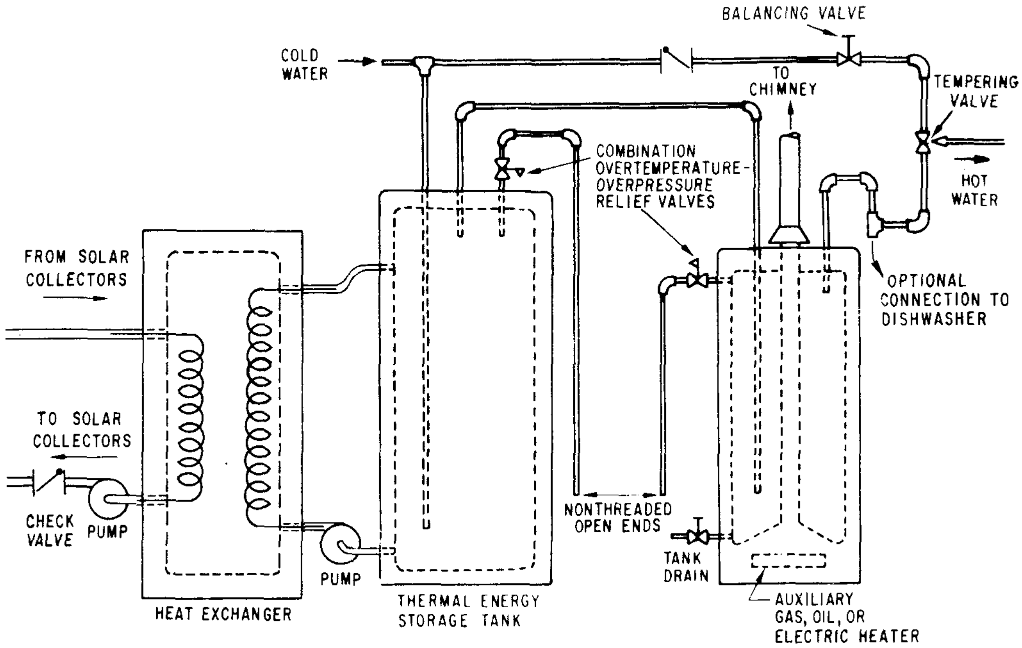


Fig. 2.26 Two-Tank DHW System for Use with Indirect Systems

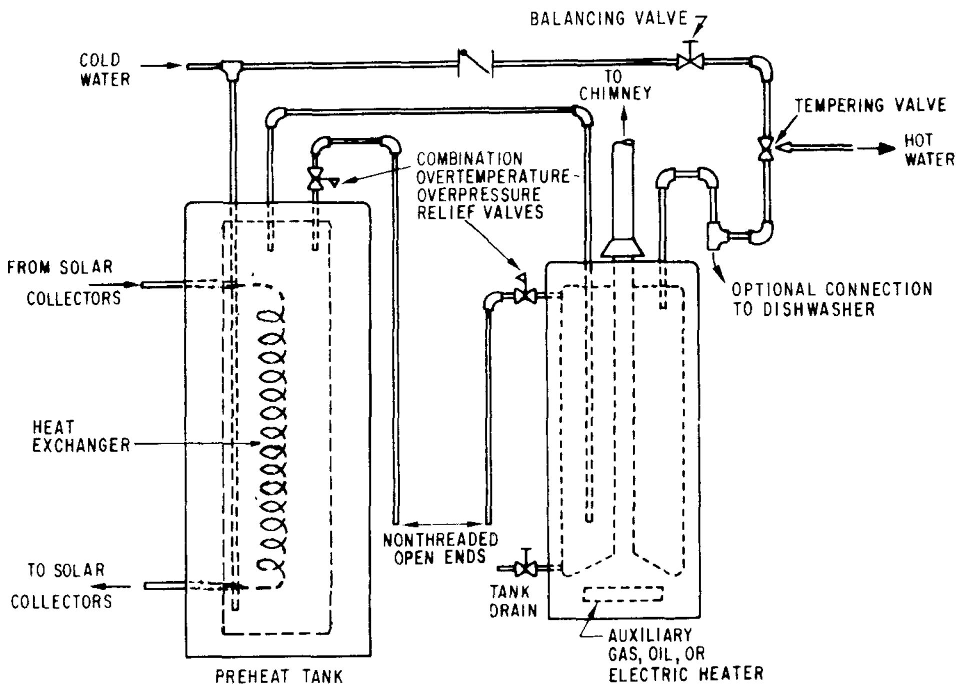


Fig. 2.27 Two-Tank DHW System with Heat Exchanger in the Preheat Tank

joints in the tank body. The most frequent failure location is the joint between cylindrical body and heads.

Corrosion can be controlled with anodes, by water treatment that is appropriate to the region, and by limiting the water temperature to approximately 180°F (82°C). Although corrosion varies with water quality, it is generally acknowledged that the corrosion rate doubles for every 20°F (10°C) that glass-lined tanks operate above 180°F (82°C).

2.4.6 Estimated Storage-Tank Failure Rates

The estimated failure rates for storage tanks range from 7.6×10^{-6} to 2.3×10^{-5} failures/hr. These failure rates correspond to tank lives of 5 to 15 years.[47] Variations in tank life depend on operating temperatures and water quality. For maximum tank life, local water quality must be determined and, if needed, the water should be treated properly. Section 2.3 describes accepted water treatments.

2.5 INTERCONNECTIONS

Interconnections join adjacent collectors or individual collectors to inlet and outlet manifolds. This section lists materials that are compatible with the heat-transfer fluids, describes hose clamps and end fittings, and estimates the mean lives of interconnections.

2.5.1 Thermal Expansion

Metallic absorber plates in solar collectors expand approximately 1/8 in. (3.2 mm) for a temperature difference of 200°F (110°C). Supply and return manifolds connecting system components also expand with increasing temperature. Figure 2.28 gives the changes in length in 100 ft (30.5 m) of pipe of three different materials for a range of temperature differences.

In solar DHW systems, the risers are usually long enough and flexible enough to absorb the thermal expansion of the headers. For example, a 25-ft (7.62-m) copper header will expand about 0.6 in. (1.52 cm). Risers approximately 30 ft (9.14 m) high easily absorb a horizontal movement on the order of 0.6 in. (1.52 cm).

2.5.2 Collector-to-Collector Interconnections

Interconnections of the type shown in Fig. 2.29 are used when collectors are joined in series, although series arrays are not typical of solar DHW systems. Figure 2.29 also shows metal tubing with a union or flared fittings connecting two collector panels and a connection with flexible hose.

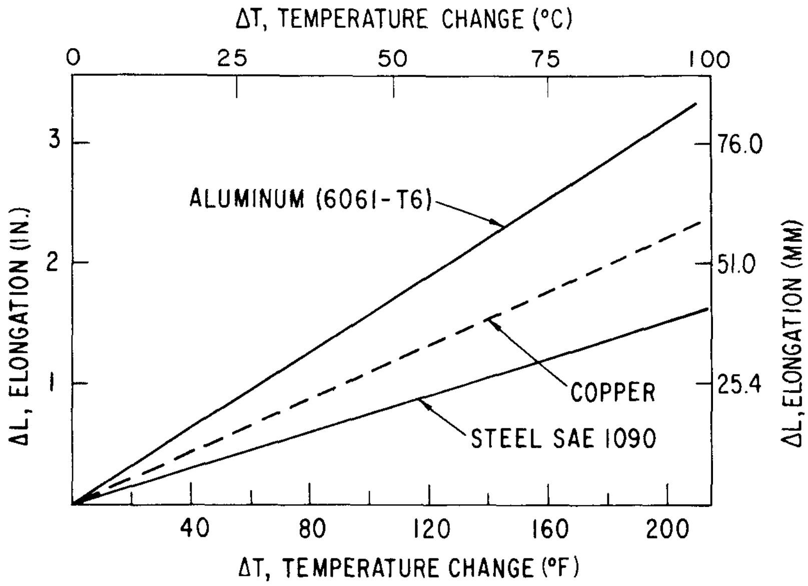


Fig. 2.28 Linear Thermal Expansion per 100 ft of Pipe

2.5.3 Collector-to-Manifold Interconnections

Collectors usually are installed in parallel in solar DHW systems, as shown in Fig. 2.30. Figure 2.31 shows three common interconnections for multiple collectors. Although the interconnection with the 8-in. loop in Fig. 2.31 has been used successfully on several DOE-sponsored systems, it is difficult to purge air from this configuration.[48] Other geometries that are used in power plants or in chemical processing can be found in Ref. 49.

A designer may choose to use either metallic or elastomeric interconnections. Elastomeric interconnections cost less initially than metallic parts, but metal interconnections, designed within their elastic limits, should last at least 20 years. Elastomeric interconnections, on the other hand, will require periodic maintenance during that time. Appendix D provides design equations for typical metallic interconnections. If elastomeric interconnections are selected, they should be installed to be readily accessible for maintenance and replacement, for they may be expected to last only three to five years in solar DHW service.

2.5.4 Selection of Interconnection Materials

Interconnection materials must be compatible with the heat-transfer fluid and other materials in the system. Copper, aluminum, or stainless steel may be used for collector and manifold interconnections. Of these materials, copper and aluminum usually are preferred when initial cost is the primary consideration.

The choice of copper or aluminum depends on service conditions and the other metals in the system. A copper-steel or aluminum-steel joint is

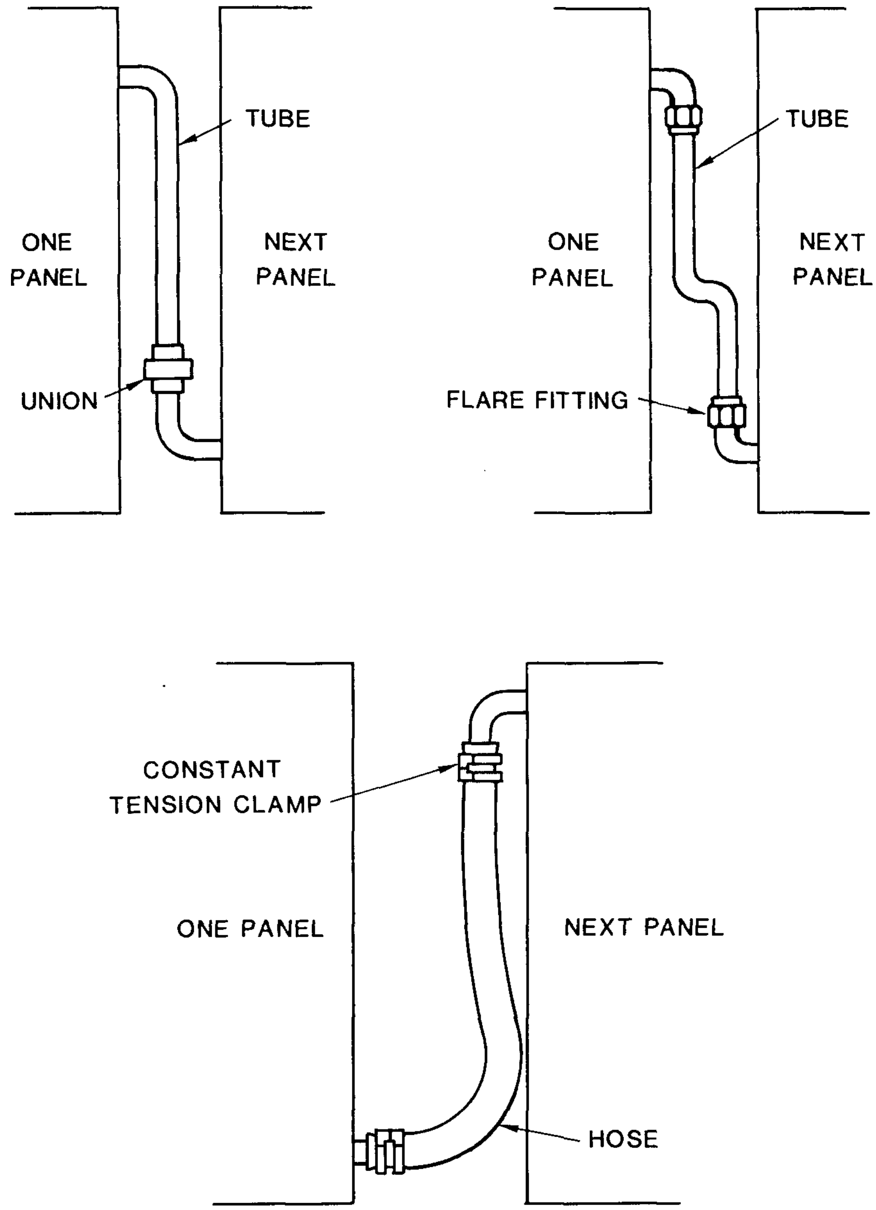


Fig. 2.29 Three Collector-Connecting Methods

acceptable, although some galvanic corrosion will occur. However, a copper-aluminum or copper-galvanized-steel joint is unacceptable because of severe galvanic corrosion.

If dissimilar metals must be joined, dielectric couplings must be specified. Sacrificial anodes or getters also may be placed in the fluid stream. The location of these sacrificial anodes depends on the material to be protected, the anode material, and the electrical conductivity of the heat-transfer fluid. Because there are so many possibilities, each combination must be evaluated on its merits.

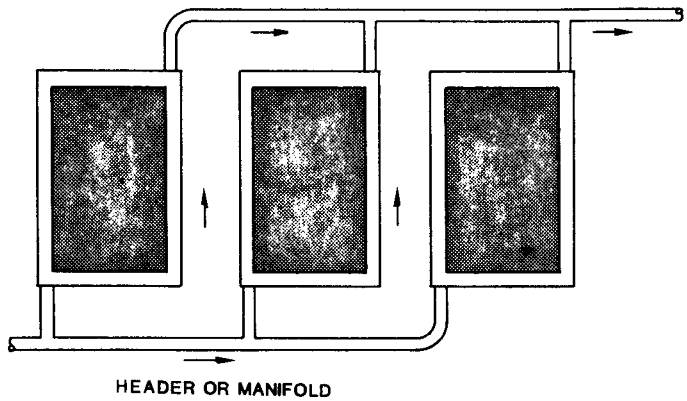


Fig. 2.30 Parallel (Reverse-Return) Collector Connection

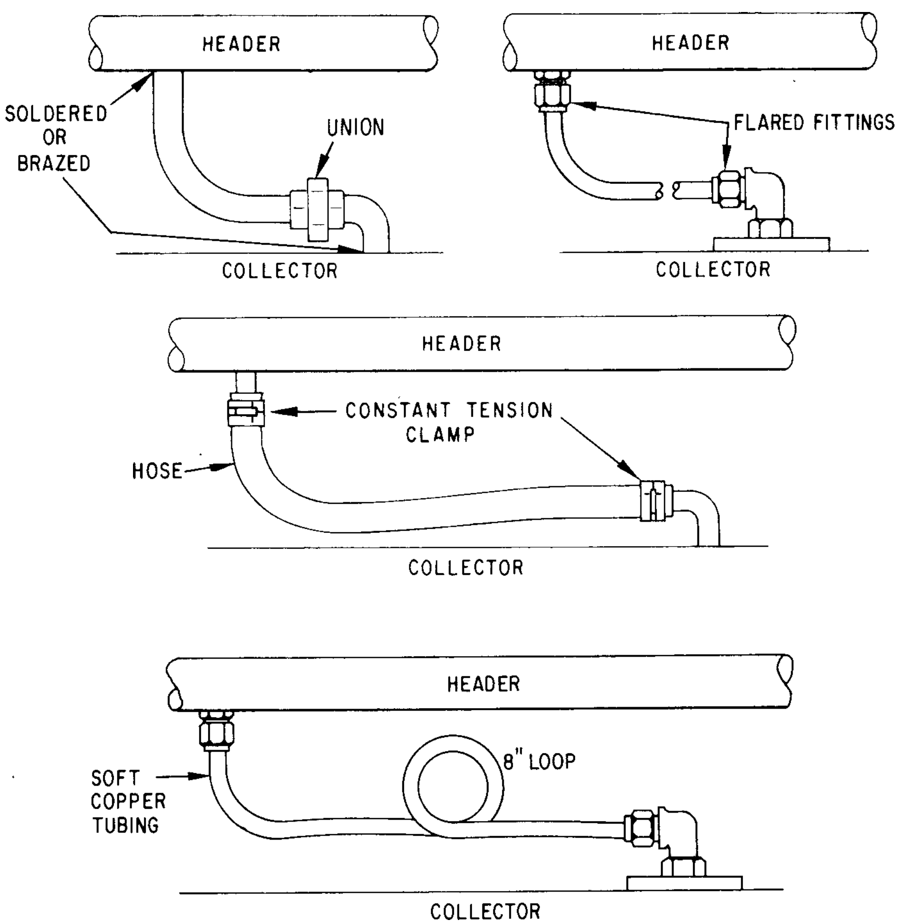


Fig. 2.31 Manifold Connections

Metallic interconnections are attached to collectors or manifolds by soldering or with flared fittings. If joints are to be soldered, a 95/5 tin/antimony solder is recommended. A brazing alloy with a melting point above 1000°F would be an improvement over 95/5 solder. If joints are brazed, collectors with nearby soldered joints must be protected from the higher brazing temperature.

Polymeric hoses can be and are used to interconnect manifolds. A review of hose literature and contacts with hose manufacturers provided the information in Table 2.16. From the table, EPDM, Viton,* and silicone appear to be good choices. Silicone is less resistant to abrasion and tearing than the other materials, but these shortcomings are not a factor in most installations. Viton* generally has a less expensive covering to reduce cost. Hypalon,* butyl, and neoprene hoses also are acceptable. Buna N rubber (nitrile), natural rubber, and Buna S or SBR rubber (styrene-butadiene) deteriorate on exposure to ozone and ultraviolet radiation and should not be used.

Two types of hose clamps are used (Fig. 2.32). A greater tightening force can be applied initially to a screw-type than to a constant-tension clamp. With proper tools, installation should not be a problem with either type of clamp. Although the screw clamp can apply more force than the constant-tension clamp, the screw-type hose clamp tends to loosen as the hose takes a compression set. A constant-tension clamp made of flat, noncorroding spring material tends to maintain sealing pressure as the hose takes a permanent set. Constant-tension clamps maintain a tight seal to about 30 psig (208 kPa).

All hose-clamp manufacturers advise against seals on straight tubing. They point out that to achieve improved reliability in pressure sealing, the tubing must have some irregularity, such as serrations, humps, or ferrules, over which the hose is stretched. So a good rule is that clamps are more effective over or between serrations (Fig. 2.33).

2.5.5 Air Ducts

Leaks in air systems usually are the result of poor joint design, location, or installation. To prevent excessive air leakage, ducts should be constructed in accordance with Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) standards for duct pressures of 3 in. WC (747 Pa).[51] As an additional safety measure, all joints should be sealed with sealing compound and the ductwork tested for leaks.

2.5.6 Interconnection Failure Rates

As long as properly designed and installed metallic interconnections operate in the elastic range, they can be expected to have service lives and failure rates on the order of 4.6×10^{-6} failures/hr. In contrast to this long service life, Ref. 54 indicates that rubber or polymeric hoses have failure rates of 7.6×10^{-5} failures/hr. When Table 2.16 was being compiled,

*Trademark of E.I. DuPont de Nemours & Co.

Table 2.16 Possible Elastomers for Solar DHW Applications[28,50]

Property	EDPM Rubber[b]	Viton[c]	Silicone[d]	Hypalon[e]	Neoprene[f]	Butyl[g]
	Compound[a]					
Sunlight aging	E[h]	E	E	E	G	G
Oxidation	E	E	E	E	E	E
Ozone resistance	E	E	E	E	E	E
Temperature aging	E	E	E	G	G	G
Low-temperature resistance	E	G	E	G	G	G
Compression set	G	E	F	F	G	G
Abrasion resistance	G	G	F	E	E	F
Tear resistance	F	G	F	F	G	G
Resistance to solar fluids						
Water	E	G	E	G	G	G
Glycol-water	E	G	E	G	G	G
Mineral oil	NR	E	F	G	G	NR
Aromatic hydrocarbon oil	NR	E	F	F	F	NR
Alkylated aromatic hydrocarbon oil	NR	E	F	F	F	NR
Silicone oils	E	E	F	G	G	G

[a]Also examined were natural rubber (polyisoprene), nitrile or Buna N rubber (acrylonitrile-butadiene-styrene) and Buna S rubber (butadiene-styrene); none of these can be recommended for solar-energy-system applications.

[b]Ethylene propylene-diene terpolymer.

[c]Fluoroelastomer.

[d]Polysiloxane polymer.

[e]Chloro-sulfonyl-polyethylene.

[f]Chloroprene.

[g]Isobutylene isoprene.

[h]Rating: E - excellent, G - good, F - fair, NR - not recommended.

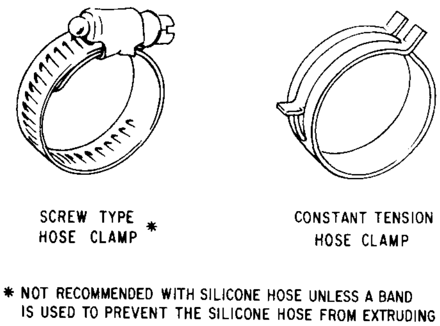


Fig. 2.32 Two Hose-Clamp Types

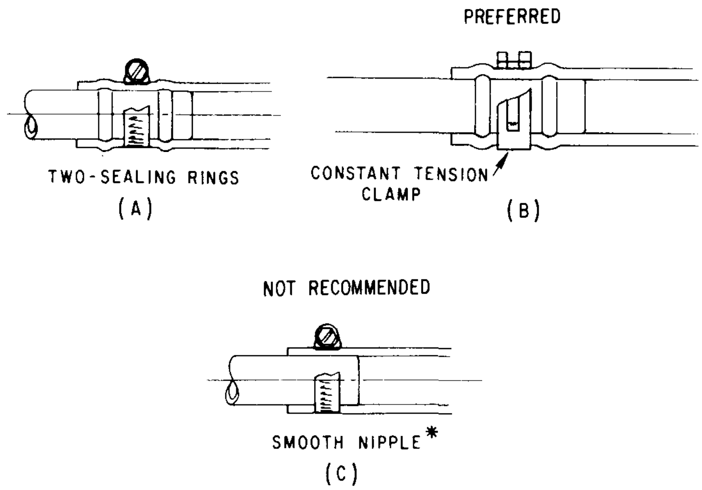


Fig 2.33 Practices in Securing of Hose Clamps

most of the hose manufacturers expressed the opinion that maximum hose life would be 5 yr ($\lambda = 2.3 \times 10^{-5}$ failures/hr) under solar-energy collection conditions.

Polymeric-hose-performance predictions suggest that systems be designed with ready access to hose connections for periodic inspection, tightening, and replacement. Hoses should not be placed inside finished walls or collector enclosures. Where possible, drains should be provided under the solar panels to protect the roof structure from damage in case leaks develop in the outside system.

2.6 HEAT EXCHANGERS

A heat exchanger is a device that transfers heat from one fluid to another. This section describes the heat exchangers in solar DHW systems, including the different types, their estimated mean lives, failure modes, and construction materials.

Antifreeze solutions, which circulate through the heat exchangers, are used to protect the solar collectors from freezing. The safety aspects of circulating toxic antifreeze solutions through heat exchangers containing potable water are discussed in Appendix E. Appendix E contains the standards recommended by the U.S. Department of Housing and Urban Development (HUD) for liquid-to-liquid heat exchangers.

2.6.1 Liquid-to-Liquid Heat Exchangers

Many antifreeze solutions are toxic and must be separated from the potable water by double-walled heat exchangers. Some of the heat exchangers that may be considered to be double-walled are:

- Wraparound-shell (see Fig. 2.34)
- Coil-in-tank (see Fig. 2.35)
- Coil-around-tank, also called trace-tank (see Fig. 2.36)
- Shell-and-double-tube (see Fig. 2.37)
- Two single-walled heat exchangers with an intermediate loop.

A wraparound-shell heat exchanger (Fig. 2.34) can be single-walled or double-walled, as shown in Fig. 2.38. The bleed hole for visual leak indication must drain so the fluid will be visible.

The coil-in-tank heat exchanger shown in Fig. 2.35 is considered double-walled if the coil is made of double-walled tubing. Figure 2.39 shows (at left) a type of double-walled tubing that is considered an extra-thick single wall, according to most interpretations of HUD Intermediate Minimum Property Standards. Figure 2.39 also illustrates (at right) a type with vented air spaces that may meet the requirements, although external leak indication may be a problem.

A heat exchanger consisting of a coil wrapped around a tank, as in Fig. 2.36, also may be considered either single- or double-walled. If the coil is not soldered to the tank, it definitely is double-walled. However, soldered coils may be considered single-walled if the soldered area is large enough to sustain a leak without any fluid leaking outside.

The shell-and-double-tube heat exchanger shown in Fig. 2.37 satisfies code requirements only if the intermediate heat-transfer fluid is potable water or air.

If a heat exchanger is required, system thermal performance is affected and an operating penalty must be assessed. Reference 46 shows how to compute a heat-exchanger operating penalty and describes the effect of the exchanger on system thermal performance. This reference also summarizes the state of the art for sizing heat exchangers for solar DHW systems.

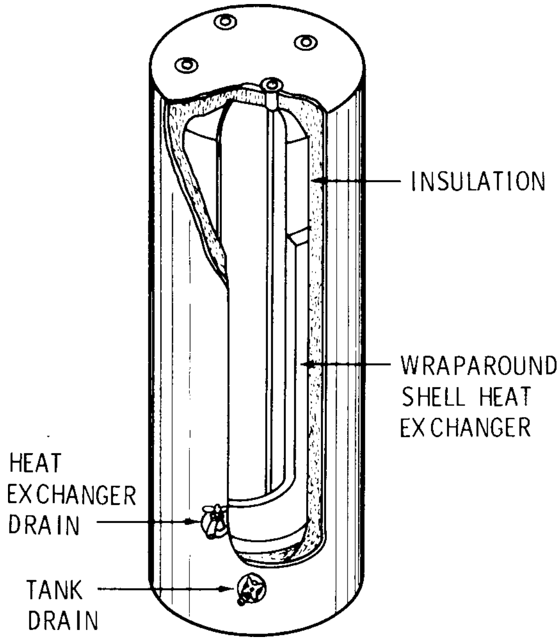


Fig. 2.34 Wraparound-Shell Heat Exchanger

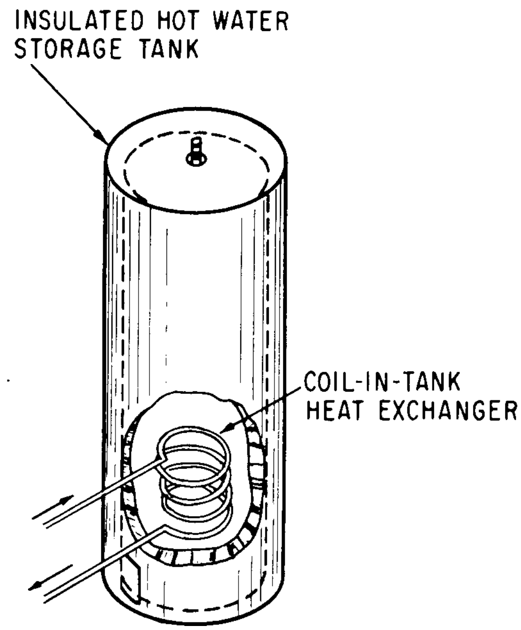


Fig. 2.35 Coil-in-Tank Heat Exchanger

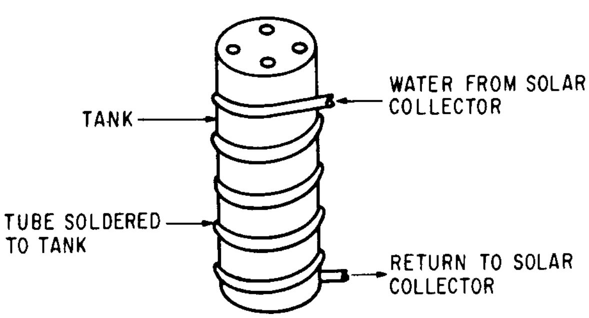


Fig. 2.36 Wraparound (Trace-Tank) Heat Exchanger

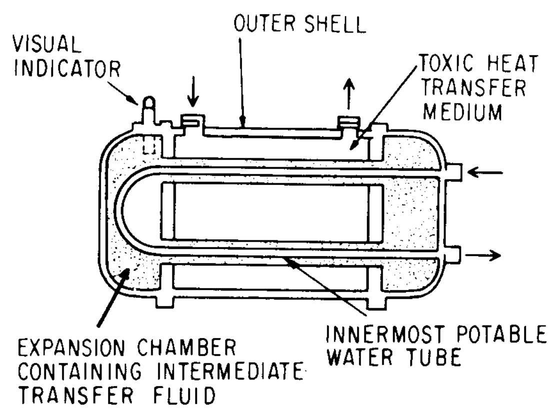


Fig. 2.37 Shell-and-Double-Tube Heat Exchanger

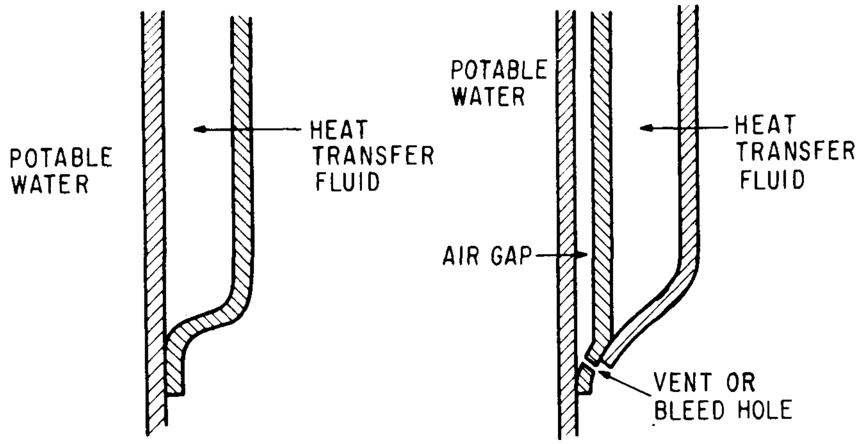


Fig. 2.38 Wraparound-Shell Heat Exchangers in Cross-Section

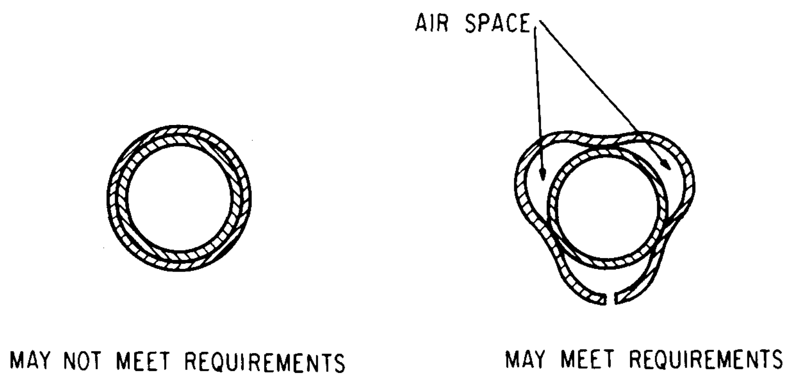


Fig. 2.39 Double-Walled Tubing

2.6.2 Air-to-Water Heat Exchangers

Air collector systems for preheating solar DHW systems must have an air-to-water heat exchanger between the collector loop and the DHW tank. This heat exchanger is a single-walled, finned-tube unit, such as that shown in Fig. 2.40. The procedures in Ref. 46 can be used to size air heat exchangers and calculate operating penalties.

2.6.3 Heat-Exchanger Construction Materials

Heat exchangers of the wraparound-shell type shown in Figs. 2.34 and 2.38 generally are fabricated from cold-rolled steel. The external surfaces are painted or coated to reduce corrosion.

Coil-in-tank or coil-around-tank heat exchangers (shown in Figs. 2.35 and 2.36) employ either stainless-steel or copper tubing. For the coil-in-tank design, fins on the copper tubing increase the heat-transfer area.

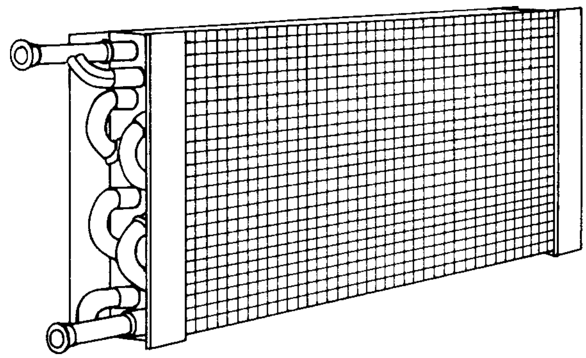


Fig. 2.40 Liquid-to-Air or Air-to-Liquid Heat Exchanger

Single-walled tubing is satisfactory for the coil-in-tank design, as long as the collector is cooled by potable water. For other heat-transfer fluids, double-walled tubing usually is required. Local plumbing codes specify whether single- or double-walled tubing is to be used with heat-transfer fluids other than water.

Shell- and double-tube heat exchangers, as shown in Fig. 2.37, and single-walled heat exchangers usually are made with copper tubes. The heat-exchanger shells are steel, and the heat-exchanger heads are cast iron.

Some finned-tube air heat exchangers are all copper or all aluminum. The most common practice, however, is to use copper tubes and aluminum fins.

2.6.4 Heat-Exchanger Failure Modes

The primary failure modes of heat exchangers are decreased performance caused by scaling, and failure of the tube bundle caused by corrosion.

Scaling occurs in water systems because carbonate and sulfate salts in the water supply are less soluble at temperatures over 100°F (38°C) than at room temperature. The rate of scaling is difficult to determine, but a scale thickness of 0.1 in. (2.54 mm) on a heat-transfer surface produces a heat-transfer loss of 40%.[53]

To prevent scale from forming, the water must be treated. Section 2.3 discusses several water-treatment procedures.

Corrosion failures can be attributed to the water or to degraded glycols. Treating the water holds the corrosion rate within acceptable limits. If the glycol heat-transfer fluid has degraded from oxidation and has become acidic, heat-exchanger surfaces corrode rapidly. To prevent corrosion as a failure mode, the heat-transfer fluid must be checked on a regular basis (see Sec. 2.3).

A failure mode observed in several solar DHW systems is freeze damage of air-to-water or glycol-to-water heat exchangers. This failure is caused by thermosiphoning between cold collectors and warm heat exchangers. By installing antithermosiphoning devices, such as spring- or weight-loaded check valves, or motorized dampers, in the collector piping, this failure mode can be prevented.

2.6.5 Heat-Exchanger Failure Rates

Failure-rate data for heat exchangers are obtained from Ref. 52. These data are for heat exchangers that are not immersed in either the storage tank or a preheat tank. In addition, it is assumed that the corrosivity of the heat-transfer fluid is monitored and controlled. Under such conditions, the failure rate for heat exchangers ranges from 2.3×10^{-6} to 1.4×10^{-5} failures/hr.

The failure rate of coil-in-tank heat exchangers will be assumed to be the same as for the storage tank. This assumption should be valid, because the heat exchanger must be replaced when the tank is replaced.

2.7 PUMPS

The centrifugal pumps used in typical residential solar DHW systems are rated between 1/40 and 1/4 horsepower. These pumps have pumping capacities of 0.5-3.0 gal/min (0.03-0.19 L/s). This section discusses these and other pump characteristics and describes pump seals, materials, and failure modes. Estimates of pump mean life also are provided.

2.7.1 Pump Characteristics

Centrifugal pumps in solar DHW systems must have a back pressure, or net-positive-suction head (NPSH), at the pump inlet in order to protect the pump. Without sufficient back pressure, the pump cavitates, is noisy, and will fail.

Positive-displacement pumps rarely are used, unless the head requirements exceed 35 ft of water. If a positive-displacement pump is specified, a relief valve is required on the pump outlet as a safety measure. The relief valve prevents pressure buildup if a pipe becomes plugged. Solar DHW systems are either open or closed to the atmosphere, as far as pump requirements are concerned.

2.7.1.1 Collector-Loop Pumps for Open Systems

Open-loop collector systems are designed to drain each time the collector-loop pump shuts off. When these open systems are shut down, air displaces the water in the collector loop. To restart the system, the collector-loop pump must expel the air and raise the water to the highest point in the loop. The pump also must overcome frictional losses in the collectors, valves, tees, elbows, and piping. These frictional losses are proportional to the square of the flow velocity. Thus, if flow rate is doubled, frictional losses increase by a factor of four, so the pump head must be increased accordingly. References 54 and 55 show how to calculate frictional losses.

2.7.1.2 Collector-Loop Pumps for Closed Systems

Collector loops containing a heat-transfer fluid other than potable water are not open to the atmosphere. In these systems, the heat-transfer fluid is used until it becomes acidic and is replaced. (Section 2.3 describes ways to check the corrosivity of heat-transfer fluids.)

Except for closed-loop drain-back systems, the vertical distance from the pump to the top of the collector loop is not a factor in determining pump size. Once the collector loop is filled, the weight of the fluid in the riser balances the weight in the return piping. Therefore, only the frictional losses need be known in sizing the pump.[54,55]

In closed-loop drain-back systems, the collector-loop pump must be capable of filling the collector loop each time the system starts up. After the loop has been filled and flow established, the pump must overcome only the frictional losses in the system.

Heat-transfer fluids in closed collector-loop systems increase in viscosity as the temperature drops, which increases frictional losses. Correction factors for this effect can be obtained from the heat-transfer-fluid manufacturer.

2.7.1.3 Storage-Loop Pumps

In the two-tank system illustrated in Fig. 2.26, the pump circulates fresh water from the community main or well through the potable-water side of the collector-loop heat exchanger. With this configuration, the oxygen content and pH of the make-up water vary.

If the preheat tank in a two-tank system is designed properly and purged of air at start-up, the pump does not have to work against a head, so it can be sized to overcome only frictional losses in the heat exchanger and connecting piping.

2.7.2 Pump Seals

Centrifugal pumps on recently installed solar DHW systems are generally of the canned wet-rotor type, illustrated in Fig. 2.41. Mechanical seals are not required, and these pumps are self-lubricated with the fluid that initially fills the pump's motor-rotor chamber. Although there are no seals to leak, the pump bearings and pump materials must be compatible with the fluid being pumped.

Other pumps that have been used on solar DHW systems are illustrated in Figs. 2.42 and 2.43. Of these pump types, the adjustable packing seal in Fig. 2.42(a) is the least desirable, because it needs frequent inspection and adjustment. In this seal a packing gland squeezes the packing between the

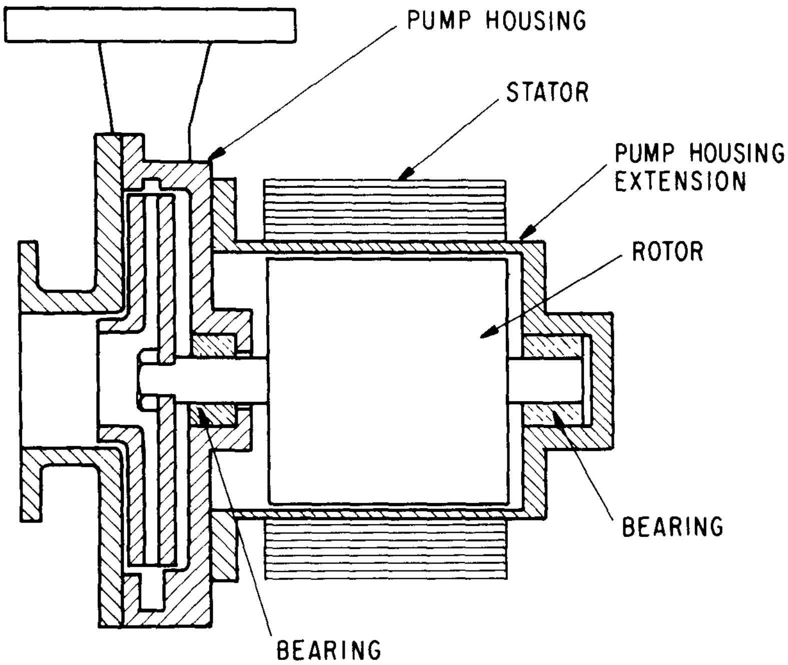


Fig. 2.41 Cross-Section of Canned Wet-Rotor Pump

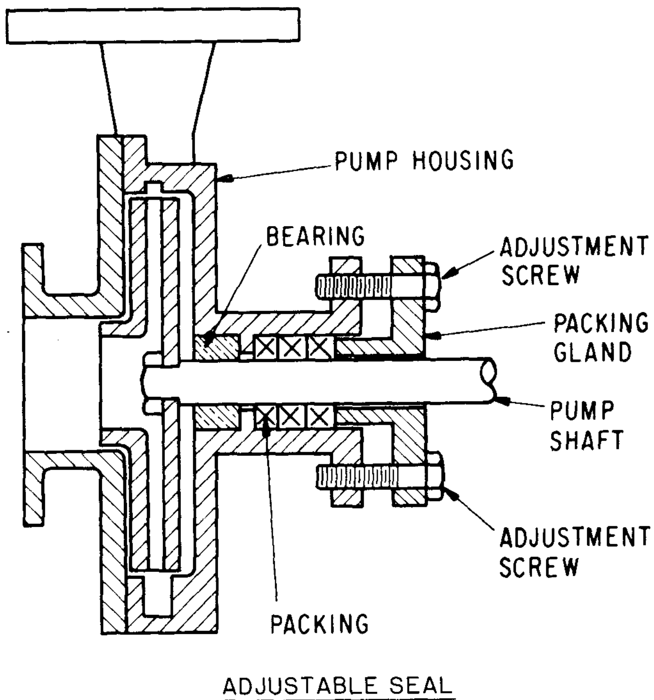
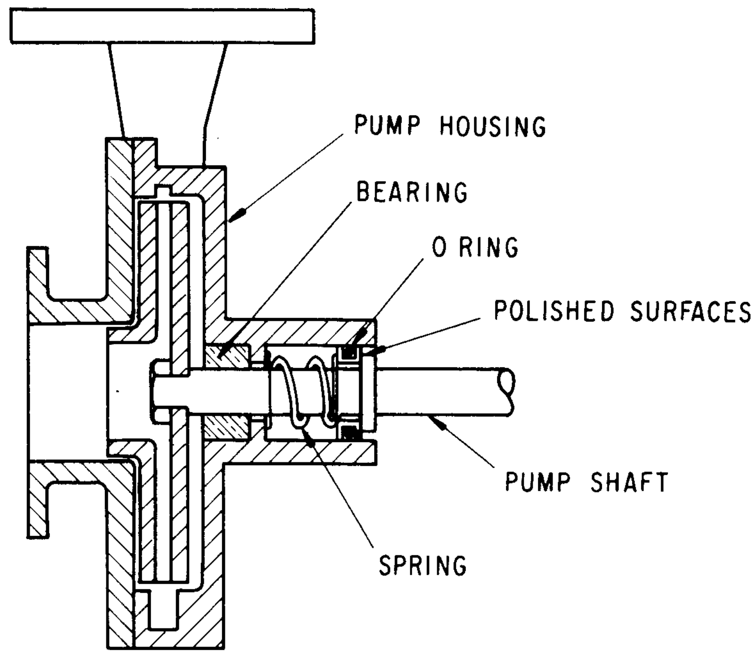


Fig. 2.42(a) Adjustable and Mechanical Pump-Shaft Seals



MECHANICAL SEAL

Fig. 2.42(b) Adjustable and Mechanical Pump-Shaft Seals

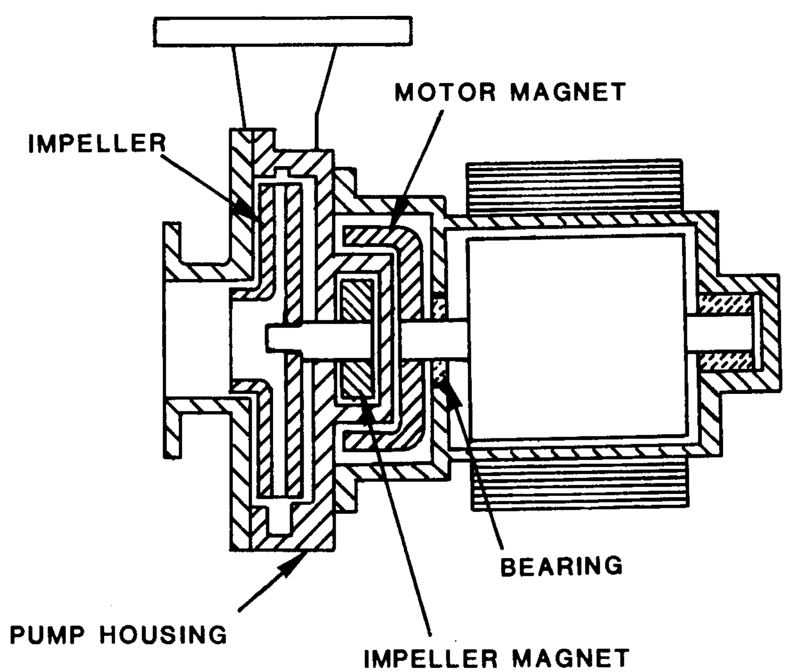


Fig. 2.43 Magnetically Coupled Pump

pump housing and shaft. As the packing wears, the gland must be tightened. If the gland is too tight, the packing binds on the shaft. If it is too loose, the seal leaks. Therefore, adjustable packing seals should not be used where access to the pump is difficult, where seal leakage could cause system failure, where leakage would be a hazard to humans, or where antifreeze fluids are used.

The mechanical or face seal in Fig. 2.42(b) consists of two carefully polished surfaces pressed together by a spring. One surface is part of the pump shaft, the other is sealed against the pump housing with an O-ring. A minute amount of leakage, so small that it evaporates before becoming visible, lubricates the seal surfaces.

Experience with hydronic heating systems shows that mechanical seals can last the life of a system without adjustment. However, the fluid system must be kept clean, otherwise the polished surfaces may become scratched and leak. In one instance, for example, chromate-type corrosion inhibitor caused seal failure when the slight leakage evaporated, depositing hard chromate crystals that scratched the polished surfaces. High temperatures and pressures also cause premature failure of mechanical seals. And some antifreeze fluids, such as silicone oils, leak excessively through mechanical seals.

The pump in Fig. 2.43 has a magnetic coupling. The rotor of the electric motor and its bearings are inside an extension of the pump housing. The motor stator is outside the pump housing. The motor drives the impeller by a rotating magnetic field. In some designs, an external electric motor rotates the driving magnets. Magnetically coupled pumps may be expected to last the life of the system.

2.7.3 Pump Construction Materials

The materials for solar-DHW-system pumps depend on pump service. This section is concerned only with components in contact with the pumped fluid. Thus, the interior of a pump may be bronze, while the external pump body is cast iron.

Collector-loop pumps must be able to stand temperatures over 200°F (93°C), so polymeric materials should not be used.

If the collector-loop heat-transfer fluid is water obtained from the local water supply and the system is open to the atmosphere, the mineral content, oxygen content, and pH may vary from day to day. For these reasons, bronze or stainless-steel pumps are needed.

For glycol-water or silicone-oil systems, collector-loop pumps can be bronze, stainless steel, or cast iron, because these systems are closed to the atmosphere. However, galvanized pumps must not be used for glycol-water systems.

For a two-tank system with heat exchanger, the pumps should be bronze or stainless steel, because the pump is exposed to potable water. Pump outlet and inlet gaskets must be compatible with heat-transfer fluids. Pump manufacturers should be asked to recommend gasket materials for specific applications.

2.7.4 Pump Failure Modes

There is little published information on failure rates and failure modes for solar DHW pumps. Reference 56 provides some data on water pumps used in the electric industry. These data, summarized in Fig. 2.44, are based on a sample of 536 pumps and should be typical of pumps with adjustable and mechanical seals.

In the cited utility study, 57% of the pump failures were the result of seal and bearing problems. Externally coupled pumps can fail because the motor mounts take a permanent set, resulting in a misalignment between the bearing and the motor. This misalignment eventually causes coupling failure and/or worn bearings.

Limited failure data on canned wet-rotor pumps indicate that bearing and motor failures are the predominant failure modes. The bearing failures are caused by air that is not purged out of the pump when the system is filled initially. With air in the pump chamber, the bearings are not lubricated properly, and the motor can overheat. In addition, the pump can cavitate and destroy the impeller.

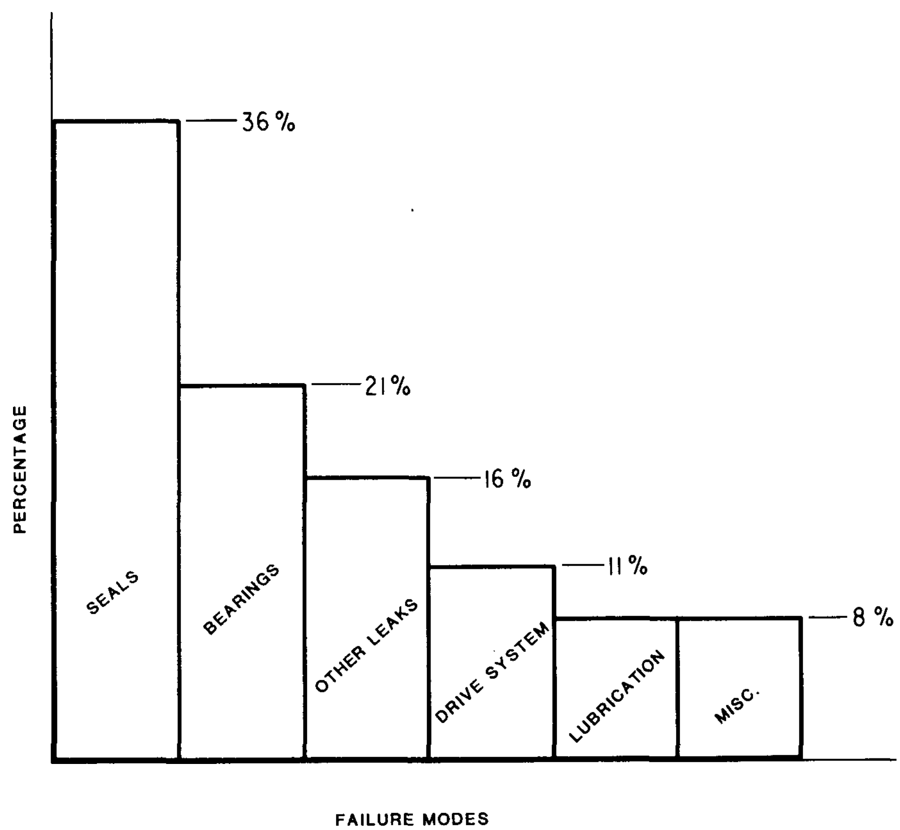


Fig. 2.44 Failure-Mode Distribution for Water Pumps[56]

2.7.5 Pump Failure Rates

Pumps used for solar DHW applications are warranted for 12 to 18 months from date of installation. If these pumps operate for six hours per day, then during the warranty period they accumulate 2200 to 3300 operating hours. To pass through the warranty period (while operating at six hours per day), the pump failure rate must be less than 3×10^{-4} failures/hr. This estimate is consistent with data from Ref. 56 that indicate failure rates of 1×10^{-4} failures/hr. In addition, Ref. 56 presents pump-failure data that span the range from 3×10^{-6} to 3.5×10^{-4} failures/hr.

Data from Ref. 55 on the low-failure-rate pump (3×10^{-6} failures/hr) imply a MTBF of 38 years. This data point could be for a well-maintained unit and is probably not typical of pumps used with solar DHW systems. Therefore, the pump-failure-rate range of 8×10^{-6} to 1.5×10^{-4} failures/hr will be used to assess the reliability of solar DHW systems.

2.8 VALVES

Valves are required in solar DHW systems to direct or control the flow of heat-transfer fluid and potable water through the system and to isolate components in the system. This section describes those valves and their failure modes and provides failure-rate data.

2.8.1 Hand-Operated Valves

Hand-operated valves are the same as those in conventional residential plumbing systems. They are installed with the valve stem at or above the horizontal plane, so sediment will not accumulate in the bonnet. When the valve is in this position, the bonnet also will not trap water during a drain-down; this precaution is essential to avoid a freeze-up.

2.8.1.1 Globe Valves

Globe valves, such as the one in Fig. 2.45, control or throttle liquid flow in a pipeline. Globe valves have more flow resistance than gate valves. When globe valves are used in horizontal lines, the lines do not drain completely.

2.8.1.2 Gate Valves

Figure 2.45 also illustrates a typical gate valve, which is designed to completely open or close a pipeline. Using a gate valve to control or throttle a flow causes the gate to chatter and possibly destroy itself.

Gate valves should be used as isolation valves on major components of the system (i.e., so a pump or heat exchanger can be removed for service). An isolation valve eliminates the need to drain the entire system.

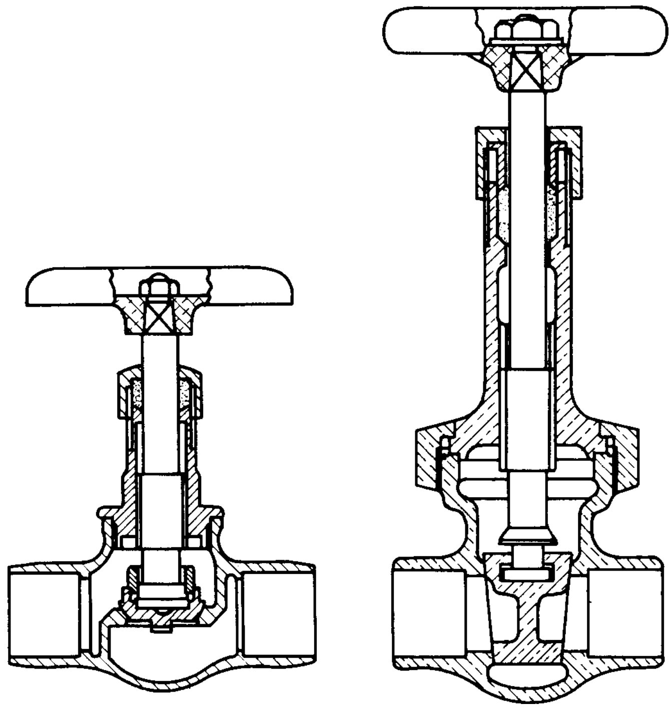


Fig. 2.45 Cross Sections of Typical Globe and Gate Valves

2.8.1.3 Ball Valves

Ball valves like the one shown in cross-section in Fig. 2.46 are being used more frequently in solar DHW systems. These valves cost more than gate valves, but they open rapidly, can be used for flow control, and have a lower leakage rate than gate valves. Because these valves open and close quickly, they also can be used to isolate system components.

2.8.2 Other Valves

2.8.2.1 Check Valves

Many collector loops containing antifreeze solutions employ at least one check valve between the pump outlet and the collector inlet to prevent thermosiphoning on cold nights. Failure to install this check valve has caused the water side of a glycol-to-water heat exchanger to freeze.

Two common mistakes concerning check valves are selection of the wrong type of valve and backward installation of the valve. These problems can be avoided by using care during system design and valve installation. It also helps to compare the installed system with the plans prior to start-up and to test the system prior to full operation to be certain all components function properly.

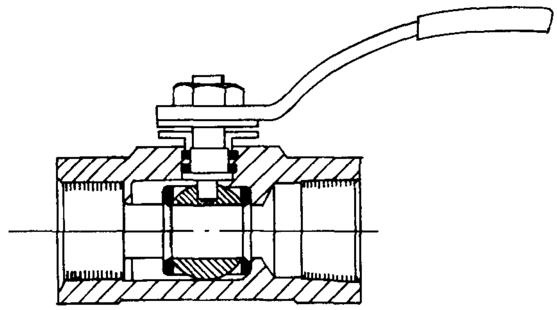


Fig. 2.46 Cross Section of Ball Valve

There are two basic types of check valves, those that are closed by gravity and those that are closed by a spring. Gravity-operated check valves must be installed carefully. Installed upside down or at 90° to their proper orientation, they will not block a backward flow. Gravity-operated check valves usually have hard seats that allow a small amount of leakage, conceivably enough to cause thermosiphoning. This condition is to be avoided.

Spring-operated check valves can be installed in any position. Resilient seats and a spring-operated closing action stop any backward flow. Spring-operated check valves cost more and have a higher pressure drop than gravity-operated check valves, but these disadvantages are outweighed by greater reliability. However, if these valves are installed outdoors in drain-back systems, the linkage can freeze.

2.8.2.2 Temperature and Pressure Relief Valves

Any closed subsystem must contain a temperature and pressure (T&P) relief valve to prevent damage to the system from excessive temperature or pressure. T&P valves for domestic hot-water tanks usually have 210°F (99°C) temperature and 150 psi (1.03×10^6 Pa) pressure settings. The sensor elements of these valves must always be immersed in the heated fluid. Temperature and pressure settings for other types of tanks will differ from settings for domestic hot-water tanks. All T&P valves must meet ASME Boiler and Pressure Vessel Code requirements.

2.8.2.3 Vacuum Relief Valves

Vacuum relief valves similar to the one in Fig. 2.47 are required in drain-down systems and are installed at the highest point in the system. When the pump shuts down, atmospheric pressure opens the valve, allowing the system to drain. A gooseneck adaptor should be added to vacuum relief valves to prevent dirt and ice from accumulating on top of the ball and holding the valve closed.

2.8.2.4 Air-Vent Valves

Air-vent valves are used on drain-down solar DHW systems to allow purged air to escape from the piping when the pump starts refilling the system after a drain-down.

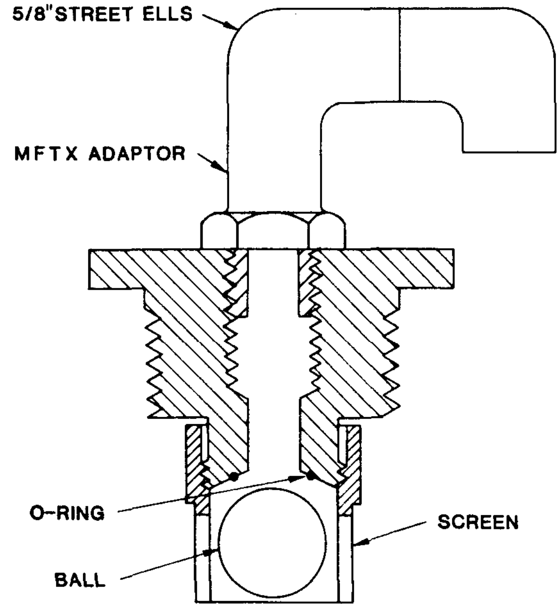


Fig. 2.47 Vacuum Relief Valve

2.8.2.5 Tempering Valves

Tempering valves maintain the temperature of water going to the faucets by mixing hot water with cold make-up water. Such valves are positioned as in Fig. 2.48.

The bimetallic spring element must be removed before soldering a tempering valve into a pipeline. Also, a heat trap or a check valve must be installed to isolate the tempering valve from the hot-water supply. If this precaution is not taken, and the tempering valve is always exposed to hot water, valve life is reduced and temperature control is erratic.

Another type of tempering valve uses a temperature sensor that contains a low-boiling-point liquid. As the sensor temperature rises, the liquid vaporizes; the resulting pressure forces a bellows to expand, moving the valve seat.

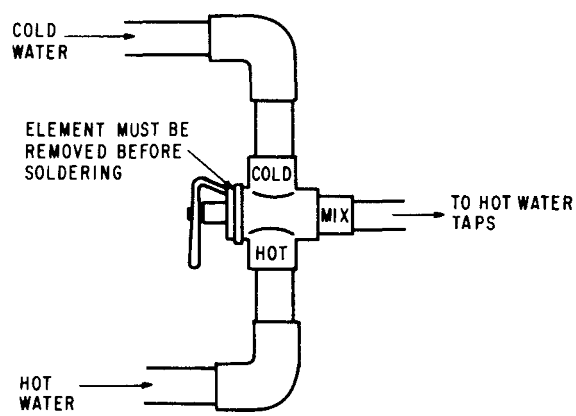


Fig. 2.48 Tempering Valve

2.8.2.6 Power-Actuated Valves

Some valves in solar DHW systems must operate automatically to drain the system or perform other control functions. Electricity is used to power these valves, which are on/off devices and are not used for flow throttling.

Drain-down systems have two solenoid-actuated valves. One valve is normally open so it drains the collector loop when power fails or the pump is shut down. The other valve, located in the collector supply line, is normally closed. When the collector-loop pump starts, the supply-line valve opens. At the end of the solar collection period, when the pump stops, the valve closes. Unless proper air chambers are provided, the actuation of solenoid valves can cause severe water-hammer problems.

A California manufacturer recently introduced a heat-actuated valve that combines the functions of the two solenoid valves. This slow-operating valve should be more reliable than the valves it replaces. Naturally, any time the number of components in a system is reduced, system reliability increases. However, field-performance data are not yet available on this product.

2.8.3 Construction Materials

Valve-body and valve-stem materials are usually brass and stainless steel. Valve seats and valve packings must be compatible with the heat-transfer fluids being used. Valve manufacturers, who offer many material combinations, should be consulted before a valve is selected.

2.8.4 Valve Failure Modes

The major failure mode for valves is leaking, which occurs at the valve seat or through the valve packing. Another failure mode is failure to open or close, which usually is the result of the valve stem seizing or, if the valve is electrically operated, failure of the driving mechanism.

Solenoid valves become sticky if not cycled regularly, probably because of heat generated by the solenoid coil windings. In some installations, if a proper heat sink is not provided, a valve will burn up.

Vacuum relief valves sometimes stick in the open position, because flux used to make the joints has not been completely removed from the solar loop. This flux builds up on the screen and holds the ball in the open position.

2.8.5 Valve Failure Rates

Failure rates for valves are based on data in Ref. 51. Manual gate, globe, or ball valves have a failure-rate range of 5.7×10^{-6} to 2.3×10^{-5} failures/hr. The packing may fail in these valves, but it can be replaced and the valve returned to service quickly.

Check valves have failure rates that vary by a factor of two, from 5.7×10^{-6} to 11.4×10^{-6} failures/hr. The larger figure is based on mean time between failures, meaning that properly selected check valves should last the life of the system.

Spring-loaded pressure relief valves can be expected to have failure rates of 5.7×10^{-6} to 1.1×10^{-5} failures/hr. The primary reason these valves have to be replaced is that the polymeric seat material takes a permanent set, causing the valve to leak.

Minimum-quality solenoid valves have failure rates of 57×10^{-6} failures/hr. Data in Ref. 52 indicate that the failure rate for reliable solenoid valves is approximately 5.7×10^{-6} failures/hr.

2.9 AIR DAMPERS

Air dampers in solar DHW systems are the same as in conventional heating, ventilating, and air-conditioning (HVAC) systems. This section describes these dampers and their failure modes and provides an estimate of damper mean life.

2.9.1 Damper Types

In air systems for preheating water, dampers direct the heated air across the heat exchanger or shut off the air. Depending on system design, dampers are operated manually, by a motor, or by air pressure, an example of the last being back-draft dampers that close when the air flow is reversed.

2.9.1.1 Manual Dampers

Manual dampers are designed for infrequent movement. Their primary function is to permit or prevent air flow. A properly constructed slide-gate damper (guillotine-type) provides tight closure and minimum air leakage. Another common type of shutoff damper is a single disc that is positioned in an air duct. A knob on the end of the shaft to which the disc is fixed provides manual control. The advantages of a manual disc-type damper are simplicity of operation and low air-flow resistance when open. These disc-type dampers can allow as much as 20% of full air flow when closed and should be used only as balancing dampers.

2.9.1.2 Powered Dampers

Powered dampers have louvers or blades, as in Fig. 2.49. The louvers or blades are connected so they can be opened or closed together with a single electric or pneumatic actuator. Sealing is metal-to-metal, which is acceptable if most of the air flow is stopped. Depending on the effectiveness of the metal-to-metal seal and the mechanical pressure exerted on the blades in the closed position, powered dampers leak 5% to 30% of normal flow. Although higher leakage rates are acceptable in HVAC systems, they are unacceptable in solar DHW systems, because the air-to-water heat exchanger can freeze.

The manufacturer of a recently introduced disc-type damper with elastomeric seals claims a leakage rate of 0.001% at a pressure differential of 5 in. of water (1250 Pa). Disc dampers can be equipped with electric or pneumatic actuators.

2.9.1.3 Back-Draft Dampers

Back-draft dampers are considered to be automatic, because they close when the air-handling unit shuts down. They are similar to the powered dampers in Fig. 2.49 in design and in leakage rate (5% to 30% of normal flow). Again, such leakage may allow an air-to-water heat exchanger to freeze.

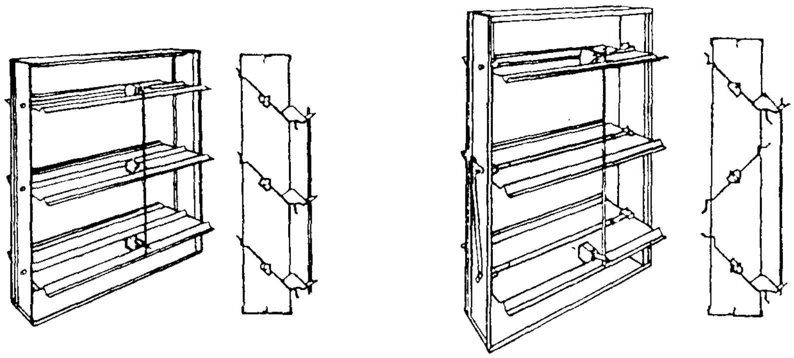


Fig. 2.49 Powered Air Dampers

2.9.2 Freeze Protection

Although air doesn't freeze, an air-cooled collector array can thermosiphon, and the cold-air flow can freeze an air-to-water heat exchanger. In fact, the freezing that has occurred in air systems was caused by a combination of thermosiphoning and leakage in dampers of the type shown in Fig. 2.49.

For solar DHW systems, it is not cost-effective to install multiple dampers for protection against freezing. Other freeze-protection techniques are to circulate hot water through the air-to-water heat exchanger when air upstream of the heat exchanger approaches 32°F (0°C) or to provide an electric heater to keep air upstream of the heat exchanger above this temperature.

2.9.3 Damper Failure Modes

The primary failure mode for dampers is excessive leakage. To minimize the chance of such failure, sealing material on damper-blade edges and alignment of blades should be checked prior to winter operation.

For motorized dampers, the linkage mechanism and the drive motor are critical failure sources. Linkage bearings usually are porous and lose their lubrication when exposed to high air temperatures. Drive motors generally are more reliable than linkage bearings, but motor failures can occur from overloads caused by faulty linkage bearings or misaligned dampers and pushrods.

2.9.4 Damper Failure Rates

Data are scarce on damper failure rates. Therefore, failure-rate estimates for dampers were obtained using reliability block diagrams. The data for the numerical evaluation of the block diagram were taken from Refs. 23 and 52. The calculations indicate that power dampers have failure rates from 1.1×10^{-5} to 3.8×10^{-5} failures/hr.

Back-draft dampers are similar to powered dampers, except that the former do not have power actuators. For back-draft units, the failure-rate range is 9.5×10^{-6} to 2.9×10^{-5} failures/hr.

2.10 INSULATION

Pipes, ducts, and storage tanks must be insulated to reduce heat losses. This section provides a method for calculating heat losses and describes properties of insulating materials used in solar DHW systems.

2.10.1 Thermal Insulation Characteristics

The most important characteristic of thermal insulation is resistance to the flow of heat, which is designated by an R value and is expressed in units of °F-ft^2-hr/Btu (°C-m^2/W). The larger the R value, the greater the resistance to heat flow. Since insulation is applied in different thicknesses, it is sometimes more convenient to express R in terms of unit thickness. This value is represented by the symbol r and is written as °F-ft^2-hr/(Btu-in.) [°C-m^2/(W-cm)]. Table 2.17 gives r values for various insulating materials.

2.10.2 Insulation Requirements

Pipes and ducts must be sealed and insulated to reduce heat losses that occur when the storage tank is being charged with heat from the collector fluid. Insulation also is needed on piping between preheat tank and storage tank.

Heat loss from an insulated circular pipe may be calculated from the following equation:

$$Q_L = \frac{0.262\ L(\Delta T)}{\frac{R_s}{(D + 2s)} + 0.5\ r\left(\ln \frac{D + 2s}{D}\right)} \qquad (2.1)$$

Table 2.17 Typical Values of Heat-Flow Resistance by Length for Insulation Materials[a]

Material	r-value °F-ft^2-hr/(Btu-in.)	r-value C°-m^2/(W-cm)
Fiberglass	3.85	0.27
Elastomers	4.2	0.29
Urethane	6.3	0.44
Isocyanurates	7.2	0.50

[a]These values represent an average of several manufacturers' values.

where:

R_s = surface resistance of pipe in °F-ft^2-hr/Btu (°C-m^2/W) (Table 2.18)

r = thermal resistance of insulation in °F-ft^2-hr/(Btu-in.) [°C-m^2/(W-cm)] (Table 2.17)

s = thickness of insulation in in. (cm)

D = outside diameter of pipe in in. (cm)

L = length of pipe in ft (m)

ΔT = difference between heated-fluid temperature and ambient temperature in °F(°C)

Q_L = heat loss in Btu/hr (W)

Surface resistance exists only when the insulating surface is exposed to air. For example, insulation in contact with earth or water does not have surface resistance. Exposed air ducts have surface resistance on the inside as well as on the outside. Surface resistances are shown in Table 2.18.

As an example of the calculation procedure in Eq. 2.1, assume a standard 50-ft, 1-in. pipe is covered with 3/4-in.-thick fiberglass. The pipe carries water at 130°F, the outside temperature is 40°F, and the air is still. The values assigned for heat-loss calculations are:

R_s = 0.68 °F-ft^2-hr/Btu (0.27°C-m^2/W)

r = 3.85 °F-ft^2-hr/(Btu-in.) [0.12°C-m^2/(W-cm)]

s = 0.75 in. (1.905 cm)

D = 1.315 in. (5.245 cm)

L = 50 ft (15.24 m)

ΔT = 90°F (50°C)

Table 2.18 Surface Resistance for Nonreflective Surfaces[57]

			Surface Resistance	
Wind (mi/hr)	Position of Surface	Direction of Heat Flow	°F-ft^2-hr/Btu	°C-m^2/W
0	Horizontal	Upward	0.61	0.11
0	45° slope	Upward	0.62	0.11
0	Vertical	Horizontal	0.68	0.12
0	45° slope	Downward	0.76	0.13
0	Horizontal	Downward	0.92	0.16
7.5	Any	Any	0.17	0.03
15.0	Any	Any	0.25	0.04

Heat loss, computed from Eq. 2.1, is 690 Btu/hr (202.2 W). If the pipe were not insulated, heat loss would be 2280 Btu/hr (668.2 W).

A good solar-insolation day is one when solar insolation is on the order of 250 Btu/(hr-ft^2) (789 W/m^2). If the collector has an efficiency of 40%, the amount of heat that can be transferred to storage is 100 Btu/(hr-ft^2) (310 W/m^2). If the pipe from the collector to the storage tank is not insulated and has a heat loss of 2280 Btu/hr (668.2 W), approximately 23 ft^2 (2.14 m^2) of the collector array is not available to meet the solar-energy-system load.

The equivalent R value for pipe and duct insulation is given by:

$$R_e = R_s + rs \tag{2.2}$$

where:

R_s = surface resistance (Table 2.18)

s = thickness of insulation in in. (cm)

r = thermal resistance of insulation per unit thickness (Table 2.17)

The equivalent R value for this example, calculated from Eq. 2.2, would be:

$$R_e = 0.68 + 0.75(3.85)$$
$$= 3.6\ ^\circ\text{F-ft}^2\text{-hr/Btu}\ (0.63\ ^\circ\text{C-m}^2\text{/W}).$$

This value is less than the R-4 value recommended by the Polytechnic Institute of New York for pipes up to one inch in diameter.[58] Because the computed value of R_e is close to the recommended value, the designer must decide, based on the economics of the application, whether to use improved insulation or increase the insulation thickness. An economic-optimization calculation procedure for such a decision is given in Ref. 46.

For pipes larger than one inch in diameter, the recommended insulating value is R-6.[58]

2.10.3 Storage-Tank Insulation

Insulation in typical solar DHW tanks has an R value of approximately 10°F-ft^2-hr/Btu (1.76°C-m^2/W). If the heat loss is to be limited to 2% in 12 hr, assuming a tank temperature of 140°F and an ambient temperature of 70°F, the solar DHW tank should have an R value of approximately 30°F-ft^2-hr/Btu (5.28 °C-m^2/W). If the insulation requirements are reduced to limit the heat loss to 10% in 24 hr, as specified in the HUD Intermediate Minimum Property Standards, the tank should have an R value of 12 to 14°F-ft^2-hr/Btu (2.11 to 2.47 °C-m^2/W). These values indicate that additional insulation should be applied to the tank.

2.10.4 Insulation Protection

Insulation must be protected from the elements. If moisture enters insulation, the air spaces fill with water and insulating value is lost. In addition, insulation exposed to sunlight must be protected from ultraviolet-light degradation. Elastomeric insulation is particularly susceptible to ultraviolet radiation and will crumble and fall away if not protected from sunlight.

The best protection for exposed insulation is properly installed, watertight metal jacketing, which is available from several manufacturers.

Polyvinyl-chloride (PVC) jackets are not recommended for insulation exposed to the outdoors. Exposed to the sun, PVC degrades and cracks, allowing water to enter and degrade the insulation. Degraded PVC jackets were destroyed by hail at one DOE-sponsored commercial demonstration site. They were replaced with metal covers.[20]

Some insulation can be painted, but the paint must meet the insulation manufacturer's requirements and must be able to withstand ultraviolet exposure. In addition, the paint manufacturers' recommendations must be followed explicitly with regard to surface preparation, application temperature, air temperature, and air quality. The paint will probably have to be reapplied at three-year intervals.

Supports must be provided for piping runs from the collectors to the storage tank. When supports are installed for insulated pipe, they must be fitted over the protective jacket, because if the supports touch the hot pipe heat-loss paths are formed. Reference 59 describes techniques for supporting heated pipes.

Piping runs inside the residence also must be insulated. Additional insulation protection generally is not required for interior pipe runs but may be applied to improve appearances.

3 GENERIC SOLAR DHW SYSTEMS

Solar DHW systems are classified as either direct or indirect systems. In direct systems, potable water is both the collector coolant and the storage medium. Indirect systems have a heat exchanger between the collector loop and the DHW load. Indirect systems use inhibited water, glycol-water mixtures, hydrocarbon or silicone oils, or air to cool the collectors.

Thermal-performance studies of six generic residential solar DHW systems are in progress at the National Bureau of Standards (NBS).[60] Using NBS data, Farrington et al. at the Solar Energy Research Institute (SERI) have evaluated the economics of these systems.[61]

The NBS and SERI investigations have concentrated on six DHW systems. There are two other popular systems: an indirect drain-back system that uses inhibited water to cool collectors, and a recirculating water system that circulates water to prevent the collectors from freezing.

Additional systems being marketed use refrigerant as the collector coolant. These systems operate with or without a compressor for moving the refrigerant through the collector loop. Data on such systems are not available, primarily because they have not been used in either the HUD hot-water program or the DOE-sponsored commercial demonstration program. Available refrigerant-system schematics are shown in Appendix F.

The following six systems are discussed in this chapter:

- Drain-down with one or two tanks
- Circulating water with one or two tanks
- Thermosiphon with one tank
- Indirect drain-back with one or two tanks
- Indirect (antifreeze) with one or two tanks
- Indirect air systems with two tanks.

Although the schematics for the six solar domestic hot-water systems are generic in nature and not representative of any manufactured system, they do contain the components necessary for a complete and functional system. Because new components are being developed continually, the system configurations will change. For example, a California manufacturer recently introduced a spool-type valve that could replace two of the valves used in drain-down systems.

Some of the plumbing configurations in these schematics may not be representative of configurations installed in various parts of the country. No attempt was made to conform to specific local codes or practices.

The information provided is specific to a generic system and includes operating modes, control schematics, start-up procedures, and mean-life estimates, as well as maintenance and troubleshooting information. Each system description is complete and is intended to stand alone.

If a system manufacturer modifies these generic-system schematics to meet goals or specifications, then the operating modes, control schematics, start-up procedures, etc. will be different from those presented in these DHW guidelines. The MTBF estimates will also change; the procedure for computing the new values can be found in Appendix A.

Control schematics for the DHW systems are presented in ladder-diagram format. At first glance these diagrams appear complicated, compared with the hook-ups for packaged control systems. However, similar ladder diagrams probably were used by control manufacturers to develop their current off-the-shelf hardware.

Also, newer solid-state control systems incorporate several thermostats in one unit. As a result, commercially available residential systems are probably less complicated than the systems described in these guidelines. However, each control manufacturer regards his system as proprietary, and specific control-system schematics are not available.

At present, the majority of system-design and service engineers are more familiar with electromechanical controls than with solid-state controls. As a consequence, descriptions of solar-energy-system operations, maintenance, and troubleshooting are tailored for electromechanical controls. This should not discourage the use of solid-state controls, which can be more economical and reliable, especially when designed to operate in conjunction with a packaged solar DHW system.

3.1 DIRECT SYSTEMS

Direct solar DHW systems use potable water in the collector loop to cool the collectors. A heat exchanger is not required. The solar-heated water is used directly in the residential DHW system.

There are three generic types of direct solar DHW systems. Two of these systems use pumps to circulate the potable water through the collector array. The third, a thermosiphon system, does not require a pump.

Protection against freezing for direct systems is provided by draining the system or by circulating warm water through the collector array. There is also a commercially available system that uses an air compressor to maintain an air head in the storage tank. This air head displaces the water in the collector array and exposed piping when the collector-loop pump shuts down.

3.1.1 Drain-Down Systems

The drain-down systems shown in Figs. 3.1 and 3.2 use potable water in the collector loop. An appropriate control circuit for these systems is shown in Fig. 3.3. To protect against freezing, the exposed portions of the collector loop are drained.

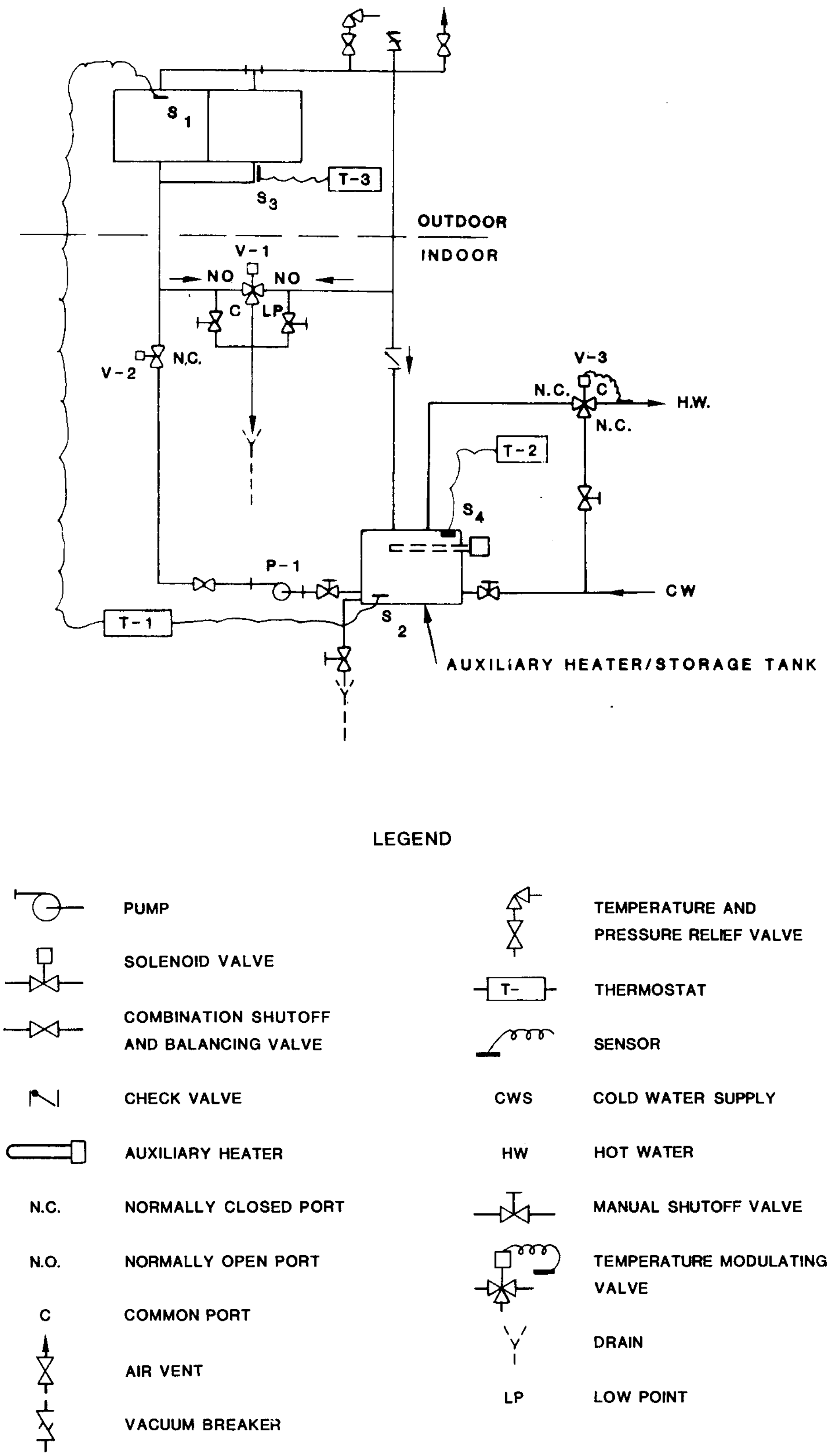


Fig. 3.1 Drain-Down One-Tank System

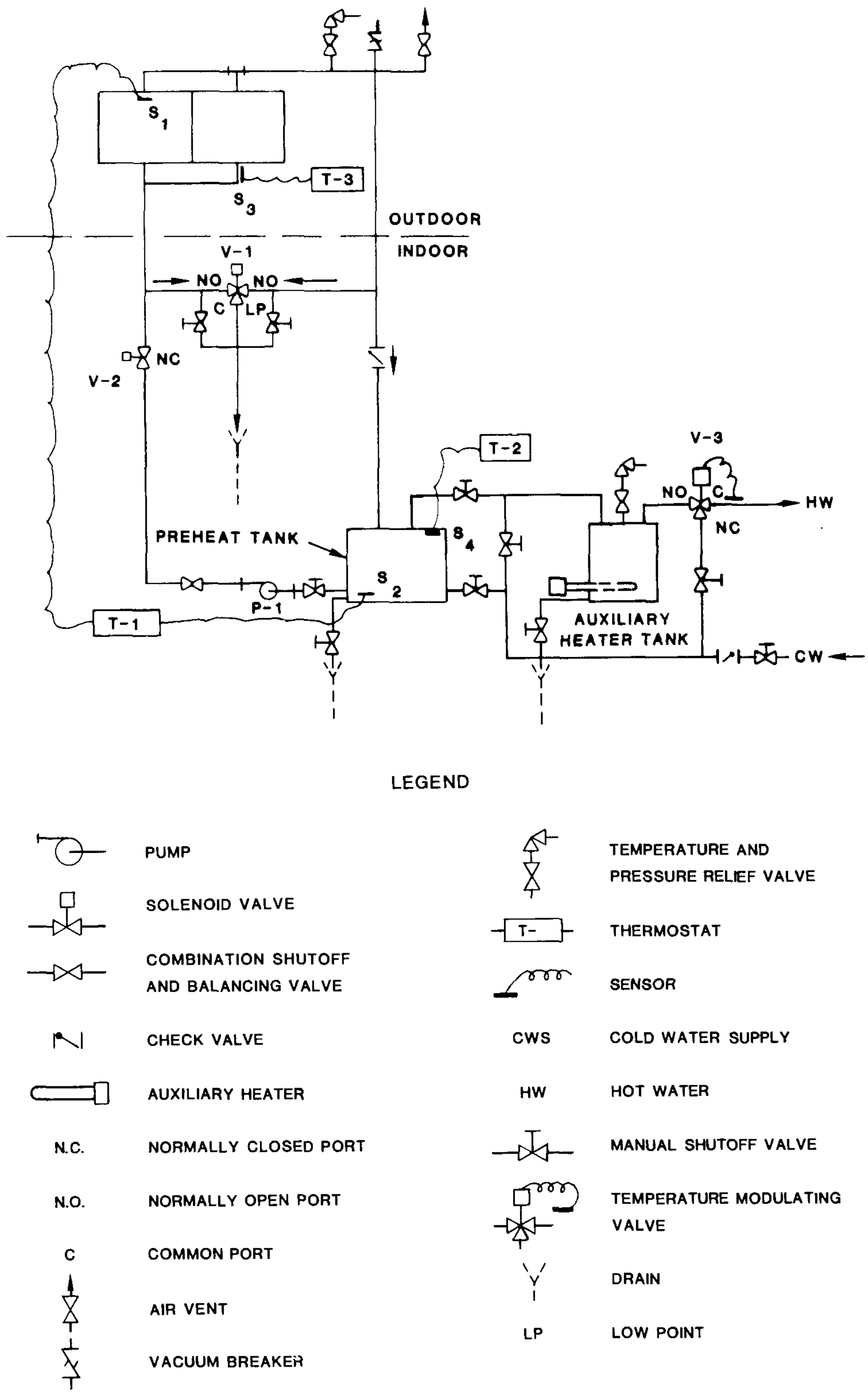
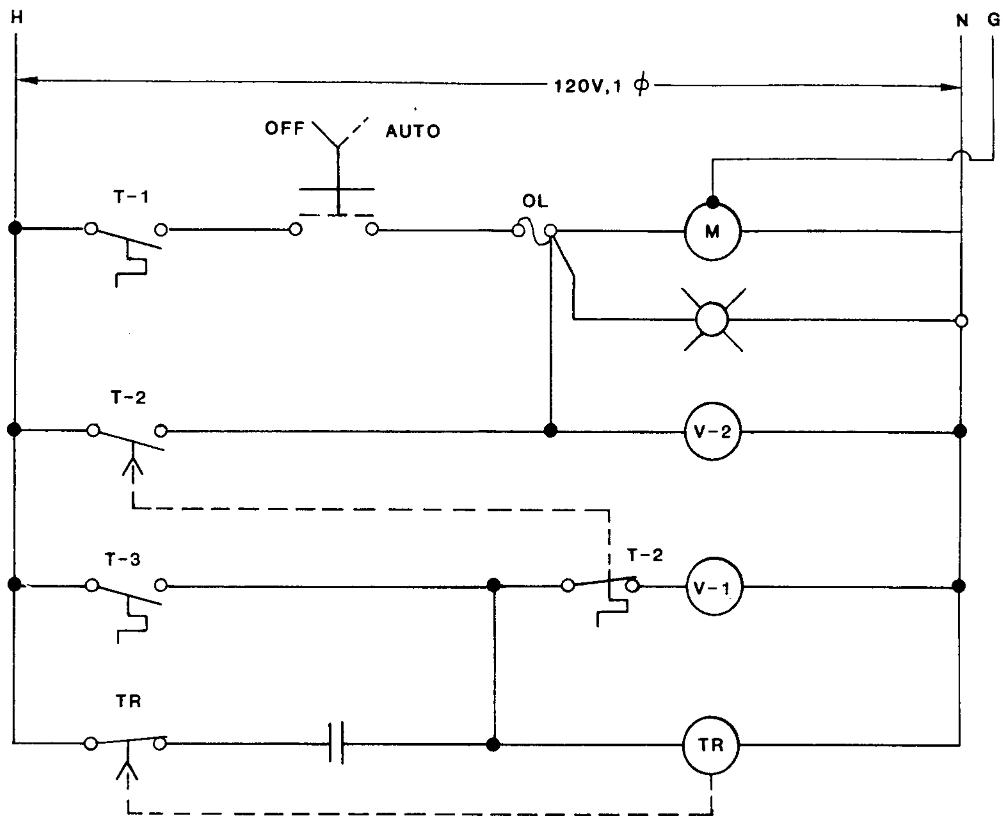


Fig. 3.2 Drain-Down Two-Tank System



LEGEND

- (T-1) Thermostat; single-pole-single-throw; normally open contact closes when temperature rises above high temperature differential set point and opens when temperature drops below low temperature differential set point.
- (T-2) Thermostat; double-pole-single-throw; normally open and normally closed contacts. Normally open contact closes and normally closed contact opens on temperature rise.
- (T-3) Thermostat, single-pole-single-throw; normally open contact closes on temperature rise.
- H Hot wire
- N Neutral wire
- G Ground wire
- TR On-delay time delay relay; adjustable from 0-5 min. Normally closed contact opens on time delay after relay coil is energized.
- M Fractional HP pump motor
- V-1 Valve actuator; valve open when de-energized.
- V-2 Valve actuator; valve closed when de-energized.
- Normally open motor contact.
- OFF / AUTO Manual two-position motor starter switch with thermal overload protection and indicator light

Fig. 3.3 Control-System Ladder Diagram for Drain-Down Systems

3.1.1.1 Operation

Solar-Energy Collection. Solar DHW systems begin to collect energy when the temperature difference between the collector absorber-plate sensor S_1 and auxiliary-heater/storage-tank sensor S_2, or preheat tank in two-tank systems, reaches the predetermined value of the high-temperature differential set point, which is 20°F (11°C) in many installations. When this set point is exceeded, the normally open contacts in thermostat T-1 close, and the electrical circuit to pump P-1 and valve V-2 is energized.

With this circuit energized, valve V-2 goes from its normally closed position to open and pump P-1 starts. Starting the pump motor closes the normally open motor contacts in the valve V-1 circuit, energizing the time-delay relay (TR). As the V-1 circuit is now energized, valve V-1 goes from its normally open position to closed.*

Pump P-1 circulates water from the bottom of the auxiliary-heater/storage tank, or preheat tank for two-tank systems, through the collectors and back to the tank. This water circulation continues as long as the following conditions are met:

- The temperature difference between sensors S_1 and S_2 remains within the range of the high-to-low-temperature differential set point of thermostat T-1.
- The temperature measured by sensor S_4 is below the set point of the overheat-protection thermostat T-2.
- After the time-delay relay has "timed" out, the temperature measured by the freeze-protection sensor S_3 is above the thermostat T-3 set point.

A time-delay relay in the control circuit is recommended for the following reason: When the system has been drained during a cold night, the temperature of the outdoor piping may be below freezing. When pump P-1 starts on a cold but sunny day, little or no water from the storage tank may reach the collectors, because thermostat T-3 keeps valve V-1 open and most of the water from storage is discharged. However, depending on pipe diameters, the pump head, and plumbing design, some water may reach the collectors.

Any water that does reach the collectors will be cooled by the cold exposed piping. For valve V-1 to close, the temperature at sensor S_3 must exceed the thermostat T-3 set-point temperature of approximately 40°F (4°C). Depending on the length of the piping run and the ambient temperature, several minutes or even hours may elapse before water from the heated storage overcomes the heat losses and warms sensor S_3 above the thermostat T-3 set point. Meanwhile, water from the preheat tank is draining continuously through valve V-1, causing large thermal losses, increased water bills, and increased auxiliary-heater operating costs.

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*V-1 and the time-delay relay already could have been energized by the action of thermostats T-3 (water temperature as sensed by S_3 is above 40°F or 4°C) and T-2 (water temperature in the auxiliary-heater/storage tank is within normal operating range).

To avoid this continuous draining during system start-up, a time-delay relay is installed to override the actions of thermostat T-3. When solar collection is initiated, valve V-2 opens and pump P-1 starts. The start-up of pump P-1 closes the normally open motor contacts in the valve V-1 control circuit. It also energizes the coil of valve V-1 and the coil of the time-delay relay through its normally closed contacts.

With valve V-2 open and the pump running, the warm storage water flows to the collectors. By this technique, the warm storage water overcomes the thermal inertia of the piping system and brings the temperature to be sensed by sensor S_3 above the thermostat T-3 set point. The system can now operate in an efficient manner.

When the temperature difference between the collector and auxiliary-heater/storage tank, or preheat tank for two-tank systems, decreases to the predetermined value of the low-temperature differential set point, thermostat T-1 opens the control circuits for pump P-1 and valve V-2. The system is now shut down. For the system to restart, the temperature difference between sensors S_1 and S_2 again must increase to the predetermined value of the high-temperature differential set point.

Freeze Protection. Because water is the collector coolant, the collector array must be protected against freezing. The freeze-protection system is controlled by the temperature signals from sensor S_3, located at the bottom of the collector array, and the actions of thermostat T-3. Multiple sensors could be used, as discussed in Chapter 2, but control-system modifications would be required.

If the temperature at the bottom of the collectors decreases to approximately 40°F (4°C), the contacts in thermostat T-3 open, and power is removed from valve V-1. With valve V-1 open and valve V-2 closed, atmospheric pressure and gravity open the vacuum breaker at the top of the collector array and water drains from the collector array and the piping above valve V-1. It is essential that all the piping be pitched continuously toward a low point. Piping slopes of 1/4-1/2 inch per foot (20 to 40 millimeters per meter) of pipe run are recommended.[62]

A check valve must be installed in the return line between the tank and the branch line to valve V-1. This check valve prevents make-up water from entering the collector return line when the collector is drained. If this check valve were not installed, incoming make-up water would flow continuously through valve V-1, and the collectors could not drain. This would cause the collectors to freeze.

Figure 3.4 illustrates some of the ways that drain-down systems can freeze or have frozen. This figure gives the system designer a checklist of potential problems. Additional recommendations to avoid freezing are presented in Ref. 62.

Overheat Protection. When solar energy is available and DHW demand is low, the water temperature in the solar-energy system can approach or exceed the boiling point. To protect the user and the system, protection against overheating is incorporated into the control system.

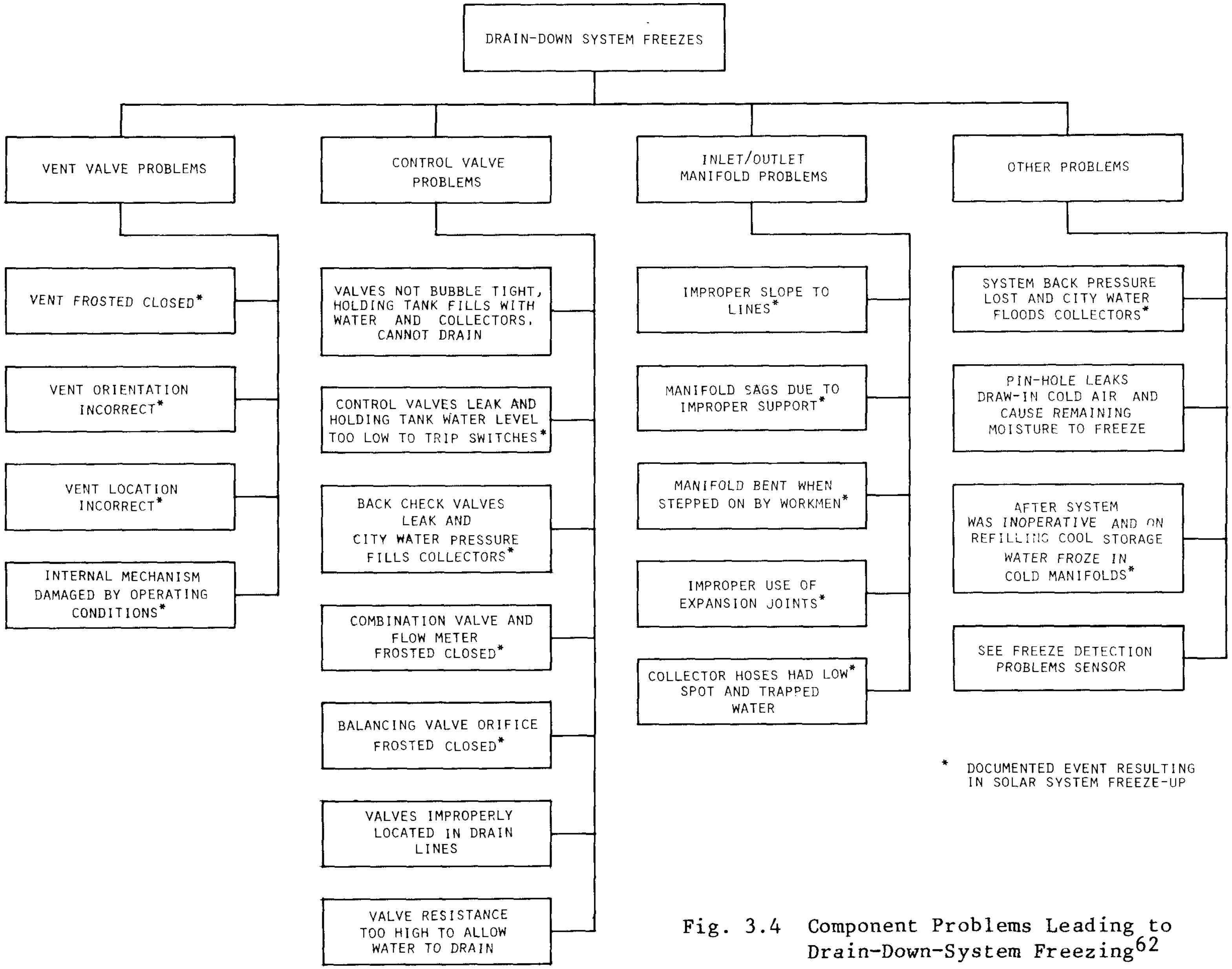


Fig. 3.4 Component Problems Leading to Drain-Down-System Freezing[62]

There are several design options for protecting the system from overheating. One option, incorporated into Fig. 3.5, provides overheat protection by discharging hot water from the system. This option operates as follows.

Thermostat T-2, a double-pole-single-throw unit, provides the overheat protection. This thermostat, activated by temperature signals from sensor S_4, has one normally open and one normally closed contact. When the temperature sensed by sensor S_4 exceeds the high set point of approximately 180°F (82°C), the normally open contact closes and the normally closed contact opens. Closing the normally open contact energizes the electrical circuits to valve V-2 (valve opens) and pump P-1 (pump starts). Note that the same electrical circuit already could have been energized by action of thermostat T-1.

Opening of the normally closed contact on thermostat T-2 interrupts power to valve V-1 and the valve opens. With the pump P-1 running and valves V-1 and V-2 open, the system discharges through valve V-1. Cold make-up water replaces the discharged hot water from the auxiliary-heater/storage tank, and the temperature in the tank decreases.

However, with the system configuration in Fig. 3.1, there is a possibility that the cold incoming water could bypass the hot water in the storage tank. If this occurs, it could take some time before the water temperature in the vicinity of sensor S_4 drops to the low set point of approximately 170°F (77°C). This bypassing problem can be eliminated by installing an additional valve, V-4, in the piping loop, as shown in Figs. 3.5 and 3.6. The control schematic for this modification, Fig. 3.7, shows that thermostat T-2, a single-pole-single-throw unit, now controls valve V-4. (In Fig. 3.3, T-2 is a double-pole-single-throw thermostat that controls valves V-1 and V-2). When the water temperature in the tank reaches the high-temperature set point, thermostat T-2 closes the normally open contacts, and valve V-4 opens. Cold make-up water now flows to the top of the tank and discharges to the drain through valve V-4.

The system designer must evaluate the cost-effectiveness of putting an additional valve in the system to eliminate the bypassing problem. This valve might be used rarely, and the cost of the valve (as well as installation and maintenance) must be compared with the cost of water and energy that would be wasted.

The main features of overheat protection that depends on discharging hot water out of the system are:

- Both auxiliary-heater/storage tank, or preheat tank in two-tank systems, and collectors are protected against high temperatures.
- Water is wasted, so this technique is not recommended for use in dry climates.

Another overheat-protection method, which does not discharge hot water from the system, uses an overheat-protection thermostat, T-2, to lock out pump P-1 and close valve V-2 until the temperature in the auxiliary-heater/storage tank, or preheat tank in two-tank systems, decreases. The control circuit for this method is similar to the schematic in Fig. 3.3, except that thermostat

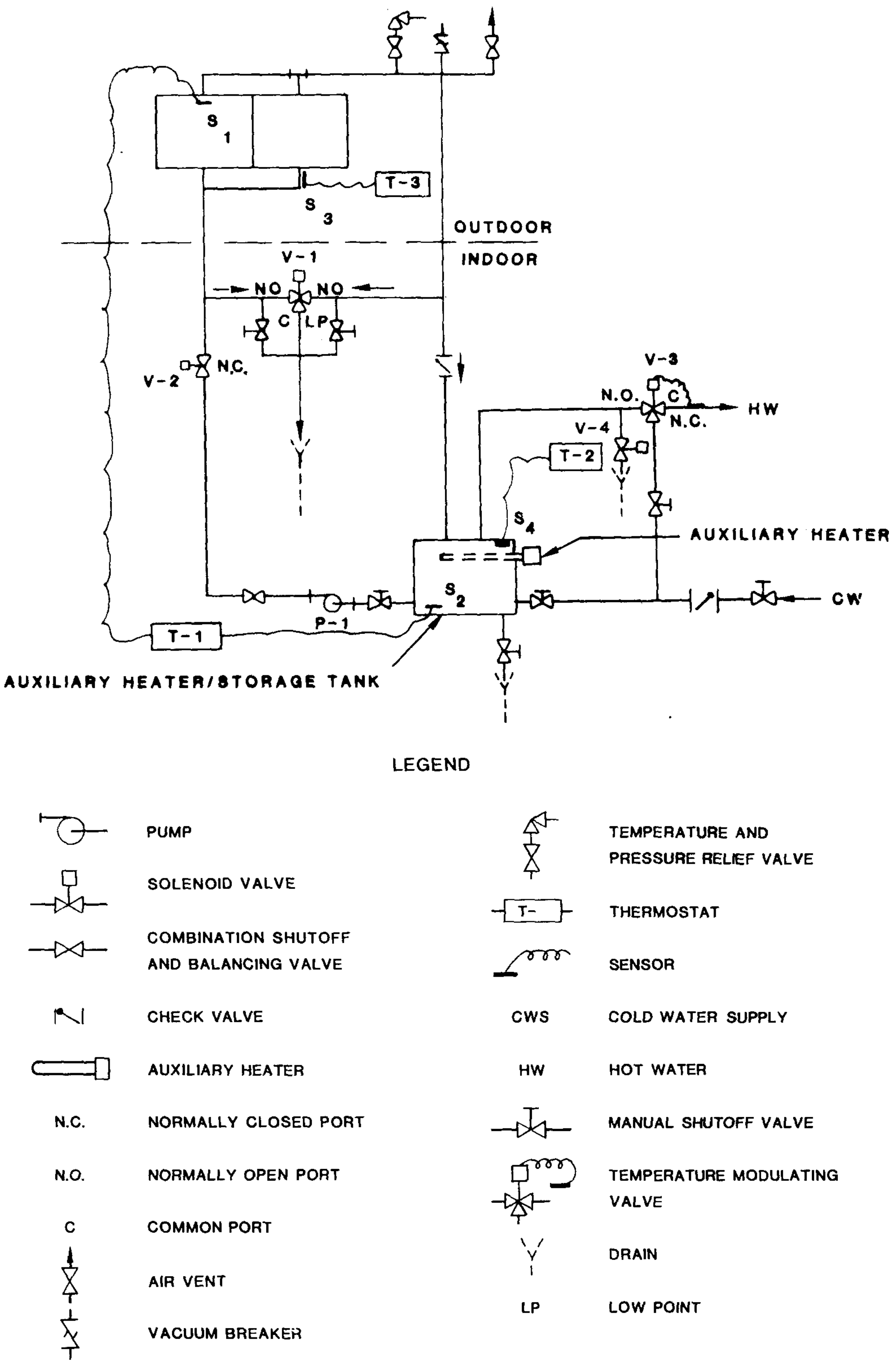


Fig. 3.5 Drain-Down One-Tank System with Separate Overheat-Protection Valve

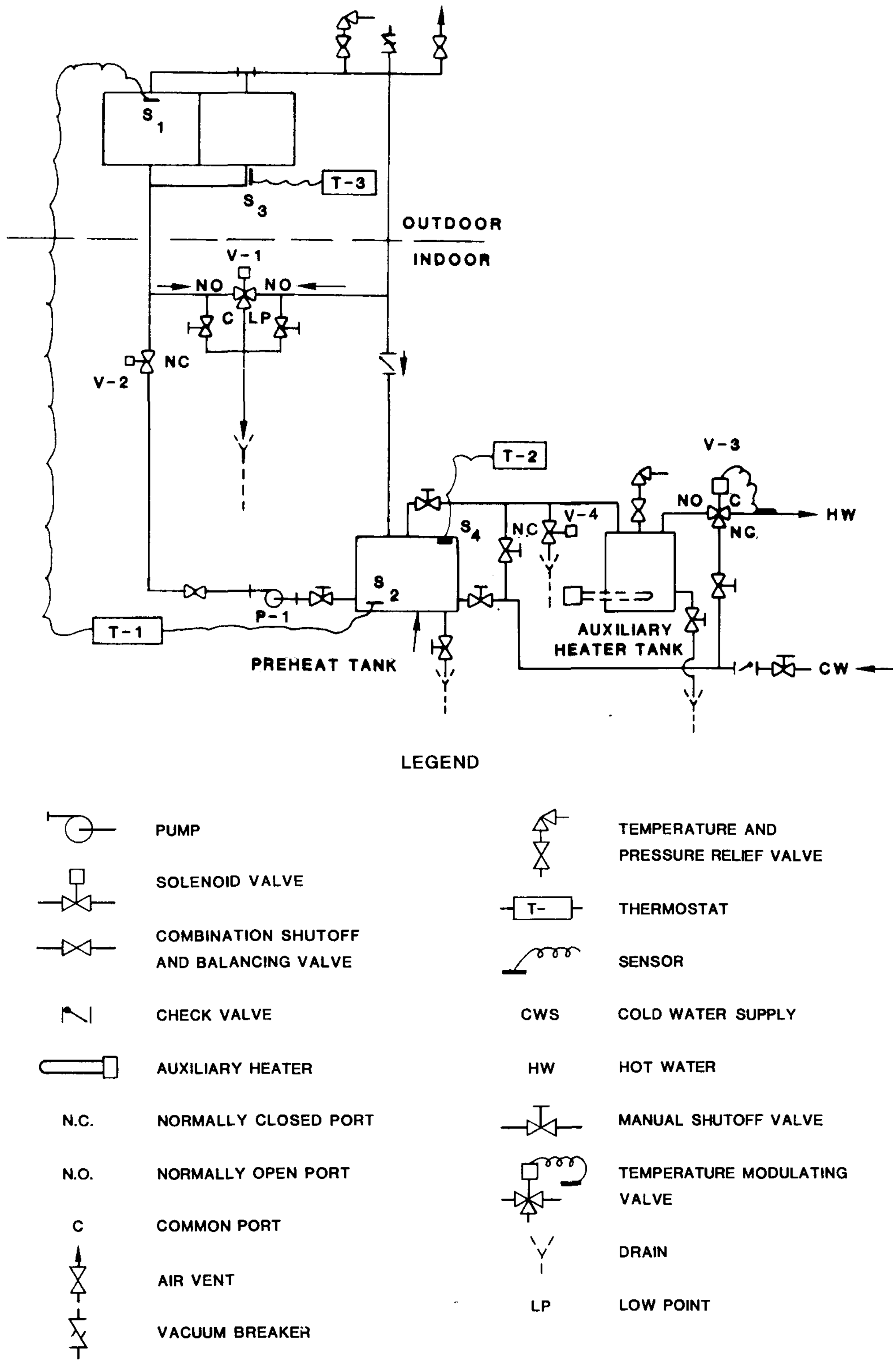
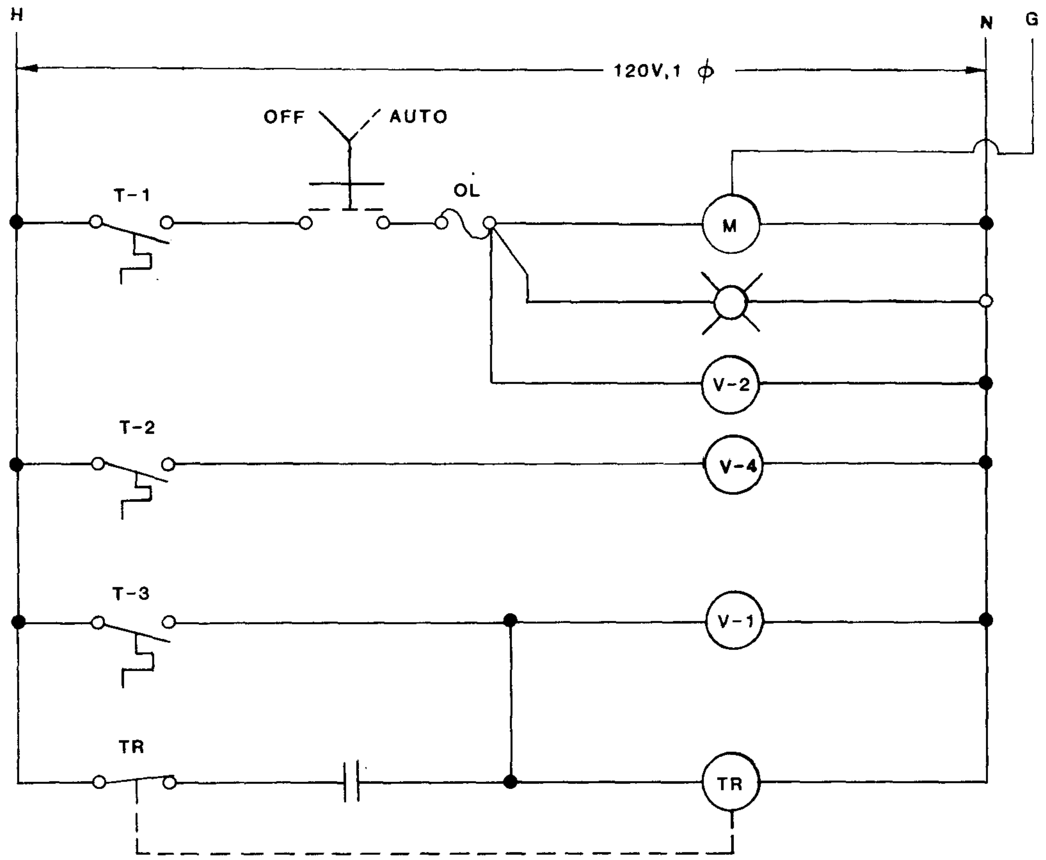


Fig. 3.6 Drain-Down Two-Tank System with Separate Overheat-Protection Valve



LEGEND

(T-1) Thermostat; single-pole-single-throw; normally open contact closes when temperature rises above high temperature differential set point and opens when temperature drops below low temperature differential set point.

(T-2), (T-3) Thermostat, single-pole-single-throw; normally open contact closes on temperature rise.

H Hot wire

N Neutral wire

G Ground wire

TR On-delay time delay relay; adjustable from 0-5 min. Normally closed contact opens on time delay after relay coil is energized.

M Fractional HP pump motor

V-1 Valve actuator; valve open when de-energized.

V-2 V-4 Valve actuator: valve closed when de-energized.

Normally open motor contact.

OFF AUTO Manual two-position motor starter switch with thermal overload protection and indicator light.

Fig. 3.7 Control-System Ladder Diagram for Drain-Down Systems in Figs. 3.5 and 3.6

T-2 has only one set of normally open contacts. These contacts are between T-1 and the line to pump P-1 and valve V-2.

Features of this overheat-protection method are:

- Although the auxiliary-heater/storage tank, or preheat tank in two-tank systems, is protected against high temperatures, the collectors are not. Therefore, the collectors may be subject to stagnation conditions. If overheating occurs and the pressure becomes excessive, the temperature/pressure relief valve opens, relieving the pressure.
- Hot water is not wasted.

A third overheat-protection method has a heat-rejection coil and two control valves to remove excessive heat from the system. Main features of this overheat-protection method are:

- Water is not wasted.
- Initial cost of coil and valves is higher.
- Both auxiliary-heater/storage tank, or preheat tank in two-tank systems, and collectors are protected against overheating.
- Pump is required for overheat protection.

All three of these overheat-protection methods protect the auxiliary-heater/storage tank, or preheat tank in two-tank systems, from overheating and from the high water temperatures that damage tank linings. Two of the methods protect the collectors from wet stagnation conditions.

The system designer must evaluate the cost of the collector's protection against overheating with regard to the 1-to-10-yr range of collector warranty periods, collector degradation owing to occasional stagnation conditions, the installed cost of additional valves, the cost of control-system modifications, and the cost of wasted water. In a conservative design, collectors capable of withstanding stagnation for 30 days without degradation, as verified by ASHRAE 93-77, should be specified.[63]

Auxiliary-Heater Operation. In a one-tank system, a factory-packaged electric heater maintains the desired water temperature. The package combines thermostat, temperature sensor, electric resistance-heating element, and emergency-cutout (ECO) switch in one unit.

A factory-installed and calibrated temperature sensor detects the temperature of the tank surface. When the temperature drops below the low-temperature set point, the thermostat energizes the heating element. When the water has been heated to a predetermined value, usually 10° to 20°F (5° to 11°C) higher than the low set point, the thermostat de-energizes the heating element.

This auxiliary-heater operation is typical of residential electric DHW service. An alternate system can lock out the auxiliary heater whenever the collector loop is functioning.

For a two-tank system, a gas heater usually is employed to maintain the desired water temperature in the auxiliary-heater tank. Controls on gas-fired systems combine an automatic pilot valve, manual gas valve, thermostatic valve, pilot gas filter, and gas regulators in one unit.

In the two-tank system, the water temperature is sensed by the thermostatic-valve sensor. When the temperature drops below the low-temperature set point, the thermostatic valve opens the gas supply and the pilot light ignites the gas at the burner. When the water temperature increases to a predetermined value, which is usually between 10 to 20°F (5 to 11°C) higher than the low-temperature set point, the thermostatic valve shuts off the gas supply.

Temperature-Modulating Valve. Whenever the temperature of hot water leaving the auxiliary-heater tank exceeds a value specified by local codes, the temperature-modulating valve V-3 begins mixing hot water and cold make-up water to maintain the preset temperature.

Operation of a temperature-modulating valve is described in Sec. 2.8. Installation of this valve is required by local codes in some areas, because it serves as a safety device to protect the user against excessively hot water.

3.1.1.2 Estimated Mean Time between Failures (MTBF)

The drain-down-system MTBF estimates in Table 3.1 were obtained with the reliability-block-diagram technique presented in Appendix A. Component failure-rate data are presented in Chapter 2 and summarized in Appendix A. The data in Table 3.1 are based on the assumption that the solar DHW system operates for 6 hr/d.

The data indicate that the minimum estimated MTBF of any of the collector designs is not influenced strongly by the type of interconnections used in the system. However, maximum MTBF values are reduced by approximately 30% if hoses are used instead of metal tubing with soldered or brazed connections. Use of two storage tanks reduces system estimated MTBF by 15%, compared with use of a single storage tank in a system.

3.1.1.3 Drain-Down-System Start-Up and Testing

After the system has been installed, all components cleaned, the system purged, and all sensors calibrated, but before the insulation has been installed, the system must be started and tested. Testing is necessary to detect leaks, to verify the control sequence, to locate any defective pumps or valves, and to identify and eliminate installation or design errors.

Table 3.1 Estimated Mean Time between Failures (MTBF) of Drain-Down Solar DHW Systems

Number of Collectors in System	Approximate Solar Load (%)	One-Tank Systems Estimated MTBF (days): Without hose interconnections		One-Tank Systems Estimated MTBF (days): With hose interconnections		Two-Tank Systems Estimated MTBF (days): Without hose interconnections		Two-Tank Systems Estimated MTBF (days): With hose interconnections	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
2	At least 50	91	940	84	620	87	803	80	558
2	100	72	838	67	573	68	727	64	519
4	At least 50	91	943	82	621	87	805	81	557
4	At least 75	82	914	78	610	78	786	74	551
4	100	57	752	53	530	56	661	53	484

The recommended testing procedure for one-tank and two-tank drain-down systems consists of the following 14 steps:

Step 1. Place control system in "off" position.

Step 2. Set temperature-modulating valve to maintain water temperature established by local codes.

Step 3. Open hot-water faucets and make-up-water supply valve.

Incoming cold water will purge tank(s), piping, and faucets of air. After air has been purged, close faucets. Shutoff valve connecting system to make-up water supply must remain open.

Step 4. Adjust set points of thermostats according to system designer's recommendations.*

At this point, piping runs have not been insulated. Therefore, the low-temperature differential set point of thermostat T-1 should be arbitrarily set at 5°F (3°C). Final adjustment of this set point is made after the insulation work is complete, according to the procedures in Appendix B.

Step 5. Adjust setting of time-delay relay.*

Recommended setting of the time-delay relay is five minutes. After the time delay has expired, the normally closed contacts of the relay open and freeze-protection control returns to thermostat T-3. The normally closed contacts of the time-delay relay will remain open as long as the relay coil remains energized, or as long as pump P-1 is operating or thermostat T-3 contacts are closed because collector-loop water temperature is above 40°F (4°C).

Step 6. Switch control system into "auto" position.

If the temperature difference between the collector absorber plate and storage is large enough, pump P-1 starts, and normally closed valve V-2 opens. Regardless of the temperature sensed by S_3, start-up of pump P-1 actuates time-delay relay TR and closes valve V-1 (see Figs. 3.3 or 3.7). This condition lasts until the time delay expires, after which thermostat T-3 determines the position of valve V-1.

If the temperature difference between the absorber plate and the storage tank is too small, pump P-1 does not activate and valve V-2 remains closed. Under these conditions, temperature-differential thermostat T-1 may be bypassed using a jumper wire in order to balance and leak-test the system. A more sophisticated method would be to use a variable potentiometer to start the system. A properly calibrated potentiometer can also be used to verify the operating set points.

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*Prepackaged-system thermostats and time-delay relays may have been factory-set, so that field adjustments are not possible. It is assumed manufacturers have the testing data to set thermostat and time-delay relays.

If thermostat T-1 is jumped and thermostat T-3 is defective, the system can freeze. To eliminate this possibility, use an accurate thermometer to measure the water temperature in the vicinity of sensor S_3. This thermometer must be checked periodically to verify that the water temperature is above freezing. At this time, it is convenient to verify the reliability and accuracy of thermostat T-3. Set thermostat T-3 to coincide with the water temperature measured in the vicinity of sensor S_3. At this setting, thermostat T-3 should de-energize and valve V-1 should open.

If the system is started for the first time on a cool day, a freezing condition, as sensed by sensor S_3, may exist. After a time delay of five minutes, valve V-1 opens to drain the system. If this condition occurs, the control system must be switched off. System start-up and testing must be postponed until weather conditions improve.

Step 7. Balance collector-loop flow.

Flow through the collectors must be balanced to avoid hot spots in the collector array that cause inefficient operation. This requirement becomes especially important when there are more than six panels in the collector array. However, for arrays up to six panels, the usual number in residential applications, flow balancing is still required.

Flow balancing indicates if any lines are blocked with solder or if a collector has an unusually high pressure drop. If the pressure drop across the collector exceeds the manufacturer's specification, some of the collector heat-transfer passages could be blocked or deformed. Conversely, if water flow exceeds the design flow, it must be throttled to the specified value to achieve design performance.

Balanced flow conditions can be achieved by measuring the flow rate through each collector panel or group of panels. These measurements can be made by using anubars, flowmeters, orifices, and circuit setters. Circuit setters are commercially available units that combine orifice, pressure taps, and a globe valve into one unit for the purpose of measuring and balancing water flow.

Regardless of the flow-measuring technique used, the measuring device should be installed as far as possible from flow deviators such as elbows, valves, or tees. The minimum distance is specified in the manufacturer's literature, and this distance must be maintained to obtain accurate readings.

A circuit setter or a manual throttling valve should be provided on the discharge side of the pump for balancing the flow. If this valve is installed on the suction side of the pump, the pump may cavitate and destroy itself.

Flow balancing should be started with the throttling valve in a partially open position. If an oversized pump has been installed and the throttling valve is wide open, higher flow rates than expected will occur, which may overload the pump motor.

If the water flow is significantly below the design rate, the problem could be caused by: restricted or closed balancing valve; blocked or deformed water lines or collector passages; pump suction side connected to the collectors instead of storage; or an improperly wired or defective pump motor.

If the pump has an induction single-phase or a three-phase motor, the pump could be improperly wired and rotating in the reverse direction. For these two motor types, interchanging the motor leads will eliminate the problem. For other types of motors, the pump cannot rotate in the reverse direction. If all of the preceding possibilities have been eliminated and the pump does not deliver the specified flow rate, the pump is defective and must be replaced.

Step 8. Adjust temperature and pressure relief valve.

Pressurize the preheat tank to 12 psi (83 kPa) above the highest expected pressure in the system. With the collector pump running, adjust the pressure relief valves to the onset of bleeding. If the pressure relief valve has been set at the factory, verify that the valve opens at the set pressure.

Step 9. Test system for leaks.

Pressurize storage tank to 10 psi (69 kPa) above the highest pressure expected in the system. With the pump running, inspect all pipe joints for leaks. Pay special attention to the piping connecting the solar collectors and to valve V-1. If leaks are discovered, system must be shut down and drained and the leaks repaired.

To drain the system, thermostat T-3 has to be de-energized or the manual drain-down valves must be opened. After the leaks have been repaired, the leak-testing procedure is repeated until leaks are completely eliminated.

Step 10. Test valve V-2 and the check valve for leaks.

Shut off the make-up water supply. Switch control system to the "off" position and open the manual by-pass valve to drain the system. After all water has been drained out of the collector array, turn on make-up water supply to the tank. After 10 min, check to see if any water is draining from the system. Draining indicates that either the check valve or valve V-2 is leaking (or both may be leaking). Check both valves to find out which one leaks. Install a new or repaired valve and check again for leakage.

After Steps 9 and 10 are complete and all leaks have been fixed, piping runs must be insulated. When the insulation is installed, the system is ready for final testing.

Step 11. Adjust low-temperature differential set point of thermostat T-1.*

When the system has been tested and insulated, and if sufficient solar energy is available, turn system on. If field testing is selected for

*On prepackaged systems, thermostats may have been factory-set, so that field adjustment is not possible. It is assumed that the manufacturers of prepackaged solar DHW systems have sufficient testing data to properly set the thermostats.

determining the low differential set point (see Appendix B), use a wattmeter to measure electric-energy consumption. Use Eqs. B.8 and B.10 in Appendix B to calculate the temperature differential and adjust thermostat T-1. If field testing was not selected by the system designer, set thermostat T-1 according to the design specifications.

To verify the accuracy of the low-temperature differential set-point adjustment, use calibrated thermometers to measure temperatures in the vicinity of sensors S_1 and S_2. By partially shading the collectors, available insolation can be reduced until the low-temperature differential set point of thermostat T-1 is reached, and the pump de-energizes.

When the pump shuts off, measure the temperature difference with the thermometers. If the measured difference does not fall within 0.5°F (0.3°C) of the low-temperature differential set point, adjust the thermostat T-1 setting. Repeat this procedure until the pump shuts off at the required temperature differential.

Step 12. Test the overheat-protection mode.

On the systems with adjustable T-2 setting, simulate overheating conditions by setting T-2 below the water temperature in the auxiliary heater tank. T-2 should be activated and valves V-1 and V-2 should open and drain the system.

In systems in which T-2 is not adjustable, use a jumper to bypass thermostat T-2, simulating overheating conditions. Valves V-1 and V-2 should open and drain the system.

Step 13. Test operation of auxiliary heater.

Adjust the set point of the auxiliary heater according to design specifications and activate the heater. To verify temperature setting of auxiliary heater, insert a calibrated thermometer into thermal well to measure water temperature at top of auxiliary-heater tank. Auxiliary heater should activate when temperature at top of tank drops to within ±2°F (±1°C) of desired set temperature. If this requirement is not met, readjust auxiliary-heater setting.

Step 14. Test operation of temperature-modulating valve.

Adjust setting of temperature-modulating valve to maintain the value specified by local codes. Set auxiliary heater for 170°F (77°C). Verify water temperature at top of tank using a calibrated thermometer inserted into thermal well. When the temperature reaches 170° ±5°F (77° ±3°C), open hot-water faucets. Measure temperature of water leaving the modulating valve. If the temperature is not within ±3°F (±2°C) of the local code values, readjust valve setting. Repeat procedure until temperature is correct. Then reset heater to maintain desired tank-water temperature.

On completion of above steps, all system operating modes have been verified, and the system tested for leaks. The system should be ready to operate.

3.1.1.4 Drain-Down-System Preventive Maintenance

To ensure that drain-down systems perform reliably and meet the MTBF estimates in Table 3.1, basic system preventive maintenance must be performed. Most of the suggested actions can be performed by the homeowner, with the possible exceptions of washing roof-mounted collectors and verifying sensor calibration. Unless the system manufacturer provides special test points and thermowells, as in Fig. 3.8, checking sensor calibration and automatic-valve operation is best left to an experienced service person.

At least once each year, the following preventive-maintenance actions should be performed:

- Wash outer glazing of collector array with compounds approved by the manufacturer. (Do not remove dust or dirt from polymeric glazings with a dry cloth, because they will be scratched.) During washing, absorber plates should be inspected for degradation.
- Inspect flashing and collector-mounting hardware. Tighten, replace, and recaulk as required.
- Inspect, tighten, or replace hose connections on collector array.
- Verify that sensors are still in correct locations and check sensor calibration.
- Inspect hand-operated valves for leaks and adjust packing. Open or close valves to verify their operation.
- Drain and flush tanks, cleaning any strainers or valve filters.

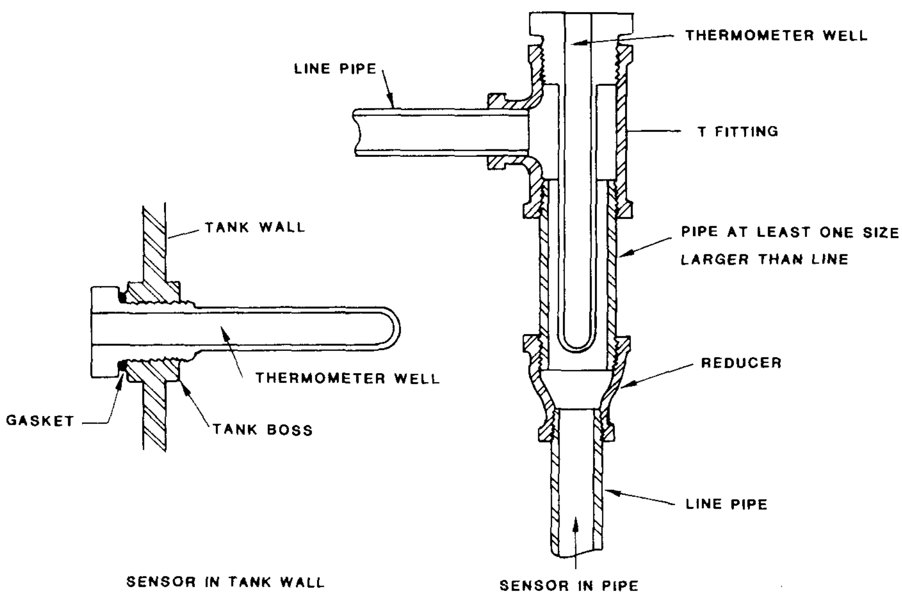


Fig. 3.8 Thermometer Wells

- Inspect pressure relief valves on tank(s) and on the collector array to be sure that valves operate and exit ports are not plugged.

System should be checked periodically for:

- Insulation deterioration.
- System leaks.
- Correct thermostat setting, to make certain setting has not drifted from position established during start-up and testing.
- Proper operation of valve V-1. This valve is closed during summer months and may stick and not open when needed to prevent a freeze-up.
- Correct operating mode:

  Verify that pump does not operate at night, using a flowmeter, sight glass, or pressure gauges if such gauges are installed.

  Verify draining down by measuring temperature in vicinity of sensor S_3. Thermowells similar to those in Fig. 3.8 are recommended. If water temperature is below 40°F (4°C) and system has not drained, drain system manually and call a service person.

  On a sunny day, verify pump operation by noting if flowmeter or sight glass indicates fluid motion. In addition, check temperature differential between collectors and storage, using thermometers and thermowells. If temperature differential is above high-temperature differential set point and system has not started, be sure the pump and controller are energized. If power is available and the system does not start, call a service person. Similarly, if temperature differential is below low-temperature differential set point and system is running, call a service person.
- Check pump lubrication per manufacturer's specifications.

3.1.1.5 Drain-Down-System Troubleshooting

Although the exact configuration of a drain-down one- or two-tank system depends on the manufacturer, the troubleshooting information in Table 3.2 should help locate and correct typical problems. This information also should help the owner or service person troubleshoot a system that has been in the field for some time. In addition, this information may be useful to the system designer during system analysis, equipment selection, and specification preparations.

Table 3.2 Troubleshooting Drain-Down Systems

Problem	Components	Possible Causes	Corrective Action
System does not start	Power supply	1. Tripped on overload. 2. Open circuit breaker. 3. Defective transformer. 4. Line voltage fluctuating. 5. Brownout. 6. Control switch on "off" position.	1. Determine cause and replace fuse or breaker. 2. Check and close. 3. Replace. 4. Inform power company. 5. Provide brownout protective device and inform power company. 6. Turn to "auto" position.
	Thermostat	1. High and low temperature differential set points too high. 2. Defective component. 3. Loose contacts. 4. Thermostat is out of calibration.	1. Reset according to specifications and/or results obtained during system start-up and testing. 2. Replace thermostat. 3. Tighten wires. 4. Recalibrate.
	Sensor	1. Defective. 2. Improper installation. 3. Defective control cable. 4. Sensor out of calibration	1. Replace. 2. Reinstall. 3. Replace. 4. Recalibrate.
	Pump	1. Motor failure. 2. Overload protection switch shuts down pump motor. 3. Defective shaft; impeller or coupling. 4. Defective bearings.	1. Check brush holders, throw-out mechanisms, centrifugal switches, or other mechanical components that may be loose, worn, dirty, or gummy. Replace worn components and reassemble. 2. Determine cause of overloading; check if balancing valve is in proper position. 3. Replace defective components. 4. Replace bearings.
	Control circuitry	1. Circuit continuity lost. 2. Bad contacts.	1. Check and repair. 2. Check and correct.
System starts but cycles	Thermostat	High and low temperature differential set points are too close together.	Reset according to specification and/or results obtained during system start-up and testing.
	Time delay relay	Time delay "times out" too soon (freeze-protection sensor does not heat up in time).	Increase time delay relay setting.
	Control circuitry	1. Circuit continuity lost. 2. Bad contacts. 3. Pump cycles on internal overload.	1. Check and repair. 2. Check and correct. 3a. Check voltage; b. Check pump flow; c. On shaded-pole motor, verify that shading pole ring is open and replace.
Pump runs but water does not flow to collectors	Valve V-2 closed	1. Actuator defective. 2. No power to actuator. 3. Valve sticks.	1. Replace actuator. 2. Check wiring. 3. Cycle valve by jumping control system or replace actuator.
	Valve V-1 open	1. Actuator defective. 2. No power to actuator. 3. Valve sticks.	1. Replace actuator. 2. Check wiring. 3. Cycle valve by jumping control or replace actuator.
	System air locked	Air vent(s) jammed closed.	Loosen cap. Replace vent(s).
	Pump impeller	Impeller broken or separated from shaft.	Replace impeller and/or shaft assembly.
	Blocked liquid flow passage	Pipe damaged.	Replace damaged section.

Table 3.2 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
System runs continuously	Thermostat	1. Low temperature differential set point set too low. 2. Defective component. 3. *Thermostat is out of* calibration.	1. Reset according to specifications or results obtained during start-up. 2. Replace thermostat. 3. *Recalibrate.*
	Sensor(s)	1. Defective sensor(s). 2. Sensor(s) is out of calibration. 3. Incorrect sensor in circuit.	1. Replace. 2. Recalibrate. 3. Replace.
	Control circuitry	Bad contacts.	Check and correct.
System does not drain	Freeze protection thermostat	1. Set point drifted. 2. Defective components. 3. Loose contacts. 4. Thermostat is out of calibration.	1. Reset. 2. Replace. 3. Tighten wires. 4. Recalibrate.
	Sensor(s)	1. Sensor(s) out of calibration. 2. Defective sensor. 3. Improper sensor. 4. Improper installation.	1. Recalibrate. 2. Replace. 3. Replace with correct sensor. 4. Reinstall.
	Vacuum breaker	1. Does not open. 2. Frozen.	1. Replace. 2. Add heat tape.
	Drain-down valve V-1 closed	1. Actuator defective. 2. No power to actuator. 3. Valve sticks.	1. Replace actuator. 2. Check control wiring. 3. Cycle valve by jumping control system or replace actuator.
System drains continually	Drain-down valve V-1 open	1. Actuator defective 2. No power to actuator. 3. "Sticky" valve. 4. "O" ring leaks.	1. Replace actuator. 2. Check wiring. 3. Cycle valve by jumping control system or replace actuator. 4. Replace.
	Check valve	Check valve leaks.	Isolate valve and replace.
	Freeze protection thermostat	1. Set point drifted. 2. Defective components. 3. Loose contacts. 4. Thermostat is out of calibration.	1. Reset. 2. Replace. 3. Tighten wires. 4. Calibrate.
	Sensor(s)	1. Sensor(s) out of calibration. 2. Defective sensor or wiring. 3. Sensor improperly installed.	1. Calibrate. 2. Replace. 3. Reinstall.
System leaks	Pipe joints	1. Thermal expansion and contraction. 2. Joint improperly made.	1. Provide flexibility and reassemble. 2. Reassemble leaky joint.
	Hose connection	Clamp does not hold tight.	Tighten up the hose clamp. Replace clamp or hose.
	Vacuum breaker	Ball held down.	1. Clean flux from screen. 2. Replace if basket is crushed.
	Relief valve	1. Improper pressure setting. 2. Defective component.	1. Check pressure setting and correct. 2. Replace.
Poor solar energy collection	Collector array	1. Undersized collector area. 2. Collectors shaded. 3. Flow rate too high or too low. 4. Heat transfer surface covered with scale deposits. 5. Leaks.	1. Install more collector area. 2. Remove obstacle or install collectors in more appropriate location. 3. Rebalance flow. 4. Flush collector loop. 5. Repair.
	Piping	1. Insufficient insulation. 2. Improper weather protection. 3. Insulation damaged.	1. Add additional insulation. 2. Provide proper weather protection. 3. Repair.

Table 3.2 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
System noisy when operating	Pump cavitation	1. Restricted pump suction line. 2. Air in the system.	1. Remove restrictions. 2. Manually vent the system if automatic air vents are not adequate. May require air vent at storage tank.
	Pump bearings	1. Bearing worn. 2. Bearing damaged due to improper alignment.	1. Replace bearing. 2. Replace bearing and align pump and motor shaft.
	Air vents	1. Improperly sized. 2. Cap too tight.	1. Install proper air vents. 2. Loosen cap or install air-vent tubing.
No hot water	Make-up water shut-off valve	Valve closed.	Open valve.
	Heater failed to actuate	1. Electric heater (single-tank systems). No power to electric heater (single-tank system only).	Check overload protection and correct.
		2. Gas heater (double-tank systems only).	
		a. Failure to ignite (gas off).	a. Open manual valve.
		b. Safety switch malfunctioning.	b. Check and replace.
		c. Defective thermocouple and/or automatic pilot valve.	c. Check and replace.
		d. Pilot won't stay lit.	
		d(1). Too much primary air.	d(1). Adjust pilot shutter.
		d(2). Dirt in pilot orifice.	d(2). Open orifice.
		d(3). Pilot valve defective.	d(3). Replace.
		d(4). Loose thermocouple connection.	d(4). Tighten.
		d(5). Defective thermocouple.	d(5). Replace.
		d(6). Improper pilot gas adjustment.	d(6). Adjust.
		3. Both systems. a. Thermostat defective. b. Bad contacts.	1. Replace. 2. Correct.
	Temperature modulating valve	1. Valve defective. 2. Sensor defective. 3. Leak in capillary tubing.	1. Replace. 2. Replace. 3. Replace.
Hot water temperature not high enough	Hot water thermostat	1. Thermostat setting too low. 2. Thermostat out of calibration.	1. Set thermostat higher. 2. Recalibrate or replace thermostat.
	Auxiliary heater	Undersized heater for hot water demand.	Replace when heater fails.
	Safety switch	Set too low.	Check and reset.
	Burner (two-tank systems)	1. Burner clogged. 2. Undersized burner orifice.	1. Clean. 2. Provide correctly sized orifice.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too low. 3. Valve spring too weak.	1. Recalibrate. 2. Reset. 3. Replace.

Table 3.2 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
Water temperature too high	Hot water temperature	1. Thermostat setting too high. 2. Thermostat out of calibration. 3. Bad contacts.	1. Reset. 2. Recalibrate. 3. Correct.
	Sensor	Out of calibration.	Recalibrate or replace.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too high.	1. Recalibrate. 2. Reset.
Overheating of the system	Drain-down valve V-1	1. Valve sticks. 2. Return spring failed.	1. Cycle valve by jumping control system or replace actuator. 2. Replace.
	Make-up water supply valve	Valve closed.	Open the valve.
	Collector loop valve V-2 closed	1. Actuator defective. 2. No power to actuator. 3. Valve sticks.	1. Replace actuator. 2. Check wiring. 3. Cycle valve by jumping control system or replace actuator.
	Overheat protection thermostat	1. Thermostat setting too high. 2. Defective component. 3. Thermostat is out of calibration. 4. Loose contacts.	1. Reset in accordance with specifications. 2. Replace thermostat. 3. Recalibrate. 4. Tighten wire.

3.1.2 Circulating-Water Systems

The circulating-water systems in Figs. 3.9 and 3.10 use potable water in the collector loop. A control circuit for this system is shown in Fig. 3.11. To protect the system from freezing, warm water from the auxiliary-heater/storage tank, or preheat tank on two-tank systems, is circulated through the collector loop when freezing temperatures are sensed.

3.1.2.1 Operation

Solar-Energy Collection. Circulating-water systems begin to collect energy when the temperature difference between the collector absorber-plate sensor S_1 and the DHW tank sensor S_2 reaches a preset high-temperature differential set point, which is 20°F (11°C) in many installations. When this set point is exceeded, the normally open contacts in thermostat T-1 close, and the electric circuit serving pump P-1 and valve V-1 is activated.*

*Solenoid valve V-1 prevents thermosiphoning. It can be replaced with a check valve. When a check valve is used, the control schematic is simplified and the system should be less expensive. However, the check valve must be either spring- or weight-loaded, carefully selected, and carefully installed. Improper selection of check valves has caused some systems to freeze. The designer must verify that if thermosiphoning is initiated in the collector loop, the resulting fluid pressure cannot overcome the resistive force (spring or weight) of the check valve.

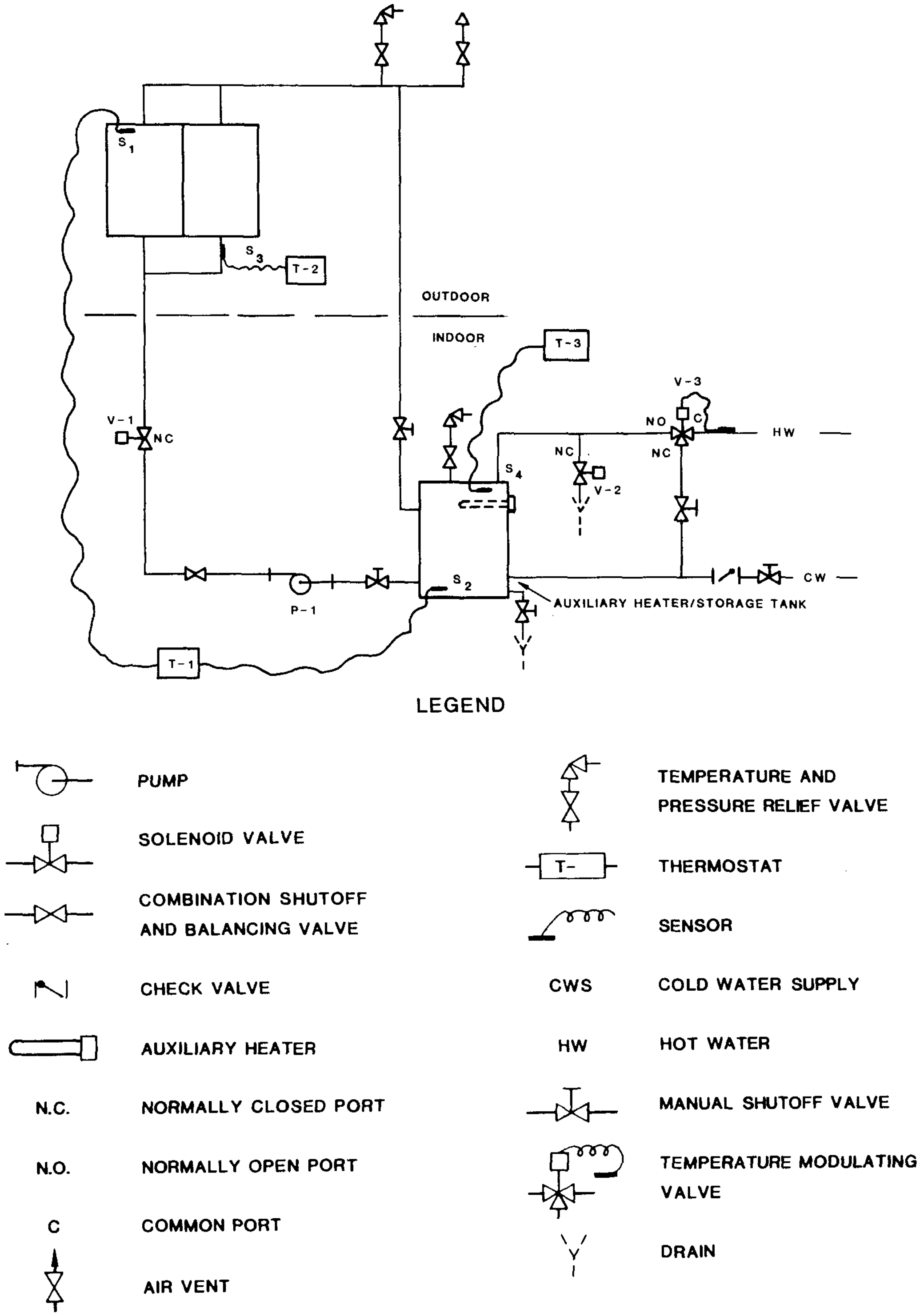


Fig. 3.9 Circulating-Water One-Tank System

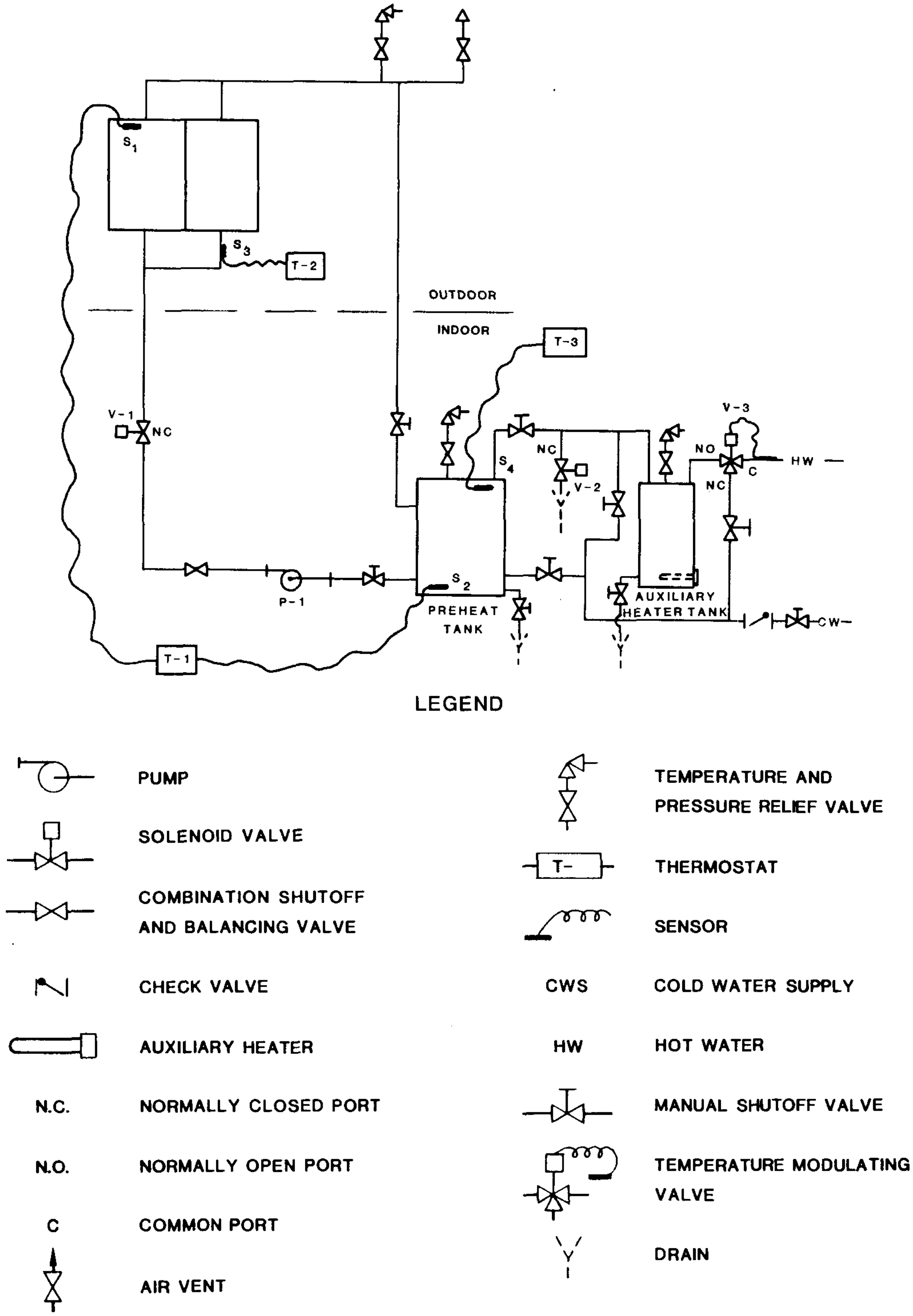
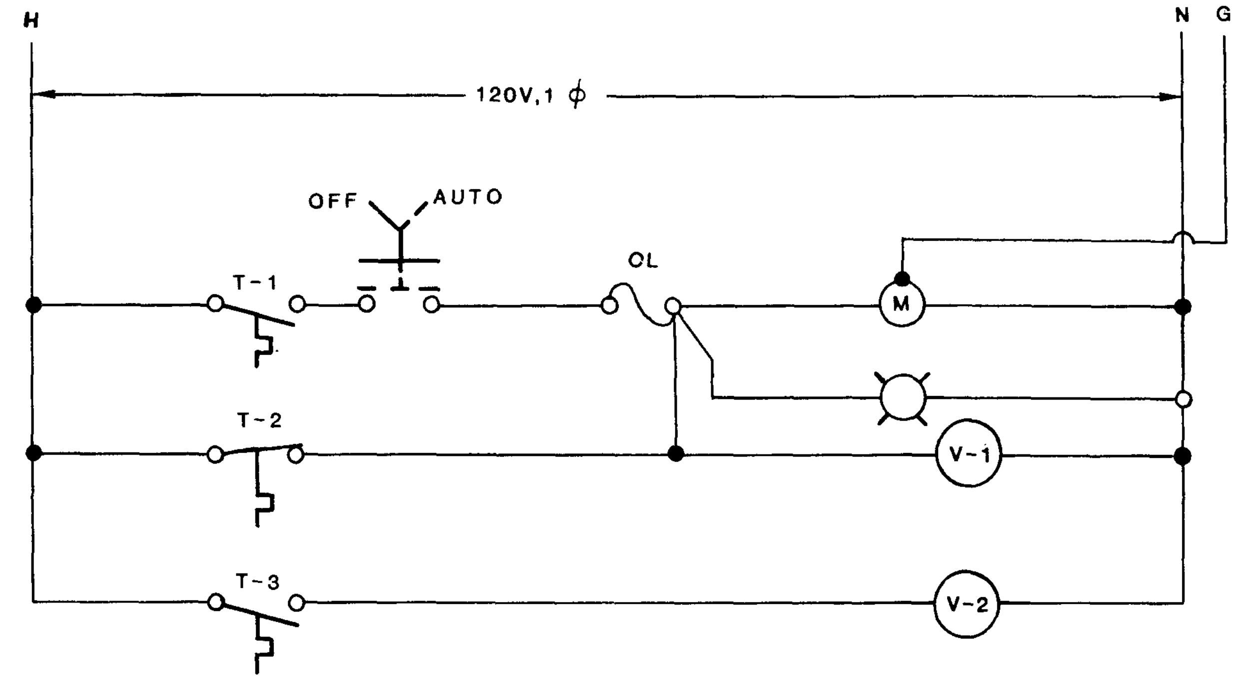


Fig. 3.10 Circulating-Water Two-Tank System



LEGEND

(T-1) Thermostat; single-pole-single-throw; normally open contact closes when temperature rises above high temperature differential set point and opens when temperature drops below low temperature differential set point.

(T-2) Thermostat; single-pole-single throw; normally closed contact opens on temperature rise.

(T-3) Thermostat, single-pole-single-throw; normally open contact closes on temperature rise.

(M) Fractional HP pump motor

(V-1) (V-2) Valve actuator; valve closed when de-energized.

OFF / AUTO — Manual two-position motor starter switch with thermal overload protection and indicator light.

H Hot wire

N Neutral wire

G Ground wire

Fig. 3.11 Control-System Ladder Diagram for Circulating-Water System

With the pump and valve V-1 circuit energized, V-1 goes from its normally closed position to open and P-1 starts. Pump P-1 now circulates water from the bottom of the auxiliary-heater/storage tank, or preheat tank in two-tank systems, through the collector and back to the tank. This process continues as long as the temperature difference between sensors S_1 and S_2 remains within the range of the high-to-low-temperature differential set point.

When the temperature difference between the collector and storage decreases to the preset value of the low-temperature differential set point, the thermostat T-1 opens the control circuits for pump P-1 and valve V-1. The system is now shut down. For the system to restart, the temperature difference between sensors S_1 and S_2 must increase to the predetermined value of the high-temperature differential set point.

Freeze Protection. Because water is the collector coolant, the collector array must be protected against freezing. The freeze-protection system is controlled by the signals from sensor S_3 at the bottom of the collector array and the response of thermostat T-2. Multiple sensors could be used, as discussed in Chapter 2, but control-system modifications would be required.

If the temperature at the bottom of the collectors decreases to approximately 40°F (4°C), the open contacts in thermostat T-2 close, and pump P-1 and valve V-1 are energized. With valve V-1 open and pump P-1 running, warm water from the auxiliary-heater/storage tank, or preheat tank in two-tank systems, circulates through and warms up the collector loop. This warmer temperature is sensed by sensor S_3, and a temperature signal is sent to thermostat T-2. When the water temperature sensed by sensor S_3 increases above the thermostat set point by enough to overcome hysteresis of the thermostat T-2, its contacts open and the system shuts down. This cycle repeats as often as necessary to keep the collector from freezing.

Overheat Protection. When solar energy is available and DHW demand is low, the water temperature in the solar-energy system can approach or exceed the boiling point. To protect the user and the solar DHW system, overheat protection must be incorporated into the control system.

There are several design options to protect the system from overheating. One option, incorporated into Fig. 3.11, provides overheat protection by discharging hot water out of the system. This option operates in the following manner.

Thermostat T-3, a single-pole-single-throw switch, provides overheat protection. It receives temperature signals from sensor S_4. When the S_4 temperature exceeds the high set point of approximately 180°F (82°C), the normally open contact closes, the electrical circuit to valve V-2 energizes, valve V-2 opens, and the water in the tank discharges to the drain. The hot water discharged from the top of the auxiliary-heater/storage tank (preheat tank for two-tank systems) is replaced by cold make-up water entering at the bottom of the tank, causing the water temperature in the tank to decrease.

When the S_4 temperature drops to the low set point of approximately 170°F (77°C), the contacts on T-3 open, and valve V-2 de-energizes and closes. The overheat protection mode is reactivated when the water temperature increases to the high-temperature set point of thermostat T-3.

The features of an overheat-protection mode that discharges hot water from the system are:

- Both auxiliary-heater/storage tank (preheat tank for two-tank systems) and collectors are protected against high temperatures.
- Water is wasted, so this technique is not recommended for use in dry climates.

Another overheat-protection method, which does not discharge hot water from the system, uses an overheat-protection thermostat, T-3, to lock out pump P-1, and close valve V-1, until the temperature in the auxiliary-heater/storage tank, or preheat tank for two-tank systems, decreases. The control circuit for this method is similar to the Fig. 3.11 schematic, except the normally closed T-3 contacts, which open with a temperature rise, are between T-1 and pump P-1.

Features of this method are:

- Although the auxiliary-heater/storage tank, or preheat tank in two-tank systems, is protected against high temperatures, the collectors are not protected and therefore may be subject to stagnation conditions. If overheating occurs and the pressure becomes excessive, the temperature/pressure relief valve opens, relieving the pressure.
- Hot water is not wasted.

A third overheat-protection method has a heat-rejection coil and two control valves to remove excessive heat from the system. Main features of this overheat-protection method are:

- Water is not wasted.
- Initial cost of coil and valves is higher.
- Both auxiliary-heater/storage tank, or preheat tank for two-tank systems, and collectors are protected against overheating.
- Pump is required for overheat protection.

All three of these overheat-protection methods protect the auxiliary-heater/storage tank, or preheat tank for two-tank systems, from the high water temperatures that degrade tank linings. Two of the methods protect the collectors from wet stagnation conditions.

The system designer must evaluate the cost of the collector's overheating protection with regard to the 1-to-10-yr range of collector warranty periods, collector degradation owing to occasional stagnation conditions, the installed cost of additional valves, the cost of control system modifications, and cost of wasted water. In a conservative design, collectors capable of withstanding stagnation for 30 days, as verified by ASHRAE 93-77, should be specified.[63]

Auxiliary-Heater Operation. In a one-tank system, a factory-packaged electric heater maintains the desired water temperature. The package combines thermostat, temperature sensor, electric resistance-heating element, and emergency-cutout (ECO) switch in one unit.

A factory-installed and calibrated temperature sensor detects the temperature of the tank surface. When the temperature drops below the low-temperature set point, the thermostat energizes the heating element. When the water has been heated to a predetermined value, usually 10° to 20°F (5° to 11°C) higher than the low set point, the thermostat de-energizes the element. This auxiliary-heater operation is typical of residential electric DHW service. An alternate system locks out the auxiliary heater whenever the collector loop is functioning.

For two-tank systems, a gas heater usually is employed to maintain the desired auxiliary-heater tank-water temperature. Controls on gas-fired systems combine an automatic pilot valve, manual gas valve, thermostatic valve, pilot gas filter, and gas regulators in one unit.

In the two-tank system, the water temperature is sensed by the thermostatic-valve sensor. When the temperature drops below the low-temperature set point, the thermostatic valve opens the gas supply and the pilot light ignites the gas at the burner. When the water temperature increases to a predetermined value, which is usually between 10° to 20°F (5° to 11°C) higher than the low-temperature set point, the thermostatic valve shuts off the gas supply.

Temperature-Modulating Valve. Whenever the temperature of hot water leaving the auxiliary-heater tank exceeds a value specified by local codes, temperature-modulating valve V-3 begins mixing hot water and cold make-up water to maintain the preset temperature. Operation of a temperature-modulating valve is described in Sec. 2.8. Installation of a temperature-modulating valve is required by local codes in some areas, because it serves as a safety device to protect the user against excessively hot water.

3.1.2.2 Estimated Mean Time between Failures (MTBF)

The circulating-water-system MTBF estimates in Table 3.3 were obtained using the reliability-block-diagram technique presented in Appendix A. Component failure-rate data are presented in Chapter 2 and summarized in Appendix A. In obtaining the data in Table 3.3, it was assumed that the solar DHW system operates 6 hr/d.

The data indicate that the minimum estimated MTBF of any of the collector designs is not influenced by the type of interconnectors used in the system. Maximum estimated MTBF, on the other hand, is reduced by approximately 30% if hoses are used instead of soldered or brazed connections. Use

Table 3.3 Estimated Mean Time between Failures (MTBF) of Circulating-Water Solar DHW Systems

Number of Collectors in System	Approximate Solar Load (%)	One-Tank Systems Estimated MTBF (days): Without hose interconnections		One-Tank Systems Estimated MTBF (days): With hose interconnections		Two-Tank Systems Estimated MTBF (days): Without hose interconnections		Two-Tank Systems Estimated MTBF (days): With hose interconnections	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
2	At least 50	106	1198	97	693	100	931	92	616
2	100	80	975	75	635	77	829	72	568
4	At least 50	107	1120	97	695	101	931	92	612
4	At least 75	94	1078	86	682	90	904	83	608
4	100	63	862	60	584	61	744	58	528

of two storage tanks reduces system estimated MTBF by 18%, compared with use of a one-tank system.

The maximum MTBF estimates indicate that circulating-water systems are approximately 15% to 22% more reliable than drain-down systems. This increase in reliability occurs because fewer powered valves are required.

3.1.2.3 Circulating-Water-System Start-Up and Testing

After the circulating-water system has been installed, all the components cleaned, the system purged, and all sensors calibrated, but before the insulation is installed, the system must be started and tested. Testing is necessary to detect leaks, to verify the control sequence, to locate any defective pumps or valves, and to identify and eliminate installation or design errors.

The recommended testing procedures for single- and double-tank circulating-water systems comprise 13 steps, identical for both systems.

Step 1. Place the control system in the "off" position.

Step 2. Set temperature-modulating valve V-3 according to local code.

Step 3. Fill the domestic hot-water loop.

Open the hot-water faucets and the make-up water supply valve to purge air from the system. After the tank and piping have been filled with water, close the hot-water faucets.

Step 4. Adjust the set points of the thermostats in accordance with the system designer's recommendations.*

Note that at this point, the piping runs have not been insulated. Therefore, the low-temperature differential set point of thermostat T-1 should be arbitrarily set at 5°F (3°C). The final adjustment for the low-temperature differential set point is made after the insulation work is complete.

Step 5. Switch the control system to the "auto" position.

If the temperature difference between the collector absorber plate and storage is large enough, pump P-1 starts and the normally closed valve V-1 opens. If the temperature difference between the absorber plate and storage is too small, pump P-1 does not activate and valve V-1 remains closed. Under these conditions, the temperature-differential thermostat T-1 may be bypassed manually by inserting a jumper in order to balance the collector-loop flow and to test the system for leaks.

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*On prepackaged solar DHW systems, the thermostats may have been factory-set, so that field adjustment is not possible. It is assumed that the manufacturers of prepackaged solar DHW systems have sufficient testing data to properly set the thermostats.

Step 6. Balance the collector-loop flow.

The flow through the collectors must be balanced to avoid hot spots within the collector array that could lead to inefficient operation. This requirement becomes especially important when there are more than six panels in the collector array. However, for arrays with up to six panels, the usual arrangement in residential applications, flow balancing is still required.

This flow-balancing procedure indicates if any lines are blocked with solder or if a collector has an unusually high pressure drop. If the pressure drop across the collector exceeds the manufacturer's specification, some of the collector heat-transfer passages could be blocked, deformed, or leaking. Conversely, if the water flow exceeds the design flow, it must be throttled to the design value, or system efficiency will decrease.

Balanced-flow conditions can be achieved by measuring the flow rate through each collector panel or group of panels. These measurements can be made by using anubars, flowmeters, orifices, and circuit setters. Circuit setters are commercially available units that combine orifice, pressure taps, and a globe valve into one unit for the purpose of measuring and balancing the water flow.

Regardless of the flow-measuring technique, the measuring device should be installed as far as possible from flow deviators such as elbows, valves, or tees. The minimum distance is specified in the manufacturer's literature, and this distance must be maintained to obtain accurate readings.

A circuit setter or a manual throttling valve located on the discharge side of the pump should be provided for flow balancing. If this valve is installed on the suction side of the pump, the pump could cavitate and destroy itself.

Flow balancing should be started with the throttling valve in a partially open position. If an oversized pump has been installed and the throttling valve is fully open, higher flow rates than expected will occur, which may overload the pump motor.

If the water flow is significantly below the design flow rate, the problem could be caused by: restricted or closed balancing valve; blocked or deformed water lines or collector passages; pump suction side connected to the collectors instead of storage; or an improperly wired or defective pump motor.

If the pump has an induction single-phase or a three-phase motor, the pump could be improperly wired and rotating in the reverse direction. For these two motor types, interchanging the motor leads will eliminate the problem. For other types of motors, the pump cannot rotate in the reverse direction. If all of the preceding possibilities have been eliminated and the pump does not deliver the specified flow rate, the pump is defective and must be replaced.

Step 7. Adjust the pressure relief valve.

Pressurize the system tank to 12 psi (83 kPa) above the highest expected pressure in the system. With the collector pump running, adjust the pressure relief valves to the onset of bleeding. If the pressure relief valves have been set at the factory for the desired pressure, verify that the relief valve will open at the correct pressure.

Step 8. Test the system for leaks.

Pressurize the storage tank to 10 psi (69 kPa) above the highest expected pressure in the system. Also verify that valve V-2 does not leak and drains warm water out of the storage tank. With the pump running, inspect all piping joints for leaks. Special attention must be paid to the piping connecting the solar collectors. If leaks are discovered, the system must be shut down and drained and the leaks repaired. After the leaks have been repaired, the leak-testing procedure is repeated until all leaks are eliminated.

After Step 8 is complete, the piping runs must be insulated. Once all of the insulation work is finished, the system is ready for final testing.

Step 9. Adjust the low-temperature differential set point of thermostat T-1.*

Once the system has been tested and insulated, and if sufficient solar energy is available, turn the system to "auto." If field testing is selected for determining the low-temperature differential set point (see Appendix B), use a wattmeter to measure the electric energy consumption. Use Eqs. B.8 and B.10 to calculate the temperature differential and adjust the thermostat T-1 setting. If field testing was not selected by the system designer, set the thermostat T-1 according to the design specifications.

To verify accuracy of the low-temperature differential set-point adjustment, use calibrated thermometers to measure temperatures in the vicinity of sensors S_1 and S_2. By partially shading the collectors, available insolation can be reduced until the low-temperature differential set point of thermostat T-1 is reached, and the pump de-energizes.

When the pump shuts off, measure the temperature difference with the thermometers. If the measured difference does not fall within 0.5°F (0.3°C) of the low-temperature differential set point, adjust the thermostat T-1 setting. Repeat this procedure until the pump shuts off at the required temperature difference.

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*On prepackaged solar DHW systems, the thermostats may have been factory-set, so that field adjustment is not possible. It is assumed that the manufacturers of prepackaged solar DHW systems have sufficient testing data to properly set the thermostats.

Step 10. Test the overheat-protection mode.

Use a jumper to bypass thermostat T-3 and simulate the overheating of the storage tank. Valve V-2 should open, and the system should drain. Remove the jumper from across thermostat T-3.

Step 11. Test operation of auxiliary heater.

Adjust the set point of the auxiliary heater according to design specifications. To verify the temperature setting of the auxiliary heater, insert a calibrated thermometer into the thermal well to measure the water temperature at the top of the auxiliary-heater tank. The auxiliary heater should activate when the temperature at the top of the tank drops to within ±2°F (±1°C) of the desired temperature. If this requirement is not met, readjust the auxiliary-heater setting.

Step 12. Test operation of the temperature-modulating valve.

Adjust the setting of the temperature-modulating valve V-3 to maintain the value specified by local codes. Set the auxiliary heater to heat up the water to 170°F (77°C). Verify the water temperature at the top of the tank using a calibrated thermometer inserted into the thermal well. When the temperature reaches 170° ±5°F (77° ±3°C), open the hot-water faucets. Measure the temperature of the water leaving valve V-3. If the temperature is not within ±3°F (±2°C) of the local code value, adjust valve V-3 setting. Repeat the procedure until the temperature is correct. Then reset the heater to maintain the desired water temperature in the tank.

Step 13. Test freeze-protection mode.

When solar energy is not available, insert a jumper across thermostat T-2 to simulate freezing conditions. The electrical circuit to valve V-1 and pump P-1 should energize, and the system should start circulating water through the collectors. After this mode has been verified, remove the jumper.

With the completion of the above steps, all of the system operating modes have been verified, and the system has been tested for leaks. The solar DHW system should be ready to operate.

3.1.2.4 Circulating-Water-System Preventive Maintenance

To assure that circulating-water systems will perform reliably and will meet the MTBF estimates presented in Table 3.3, basic system preventive maintenance must be performed. Most of the suggested actions can be performed by the homeowner, with the possible exceptions of washing collectors mounted on the roof and verifying sensor calibration. Unless the system manufacturer provides special test points and thermowells as in Fig. 3.8, checking sensor calibration and automatic valve operation is best left to an experienced service person.

At least once each year, the following preventive maintenance actions should be performed:

- Wash the outer glazing of the collector with compounds approved by the manufacturer. (Do not wipe dust or dirt from polymeric glazings with a dry cloth, because they will be scratched.) During washing, the absorber plates should be inspected for degradation.
- Inspect the flashing and collector-mounting hardware. Tighten or replace and recaulk as required.
- Inspect, tighten, or replace the hose connections around the collector array.
- Verify that the sensors are still in the correct location and check sensor calibration.
- Inspect hand-operated valves for leaks and adjust the packing. Open or close the valves to verify their operation.
- Drain and flush the tanks, cleaning any strainers or valve filters.
- Inspect the pressure relief valve on the tank(s) and on the collector array to be sure the valve operates and that the exit port is not plugged.

The systems should be checked periodically for:

- Insulation deterioration.
- System leaks.
- Correct thermostat setting, to be sure the setting has not shifted from the position established during start-up and testing.
- Proper operation of valve V-2. This valve is closed most of the time and might stick and not open when needed to relieve overheating.
- Correct operating mode:

  Verify pump does not operate at night, or does operate when freezing conditions exist, using flowmeter, sight glass, or pressure gauges (if installed).

  On a sunny day, verify pump operation by noting if the flowmeter or the sight glass indicates fluid motion. In addition, check the temperature differential between collectors and storage using thermometers and thermowells as in Fig. 3.8. If the temperature differential is above the high-temperature differential set point of T-1 and the system has not started, call a service person. If temperature differential is below the low-temperature differential set point of T-1, and the system is running, also call a service person.

- Check pump lubrication, using manufacturer's specifications.

3.1.2.5 Circulating-Water-System Troubleshooting

Although the designs of circulating-water, one- or two-tank solar DHW systems vary with the individual manufacturers, the troubleshooting information in Table 3.4 should help find and correct the problems likely to occur with these systems. This information also should assist the owner or service person to troubleshoot systems that have been in the field for some time. In addition, this information will be useful to the designer concerned with system analysis, equipment selection, and component and system specifications.

Table 3.4 Troubleshooting Circulating-Water Systems

Problem	Components	Possible Causes	Corrective Action
System does not start	Power supply	1. Tripped on overload.	1. Determine cause and replace fuse or breaker.
		2. Open circuit breaker.	2. Check and close.
		3. Defective transformer.	3. Replace.
		4. Line voltage fluctuating.	4. Inform power company.
		5. Brownout.	5. Provide brownout protective device and inform power company.
		6. Control switch on "off" position.	6. Turn to "auto" position.
	Thermostat T-1	1. High and low temperature differential set points too high.	1. Reset according to specifications or results obtained during system start-up and testing.
		2. Defective component.	2. Replace thermostat.
		3. Loose contacts.	3. Tighten wires.
		4. Thermostat is out of calibration.	4. Recalibrate.
	Sensor(s) S_1 or S_2	1. Defective.	1. Replace.
		2. Improper installation.	2. Reinstall.
		3. Defective control cable.	3. Replace.
		4. Sensor out of calibration.	4. Recalibrate.
	Pump	1. Motor failure.	1. Check brush holders, throw-out mechanisms, centrifugal switches, or other mechanical components that may be loose, worn, dirty, or gummy. Replace worn components and reassemble.
		2. Overload protection switch shuts down pump motor.	2. Determine cause of overloading; check if balancing valve is in proper position.
		3. Defective shaft; impeller or coupling.	3. Replace.
		4. Defective bearings.	4. Replace.
	Control circuitry	1. Circuit continuity lost.	1. Check and repair.
		2. Bad contacts.	2. Check and correct.
System starts but cycles	Thermostat T-1	High and low temperature differential set points are too close together.	Reset according to specification or results obtained during system start-up and testing.
	Thermostat T-2	Thermostat setting too high.	Reset thermostat.

Table 3.4 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
System starts but cycles (cont'd)	Control circuitry	1. Circuit continuity lost. 2. Bad contacts. 3. Pump cycles on internal overload.	1. Check and repair. 2. Check and correct. 3a. Check voltage; b. Check pump flow; c. On shaded-pole motor, verify that shading-pole ring is open and replace.
Pump runs but water does not flow to collectors	Valve V-1 closed	1. Actuator defective. 2. No power to actuator. 3. Valve sticks.	1. Replace actuator. 2. Check wiring. 3. Cycle valve by jumping control system or replace actuator.
	Pump impeller	Impeller broken or separated from shaft.	Replace impeller and/or shaft assembly.
	Blocked liquid flow passage	1. Pipe damaged. 2. Air lock.	1. Replace damaged section. 2. Purge and vent.
System runs continuously	Thermostat T-1	1. Low temperature differential set point set too low. 2. Defective component. 3. Thermostat is out of calibration.	1. Reset according to specifications or results obtained during start-up. 2. Replace thermostat. 3. Recalibrate.
	Freeze protection thermostat T-2	1. Set point drifted. 2. Defective components or fused contacts. 3. Loose contacts. 4. Thermostat is out of calibration.	1. Reset. 2. Replace. 3. Tighten wires. 4. Recalibrate.
	Sensor(s)	1. Sensor(s) out of calibration. 2. Defective sensor. 3. Improper installation.	1. Recalibrate. 2. Replace. 3. Reinstall.
	Control circuitry	Bad contacts.	Check and correct.
System discharges continually	Overheat protection valve V-2	1. Valve leaks. 2. Valve sticks. 3. "O" ring cut.	1. Replace. 2. Cycle valve by jumping control system or replace actuator. 3. Replace.
	Overheat protection thermostat T-3	1. Defective. 2. Out of calibration. 3. Set point too low.	1. Replace. 2. Recalibrate. 3. Reset
	Control circuitry	Bad contacts.	Check and replace.
System leaks	Pipe joints	1. Thermal expansion and contraction. 2. Joint improperly made.	1. Provide flexibility and reassemble. 2. Reassemble leaky joint.
	Hose connection	Clamp does not hold tight.	Tighten up the hose clamp. Replace clamp or hose.
	Relief valve	1. Improper pressure setting. 2. Defective component.	1. Check pressure setting and correct. 2. Replace.
	Storage tank	Air leak at sight gauge, and expansion section fills with water. On heating, water expands and pressure as well as leakage increases.	Drain system. Refill system.

Table 3.4 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
Poor solar energy collection	Collector array	1. Undersized collector area.	1. Install more collector area.
		2. Collectors shaded.	2. Remove obstacle or install collectors in more appropriate location.
		3. Flow rate too high or too low.	3. Rebalance flow.
		4. Heat transfer surface covered with scale deposits.	4. Flush collector loop.
		5. Leaks.	5. Repair.
	Piping	1. Insufficient insulation.	1. Add additional insulation.
		2. Improper weather protection.	2. Provide proper weather protection.
		3. Insulation damaged.	3. Repair.
System noisy when operating	Pump cavitation	1. Restricted pump suction line.	1. Remove restrictions.
		2. Air in the system.	2. Manually vent the system if automatic air vents are not adequate.
	Pump bearings	1. Bearing worn.	1. Replace bearing.
		2. Bearing damaged due to improper alignment.	2. Replace bearing and align pump and motor shaft.
	Piping	1. Air locked in the piping.	1. Air vent the system.
		2. Piping vibrates.	2. Provide adequate pipe support.
	Air vents	Residual air in system or air leak.	Purge air from system.
No hot water	Make-up water shut-off valve	Valve closed.	Open valve.
	Heater failed to actuate	1. Electric heater, single-tank systems	
		a. No power to electric heater (single-tank system only).	a. Check overload protection, correct.
		2. Gas heater (double-tank systems only).	
		a. Failure to ignite (gas off).	a. Open manual valve.
		b. Safety switch malfunctioning.	b. Check and replace.
		c. Defective thermocouple and/or automatic pilot valve.	c. Check and replace.
		d. Pilot won't stay lit.	
		(1) Too much primary air.	(1) Adjust pilot shutter.
		(2) Dir in pilot orifice.	(2) Open orifice.
		(3) Pilot valve defective.	(3) Replace.
		(4) Loose thermocouple connection.	(4) Tighten.
		(5) Defective thermocouple.	(5) Replace.
		(6) Improper pilot gas adjustment.	(6) Adjust.
		3. Both systems	
		a. Thermostat defective.	a. Replace.
		b. Bad contacts.	b. Correct.
	Temperature modulating valve	1. Valve defective.	1. Replace.
		2. Sensor defective.	2. Replace.
		3. Leak in capillary tubing.	3. Replace.

Table 3.4 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
Hot water temperature not high enough	Hot water thermostat	1. Thermostat setting too low. 2. Thermostat out of calibration.	1. Set thermostat higher. 2. Recalibrate or replace thermostat.
	Auxiliary heater	Undersized heater for hot water demand.	Replace when heater fails.
	Safety switch	Set too low.	Check and reset.
	Burner-double-tank system only	1. Burner clogged 2. Undersized burner orifice.	1. Clean. 2. Provide correct sized orifice.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too low. 3. Valve spring too weak.	1. Recalibrate. 2. Reset. 3. Replace.
Water temperature too high	Hot water temperature	1. Thermostat setting too high. 2. Thermostat out of calibration. 3. Bad contacts.	1. Reset. 2. Recalibrate. 3. Correct.
	Sensor	Out of calibration.	Recalibrate or replace.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too high.	1. Recalibrate. 2. Reset.
Overheating of the system	Overheat protection valve V-2	Valve sticks.	Cycle valve by jumping control system or replace actuator.
	Make-up water supply valve	Valve closed.	Open the valve.
	Overheat protection thermostat	1. Thermostat setting too high. 2. Defective component. 3. Thermostat is out of calibration. 4. Loose contacts.	1. Reset in accordance with specifications. 2. Replace thermostat. 3. Recalibrate. 4. Tighten wire.
	Control circuitry	1. Circuit continuity lost. 2. Loose contacts. 3. Coil of the contacts burned out.	1. Check and repair. 2. Tighten contacts. 3. Replace.
	Sensor(s)	Out of calibration.	Recalibrate.

3.1.3 Thermosiphon One-Tank System

The generic thermosiphon one-tank system in Fig. 3.12 uses potable water in the collector loop. The system is based on cold, high-density water flowing down from the storage tank, forcing warm, low-density water in the collectors up to the top of the storage tank. The storage tank must be installed above the collectors. Rate of water flow and energy collection by the collectors is determined by the differences in elevation and water temperature of the bottom of the storage tank and top of the collectors.

When water at the bottom of the storage tank is warmer than water in the collectors, thermal siphoning cannot occur, which automatically protects the system from losing energy when solar energy is not available.

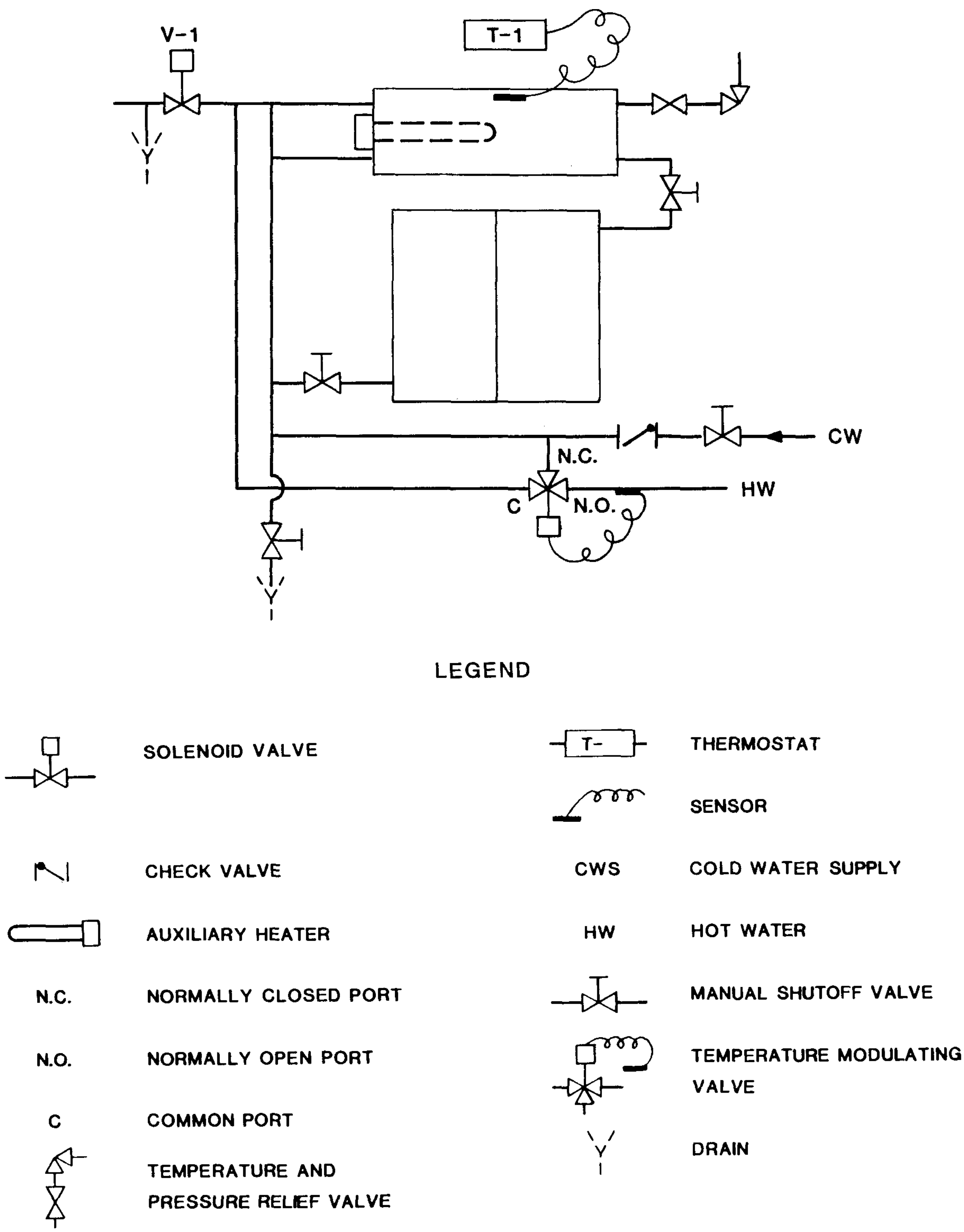

Fig. 3.12 Thermosiphon One-Tank System

Thermosiphon systems usually are installed in regions where freezing temperatures either do not occur or occur seldom. When freezing temperatures do occur, some method of freeze protection must be provided. The usual method is to install electric heaters in the collector array. This freeze-protection technique is not recommended for use in cold climates, however, because the cost of electricity to power the heaters will exceed the benefits derived from solar energy. The generic thermosiphon system shown in Fig. 3.12 does not have freeze protection.

3.1.3.1 Operation

Solar-Energy Collection. When solar energy is available, the temperature of the water in the collectors is greater than the water temperature in the middle/top portions of the storage tank, starting the collection cycle. The cycle continues as long as collector water temperature exceeds the water temperature in the middle/top portions of the storage tank. As the water temperature increases, the collector efficiency decreases.

Overheat Protection. When solar energy is available and DHW demand is low, the water temperature in the solar system can approach 190 to 200°F (88 to 93°C). To protect the user and the system, overheat protection can be incorporated into the control system.

There are several designs for protection against overheating. One design, which is incorporated in Fig. 3.13, provides overheat protection by discharging hot water from the system. It operates in the following manner: Thermostat T-1, a single-pole-single-throw switch, receives its temperature signal from sensor S_1. When S_1 temperature exceeds the high set point of approximately 180°F (83°C), the normally open contact on thermostat T-1 closes, the electrical circuit to valve V-1 energizes, valve V-1 opens, and water in the storage tank discharges to the drain. Hot water discharged from the top of the tank is replaced by cold water entering the bottom, lowering the tank-water temperature.

When S_1 temperature drops to the low set point of approximately 170°F (77°C), thermostat T-1 contacts open and valve V-1 de-energizes and closes. The overheat-protection mode is reactivated when the water temperature increases to the high-temperature set point of thermostat T-1.

The main features of an overheat-protection method that depends on discharging hot water from the system are:

- Both auxiliary-heater/storage tank, or preheat tank for two-tank systems, and collectors are protected against high temperatures.
- Water is wasted, so this method is not recommended for use in dry climates.

Some thermosiphon systems rely on a pressure/temperature relief valve, instead of a solenoid valve, to discharge hot water out of the system. The

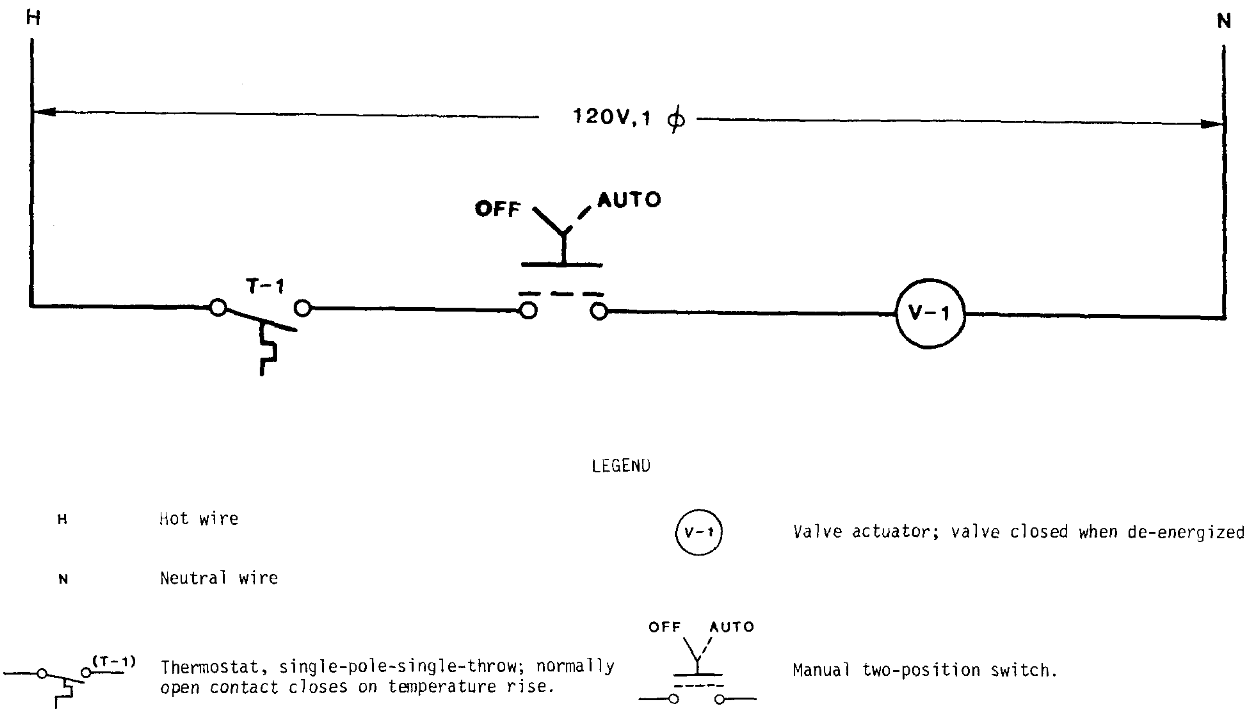

Fig. 3.13 Control Schematic for Thermosiphon One-Tank System

pressure/temperature relief valve is actuated when system pressure or temperature exceeds the valve's set point. A valve spring is used to open the relief valve when system pressure is exceeded, and a fusible plug is used to open the relief valve at excessive system temperatures.

The advantages of the relief-valve method are lower cost and simplicity; however, there are the following disadvantages:

- Primary function of a pressure/temperature relief valve is safety; thus, the valve should be used for that purpose only.
- Temperature and pressure are not correlated, and a pressure setting cannot be selected to correspond to the 180°F (83°C) system temperature needed to protect storage-tank lining.
- If the relief valve is actuated by means of a fusible plug (when system temperature exceeds 180°F or 83°C), the valve will continue to discharge water until the fusible plug is replaced. If the homeowner is on vacation and the house is unattended, the temperature actuation of the relief valve may result in substantial water and energy losses.

Keeping the auxiliary-heater/storage tank from overheating prevents the high water temperatures from degrading tank corrosion-protection linings. It also protects the collectors from wet stagnation conditions. System designers must evaluate the cost of the collector overheating protection with regard to the 1-to-10-yr range of collector warranties, collector degradation owing to occasional stagnation conditions, the installed cost of additional valves and control-system modifications, and the cost of wasted water. In a conservative design, collectors capable of withstanding stagnation for 30 days without degradation, as verified by ASHRAE 97-33, should be specified.[63]

Auxiliary-Heater Operation. In thermosiphon systems, a factory-packaged electric heater maintains the desired water temperature. The package combines thermostat, temperature sensor, electric resistance-heating element, and emergency-cutout (ECO) switch in one unit.

A factory-installed and calibrated temperature sensor detects the temperature of the tank surface. When this temperature drops below the low-temperature set point, the thermostat energizes the heating element. When the water has been heated to a predetermined value, usually 10° to 20°F (5° to 11°C) higher than the low set point, the thermostat de-energizes the heating element. This auxiliary-heater operation is typical of residential electric DHW service.

Temperature-Modulating Valve. When the temperature of hot water leaving the auxiliary-heater tank exceeds a value specified by local codes, the temperature-modulating valve V-2 begins mixing hot water and cold make-up water to maintain the preset temperature.

Operation of a temperature-modulating valve is described in Sec. 2.8. Installation of a temperature-modulating valve is required by local codes in some areas, because it serves as a safety device to protect the user against excessively hot water.

3.1.3.2 Estimated Mean Time between Failures (MTBF)

The thermosiphon-system MTBF estimates in Table 3.5 were obtained using the reliability-block-diagram techniques presented in Appendix A. Component failure-rate data are presented in Chapter 2 and summarized in Appendix A. In obtaining the data in Table 3.5, it was assumed that the solar DHW system operates for 6 hr/d.

The data indicate that the minimum estimated MTBF of any of the collector designs is not influenced especially by the type of interconnectors used in the system. The maximum estimated MTBF of the system, on the other hand, is reduced by approximately 40% if hoses are used instead of soldered or brazed connections.

The thermosiphon systems have the highest reliability of any of the DHW systems. (See Tables 3.1, 3.3, 3.7, and 3.11 for data.) The increased reliability of approximately 12% to 40% is the result of simple control systems and the fact that the collector loop does not require a pump and associated controls to circulate the potable water.

Table 3.5 Estimated Mean Time between Failures (MTBF) of Thermosiphon Solar DHW Systems

Number of Collectors in System	Approximate Solar Load (%)	One-Tank Systems Estimated MTBF (days): Without hose interconnections, Minimum	Without hose interconnections, Maximum	With hose interconnections, Minimum	With hose interconnections, Maximum
2	At least 50	411	2361	320	1010
2	100	201	1835	174	893
4	At least 50	586	2367	298	1012
4	At least 75	240	2120	209	989
4	100	119	1468	109	796

3.1.3.3 Thermosiphon-System Start-Up and Testing

After the system has been installed, all the components cleaned, the system purged, and all sensors calibrated, but prior to installing the insulation, the system must be started and tested. Testing is necessary to detect leaks, verify operation of auxiliary heater and overheat protection, and identify and eliminate installation or design errors. The recommended testing procedure for the thermosiphon system follows:

Step 1. Place the control system in the "off" position.

Step 2. Open valve V-1 and water-supply valve to fill the system.

Install a jumper bypassing thermostat T-1 in order to open valve V-1. The incoming water will purge air out of piping, collectors, and storage tank. After the system has been filled, remove jumper.

Step 3. Adjust settings of overheat-protection thermostat T-1 in accordance with system designer's recommendations.

Step 4. Adjust pressure relief valve.

Pressurize the storage tank to 12 psi (83 kPa) above the highest expected pressure in the system. Adjust pressure relief valves to onset of bleeding. If pressure relief valves have been set at the factory, verify that valves open at correct pressures.

Step 5. Test system for leaks.

Pressurize the storage tank to 10 psi (69 kPa) above the highest expected pressure in the system. Inspect all piping joints for leaks. Pay special attention to piping connecting solar collectors and to overheat-protection valve V-1. If system leaks, system must be shut down and drained, and the leaks repaired. After leaks have been repaired, insulate system.

Step 6. Test the overheat-protection mode.

Jump thermostat T-1 to simulate overheating of the storage tank. Valve V-1 should open and drain the system. Remove jumper from system.

Step 7. Test operation of auxiliary heater.

Adjust set point of auxiliary electric heater to designer's specifications. To verify setting, insert a calibrated thermometer in the thermal well to measure water temperature at top of storage tank. The auxiliary electric heater should activate when temperature at top of tank drops to ±2°F (±1°C) of desired set temperature. If this requirement is not met, readjust auxiliary-heater setting.*

Step 8. Test operation of temperature-modulating valve.

Adjust setting of temperature-modulating valve V-2 to the value specified by local codes. Set auxiliary heater for 170°F (77°C). Verify water temperature at top of tank with a calibrated thermometer inserted into thermal well. When temperature reaches 170° ± 5°F (77° ± 3°C), open hot-water faucets. Measure temperature of water leaving valve V-3. If temperature is not within ±3°F (±2°C) of the value specified by local codes, readjust valve V-2 setting. Repeat procedure until temperature is correct. Then reset heater to maintain desired water temperature in tank.

On completion of the above steps, all system operations have been verified, and the system tested for leaks. It should now be ready to operate.

3.1.3.4 Thermosiphon-System Preventive Maintenance

To assure that a thermosiphon system will perform reliably and meet the MTBF estimates in Table 3.5, basic system preventive maintenance must be performed. Most of the suggested work can be performed by the homeowner, with the possible exceptions of washing collectors mounted on roofs and verifying sensor calibration. Unless the system manufacturer provides special test points and thermowells, as in Fig. 3.8, checking sensor calibration and automatic-valve operation is best left to an experienced service person.

At least once each year, the following preventive-maintenance actions should be performed:

- Wash the outer glazing of the collector with compounds approved by the manufacturer. (Do not remove dust or dirt from polymeric glazings with dry cloth, because they will be scratched.) During washing, the absorber plates should be inspected for degradation.

*On prepackaged thermosiphon systems, the auxiliary-heater thermostats are factory-set. Varying their settings may void the system warranty.

- Inspect the flashing and collector-mounting hardware. Tighten, replace, and recaulk as required.
- Inspect, tighten, or replace hose connections for the collector array.
- Verify that sensors are still in the correct location and check sensor calibration.
- Inspect hand-operated valves for leaks, adjusting packing as necessary. Open or close valves to verify proper operation.
- Drain and flush the tanks, and clean strainers and valve filters.
- Inspect pressure relief valve on the tank and on collector array to verify that valve operates and that exit port is not plugged.

In addition to performing this scheduled maintenance, one should check the system periodically for:

- Insulation deterioration.
- System leaks.
- Correct thermostat setting, to make sure setting has not shifted since start-up testing.
- Proper operation of valve V-1, as valve is closed most of the time and may stick and not open when needed.

3.1.3.5 Thermosiphon-System Troubleshooting

Although the design of a thermosiphon solar DHW system depends on the designer/manufacturer, the troubleshooting information in Table 3.6 should help find and correct typical problems with this system. This information should help the owner or the service person to troubleshoot a system that has been in the field for some time. In addition, this information may be useful to the system designer during system analysis, equipment selection, and specification preparations.

Table 3.6 Troubleshooting Thermosiphon Systems

Problem	Components	Possible Causes	Corrective Action
System does not start	Piping	1. Pipe blocked 2. Hot and cold pipes reversed.	1. Remove blockage. 2. Connect pipes correctly.
System leaks	Pipe joints	1. Thermal expansion and contraction. 2. Joint improperly made.	1. Provide flexibility and reassemble. 2. Reassemble leaky joints.
	Hose connection	Clamp does not hold tightly.	Tighten up the hose clamp. Replace clamp or hose.
	Relief valve	1. Improper pressure setting. 2. Defective component. 3. Designer did not provide enough space for thermal expansion in the storage tank.	1. Check pressure setting and correct. 2. Replace. 3. Drain excessive water out of the storage tank.
No hot water	Make-up water shut-off valve	Valve closed.	Open valve.
	Electric heater	No power to electric heater.	Check overload protection and correct.
	Auxiliary heater thermostat	1. Thermostat defective. 2. Bad contacts.	1. Replace. 2. Correct.
	Auxiliary heater sensor	1. Sensor out of calibration. 2. Sensor defective.	1. Recalibrate. 2. Replace.
	Temperature modulating valve	1. Valve defective. 2. Sensor defective. 3. Leak in capillary tubing.	1. Replace. 2. Replace. 3. Replace.
Hot water temperature not high enough	Auxiliary heater thermostat and/or overheat protection thermostat T-1	1. Thermostat setting too low. 2. Thermostat out of calibration.	1. Set thermostat higher. 2. Recalibrate or replace thermostat.
	Auxiliary heater	Undersized heater for hot water demand.	Replace when heater fails.
	Safety switch	Set too low.	Check and reset.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too low. 3. Valve spring too weak. 4. Valve seat plugged with silt.	1. Recalibrate. 2. Reset. 3. Replace. 4. Clean and replace.
Water temperature too high	Auxiliary heater thermostat	1. Thermostat setting too high. 2. Thermostat out of calibration. 3. Bad contacts. 4. Shorted thermostat.	1. Reset. 2. Recalibrate. 3. Correct. 4. Replace.
	Sensor	Out of calibration.	Recalibrate or replace.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too high.	1. Recalibrate. 2. Reset.
Overheating of the system	Overheat protection valve V-1	1. Valve sticks. 2. Return spring failed.	1. Cycle valve by jumping control system or replace actuator. 2. Replace.
	Make-up water supply valve	Valve closed.	Open the valve.
	Overheat protection thermostat	1. Thermostat setting too high. 2. Defective component. 3. Thermostat is out of calibration. 4. Loose contacts.	1. Reset in accordance with specifications. 2. Replace thermostat. 3. Recalibrate. 4. Tighten wire.

Table 3.6 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
Overheating of the system (cont'd)	Control circuitry	1. Circuit continuity lost. 2. Loose contacts. 3. Coil of the contacts burned out.	1. Check and repair. 2. Tighten contacts. 3. Replace.
	Sensor	Out of calibration.	Recalibrate.
Poor solar energy collection	Collector array	1. Collector area undersized. 2. Collectors shaded. 3. Flow rate too high or too low 4. Heat transfer surface covered with scale deposits. 5. Leaks.	1. Install more collector area. 2. Remove obstacle or install collectors in more appropriate location. 3. Rebalance flow. 4. Flush collector loop. 5. Repair.
	Piping	1. Insufficient insulation 2. Improper weather protection. 3. Insulation damaged. 4. Undersized piping between storage tank and collector. 5. Piping partially blocked. 6. Air lock.	1. Add additional insulation. 2. Provide proper weather protection. 3. Repair. 4. Install adequate piping 5. Flush piping runs. 6. Drain and refill system.
System drains continually	Overheat protection valve V-1	1. Valve leaks. 2. Valve sticks. 3. "O" ring cut.	1. Replace. 2. Cycle valve by jumping control system or replace actuator. 3. Replace.
	Overheat protection thermostat T-1	1. Defective. 2. Out of calibration. 3. Set point too low.	1. Replace. 2. Recalibrate. 3. Reset
	Control circuitry	Bad contacts.	Check and replace.

3.2 INDIRECT SYSTEMS

Indirect solar DHW systems have a heat exchanger between the collector loop and the DHW load. Depending on the collector coolant, the heat exchangers are either single- or double-walled, and local codes specify the types of heat exchanger required. Section 2.6 contains information on heat exchangers, and Ref. 46 contains sizing information.

There are three generic indirect systems.* One uses potable water in the collector loop. The water drains into a reservoir each time the collector-loop pump stops. A heat exchanger is required to isolate the collector loop from the rest of the system, because make-up-water pressure would prevent the system from draining.

Another liquid-cooled system uses a freeze-resistant heat-transfer fluid, such as 30% to 50% water-glycol mixture, hydrocarbon oils, silicone oil, or R12 or R114 refrigerants.* The heat exchanger is usually double-walled.

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*See Appendix F for details on refrigerant systems.

The third indirect system uses air to cool the collectors; the heat exchanger used is a single-walled tube-and-fin type.

3.2.1 Indirect Drain-Back Systems

The closed-loop drain-back systems in Figs. 3.14 and 3.15 have water in a closed collector loop. Freeze protection is achieved by completely draining the collector loop into a reservoir not exposed to freezing temperatures. A control-circuit schematic for these systems is shown in Fig. 3.16.

Another indirect drain-back system is shown in Fig. 3.17. This system drains back into the preheat tank each time the loop pump shuts off. Another difference between this system and the systems in Figs. 3.14 and 3.15 is in heat-exchanger connections. Reference 58 describes Fig. 3.17 in greater detail. Other drain-back systems are illustrated in Ref. 64, and in product literature provided by prepackaged-system manufacturers.

3.2.1.1 Operation of Indirect Drain-Back Systems

Solar-Energy Collection. Indirect systems begin to collect solar energy when the temperature difference between the absorber-plate sensor and sensor S_2 in the auxiliary-heater/storage tank, or preheat tank in two-tank systems, reaches the high-temperature differential set point, which is usually 20°F (11°C). When this set point is reached, the normally open contact in thermostat T-1 closes, energizing pump P-1.

As water is pumped from the reservoir, displaced air is purged from the collector loop to the reservoir. Initially the pump must lift the water to the top of the collector array. Once this occurs, a siphon return is established as the air is purged from the lines. From then on, the pump works only against friction. Energy collection continues as long as the low-temperature differential requirement is satisfied.

When the low-temperature differential requirement is no longer met, thermostat T-1 contact opens and pump P-1 is switched off. Air in the reservoir bubbles up to the collectors through the collector-loop return line, and the water in the collectors and piping drains back automatically into the reservoir. The piping to and from the reservoir is usually oversized to allow the collector loop to drain more rapidly.

Freeze Protection. Freeze protection is achieved automatically and passively in the indirect drain-back system by keeping the collectors and outdoor piping empty, except when solar energy is sufficient to run the system. Thermosiphoning cannot occur when the system is off, because the collector loop is filled with air. However, if the reservoir is overfilled and water closes off the down-comer, the collector will not drain.

Overheat Protection. When solar energy is available and hot-water demand is low, the water temperature in the collectors may approach or exceed

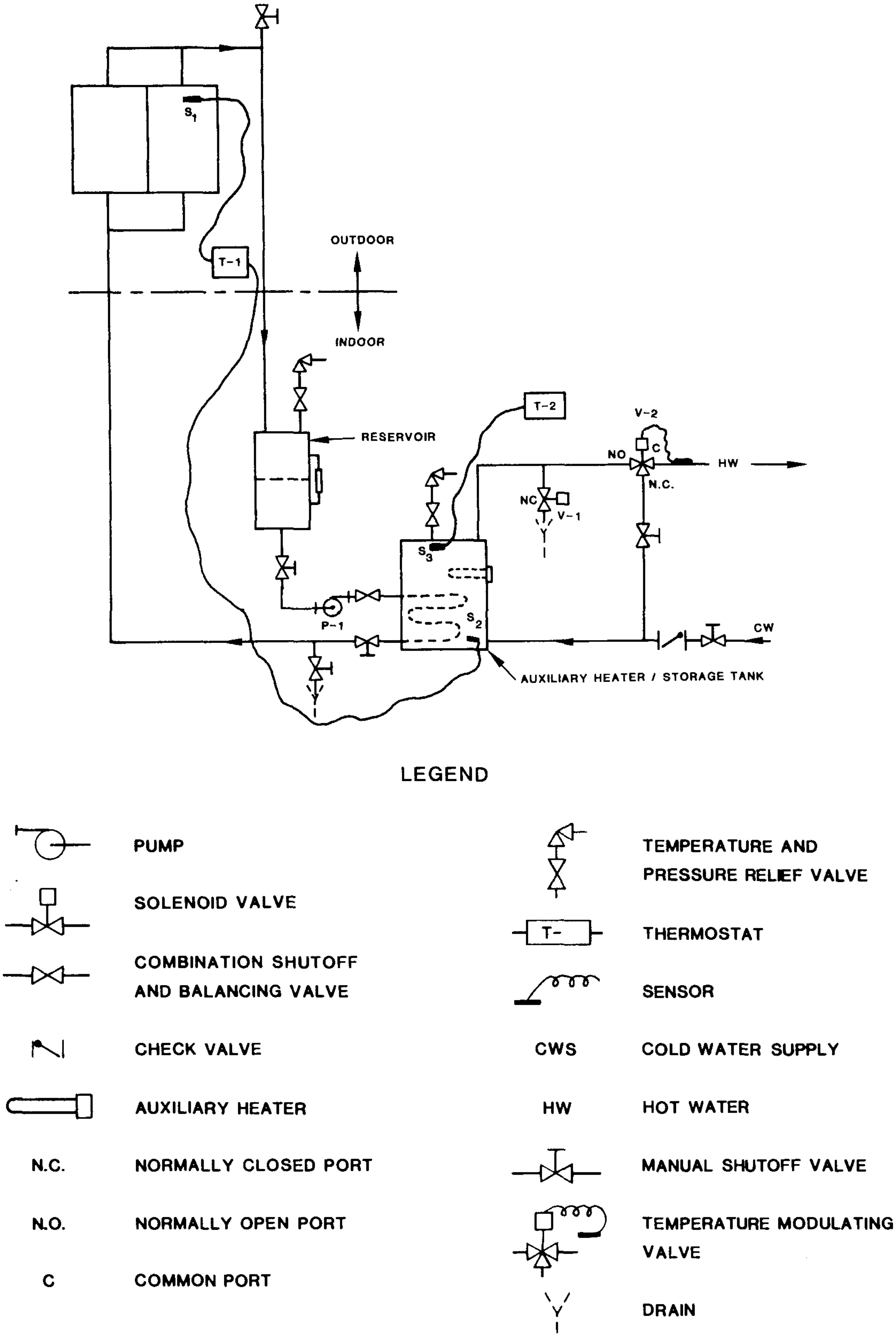

Fig. 3.14 Indirect Closed-Loop Drain-Back One-Tank System

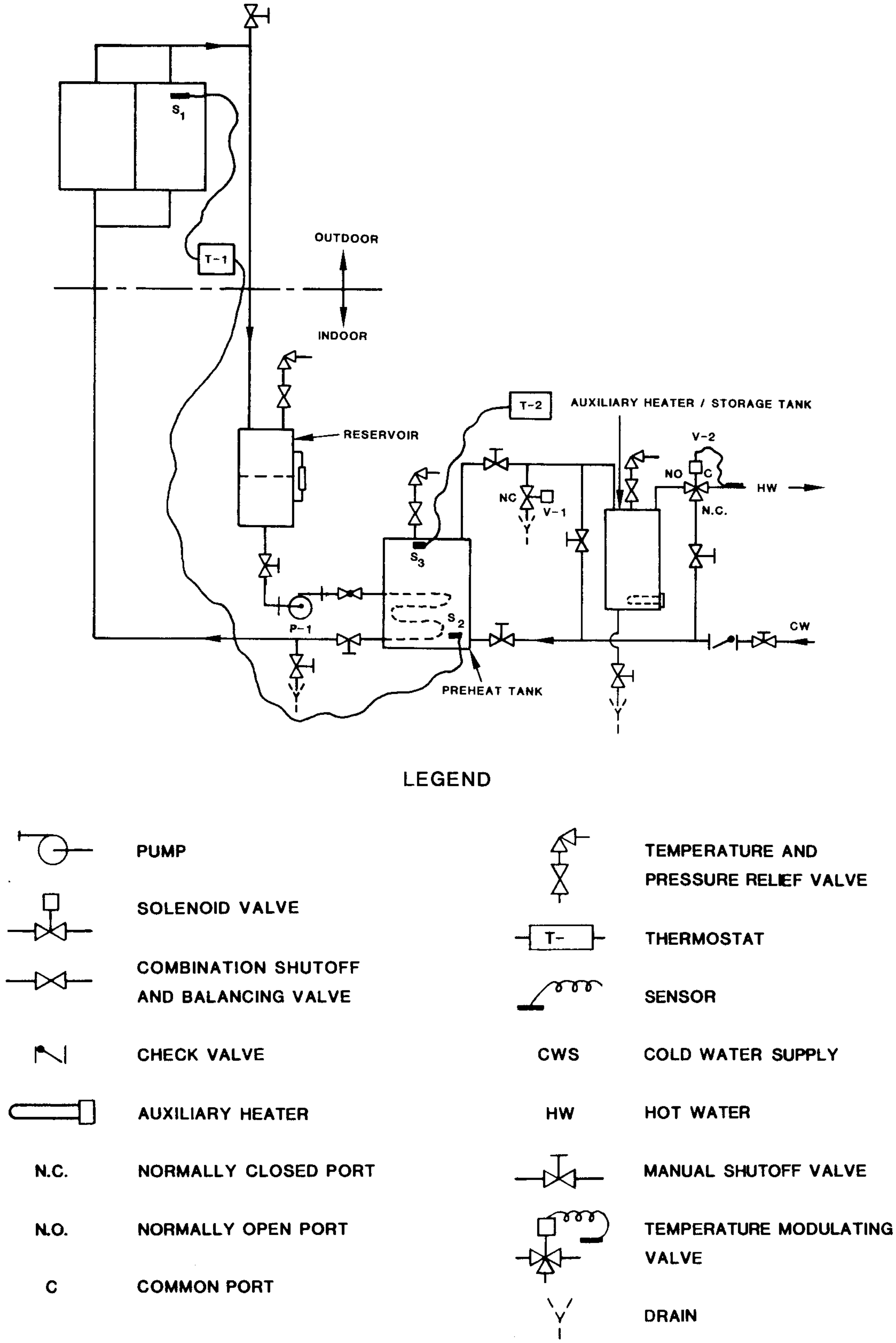

Fig. 3.15 Indirect Closed-Loop Drain-Back Two-Tank System

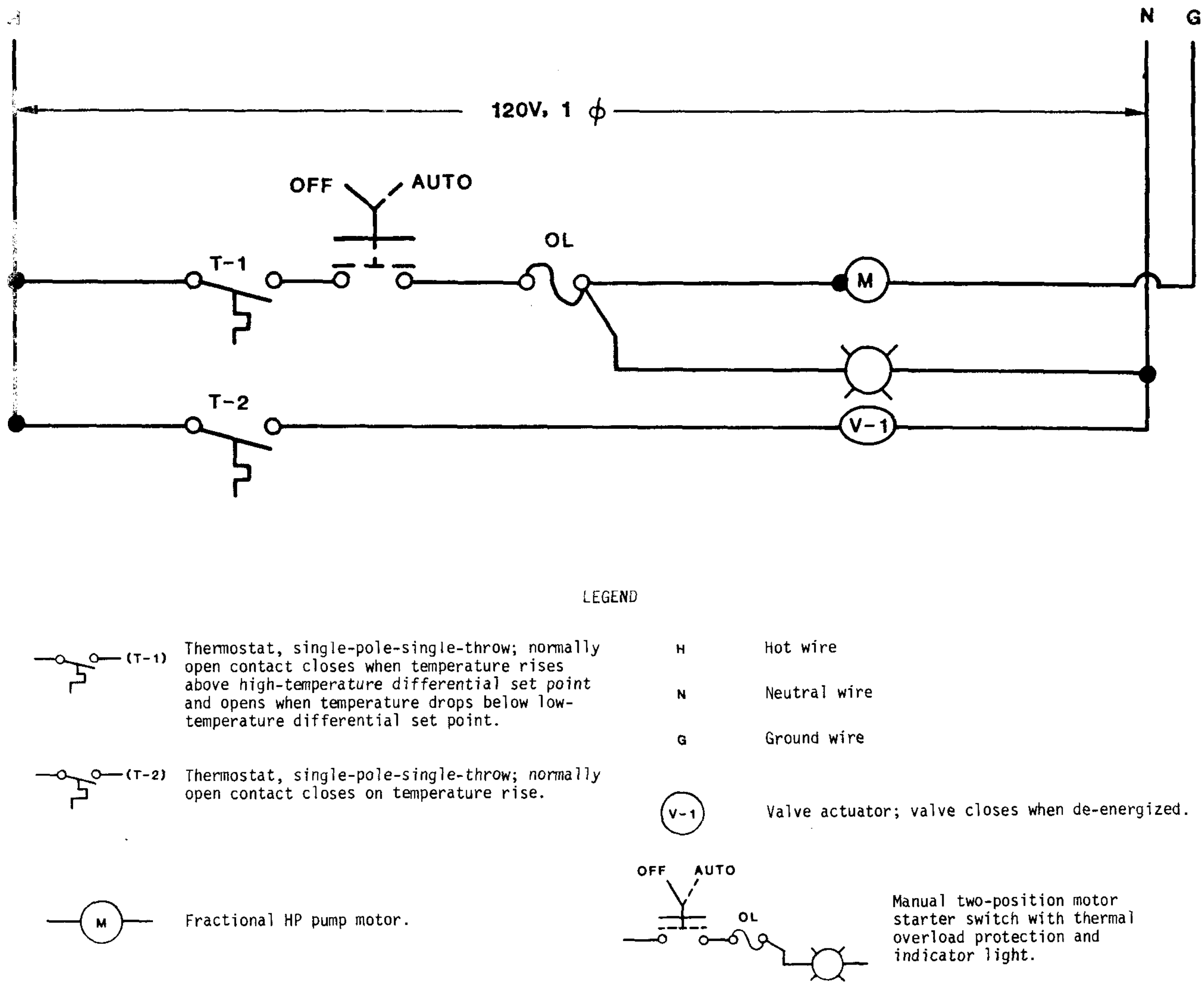

Fig. 3.16 Control Schematic for Indirect Closed-Loop Drain-Back System

the boiling point. To protect the user and the system, overheat protection may be incorporated into the control system. There are several ways to protect the system from overheating. One method, shown in the ladder diagram in Fig. 3.16, provides protection by discharging the hot water from the system.

Thermostat T-2, a single-pole-single-throw switch, provides the overheat protection by acting on signals from sensor S_3. When the temperature sensed by S_3 exceeds the high-temperature set point of approximately 180°F (82°C), the normally open T-2 contact closes, energizing valve V-1, which opens, draining the water from the auxiliary-heater/storage tank

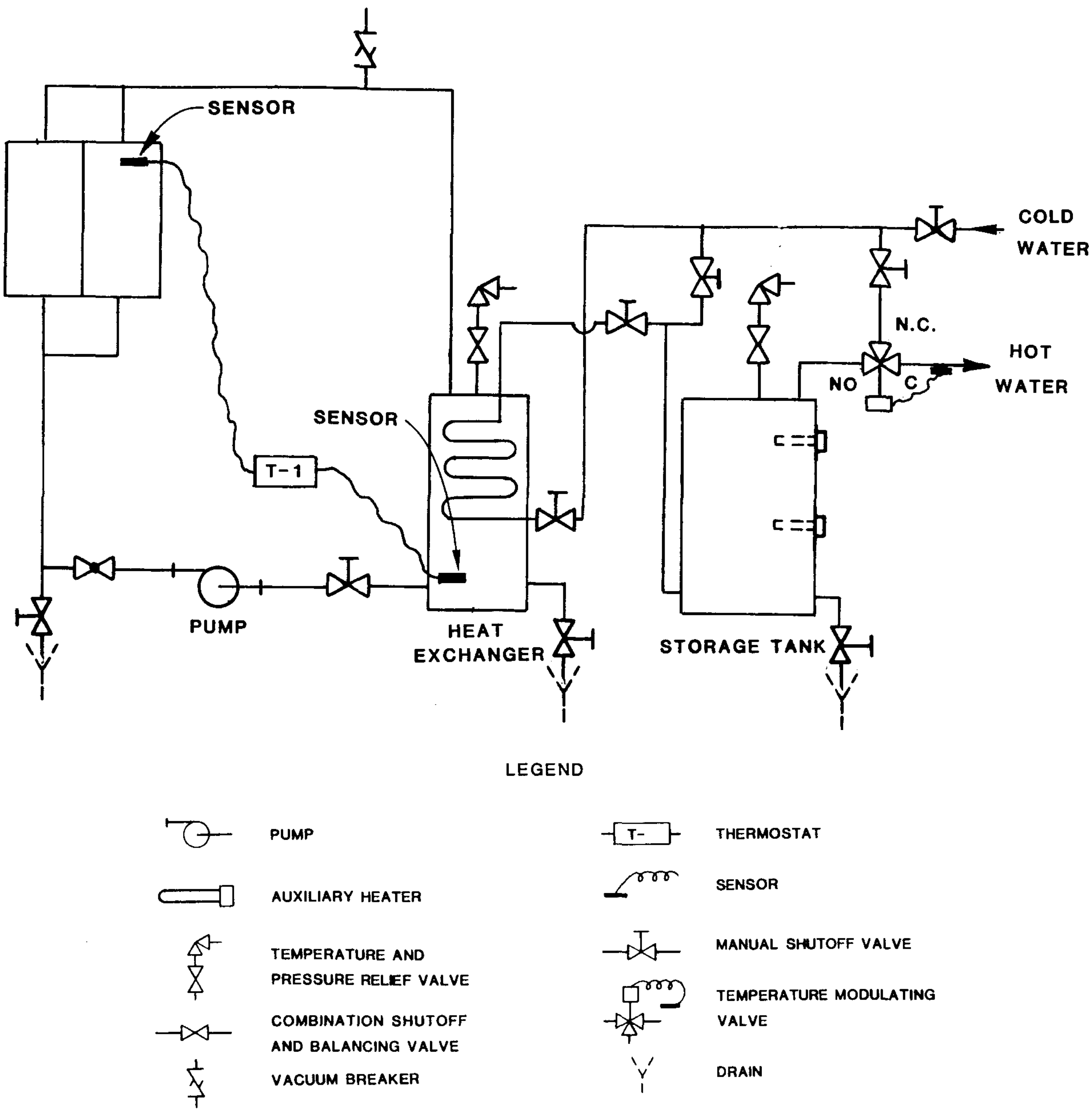

Fig. 3.17 Indirect Drain-Back System[58]

(preheat tank for two-tank system). Hot water discharged from the top of the tank is replaced by cold make-up water entering at the bottom, lowering the water temperature.

When the water temperature sensed by S_3 drops to the low-temperature differential set point of approximately 170°F (77°C), the T-2 contact opens, de-energizing valve V-1, which closes. The overheat-protection mode is reactivated any time the water temperature increases to the high-temperature differential set point of thermostat T-2.

The important features of overheat protection by discharging hot water from the system are:

- Both auxiliary-heater/storage tank (preheat tank for two-tank systems) and collectors are protected against high temperatures.
- Water is wasted, so this technique is not recommended for use in dry climates.

Another overheat-protection method, which does not discharge hot water from the system, employs overheat-protection thermostat T-2 to lock out pump P-1, allowing automatic drain-back, until the temperature in the auxiliary-heater/storage tank, or preheat tank for two-tank systems, decreases. The control schematic for this method is similar to the control schematic in Fig. 3.16, except that valve V-1 is not used and thermostat T-2 has normally closed contacts, which open with a rise in temperature. These contacts are in the circuit between T-1 and pump P-1.

The important features of this overheat protection method are:

- The auxiliary-heater/storage tank (preheat tank for two-tank systems) is protected against high temperatures, but the collectors are not protected and stagnation may occur.
- Hot water is not wasted.

A third overheat-protection method has a heat-rejection coil with two control valves. Features of this overheat-protection mode are:

- Water is not wasted.
- Initial costs, for the heat-rejection coil and control valves, are higher.
- The auxiliary-heater/storage tank (preheat tank for two-tank systems) and collectors are protected.
- A pump is required for overheat protection.

All of these overheat-protection methods protect the auxiliary-heater/storage tank, or preheat tank in two-tank systems, from water temperatures that can damage tank linings. Two of the systems also protect the collectors from dry stagnation.

The system designer must evaluate the cost of overheating protection with regard to the 1-to-10-yr range of collector warranties, collector degradation from occasional stagnation conditions, the installed cost of additional valves and necessary control modifications, and the cost of wasted water. In a conservative design, collectors capable of withstanding stagnation for 30 days without degradation, as verified by ASHRAE 93-77, would be selected.[63]

Auxiliary Heater Operation. For an indirect one-tank drain-back system, a factory-packaged electric heater maintains the desired water temperature. The package combines thermostat, temperature sensor, electric resistance-heating element, and emergency-cutout (ECO) switch in one unit.

A factory-installed and calibrated sensor senses the temperature of the tank surface. When the tank-surface temperature drops below the predetermined low-temperature set point, the thermostat energizes the heating element, turning it off when the tank surface reaches the high-temperature set point.

This heater operation is typical of conventional residential electric hot-water systems. An alternative system locks out the auxiliary heater whenever solar heating is on.

For a two-tank system, a gas heater usually is employed to maintain the desired water temperature in the auxiliary-heater tank. The controls are the same as for gas-fired domestic hot-water systems, combining the automatic pilot valve, manual gas valve, thermostatic valve, pilot gas filter, and the gas regulator in one unit.

In gas-heater designs, the tank-water temperature is sensed by the thermostatic-valve sensor. When the temperature falls below the low-temperature set point, the thermostatic valve opens and the pilot light ignites the gas burner. When the water temperature reaches the predetermined high-temperature set point, which is usually 10° to 20°F (5° to 11°C) above the low-temperature set point, the thermostatic valve shuts off the burner gas.

<u>Temperature-Modulating Valve</u>. When the temperature of hot water leaving the auxiliary-heater tank exceeds a predetermined value, temperature-modulating valve V-2 mixes cold make-up water with the hot water to maintain the preset tap-water temperature.

Temperature-modulating-valve operation is described in Sec. 2.8. These valves are required by local codes in some areas, because they serve as safety devices to protect the solar DHW user from dangerously hot water.

3.2.1.2 Estimated Mean Time between Failures (MTBF)

The drain-back system MTBF estimates in Table 3.7 were obtained from the reliability-block-diagram technique presented in Appendix A. Component failure-rate data are presented in Chapter 2 and summarized in Appendix A. In developing the data in Table 3.7, a 6-hr operating day was assumed.

These data indicate that the minimum estimated MTBF for the collector designs is not influenced especially by the interconnectors. The maximum estimated MTBF of the system, on the other hand, is reduced by approximately 45% if hoses are used instead of tubing with soldered or brazed connections. Two storage tanks reduce the estimated system MTBF by 16%, compared with a one-tank system.

A comparison of Tables 3.1 and 3.7 indicates the drain-back system has a maximum MTBF approximately 40% greater than the drain-down system. Drain-back systems also appear to be more reliable than water-glycol systems (see

Table 3.7 Estimated Mean Time between Failures (MTBF) of Indirect Drain-Back Solar DHW Systems

Number of Collectors in System	Approximate Solar Load (%)	One-Tank Systems Estimated MTBF (days)				Two-Tank Systems Estimated MTBF (days)			
		Without hose interconnections		With hose interconnections		Without hose interconnections		With hose interconnections	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
2	At least 50	227	1742	202	920	204	1325	174	768
2	100	140	1431	124	800	130	1135	116	698
4	At least 50	219	1749	186	895	198	1329	171	770
4	At least 75	167	1623	148	870	155	1265	138	753
4	100	95	1197	87	721	90	982	83	637

Table 3.9). The increased reliability of this drain-back design, compared with that of drain-down water-glycol systems, is attributed to the number of valves and their arrangement in the system.

3.2.1.3 Indirect-Drain-Back-System Start-Up and Testing

After the system has been installed, all the components cleaned, the system purged, and all sensors calibrated, but prior to installing the insulation, the system must be started and tested. Testing is necessary to reveal leaks, verify the control sequence, locate any defective pumps or valves, and identify and eliminate design or installation errors.

The recommended testing procedure for one- and two-tank systems follows:

Step 1. Place control system in "off" position.

Step 2. Set temperature-modulating valve V-2 to maintain temperature required by local codes.

Step 3. Fill hot-water loop.

Open make-up-water supply valve and hot-water faucets to purge air from faucets.

Step 4. Check hot-water loop for leaks.

Pressurize system to 20 psi (138 kPa) above expected make-up water pressure. Check for leaks. Pay special attention to valve V-1, because leaks from valve V-1 cause continuous hot-water loss. Drain hot-water loop and repair any leaks.

Step 5. Check collector loop for leaks.

Test the collector loop hydrostatically to the pressure specified by the system designer/manufacturer. Inspect the piping array for leaks. Relieve test pressure and repair any leaks. Do not check the collector array for leaks if ambient temperature is below freezing. When testing is completed, fill the system with potable water to the reservoir level specified by the designer/manufacturer.

Step 6. Switch control system to "auto" position while keeping auxiliary heater in "off" position.

If the temperature difference between sensors S_1 and S_2 is large enough, thermostat T-1 will activate, energizing the circuit to pump P-1. If the temperature difference between S_1 and S_2 is not great enough to activate thermostat T-1, insert a jumper wire across T-1 to start pump P-1 in order to balance the water flow through the collectors. Do not jump thermostat T-1 if the ambient temperature is below freezing.

Step 7. Balance collector flow.*

Water flow through the collectors must be balanced to avoid hot spots that result in inefficient operations. This requirement is especially important when there are more than six panels in the array. However, flow balancing also is important for the efficient operation of arrays of six or fewer panels, the usual range in residential systems.

Flow balancing reveals any lines that are blocked with solder, or an unusually high pressure drop in a collector. If the pressure drop across a collector exceeds the manufacturer's specification, some of the collector passages may be blocked, deformed, or leaking. Conversely, if coolant flow exceeds the design value, it must be reduced for efficient operation.

Balanced flow is achieved by measuring the flow rate through each collector panel or group of panels with anubars, flowmeters, orifices, or circuit setters. Circuit setters are commercially available. They combine orifice, pressure taps, and a globe valve into one unit.

Start flow balancing with throttling valve partially open, in order to avoid overloading pump motor if an oversize pump has been installed by mistake.

If the water flow is significantly below the design flow rate, the problem could be caused by: restricted or closed balancing valve; blocked or deformed water lines or collector passages; pump suction side connected to the collectors instead of storage; or an improperly wired or defective pump motor.

If the pump has an induction single-phase or a three-phase motor, the pump could be improperly wired and rotating in the reverse direction. For these two motor types, interchanging the motor leads will eliminate the problem. For other types of motors, the pump cannot rotate in the reverse direction. If all of the preceding possibilities have been eliminated and the pump does not deliver the specified flow rate, the pump is defective and must be replaced.

Step 8. Adjust pressure relief valve.

Pressurize the collector and hot-water loops to 12 psi (83 kPa) above highest pressure expected in the system. With the collector-loop pump running, adjust the pressure relief valve to the onset of bleeding. If the pressure relief valve is factory-set, check to confirm that it opens at the specified pressure.

Step 9. Insulate the system.

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*Flow balancing may not be required with prepackaged solar DHW systems; however, flow still should be verified to confirm that pump rotation is correct and that passageways are not blocked.

Step 10. Set the thermostats as specified by the designer/manufacturer.*

Step 11. Adjust low-temperature differential set point of thermostat T-1.*

If the system has been tested and insulated and sufficient solar insolation is available, turn the system on. If field testing is selected for determining the low-temperature differential set point, use a wattmeter to measure electric energy consumption (see Appendix B). Use Eqs. B.8 and B.10 to calculate the temperature differential and adjust the T-1 setting. If the set point is not determined in the field, set the thermostat T-1 to design specifications.

Verify the accuracy of the low-temperature differential set point with calibrated thermometers, measuring the temperature difference across the heat exchanger. By partially shading the collectors, insolation can be reduced until the T-1 low set point is reached and the pump P-1 shuts off.

If the measured difference does not fall within 0.5°F (0.3°C) of the low set point, adjust the T-1 setting, repeating this procedure until the pump shuts off.

Step 12. Test overheat protection.

On systems with adjustable T-2 setting, simulate overheat conditions by setting T-2 below the water temperature in the auxiliary-heater tank.* T-2 should activate and valve V-1 should open, discharging the overheated water. In systems where T-2 is not adjustable, jump thermostat T-2 to simulate overheating. Valve V-1 should open, discharging any overheated water. Remove jumper wire when test is complete.

Step 13. Test auxiliary-heater operation.

Adjust set point of auxiliary heater to design specifications. Turn heater on and check its operation. Verify the auxiliary-heater temperature setting by inserting a calibrated thermometer in the thermal well at the top of the auxiliary-heater tank. Auxiliary heater should activate when the temperature at the top of the tank drops to within ±2°F (±1°C) of the set point temperature. Adjust auxiliary-heater setting until this requirement is met.

*In a prepackaged system, thermostats may be factory-set, so that a field adjustment is not possible. It is assumed the manufacturer has sufficient testing data to set the thermostats properly.

Step 14. Test operation of temperature-modulating valve.

Adjust setting of temperature-modulating valve V-2 to maintain the local code value. Set auxiliary heater to heat the water to approximately 170°F (77°C). Verify the water temperature by inserting a calibrated thermometer in the thermal well at the top of the tank. When the measured temperature reaches 170° ±5°F (77° ±3°C), open hot-water faucets. Measure the water temperature leaving valve V-2. If the temperature is not within ±3°F (±2°C) of the local code value, adjust valve V-2 setting. Repeat this procedure until the water temperature is correct, then reset the auxiliary heater to maintain the desired tank-water temperature.

With completion of above steps, all system operations have been verified and the system tested for leaks. It should be ready to operate.

3.2.1.4 Indirect-Drain-Back-System Preventive Maintenance

To ensure that the drain-back system will perform reliably and meet the MTBF estimates in Table 3.7, basic preventive maintenance must be performed. Most of the suggested maintenance can be performed by the user, with the possible exceptions of washing roof-mounted collectors and verifying sensor calibration. If the system manufacturer has provided special test points and thermowells, as in Fig. 3.8, the user also can check sensor calibration and automatic-valve operation; otherwise, this work is better left to a service person.

The following preventive maintenance should be performed at least once per year:

- Wash the collector outer glazing with compounds approved by the manufacturer. (Do not remove dust or dirt from polymeric glazings with a dry cloth, because they will be scratched.) Inspect the absorber plates for degradation during washing.
- Inspect flashing and collector-mounting hardware. Tighten, replace, and recaulk as required.
- Inspect and tighten hose connections on collector array. Replace degraded hose.
- Verify that sensors are still in correct locations. Check sensor calibration.
- Inspect hand-operated valves for leaks. Adjust packing. Open and close valves to verify proper operation.
- Drain and flush all tanks. Clean strainers and valve filters.
- Inspect pressure relief valve on tank(s) and collector loop, verifying that valve(s) operate and that the exit port is not plugged.

The system also should be checked periodically for:

- Insulation deterioriation.
- Leaks.
- Correct thermostat setting, to make certain that setting has not shifted since start-up and testing.
- Correct operation:

  Verify that pump does not operate at night; use a flowmeter, sight glass, or pressure gauges (if installed).

  On a sunny day, verify pump operation by noting if the flowmeter or the sight glass indicates fluid motion. In addition, check the temperature difference between collectors and storage using thermometers and thermowells, as in Fig. 3.8. If the temperature difference is above the high differential set point of T-1 and the system has not started, call a service person. Also, check the temperature difference across the heat exchanger; if it is below the low differential set point of T-1, and the system is running, call a service person.
- Check pump lubrication to manufacturer's specifications.

3.2.1.5 Indirect-Drain-Back-System Troubleshooting

Although the design of a closed-loop drain-back one- or two-tank system depends on the individual manufacturer, the troubleshooting information in Table 3.8 should help find and correct the typical problems of this system. This information should assist the user or service person in troubleshooting a system that has been in the field for some time. In addition, this information may be useful to the system designer concerned with system analysis, equipment selection, and preparation of specifications.

Table 3.8 Troubleshooting Indirect Drain-Back Systems

Problem	Components	Possible Causes	Corrective Action
System does not start	Power supply	1. Tripped on overload.	1. Determine cause and replace fuse or breaker.
		2. Open circuit breaker.	2. Check and close.
		3. Defective transformer.	3. Replace.
		4. Line voltage fluctuating.	4. Inform power company.
		5. Brownout.	5. Provide brownout protective device and inform power company.
		6. Control switch on "off" position.	6. Turn to "auto" position.
	Thermostat T-1	1. High and low temperature differential set points too high.	1. Reset according to specifications and/or results obtained during system start-up and testing.
		2. Defective component.	2. Replace thermostat.
		3. Loose contacts.	3. Tighten wires.
		4. Thermostat is out of calibration.	4. Recalibrate.
	Sensor	1. Defective.	1. Replace.
		2. Improper installation.	2. Reinstall.
		3. Defective control cable.	3. Replace.
		4. Sensor out of calibration	4. Recalibrate.
	Pump	1. Motor failure.	1. Check brush holders, throwout mechanisms, centrifugal switches, or other mechanical components that may be loose, worn, dirty, or gummy. Replace worn components and reassemble.
		2. Overload protection switch shuts down pump motor.	2. Determine cause of over-loading; check if balanc-ing valve is in proper position.
		3. Defective shaft; impeller or coupling.	3. Replace.
		4. Defective bearings.	4. Replace.
	Control circuitry	1. Circuit continuity lost.	1. Check and repair.
		2. Bad contacts.	2. Check and correct.
System starts but cycles	Thermostat	High and low temperature differential set points are too close together.	Reset according to specification and/or results obtained during system start-up and testing.
	Control circuitry	1. Circuit continuity lost.	1. Check and repair.
		2. Bad contacts.	2. Check and correct.
		3. Pump cycles on internal overload.	3a. Check voltage. b. Check pump flow. c. On shaded pole motor, check if shading pole ring is open and replace.
Pump runs but water does not flow to collectors	Isolation pump valve(s)	Valve(s) closed.	Open valve(s)
	Pump impeller	Impeller broken or separated from shaft	Replace impeller and/or shaft assembly.
	Blocked liquid flow passage	Pipe damaged.	Replace damaged section.

Table 3.8 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
System runs continuously	Thermostat T-1	1. Low temperature differential set point set too low.	1. Reset according to specifications or settings determined during start-up.
		2. Defective component.	2. Replace thermostat.
		3. Thermostat is out of calibration.	3. Recalibrate.
	Sensor(s)	1. Defective sensor(s).	1. Replace.
		2. Sensor(s) is out of calibration.	2. Recalibrate.
		3. Incorrect sensor in circuit.	3. Replace.
	Control circuitry	Bad contacts.	Check and correct.
System leaks	Pipe joints	1. Thermal expansion and contraction.	1. Provide flexibility and reassemble.
		2. Joint improperly made.	2. Reassemble leaky joint.
	Hose connection	Clamp does not hold tightly.	Tighten up the hose clamp, replacing clamp or hose if necessary.
	Relief valve	1. Improper pressure setting.	1. Check pressure setting and correct.
		2. Defective component.	2. Replace.
Poor solar energy collection	Collector array	1. Undersized collector area.	1. Install more collector area.
		2. Collectors shaded.	2. Remove obstacle or install collectors in sunlit location.
		3. Flow rate too high or too low.	3. Rebalance flow.
		4. Heat transfer surface covered with scale deposits.	4. Flush collector loop.
		5. Leaks.	5. Repair.
	Piping	1. Insufficient insulation.	1. Add additional insulation.
		2. Improper weather protection.	2. Provide proper weather protection.
		3. Insulation damaged.	3. Repair.
	Heat exchanger	1. Undersized.	1. Install proper size unit.
		2. Clogged.	2. Clean heat exchanger.
System noisy when operating	Pump cavitation	1. Restricted pump suction line.	1. Remove restrictions.
		2. Air in the system.	2. Check pipe installation at pump inlet.
		3. Low fluid level in reservoir.	3. Refill to proper level.
	Pump bearings	1. Bearing worn.	1. Replace bearing.
		2. Bearing damaged owing to misalignment.	2. Align pump and motor shaft.
	Piping	1. Air locked in the piping.	1. Check pipe installation.
		2. Piping vibrates.	2. Provide adequate pipe support.
No hot water	Make-up water shut-off valve	Valve closed.	Open valve.
	Heater failed to actuate	1. Electric heater, single-tank systems. No power to electric heater (single-tank system only).	Check overload protection and correct.
		2. Gas heater, two-tank systems only.	
		a. Failure to ignite (gas off).	a. Open manual valve.
		b. Safety switch malfunctioning.	b. Check and replace.
		c. Defective thermocouple and/or automatic pilot valve.	c. Check and replace.
		d. Pilot won't stay lit.	
		(1) Too much primary air.	(1) Adjust pilot shutter.
		(2) Dirt in pilot orifice.	(2) Open orifice.
		(3) Pilot valve defective.	(3) Replace.

Table 3.8 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
No hot water (cont'd)		(4) Loose thermocouple connection.	(4) Tighten.
		(5) Defective thermocouple.	(5) Replace.
		(6) Improper pilot gas adjustment.	(6) Adjust.
		3. Both systems.	
		a. Thermostat defective.	a. Replace.
		b. Bad contacts.	b. Correct.
	Temperature modulating valve	1. Valve defective.	1. Replace.
		2. Sensor defective.	2. Replace.
Hot water temperature not high enough	Hot water thermostat	1. Thermostat setting too low.	1. Set thermostat higher.
		2. Thermostat out of calibration.	2. Recalibrate or replace thermostat.
	Auxiliary heater	Heater undersized for hot water demand.	Replace when heater fails.
	Safety switch	Set too low.	Check and reset.
	Burner, two-tank system only	1. Burner clogged.	1. Clean.
		2. Undersized burner orifice.	2. Provide correct size orifice.
	Temperature modulating valve	1. Sensor out of calibration.	1. Recalibrate.
		2. Temperature set too low.	2. Reset.
		3. Valve spring too weak.	3. Replace.
Water temperature too high	Hot water temperature thermostat	1. Thermostat setting too high.	1. Reset.
		2. Thermostat out of calibration.	2. Recalibrate.
		3. Bad contacts.	3. Correct.
	Sensor	Out of calibration.	Recalibrate or replace.
	Temperature modulating valve	1. Sensor out of calibration.	1. Recalibrate.
		2. Temperature set too high.	2. Reset.
System overheats	Overheat protection valve V-1	1. Valve sticks.	1. Cycle valve by jumping control system or replace actuator.
		2. Return spring failed.	2. Replace.
	Make-up water supply valve	Valve closed.	Open the valve.
	Overheat protection thermostat	1. Thermostat setting too high.	1. Reset in accordance with specifications.
		2. Defective component.	2. Replace thermostat.
		3. Thermostat is out of calibration.	3. Recalibrate.
		4. Loose contacts.	4. Tighten wire.
	Control circuitry	1. Circuit continuity lost.	1. Check and repair.
		2. Loose contacts.	2. Tighten contacts.
		3. Coil contacts burned out.	3. Replace.
	Sensor(s)	Out of calibration.	Recalibrate.
System discharges continually	Overheat protection valve V-1	1. Valve leaks.	1. Replace.
		2. Valve sticks.	2. Cycle valve by jumping control system or replace actuator.
	Overheat protection thermostat T-1	1. Defective.	1. Replace.
		2. Out of calibration.	2. Recalibrate.
		3. Set point too low.	3. Reset
	Control circuitry	Bad contacts.	Check and replace.

3.2.2 Indirect Liquid (Antifreeze) Systems

The indirect systems in Figs. 3.18 and 3.19 have an ethylene-glycol/ water solution, or some other antifreeze solution, in the collector loop to protect the loop from freezing. A control-circuit schematic for this system is shown in Fig. 3.20.

3.2.2.1 Operation

Solar-Energy Collection. The indirect liquid systems shown have multiple sensors and control circuitry, with two differential thermostats for optimum operating efficiency. Differential thermostat T-1, which receives signals from sensors S_1 and S_2, initiates the energy-collection cycle. Sensor S_1 is attached to the absorber plate and sensor S_2 is in the auxiliary-heater/storage tank, or preheat tank in two-tank systems. The cycle begins when the high-temperature differential set point for thermostat T-1 is reached and the normally open contacts in T-1 close, which starts pump P-1 and opens valve V-1.

The function of solenoid valve V-1 is to prevent thermosiphoning. It can be replaced with a check valve. A check valve simplifies the control circuit and may reduce the system's cost. However, the check valve must be spring- or weight-loaded and carefully selected and installed. The designer must verify that the check valve is capable of resisting the fluid pressures produced when the collector loop tries to thermosiphon.

When the T-1 circuit for pump P-1 and valve V-1 is closed, an adjustable time-delay relay also is energized. When the time-delay relay has "timed out," its contacts open, transferring system control to differential thermostat T-2. This thermostat, which also has normally open contacts, receives signals from temperature sensors S_3 and S_4 on the piping going to and from the heat exchanger. When the temperature difference between sensors S_3 and S_4 exceeds the high-temperature differential set point of thermostat T-2, its contacts close, the pump P-1 and valve V-1 power circuit is again energized, and the collection of solar energy resumes.

The two thermostats, T-1 and T-2, are needed to protect the system from inefficient operation caused by the poor heat-transfer capability of the wraparound heat exchanger.* For instance, while the temperature difference

*Present industry practice is not to use thermostat T-2 and the time-delay relay. These components could be eliminated by raising the low differential set point of T-1, provided the efficiency of the heat exchanger is known or is determined by testing. However, if only thermostat T-1 is used, the temperature difference across the heat exchanger cannot be measured accurately for the following reasons: Sensor S_1 senses temperature in the collector loop and S_2 senses temperature in the potable-water loop, which is the auxiliary-heater/storage tank in a one-tank system or the preheat tank in a two-tank system. The signals from S_2 are affected by hot water usage, the thermal inertia of the tank, and water mixing in the tank. For these reasons, the measured temperature difference between S_1 and S_2 does not represent the actual temperature difference across the heat exchanger.

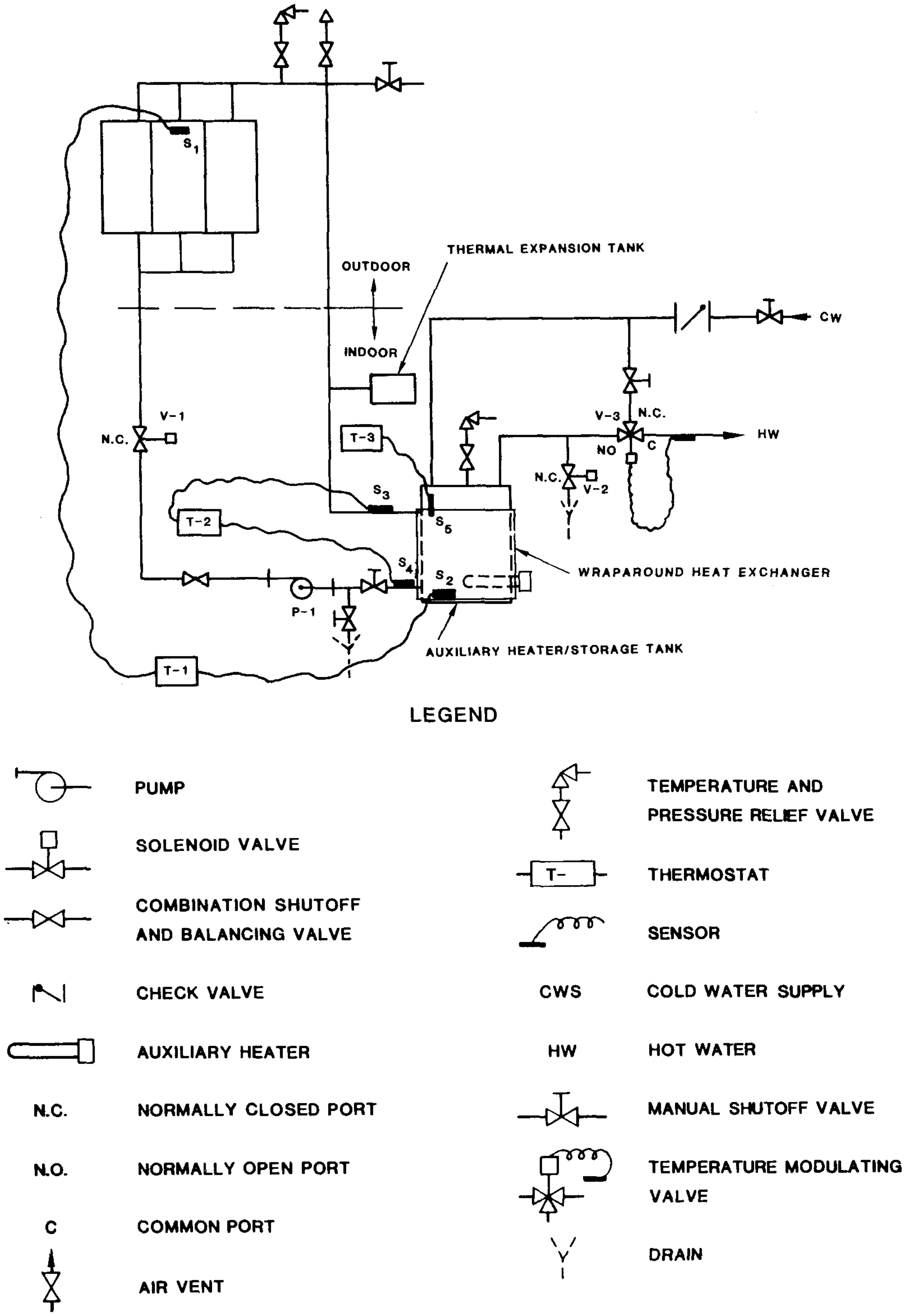


Fig. 3.18 Indirect Liquid (Antifreeze) One-Tank System

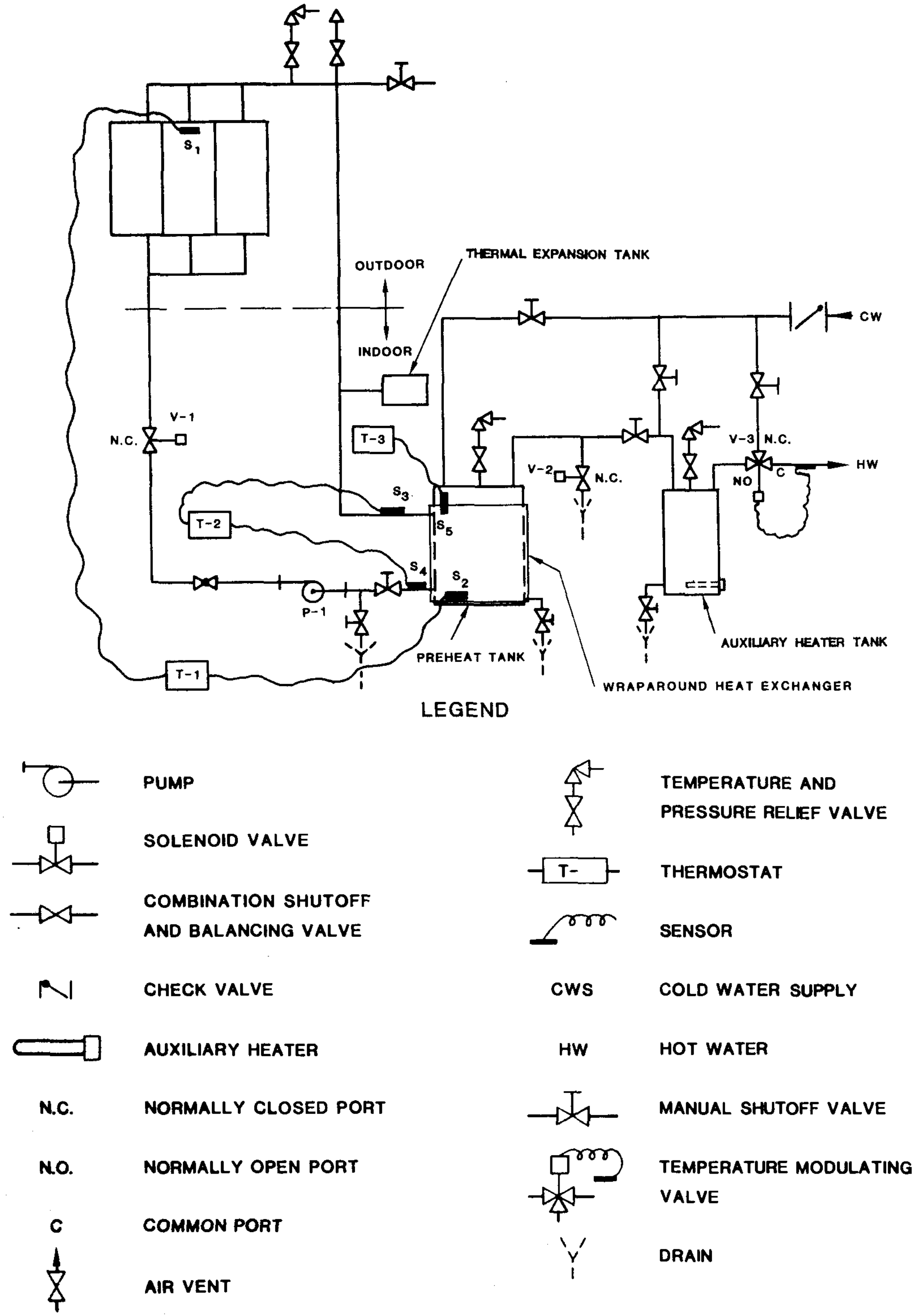
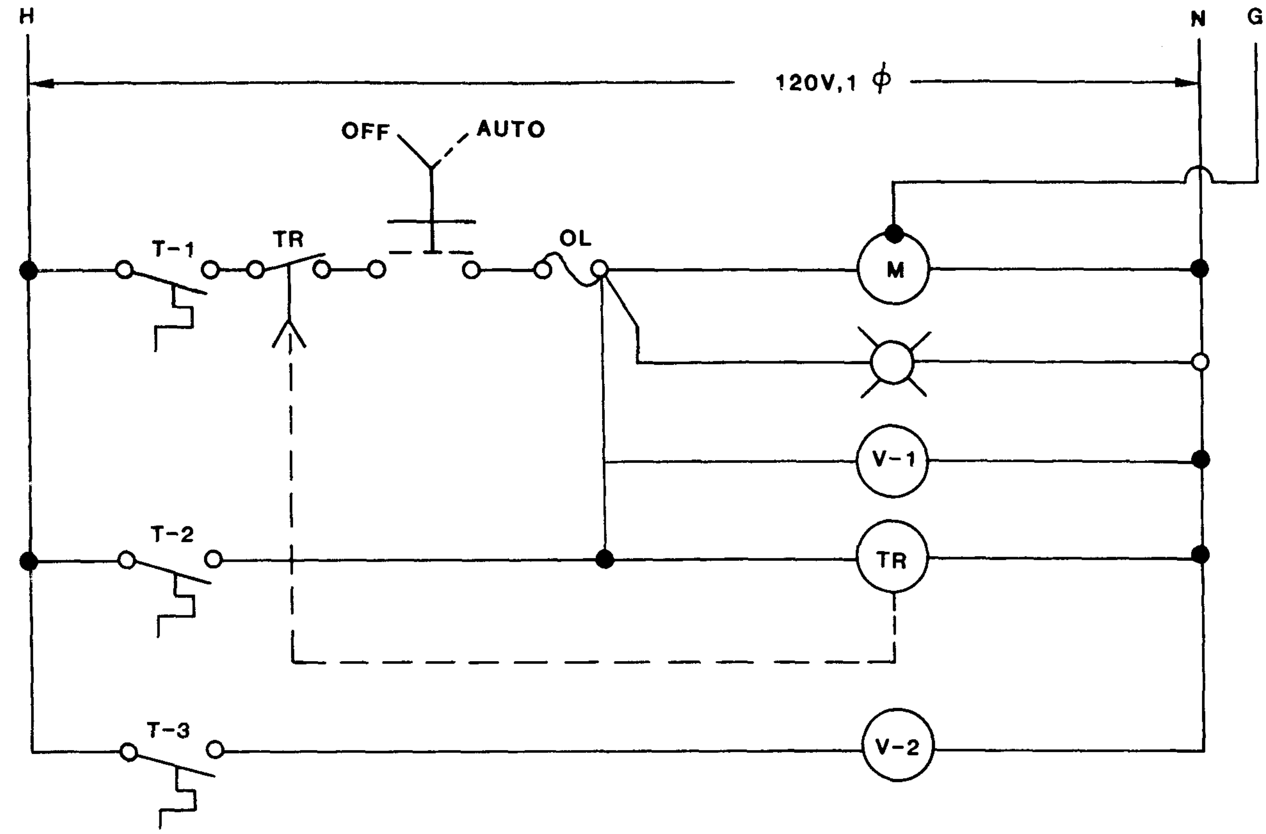


Fig. 3.19 Indirect Liquid (Antifreeze) Two-Tank System



LEGEND

(T-1), (T-2) — Thermostat; single-pole-single-throw; normally open contact closes when temperature rises above high temperature differential set point and opens when temperature drops below low temperature differential set point.

(T-3) — Thermostat, single-pole-single-throw; normally open contact closes on temperature rise.

(TR) — On-delay time delay relay; adjustable from 0-5 min. Normally closed contact opens on time delay after relay coil is energized.

M — Fractional HP pump motor

V-1, V-2 — Valve actuator; valve open when de-energized.

OFF / AUTO — Manual two-position motor starter switch with thermal overload protection and indicator light.

H — Hot wire

N — Neutral wire

G — Ground wire

Fig. 3.20 Control Schematic for Indirect Liquid (Antifreeze) Two-Tank System between the collectors and the tank may be sufficient to justify operation of pump P-1, the amount of heat actually transferred to the water in the tank as measured by sensors S_3 and S_4 may not justify the energy cost of pump P-1. So, thermostat T-2 is used to terminate solar collection. When the temperature difference between sensors S_3 and S_4 decreases below the low-temperature differential set point of thermostat T-2, its contacts open, de-energizing pump P-1 and valve V-1.

The time-delay relay provides the time needed for the hot heat-transfer liquid from the collectors to reach the heat exchanger and to activate thermostat T-2. It also eliminates thermostat T-1 from the control circuit once control has been transferred to thermostat T-2.

If solar collection has been terminated by thermostat T-2, the system will not restart until the temperature differential between the collectors and the storage or preheat tank reaches the high-temperature differential set point of thermostat T-1. To prevent cycling of the system, the low-temperature differential set points of thermostats T-1 and T-2 must be carefully selected. Section 3.2.2.3 describes the procedure for selecting thermostat set points.

Freeze Protection. An ethylene-glycol/water solution protects the system from freezing. However, because of the temperature and elevation difference between the collectors and the auxiliary-heater/storage tank, thermal siphoning will occur, resulting in thermal energy losses and increased operating costs. To prevent energy losses, a normally closed valve V-1 is installed in the collector loop. It is open only when pump P-1 is operating.

It is important to maintain the proper amount of ethylene glycol in the solution. In one instance a glycol system froze when a leak developed at a collector joint and make-up water was added, instead of the proper glycol/water solution. For proper freeze protection, the necessary amounts of make-up glycol should be added manually. Automatic-refill systems should not be used.

Overheat Protection. When solar energy is available and hot-water demand is low, the water temperature in the system can approach or exceed the boiling point. To protect the user and the system, overheat protection can be incorporated into the control system.

There are several ways to protect the system from overheating. One, shown in Figs. 3.18 and 3.19, provides protection by discharging hot water from the system, operating as follows.

Thermostat T-3, a single-pole-single-throw switch, provides the overheat protection, using signals from sensor S_5. When the temperature sensed by sensor S_5 exceeds the high-temperature set point of approximately 180°F (82°C), the normally open contact of T-3 closes, energizing valve V-2. Valve V-2 opens, draining hot water from the auxiliary-heater/storage tank, or preheat tank in two-tank systems. Hot water discharged from the top of the tank is replaced by cold make-up water entering at the bottom of the tank, lowering the tank-water temperature.

When the tank-water temperature, as sensed by sensor S_5, drops to the low-temperature differential set point of approximately 170°F (77°C), the T-3 contact opens, de-energizing valve V-2, which closes. Overheat protection is reactivated if the water temperature again increases to the T-3 high-temperature differential set point.

The important features of overheat protection by discharging hot water from the system are:

- Both auxiliary-heater/storage tank, or preheat tank in two-tank systems, and collectors are protected against high temperatures.
- Water is wasted, so this technique is not recommended for use in dry climates.

Another overheat-protection method, one that does not discharge hot water from the system, employs an overheat-protection thermostat T-3 to lock out pump P-1 and close valve V-1 until the temperature in the auxiliary-heater/storage tank, or preheat tank in two-tank systems, decreases. The control schematic for this method is similar to the control schematic in Fig. 3.20, except that V-2 is eliminated and T-3 is incorporated into the electric circuit in series with T-1 and T-2.

The important features of this overheat-protection method are:

- The auxiliary-heater/storage tank, or preheat tank in two-tank systems, is protected against high temperatures, but the collectors are not protected and stagnation may occur. A thermal-expansion tank protects the collector loop against excessive pressures.
- Hot water is not wasted.

A third overheat-protection method has a heat-rejection coil with two control valves. Features of this overheat-protection mode are:

- Water is not wasted.
- Initial costs, for the heat-rejection coil and control valves, are higher.
- The auxiliary-heater/storage tank, or preheat tank in two-tank systems, and collectors are protected.
- A pump is required for overheat protection.

All of these overheat-protection methods protect the auxiliary-heater/storage tank, or preheat tank in two-tank systems, from water temperatures that can damage tank linings. Two of the systems also protect the collectors from wet stagnation.

The system designer must evaluate the cost of overheat protection with regard to the 1-to-10-yr range of collector warranties, collector degradation from occasional stagnation conditions, the installed cost of additional valves and necessary control modifications, and the cost of wasted water. In a conservative design, collectors capable of withstanding stagnation for 30 days without degradation, as verified by ASHRAE 93-77, should be specified.[63]

Auxiliary-Heater Operation. For an antifreeze one-tank system, a factory-packaged electric heater maintains the desired water temperature. The package combines thermostat, temperature sensor, electric resistance-heating element, and emergency-cutout (ECO) switch in one unit.

A factory-installed and calibrated sensor senses the temperature of the tank surface. When the tank-surface temperature drops below the predetermined low-temperature set point, the thermostat energizes the heating element, turning it off when the tank surface reaches the high-temperature set point.

This heater operation is typical of conventional residential electric hot-water systems. An alternative for solar DHW systems is to lock out the auxiliary heater whenever solar heating is on.

For a two-tank system, a gas heater usually is employed to maintain the desired auxiliary-heater-tank water temperature. Controls in gas-fired domestic hot-water systems combine the automatic pilot valve, manual gas valve, thermostatic valve, pilot gas filter, and gas regulators in one unit.

In gas-heater designs, the tank-water temperature is sensed by the thermostatic-valve sensor. When the temperature falls below the low-temperature set point, the thermostatic valve opens and the pilot light ignites the gas burner. When the water temperature reaches the high-temperature set point, which is usually 10° to 20°F (5° to 11°C) above the low-temperature set point, the thermostatic valve shuts off the burner gas.

Temperature-Modulating Valve. When the temperature of hot water leaving the auxiliary-heater tank exceeds a predetermined value, temperature-modulating valve V-3 mixes cold make-up water with the hot water to maintain the preset tap-water temperature.

Temperature-modulating-valve operation is described in Sec. 2.8. These valves are required by local codes in some areas, because they serve as safety devices to protect the solar DHW user from dangerously hot water.

3.2.2.2 Estimated Mean Time between Failures (MTBF)

The antifreeze-system MTBF estimates in Table 3.9 were obtained using the reliability-block-diagram technique presented in Appendix A. Component failure-rate data are presented in Chapter 2 and summarized in Appendix A. In developing the data in Table 3.9, a 6-hr operating day was assumed.

The data indicate the minimum estimated MTBF for collectors is not influenced especially by the interconnectors. However, the maximum estimated MTBF of the system is reduced by approximately 30% if hoses are used instead of metal tubing with soldered or brazed connections. Two storage tanks reduce the estimated system MTBF by 18%, compared with a one-tank system.

Table 3.9 Estimated Mean Time between Failures (MTBF) of Indirect Liquid (Antifreeze) Solar DHW Systems

Number of Collectors in System	Approximate Solar Load (%)	One-Tank Systems Estimated MTBF (days): Without hose interconnections		One-Tank Systems Estimated MTBF (days): With hose interconnections		Two-Tank Systems Estimated MTBF (days): Without hose interconnections		Two-Tank Systems Estimated MTBF (days): With hose interconnections	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
2	At least 50	334	1383	263	747	287	1107	232	689
2	100	178	1177	153	681	162	970	141	632
4	At least 50	309	1389	250	749	270	1111	223	690
4	At least 75	214	1316	184	733	203	1069	170	677
4	100	111	1014	101	620	104	856	96	582

Comparison of data in Tables 3.1, 3.3, and 3.9 indicates that the MTBF of generic antifreeze systems is approximately 30% greater than that for drain-down systems and approximately 20% greater than that for circulating-water systems.

3.2.2.3 Indirect Liquid (Antifreeze) System Start-Up and Testing

After the system has been installed, all components cleaned, the system purged, and all sensors calibrated, but prior to installing the insulation, the system must be started and tested. Testing is necessary to reveal leaks, verify the control sequence, locate any defective pumps or valves, and identify and eliminate design or installation errors.

The following testing procedure is recommended:

Step 1. Place the control system in the "off" position.

Step 2. Test the collector loop hydrostatically for leaks.

Using potable water,* pressurize the system slowly up to the test pressure specified by the system designer. Inspect for leaks, paying special attention to piping, connections, and collectors. Drain the collector loop and repair any leaks. Do not test the collector loop for leaks if the ambient temperature is below freezing.

Step 3. Adjust pressure relief valve in collector loop.

Pressurize collector loop to 12 psi (83 kPa) above highest pressure expected in the system. With collector-loop pump running, adjust the pressure relief valve to the onset of bleeding. If the pressure relief valve is factory set, check to verify it opens at the specified pressure.

After the pressure relief valve is adjusted, reduce system pressure to the design level. Recheck for leaks, paying special attention to piping, connections, and collectors. If leaks are discovered, shut down and drain the system to repair any leaks.

Step 4. Check valve V-1 for leakage and proper operation.

Disconnect wires to valve V-1 and install a jumper to bypass thermostat T-1 and start the pump. Valve V-1 should be closed. There should be no flow through the collector loop, even though pump P-1 is running. If flow through the collectors is detected, shut down the system and repair or replace valve V-1. Remove jumper wire when testing is complete.

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*If hydrocarbon or silicone oil is used, test the system for leaks with pressurized air.

Step 5. Fill collector loop with heat-transfer fluid, in this case an ethylene- or propylene-glycol/water solution, or hydrocarbon or silicone oil.

Follow the designer/manufacturer's instructions for filling system. Check to ensure heat-transfer-fluid level in the expansion tank does not exceed specifications.

Step 6. Switch control system to "auto" position, keeping auxiliary heater in "off" position.

If the temperature difference between sensors S_1 and S_2 is large enough, thermostat T-1 will energize the power circuits to pump P-1 and valve V-1. This starts pump P-1 and opens the normally closed valve V-1. If the temperature difference between S_1 and S_2 is not sufficient, insert a jumper wire across thermostat T-1 to start pump P-1 and to open valve V-1. Remove jumper when this test is complete.

Step 7. Balance the collector-loop flow.

Liquid flow through the collectors must be balanced to avoid hot spots that cause inefficient operation. This requirement is especially important when the array has more than six panels. However, flow balancing also is important for the efficient operation of arrays of six or fewer panels, the usual range in residential applications.

Flow balancing reveals lines that are blocked with solder, or an unusually high pressure drop in a collector. If the pressure drop across a collector exceeds the manufacturer's specification, some of the collector passages may be blocked, deformed, or leaking. Conversely, if coolant flow exceeds the design value, it must be reduced for efficient operations.

Balanced flow is achieved by measuring the flow rate through each collector panel or group of panels with anubars, flowmeters, orifices, and circuit setters. Circuit setters, which combine an orifice, pressure taps, and a globe valve into one unit, are commercially available.

Regardless how flow is measured, the measuring device should be installed as far as possible from flow deviators, such as elbows, valves, or tees. The minimum distance is specified in the manufacturer's literature. This distance must be maintained to obtain accurate readings.

A circuit setter or a manual throttling valve should be located on the discharge side of the pump for flow balancing. If the throttling valve is on the suction side of the pump, the pump may cavitate and destroy itself.

Flow balancing should be started with the throttling valve only partially open to avoid overloading the pump motor, on the chance an oversize pump has been installed by mistake.

If the water flow is significantly below the design flow rate, the problem could be caused by: restricted or closed balancing valve; blocked or deformed water lines or collector passages; pump suction side connected to the collectors instead of storage; or an improperly wired or defective pump motor.

If the pump has an induction single-phase or a three-phase motor, the pump could be improperly wired and rotating in the reverse direction. For these two motor types, interchanging the motor leads will eliminate the problem. For other types of motors, the pump cannot rotate in the reverse direction. If all of the preceding possibilities have been eliminated and the pump does not deliver the specified flow rate, the pump is defective and must be replaced.

After Step 7 is completed successfully, switch the control system to the "off" position and insulate the collector-loop piping. Remove jumper from T-1 if one was used during Step 7. While system is shut down, cover the collectors to prevent system from overheating.

Step 8. Fill hot-water loop.

If collector loop is insulated, open make-up-water supply valve and hot-water faucets to purge air from system. After tank(s) and piping have filled with water, close hot-water faucets.

Step 9. Check hot-water loop for leaks.

Pressurize system to 20 psi (138 kPa) above expected make-up-water pressure and check for leaks, paying special attention to valve V-2. Valve V-2 leaks cause continuous hot-water loss. Drain hot-water loop and repair any leaks.

Step 10. Insulate hot-water loop.

Step 11. Switch control to "auto" position.

When sufficient solar energy is available to operate the system, switch control to "on" and uncover collector panels.

Step 12. Set thermostats according to system designer/manufacturer's recommendation.*

High-temperature differential set point of thermostat T-2 should be at least 3°F (2°C) above the low-temperature differential set point of thermostat T-1.

Step 13. Adjust low-temperature differential set point of thermostat T-2.*

Since thermostat T-2 is used to terminate solar collection, the low-temperature differential set point has to be carefully adjusted to achieve optimum efficiency. If the low differential set point is determined by field testing, use a wattmeter to measure electric-energy consumption. Use Eqs. B.8 and B.10 in Appendix B to calculate the temperature differential and adjust thermostat T-2 setting. If the set point is not determined in the field, set thermostat T-2 according to design specifications.

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*Prepackaged system thermostats may be factory-set, and field adjustment may not be possible. It may be assumed the manufacturer of a prepackaged system has sufficient testing data to set the thermostats properly.

Verify the accuracy of the low-temperature differential set point with calibrated thermometers, measuring temperatures in the vicinity of sensors S_3 and S_4. By partially shading the collectors, insolation can be reduced until the low-temperature differential set point of thermostat T-2 is reached, and the collector-loop pump shuts off. If the measured temperature difference does not fall within 0.5°F (0.3°C) of the low set point, adjust the T-2 setting. Repeat this procedure until the pump shuts off.

Step 14. Adjust setting of time-delay relay.*

After a cold night, the temperature of the ethylene-glycol/water solution in the collector loop approaches ambient temperature. Solar energy warms the solution in the collectors in the morning; however, the solution in the collector-loop piping is slow to warm up. Thus, the collector-loop fluid may be hot enough to activate thermostat T-1 and start solar collection, while the fluid in the remaining piping is cold. When the cold fluid is sensed by sensor S_3 and thermostat T-2, pump P-1 shuts down and valve V-1 closes, stopping solar collection.

To solve this problem, a time-delay relay is added to the control circuit. It overrides thermostat T-2 for the duration of its setting, allowing the solar-collection cycle to operate until hot fluid comes down the piping from the collectors to warm up sensors S_3 and S_4. The time-delay setting depends on pump flow rate, piping sizes, and length of piping between the solar collectors and the storage-tank heat exchanger. If the setting of the time-delay relay is not specified by the system designer, adjust the relay in the field as follows:

- Cover solar collectors overnight.
- Set relay to delay action of thermostat T-2 for five minutes.
- Uncover solar collectors, allowing fluid in collectors to heat up.
- Using a thermometer, continuously keep track of temperature of collector-loop fluid in vicinity of sensors S_3 and S_4.
- After fluid temperature in collectors has increased sufficiently to initiate start-up of system, start a stopwatch.
- Read fluid temperature at S_3 and S_4. When warmer fluid from collectors flows down and warms up thermometers, stop the stopwatch.
- Add a safety factor of 15 to 20 s to the stopwatch time, and set time-delay relay accordingly.

*Prepackaged-system time-delay relays may be factory-set, so that field adjustment is not possible. It may be assumed the manufacturer of a prepackaged system has sufficient testing data to set the relays properly.

Step 15. Test overheat protection.

Insert a jumper wire across overheat-protection thermostat T-3 to simulate overheating of storage tank. Valve V-2 should open, and system should drain. After overheat protection is verified, remove jumper.

Step 16. Test operation of auxiliary heater.

Adjust set point of auxiliary heater according to design specifications. Turn heater on and check its operation. To verify the temperature setting, insert a calibrated thermometer into thermal well at top of auxiliary-heater tank to measure the water temperature. Auxiliary heater should activate when water temperature at top of tank drops to within ±2°F (±1°C) of desired temperature. Readjust setting if this requirement is not met.

Step 17. Test operation of temperature-modulating valve.

Adjust setting of temperature-modulating valve V-3 to maintain the value specified by the local codes. Set auxiliary heater to heat the water to 170°F (77°C). Verify the water temperature by inserting a calibrated thermometer in the thermal well at the top of the tank. When the measured temperature reaches 170° ± 5°F (77° ± 3°C), open hot-water faucets. Measure temperature of water leaving valve V-3. If the modulating-valve temperature is not within ±3°F (±2°C) of the local code value, readjust valve V-3, repeating this procedure until water temperature is correct. Then reset auxiliary heater to maintain desired tank-water temperature.

With completion of above steps, all system operations have been verified, and system has been tested for leaks. It should be ready to operate.

3.2.2.4 Indirect Liquid (Antifreeze) System Preventive Maintenance

To ensure that the indirect liquid (antifreeze) system will perform reliably and meet the MTBF estimates in Table 3.9, basic preventive maintenance must be performed. Most of the suggested preventive maintenance can be performed by the user, with the possible exceptions of washing roof-mounted collectors and verifying sensor calibration. If the system manufacturer has provided special test points and thermowells, as in Fig. 3.8, the user also can check sensor calibration and automatic-valve operation; otherwise, this work is better left to a service person.

The following preventive maintenance should be performed at least once a year:

- Wash collector outer glazing with compounds approved by the manufacturer. (Do not remove dirt or dust from polymeric glazings with a dry cloth, because the glazings will be scratched.) Inspect absorber plates for degradation during washing.
- Inspect flashing and collector-mounting hardware. Tighten, replace, and recaulk as required.

- Inspect and tighten hose connections around collector array. Replace any degraded hoses.
- Verify that sensors are still in correct locations. Check sensor calibration.
- Inspect hand-operated valves for leaks. Adjust packing. Open and close valves to verify proper operation.
- Drain and flush all tanks. Clean strainers and valve filters.
- Inspect pressure relief valve on tank(s) and collector loop, verifying that valve(s) operates and that exit port is not plugged.
- Check level of heat-transfer fluid in expansion tank. Add fluid if needed.
- Check the glycol concentration.
- Verify pH of glycol/water solution. Replace or buffer, according to manufacturer's specifications.

System should be checked periodically for:

- Insulation deterioriation.
- Leaks.
- Correct thermostat setting, to ensure that setting has not drifted since start-up and testing.
- Correct operation:

  Verify that pump does not operate at night; use a flowmeter, sight glass, or pressure gauges (if installed).

  On a sunny day, verify pump operation by noting if flowmeter or sight glass indicates fluid motion. In addition, check temperature difference between collectors and storage using thermometers and thermowells, as in Fig. 3.8. If temperature difference is above high differential set point of T-1 and system has not started, call a service person. Also, if temperature difference across heat exchanger is below the low differential set point of T-2, and system is running, call a service person.
- Check pump lubrication to manufacturer's specifications.

3.2.2.5 Indirect Liquid (Antifreeze) System Troubleshooting

Although the exact design of an indirect liquid one- or two-tank system depends on the individual manufacturer, the troubleshooting information in Table 3.10 should help find and correct the problems typical of this system. This information should help the user or service person to troubleshoot a system that has been in the field for some time. In addition, this information may be useful to the system designer concerned with system analysis, equipment selection, and specification preparation.

Table 3.10 Troubleshooting Glycol or Oil Systems

Problem	Components	Possible Causes	Corrective Action
System does not start	Power supply	1. Tripped on overload.	1. Determine cause and replace fuse or breaker.
		2. Open circuit breaker.	2. Check and close.
		3. Defective transformer.	3. Replace.
		4. Line voltage fluctuating.	4. Inform power company.
		5. Brownout.	5. Provide brownout protective device and inform power company.
		6. Control switch on "off" position.	6. Turn to "auto" position.
	Thermostat T-1 and T-2	1. High and low temperature differential set points too high.	1. Reset according to specifications and/or results obtained during system start-up and testing.
		2. Defective component.	2. Replace thermostat.
		3. Loose contacts.	3. Tighten wires.
		4. Thermostat is out of calibration.	4. Recalibrate.
	Sensor	1. Defective.	1. Replace.
		2. Improper installation.	2. Reinstall.
		3. Defective control cable.	3. Replace.
		4. Sensor out of calibration	4. Recalibrate.
	Pump	1. Motor failure.	1. Check brush holders, throw-out mechanisms, centrifugal switches, or other mechanical components that may be loose, worn, dirty, or gummy. Replace worn components and reassemble.
		2. Overload protection switch shuts down pump motor.	2. Determine cause of overloading; check if balancing valve is in proper position.
		3. Defective shaft; impeller or coupling.	3. Replace.
		4. Defective bearings.	4. Replace.
	Control circuitry	1. Circuit continuity lost.	1. Check and repair.
		2. Bad contacts.	2. Check and correct.
System starts but cycles	Thermostat	High and low temperature differential set points are too close together, or insufficient overlapping of thermostat T-1 low and thermostat T-2 high set points.	Reset according to specification and/or results obtained during system start-up and testing.
	Time delay relay	Time delay "times out" too soon (freeze protection sensor does not heat up in time).	Increase time-delay relay setting.
	Control circuitry	1. Circuit continuity lost.	1. Check and repair.
		2. Bad contacts.	2. Check and correct.
		3. Pump cycles on internal overload.	3a. Check voltage; b. Check pump flow; c. On shaded-pole motor, verify that shading-pole ring is open and replace.
Pump runs but coolant does not flow to collectors.	Valve V-1 closed	1. Actuator defective.	1. Replace actuator.
		2. No power to actuator.	2. Check wiring.
		3. Valve sticks.	3. Cycle valve by jumping control system or replace actuator.
	System air locked	Air vent(s) jammed closed.	Replace vent(s).
	Pump impeller	Impeller broken or separated from shaft.	Replace impeller and/or shaft assembly.
	Blocked liquid flow passage	Pipe damaged.	Replace damaged section.

Table 3.10 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
System runs continuously	Thermostat T-2	1. Low temperature differential set point set too low. 2. Defective component. 3. Thermostat is out of calibration.	1. Reset according to specifications or results obtained during start-up. 2. Replace thermostat. 3. Recalibrate.
	Sensor(s)	1. Defective sensor(s). 2. Sensor(s) is out of calibration. 3. Incorrect sensor in circuit.	1. Replace. 2. Recalibrate. 3. Replace.
	Control circuitry	Bad contacts.	Check and correct.
System leaks	Pipe joints	1. Thermal expansion and contraction. 2. Joint improperly made.	1. Provide flexibility and reassemble. 2. Reassemble leaking joint.
	Hose connection	Clamp does not hold tight.	Tighten up the hose clamp. Replace clamp or hose.
	Relief valve	1. Improper pressure setting. 2. Defective component.	1. Check pressure setting and correct. 2. Replace.
Poor solar energy collection	Collector array	1. Undersized collector area. 2. Collectors shaded. 3. Flow rate too high or too low. 4. Heat transfer surface covered with scale deposits. 5. Leaks.	1. Install more collector area. 2. Remove obstacle or install collectors in sunlit location. 3. Rebalance flow. 4. Flush collector loop. 5. Repair.
	Piping	1. Insufficient insulation. 2. Improper weather protection. 3. Insulation damaged.	1. Add insulation. 2. Provide proper weather protection. 3. Repair.
	Collector fluid	1. Antifreeze/water concentration in collector loop fluid is improper. 2. Collector loop degraded.	1. Provide proper concentration. 2. Follow procedure outlined in Sec. 2.3 or manufacturer's recommendations.
System noisy when operating	Pump cavitation	1. Restricted pump suction line. 2. Air in the system.	1. Remove restrictions. 2. Manually vent the system if automatic air vents are not adequate.
	Pump bearings	1. Bearing worn. 2. Bearing damaged due to improper alignment.	1. Replace. 2. Properly align pump and motor shaft.
	Piping	1. Air locked in the piping. 2. Piping vibrates.	1. Air vent the system. 2. Provide adequate pipe support.
	Air vents	1. Improperly sized. 2. Plugged.	1. Install proper air vents. 2. Clean and/or replace.
No hot water	Make-up water shut-off valve	Valve closed.	Open valve.
	Heater failed to actuate	1. Electric heater, single-tank systems. No power to electric heater (single-tank system only). 2. Gas heater, two-tank systems only. a. Failure to ignite (gas off). b. Safety switch malfunctioning. c. Defective thermocouple and/or automatic pilot valve.	Check overload protection and correct. a. Open manual valve. b. Check and replace. c. Check and replace.

Table 3.10 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
No hot water (cont'd)		d. Pilot won't stay lit. (1) Too much primary air. (2) Dirt in pilot orifice. (3) Pilot valve defective. (4) Loose thermocouple connection. (5) Defective thermocouple. (6) Improper pilot gas adjustment.	 (1) Adjust pilot shutter. (2) Open orifice. (3) Replace. (4) Tighten. (5) Replace. (6) Adjust.
		3. Both systems. a. Thermostat defective. b. Bad contacts.	 a. Replace. b. Correct.
	Temperature modulating valve	1. Valve defective. 2. Sensor defective.	1. Replace. 2. Replace
Hot water temperature not high enough	Hot water thermostat	1. Thermostat setting too low. 2. Thermostat out of calibration.	1. Set thermostat higher. 2. Recalibrate or replace thermostat.
	Auxiliary heater	Heater undersized for hot water demand.	Replace when heater fails.
	Safety switch	Set too low.	Check and reset.
	Burner, two-tank system only	1. Burner clogged. 2. Undersized burner orifice.	1. Clean. 2. Provide correctly sized orifice.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too low. 3. Valve spring too weak.	1. Recalibrate. 2. Reset. 3. Replace.
Water temperature too high	Hot water thermostat	1. Thermostat setting too high. 2. Thermostat out of calibration. 3. Bad contacts.	1. Reset. 2. Recalibrate. 3. Correct.
	Sensor	Out of calibration.	Recalibrate or replace.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too high.	1. Recalibrate. 2. Reset.
Overheating of the system	Overheat protection valve V-2	1. Valve sticks. 2. Return spring failed.	1. Cycle valve by jumping control system or replace actuator. 2. Replace.
	Make-up water supply valve	Valve closed.	Open the valve.
	Collector loop valve V-1 closed	1. Actuator defective. 2. No power to actuator. 3. Valve sticks.	1. Replace actuator. 2. Check wiring. 3. Cycle valve by jumping control system or replace actuator.
	Overheat protection thermostat	1. Thermostat setting too high. 2. Defective component. 3. Thermostat is out of calibration. 4. Loose contacts.	1. Reset in accordance with specifications. 2. Replace thermostat. 3. Recalibrate. 4. Tighten wire.
	Control circuitry	1. Circuit continuity lost. 2. Loose contacts. 3. Coil of the contacts burned out.	1. Check and repair. 2. Tighten contacts. 3. Replace.
	Sensor(s)	Out of calibration.	Recalibrate.

Table 3.10 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
System drains continually	Overheat protection valve V-2	1. Valve leaks. 2. Valve sticks.	1. Replace. 2. Cycle valve by jumping control system or replace actuator.
	Overheat protection thermostat T-3	1. Defective. 2. Out of calibration. 3. Set point too low.	1. Replace. 2. Recalibrate. 3. Reset.
	Control circuitry	Bad contacts.	Check and replace.

3.2.3 Indirect Air Two-Tank System

Air is the heat-transfer fluid in the indirect two-tank solar DHW system in Fig. 3.21. A centrifugal fan circulates the air through the collectors to an air-to-water heat exchanger. The solar heat in the air is transferred to potable water, which circulates between the heat exchanger and a preheat tank. A control circuit for this system is shown in Fig. 3.22.

3.2.3.1 Operation

Solar-Energy Collection. This system has multiple sensors and two differential thermostats for optimum operating efficiency. Differential thermostat T-1, which initiates solar collection, receives temperature signals from sensor S_1 on a collector absorber plate and sensor S_2 in the preheat tank. When the T-1 high-temperature differential set point is exceeded, the normally open T-1 contacts close, energizing pump P-1 and valve V-1 in the water loop, fan F-1 and motorized dampers D-1 and D-2 in the collector loop, and a time-delay relay.* These actions signal the start of solar-energy collection.

After the adjustable time-delay relay has "timed out," the relay contacts open, transferring system control to the differential thermostat T-2. This thermostat, which also has normally open contacts, receives signals from sensors S_3 and S_4, located in the inlet and outlet piping, respectively, of the heat exchanger. When the temperature difference between sensors S_3 and S_4 exceeds the T-2 high-temperature differential set point, T-2 energizes the pump, fan, valve V-1, and dampers D-1 and D-2, continuing the solar-energy-collection process.

*Solenoid valve V-1 is used only to prevent thermosiphoning. It can be replaced with a check valve. A check valve simplifies the control circuit and reduces the cost of the system. However, the check valve must be spring- or weight-loaded, carefully selected, and carefully installed. The designer must confirm that the check valve is capable of holding the fluid pressures of thermosiphoning in each system.

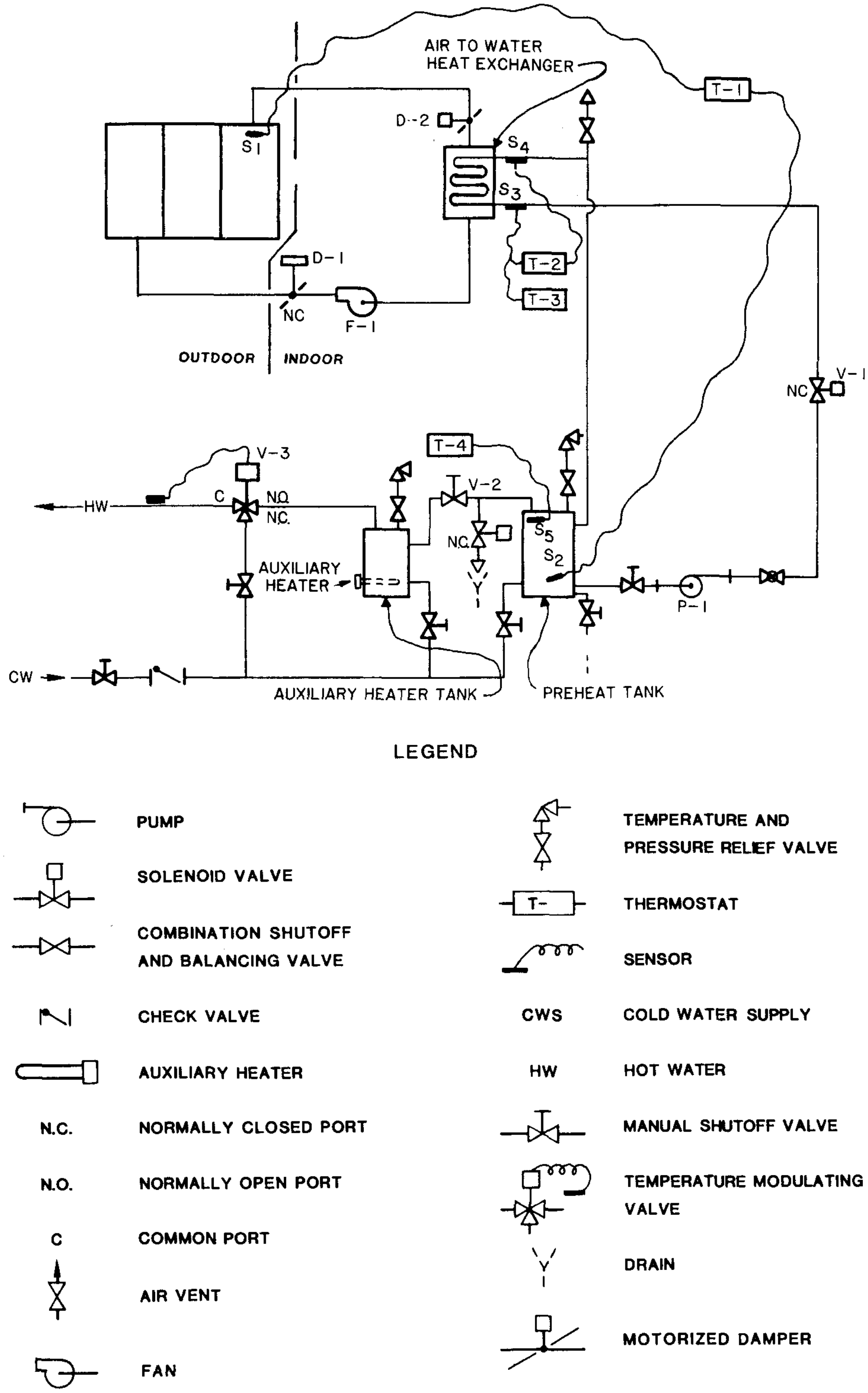
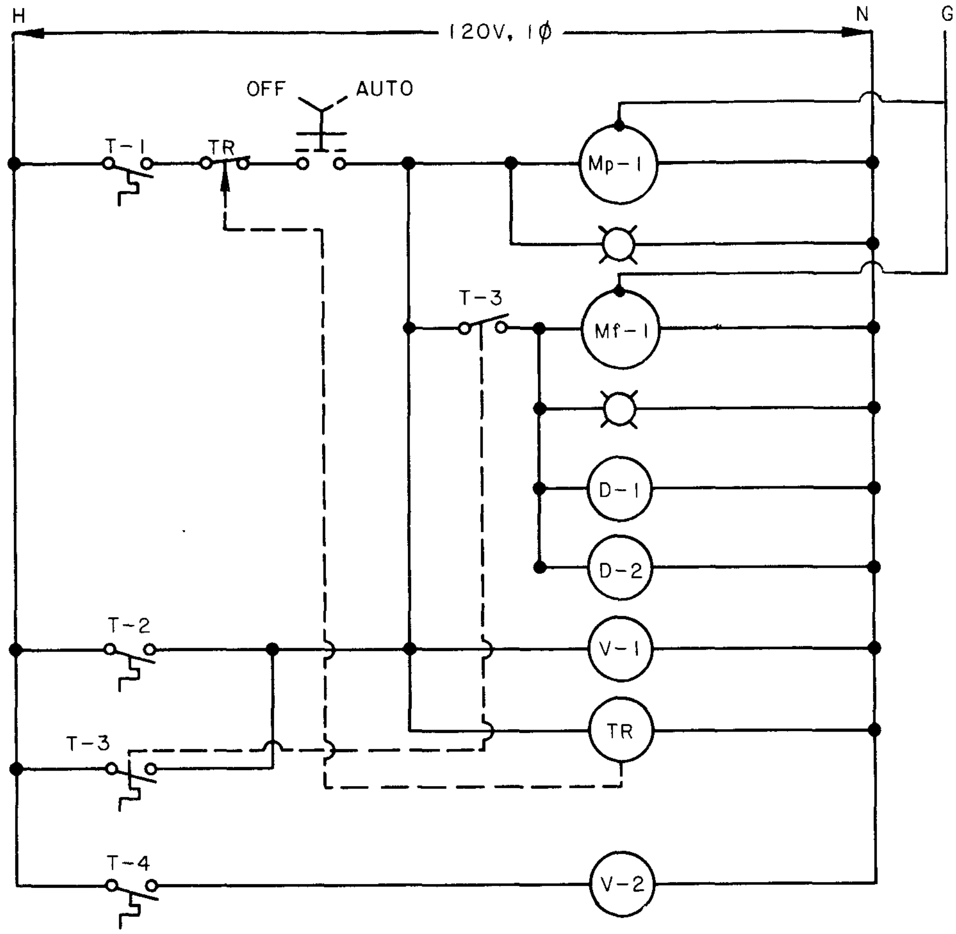


Fig. 3.21 Indirect Air Two-Tank System



LEGEND

T-1 T-2	Thermostat, single-pole-single-throw; normally open contact closes when temperature rises above high-temperature differential set point and opens when temperature drops below low-temperature differential set point.
T-3	Thermostat, double-pole-single-throw; normally open and normally closed contacts. Normally open contact closes and normally closed contact opens on temperature drop.
T-4	Thermostat, single-pole-single-throw; normally open contact closes on temperature rise.
H	Hot wire
N	Neutral wire
G	Ground wire
TR / TR	On-delay time-delay relay; adjustable from 0 -- 15 min. Normally closed contact opens on time delay after relay coil is energized.
Mp-1 Mf-1	Fractional HP pump and fan motors with built-in thermal-overload protection.
V-1 V-2	Valve actuators; valve opens when energized.
D- D-2	Damper actuators; damper opens when energized.
(indicator light symbol)	Indicator light.
OFF AUTO	Manual two-position switch.

Fig. 3.22 Control-System Ladder Diagram for Indirect Air Two-Tank System

Two thermostats are required to protect the air system from inefficiencies that may result from temperature-differential requirements between the water and air in the heat exchanger. For example, although the temperature difference between the collectors and the preheat tank may be sufficient to justify operation of pump P-1, the amount of heat actually transferred to the water in the heat exchanger, as measured by sensors S_3 and S_4, may not justify the energy cost to run pump P-1 and fan F-1.

Therefore, thermostat T-2 terminates solar collection when the temperature difference between sensors S_3 and S_4 is below the T-2 low-temperature differential set point. When this happens, the contacts in thermostat T-2 open, de-energizing valve V-1, pump P-1, fan F-1, and dampers D-1 and D-2. The time-delay relay provides the time needed for hot air from the collectors to reach the heat exchanger, thereby activating thermostat T-2.*

If solar collection is terminated by thermostat T-2, the system will not restart until the temperature difference between the collectors and the tank reaches the high-temperature differential set point of thermostat T-1. The low-temperature differential set points of thermostats T-1 and T-2 must be carefully selected to prevent on-off cycling of the system.

Freeze Protection. Using air as the heat-transfer fluid in the collector loop eliminates freezing as a problem in the collection function. However, at low ambient temperatures, natural convection or thermosiphoning can occur between cold air in the collectors and warm air in the heat exchanger. The higher-density cold air flows down the ductwork towards the heat exchanger, pushing the lower-density warm air toward the collectors. This cycle continues until the air temperatures in the collectors and the heat exchanger are equal. In addition to heat losses, some air-to-water heat exchangers have frozen when ambient temperatures were sufficiently low.[62]

To counter thermosiphoning, two tight-fitting dampers, D-1 and D-2, are installed in the ductwork across the heat exchanger. Disc type, no-leakage dampers, such as those described in Sec. 2.9, are recommended. Dampers D-1 and D-2, which are normally closed, are open only during active solar collection when the water temperature at the heat exchanger, as sensed by sensor S_3, is above the set point of freeze-protection-thermostat T-3.

Owing to a failure of the damper(s) or to the inadvertent installation of the heat exchanger in an unheated area, water temperature in the heat-exchanger piping may decrease. When the water temperature, as sensed by

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*Thermostat T-2 and the time-delay relay could be eliminated by raising the low differential set point of T-1, provided the efficiency of the heat exchanger is known or is determined by testing. However, if only thermostat T-1 is used, the temperature difference across the heat exchanger cannot be measured accurately for the following reasons: Sensor S_1 senses temperature in the collector loop, and S_2 senses temperature in the hot-water loop, the auxiliary-heater/storage tank in a one-tank system or preheat tank in a two-tank system. Output from S_2 is affected by hot-water usage, thermal inertia of the tank, and water mixing in the tank. Consequently, the measured temperature difference between S_1 and S_2 does not represent the actual temperature difference across the heat exchanger.

sensor S_3, decreases below the set point of freeze-protection thermostat T-3, a double-pole-single-throw switch, the normally open contact closes and the normally closed contact opens. Closing of the normally open contact energizes valve V-1, which opens, and pump P-1, which starts. However, opening the normally closed contact ensures that the fan motor is shut off and dampers D-1 and D-2 are closed. Consequently, warm water circulates from the preheat tank to the heat exchanger and back, while air circulation is shut down.

Warm water circulating from the preheat tank warms up sensor S_3. When sensor S_3 warms to above the set point of thermostat T-3, the normally open contact returns to its normal position, interrupting power to pump P-1 and valve V-1.

This freeze-protection cycle occurs whenever the heat-exchanger water temperature falls below the recommended thermostat T-3 set point of 40°F (4°C). This cycling wastes energy but is mandatory for safe, reliable operation. To minimize energy loss, the following design guidelines are recommended:

- Install leakproof dampers.
- Insulate ductwork and heat exchanger.
- If possible, install heat exchanger in a location where ambient air temperatures always are above freezing.
- During system start-up and testing, verify that dampers do not leak.

Some air DHW systems use back-draft dampers instead of motorized dampers D-1 and D-2. This component substitution simplifies the control system and reduces cost, but back-draft dampers leak. Depending upon the leakage rate, the energy loss can be significantly greater than when tight-fitting motorized dampers are used.

Overheat Protection. When solar energy is available and demand for hot water is low, the water temperature in the system can approach or exceed the boiling point. To protect the system, overheat protection is incorporated into the controls.

There are several ways to protect this system from overheating. One, shown in Fig. 3.21, provides protection by discharging hot water from the system in the following manner.

Thermostat T-4, a single-pole-single-throw switch, provides the overheat protection, receiving its temperature signals from sensor S_5. When the temperature sensed by S_5 exceeds a high set point of approximately 180°F (82°C), the normally open T-4 contact closes, energizing valve V-2, which opens, discharging hot water in the preheat tank to the drain. This water is replaced by cold make-up water, which enters the bottom of the preheat tank, causing the tank-water temperature to decrease.

When water temperature in the preheat tank, as sensed by S_5, drops to the low set point of approximately 170°F (77°C), the T-4 contacts open, de-energizing valve V-2, which closes. Overheat protection is reactivated whenever the water temperature again increases to the high-temperature set point of thermostat T-4.

The important features of overheat protection by discharging hot water from the system are:

- Preheat tank and collectors are protected against high temperatures.
- Water is wasted, so this technique is not recommended for use in dry climates.

Another overheat-protection method, which does not discharge hot water from the system, employs overheat-protection thermostat T-4 to keep the system shut down until the temperature in the preheat tank decreases. The control schematic for this method is similar to the control schematic in Fig. 3.22, except that V-2 is eliminated and the normally open T-4 contacts serve the pump, fan, valve V-1, and damper circuits.

The important features of this overheat-protection method are:

- Preheat tank is protected against high temperatures. However, the collectors are not protected, and stagnation may occur.
- Hot water is not wasted.

A third overheat-protection method uses two leakproof dampers with duct connections to the outside. The overheat-protection dampers must be installed so the fan can purge the collectors with ambient air. Features of this overheat-protection mode are:

- Water is not wasted.
- Initial costs, for the additional control dampers, are higher.
- Preheat tank and collectors are protected.
- Fan is needed for overheating protection.

All of these overheat-protection methods protect the preheat tank from water temperatures that can damage tank linings. Two of the systems also protect the collectors from dry stagnation.

System designers must evaluate the cost of protection against overheating with regard to the 1-to-10-yr range of collector warranties, collector degradation from occasional stagnation conditions, the installed cost of additional dampers and necessary control modifications, and the cost of wasted water. In a conservative design, collectors capable of withstanding stagnation for 30 days without degradation, as verified by ASHRAE 93-77, should be specified.[63]

<u>Auxiliary Heater</u>. A gas heater usually is employed to maintain the desired water temperature in the auxiliary-heater tank. A basic heater

control combines automatic pilot valve, manual gas valve, thermostatic valve, pilot gas filter, and gas regulators in one unit.

When the tank-water temperature, as sensed by the thermostatic-valve sensor, drops below a set point, the thermostatic-valve mechanism opens the main gas supply to the burner, which is ignited by the pilot light. When the tank-water temperature increases to a predetermined temperature differential, usually 10 to 20°F (5 to 11°C), the thermostatic valve shuts off the gas.

Temperature-Modulating Valve. When the temperature of hot water leaving the auxiliary-heater tank exceeds a predetermined value, temperature-modulating valve V-3 mixes cold make-up water with the hot water to maintain the preset tap-water temperature.

Temperature-modulating-valve operation is described in Sec. 2.8. These valves are required by local codes in some areas as safety devices to protect users from excessively hot water.

3.2.3.2 Estimated Mean Time between Failures (MTBF)

The air-system MTBF estimates in Table 3.11 were obtained using the reliability-block-diagram technique presented in Appendix A. In developing the data in Table 3.11, it was assumed that the solar DHW system operates for 6 hr/d.

The low estimated MTBF for this system arises from the design of the series collector, for the entire system is shut down if any one of the collectors fails. The air system may also have been penalized by assuming that the failure rates for air collectors are identical to the failure rates for liquid-cooled flat-plate collectors. Presently available data do not permit a more detailed analysis.

3.2.3.3 Indirect Air Two-Tank System Start-Up and Testing

After the system has been installed, the components cleaned, the system purged, and all sensors calibrated, but prior to installing the insulation, the system must be started and tested. Testing is necessary to detect leaks, verify the control sequence, locate any defective pumps, valves, fans, or dampers, and identify and eliminate design or installation errors.

The recommended test procedure follows:

Table 3.11 Estimated Mean Time between Failures (MTBF) of Indirect Air Two-Tank DHW System

Number of Collectors in System	Estimated MTBF (days) with Duct Interconnections	
	Minimum	Maximum
2 (in series)	108	635
3 (in series)	90	610
4 (in series)	78	585

Step 1. Place control system in "off" position.

Step 2. Test collector loop for leaks.

Using a separate pressurization blower, pressurize all sections of the collector loop with air to 3 in. of water column (747 Pa). During leak testing, isolate air-circulating fan F-1 from the system, because air can leak through the fan's shaft seal when the system is pressurized. This leakage could interfere with the testing of the remaining sections of the collector loop. Although air leakage through the fan's shaft seal is inevitable, the leakage rate is not great enough to affect system reliability and efficiency.

After the fan has been isolated with blank-off flanges and the system pressurized, test all duct joints, access doors, collector-panel-to-duct and collector-panel-to-collector-panel connections for leaks, using the soap-bubble method. A maximum of five linear feet of duct joint should be tested at a time. Apply the soap liquid directly but gently to preclude bubble formation during application. Joints and connections are considered airtight if there is no visible movement within 20 s after the liquid is applied.

Leaking joints and other connections should be sealed with duct-sealant compound and retested. Tighten and retest any leaking flange connections.

Step 3. Balance collector-loop air flow.

To avoid hot spots in the collector array that can reduce system efficiency, and to ensure design air flow through the collector loop, the air flow must be balanced. This is usually accomplished by means of manual throttling dampers in the duct and variations in fan speed. Balanced air flow can be verified by measuring air flow through each collector panel or group of collector panels and by measuring total air flow in the ductwork leading to and from the air-circulating fan. These measurements can be made with a pitot tube and the pitot traverse method, as described in Ref. 57. This reference also provides information on the minimum distance to be maintained to obtain accurate readings.

During flow balancing, if the measured air flow is significantly below design flow, check the direction of fan rotation. If the fan rotates in the reversed direction, interchange motor leads.

After steps 2 and 3 are complete, insulate the duct runs.

Step 4. Fill hot-water loop.

When the collector loop is insulated, test the hot-water loop. Open the make-up-water supply valve and hot-water faucets to purge air from the loop. After tanks and piping have filled with water, close hot-water faucets.

Step 5. Check hot-water loop for leaks.

Shut off make-up water supply. Pressurize system to 20 psi (137 kPa) above expected system water pressure and check for leaks. Pay special attention to valve V-2, because a leaking V-2 means continuous hot-water loss. Drain the hot-water loop to correct any leaks.

Step 6. Balance water flow.

Flow balancing is necessary to ensure design flow rates through the heat exchanger, which optimizes heat-exchanger performance. In addition, this flow balancing will reveal if lines are blocked with solder or other obstructions.

Install a jumper wire to bypass freeze-protection thermostat T-3 so the normally open contacts close and the normally closed contacts open. This energizes pump P-1, which starts, and valve V-1, which opens, while fan F-1 remains off and dampers D-1 and D-2 remain closed. With just the hot-water loop in operation, balance the water flow.

A circuit setter or manual throttling valve should be provided on the discharge side of pump P-1 for balancing water flow. Make certain this valve is not installed on the suction side of the pump, where it could cause the pump to cavitate and destroy itself.

Flow balancing should be started with the throttling valve partially open. If an oversized pump has been installed and the throttling valve is fully open, flow rates higher than specified will occur, possibly overloading the pump motor.

Balanced flow can be verified by measuring the flow rate through the piping, using anubars, flowmeters, orifices, and circuit setters. Circuit setters, which combine orifice, pressure taps, and a globe valve in one unit, are commercially available to measure and balance flows.

Whatever flow-measuring method is used, the measuring device should be installed as far as possible from flow deviators, such as elbows, valves, or tees. The minimum distance specified in manufacturer's literature must be maintained to obtain accurate readings.

During flow balancing, if the measured flow is significantly below design flow, check the direction of pump rotation. Pump-rotation direction can be reversed during installation by interchanging motor leads.

When flow is balanced, remove jumper wire.

Step 7. Adjust pressure relief valve(s).

Pressurize the hot-water loop 25 psi (172 kPa) above the expected system water pressure. With pump P-1 running, adjust pressure relief valve to onset of bleeding. If pressure relief valve has been set at factory, verify that relief valve will open at preset pressure.

After pressure relief valve is adjusted, reduce system pressure to design level. Open make-up water-valve. Recheck system for leaks. Shut down and drain system to repair any leaks.

Step 8. Insulate the hot-water loop.

Step 9. Adjust the set points of the thermostats in accordance with the designer's recommendations.*

Note that the high-temperature differential set point of thermostat T-2 should be at least 3°F (2°C) above the low-temperature differential set point of thermostat T-1.

Step 10. Adjust low-temperature differential set point of thermostat T-2.*

Since thermostat T-2 is used to terminate solar collection, the T-2 low-temperature differential set point has to be finely adjusted for maximum solar-collection efficiency. If this set point is determined by field testing, measure the electric-energy consumption of pump P-1 and fan F-1 with a wattmeter. Calculate temperature differential using Eqs. B.8 and B.10 in Appendix B and adjust thermostat setting. If the set point was not determined with field testing, set thermostat to designer's specifications.

To verify accuracy of low differential set-point adjustment, measure temperatures in the vicinity of sensors S_3 and S_4 with calibrated thermometers.

By partially shading the collectors, available insolation can be reduced until low differential set point of thermostat T-2 is reached and pump de-energizes.

When pump P-1 shuts off, measure temperature difference between S_3 and S_4 with the thermometers. If measured temperature difference does not fall within 0.5°F (0.3°C) of T-2 low-temperature differential set point, thermostat setting should be readjusted. Repeat procedure until pump shuts off at specified temperature-differential value.

Step 11. Adjust setting of time-delay relay.**

After a cold night, the temperature of air in the collector loop approaches the ambient temperature. As solar energy becomes available, air in the collectors warms. The air in the collectors may be hot enough to activate thermostat T-1. However, air in the rest of the collector loop warms more slowly. Also, water in the heat exchanger may have cooled down during the night from thermal losses to the cold air.

Under these conditions the temperature difference between the collectors and storage tank causes thermostat T-1 to start pump P-1 and fan F-1 and open valve V-1 and dampers D-1 and D-2. So the system starts, but the

*Thermostats in prepackaged systems may have been factory-set, so that field adjustments are not possible. It is assumed that manufacturers of these systems have sufficient test data to set thermostats properly.

**Prepackaged time-delay relays may have been factory-set, so that field adjustment is not possible. It is assumed that manufacturers of prepackaged systems have sufficient test data to determine the proper time-delay relay setting.

cold water in the heat exchanger continues to be cooled by the cold air in the ductwork. Since there is no immediate heat pickup across the heat exchanger to activate thermostat T-2, the time-delay relay is set to override thermostat T-2 until warm air arrives from the collector. If the time-delay is too short, thermostat T-2 will shut down the system while thermostat T-1 is trying to operate it, resulting in undesired system cycling.

To avoid this cycling, the time-delay relay has to be set correctly, depending on pump and fan flow rates, duct sizes, and duct length between the collectors and heat exchanger. If the system designer did not specify the time setting, setting can be adjusted in the field as follows:

- Cover solar collectors overnight.
- When sufficient solar energy is available in the morning, set time-delay relay to delay action of thermostat T-2 for 10 min.
- Uncover solar collectors so collector air heats up.
- After air temperature in collectors has warmed sufficiently to start system, start timing the operation with a stopwatch. Measure water temperature continuously in vicinity of sensors S_3 and S_4 with calibrated thermometers.
- When warm air from collectors has warmed the water in the heat exchanger enough to activate thermostat T-2, stop the stopwatch and record elapsed time.
- Add a safety factor of one or two minutes to the elapsed time, and set time-delay relay accordingly.

Step 12. Test auxiliary heater.

Adjust set point of auxiliary gas heater to designer's specifications. Ignite pilot light at heater and verify operation of heater. To verify set point, insert calibrated thermometer in thermal well at top of tank and measure water temperature. Auxiliary heater should activate when temperature at top of tank drops to ±2°F (±1°C) of desired temperature. Readjust setting until this requirement is met.

Step 13. Test overheat protection.

Insert a jumper wire across overheat-protection thermostat T-4 to simulate overheating of storage tank. Valve V-2 should open and system should drain. After overheat protection is verified, remove jumper wire. Verify that auxiliary heater maintains water temperature within specified limits.

Step 14. Test operation of temperature-modulating valve.

Adjust setting of temperature-modulating valve V-3 to maintain the value specified by the local codes. Set auxiliary-heater thermostat to 170°F (77°C). Verify water temperature at top of tank with calibrated thermometer in thermal well. When the measured temperature reaches 170° ±5°F (77° ±3°C), open hot-water faucets. Measure temperature of water leaving valve V-3. If V-3 water temperature is not within ±3°F (±2°C) of the code-specified value, readjust V-3 setting. Repeat procedure until temperature is correct. Then reset heater to maintain desired water temperature in tank.

On completion of testing procedures, all system operations have been verified. The system should be ready for regular operation.

3.2.3.4 Indirect Air Two-Tank System Preventive Maintenance and System Checkout

To ensure that an indirect air two-tank system will perform reliably and meet the MTBF estimates in Table 3.11, basic system preventive maintenance must be performed. Most of the preventive maintenance can be performed by the user. Exceptions might include washing roof-mounted collectors, verifying sensor calibration, and replacing worn-out bearings.

Perform the following preventive maintenance at least once a year:

- Wash outer glazing of collector with compounds approved by manufacturer. (Do not remove dirt or dust from polymeric glazings with a dry cloth, because the glazings will be scratched.) During washing, inspect absorber plates for degradation.
- Inspect flashing and collector-mounting hardware. Tighten or replace and recaulk as required.
- Inspect duct connections around collector array. Tighten or repair connections as required.
- Verify that sensors are in correct location. Check sensor calibration.
- Inspect hand-operated valves for leaks; adjust packing. Open and close valves to verify proper operation.
- Drain and flush tanks. Clean strainers and valve filters.
- Inspect pressure relief valve on tanks to make sure valve operates properly and that exit port is not plugged.
- Lubricate pump and fan bearings per manufacturers' specifications.
- Check motor mounts for tightness.

In addition to once-a-year maintenance, check periodically for:

- Deteriorated insulation.
- Leaks.
- Correct thermostat settings, to ensure settings have not changed since start-up and testing.
- Proper valve V-2 operation. Valve is closed most of the time and may stick and not open when needed.

- Proper system operation:

  Verify that pump and fan do not operate at night by using a flowmeter, sight glass -- for water-flow verification -- or pressure gauges across the pump and fan (if installed).

  Verify operation of freeze protection by measuring water temperature in vicinity of sensor S_3. If water temperature is below 40°F (4°C) and pump does not circulate warm water from preheat tank, or dampers D-1 and D-2 are open, drain system manually and call service person. To drain system, close make-up water valve and open hot-water faucets and drain valve on preheat tank.

  Verify pump and fan operation on a sunny day, using flowmeters, pressure gauges across pump and fan, or a sight glass if one is installed. Check temperature difference between collectors and preheat tank with calibrated thermometers in thermowells. If difference is above high differential set point of thermostat T-1 and system does not start, call a service person. Also, measure temperature difference across heat exchanger. If difference is below low differential set point of thermostat T-2 and system is operating, call service person.

3.2.3.5 Indirect Air Two-Tank System Troubleshooting

Although the exact design of an indirect air two-tank system depends on the individual manufacturer, the troubleshooting information in Table 3.12 should help correct problems typical of this system. This information also may be helpful to the user or service person who is troubleshooting a system that has been in the field for some time. Also, Table 3.12 may be useful to designers concerned with analysis, equipment selection, and system specifications.

Table 3.12 Troubleshooting Indirect Air Two-Tank System

Problem	Components	Possible Causes	Corrective Action
System does not start	Power supply	1. Tripped on overload.	1. Determine cause and replace fuse or breaker.
		2. Open circuit breaker.	2. Check and close.
		3. Defective transformer.	3. Replace.
		4. Line voltage fluctuating.	4. Inform power company.
		5. Brown out	5. Provide brownout protective device and inform power company.
		6. Control switch on "off" position.	6. Turn to "auto" position.
	Thermostat T-1	1. High and low temperature differential set points too high.	1. Reset to specifications or settings determined during system start-up and testing.
		2. Defective component.	2. Replace thermostat.
		3. Loose contacts.	3. Tighten wires.
		4. Thermostat is out of calibration.	4. Recalibrate.

Table 3.12 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
System does not start (cont'd)	Sensor	1. Defective. 2. Improper installation. 3. Defective control cable. 4. Sensor out of calibration.	1. Replace. 2. Reinstall. 3. Replace. 4. Recalibrate.
	Pump and/or fan	1. Motor failure. 2. Overload protection switch shuts down pump motor. 3. Defective shaft or coupling 4. Defective bearings.	1. Check brush holders, throw-out mechanisms, centrifugal switches, or other mechanical components that may be loose, worn, dirty, or gummy. Replace worn components and reassemble. 2. Determine cause of overloading; check if balancing valve is in proper position. 3. Replace. 4. Replace.
	Control circuitry	1. Circuit continuity lost. 2. Bad contacts.	1. Check and repair. 2. Check and correct.
System starts but cycles	Thermostat(s) T-1 and T-2	High and low temperature differential set points are too close together.	Reset according to specification or settings determined during system start-up and testing.
	Time-delay relay	Time delay "times out" too soon (sensors do not heat up in time).	Increase time-delay relay setting.
	Control circuitry	1. Circuit continuity lost. 2. Bad contacts.	1. Check and repair. 2. Check and correct.
Pump runs but no water flows to the heat exchanger	Valve V-1 closed	1. Actuator defective. 2. No power to actuator. 3. Valve sticks.	1. Replace actuator. 2. Check wiring. 3. Cycle valve by jumping control system or replace actuator.
	System air locked	1. Poor pump inlet connection. 2. Air vent(s) jammed closed.	1. Remake according to good installation practice. 2. Replace vent(s).
	Pump impeller	Impeller broken or separated from shaft.	Replace impeller and/or shaft assembly.
	Blocked liquid flow passage	Pipe damaged.	Replace damaged section.
Fan runs but no air flows to the heat exchanger	Damper(s) D-1 and/or D-2 closed	1. Actuator defective. 2. No power to actuator. 3. Damper linkage defective.	1. Replace actuator. 2. Check wiring. 3. Repair or replace.
System runs continuously	Thermostat T-2	1. Low temperature differential set point set too low. 2. Defective component. 3. Thermostat is out of calibration.	1. Reset to specifications or settings determined during start-up. 2. Replace thermostat. 3. Recalibrate.
	Sensor(s)	1. Defective sensor(s). 2. Sensor(s) is out of calibration.	1. Replace. 2. Recalibrate.
	Control circuitry	Bad contacts.	Check and correct.
	Thermostat T-3	1. Defective components. 2. Thermostat is out of calibration.	1. Replace. 2. Recalibrate

Table 3.12 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
System does not provide freeze protection	Valve V-1 closed	1. Actuator defective. 2. No power to actuator. 3. Valve sticks.	1. Replace actuator 2. Check control wiring. 3. Cycle valve by jumping control system, or replace actuator.
	Freeze protection thermostat T-3	1. Set point has drifted. 2. Defective components. 3. Loose contacts. 4. Thermostat is out of calibration.	1. Reset. 2. Replace. 3. Tighten wires. 4. Recalibrate.
	Sensor S_3	1. Sensor out of calibration. 2. Defective sensor. 3. Improper installation.	1. Recalibrate. 2. Replace. 3. Reinstall.
	Power supply and pump P-1	See power supply and pump causes.	See power supply and pump causes.
	Control circuitry	Bad contacts.	Check and correct.
	Dampers D-1 and D-2 open	1. Damper linkage defective. 2. Shaft broken.	1. Repair or replace. 2. Replace.
Air system leaks	Duct joints at collector	1. Thermal expansion and contraction. 2. Joint improperly made.	1. Provide flexibility and reassemble. 2. Reassemble leaky joint.
	Hose connection	Clamp or flange is not tight.	Tighten hose clamp. Replace clamp or hose.
	Collectors on systems where collector panels butt together	1. Seals leak. 2. Clamps or other methods of joining.	1. Replace. 2. Tighten up joints between panels.
Poor solar energy collection	Collector array	1. Undersized collector area. 2. Collectors shaded. 3. Air flow rate too high or too low. 4. Leaks.	1. Install more collector area. 2. Remove obstacle or install collectors in sunlit location. 3. Check collector loop and rebalance flow. 4. Repair.
	Ductwork	1. Leaks. 2. Insufficient insulation. 3. Improper weather protection. 4. Insulation damaged.	1. Repair 2. Add insulation. 3. Provide proper protection. 4. Repair.
	Heat exchanger	1. Undersized heat exchanger. 2. Heat transfer surface covered with dirt and scale deposits.	1. Install adequate heat exchanger. 2. Clean surface.
System noisy when operating	Fan	Fan noise too high.	Attenuate noise if annoying.
	Pump	1. Restricted pump suction results in cavitation. 2. Air in system.	1. Remove restrictions. 2. Manually vent system if automatic air vents are not adequate.
	Pump or fan bearings	1. Bearing worn. 2. Bearing damaged owing to misalignment.	1. Replace. 2. Align pump and motor shaft.
	Piping	1. Air locked in the piping. 2. Piping vibrates.	1. Vent system. 2. Provide adequate pipe support.
	Air Vents	Improperly sized	Install proper vents.

Table 3.12 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
No hot water	Make-up water shutoff valve	Valve closed.	Open valve.
	Heater failed to actuate	1. Failure to ignite a. Gas off. b. Safety switch malfunctioning. c. Defective thermo-couple and/or automatic pilot valve. 2. Pilot won't stay lit. a. Too much primary air. b. Dirt in pilot orifice. c. Pilot valve defective. d. Loose thermo-couple connection. e. Defective thermocouple. f. Improper pilot gas adjustment. 3. Thermostat defective 4. Bad contacts.	 a. Open manual valve. b. Check and replace. c. Check and replace. a. Adjust pilot shutter. b. Open orifice. c. Replace. d. Tighten. e. Replace. f. Adjust. 3. Replace 4. Correct.
	Temperature modulating valve	1. Valve Defective. 2. Sensor defective. 3. Leak in capillary tubing.	1. Replace 2. Replace. 3. Replace.
Hot water temperature not high enough	Hot water thermostat	1. Thermostat setting too low. 2. Thermostat out of calibra-tion.	1. Set thermostat higher. 2. Recalibrate or replace thermostat.
	Auxiliary heater	Heater undersized for hot water demand.	Replace when heater fails.
	Safety switch	Set too low.	Check and reset.
	Burner	1. Burner clogged. 2. Undersized burner orifice.	1. Clean. 2. Provide correct orifice.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too low. 3. Valve spring too weak.	1. Recalibrate. 2. Reset. 3. Replace.
Water tempera-ture too high	Hot water thermostat	1. Thermostat setting too high. 2. Thermostat out of calibration. 3. Bad contacts.	1. Reset. 2. Recalibrate. 3. Correct.
	Sensor	Out of calibration.	Recalibrate or replace.
	Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too high.	1. Recalibrate. 2. Reset.
System overheats	Hot water loop valve V-1	1. Valve sticks. 2. Return spring failed.	1. Cycle valve by jumping control system, or replace actuator. 2. Replace.
	Make-up water valve	Valve closed.	Open valve.
	Overheat protection valve V-2 closed	1. Actuator defective. 2. No power to actuator. 3. Valve sticks.	1. Replace actuator. 2. Check wiring. 3. Cycle valve by jumping control system, or replace actuator.

Table 3.12 (Cont'd)

Problem	Components	Possible Causes	Corrective Action
System overheats (cont'd)	Overheat protection thermostat	1. Thermostat setting too high. 2. Defective component. 3. Thermostat is out of calibration. 4. Loose contacts.	1. Reset to specifications. 2. Replace thermostat. 3. Recalibrate. 4. Tighten wire.
	Control circuit	1. Circuit continuity lost. 2. Loose contacts. 3. Contacts coil burned out.	1. Check and repair. 2. Tighten contacts. 3. Replace.
	Sensor S_5	Out of calibration.	Recalibrate.

4 SUMMARY OF SOLAR DHW SYSTEMS

This section contains a summary of the advantages and disadvantages of the generic solar domestic hot-water systems described in these guidelines. Also, system reliabilities are compared relative to three undesirable conditions: no hot water, freezing, and overheating. The minimum instrumentation needed to verify system performance is described. The section concludes with recommendations for the designers and manufacturers of solar domestic hot-water heating components and systems.

4.1 ADVANTAGES AND DISADVANTAGES OF THE GENERIC SYSTEMS

The advantages and disadvantages associated with each of the six generic systems are summarized in Table 4.1. As this table indicates, each system has unique characteristics, all of which should be evaluated carefully before a system is selected for a specific installation. An advantage shared by all systems, of course, is that fossil fuel is saved.

4.2 COMPARISON OF SYSTEM RELIABILITIES

The reliability and mean maintenance-free time of each generic system was computed, using the reliability-block-diagram technique described in Appendix A, for the following conditions:

- No hot water
- Freezing
- Overheating

4.2.1 No Hot Water

Figure A.3 in Appendix A shows the reliability block diagram for a drain-down system. Reliability block diagrams for other systems are similar and contain either more or fewer component blocks. The results of these analyses, based on nonsolar-component failure rates and a 6-hr/d duty cycle, are given in the tables provided with each generic-system description. Table 4.2 summarizes this information for two common collector designs.

One design represents a system with two collector panels. If the two panels are connected in series, both collector panels must function for the system to operate. This is the two-out-of-two-collector case. The same mathematical expression also applies to two collectors connected in parallel when both are required to meet the hot-water load.

The other design specifies four collectors connected in parallel. When two or more of the four collectors are working, the collector array supplies at least 50% of the load. When three or four collectors are working, at least 75% of the load is met.

Table 4.1 Summary - Advantages and Disadvantages of Solar DHW Systems

---

Drain-Down Systems

Advantages

- No heat exchanger is required in collector loop, so system should be more thermally efficient than indirect systems.
- Pipe diameters are small.
- System is relatively easy to install.
- Some measure of freeze protection exists.

Disadvantages

- Several components must operate for freeze protection to be effective.
- Collectors and piping must be pitched to drain properly.
- Air is introduced each time system drains, so potential for corrosion is greater than in permanently filled systems.
- Solenoid valves may stick if not cycled regularly.
- Water is lost each time system drains.
- Scaling may be a problem.
- System is more complicated than thermosiphon or circulating-water systems.
- Electric power is required for overheat protection.

Circulating-Water Systems

Advantages

- No heat exchanger is required in the collector loop, so system should be more thermally efficient than indirect systems.
- Pipe diameters are small.
- System is relatively easy to install.
- Some measure of freeze protection exists.

Disadvantages

- System is limited to those regions where freezing rarely occurs.
- Collectors must be able to drain in the event of power failure.
- Solenoid valves may stick if not cycled regularly.
- Scaling may be a problem.
- Electric power is required for freeze protection and for overheat protection.

Table 4.1 (Cont'd)

Thermosiphon Systems

Advantages

- Simple design.
- No pumps.
- Simple controls.
- No heat exchanger is required in collector loop.
- System is most cost-effective.[61]

Disadvantages

- Systems generally are restricted to locations where freezing conditions do not occur, or occur infrequently.
- System must be drained manually.
- Roof may have to be reinforced to support system.
- Larger pipe diameters are needed than for pumped systems.
- Scaling may be a problem.

Drain-Back (Closed-Loop) Systems

Advantages

- Small-diameter piping.
- No control valves are needed in collector loop.
- Freeze protection is automatic.
- Collector-loop fluid is de-ionized or distilled water in a closed loop.
- System is relatively easy to install.

Disadvantages

- Collectors and piping must be pitched to drain.
- System thermal efficiency is reduced because of heat exchanger.
- Pumps must be sized to pump water to top of collector array each time system starts.
- Electric power is required for overheat protection.

Glycol/Water-Solution (Antifreeze) Systems

Advantages

- Small-diameter piping.
- Freeze protection is practically assured.
- System can be used in cold climates.

Table 4.1 (Cont'd)

Glycol/Water-Solution (Antifreeze) Systems (Cont'd)

Disadvantages

- To contain glycol/water solution, joints must be tighter than for a water-filled system.
- Double-walled heat exchanger is required to separate heat-transfer fluid and potable water.
- Expansion tank is required.
- Glycol/water solution must be checked periodically for pH and inhibitor levels.
- Glycol/water solution must be replaced periodically.
- Glycol/water-solution viscosity is more dependent on temperature than is the case with water alone.
- Electric power is required for overheat protection.

Silicone- or Hydrocarbon-Oil Systems

Advantages

- Freeze protection is practically assured.
- System can be used in any climate.

Disadvantages

- Larger-diameter pipes are needed than for water or glycol/water systems.
- To contain fluid, joints must be tighter than for water-filled systems.
- Double-walled heat exchanger may be required to separate heat-transfer fluid and potable water.
- Expansion tank is required.
- Fluid viscosity is more dependent on temperature than is the case with water or glycol/water solution.
- Fluid flow rates must be greater than for water or glycol/water systems.

Air Systems

Advantages

- Collector fluid does not require maintenance.
- No collector-fluid corrosion problems exist.
- Some measure of freeze protection exists.
- Leaks are not as costly as in liquid-cooled systems.

Table 4.1 (Cont'd)

Air Systems (Cont'd)

Disadvantages

- Dampers must be maintained.
- Large ducts must be used instead of small-diameter pipes.
- Retrofitting may be difficult (because 10-in.-diameter ducts are required).
- Fan and pump are required.

The data in Table 4.2 can be used by system manufacturers to estimate how long a solar DHW system should last before major maintenance is required. For example, a drain-down system with two panels in parallel would be expected to operate from 64 to 838 days at full load before major maintenance would be required. If system performance is allowed to deteriorate to no lower than a 50% level, the expected system MTBF can be extended approximately 12%. Similar conclusions can be drawn for the other systems and collector designs.

The large estimated MTBF values for the thermosiphon system are based on its design. This system has simple controls, does not require a pump, and has only one powered valve for overheat protection. However, while this system is self-regulating, the state-of-the-art designs do not include built-in freeze protection. If users of thermosiphon systems could be relied on to drain the systems when freezing temperatures were expected, these systems could be used in all climates.

The small MTBF values for the air system are due to the number of components in the system. The two motorized dampers have the same effect as the powered valves in other systems. In addition, the air vent accounts for approximately 25% of the system failure rate. If a higher-quality air vent and dampers were installed, then the MTBF of the two-collector system would approach 1000 days.

Indirect liquid (antifreeze) systems have estimated MTBFs approximately 15% greater than those of drain-down systems. The larger MTBF values for glycol/water systems over drain-down systems occur because the former do not have vent valves and vacuum breakers. However, the glycol/water-system estimates are based on the assumptions that the glycol/water-solution pH and inhibitors are checked regularly, that solution buffers are added when needed, and that the solution is changed when necessary.

Estimated MTBFs in Table 4.2 are based on an assumed 6-hr operating day. Although a 6-hr day is typical of systems in the National Solar Data Network, Appendix A provides a technique for estimating an average duty-cycle factor for solar DHW systems. Data for Eq. A.25 can be obtained from Ref. 65 or from local U.S. Weather Service data.

Table 4.2 Summary of Mean Time between Failures (MTBF) of Generic Solar DHW Systems[a]

Number of Collectors in System	Approximate Solar Load (%)	Range of MTBFs for Different Systems (days)[b]					
		Drain-Down	Circulating-Water	Thermo-siphon	Drain-Back	Indirect	
						Liquid	Air
2	At least 50	80-940	97-1198	320-2361	174-1742	232-1383	-
2	100	64-838	72-975	174-1835	116-1434	141-1177	108-732
4	At least 50	81-943	92-1120	298-2367	171-1749	223-1389	-
4	At least 75	82-914	83-1078	209-2120	138-1623	170-1316	-
4	100	53-530	60-862	109-1468	87-982	96-1014	78-666

[a]Summarizes Tables 3.1, 3.3, 3.5, 3.7, 3.9, and 3.11.

[b]Assumes system operates 6 hr/d.

The data concerning estimated MTBFs for the generic systems indicate that:

- Dual storage tanks reduce the mean life of a system by approximately 15%, compared with a single-tank system.
- Flexible-hose interconnections reduce system mean life by approximately 50% compared with tubing with soldered or brazed connections.
- An order-of-magnitude difference exists between minimum and maximum estimated system mean lives.

This order-of-magnitude difference reflects the spread in component mean-life data. The data, drawn from several nonsolar sources and summarized in Appendix A, give the best available information in the open literature.

The MTBF estimates in Table 4.2 could be used by system manufacturers to estimate warranty periods and set up maintenance schedules. However, this information is appropriate only for the generic systems described in these guidelines and is based on data in Appendix A. System manufacturers must develop comparable data based on the performance of their systems.

4.2.2 Freeze-Protection Reliability

If water-cooled solar DHW systems are to be widely accepted in the continental United States, the systems must not freeze in cold weather. Figure 4.1, which is based on Ref. 62, describes how solar-energy systems freeze. The parts of Fig. 4.1 that are based on field data are indicated by asterisks; the other freeze-up failure modes were deduced from system drawings.

Reliability of freeze-protection methods for drain-down, drain-back, and circulating-water systems may be derived with reliability block diagrams and generic-system schematics. The results for these generic systems are shown in Table 4.3.

Table 4.3 does not include results for the indirect or thermosiphon systems. Indirect systems that use glycol/water solution should not freeze. If freezing occurs, either the glycol concentration was inadequate for conditions, or the system thermosiphoned. These problems are recorded in Fig. 4.1 and are the result of design errors or omissions. They are not reliability problems.

The probability that all three system designs could freeze after one year of operation is based on maximum failure rates associated with vent valves and vacuum breakers. The drain-back system should be more reliable than the drain-down system, because control valves are not required in the collector loop and the air vent is not exposed to the outdoors.

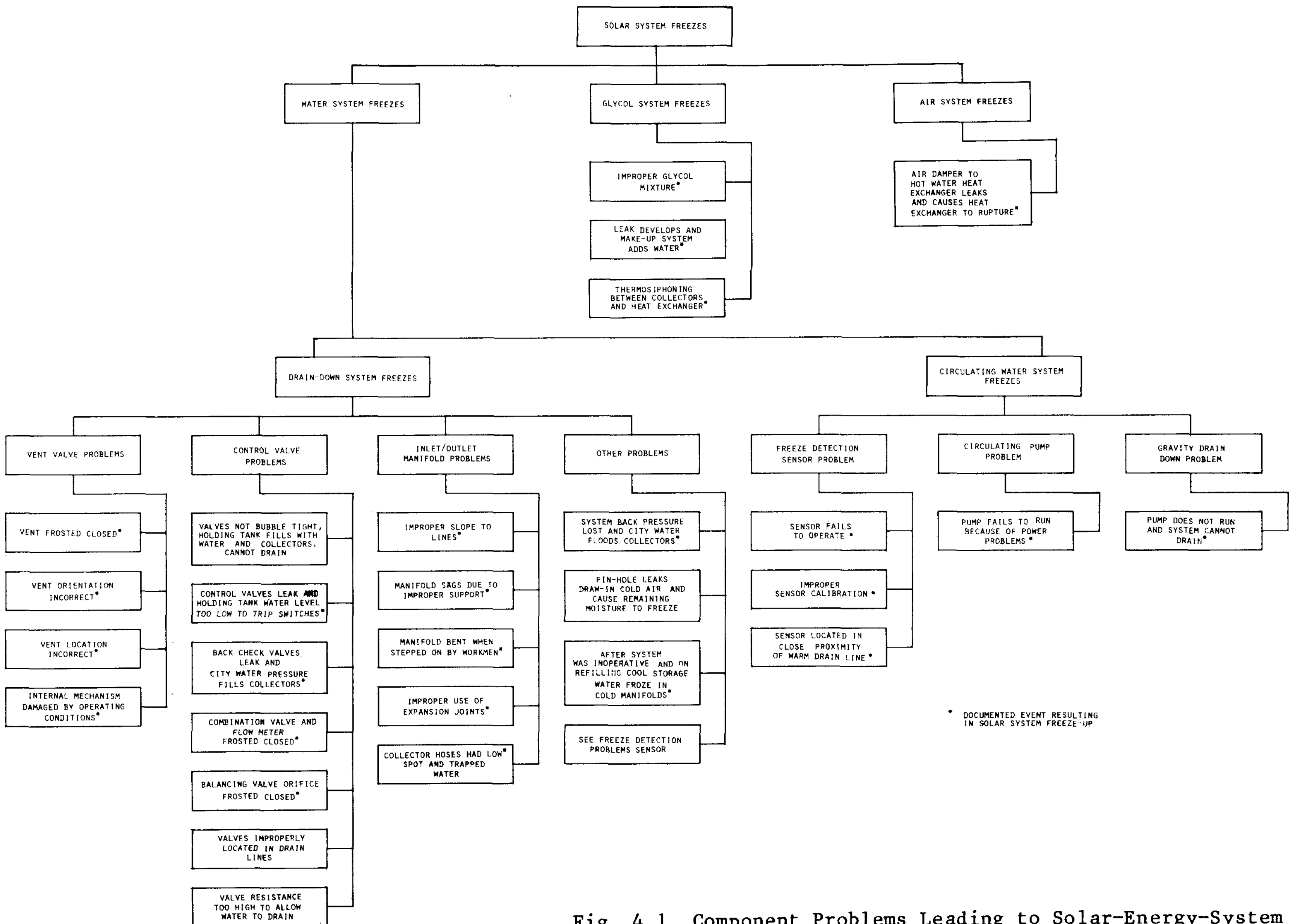

Fig. 4.1 Component Problems Leading to Solar-Energy-System Freeze-Ups[62]

Table 4.3 Freezing Probabilities of Solar DHW Systems

System	Probability Range (%) After First Year	After Second Year	After Third Year
Drain-down	27-98	47-100	62-100
Drain-back	21-87	37-100	50-100
Circulating-water	8-70	15-100	21-100

The circulating-water method* for preventing freezing appears to be more reliable than either the drain-down or drain-back methods. In comparison with drain-back systems, at least, this reliability is the direct result of the absence of vent valves. An additional assumption is that electric power is available on demand. If electric power fails and the system is not designed to drain, the system will freeze.

The hot-water loops of air systems should not freeze. However, as shown in Fig. 4.1, these systems can freeze if the air dampers leak. Freeze protection for an air-to-water heat exchanger is proposed in Sec. 3.2. It is similar to the protection described for circulating-water systems. The reliability of this freeze protection should be the same as shown in the last line of Table 4.3.

4.2.3 Overheat-Protection Reliability

If hot-water demand is low and insolation is high, DHW systems can overheat. Chapter 3 describes three ways to prevent overheating. In one method, as overheated water is discharged from storage, cold make-up water enters the storage tank. As the storage tank cools down, the solar-collection cycle is started and cool water enters the collectors. A second method locks out the collector-loop pump, which protects the storage tank but subjects the collector to stagnation. The third method relies on a heat exchanger, valves, and a pump to dissipate collector-loop heat, which protects the collectors from stagnation and the storage tank from high temperatures.

The reliability of these overheat-protection methods may be assessed by reliability block diagrams. Table 4.4 summarizes the results. Data for these block diagrams are in Appendix A.

Discharging heated water for overheat protection relies on a pump in a drain-down system, or on make-up water for the other systems. Data in Table 4.4 indicate that the make-up-water method is approximately twice as reliable as the pump method.

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*This method of freeze protection is recommended only for geographical regions where freezing conditions rarely occur.

Table 4.4 First-Year Overheating Probabilities for Solar DHW Systems

System	Probability Range (%)		
	Water-Discharge Method	Pump-Lockout Method	Exchanger Method
Drain-down	9-99	5-53	14-100
Circulating-water	5-40	5-53	13-100
Thermosiphon	5-40	NA[a]	NA[a]
Drain-back	10-40	2-15	9-99
Indirect (antifreeze)	5-40	5-40	13-100
Air	5-40	5-40	14-100

[a]NA - not applicable.

Overheating protection based on locking out the collector-loop pump is as reliable as introducing cold make-up water, but the solar collector must be able to withstand wet stagnation, or dry stagnation in drain-back or air systems.

The third overheat-protection method, which employs a heat exchanger, is the least reliable of the three methods, owing to the need for additional valves, a pump, and a heat exchanger. This method is the most sophisticated but is not recommended for residential DHW systems.

4.3 MINIMUM INSTRUMENTATION FOR SYSTEM MONITORING

Temperature sensors and differential thermostats are needed to operate a DHW system. However, additional instruments are needed for system monitoring, check-out, and troubleshooting.

For residential DHW systems, minimum instrumentation includes thermometers, pressure gauges, and sight gauges. If feasible, thermometers are installed close to temperature sensors. If thermometers are not installed permanently, test plugs or thermowells should be provided so thermometers can be inserted when needed.

Pressure gauges or gauge cocks should be installed across pumps, fans, and heat exchangers. A large pressure drop across a pump or a heat exchanger indicates flow passages are blocked.

To monitor fluid flows, flowmeters, anubars, pitot tubes with pressure indicators, or circuit setters may be installed. However, if fluid measurements are not needed, sight glasses in major loops should be adequate.

A sophisticated monitoring system provides readouts for temperature sensors, valve or damper positions, pump or fan operations, operating modes, and possibly fluid flow rates. At present, the expense of such sophistication may not be justified. However, significant cost reductions are possible with mass-produced integrated circuits, so sophisticated monitoring systems may be cost-effective in a few years.

4.4 STANDARDS FOR SOLAR-ENERGY COMPONENTS AND SYSTEMS

The American Society for Testing Materials (ASTM), through its E-44 Committee on Solar-Energy Conversion, is preparing standards on absorptive coatings, cover-plate materials, heat-transfer fluids, optical properties, and insulation. These standards are in various stages of development and may be available in 6 to 18 months.

There are nine ASTM standards concerning solar-energy systems that have completed the ASTM approval process. One standard provides specifications for copper and copper-alloy absorber panels,[66] and there are standards covering rubber seals for flat-plate collectors, concentrating collectors, contacting liquids, and air-heat-transport systems.[67-70] A recently prepared NBS draft standard on rubber hoses[71] is now an ASTM standard.[72]

Two ASTM standards deal with metallic containment materials for solar heating and cooling systems. One is a laboratory screening procedure.[73] The other covers simulated service testing for corrosion of metallic containment materials for use with heat-transfer fluids.[74] The ninth ASTM standard deals with installing and servicing space-heating systems.[75]

Committee E-44 also is preparing a standard on sizing solar DHW systems for one- and two-family dwellings. Other standards being developed include measurement of on-site system performance and subsystem reliability.

4.5 RECOMMENDATIONS

These recommendations summarize available information on six generic DHW systems. In time, the reliability of solar DHW systems will improve and systems will be more cost-effective. Toward that goal, the following recommendations are offered to component and system designers and manufacturers.

4.5.1 Components

- Collectors should be fabricated so temperature sensors can be installed in collector-liquid passages.
- Buckling strength of absorber plates should be stated for each type of collector manufactured.
- NPSH curves or data should be provided for the small-horsepower pumps in DHW systems.
- Control sensors for gas-heater units should be relocated to the upper one-third of the water tanks.

- Temperature sensors should be developed expressly for solar DHW applications.
- Solar DHW tanks with R-30 insulation should be developed.

4.5.2 Design and Manufacturing

- Estimate system reliability during the preliminary system-design phase.
- Provide installation details.
- Prepare detailed system start-up and testing procedures, as well as system acceptance criteria, during the detail design phase.
- Witness start-up and testing of installed systems to verify that they are performing as designed.
- Maintain records on equipment failures after systems are in operation and use these data to update failure statistics and reliability estimates.
- Provide taps for indirect liquid (antifreeze) systems, so that samples of collector heat-transfer fluids can be taken for testing.
- Specify ductwork for air systems that meets the criteria for medium-pressure ductwork of the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA).
- Specify thermowells in the vicinity of each temperature sensor for use in system start-up, testing, trouble-shooting, and periodic checkouts.
- Provide flow indicators, such as sight glasses and pressure gauges, for troubleshooting of systems.

APPENDIX A

ASSESSMENT OF SOLAR DHW SYSTEM RELIABILITY

A.1 INTRODUCTION

This appendix presents techniques for estimating the reliability or the consistency of service of solar DHW components and systems. These techniques are not unique to solar-energy systems but are used daily in various industries, such as: the aerospace and nuclear industries, to insure system safety; the electric-power industry, to obtain consistent system operations, and consumer-products industries, to reduce warranty costs or to anticipate potential manufacturing problems.

The most commonly accepted definition of reliability is:

> Reliability is the probability that a component or a system will perform its required function under the specified conditions for a specified time.

Figure A.1 depicts a typical failure-rate curve for a system assembled from components. When the system is put on line initially (break-in period), the failure rate is high because of design errors, omissions, or operator errors.

After the break-in period, the useful-life portion of the system's life cycle begins. The failure rate drops and remains virtually constant. Any malfunctions or failures are random, the results of fatigue, creep, or poor maintenance.

After the system has been in service an appreciable time, wear begins to affect its performance, and the failure rate increases. At this point, the decision must be made either to overhaul the system or abandon it.

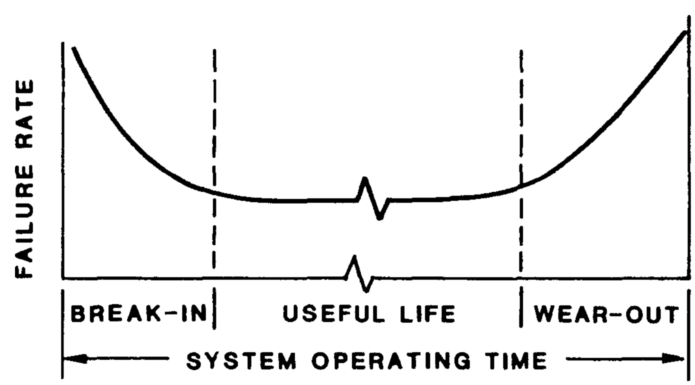

Fig. A.1 Typical System Failure-Rate Curve

A.2 COMPONENT RELIABILITY

One of the major parameters of system reliability is the estimate of mean time between failures (MTBF) or the mean life (ML) during the useful portion of the component or system life cycle. As illustrated in Fig. A.1, the useful life of a component generally is characterized by a virtually constant failure rate. Component reliability is characterized by an exponential distribution function and can be expressed as:

$$R = \exp(-\lambda t) \tag{A.1}$$

where:

- R = probability that a component will operate without malfunction or failure for a specified period of time under the stated operating conditions
- λ = component failure rate, usually expressed as the number of malfunctions or failures per unit of time
- t = time during which component is subjected to operating conditions

In presenting the analytical techniques in this appendix, it is assumed that failure rates are constant and that component reliability can be expressed by Eq. A.1.

To evaluate Eq. A.1, the component failure rate must be known. The best sources for component failure rates are field data or accelerated testing results. If these failure-rate data are not available, component failure rates may be estimated from the failure rates of the elements that make up the component or subsystem.

The time t used to compute component reliability in Eq. A.1 is the continuous operating time. When components such as pumps or powered valves in solar DHW systems do not operate continuously, the time t has to be modified and replaced by td, where d is the period-of-operation (duty-cycle) factor expressed as the ratio of operating time to total mission time.[1]

A.3 COMPONENT FAILURE RATES

Component failure rates are expressed in terms of the number of failures within a specified number of operating hours. These failure rates imply that the component functioned continuously under normal operating conditions until failure occurred. The failure-rate values generated through testing under normal operating conditions are defined as base failure rates.

A.3.1 Base Failure Rates

Depending on the component and on available data, base failure rates can be estimated by several techniques. One approach, presented in Ref. 1, is based on extensive testing data. In this example, testing data on electric relays can be placed in the following functional form:

$$\lambda_b = A \exp (x + y) \tag{A.2}$$

where:

λ_b = the base failure rate in failures/hr

$x = [(T + 273)N_t]^G$

$y = (S/N_t)^H$

A, G, N_t = temperature-dependent coefficients

H = number of operating hours per day

S = ratio of operating load current to rated resistance load current

T = operating temperature in C°

This formulation can be extended to other components if testing data are available.

Although field data or laboratory data provide the most accurate failure-rate information, these data are not usually in the public domain. Manufacturers regard these data as confidential, because they are expensive to generate and their publication would reveal the corporation's design criteria. Without actual failure data, failure-rate estimates can be generated from warranty data, or from reliability analyses.

A.3.2 Base Failure Rate Estimates From Warranty Specifications

Assume that a component has a manufacturer's warranty that extends for one year from date of installation. It is the judgment of the engineer specifying the component that this piece of equipment will operate on the average of H hours per day. With this background information, an upper bound on the base failure rate can be estimated from:

$$\lambda_{bu} = (2.74 \times 10^{-3})/WH \tag{A.3}$$

where:

λ_{bu} = upper bound on the base failure rate (failures/hr)

W = warranty period in years

H = number of operating hours per day

Manufacturers' warranties are conservative. A lower bound on the base failure rate can be estimated by assuming the component will operate continuously for at least as long as the warranty period. In this case,

$$\lambda_{bL} = (1.14 \times 10^{-4})/W \tag{A.4}$$

A.3.3 Base Failure Rate Estimates From Reliability Studies

If failure-rate data and warranty data are not available, component failure rates can be estimated from the failure rates of the elements that make up the component. For any component having a number of series-connected elements that must function for the component to function, the overall failure rate is:[1,76,77]

$$\lambda_b = \lambda_1 + \lambda_2 + ... + \lambda_n \qquad (A.5)$$

where λ_1 through λ_n are the failure rates of the individual elements that make up the component.

More complicated components can be represented as a combination of series- or parallel-connected elements.[77]

A.3.4 Collector Failure Rate

As a first approximation, a flat-plate solar collector can be idealized as a group of series-connected elements as in Fig. A.2. In preparing the failure-rate estimates, it was assumed that:

- The heat-transfer-fluid coolant passages are correctly bonded to or are integral with the absorber plate.
- The condition of the heat-transfer fluid is periodically checked to verify that the fluid is not corrosive.

With these assumptions, and using Fig. A.2 and Eq. A.5, the base failure rate of a collector is:

$$\lambda_{bc} = \lambda_g + \lambda_s + \lambda_i + \lambda_a + \lambda_{ac} \qquad (A.6)$$

With the failure-rate data for the individual elements presented in Table 2.9, λ_{bc} ranges from 2.28 x 10^{-4} to 2.28 x 10^{-5} failures/hr. The failure rates correspond to MTBFs of six months to five years, respectively, under continuous full-load operation.

These MTBFs are conservative values, because it was assumed that all of the elements are in series. Some collector manufacturers provide limited warranties on their collectors for up to 15 years. As a result, the collector failure rate will be assigned a value that ranges from 11.4 x 10^{-6} to 114 x 10^{-6} failures/hr. These λ's correspond to MTBFs of from one to ten years.

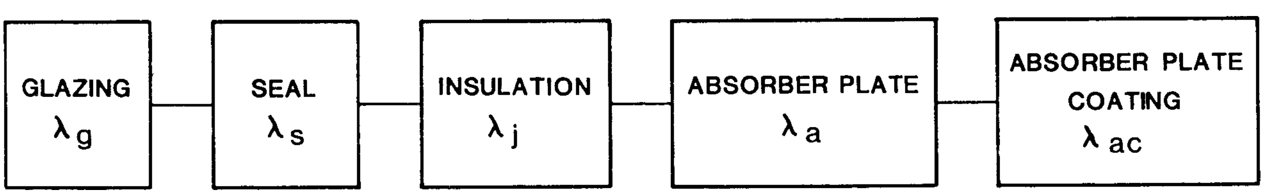

Fig. A.2 Reliability Block Diagram of Collector Panel

A.3.5 Operational Failure Rates

Base failure rates obtained from field data, warranty information, or reliability studies are based on the assumption the component operates under normal conditions. However, operational parameters such as temperature, voltage, time of day, etc. modify the base-failure-rate values.

Reference 1 suggests the following functional expressions for a component's failure rate, depending on the component and on available testing data:

$$\lambda_p = \lambda_b \, (f_1 \times f_2 \times f_3 \times \ldots \times f_n) \tag{A.7}$$

where:

λ_p = component failure rate

λ_b = base failure rate under normal operating conditions

$f_1, f_2, \ldots, f_n$ = environmental parameters affecting the failure rate

For the majority of the components used in solar DHW systems, the various environmental parameters used in Eq. A.7 are not available at the present time. However, data from the National Solar Data Network indicate that certain components have duty cycles, operating for only a portion of each day.[65] In this situation, a component's operational failure rate can be estimated from:

$$\lambda_p = \lambda_b[d + (1 - d)a] \tag{A.8}$$

where:

λ_p = component failure rate

λ_b = component's base failure rate

d = daily duty cycle (operating hr/24)

a = parameter to account for degradation during non-operating periods

The values assigned to the degradation parameter by the military range from zero to one-half. When the value is zero, the component is not degraded during non-operational periods. If a is assigned a value, say one-half, then under non-operating conditions, the component degrades at one-half of the fully-operational rate.

A.3.6 Solar DHW Operational Failure Rate Summary

The operational failure rates (λ_p) for solar DHW components are computed from Eq. A.8. Table A.1 summarizes this information, as well as the duty-cycle parameters, degradation parameters, and MTBFs.

Table A.1 Failure-Rate Ranges for Solar DHW Components

Component	Base Failure Rate[a] λ_b (failures/10^6 hr)	Duty-cycle Parameter[b] d	Assumed Degradation Parameter[c] a
Single collector panel	11.4-114	0.25	0.0-0.5
Control system	5.7-28.5	1.0	0.0
Storage tank or expansion tank	7.6-23	1.0	0.0
Polymeric hose	23-38	1.0	0.0
Piping system	0.02-5	1.0	0.0
Pump	8-150	0.25	0.2-0.4
Powered valves	5.7-57	0.25	0.0-0.5
Check valves	5.7-11.4	1.0	0.0
Pressure relief valves	5.7-11.4	1.0	0.0
Air vent or air separator	14-200	1.0	0.0
Heat exchanger	2.3-14	0.25	0.2-0.4
Heat exchanger in storage tank	11.4-23	1.0	0.0
Motorized damper	11-38	0.25	0.2
Back-draft damper	4.5-29	0.25	0.2
Fan	22-44	0.25	0.0

[a]Base failure rate is obtained from Refs. 23, 52, or 66, or by calculation.

[b]Duty-cycle parameter comes from Ref. 65.

[c]Degradation parameter is based on engineering judgment. This parameter ranges from 0 to 0.5.[1]

A.4 SYSTEM RELIABILITY

In developing a reliability model for a specific system, the main concern is to include a degree of complexity that is appropriate for the accuracy required and the data available. An overly complex model produces analytical difficulties and insufficient data. A simplified model can lead to inaccurate conclusions and difficulties in substantiating the assumptions.

One of the tasks in deriving a reliability formula is to prepare a functional diagram of the system describing how the input and output elements are related. System reliability is, therefore, a reflection of the successful operation of one or more of the component parts. Conversely, system malfunction is represented by one or more component malfunctions. The failures or successes of the components can combine in series so that if any one fails, the system fails. On the other hand, components can be combined in parallel, so that when one component fails, another is available to perform the same function.

A more complex configuration consists of system components operating in series and parallel combinations. System reliability is computed by entering the block reliabilities and failure rates in the system-reliability formula and evaluating the resulting equation for the time periods of interest. Computation of system reliability provides an estimate of the MTBF. The MTBF then can be used to estimate system availability.

An example of a reliability block diagram for a drain-down solar DHW system is shown in Fig. A.3. This figure represents all of the major system components and indicates that the two collector panels are connected in parallel. The reliability of this system, given the assumption that at least one of the two collector panels must be working, is given by:

$$R_s(t) = 2\exp[-(\lambda_c + \lambda_x)t] - \exp[-(2\lambda_c + \lambda_x)t] \tag{A.9}$$

and the mean time between failures is:

$$MTBF = [2/(\lambda_c + \lambda_x)] - [1/(2\lambda_c + \lambda_x)] \tag{A.10}$$

where $\lambda_x = \lambda_{cs} + 2\lambda_v + \lambda_t + \lambda_p + \lambda_{ps} + \lambda_{cv} + \lambda_{rv} + \lambda_{av}$

and the description of the various λs is shown in Fig. A.3.

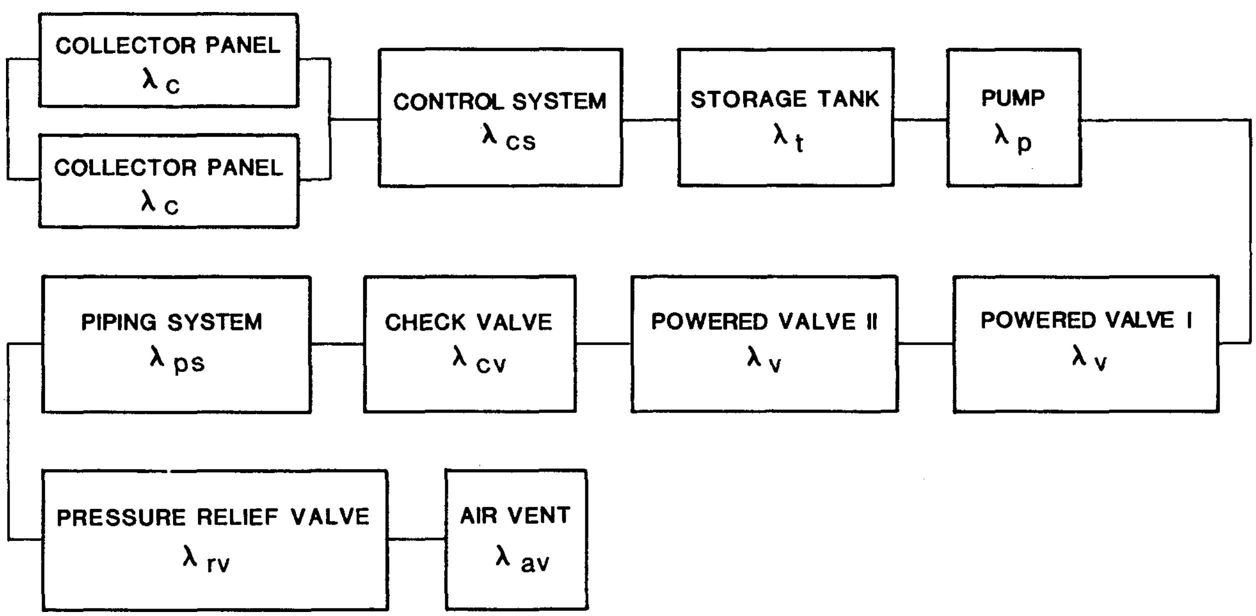

Fig. A.3 Reliability Diagram of Drain-Down System with Two Collector Panels

If both collectors are required to meet the load, the system reliability is:

$$R_s(t) = \exp[-(2\lambda_c + \lambda_x)t] \quad (A.11)$$

and the mean time between failures is:

$$MTBF = 1/(2\lambda_c + \lambda_x) \quad (A.12)$$

where λ_x has been previously defined.

Because some of the components, such as collectors, pumps, and solenoid valves, operate for only a portion of each day, Eq. A.8 and data in Table A.1 must be used to modify the expressions for λ_x and λ_c. The new expressions are:

$$\lambda_x = \lambda_{cs} + \lambda_t + \lambda_{cv} + \lambda_{rv} + \lambda_{av} + 2\lambda_{bv}[d + (1 - d)a] + d\lambda_{bp} \quad (A.13)$$

and $\lambda_c = \lambda_{bc}[d + (1 - d)a]$

where:

λ_{cs}, λ_t, λ_{cv}, λ_{rv}, λ_{av} are defined in Fig. A.3

λ_{bv} is the base failure rate for the powered valve

λ_{bp} is the base failure rate for the powered pump

d is the duty-cycle parameter

a is the degradation parameter

The form of Eqs. A.9 through A.12 remains the same.

Based on Eqs. A.9 through A.12 and the component failure rates summarized in Table A.1 of this appendix, the reliability curves for the drain-down system (see Fig. A.3) are shown in Fig. A.4. These results do not include the effects of a duty cycle. The large variation in system reliabilities and mean lives reflects the wide failure-rate band for some of the components, such as pumps and air vents.

The curves in Fig. A.4 bound the reliability of drain-down one-tank systems that do not use polymeric hose interconnections. Curves 1 and 3 indicate that with low-failure-rate components, a two-panel parallel-collector array is approximately 1.2 times more reliable after one year of operation than the same panels connected in series. At the other extreme of the failure-rate data, curves 2 and 4, it does not matter if the collector panels are connected in series or parallel.

A.5 SUMMARY OF SYSTEM-RELIABILITY EQUATIONS

Solar DHW systems are designed around two to four collector panels. Depending on the system configurations, the collectors can be arranged in

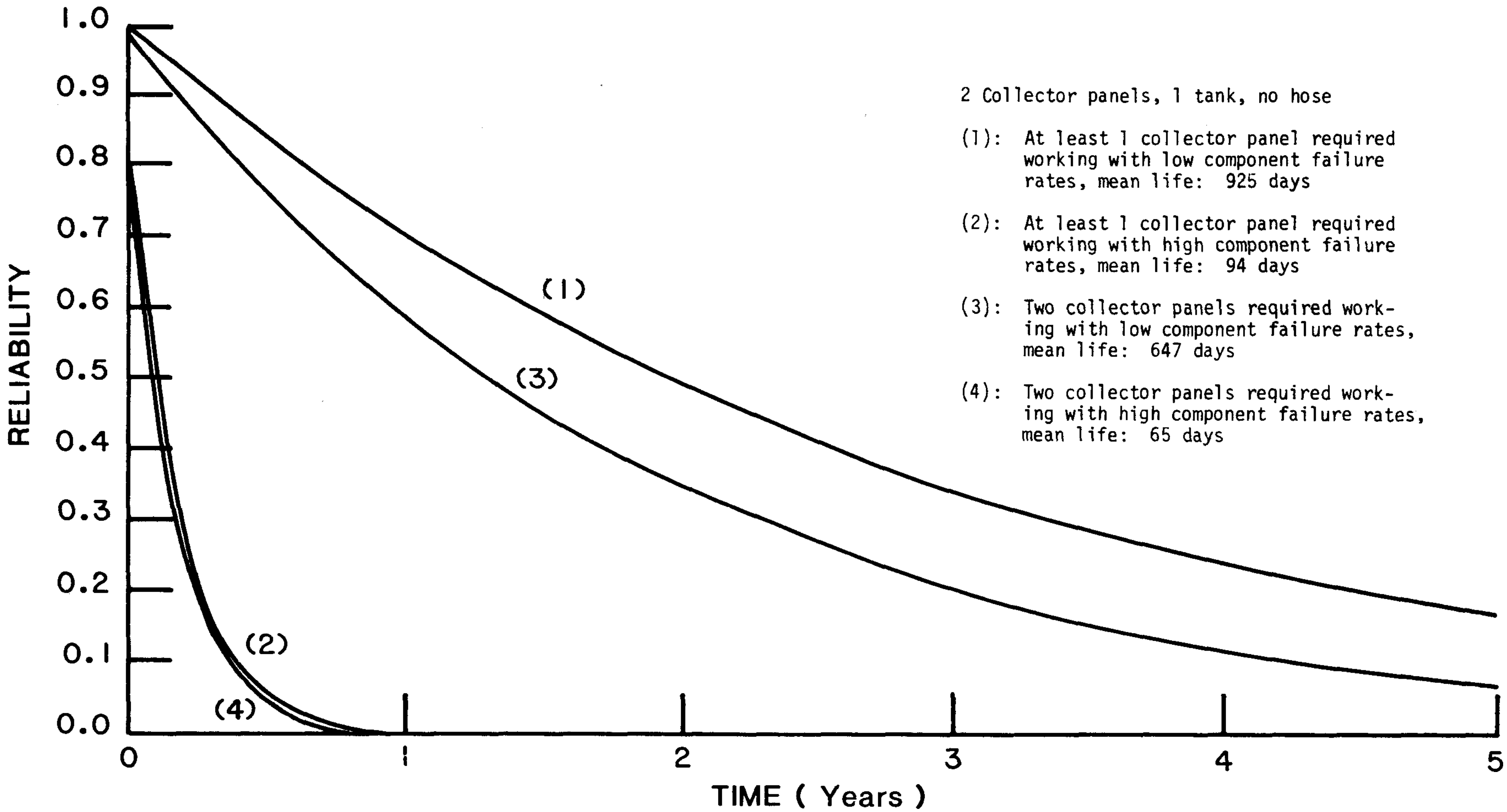

Fig. A.4 Reliability Estimates for Drain-Down Systems series or in parallel. The following expressions are used to estimate reliability worth, $R_s(t)$, and mean operating life, MTBF, of solar DHW systems.

For systems with two collector panels and at least one collector panel required at a working condition of at least 50% load:

$$R_s(t) = 2 \exp[-(\lambda_c + \lambda_r)t] - \exp[-(2\lambda_c + \lambda_r)t] \quad (A.14)$$

$$MTBF = [2/(\lambda_c + \lambda_r)] - [1/(2\lambda_c + \lambda_r)] \quad (A.15)$$

For systems with two collector panels and both collector panels required at a working condition of full load:

$$R_s(t) = \exp[-(2\lambda_c + \lambda_r)t] \quad (A.16)$$

$$MTBF = 1/(2\lambda_c + \lambda_r) \quad (A.17)$$

For systems with four collector panels and at least two collector panels required at a working condition of at least 50% load:

$$R_s(t) = 6 \exp[-(2\lambda_c + \lambda_r)t] - 8 \exp[-(3\lambda_c + \lambda_r)t] + 3 \exp[-(4\lambda_c + \lambda_r)t] \quad (A.18)$$

$$MTBF = [6/(2\lambda_c + \lambda_r)] - [8/(3\lambda_c + \lambda_r)] + [3/(4\lambda_c + \lambda_r)] \quad (A.19)$$

For systems with four collector panels and at least three collector panels required at a working condition of at least 75% load:

$$R_s(t) = 4 \exp[-(3\lambda_c + \lambda_r)t] - 3 \exp[-(4\lambda_c + \lambda_r)t] \quad (A.20)$$

$$MTBF = [4/(3\lambda_c + \lambda_r)] - [3/(4\lambda_c + \lambda_r)] \quad (A.21)$$

For systems with four collector panels and all four collector panels required at a working condition of full load:

$$R_s(t) = \exp[-(4\lambda_c + \lambda_r)t] \quad (A.22)$$

$$MTBF = 1/(4\lambda_c + \lambda_r) \quad (A.23)$$

where:

λ_c = the failure rate of a single collector panel, from Eq. A.13.

λ_r = the sum of the failure rates of all system components except collector panel. For cyclic operations of pumps and powered valves, λ_r should be modified as in Eq. A.13.

The preceding equations for estimating system reliability and MTBF are based on the assumption that the same duty cycle applies for each day of the year. If the components undergo n different duty cycles (n different values of d), through a period of time T (number of sunny days in one year), system MTBF may be estimated by the following:

An averaged daily-duty-cycle factor, $\bar{d}$, is computed from:

$$\bar{d} = \frac{1}{365} \sum_{i=1}^{n} d_i t_i \qquad (A.24)$$

where d_i is the i-th duty-cycle factor and corresponds to the number of hours per day that sufficient insolation is available, and t_i is the number of days in a year having a duty cycle of d_i.

The value of $\bar{d}$ is then substituted for d in Eq. A.13 to compute λ_x and λ_c. With the new values of λ_c and λ_x known, Eqs. A.14 through A.23 are used to evaluate the system MTBF.

The following example illustrates the method:

A drain-down system with one storage tank and two collector panels, of which one is required to meet load, and without polymeric-hose interconnections, was chosen for analysis. The degradation parameter a is set at zero.

It is assumed that within one year the number of days the system has 2, 4, 6, and 8 hours of operation are 60, 80, 155, and 40 days respectively. The estimated MTBFs (Eq. A.15) corresponding to the specific duty-cycle factors are presented in Table A.1.

From Eq. A.24, the averaged duty-cycle factor is:

$$\begin{aligned}\bar{d} &= [(60 \times 2/24) + (80 \times 4/24) + (155 \times 6/24) \\ &\quad + (40 \times 8/24)]/365 \\ &= 4.63/24\end{aligned}$$

This value of $\bar{d}$ could then be substituted for d in Eq. A.13, and the MTBF calculated from Eq. A.15 would range from 145 to 923 days.

A.6 FAILURE RATES FROM FAILURE-MODES-AND-EFFECTS ANALYSIS

Failure-modes-and-effects analysis (FMEA) is a reliability-analysis technique that is well suited to solar-energy systems, because solar DHW systems tend not to have any redundancies to avoid single-failure modes. In the FMEA technique, each component is examined to determine the ways that the component can fail, and the consequences of each failure mode are assessed with respect to the total system. The probability of failure is computed by summing the failure probabilities that contribute to a specific failure. Table A.2, a portion of the FMEA for a DHW control system, illustrates the technique, and Refs. 78 and 79 present other applications.

For the control systems used in solar DHW systems, FMEA yields failure rates between 5.7 x 10^{-6} and 28.5 x 10^{-6} failures/hr.

Table A.2 Portion of Failure-Modes-and-Effects Analysis for DHW Control System

Component	Failure Mode	Direct Effect	Effect on System	Failure Rate ($/10^6$ hr)
Resistor R1	Open	Sensor S_1 signal becomes erratic.	System operates in an erratic manner.	0.003
	Shorted	Sensor S_1 signal rises to saturation level.	Pump does not start when solar energy is available.	0.003
Resistor R9	Open	Integrated-circuit reference voltage is out of range, and amplifier can not turn on.	Pump can not operate in automatic mode.	0.003
	Shorted	Integrated circuit reference input is too low, and amplifier is on.	Pump runs continuously.	0.003

APPENDIX B

PROCEDURE FOR DETERMINING APPROXIMATE LOW-TEMPERATURE DIFFERENTIAL SET POINT

The selection of the low-temperature differential set point is more critical than the choice of the high set point. If the low-temperature set point is too low, the collector-loop pump either runs continuously or runs too late in the day. In either case, the electric energy required to operate pump P-1 may exceed the solar energy available for use by the homeowner.

Proper low-temperature-set-point selection requires a comparison between the value of the energy collected and the operating cost to collect the solar energy. The following five-step procedure includes an example showing how to estimate the proper low-temperature set point.

Step 1: Estimate or Measure the Power Consumption of Pump P-1

The first step in estimating the low-temperature set point is to calculate the electric power required to operate the solar-energy system. There are two approaches for computing the electric-power consumption, design and field.

Design Approach

- Compute the total pressure drop at the design flow rate for the proposed system.
- Select a pump that meets these requirements.
- For the selected pump, use manufacturers' curves to determine brake horsepower of pump (BHP).
- Compare the pump head at the required flow rate with the full-load capacity of the pump/motor combination.
- Use curves similar to those in Fig. B.1 to determine the motor efficiency (η). If the selected motor is oversized, the motor-efficiency rating is reduced.
- Compute the power consumed by the pump/motor combination in kilowatts by using:

$$P = 0.745\ (\mathrm{BHP})/\eta \qquad (\mathrm{B.1})$$

Field Approach. After the solar DHW system has been installed, the design calculations for pump power consumption should be verified by measurements on the actual system. A wattmeter can be used as shown in Fig. B.2 to make the measurement. If a wattmeter is not available, the voltage and current must be measured. Figure B.3 indicates how to attach the voltmeter and ammeter. The following equations give pump power in kW:

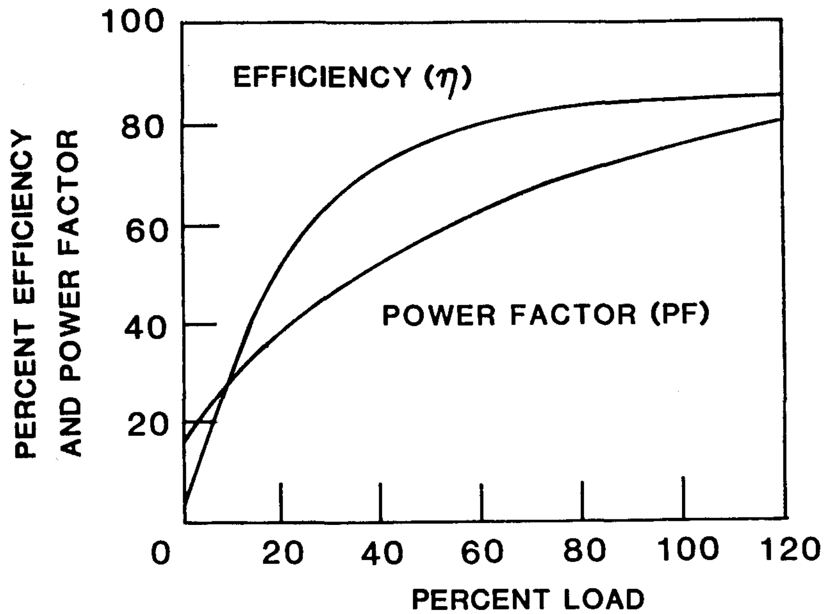

Fig. B.1 Motor Efficiency Curves. (Curves apply only to one motor design of one manufacturer and are not to be generalized. There are many electric motors of different designs and efficiencies. Without the manufacturer's data, determination of motor efficiency is impossible. However, such data may give efficiency as 90%, 80%, etc. This rating is only for full-load conditions. Other operating points are required to establish a curve showing true motor efficiency.)

$$P_3 = 1.732\ V_L I_L(PF)/1000 \qquad (B.2)$$

for three-phase motors, and

$$P_1 = VI(PF)/1000 \qquad (B.3)$$

for single-phase motors.

The symbols are identified in Fig. B.3. Note that if a voltmeter and an ammeter are used, motor power factor (PF) has to be known in order to calculate the power consumption.

Advantages and Disadvantages of Design versus Field Approach

The advantage of the design approach is that the designer can select the low-temperature differential set point during the design phase and have the necessary information prepared prior to adjusting the differential thermostat in the field. The disadvantages of this approach are:

- The pump head and brake horsepower calculated during the design phase may not coincide with the pump head and brake horsepower of the installed system.
- It may be difficult, if not impossible, to obtain manufacturers' data on motor efficiency at different operating points.
- It is difficult to obtain qualified personnel and equipment to make accurate measurements.

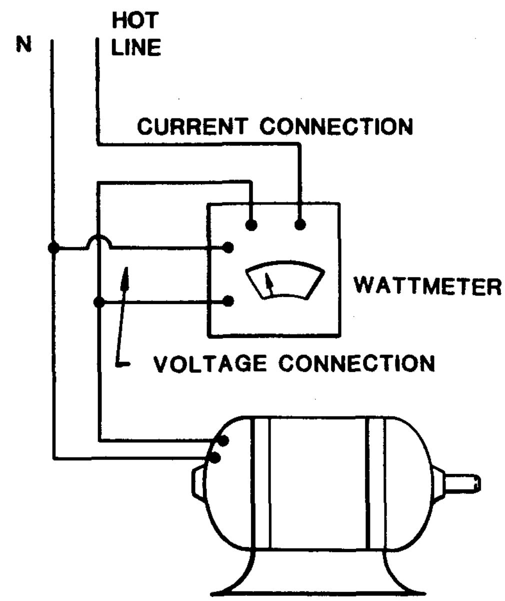

Fig. B.2 Wattmeter Connections across Pump Power Lines

The field approach has the advantage that, within the accuracy of the instruments, the actual electric-power consumption of the solar-energy-collection system can be measured. However, even if the designer provides the control-equipment installer with detailed instructions on how to use these measurements to compute the low-temperature differential set point, the final setting depends on the skill and experience of the installer.

Step 2: Determine Collection-System Energy Costs

The electrical operating costs of the solar DHW system can be computed from:

$$COE = P_c C_e \quad (B.4)$$

where:

COE = operating cost in \$/hr

P_c = power consumed by the pump in kW

C_e = electrical energy cost in \$/kWh

The power consumed by the pump is obtained from field measurement using a wattmeter or can be calculated from Eqs. B.1, B.2, or B.3.

Step 3: Determine the Maximum Energy That Can Be Transported to Storage

Energy transported to storage is expressed as:

$$Q_c = MC(\Delta T) \quad (B.5)$$

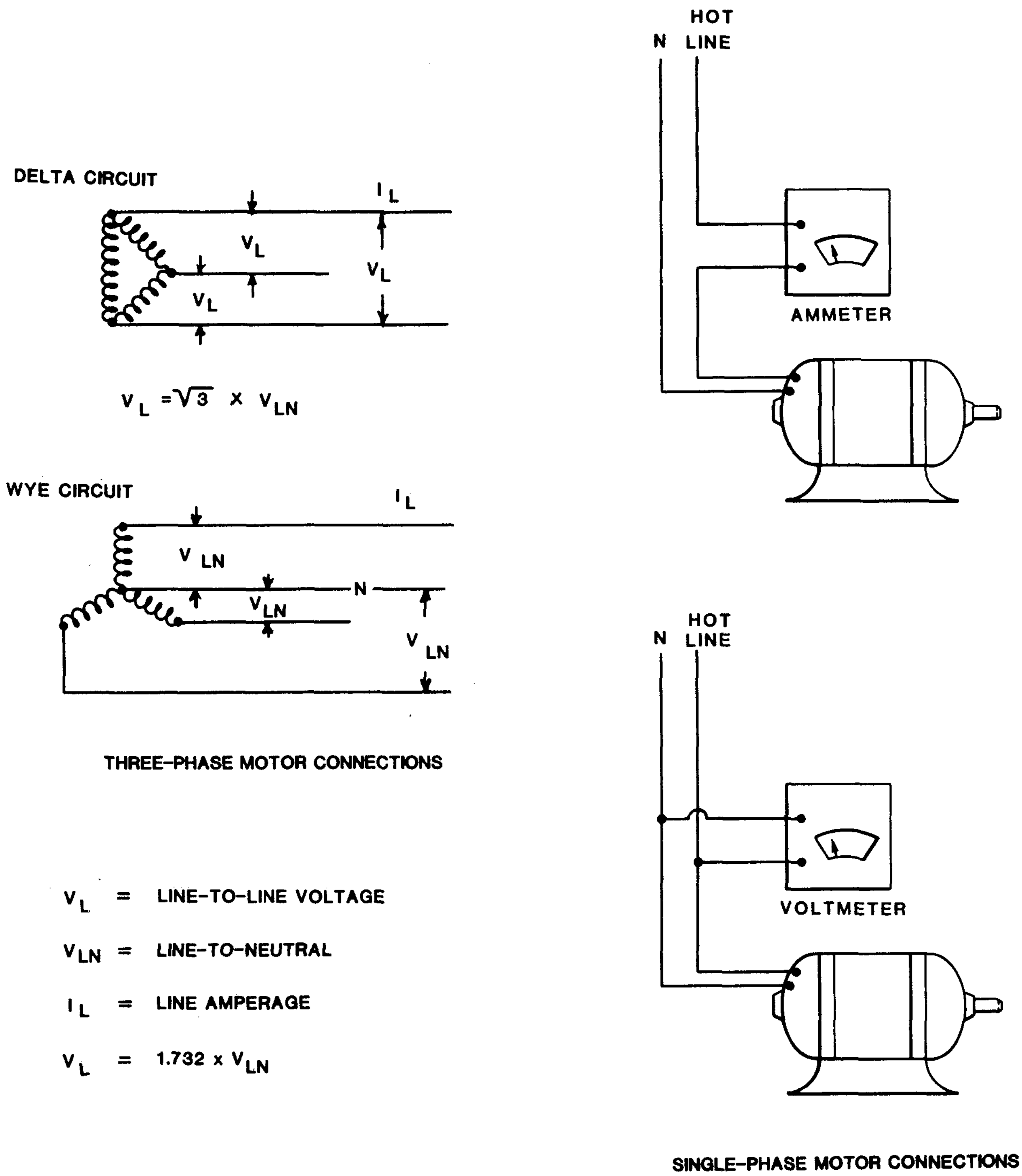

Fig. B.3 Ammeter and Voltmeter Connections into Three-Phase and Single-Phase Motor Circuits where:

Q_c = solar energy collected

M = mass flow rate

ΔT = difference between the temperature in the storage tank and the temperature of the liquid leaving the collectors

C = specific heat

If water is the heat-transport medium, Eq. B.6 gives the energy in Btu/hr:

$$Q_c = 500\ W(\Delta T) \tag{B.6}$$

where:

W = flow of water through the collector loop in gal/min

ΔT = temperature difference in °F

Step 4: Determine the Cost of Solar Energy Collected

To determine the economic benefit of the solar-energy system, the energy collected has to be adjusted for the cost of auxiliary energy needed to produce an equivalent amount of thermal energy. This requires that the seasonal efficiency of auxiliary heaters be considered. Table B.1 gives the seasonal efficiency of an average auxiliary hot-water heater.

The seasonal efficiency values in Table B.1 do not include the standby-heater losses. These losses depend on the size of the tank and tank location (such as a heated or unheated area), as well as on any losses from the preheat tank and associated piping.

The purpose of the cost calculation is to compare the cost of adding heat to storage from a solar heater with the cost of heating with an auxiliary heater. The tank standby losses exist in either case and do not affect the low-temperature differential set point of the solar portion of the DHW system.

Table B.1 Values Characterizing Seasonal Efficiency of Heating Elements

	Seasonal Efficiency (η_s)	
Auxiliary Fuel	Typical DHW Heater	Tankless Coil Heater
Gas	0.5-0.75	-
Oil	0.5-0.7	0.4[a]
Electricity	1	-

[a]Private communication, J. Meeker, Northeast Solar Energy Center.

The cost of the solar energy collected is

$$C_b = C_b'(\Delta T), \text{ and} \quad (B.7)$$

$$C_b' = \left(Q_c/[\eta_s(\Delta T)]\right)C_a \quad (B.8)$$

where:

C_b = cost of solar energy collected in \$/hr

C_b' = cost of solar energy collected per degree of temperature difference in \$/(°F-hr)

C_a = cost of auxiliary energy used in \$/Btu

Step 5: Determine Low-Temperature Differential Set Point

The ideal ΔT is at the point where cost to operate the solar-energy-collection system is equal to the cost of solar energy collected:

$$COE = C_b \quad (B.9)$$

$$= C_b'(\Delta T), \text{ or}$$

$$\Delta T = (COE)/C_b' \quad (B.10)$$

The value of ΔT calculated using Eq. B.10 does not account for sensor inaccuracies. Unless field testing is used to determine the actual temperature difference when solar collection is terminated, the sensor inaccuracies must be added to the calculated temperature difference. See Sec. 2.2.6 for data on sensor accuracies.

Sample Calculation of Low-Temperature Differential Set Point

Assume a collector loop utilizing water as the heat-transport medium at a flow rate of 1.5 gal/min. The auxiliary heater is a gas burner with a seasonal efficiency of $\eta_s = 0.7$. The cost of gas in the area is \$2/10^6 Btu. During field testing, system power consumption was measured using a wattmeter and found to be 120 W (i.e., 0.12 kWh/hour-of-operation). The cost of one kWh is \$0.05. Then the calculation proceeds as follows:

$$COE = P_c C_e$$

$$= 0.12\ (0.05)$$

$$= \$0.006/\text{hr}$$

$$C_a = \$2 \times 10^{-6}/\text{Btu}$$

$$Q_c = 500\ (1.5)(\Delta T)$$

$$= 750\ \Delta T$$

$$C_b' = \left(Q_c/[\eta_s(\Delta T)]\right)C_a$$

$$= 2\left(\frac{750}{0.7}\right) \times 10^{-6}$$

$$= \$0.00214/°F\text{-hr}$$

$$\Delta T = (COE)/C_b'$$

$$= \frac{0.006}{0.00214}$$

$$= 2.8°F\ (1.6°C)$$

APPENDIX C

CALCIUM-CARBONATE-SCALING PREDICTION[44]

The American Society of Testing Materials lists 32 common deposits found in water-handling systems.[80] The nature of the deposits depends on the chemical composition of the water, the thermal conditions under which they are formed, and other factors. These deposits affect DHW system performance by reducing the carrying capacity of the pipes, reducing the efficiency of heat transfer, localizing corrosion attack, and raising operating costs due to inefficiency, increased downtime, and maintenance. Water-treatment techniques can overcome the problem of mineral scale. For these techniques to be effective, the scaling tendency of the water supply must be estimated.

A review of the literature indicates that semiquantitative methods such as the Saturation Index, the Ryznar Index, the critical pH of scaling, and the Palin Index can all be used to predict the point at which a water can scale with respect to the calcium-carbonate concentration. Quantitative techniques, such as the Caldwell-Lawrence (C-L) method, require sophisticated computer programs. A simple computer program in FORTRAN IV, based on the C-L approach, was developed to carry out scaling-prediction analysis.[44] This program is reproduced at the end of this appendix.

To use the computer program to predict the scaling tendency of local water supplies, a water analysis must be performed. This water analysis must include the following information:

- Temperature of the water sample in C°.
- Water pH at the sample temperature.
- Calcium concentration in mg/L of solution.
- Total dissolved solids in mg/L of solution.
- Alkalinity of the solution expressed in ppm of calcium carbonate.

These input data are used to compute various dissociation coefficients and the concentration of various chemical species, as well as the predicted value for the scaling potential in ppm of calcium carbonate at a specified operating temperature.

Although the computer program was written in FORTRAN IV, it can be adapted to any of the available hand-held programmable calculators. This program might sometimes indicate a negative value for the calcium-carbonate scaling potential. If negative values occur, this implies that scaling <u>cannot</u> occur when this water sample is used at the specified temperature.

The input-data format for use with the computer program is:

Card Number	Variable	Definition	Card Columns
1	NS	Number of samples	1-2
2	ID	Sample identification number	1-5
	PH	Sample pH	6-10
	CA	Calcium concentration	11-15
	ALKPPM	Alkalinity in ppm of calcium carbonate	16-20
	TDS	Total dissolved solids in mg/L	21-25
	TS	Temperature of sample in C°	26-30
	TS1	Temperature at which results are required	31-35
	PHL	Lower bound for iteration on pH	36-40
	PHH	Upper bound for iteration on pH	41-45
	AINC	Iteration increment for pH	46-50
	ERR	Error bound for terminating iteration	51-55

Additional cards are for additional samples and have the same format as card No. 2. The total number of cards following the first card is equal to the number of samples (NS).

The values of input data and the results for Sample 9 are listed in Table C.1, followed by the FORTRAN IV computer program:

Table C.1 Input Data and Output Results for Sample 9[a]

Input Data

PH = 7.47
Calcium in PPM = 82.00
Alkalinity in PPM CACO3 = 333.00
Total Solids = 376.00
Low Temp. = 27.00, High Temp = 73.00
Low PH = 6.00, High PH = 9.00
PH Increment in Iteration = 0.00, Error in Iteration = 0.1000

Output Results at 300°K

Alkalinity in PPM CACO3 = 324.64, PH = 7.40
New CA in PPM CACO3 = 196.54, Old CA = 82.00
Old CA as PPM CACO3 = 205.00, Scaling Pot. as CACO3 = 8.36, AT = 300.00DEG K

Output Results at 346 °K

Alkalinity in PPM CACO3 = 266.68, PH = 6.90
New CA in PPM CACO3 = 138.88, Old CA = 82.00
Old CA as PPM CACO3 = 205.00, Scaling Pot. as CACO3 = 66.32, AT = 346.00DEG K

[a]Data for Ulery Greenhouse in Springfield, Ohio.

```
      DOUBLE PRECISION HCO3
      REAL K1,K2,KW,KS
      REAL K1P,K2P,KWP,KSP
      REAL NA,MG
 5    FORMAT (I2)
      READ 5,NS
      DO 560 I=1.AS
      AINC=10.*AINC
      PRINT 1
 1    FORMAT('1')
      READ 10, IC,PH,CA,ALKPPM,TDS,TS,TS1,PHL,PHH,AINC,ERR
 10   FORMAT(1X,A4,10F5.C)
      PRINT 2,ID
 2    FORMAT(10X,'              INPUT T DATA FOR SAMPLE   ',A4,////)
      PRINT 11,PH
 11   FORMAT(10X,'PH =',F10.2)
      PRINT 12,CA
 12   FORMAT(10X,'CALCIUM IN PPM =',F10.2)
      PRINT 13,ALKPPM
 13   FORMAT(10X,' ALKALINITY IN PPM CACO3',F10.2)
      PRINT 14,TDS
 14   FORMAT(10X,' TOTAL SOLIDS =',F10.2)
      PRINT 16,TS,TS1
 16   FORMAT(10X,'LOW TEMP. =',F10.2,'   HIGH TEMP = ',F10.2)
      PRINT 17,PPL,PHH
 17   FORMAT(10X,'LOW PH =',F10.2,'   HIGH PH =',F10.2)
      PRINT 18,AINC,ERR
 18   FORMAT(10X,' PH INCREMENT IN ITERATION ='F10.2,' ERROR IN ITERATION =H
      1ON =',F10.5)
      AINC=10.*AINC
C
      U=2.5*10.E-05*TDS
      U1=U**0.5
      FD=2.0*((U1/(1.0+U1))-0.2*U)
      FD=10.**FD
      FD=1.0/FD
      FM=0.5*((U1/(1.0+U1))-0.2*U)
      FM=10**FM
      FM=1.0/FM
C
      DO 555 J=1,2
      TA=TS+273.0
      IF(J.EQ.2)TA=TS1+273.
      IF(J.EQ.2)TS=TS1
      PK1=(17052./TA)+215.21*ALOG10(TA)-0.12675*TA -545.56
      K1=1.0/10.**PK1
      PK2=(2902.39/TA)+(0.02379*TA)-6.498
      K2=1.0/10.0**PK2
      PKS=(0.01183*TS)+8.03
      KS=1.0/10.**PKS
      PKW=(4787.3/TA)+7.1321*ALOG10(TA) +(0.01037*TA)-22.801
      KW=1.0/10.**PKW
C
      K1P=K1/FM**2
      K2P=K2/FD
      KWP=KW/FM**2
      KSP=KS/FD**2
      K1=K1/FM**2
      K2=K2/FD
      KW=KW/FM**2
      KS=KS/FD**2
      K1=K1*2.5*10.**4
      K2=K2*10.**5
      KW=KW*2.5*10.**9
      KS=KS*10.**10
      IF(J.EQ.2) GO TO 30
C
      HL=-PH-ALOG10(FM)
      HI=10.**HL
      OHL =PH-PKW-ALOG10(FM)
      OHI=10.**OHL
      XP=(HI/K1P)+(K2P/HI)+1.0
      H=HI*(5.0*10,**4)
      ACIDTY=(ALKPPM-(KW/H)+H)*(1.0+(H/K1))/(1.0+K2/H)
      ACIDTY=ACIDTY+H-KW/H
      CONTINUE
```

```
      H=1./(10.**PHL)/FM
      H=(5.0*10.**4)*H
      OH=KW/H
      C2=ALKPPM-(CA/40.)*100.
      B=C2-OH+H
      B2=B**2
      AC4=4.0*((K2/H)+1.0)*KS*H/K2
      Z=(B2+AC4)
      SRZ=Z**0.5
      A2=2.0*((K2/H)+1.0)
      HCO3=(B+SRZ)/A2
      CO2=HCO3*H/K1
      C1=OH-HCO3-CO2-H
      CERR=-C1-ACIDTY
       IF(CERR.LE.ERR) GO TO 500
      IF(PHL.GT.PHH) GO TO 560
      PHL=PHL+AINC
      GO TO 20
500   CONTINUE
      ALKPP=HCO3+K2*HCO3/H+KW/H-H
      CAN=ALKPP-C2
       DCA=(CA/40.)*100.-CAN
      CAP=(CA/40.0)*100.
      PRINT 540
540   FORMAT(//)
      PRINT 550,ID
550   FORMAT(10X,'       OUTPUT RESULTS FOR SAMPLE  ', A4,////)
      PRINT 40,ALKPP,PHL
40    FORMAT(10X,'ALKALINITY IN PPM CACO3 =',F10.2,'   PH =',F10.2)
41    FORMAT(10X,'NEW CA    IN PPM CACO3 ='F10.2,'  OLD CA=', F10.2)
      PRINT 41,CAN,CA
      PRINT 42,CAP,CCA,TA
42    FORMAT(10X,'OLD CA AS PPM CACO3= ',F10.2,'  SCALING POT. AS CACO3 =
      13=',F10.2,' AT=' F10.2, 'DEG  K )
600   FORMAT(10X,'ACIDITY =',F10.2)
      PHL=PHW
555   CONTINUE
560   CONTINUE
700   STOP
      END
```

APPENDIX D

CALCULATION OF THERMALLY INDUCED LOADS FOR SELECTED INTERCONNECTION GEOMETRIES

D.1 INTRODUCTION

The differential thermal expansion that occurs between collectors or between collectors and manifolds can be absorbed by elastomeric connections or tubing configurations. For a given geometry and maximum operating-temperature difference, the thermal load that is applied to the interconnection must be calculated. If these calculations indicate that the interconnection would be overstressed, the interconnection geometry must be modified.

Three basic configurations used for interconnecting collectors and manifolds are shown in Fig. D.1. In each of these cases, tubing is used to make the connections between collector and manifold. In addition, the inlet or outlet at Point B is assumed to be fixed and the interconnection is attached to the manifold at Point A. Because of the thermal expansion of the manifold, the end of the interconnection moves a distance D, generating a force P and a moment M at the end of the interconnection. Figure D.1 illustrates the initial and deformed configurations. The governing equations for these configurations were developed in Ref. 50.

D.1.1 Case I, Straight Metal Tube

The deflection at Point A is

$$D = \alpha(\Delta T)L_m \tag{D.1}$$

where:

α = coefficient of thermal expansion for the manifold in in./(in.-°F)

ΔT = temperature difference experienced by the manifold in °F

L_m = the manifold length in in.

The force at the end of the manifold is given by

$$P = 12\ EID/L^3 \tag{D.2}$$

and the moment exerted at Point A is

$$M = 6\ EID/L^2 \tag{D.3}$$

where:

D = deflection from Eq. D.1

E = modulus of elasticity in $lb/in.^2$

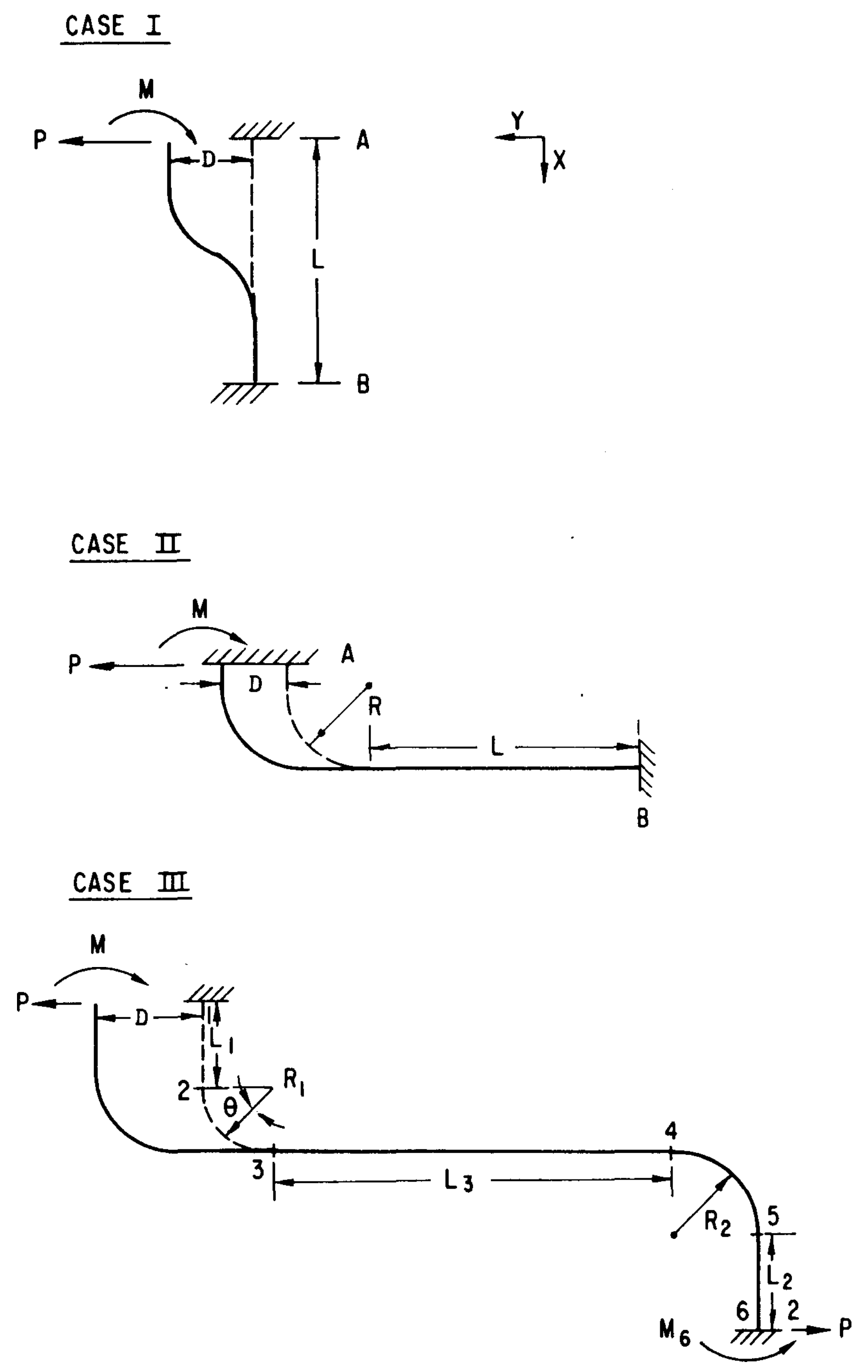

Fig. D.1 Three Collector-to-Manifold Interconnection Geometries

I = moment of inertia of the tubing cross section in $in.^4$

L = length of the interconnection in in.

D.1.2 Case II, An Elongated Ell

For this configuration, the relation between the load P and the moment M is

$$P/M = (1.57\ R + L)/(R^2 + RL) \tag{D.4}$$

The load P as a function of the displacement of the manifold is

$$P = EID\left(R^2\left[(0.785\ R + L) - (R + L)^2/(1.57\ R + L)\right]\right)^{-1} \tag{D.5}$$

where R is the radius in inches, the other symbols having been defined previously.

D.1.3 Case III, A Zee

This configuration is the most complicated, because the designer can vary R_1 and R_2, as well as L_1, L_2, and L_3. For this configuration, the relation between P and M is given in Eqs. D.6 and D.7.

$$\begin{aligned} P/M = {} & [L_1^2 + R_1(2R_1 + 3.14L_1) + 2L_3(L_1 + R_1) \\ & + R_2(1.14R_2 + 3.14(L_1 + R_1)) + L_2(L_2 + 2(L_1 + R_1 + R_2))]^{-1} \\ & [2(L_1 + L_2 + L_3) + 3.14(R_1 + R_2)] \end{aligned} \tag{D.6}$$

$$\begin{aligned} P = EID\Big\{ & 0.33\ L_1^3 + R_1(0.79R_1^2 + L_1R_1 + 1.57\ L_1^2) + L_3(L_1 + R_1)^2 \\ & + R_2[0.37R_2^2 + 1.14R_2\ (L_1 + R_1) + 3.14(L_1 + R_1)^2] \\ & + L_2[0.33L_2^2 + L_2(L_1 + R_1 + R_2) + (L_1 + R_1 + R_2)^2] \\ & - [L_1^2 + R_1\ (2R_1 + 3.14L_1) + 2L_3(L_1 + R_1) \\ & + R_2(1.14R_2 + 3.14(L_1 + R_1)) \\ & + L_2(L_2 + 2(L_1 + R_1 + R_2))]^2\ [4(L_1 + L_2 + L_3) \\ & + 6.28\ (R_1 + R_2)]^{-1}\Big\}^{-1} \end{aligned} \tag{D.7}$$

where the various symbols have been defined previously.

D.2 SAMPLE CALCULATION

To illustrate the effect of length or radius on the loads that can develop as a result of thermal expansion, consider the following:

A steel manifold is 10 ft long, and the maximum temperature difference is 200°F. The interconnection between the manifold and the collector is a copper tube with an outer diameter of 1.0 in. and an inside diameter of 0.86 in. For these conditions, the variation of the load P with either L or R is shown in Fig. D.2. From these results, it can be seen that for cases I and II, a critical length dimension is approximately 8.0 in. For any length less than 8.0 in., the thermally induced loads increase sharply. Similarly, a critical radius for case III is approximately 6.0 in.

Knowing the magnitude of the thermally induced load, the designer must then compare the load P with the load that can be carried by the absorber panel. (This information must be obtained from the collector manufacturer.) If P exceeds the collector manufacturer's specifications, the interconnection must be redesigned and made more flexible.

After the thermally induced load P has been reduced to the point where it can be carried by the absorber plate, the load probably can be carried by the mechanical attachment, such as elbows, flare fittings, and solder, at the manifolds. However, a stress analysis should be performed to determine how much of a safety factor exists.

The results presented in Fig. D.2 are for a steel manifold and a copper tube. These results can be extended to other materials and tube diameters. For a fixed interconnection geometry, the load equations can be rewritten in the following form:

$$P = \frac{\alpha L_m E I(\Delta T)}{k} \tag{D.8}$$

where k is a constant specifying the interconnection geometry (L, R). The form of Eq. D.8 allows comparison to be made by developing the following ratio:

$$\frac{P_2}{P_1} = \frac{\alpha_2 L_{m2} E_2 I_2 (\Delta T_2)}{\alpha_1 L_{m1} E_1 I_1 (\Delta T_1)} \tag{D.9}$$

where the subscript 1 corresponds to the conditions represented in Fig. D.2 and the subscript 2 corresponds to the new conditions.

If only the manifold L_m changes, then the magnitude of the new load to be carried by the interconnection is given by

$$P_2 = P_1 \left(\frac{L_{m2}}{L_{m1}} \right) \tag{D.10}$$

For a fixed manifold length, temperature difference, and tubing cross-section, a new material for either the interconnection or the manifold will change the interconnection load to

$$P_2 = P_1 \left(\frac{\alpha_2 E_2}{\alpha_1 E_1} \right) \tag{D.11}$$

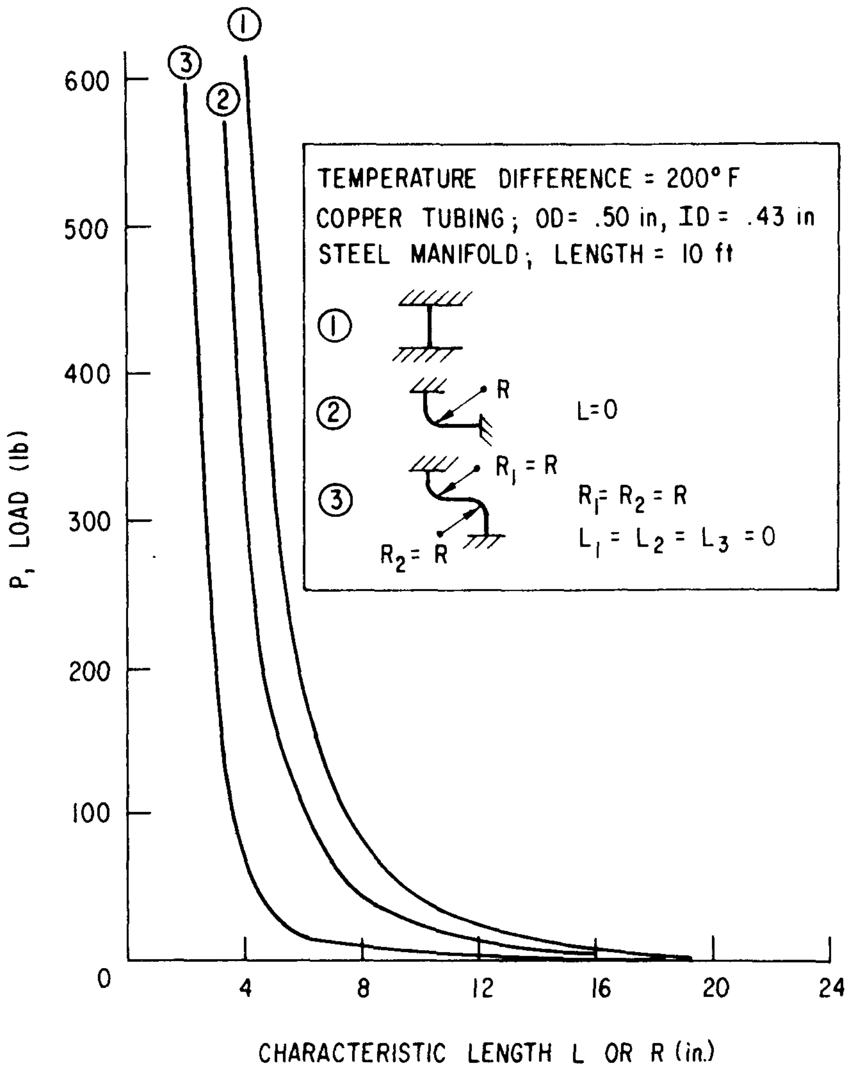

Fig. D.2 Applied Thermal Loads and Characteristic Lengths for Three Interconnection Designs

For a copper tube and a copper manifold

$$P_2 = 1.41\ P_1 \tag{D.12}$$

and for a steel tube and steel manifold

$$P_2 = 2\ P_1 \tag{D.13}$$

Therefore, by changing materials, the loads in the interconnection tubing have increased. To determine if the tubing can sustain these loads, the tubing stress must be calculated and compared with the allowable values.

APPENDIX E

EXCERPTS FROM U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT INTERMEDIATE PROPERTY STANDARDS ON HEAT-EXCHANGER REQUIREMENTS

To protect solar collectors from freezing, antifreeze solutions are used. These solutions are toxic and must be separated from the potable-water supply by double-walled heat exchangers. The standards recommended by the U.S. Department of Housing and Urban Development (HUD) for liquid-to-liquid heat exchangers are summarized below.

S-615-10 Plumbing

S-615-10.1 Handling of Nonpotable Substances

Potable-water supply shall be protected against contamination in accordance with the prevailing model plumbing code having jurisdiction in the area, as well as following requirements.

S-615-10.1.1 Separation of Circulation Loops

Circulation loops of subsystems utilizing nonpotable heat-transfer fluids shall either be separated from the potable-water system in such a manner that a minimum of two walls or interfaces is maintained between the nonpotable liquid and the potable-water supply or otherwise protected in such a manner that equivalent safety is provided.

Commentary: Double-walled heat-exchanger designs are one way of meeting the intent of this criterion. When double-walled heat-exchanger designs consisting of two single-walled heat exchangers in combination with an intermediary potable heat-transfer liquid are used, leakage through one of the walls would result in a single-walled configuration. Although this design is considered to meet the intent of this criterion, there are several other designs that avoid this problem.

The use of single-walled configurations that rely solely upon potable-water pressure to prevent contamination is not considered to be an acceptable solution. Similarly, extra-thick single walls do not meet the intent of this criterion.

For approval of other than double-walled designs, the procedures described in S-101 should be utilized.*

---

*S-101, "Variations to Standards," an earlier section of HUD Intermediate Minimum Property Standards, lists general goals and refers to Section 101-4 of MPS 4900.1, Minimum Property Standards for One- and Two-Family Dwellings, which contains details for approval of single- and multiple-occurrence variations.

S-615-10.1.2 Identification of Nonpotable and Potable Water
In buildings where dual fluid systems, one potable water and the other nonpotable fluid, are installed, each system may be identified either by color marking or metal tags as required in ANSI A13.1-1956 (Scheme for the Identification of Piping Systems, American National Standards Institute) or other appropriate method as may be approved by the local administrative code authority. Such identification may not be required in all cases.

S-615-10.1.3 Backflow Prevention
Backflow of nonpotable heat-transfer fluids into the potable-water system shall be prevented in a manner approved by the local administrative code authority.

Commentary: The use of air gaps and/or mechanical backflow preventers are two possible solutions to this problem.

At present, the Uniform Plumbing Code (UPC) published by the International Association of Plumbing and Mechanical Officials (IAPMO), the Standard Building Code (SBC) published by the Southern Building Code Congress International (SBCCI), and the National Standard Plumbing Code (NSPC) published by the National Standard Plumbing Code Committee (NSPCC) require double-walled heat exchangers having separated walls to separate potable water from nonpotable fluids. If one wall of such a heat exchanger leaks, the heat exchanger must incorporate some form of leak detection, either visual, electrical, or mechanical. Most local building-code authorities adopt one of these codes.

Because of the severe performance penalty imposed by double-walled heat exchangers, the American Society of Mechanical Engineers (ASME) under the auspices of the American National Standards Institute (ANSI) is working on less restrictive standards for heat exchangers. When these standards are finished, probably in 1981, they may be adopted by the organizations listed previously.

APPENDIX F

REFRIGERANT-CHARGED SOLAR DHW SYSTEMS

A type of generic DHW system now being installed uses refrigerant to cool the collectors. These systems have not been evaluated in any of the federally funded DHW programs, and thermal-performance and reliability data are not available. In addition, the design is proprietary, patents have been applied for, and detailed design data are not available.

These systems operate in either a passive or an active mode. Figures F.1 and F.2 are schematic diagrams of the two system types.

In the passive system, the liquid refrigerant is vaporized in the collector and thermosiphons into the heat exchanger, where it condenses to a liquid. A pump circulates water through the single-walled heat exchanger to the solar preheat tank.

The active version of the refrigerant system has a compressor to move the refrigerant through the collector loop. A low-wattage circulatory pump moves water through the heat exchanger into the solar preheat tank.

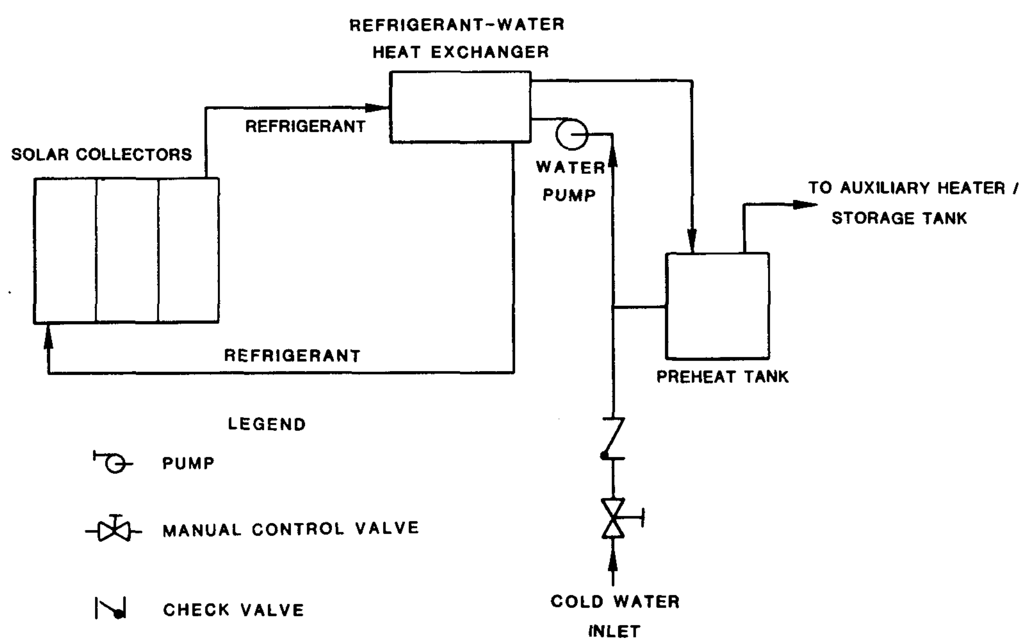

Fig. F.1 Passive Refrigerant-Charged System

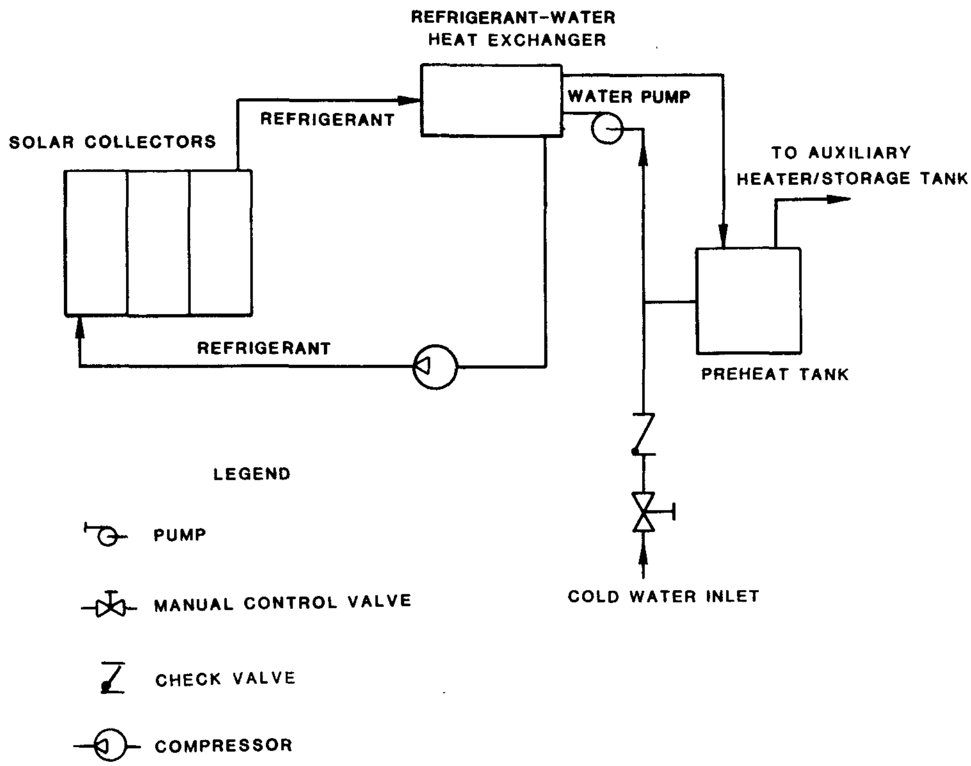

Fig. F.2 Active Refrigerant-Charged System

APPENDIX G

GLOSSARY

Active system	A solar-energy system that requires pumps or fans to circulate a heat-transfer fluid through solar collectors and heat exchangers
Air-type collector	A solar collector that uses circulating air as the heat-transfer medium
Ambient temperature	The temperature of the surrounding environment as measured by a dry-bulb thermometer
Antifreeze loop	A closed circuit consisting of the solar collectors, a pump, and a heat exchanger, through which an antifreeze solution circulates
Aqueous solution	A mixture of a given substance (such as ethylene glycol) with water
Auxiliary system	A system that provides heat when solar energy alone is insufficient (a backup system)
Cathodic protection	A method of corrosion protection in which a highly reactive metal bar is placed in the system liquid. To be effective, the metal bar must be more reactive than the most reactive metal component in the system and must have a continuous electrical path to the most reactive metal component.
Coil-in-tank heat exchanger	A coil of tubing inside a tank. One heat-transfer fluid circulates through the tubing, while the other flows over the outside surface of the tubing by natural convection.
Collector coolant	Any heat-transfer medium used in a solar collector
DHW	Potable domestic hot water
Dielectric bushing	An electrically insulating connector used to connect components composed of dissimilar metals
Differential thermostat	A device that uses a measured temperature difference to control a pump or fan
Drain-back system	In these systems, the water in the solar collectors is drained into the storage tank on cold nights to protect against freezing.
Drain-down system	In these systems, the water in the solar collectors is drained into the sewer on cold nights to protect against freezing.
Electrolytic solution	A liquid that can conduct electricity. When dissimilar metals are in contact with an electrolytic solution, galvanic corrosion can occur.

Expansion tank	A device used to limit the pressure increase caused by thermal expansion of the liquid in a sealed system
Heat exchanger	A device for transferring heat from one fluid (liquid or gas) to another while preventing mixing of the two fluids
Heat-transfer medium	A fluid (liquid or gas) used to transport heat from one location to another. Typical heat-transfer fluids include air, water, and antifreeze solutions.
Insolation	The amount of solar energy incident on a unit of surface area per unit of time
Insulation	A material used to prevent the transfer of heat, sound, or electricity
Mean time to failure (MTTF)	The mean time a component or system operates under stated conditions before failure occurs
Mean life (ML)	The total operating time of an equipment population, divided by the total number of failures. The operating time of that portion of the equipment population that did not fail must be included.
Mean time between failures (MTBF)	The mean time, after a system or component has failed and been repaired, before the system or component fails again
Net-positive-suction head	The positive absolute pressure (head) required at the inlet to a pump in order to prevent damage by cavitation
Nonpotable fluid	A fluid that does not meet federal, state, or local standards for drinking water
Potable water	Water that meets federal, state, and local quality and safety standards for drinking water; water fit for human consumption
psi	Pounds per square inch, a unit of pressure. Unless otherwise specified, pressure is measured relative to atmospheric pressure. (Compare with psig and psia.)
psia	Pounds per square inch, absolute pressure. Absolute pressure is always measured relative to vacuum and is, therefore, greater than the gauge pressure by the amount of the atmospheric pressure. (Compare with psi and psig.)
psig	Pounds per square inch, gauge pressure. Gauge pressure is always measured relative to atmospheric pressure. (Compare with psi and psia.)
R-value	Resistance of insulation to heat conduction, given in this document in units of $°F \cdot ft^2 \cdot hr/Btu$

Scale	Deposits of calcium carbonate, calcium silicate, calcium sulfate, or magnesium hydroxide that form on the insides of pipes when water containing these compounds is heated
Scaling coefficient	A factor that expresses the degradation of heat-exchanger performance resulting from formation of scale on the heat-exchange surfaces. The scaling coefficient is the inverse of the fouling factor.
Sealed system	A solar-energy system that excludes oxygen by closing all vents and inlets and outlets for liquids. Exclusion of oxygen in this manner limits one type of corrosion but requires an expansion tank to limit pressure.
Sensor	A device that measures a physical quantity (such as pressure or temperature) and relays the information to a controller
Shell-and-tube heat exchanger	A type of heat exchanger consisting of a bundle of tubes within an outer shell, with baffles to direct the fluid flow. One heat-transfer liquid is pumped through the space between the tubes and the shell.
Tempering valve	A valve that limits the temperature of water flowing from a domestic hot-water tank by mixing this water with cold water
Thermal stratification	Separation of the warmer from the cooler parts of the storage medium within the storage unit
Thermistor	A type of temperature sensor
Thermosiphoning	Motion of a fluid caused by the buoyancy of its warmer portion; natural convection
Thermosiphon system	A pumpless solar-energy system in which the buoyancy of the water heated by the collector causes the water to rise into the storage tank
Toxic fluid	A gas or liquid that is poisonous, irritating, and/or suffocating, as classified in the Hazardous Substances Act, Code of Federal Regulation, Title 16, Part 1500
Trace tank	A type of heat exchanger in which the heat-transfer fluid is carried in a tube wrapped around the storage tank
Wraparound-shell heat exchanger	A metal panel with integral fluid passages that is wrapped around and secured to the storage tank

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