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Reliability and Design Guidelines for Combined Solar-Space-Heating and Domestic Hot-Water Systems

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RELIABILITY AND DESIGN GUIDELINES FOR COMBINED SOLAR-SPACE-HEATING AND DOMESTIC HOT-WATER SYSTEMS

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FOREWORD

This report is based on solar energy system analyses performed under the Solar Reliability and Materials program conducted at Argonne National Laboratory.

The failure rates used in evaluating the space-heating and domestic hot water systems were obtained from nonsolar sources [as was done in the preceding document, "Final Reliability and Materials Design Guidelines for Solar Domestic Hot Water Systems" (ANL/SDP-11, SOLAR/0909-81-70, September 1982)], because consistent reliability data are not available from in-place systems. The available failure rate information has been modified to account for system duty cycles and for component degradation during nonoperating periods. The range of values for the degradation parameter is based on engineering judgement.

The authors gratefully acknowledge the contributions of all those who took part in the Solar Reliability and Materials Program. In particular, W. W. Schertz and his staff provided invaluable guidance and assistance.

RELIABILITY AND DESIGN GUIDELINES OF COMBINED SOLAR SPACE-HEATING AND DHW SYSTEMS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (contd)

LIST OF TABLES

RELIABILITY AND DESIGN GUIDELINES FOR COMBINED SOLAR SPACE HEATING AND DOMESTIC HOT WATER SYSTEMS

ABSTRACT

Concepts of combined solar space-heating and domestic hot water (DHW) systems, and techniques for development of such systems are summarized for engineers and designers. Minimum instrumentation requirements for determining whether such systems are operating properly are discussed, as are start-up and trouble shooting. However, detailed information on design, sizing, and installation are not included. Flat plate and tubular collector modules and generic drain-back systems that use them are analyzed by means of block-type reliability diagrams. System reliability results, based on a 6 h/d duty cycle, are given for five collector array sizes, in terms of mean time between failures. The duty-cycle analysis approach can be similarly applied to other operating cycles.

1.0 INTRODUCTION

1.1 Purpose

This report is intended to provide solar energy engineers and designers and manufacturers of solar energy systems with the concepts and techniques necessary to the development of reliable solar space-heating and domestic hot water (DHW) systems. The system chosen as the subject of this analysis is a generic drain-back type that uses either flat plate or tubular collectors. These guidelines do not provide detailed design, sizing, or installation information about such systems.*

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* System-sizing criteria are specified in various solar energy system simulation codes, such as SOLCOST, TRNSYS, and the f-chart developed by the Solar Energy Laboratory of the University of Wisconsin, as well as the DOE building simulation code, DOE-1. Design information is available from the DOE publication, "Active Solar Energy Design Practice Manual," and installation data from the HUD document, "Installation Guidelines for Solar DHW Systems."

Although this document is intended primarily for solar energy engineers and system designers, do-it-yourselfers may find it useful as a guide to selection of reliable components and to start-up, troubleshooting, and maintenance of their own systems.

1.2 Scope and Organization

This report provides a detailed discussion of closed-loop drain-back residential space-heating and DHW solar systems, which are similar to systems that have been funded and installed under various federal programs. Estimates of mean time between failures are given for closed-loop drain-back systems with flat-plate and tubular collectors, and maintenance and troubleshooting information also is included. Most of the detailed mathematical matter of this report is contained in the Appendixes, which also include information about reliability modeling and selection of low-temperature differential set points.

The component mean-life estimates are based on data from the chemical, electric-power, and nuclear-power industries. These data sources are used because solar-energy systems have not been operating long enough to accumulate appropriate failure-rate statistics.

The generic drain-back system is illustrated schematically and discussed in Section 2, which also contains information on system start-up, maintenance, and estimated mean time between failures (mean maintenance-free time). 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 on the basis of data from several residential systems being monitored by the National Solar Data Network.

1.3 Reliability Engineering Assessment

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

The accepted definition of 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 is a typical failure-rate curve for a system that is assembled from components. When the system is first put on-line (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 life cycle begins. The failure rate drops, 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.

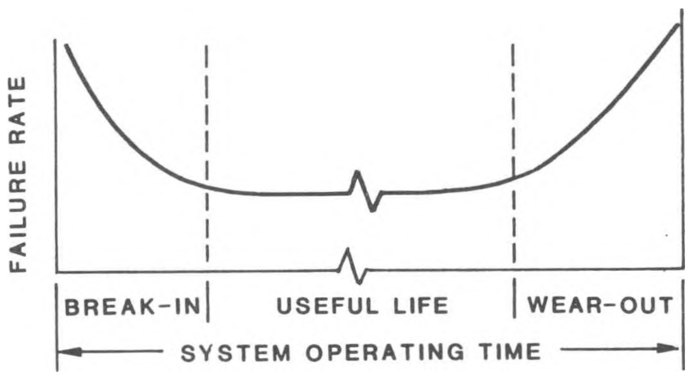

Fig. 1 Typical system failure-rate curve.

After the system has been in service for a certain length of time, wear begins to affect its performance, and the failure rate increases (the wear-out period). At this point a 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

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

Solar energy-system designs are based upon the service to be provided. Although solar energy systems are similar, they are seldom identical. Each system has specific features, and a system designed and installed in New England may not resemble one intended for use in Florida. Despite the differences, reliability engineering can be applied to any system, to reduce downtime and increase productivity.

1.3.1 Component Reliability

As shown in Fig. 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, and

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 of 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 that the manufacturer knows the component operates an average of five hours per day. With this information, an upper bound for the failure rate can be estimated.

$$\text{Operating Time} = 365\ \frac{d}{y} \times 5\ \frac{h}{d} \times 1.25\ y$$

$$= 2281\ h$$

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

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

$$\text{Operating Time} = 365\ \frac{d}{y} \times 24\ \frac{h}{d} \times 1.25\ y \times 2 = 21{,}900$$

$$\text{and } \lambda_{1} = 4.6 \times 10^{-5}\ \text{failures/h.}$$

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

Calendar Time		Operating Time (h)	Estimated Failure Rates (No. of failures/h)
Years	Hours		
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,

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

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 t must be modified and replaced by t.d, 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. Too simplified a 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 inputs and outputs 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, Fig. 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

$\lambda_s = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7$ = system failure rate, and

t = time

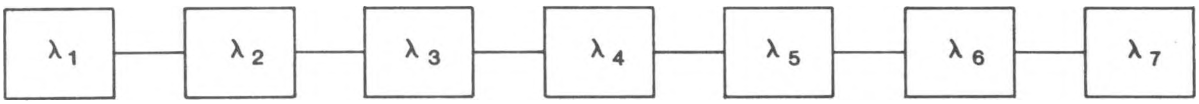

Fig. 2 Block diagram of system of seven components connected in series

The failure rates for the components are presented in Table 2.

The system failure rate, λ_s, 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 rate.

The effect of component 4 can be reduced by using a component of higher quality. If that is not possible, a parallel connection, as shown in Fig. 3, could be considered.

Table 2
Component Failure-Rate Data

Component	Assumed Failure Rate (10^{-5} failures/h)
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 reliablity becomes:

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

where

R_{sp} = system reliability with the parallel component

R_s = original system reliability

*For derivation, see Appendix A

Using data in Table 2, one finds that

$$MTBF_s = \frac{1}{\lambda_s} = 12{,}407 \text{ h}$$

$$MTBF_{sp} = \frac{1}{\lambda_{sp}} = 16{,}163 \text{ h}$$

λ_{sp} = failure rate of system with parallel component

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

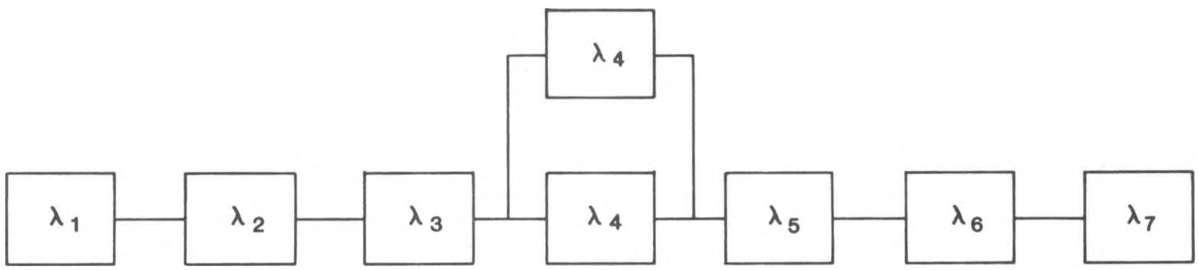

Fig. 3 Block diagram of system with redundant component

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 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 space-heating systems with a domestic hot water (DHW) loop.

2.0 CLOSED-LOOP ONE-TANK DRAIN-BACK SYSTEM FOR COMBINED SOLAR SPACE HEATING AND DHW

2.1 Solar Space-Heating Systems

Solar energy heating systems of various designs have been developed and installed in the United States; those analyzed in this Section are the closed-loop drain-back type for space heating and domestic hot water (DHW). The DHW option has been included in order to provide a load for the collector during summer.

The systems analyzed here differ only in the type of collector: one system uses flat plate collectors, the other uses tubular collectors. Although the schematics included are generic in nature, not representative of any particular design or manufacturer, they represent the components necessary for a complete, functional system. No attempt is made herein to provide for conformance to local codes or practices.

The information given in regard to the combined space-heating and DHW-loop system covers operating modes, controls, start-up procedures, maintenance and troubleshooting, and mean-life estimates. As the system designer modifies a generic system schematic to fit his own purpose, the operating modes and other functional characteristics will change, and the estimated MTBF will no longer apply. The procedures needed for calculating the consequent new values are given in Appendix A.

Solar-energy system control schematics presented here are in ladder-diagram format. Although these diagrams may appear complicated in comparison with the hook-ups for packaged control systems, the manufacturers probably used similar diagrams in developing their off-the-shelf hardware packages.

Because system design and service engineers are more familiar with electromechanical controls than with solid-state devices, this document's descriptions of operating, maintaining, and troubleshooting solar energy systems are tailored to electromechanical controls. However, this approach should not be taken to discourage the use of solid-state controls, which can be more economical and reliable when properly specified and installed.

No detailed discussions of system components per se or materials of construction are presented. Such information, and detailed presentations of material requirements and water-scaling analysis, are given in Reference 2.

2.2 Closed-Loop System Description

The closed-loop drain-back system for solar space heating and DHW depicted in Fig. 4 has water as the collector fluid in a closed collector loop. Freeze protection is accomplished by draining the collector loop completely into a storage tank that is not exposed to freezing temperature. Figure 5 is a control circuit schematic of this system. Collector fluid drain-down occurs every time the solar collector pump, P-1, is shut down. Either flat plate or evacuated tube type of solar collector can be used in the system.

2.3 Operation of the Closed-Loop Drain-Back System

2.3.1 Solar Energy Collection

The system begins to collect solar energy when the temperature differential between the collector sensor, S_1, and sensor S_2 in the storage tank, reaches the high-temperature differential set point, which usually is 20°F (11 °C). When this set point is reached (and providing that contact of a thermal shock prevention thermostat, T-5, is closed*), the normally-open contact in thermostat T-1 closes, energizing pump P-1.

As water is pumped from the storage tank, air is displaced from the collector loop and forced into the storage tank. At first, the pump must lift the water to the top of the collector array; however, unless the return piping is designed for gravity flow, siphon return is established as the air is removed from the lines. From then on, the pump works only against friction. Collection of solar energy continues as long as the low-temperature differential (usually 3-5°F, 2-3 °C) is satisfied. If the temperature differential decreases to the low-temperature set point, or if power is lost, pump P-1 will stop and the water will drain back into the storage tank.

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*For operation of T-5, see subsection 2.3.1, "Thermal Shock Prevention."

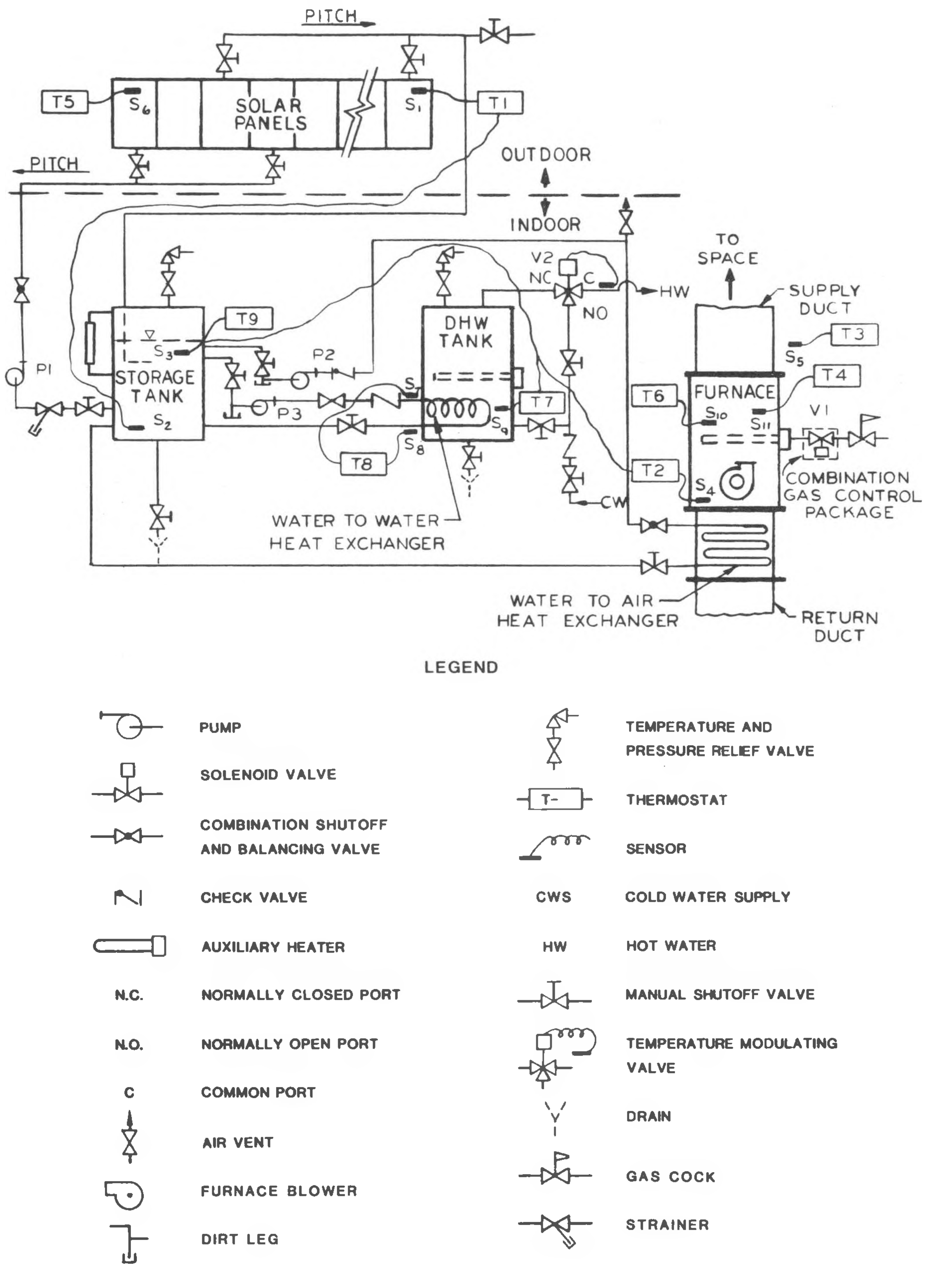


Fig. 4 Closed-loop drain-back system for space heating and domestic hot water

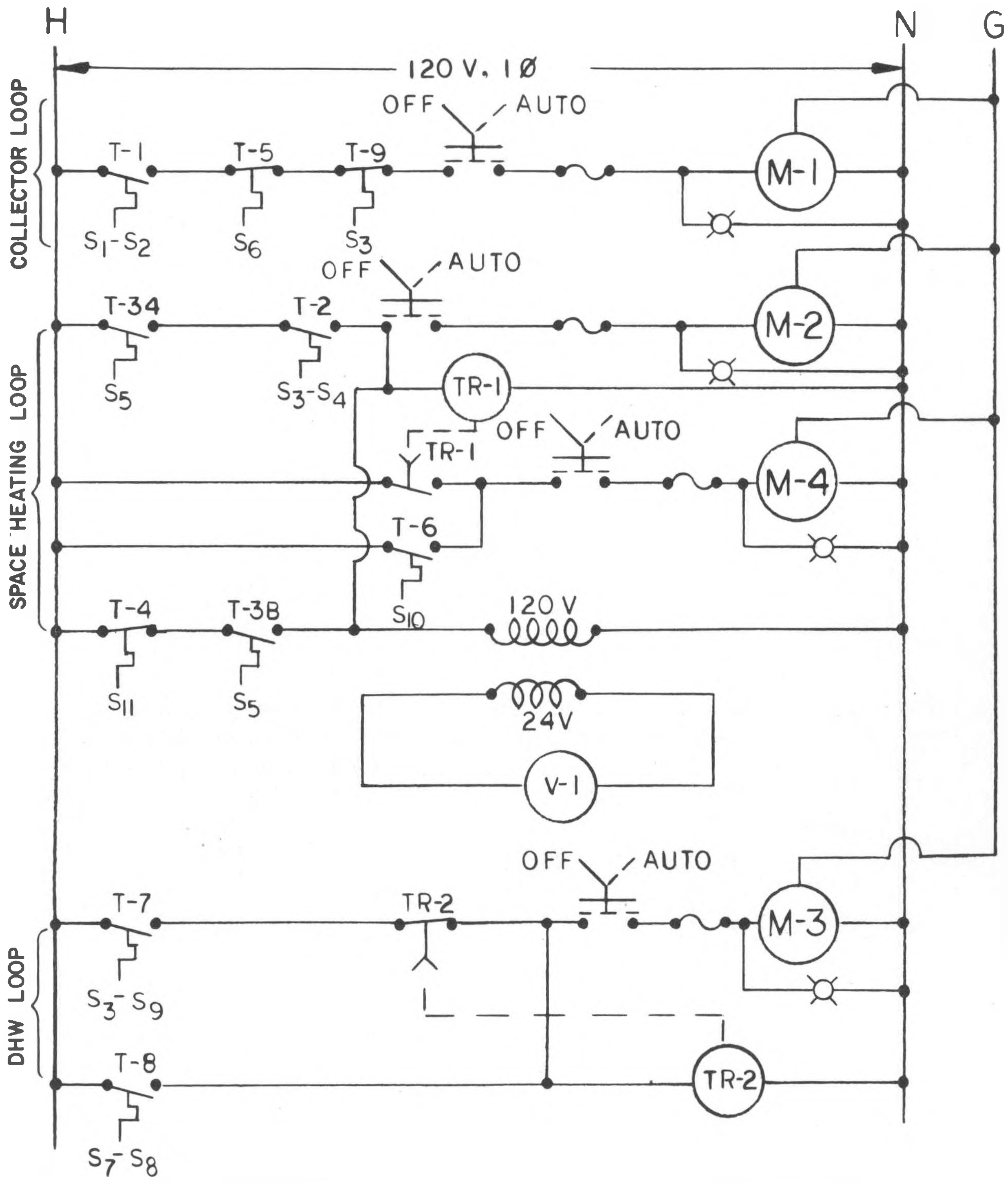
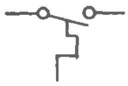


Fig. 5 Control schematic of closed-loop drain-back system for space heating and domestic hot water

(T-1),(T-2),(T-7),(T-8)



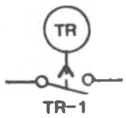
Thermostat; single-pole single-throw; normally open contact closes when temperature rises above high-temperature differential set point and opens when temperature drops below low-temperature differential set point.

(T-3A),(T-3B)

Thermostat, two-stage; (2) single-pole single-throw; normally open contact T-3A closes on temperature drop below first-stage set point, and normally open contact T-3B closes on temperature drop below second-stage set point.

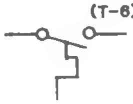
(T-4),(T-5),(T-9)

Thermostat; single-pole single-throw; normally closed contact opens when temperature rises.



On-delay/Off-delay time-delay relay, adjustable from 0 to 5 min.; normally open contact closes on time delay after relay coil is energized and opens on time delay after relay coil is de-energized.

(T-6)

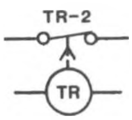


Thermostat; single-pole single-throw; normally open contact closes when temperature rises.

H Hot wire

N Neutral wire

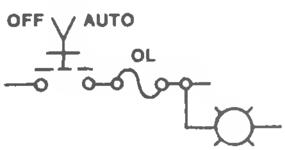
G Ground wire



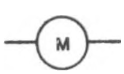
On-delay time-delay relay, adjustable from 0 to 5 min.; normally closed contact opens on time delay after relay coil is energized.

Transformer

Valve Actuator; valve is closed when de-energized.



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



Fractional HP motor; M-1, M-2, and M-3 are motors for pumps P-1, P-2, and P-3, and M-4 is furnace blower motor.

S Sensor used to actuate corresponding thermostat.

2.3.1.1 Freeze Protection

Freeze protection is achieved automatically and passively in the closed-loop 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 storage tank is overfilled and water closes off the downcomer, the collectors will not drain. The system design must provide sufficient pipe pitch and adequate pipe size to assure system drain-back.

2.3.1.2 Overheat Protection

When solar energy is available and demand for space heating or hot water is low, the water temperature in the collectors may approach or exceed the boiling point. To protect the system, overheat protection may be incorporated in the control system.

There are several ways to protect the system from overheating. One method, shown in the ladder diagram, Fig. 5, employs overheat protection thermostat T-9 to lock out pump P-1, allowing automatic drain-back until the temperature in the storage tank is decreased. Important features of this overheat protection method are:

- storage tank is protected against high temperatures;
- collectors are not protected against high temperatures, and dry stagnation will occur.

Another overheat protection method has a heat rejection coil with two control valves. Features of this overheat protection mode are:

- higher initial costs for the heat rejection coil and control valves,
- The storage tank and collectors are protected, and
- a pump is required for overheat protection.

Both overheat protection methods protect the storage tank from water temperatures that can damage tank lining. One of the systems also protects the collectors from dry stagnation.

The system designer must evaluate the cost of overheating protection with regard for the 1- to 10-y range of collector warranties, collector degradation from occasional stagnation conditions, and the installed cost of additional valves and necessary control modifications. In a conservative design, collectors capable of withstanding 30 days of stagnation, empty of fluid, without degradation would be selected.

2.3.1.3 Thermal Shock Prevention

When the system is drained by overheat protection controls or because of power loss, dry solar collectors may reach high temperatures, even stagnation temperatures, on a sunny day. If power is restored or storage tank has cooled because of increased load demand, the solar collection cycle will restart; relatively cold water will then be pumped from the storage tank to the hot solar collectors, and thermal shock will result.

To prevent this occurrence, the contact of thermostat T-5 opens when the high-temperature set point is reached, the power circuit to pump P-1 is interrupted, and the collectors cannot be filled up with water. The T-5 contact will close when collectors cool and the temperature, sensed by S-6, drops below the T-5 low-temperature set point. If, however, the system's solar collectors can withstand repeated thermal shocks without damage or degradation, this mode of operation may be avoided.

2.3.2 Space Heating

Space heating is activated by a two-stage room thermostat, T-3. When space temperature drops below the low set point of the first T-3 stage, T-3A, solar heating will be activated if energy is available in the storage tank. Only when space temperature drops below the low set point of the second T-3 stage, T-3B, will the conventional gas, electric, or oil heating be activated. Space heating by the system shown in Fig. 4 has three modes of operation: a) solar heating only, b) simultaneous solar and gas heating, and c) conventional gas heating only.

2.3.2.1 Solar Heating Only

This mode is employed when there is sufficient solar energy available to satisfy heating demand and is activated by action of two-stage room thermostat, T-3. When room temperature drops below first-stage T-3 low set point, the normally-open contact of the first stage (T-3A) closes and, providing that the contact of thermostat T-2 is also closed, solar space heating pump P-2 is started.

The normally-open contact of T-2 closes whenever temperature differential between water temperature in the storage tank and air temperature in the return duct exceeds the high-temperature differential set point, and opens when the temperature differential drops below the low-temperature differential set point. The purpose of T-2 is to assure that pump P-2 operates only if water temperature in the storage tank is high enough to contribute solar heat to the space heating and justify the expenditure of energy to operate the pump.

When started, pump P-2 circulates water from the storage tank through a check valve and heating coil, and back to the storage tank. The purpose of the check valve is to prevent any possible thermosiphoning. It must be spring- or weight-loaded and carefully selected and installed; otherwise, the undesired water circulation may not be prevented. At the time that pump P-2 is activated, an ON-OFF time-delay relay, TR-1, is energized. After its ON delay cycle, TR-1's normally-open contact closes, and the furnace blower is energized. The furnace blower, which has been delayed until the heating coil was warmed, draws air through the space return system, across the heating coil, and discharges it into the space to be heated.

Operation of the solar heating cycle will continue as long as the following conditions are satisfied.

- Room thermostat T-3 calls for heating (space temperature is below the low set point of the first stage
- Temperature differential between the water in the storage tank and the air in the return duct exceeds the low-temperature differential set point of T-2.

If either of the above conditions is unsatisfied, pump P-2 is shut down and coil of TR-1 is de-energized. After "OFF" delay time of TR-1 has timed out, the contact of TR-1 opens, and furnace blower is shut down. The shutdown of the blower is delayed, so that heat accumulated in the heating coil can be transferred to the space.

2.3.2.2 Simultaneous Solar and Gas Heating

With solar energy available, but insufficient to meet all heating requirements, the space temperature will be decreasing although the solar heating is on. If space temperature falls below the T-3 second-stage low set point, the normally-open contact of the second stage (T-3B) closes and, providing that contact of high-temperature limit switch T-4 is also closed, burner gas supply valve V-1 is energized and opens. Gas is now supplied to the burner and additional heat is added to the heating air.*

High-temperature limit switch T-4 is incorporated in every furnace control package, and is required by the codes. It is a safety device that prevents overheating the air in the furnace plenum. If the temperature in the furnace plenum exceeds the high-temperature set point of T-4, the T-4 contact opens and V-1 shuts down the gas supply to the burner.

In a typical residential application, valve V-1 is an on-off valve, not a modulating valve. When it is open, the full gas flow is provided and total heating capacity of the furnace is used. If the heating unit is of adequate size, it will provide sufficient heat to increase space temperature above the second stage high-temperature set point of thermostat T-3 in a matter of minutes. At that point, the contact of T-3B opens and V-1 closes, shutting down the gas burner. The blower will continue to run, however, and to provide solar heating as long as conditions for solar heating are fulfilled (see last paragraph of immediately preceding subsection).

2.3.2.3 Conventional Heating Only

If stored energy is not available in the storage tank and heating is demanded, the space temperature will be decreasing. When the space temperature drops below the T-3 second-stage low set point, the normally-open contact, T-3B, of the second stage will close and energize gas supply valve

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*Provided that the automatic pilot valve has been burning and the safety shut-off valve is open. Safety shut off is required by codes, and is incorporated in every conventional furnace, supplied as a package. The package usually consists of: a) basic body, b) programmed safe-lighting gas cock, c) pilostat power unit, d) pressure regulator, and e) burner gas supply valve operator.

V-1. That valve opens and the burner is ignited. The furnace plenum is heated; when the plenum temperature reaches the high set point of thermostat T-6 (called fan switch or circulator relay in residential furnace-control terminology) the normally-open contact of T-6 closes, and the blower is started.*

After the space has been heated, the T-3B contact opens, burner gas supply valve V-1 closes, and the burner is shut down. However, the blower will continue to run until the heat in the furnace plenum is depleted and the plenum temperature decreases below the low set point of T-6.

The operation of high-limit switch T-4 is as described in preceding subsection 2.3.2.2, "Simultaneous Solar and Gas Heating."

2.3.3 Domestic Hot Water Heating

2.3.3.1 Solar Heating

Operation of DHW heating is independent of space heating, regardless of whether or not solar energy is being used. Solar contribution of DHW heating is actuated whenever the temperature differential between the water temperature at the top of the storage tank, sensed by sensor S_3, and the water temperature at the bottom of the DHW tank, sensed by sensor S_9, exceeds the high set point of differential thermostat T-7. When the high set point is exceeded, the normally-open contact of T-7 closes and pump P-3 is energized. Hot water from the top of the storage tank is pumped through the check valve, the heat exchanger in the DHW tank, and back to the bottom of the storage tank. The check valve is installed to prevent any possible thermosiphoning, and is spring- or weight-loaded.

When the T-7 circuit for pump P-3 is closed, an adjustable "ON" time-delay relay, TR-2, also is energized. When the time-delay relay has "timed out," its normally-closed contact opens, transferring system control to differential thermostat T-8. This thermostat, which has normally-open contact,

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*The purpose of T-6 is to prevent the blower start-up until the furnace plenum is sufficiently heated. It can be replaced with an on-off time-delay relay, activated simultaneously with V-1. Both control items are common in residential heating application.

receives signals from temperature sensors S_7 and S_8 on the piping to and from the heat exchanger. When the temperature difference between sensors S_7 and S_8 exceeds the high-temperature differential set point of thermostat T-8, its contact closes, the pump P-3 circuit is again energized, and the contribution of solar energy resumes.

The two thermostats, T-7 and T-8, are needed to protect the system from inefficient operation caused by the sometimes poor heat transfer capability of the heat exchanger.* For instance, although the temperature differential between the storage tank and the DHW tank may be sufficient to justify operation of pump P-3, the amount of heat actually transferred to the water in the tank as measured by sensors S_7 and S_8 may not justify the energy cost of pump P-3. Hence, thermostat T-8 is used to terminate solar collection: when the temperature difference between sensors S_7 and S_8 decreases below the low-temperature differential set point of thermostat T-8, its contact opens, de-energizing pump P-3.

The time-delay relay provides the time needed for the hot water from the storage tank to reach the heat exchanger and to activate thermostat T-8. It also eliminates thermostat T-7 from the control circuit once control has been transferred to thermostat T-8.

If solar contribution has been terminated by thermostat T-8, the system will not restart until the temperature differential between the storage tank and the DHW tank reaches the high-temperature differential set point of thermostat T-7. To prevent cycling of the system, the low-temperature differential set points of thermostats T-7 and T-8 must be carefully selected.

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*Present industry practice is not to use thermostat T-8 and the time-delay relay. These components could be eliminated by raising the low differential set point of T-7, provided the efficiency of the heat exchanger is known or is determined by testing. However, if only thermostat T-7 is used, the temperature differential across the heat exchanger cannot be measured accurately for the following reasons: Sensor S_3 senses temperature in the storage tank and S_9 senses temperature in the DHW tank. The signals from S_9 are affected by hot water use, the thermal inertia of the tank, and water mixing in the tank. Hence, the measured temperature differential between S_3 and S_9 does not represent the actual temperature differential across the heat exchanger.

The procedure for selecting thermostat set points is described in subsection 2.3.4 "System Start-Up and Testing."

2.3.3.2 Auxiliary Heater Operations

A factory-packaged electrical heater maintains the desired water temperature. The package combines thermostat, temperature sensor, electric resistance heating element, and emergency cutout (ECO) switch in a single unit.

A factory installed and calibrated temperature sensor detects the temperature of the tank surface. When that temperature drops below the low-temperature set point (e.g., 120°F, 48 °C) 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 electrical DHW service.

A typical DHW tank with a gas heater at the bottom should not be used in combination with a solar heat exchanger, because the temperature sensor of a typical gas heater is also located in the lower portion of the tank. The thermostat would then maintain the desired tank temperature throughout the DHW tank, and solar contribution could be used only when the storage tank was warmer than the bottom of the DHW tank. This would eliminate the possibility of using solar energy to preheat incoming cold city water, because pump P-3 would come on only when the storage tank temperature was higher than the relatively high temperature at the bottom of the DHW tank.

However, a gas heater is recommended if it is installed in the middle or the upper half of the DHW tank. Controls on gas-fired systems combine an automatic pilot valve, manual gas valve, thermostat valve, pilot gas filter, and gas regulators in one unit.

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, 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.

2.3.3.3 Temperature Modulating Valve

Whenever the temperature of hot water leaving the auxiliary/heater tank exceeds a set point of approximately 145°F (63 °C), the temperature modulating valve, V-2, begins mixing hot water and cold make-up water to maintain the preset temperature.* 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.

2.3.4 System Start-Up and Testing

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

The following 19 steps comprise the recommended test procedure.

Step 1 Place control system in "off" position.

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

Step 3 Fill pump P-1, P-2 and P-3 loops.

Open manual shut-off valve at top of collectors. This valve serves as a vent, allowing the air in the system to escape while the system is being filled. Using a portable pump, fill the storage tank with water specified by the system designer/manufacturer (if you don't know the water specification, contact the local water treatment representative for information on proper chemicals and procedure). Jump thermostats T-2, T-3A, and T-7, to start pumps P-2 and P-3.

Slowly fill solar collectors and piping between collectors and storage tank. After air contained in collectors and associated piping has been purged through the open vent valve, allow approximately two gallons of fill-up water to bleed out. This will assure that the air has been removed. Close vent valve and remove jumper wire.

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*Temperature given is an example only. Check local codes to determine the required temperature.

Step 4 Check for leaks.

Using compressed air cylinder and manifold, pressurize water in the system to the pressure specified by the designer/manufacturer. Inspect collectors and piping for leaks, paying special attention to connections at collector manifolds. DO NOT CHECK COLLECTOR ARRAY FOR LEAKS WHEN AMBIENT TEMPERATURE IS BELOW FREEZING. Shut off compressed air and open the vent valve. Drain storage tanks and associated loops, as necessary, and repair any leaks. After completion of testing and any required repair, fill the system again to the storage tank sight glass level specified by the designer/manufacturer. Close vent valve.

Step 5 Fill DHW tank and hot water lines.

Open make-up water supply valve and hot water faucets to purge air from faucets.

Step 6 Check DHW hot water loop for leaks.

Shut off make-up water valve and hot water faucets. Pressurize system to 20 psi (138 kPa) above expected make-up water pressure. Check for leaks. Drain hot water loop and repair any leaks. After completing repairs, fill DHW tank again with city water.

Step 7 Switch P-1, P-2 and P-3 circuit controls to "auto" position, keeping auxiliary heater and furnace in "off" position.

If the temperature differential 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 differential between S_1 and S_2 is not large enough to activate thermostat T-1, insert a jumper wire in T-1 to start pump P-1 and thus balance the water flow through the collectors. DO NOT JUMP THERMOSTAT T-1 IF THE AMBIENT TEMPERATURE IS BELOW FREEZING.

It may happen that collectors are overheated, and the contact of thermal shock prevention thermostat T-5 is open, preventing start-up of P-1. Do not jumper T-5. Wait for collectors to cool, and then continue testing.

Step 8 Balance water flows*.

Water flow through the collectors must be balanced, to avoid hot

*Flow balancing may not be required with prepackaged solar systems; however, flow still should be verified, to confirm that pump rotation is correct and that passages are not blocked.

spots that result in inefficient operations. 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 manufacture'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 determined by measuring the flow rate through each collector panel or group of panels with Annubars, rotameters, 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 the throttling valve partially open, to avoid overloading the pump motor if an oversize pump has been installed by mistake.

If the measured water flow is significantly below the design flow, check the pump rotation. The direction of pump rotation may have been reversed during installation by interchanged motor leads.

After water balancing of the collector loop is completed, remove jumper wire from T-1, if used. If necessary, jumper thermostats T-2, T-3A, and T-7 to start pumps P-2 and P-3. Verify flows and pump rotation, then remove jumpers, if used.

<u>Step 9</u> Adjust pressure relief valves.

Using compressed air cylinder and manifold, 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 valves to the onset of bleeding. If the pressure relief valves are factory-set, check the settings to confirm that they open at the specified pressure.

<u>Step 10</u> Insulate the system.

<u>Step 11</u> Set the thermostats as specified by the designer/manufacturer.*

*In a prepackaged system, thermostats may be factory-set, so that a field adjustment is not possible. It is assumed the manufacturer has sufficient test data to set the thermostats properly.

Step 12 Adjust low temperature differential set point of thermostat T-1.**

If the system has been tested and insulated, and if insolation is sufficient, turn on the system. If the low-temperature differential set point is to be determined by field testing, measure electrical energy consumption with a wattmeter, refer to Appendix B and use Equations B-8 and B-10 to calculate the temperature differential, then adjust the T-1 setting. If the set point is not determined in the field, set thermostat T-1 to design specifications.*

Verify the accuracy of the low-temperature differential set point with calibrated thermometers, measuring the temperature difference between water in the storage tank and water leaving collectors. By partially shading the collectors (or by waiting until sunset), insolation can be reduced until the low set point of T-1 is reached and pump P-1 shuts off.

If the measured differential does not fall within 1°F (0.5 °C) of the low set point, adjust the T-1 setting, repeating this procedure until the pump shuts off.

Step 13 Test overheat protection.

On systems with adjustable T-9 setting, simulate overheat conditions by setting T-9 below the water temperature in the storage tank.** T-9 should open its normally-closed contact, pump P-1 should stop, and collector loop should drain into the storage tank. After testing, reset T-9 in accordance with designer/manufacturer recommendations.

In systems where T-9 is not adjustable, insert a jumper wire in thermostat T-9 to simulate overheating. Remove jumper wire after test is completed.

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*When determining T-1 settings, the system designer should note that temperature of the absorber plate, sensed by S_1, is usually 3°-4° F higher than that of the liquid leaving the collector plate. (If an evacuated tube collector is used, this sensor should be in the tube and this difference should not exist.)

**In a prepackaged system, thermostats may be factory-set, so that field adjustment is not possible. It is assumed the manufacture has sufficient test data to set the thermostats properly.

Step 14 Test thermal shock prevention thermostat T-5.

Switch P-1 control circuit to "OFF" position. With collector loop drained, let temperature in the collectors rise because of insolation. Measure temperature in the collectors. Using continuity tester, verify that the contact of T-5 is closed when collector temperature is below and open when collector temperature is above the set point temperature (± 5°F). If necessary, adjust T-5 setting to comply with the set point recommended by the system designer/manufacturer. After completing the test, switch controls to "AUTO" position.

Step 15 Adjust low-temperature differential set point of thermostat T-8.*

If the set point is to be determined by field testing, measure electrical energy consumption of pump P-3 with a wattmeter, calculate the temperature differential by using Eqs B-8 and B-10 from Appendix B, then adjust the T-8 setting. If the set point is not determined in the field, set T-8 to design specifications.

When solar radiation is adequate to warm the water in the storage tank sufficiently above the temperature of that in the DHW tank to activate T-7 and, hence, P-3, the operation of P-3 will, after completion of the TR-2 time delay cycle, be governed by thermostat T-8. After this point has been reached, verify the accuracy of the low-temperature differential set point of T-8 by measuring the temperature difference across the heat exchanger with calibrated thermometers. Using the method indicated in Step 12, the insolation can be reduced until the T-8 low set point is reached and pump P-3 shuts off.

If the measured differential does not fall within 0.5°F (0.3 °C) of the low set point, adjust the T-8 setting, repeating this procedure until the pump shuts off.

Step 16 Test auxiliary heater operation.

Adjust set point of auxiliary heater located in the DHW tank to design specifications. Turn heater on and check its operation. Verify the aux-

*In a prepackaged system, thermostats may be factory-set, so that field adjustment is not possible. It is assumed the manufacture has sufficient test data to set the thermostats properly.

iliary heater temperature setting by inserting a calibrated thermometer in the thermal well at the top of the DHW tank. Auxiliary heater should activate when the temperature at the top of the tank drops to within $\pm 2°F$ (± 1 °C) of the set point temperature. Adjust auxiliary heater setting until this requirement is met.*

Step 17. Verify operation of thermostat T-2.

Using solar energy (operating P-1), warm water in the storage tank until the temperature differential between water in the storage tank, and air temperature in the return duct, exceeds the high temperature differential set point of T-2. With continuity tester, verify that the normally-open contact of T-2 has closed. Use calibrated thermometers to measure water and air temperatures during testing.

If necessary, adjust first stage of room thermostat T-3 to call for heating. Pump P-2 should start and, after time delay relay TR-1 has timed out, furnace blower should start also. Readjust TR-1 if necessary.

Shut down pump P-1 manually, and allow heat from the storage tank to be transferred to the air in the space heating sytem. As air is heated and storage tank is cooled, the temperature differential between storage tank, sensed by S_3, and return air temperature, sensed by S_4, will decrease below the low-temperature differential set point of T-2. Contact of T-2 should open, pump P-2 should shut down and after TR-1 has timed out properly, the furnacce should turn off. Return T-3 to desired setting.

If sufficient solar energy is not available, water in the storage tank could, for the purpose of testing only, be heated by use of DHW heater as follows:

Set auxiliary heater to maintain high temperature (140°F) in the DHW tank. Jumper thermostats T-7 and T-8 to start pump P-3. Heat from DHW tank will be transferred to the storage tank. After storage tank has been warmed as needed, remove jumper wire across T-7 and T-8. Set auxiliary heater to maintain desired temperature (120°F) in the DHW tank.

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* For most household requirements, an auxiliary heater setting of 120°F is quite adequate. Higher settings, e.g., 140°F, would result in higher standby heat losses for the DHW tank. Furthermore, in hard water areas, mineral salts in the water precipitate as scale at temperatures above 140°F.

Step 18 Verify operation of conventional space heating.

Following recommendations and testing procedure of the furnace manufacturer, light the pilot burner and prepare auxiliary system for start-up on call from the room thermostat. If necessary, adjust second stage of room thermostat, T-3, to call for heating. Gas valve V-1, in the combination gas control package, should open and the gas burner should fire-up. After the second stage of T-3 has been satisfied, the burner should shut down. After verifying proper operation of auxiliary space heating, set T-3 to maintain desired space temperatures. Check operation of fan switch T-6 and overheat protection switch T-4 as specified in manufacturer's literature.

Step 19. Test operation of temperature-modulating valve.

Adjust setting of temperature-modulating valve, V-2, to maintain 145°F (63 °C).* 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 °C ± 3°), open hot water faucets. Measure the water temperature leaving valve V-2. If the temperature is not 145°F ± 3° (63 °C ± 2), adjust valve V-2 setting, repeating this procedure until the water temperature is correct, then reset the auxiliary heater to maintain the desired tank water temperature.

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

2.3.5 Drain-Back System Preventive Maintenance

To ensure that the solar system will perform reliably and meet the mean maintenance-free time estimates in Tables 3 and 4,** 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. 6, the user

*This temperature is an example only. Check local codes to determine proper temperature.

**Computed according to procedure outlined in Appendix A.

Table 3

Estimated Mean-Time-Between Failures: Solar Systems with Tubular Collectors

Collector Modules	Operational Modules	Percentage of Rated Capacity	Mean Time Between Failures (years)			
			Complete System		DHW System Only	
			Min	Max	Min	Max
6	3	50	0.31	2.18	0.40	2.75
	4	67	0.30	2.12	0.38	2.63
	6	100	0.27	1.39	0.34	1.62
8	4	50	0.31	2.18	0.40	2.75
	6	75	0.30	2.05	0.38	2.53
	8	100	0.26	1.24	0.33	1.40
10	5	50	0.31	2.17	0.40	2.75
	7	70	0.30	2.11	0.38	2.52
	10	100	0.25	1.03	0.32	1.24
12	6	50	0.31	2.17	0.40	2.75
	9	67	0.30	2.13	0.38	2.65
	12	100	0.24	1.02	0.30	1.13
14	7	50	0.31	2.18	0.40	2.75
	10	70	0.30	2.10	0.38	2.60
	14	100	0.28	0.94	0.28	1.03

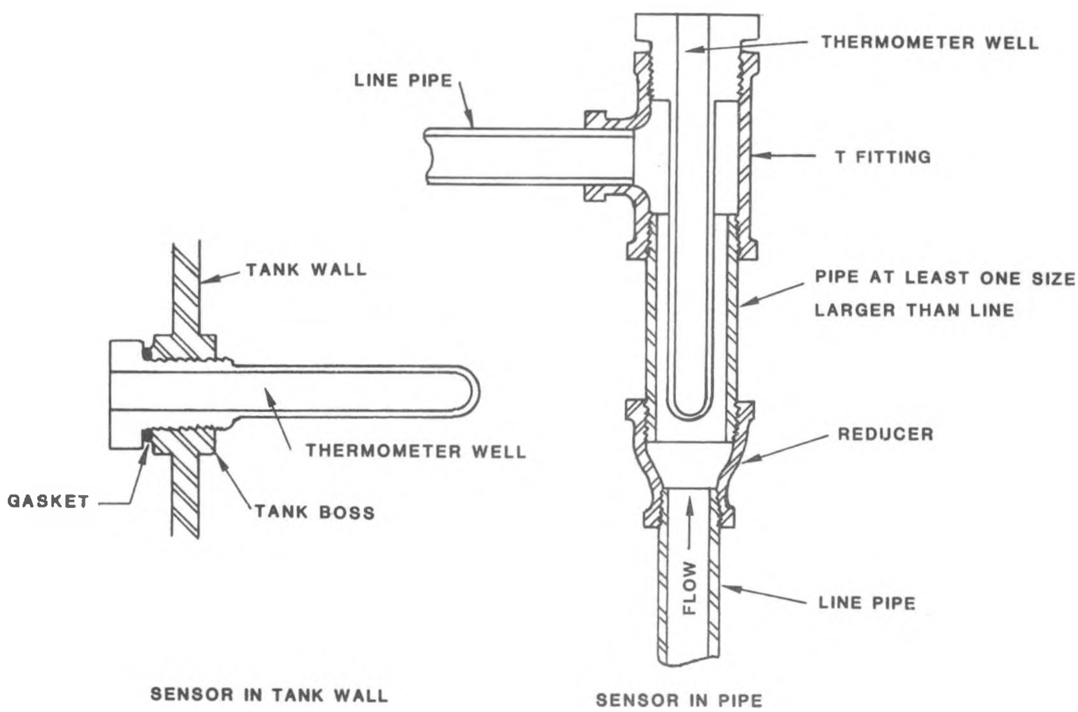


Fig. 6 Special test points and thermowells in manufactured system

Table 4.

Estimated Mean-Time-Between Failures: Solar Systems with Flat Plate Collectors

Collector Modules	Operational Modules	Percentage of Rated Capacity	Mean Time Between Failures (years)			
			Complete System		DHW System Only	
			Min	Max	Min	Max
6	3	50	0.31	2.19	0.40	2.77
	4	67	0.30	2.17	0.38	2.73
	6	100	0.22	1.63	0.28	1.96
8	4	50	0.31	2.19	0.40	2.77
	6	75	0.30	2.15	0.38	2.72
	8	100	0.19	1.51	0.24	1.78
10	5	50	0.31	2.19	0.40	2.77
	7	70	0.30	2.16	0.38	2.71
	10	100	0.28	1.39	0.32	1.63
12	6	50	0.31	2.19	0.40	2.77
	9	75	0.30	2.17	0.38	2.72
	12	100	0.16	1.30	0.20	1.52
14	7	50	0.31	2.19	0.40	2.77
	10	70	0.30	2.17	0.38	2.71
	14	100	0.15	1.22	0.19	1.42

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 outer collector glazing with compounds approved by the manufacturer. Inspect the absorber plates for degradation during washing.

Inspect flashing and collector mounting hardware. Tighten, replace, and recaulk as required.

If used, 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(s) on tank(s) and collector loop, verifying valve(s) operation, check that the exit ports are not plugged.

During nonheating periods, when the system is needed only for DHW, isolate, drain, and cover collectors that need not be used; also, isolate P-2 system. With the return of the heating season, reactivate the collectors and the P-2 system.

Check water level in the storage tank. Add make-up water if necessary. If water level is too high, drain to the proper level and check isolation valve.

Clean dirt legs.

System also should be checked periodically for:

insulation deterioriation,

leaks,

correct thermostat setting, to ensure that setting has not shifted since start-up and testing, and

correct system operation--

° Verify that collector pump does not operate at night (use flowmeter, sight glass, or pressure gauges, if installed).

° On a sunny day, verify collector pump operation by noting whether the flowmeter or the sight glass indicates fluid motion. In addition, check the temperature differential between collectors and storage, using thermometers and thermowells (Fig. 6). If the temperature differential is above the high differential set point of T-1 and the system has not started, or the temperature differential is below the low differential set point of T-1 and system is running, call a service person.

° Also, verify that operation of pumps P-2 and P-3 is in accordance with settings of their respective thermostats T-2 and T-7 and T-8. If not, call a service person.

Check lubrication of all fans, pumps, and motors.

2.3.6 Closed-Loop Drain-Back System Troubleshooting

Although the design of a closed-loop drain-back system depends on the individual manufacturer, the troubleshooting information in Table 5 should help identify and correct the typical problems of this type of system. This information should assist user or service person in troubleshooting a system

Table 5 Troubleshooting Closed-Loop Drain-Back Systems

Subsystem	Problem	Components	Possible Causes	Corrective Action
Collector Loop (Pump P-1 loop)	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(s) S_1, 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, 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 overloading; check whether balancing valve is in proper position.
			3. Defective shaft, impeller, or coupling.	3. Replace.
			4. Defective bearing.	4. Replace.
		Sensor S_6	1. Defective.	1. Replace.
			2. Improper installation.	2. Reinstall.
			3. Defective control cable.	3. Replace.
			4. Sensor out of calibration.	4. Recalibrate.
		Thermostat(s) T-5 and/or T-9	1. Defective component.	1. Replace thermostat(s).
			2. Loose contacts.	2. Tighten.
			3. Thermostat(s) out of calibration.	3. Recalibrate.
			4. Thermostat settings too low.	4. Reset.
		Sensor S_3	1. Defective.	1. Replace.
			2. Defective control cable.	2. Replace.
			3. Sensor out of calibration.	3. Recalibrate.

Table 5 Troubleshooting Closed-Loop Drain-Back Systems (contd.)

Subsystem	Problem	Components	Possible Causes	Corrective Action
Collector Loop (Pump P-1 loop)		Control circuitry	1. Circuit continuity lost. 2. Bad contacts.	1. Check and repair. 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 and/or results obtained during system start-up and testing.
		Thermostat(s) T-5 and/or T-9	1. Defective component. 2. Loose contacts. 3. Thermostat(s) out of calibration. 4. Thermostat setting(s) too low.	1. Replace thermostat(s). 2. Tighten. 3. Recalibrate. 4. Reset.
		Sensor(s) S_3 and/or S_6	Sensors out of calibration.	Recalibrate.
		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, check whether 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	1. Pipe damaged. 2. Strainer clogged.	1. Replace damaged section. 2. Clean strainer.
	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 settings determined during start-up. 2. Replace thermostat. 3. Recalibrate.

Table 5 Troubleshooting Closed-Loop Drain-Back Systems (contd.)

Subsystem	Problem	Components	Possible Causes	Corrective Action
Collector Loop (Pump P-1 loop)		Sensor(s)	1. Defective sensor(s) 2. Sensor(s) out of calibration. 3. Incorrect sensor in circuit. 4. Sensor S_1 installed above water level (applies only if evacuated collector tube is used).	1. Replace. 2. Recalibrate. 3. Replace. 4. Reinstall properly.
		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 leaky joint.
		Hose connection	Clamp does not hold tightly (applies if flat plate collector is used).	Tighten hose clamp, replace clamp or hose if necessary.
		Connection between collectors	Clamp seal (applies if evacuated tube collector is used).	Tighten clamp.
		Relief valve.	1. Improper pressure setting. 2. Defective component.	1. Check pressure setting; correct if necessary. 2. Replace.
	Poor solar energy collection	Collector array	1. Undersize 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. Apply additional insulation. 2. Provide proper weather protection. 3. Repair.
		Collector tubes	Return tube does not seal tightly and water is partially bypassing (applies only if evacuated tube collector is used).	Remove evacuated (outer) tube and reinstall return tube.

Table 5 Troubleshooting Closed-Loop Drain-Back Systems (contd.)

Subsystem	Problem	Components	Possible Causes	Corrective Action
Collector Loop (Pump P-1 loop)	System noisy when operating	Pump cavitation	1. Restricted pump suction line. 2. Air in the system. 3. Low fluid level in reservoir.	1. Remove restrictions. 2. Check pipe installation at pump inlet. 3. Refill to proper level.
		Pump bearings.	1. Bearing worn. 2. Bearing damaged owing to misalignment.	1. Replace bearing. 2. Align pump and motor shaft.
		Piping	1. Air locked in the piping. 2. Piping vibrates.	1. Check pipe installation. 2. Provide adequate pipe support.
	System overheats	Overheat protection thermostat T-9	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.
		Control circuitry	1. Circuit continuity lost. 2. Loose contacts. 3. Coil contacts burned out.	1. Check and repair. 2. Tighten contacts. 3. Replace.
		Sensor S_3	1. Out of calibration. 2. Defective.	1. Recalibrate. 2. Replace.
DHW Loop	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 undersize 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.	1. Recalibrate. 2. Reset. 3. Replace.
	Water temperature too high	Hot water temperature thermostat	1. Thermostat setting too high. 2. Thermostat out of calibration. 3. Bad contacts.	1. Reset. 2. Recalibrate. 3. Correct.

Table 5 Troubleshooting Closed-Loop Drain-Back Systems (contd.)

Subsystem	Problem	Components	Possible Causes	Corrective Action
DHW Loop		Sensor	Out of calibration.	Recalibrate or replace.
		Temperature modulating valve	1. Sensor out of calibration. 2. Temperature set too high.	1. Recalibrate. 2. Reset.
	No hot water	Make-up water shut-off valve.	Valve closed.	Open valve.
		Heater failed to actuate	1. No power to heater. 2. Thermostat defective. 3. Bad contacts.	1. Check overload protection and correct. 2. Replace. 3. Correct.
		Temperature modulating valve	1. Valve defective. 2. Sensor defective.	1. Replace. 2. Replace.
Solar/DHW Heat Transport loop (Pump P-3 loop)	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 T-7	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 specifiations and/or results obtained during system start-up and testing. 2. Replace thermostat. 3. Tighten wires. 4. Recalibrate.
		Sensor(s) S_3 and/or S_9	1. Defective. 2. Improper installation. 3. Defective control cable. 4. Sensor out of calibration.	1. Replace. 2. Reinstall. 3. Replace. 4. Recalibrate.

Table 5 Troubleshooting Closed-Loop Drain-Back Systems (contd.)

Subsystem	Problem	Components	Possible Causes	Corrective Action
Solar/DHW Heat Transport loop (Pump P-3 loop)		Pump P-3	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 overloading; check whether 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. 2. Bad contacts.	1. Check and repair. 2. Check and correct.
		Time-delay relay TR-2	1. Loose contact. 2. Defective component.	1. Tighten. 2. Replace time-delay relay.
		Water in storage tank not hot enough	1. Solar contribution depleted because of lack of solar energy or of space heating demand.	No corrective action. Wait for conditions to improve.
			2. Collector loop subsystem failed.	Troubleshoot collector loop subsystem.
	System starts but cycles	Thermostat T-8	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. 2. Bad contacts.	1. Check and repair. 2. Check and correct.
		Sensor(s) S_7 and/or S_8	1. Defective sensor(s). 2. Sensor(s) out of calibration.	1. Replace. 2. Recalibrate
		Heat exchanger	Heat exchanger covered with scale--no adequate heat transfer.	Remove scale.

Table 5 Troubleshooting Closed-Loop Drain-Back Systems (contd.)

Subsystem	Problem	Components	Possible Causes	Corrective Action
Solar/DHW Heat Rransport loop (Pump P-3 loop)	Pump runs but water does not flow	Isolation pump valve(s)	Valve(s) closed.	Open valve(s).
		Check valve	Valve installed reversed.	Reinstall properly.
		Pump impeller	Impeller broken or separated from shaft.	Replace impeller and/or shaft assembly.
		Blocked liquid flow passage	1. Pipe damaged. 2. Strainer clogged.	1. Replace damaged section. 2. Clean strainer.
	System runs continuously	Thermostat T-8	1. Low-temperature differential set point set too low. 2. Defective component. 3. Thermostat is out of calibration.	1. Reset according to specifications or settings determined during start-up. 2. Replace thermostat. 3. Recalibrate.
		Sensor(s)	1. Defective sensor(s). 2. Sensor(s) out of calibration. 3. Incorrect sensor in circuit.	1. Replace. 2. Recalibrate. 3. Replace.
		Control circuitry	Bad contacts.	Check and correct.
	System noisy when operating	Pump cavitation	1. Restricted pump suction line. 2. Air in the system. 3. Low fluid level in reservoir.	1. Remove restrictions. 2. Check pipe installation at pump inlet. 3. Refill to proper level.
		Pump bearings	1. Bearing worn. 2. Bearing damaged owing to misalignment.	1. Replace bearing. 2. Align pump and motor shaft.
		Piping	1. Air locked in the piping. 2. Piping vibrates.	1. Check pipe installation. 2. Provide adequate pipe support.
Solar/Space Heating loop (Pump P-2 loop)	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.

Table 5 Troubleshooting Closed-Loop Drain-Back Systems (contd.)

Subsystem	Problem	Components	Possible Causes	Corrective Action
Solar/Space Heating loop (Pump P-2 loop)		Thermostat T-2	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 specifiations and/or results obtained during system start-up and testing. 2. Replace thermostat. 3. Tighten wires. 4. Recalibrate.
		Sensor(s) S_3 and/or S_4, S_5	1. Defective. 2. Improper installation. 3. Defective control cable. 4. Sensor out of calibration.	1. Replace. 2. Reinstall. 3. Replace. 4. Recalibrate.
		Pump P-2	1. Motor failure. 2. Overload protection switch shuts down pump motor. 3. Defective shaft; impeller or coupling. 4. Defective bearings.	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. Determine cause of overloading; check whether 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.
		Thermostat T-3	1. Defective component. 2. Loose contacts. 3. Thermostat out of calibration.	1. Replace thermostat. 2. Tighten. 3. Recalibrate.
	System starts but cycles	Thermostat(s) T-2 and/or T-3	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. 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, check whether shading pole ring is open, and replace.

Table 5 Troubleshooting Closed-Loop Drain-Back Systems (contd.)

Subsystem	Problem	Components	Possible Causes	Corrective Action
Solar/Space Heating loop (Pump P-2 loop)	Pump runs but water does not flow	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	1. Pipe damaged. 2. Check-valve installed reversed.	1. Replace damaged section. 2. Reinstall properly.
	System runs continuously on call for heat; but ΔT is inadequate.	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 settings determined during start-up. 2. Replace thermostat. 3. Recalibrate.
		Sensor(s) S_3 and/or S_4	1. Defective sensor(s). 2. Sensor(s) out of calibration. 3. Incorrect sensor in circuit.	1. Replace. 2. Recalibrate. 3. Replace.
		Control circuitry	Bad contacts.	Check and correct.
Space Heating (furnace blower loop)	Blower does not run when T-3 first stage calls for heating and solar is available	Time-delay relay TR-1	1. Loose contacts. 2. Defective component.	1. Tighten. 2. Replace time-delay relay.
	Other problems: See troubleshooting guide furnished by the furnace manufacturer.			

that has been in the field for some time. In addition, the information may be useful to a system designer concerned with system analysis, equipment selection, and preparation of specifications.

2.3.7 Heating System Reliability Assessment

In assessing the reliability of the heating systems with a DHW option, the active time of various components was estimated from information documented in the National Solar Data Network report.[3] The active time of components (time under load) is summarized in Table 6. This table also indicates the values for the duty-cycle parameter to be used in the equation (A.7, Appendix A) for computing the operational failure-rates of components.

The duty-cycle parameter for the majority of the components listed in Table 6 is the ratio of the active time to the number of hours per day. The exceptions to straightforward calculation are for Pump P-2 and the water-to-air-heat exchanger (solar heating mode and simultaneous solar-and-gas heating mode).

The latter two components provide the heating for the home, and are not needed during the warmer months of the year. As a result, the minimum value for the duty cycle parameter was set at 0.25. The maximum value assigned to the pump and heat exchanger duty cycle was 0.40. This latter value will apply to a solar-heating system located in the northern section of the United States.

Table 6
Summary of Average Active Time of Solar Energy System Components.

System Component	Average Active Time, h/day	Duty-Cycle Parameter
Collector	6	0.25
Storage	24	1.0
DHW Tank	24	1.0
Controls	24	1.0
Pump 1	6	0.25
Pump 2	12-18	0.25-.40
Pump 3	12-18	0.25
Fan	12-18	0.5
Water-to-air heat exchanger	8-10	0.25-.40
Piping	24	1.0
Air Vent	24	1.0

The mean-time-between failure of five collector configurations was evaluated by using data in Table A.3 and the reliability equations in Appendix A. These calculations for the tubular collector systems and the flat plate systems are summarized in Tables 3 and 4. These tables also give system MTBF values for cases in which the DHW option is not included.

Data in Tables 3 and 4 indicate that the MTBF values for the two systems are almost identical. In addition, for the component data in Table A.2, Appendix A, the MTBF values at a given load level are similar for both systems.

The lack of variation in the MTBF values as a function of the size of the collector array and the number of operational collectors indicates that the collectors have little effect on the system MTBF values. For these systems, the MTBF of the system without any collectors is 2.19 years, and the MTBF at 50% load is 2.17 years. However, the economic implications of replacing collectors (price and installation charges for four collectors versus their life expectancy) during the expected life of the entire system must be considered in the selection and specification of collectors.

The greatest improvement in the system MTBF can be achieved by reducing the failure rate of the conventional components. If the combined failure rate of the off-the-shelf components is reduced by a factor of two, the MTBF of the tubular collector system approaches 5 years.

Although the MTBF values for the tubular and the flat-plate-collector systems are similar, a collector failure in the tubular systems can be repaired more easily than in the flat plate systems.

If the collector systems must only supply space heat, not both space heat and DHW, the system MTBF increases by approximately 1.26. This increase in the system MTBF value is a direct consequence of reducing the number of components in the system.

GLOSSARY

Active System	A solar-energy system that needs 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 water and a given substance (such as ethylene glycol)
Auxiliary system	A backup system that provides heat when solar energy alone is insufficient
Btu	British Thermal Unit: the amount of heat needed to raise the temperature of 1 pound of water by 1 degree Fahrenheit
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
Continuity tester	An electrical device that indicates whether an electric circuit is open or closed
DHW	Dommestic hot water (potable)
Dielectric bushing	An electrically insulating liner between dissimilar metals
Differential thermostat	A device that uses a measured temperature difference to control a pump, fan, or valve

Dirt leg	Vertical extension of a pipe drop below the horizontal takeoff, to provide for collection of dirt in piping system
Drain-back system	System in which the water in the solar collectors is drained into the storage tank on cold nights to protect against freezing
Drain-down system	System in which the water in the solar collectors is drained into the sewer whenever collector pump is shut down
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 increase in pressure 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, anti-freeze solutions, and hydrocarbons.)
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 (midpoint between extremes) 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. Must include the operating time of that portion of the equipment population that did not fail
Mean-time-between-failures (MTBF)	The mean time between the repair of a component or system that has failed and its next failure
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, psi psig (Compare with psig and psia.)
psia	Pounds per square inch pressure, absolute. Absolute pressure is 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 pressure, gauge. Gauge pressure is 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 $°F \cdot ft^2 \cdot h/Btu$
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 that results from formation of scale on the heat-exchange surfaces
Sealed system	A solar-energy system that excludes oxygen by closing all vents and inlets and outlets for liquids; this limits one type of corrosion, but requires an expansion space, to avoid excessive pressure in lines.
Sensor	A device that detects the value or change in value of a variable being measured (e.g., pressure temperature), used in the subject solar heating systems to relay this 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 tubes and the other is pumped through the space between the tubes and the shell.
Tempering valve	A valve that limits the temperature of water (also "temperature modulating valve) flowing from a domestic hot-water tank by mixing it with cold water

Thermal stratification	Separation of warmer and cooler parts of the storage medium within the storage unit
Thermistor	A type of temperature sensor; its electrical resistance varies sharply in a known manner with the temperature
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 fluid heated by the collector causes the fluid to rise and flow to the point of use
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
Wraparound heat exchanger	A metal panel with integral fluid passages that is wrapped around and secured to the storage tank

APPENDIX A

ASSESSMENT OF SOLAR HEATING SYSTEM RELIABILITY

A.1 Introduction

This appendix presents techniques for estimating the reliability or service performance of solar heating components and systems, techniques which are not unique to solar-energy systems. These techniques are used daily in various industries: 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 accepted definition of 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 is a typical failure-rate curve for a system assembled from components. When the system is first put on line (break-in period), the failure rate is high, because of design errors or omissions, or operator errors.

After the break-in period, the useful-life portion of the system life cycle begins. The failure rate drops, then remains virtually constant. Any malfunctions or failures are random, the results of fatigue, creep, or poor maintenance.

After the system has been in service, wear begins to affect its performance,

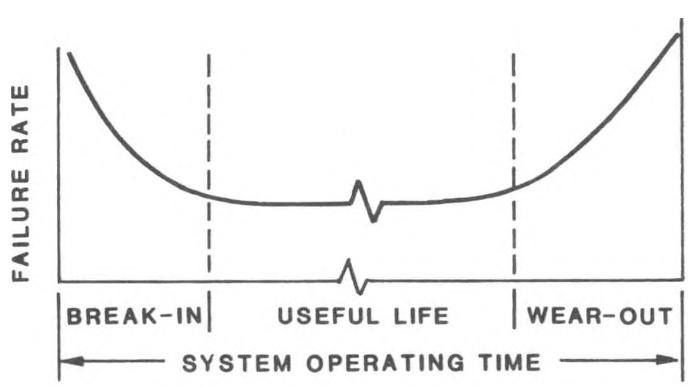


Fig. A.1 Typical system failure-rate curve and the failure rate increases. At this point, a decision must be made: either overhaul the system or abandon it.

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 = reliability, or 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, and

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 results of accelerated testing. If these are not available, component failure rates may be estimated from the failure rates of the units that comprise 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, t must be modified and replaced by t.d, 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 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.

$$\lambda_b = A \exp(x + y), \qquad (A.2)$$

where

λ_b = base failure rate in failures/h,

A = a temperature-dependent coefficient,

$x = [(T - 273)N_t]G$,

where T is the operating temperature in °C and N_t and G are temperature-dependent coefficients, and

$y = (S/N_t)H$,

where S is the ratio of operating load current to rated resistance load current and H is the number of operating hours per day.

This formulation can be extended to other components if testing data are available.

Although field or laboratory data provide the most accurate failure-rate information, these data are usually not in the public domain. Manufacturers regard them as confidential, because they are expensive to generate and their publication would reveal design criteria. In the absence of failure data, however, 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 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, λ_{bu}, can be estimated from

$$\lambda_{bu} = \frac{1}{365(\frac{d}{y}) \cdot W(y)H(\frac{h}{d})} = 2.74 \times 10^{-3}/WH, \qquad (A.3)$$

where

W = warranty period in years

Manufacturer warranties are conservative. A lower bound on the base failure rate, λ_{bL}, can be estimated by assuming the component will operate continuously for at least as long as the warranty period. In this case,

$$\lambda_{bL} = 0.57 \times 10^{-4}/W. \qquad (A-4)$$

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 a component that has a number of series-connected elements that must function for the component to function, the overall failure rate is:[1,4,5]

$$\lambda_b = \lambda_1 + \ldots\ldots + \lambda_n \qquad (A.5)$$

where λ_1 through λ_n are the failure rates of the individual elements that comprise the component.

More complicated components can be represented as a combination of series- or parallel-connected elements.[4]

A.3.4 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: temperature, voltage, time of day, etc., modify the base-failure-rate values.

Depending on the component and available testing data, Ref. 1 suggests the following functional expressions for the failure rate of a component.

$$\lambda_p = \lambda_b(f_1 \times f_2 \times f_3 \times \ldots \times f_n), \qquad (A.6)$$

where

λ_p = component operational failure rate,

λ_b = component base failure rate under normal operating conditions,

and

$f_1 \ldots f_n$ = environmental parameters affecting the failure rate

For most of the components used in solar DHW systems, the various environmental parameters used in Eq. A.6 are unavailable at the present time. However, data from the National Solar Data Network[3] indicate that certain components have duty cycles of only part-day operation.

In that situation, the failure rate for a component in solar-energy system operation can be estimated from

$$\lambda_p = \lambda_b[d + (1 - d)a], \qquad (A.7)$$

where

λ_b = component's base failure rate,

d = duty cycle per day (operating h/24), and

a = parameter to account for degradation during nonoperating 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 nonoperational periods. If "a" is assigned a value, say one-half, then the component degrades, under nonoperating conditions, at one-half of the fully-operational rate.

A.3.5 Flat Plate Collector Base Failure Rate

As a first approximation, a flat-plate solar collector can be idealized as a group of series-connected elements. 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, and
- the condition of the heat-transfer fluid is periodically checked to verify that the fluid is not corrosive.

With these assumptions, and using Eq. A.5, the base failure rate of a collector is

$$\lambda_{bc} = \lambda_g + \lambda_s + \lambda_i + \lambda_a + \lambda_{ac} \tag{A.8}$$

where the failure rates of the components are indicated by

λ_g = the glazing,

λ_s = the seal,

λ_i = the insulation,

λ_a = the absorber plate, and

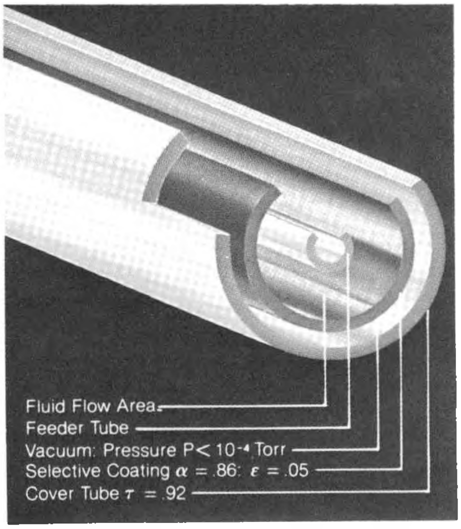
λ_{ac} = the absorber plate coating.

With the base failure-rate data for the individual elements presented in Ref. 2, λ_{bc} ranges from 2.28×10^{-4} to 2.28×10^{-5} failures/h, corresponding, in the same order, to MTBF of 6 months to five years under continuous full-load operation (for constant failure rates, MTBF = $\frac{1}{\lambda}$). To obtain MTBF of flat plate collectors under actual operating conditions, Eq A.7 must be used first, to compute the operational failure rates of components (see, also, Subsection A.3.7).

These MTBF values are conservative, because it was assumed that all of the elements are in series. Some collector manufacturers provide limited warranties of up to 15 years on their collectors. As a result, the collector base failure rate will be assigned a value that ranges from 11.4×10^{-6} to 114×10^{-6} failures/h. These rates correspond to one to ten years.

A.3.6 Tubular Collector Base Failure Rate

A tubular collector module has several tubular sections attached to a manifold. In turn, each tubular section is built-up from three concentric tubes and a seal. See Fig. A.2.



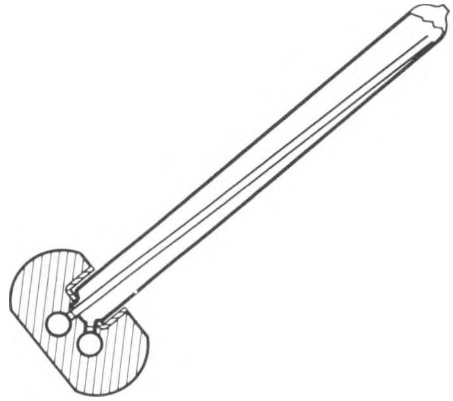


Fig. A.2 Detail of tubular collector module

Although the three tubes are concentric, failure of any one of them requires that a section of the collector module must be replaced. From a reliability analysis viewpoint, the three tubes are in series with each other and the polymer seal.

The base failure rate of a tubular section can be estimated from

$$\lambda_t = \lambda_s + \lambda_f + \lambda_v + \lambda_c + \lambda_{ct}, \tag{A.9}$$

where the failure rates are represented as

λ_t = tubular section,

λ_s = polymer seal,

λ_f = flow tube,

λ_v = vacuum tube,

λ_c = coating,

λ_{ct} = feeder tube.

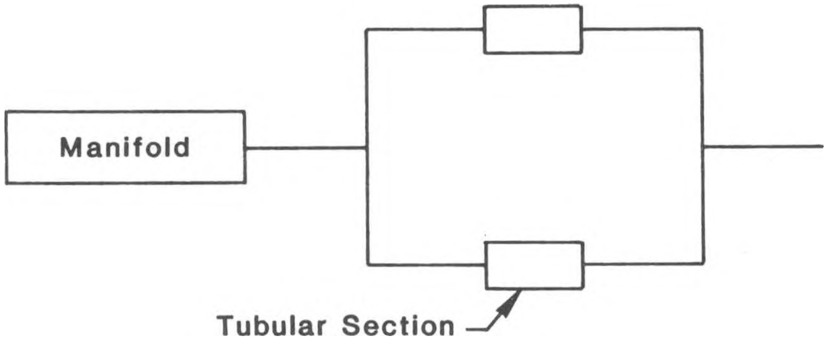


Fig. A.3 Reliability diagram for a tubular collector module

When individual collecter tubes are interconnected to form a module, the collector tubes are in parallel with each other. The manifold is the common link and is in series with those tubes. The block diagram is shown in Fig. A.3.

The overall failure rate for the collector module can be obtained by using the concept of partial redundancy. The collector module is assumed to be operational if at least "k" out of "m" tubes are functional. A nonredundant series model, where all of the tubes are in series, is too restrictive. In contrast, a maximum-redundancy model, where only one out of "m" units is required, yields too low an estimate for the collector module failure rate. The partially-redundant reliability model, which bounds the parallel and series extremes, is given by[10]

$$R_c(t) = \sum_{x=k}^{m} \frac{m\,!\; r^x \quad (1-r)^{m-x}}{x\,!\quad (m-x)\,!}, \tag{A.10}$$

where

R_c = reliability of the combined tubular sections,

k = minimum number of tubes for module operation,

m = total number of tubes in module, and

r = reliability of a single element,

= $\exp[-\lambda_t t]$

Equation A.10 estimates the reliability of the combined tubular sections, and must be integrated to obtain the MTBF of the tubular sections.

$$\text{MTBF} = \int_{0}^{\infty} R_c(t)dt. \tag{A.11}$$

Assuming an exponential failure-rate distribution, the failure rate for the tubes in the collector module is the reciprocal of the MTBF. The MTBF and the corresponding failure rates for the module (excluding manifold) in Fig. A.3 are given in Table A.1.

Table A.1

MTBF and Failure Rate Summary for a Tubular Collector Module

Number of Operating Tubes (out of 8)	MTBF (h)	Failure Rate (*/h)
4 out of 8	$0.885/\lambda_t$	$1.13\ \lambda_t$
5	$0.635/\lambda_t$	$1.57\ \lambda_t$
6	$0.434/\lambda_t$	$2.30\ \lambda_t$
7	$0.268/\lambda_t$	$3.73\ \lambda_t$
8	$0.125/\lambda_t$	8.0 $_t$

Note: λ^* = failure rate when "x" out of "m" tubes are operating.
λ_t = failure rate of single tube

Given the λ^* values from Table A.1, the failure rate of a tubular collector module including the manifold (λ_{cm}) is

$$\lambda_{cm} = \lambda^* + \lambda_m \tag{A.12}$$

where

λ_m = failure rate of manifold.

Failure rate data from Ref. 2 are summarized in Table A.2. These data indicate that the seal, the coating, and the vacuum tube are the three central items in a tubular collector.

Although the vacuum tube is manufactured from the same quality glass as the flow tube and the feeder tube, it has a higher failure rate. The factor of two between the failure rates of the glass tubes is based on engineering judgement and the fact that the vacuum tube is exposed to ambient conditions.

Based on data in Table A.2, the range of failure rates for a tubular section is 1.3×10^{-5} to 3.4×10^{-5} failures/h under full (24-h day) operating conditions. The lower bound on the failure rate of the tubular section could be reduced by 30% if the mean-life of the coating and the seal could approach 50 years.

Table A.2

Failure Rates of Components Used in Tubular Collectors

Component	Failures, 10^{-6}/h	
	Min	Max
Glass Flow Tube	1.2	4.6
Glass Feeder Tube	1.2	4.6
Vacuum Tube	2.4	4.6
Coating	3.8	15.0
Polymeric Seal	3.8	5.7

Because eight tubular sections are usually used in a collector module, the module failure rate was obtained by averaging the failure rates when 4, 5, 6 tubular sections are operating. Using data in Tables A.1 and A.2 and Eq. A.12, provides a range of operating failures that implies that a collector module should operate from two to five years under full (24-h day) operating conditions.

A.3.7 Solar Component Operational Failure Rate Summary

The operational failure rates (λ_p) for components used in solar-energy systems can be computed from Eq. A.7, using the information listed in Table A.3.

Table A.3

Failure-Rate Ranges for Solar DHW Components[2]

Component	Base Failure Rate (λ_b)[a] failures, 10^{-6} h	Duty-cycle Parameter[b] d	Assumed Degradation Parameter[c] a
Single flat plate collector panel	11.4–114	0.25	0.0–0.5
Single tubular collector module	23–73	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
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
Fan	22–44	0.25	0

[a] Base failure rate from Refs. 5, 6, 7, or by calculation.

[b] Duty-cycle parameter from Ref. 3.

[c] Degradation parameter is based on engineering judgement, and 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 results in analytical difficulties and insufficient data. An overly simplified model can lead to inaccurate conclusions and to 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 components can be so combined in series that the system fails if any one component 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 one drain-back solar system is shown in Fig. A.4. This figure represents all of the major components of the system 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[2]

$$R_s(t) = 2\exp[-(\lambda_c + \lambda_x)t] - \exp[-(2\lambda_c + \lambda_x)t], \tag{A.13}$$

and the mean time between failures is

$$\text{MTBF} = 2/(\lambda_c + \lambda_x) - 1/(2\lambda_c + \lambda_x), \tag{A.14}$$

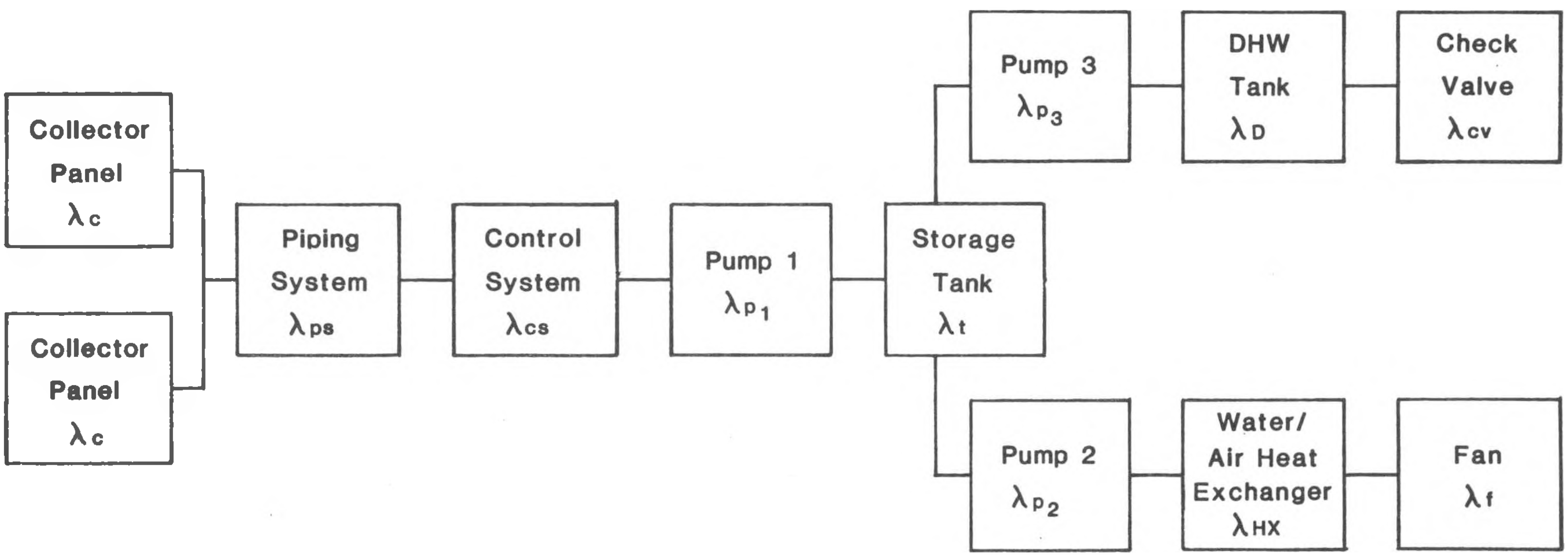


Fig. A.4 Reliability diagram of a drain-back system with two collector panels where

$$\lambda_x = \bar{\lambda} + \lambda_{p1} + \lambda_{p2} + \lambda_{p3} + \lambda_f + \lambda_{HX}$$

$$\bar{\lambda} = \lambda_{cs} + \lambda_t + \lambda_D + \lambda_{ps} + \lambda_{cv} ,$$

and the λ identifications are indicated in Fig. A.4.

If both collectors are required to meet the load, the system reliability is

$$R_s(t) = \exp[-(2\lambda_c + \lambda_x)t], \quad (A.15)$$

and the mean time between failures is

$$MTBF = 1/(2\lambda_c + \lambda_x). \quad (A.16)$$

Because some of the components, such as collectors, pumps, heat exchangers, and fans, operate for only a portion of each day, Eq. A.7 and data in Table A.3 must be used to modify the expressions for λ_x and λ_c. For those components that have duty cycles, their failure rates must be modified as in Eq. A.17:

$$\lambda_i = \lambda_{ibc} [d + (1-d)a], \quad (A.17)$$

where

λ_i = failure rate of the i-th component,

λ_{ibc} = base rate of the i-th component,

d = duty cycle parameter,

a = degradation parameter,

and Eq. A.17 is applied to the collector, pump, fan, and heat exchanger. After the modifications indicated by this equation are made, the form of the system reliability equations (A.13, A.15) and the MTBF expression (A.14, A.16) remain the same.

A.5 Summary of System Reliability Equation

Solar energy systems used for space and DHW heating use multiple panels that are connected in parallel. The systems that were analyzed had 4, 6, 8, 10, 12, or 14 collectors. The following expressions estimate system reliability,[2] [R_s (t)].

For systems with four collector panels and at least two collector panels required at a working condition of 50% load minimum:

$$R_s(t) = 6 \exp[-(2\lambda_c + \lambda_r)t] - 8 \exp[-(3\lambda_c + \lambda_r)t] + 3 \exp[-(4\lambda_c + \lambda_r)t], \quad (A.18)$$

$$MTBF = 6/(2\lambda_c + \lambda_r) - 8/(3\lambda_c + \lambda_r) + 3/(4\lambda_c + \lambda_r). \quad (A.19)$$

For systems with four collector panels and at least three collector panels required at a working condition of 75% load minimum:

$$R_s(t) = 4 \exp[-(3\lambda_c + \lambda_r)t] - \exp[-(4\lambda_c + \lambda_r)t], \quad (A.20)$$

$$MTBF = 4/(3\lambda_c + \lambda_r) - 3/(4\lambda_c + \lambda_r). \quad (A.21)$$

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 or module,

λ_r = the sum of the failure rates of all system components except collector panel. For cyclic operations of pumps, etc., λ_r should be modified as in Eq. A.17.

For systems with six panels and at least three panels at a working condition of 50% load:

$$R_s(t) = 20 \exp[-(3\lambda_c + \lambda_r)] - 45 \exp[-(4\lambda_c + \lambda_r)] \quad (A.24)$$

$$+ 36 \exp[-(5\lambda_c + \lambda_r)] - 10 \exp[-(6\lambda_c + \lambda_r)],$$

$$MTBF = 20/(3\lambda_c + \lambda_r) - 45/(4\lambda_c + \lambda_r) + 36/(5\lambda_c + \lambda_r) - 10/(6\lambda_c + \lambda_r). \quad (A.25)$$

For a system of six panels and with at least four panels at a working condition of 66.6% of load:

$$R_s(t) = 15 \exp[-(4\lambda_c + \lambda_r)] - 24 \exp[-(5\lambda_c + \lambda_r)] + 10 \exp[-(6\lambda_c + \lambda_r)] \quad (A.26)$$

$$\text{MTBF} = \frac{15}{(4\lambda_c + \lambda_r)} - \frac{24}{(5\lambda_c + \lambda_r)} + \frac{10}{(6\lambda_c + \lambda_r)}. \quad (A.27)$$

For systems with six panels and at least 5 panels at a working condition of 83% load:

$$R_s(t) = 6 \exp[-(5\lambda_c + \lambda_r)] - 5 \exp[-(6\lambda_c + \lambda_r)],$$

$$\text{MTBF} = 6/(5\lambda_c + \lambda_r) - 5/(6\lambda_c + \lambda_r).$$

For systems with six panels and all panels required at full load:

$$R_s(t) = \exp[-(6\lambda_c + \lambda_r)],$$

$$\text{MTBF} = 1/(6\,\lambda_c + \lambda_r).$$

For systems with eight panels and four panels required at a working condition of at least 80% load.

$$R_s(t) = 70 \exp[-(4\lambda_c + \lambda_r)] - 224 \exp[-(5\lambda_c + \lambda_r)] + 280 \exp[-(6\lambda_c + \lambda_r)] - 160 \exp[-(7\lambda_c + \lambda_r)] + 35 \exp[-(8\lambda_c + \lambda_r)], \quad (A.28)$$

$$\text{MTBF} = 70/(4\lambda_c + \lambda_r) - 224/(5\lambda_c + \lambda_r) + 280/(6\lambda_c + \lambda_r) - 160/(7\lambda_c + \lambda_r) + 35/(8\lambda_c + \lambda_r). \quad (A.29)$$

For a system of eight panels and six panels required at a working condition of at least 75% load:

$$R_s(t) = 28 \exp[-(6\lambda_c + \lambda_r)] - 48 \exp[-(7\lambda_c + \lambda_r)]$$

$$+ 21 \exp[-(8\lambda_c + \lambda_r)], \quad (A.30)$$

$$MTBF = 28/(6\lambda_c + \ _r) - 48/(7\lambda_c + \lambda_r)$$

$$+ 21/(8\lambda_c + \lambda_r). \quad (A.31)$$

For a system of eight panels and all panels required at a working condition of full load:

$$R_s(t) = \exp[-(8\lambda_c + \lambda_r)], \quad (A.32)$$

$$MTBF = 1/(8\lambda_c + \lambda_r) \quad (A.33)$$

The governing equations for the remaining systems are lengthy and are similar to those presented. These equations can be generated by first using the concept of partial redundancy (A.10) to estimate the collector array reliability. Because all of the remaining elements are in series, their overall failure rate is the sum of the individual failure rates. The reliability of these remaining system elements is then given by

$$R_r = \exp(-\lambda_r t).$$

The overall system reliability can then be expressed as

$$R_s(t) = \left[\sum_{x=k}^{m} \frac{m!\, r_c^x \quad (1-r_c)^{m-x}}{x! \quad (m-x)!} \right] \exp(\lambda_r t) , \quad (A.34)$$

where

k = minimum number of collector modules or panels that must be operational,

m = total number of collectors,

r_c = reliability of a collector module or panel

= $\exp(-\lambda_c t)$,

λ_r = overall failure rate of all system elements excluding the collectors, and

t = time

The MTBF of a particular system can then be obtained from

$$\mathrm{MTBF} = \int_0^\infty R_s(t)dt, \quad \text{(A.35)}$$

where $R_s(t)$ is obtained from Eq. A.34.

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 computing an averaged daily-duty-cycle factor, "$\bar{d}$," from

$$\bar{d} = \frac{1}{365} \sum_{i=1}^{n} d_i t_i, \quad \text{(A.36)}$$

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 used to compute λ_r and λ_c. With the new known values of λ_c and λ_r, the new MTBF values can be computed from the preceding equations.

A.6 Failure Rates from Analysis of Failure Modes and Effects

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 for ways in which it 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.4, a portion of the FMEA for a solar energy control system, illustrates the technique, and Refs. 8 and 9 present other applications.

For the control systems used in solar heating and DHW systems, FMEA yields failure rates of between 5.7×10^{-6} and 28.5×10^{-6} failures/h.

Table A.4

Portion of Failure-Modes-and-Effects Analysis for DHW Control System[2]

Component	Failure Mode	Direct Effect	Effect on System	Failure Rate (per 10^6 h)
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 cannot turn on	Pump cannot 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 POINTS

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 needed 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 of the value of the energy collected and the operating cost of collecting the solar energy. The following five-step procedure includes an example of 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 to computing the electric power consumption, design approach and field approach.

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 manufacturer's curves to determine brake horsepower (BHP) of pump.
- 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 oversize, the motor-efficiency rating is lower.

° Compute the power, in kilowatts, consumed by the pump/motor combination using:

$$P = 0.745\ (BHP)/\eta \qquad (B.1)$$

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 depicted in Fig. B.2 for the purpose. If a wattmeter is not available, the voltage and current must be measured. Figure B.3 illustrates methods of attaching the voltmeter and ammeter. The following equations give pump power in kW.

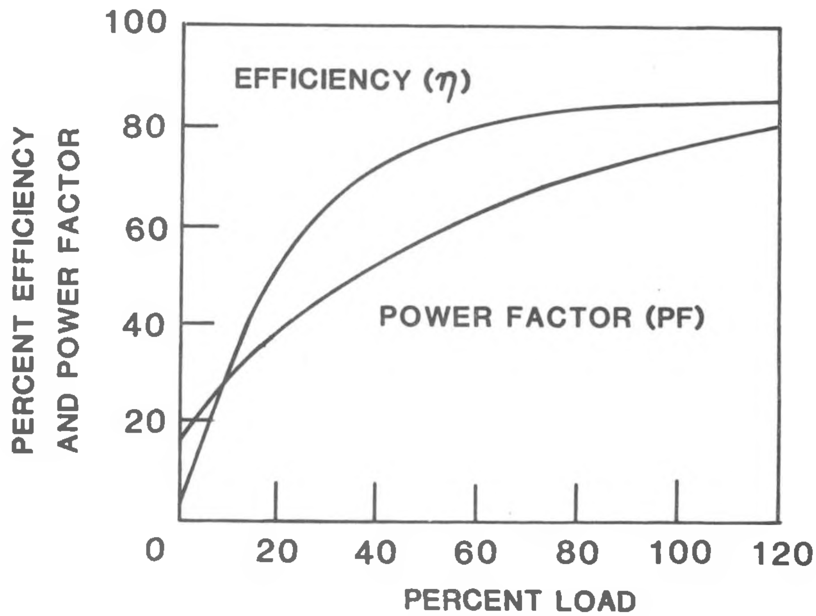


Fig. B.1 Motor Efficiency Curves. (Curves apply only to one motor design of one manufacturer and are not to be generalized. There are many electric motors of different designs and efficiencies. Without the manufacturer's data, determination of motor efficiency is impossible. However, such data may give 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.)

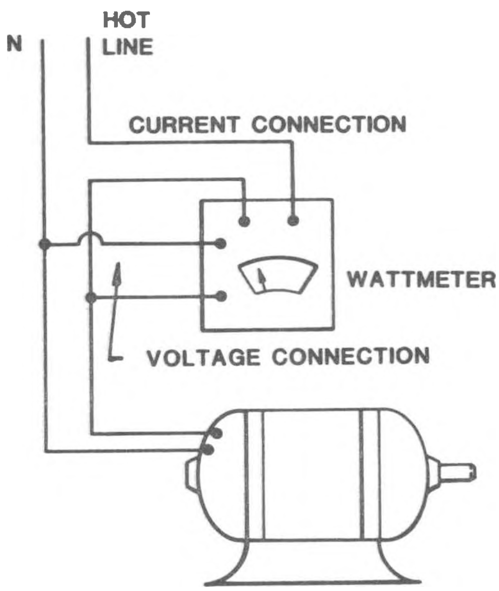


Fig. B.2 Wattmeter Connections across Pump Power Lines

$$P_3 = 1.732\ V_L I_L (PF)/1000 \tag{B.2}$$

for three-phase motors, and

$$P_1 = VI(PF)/1000 \tag{B.3}$$

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) must 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 before 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.

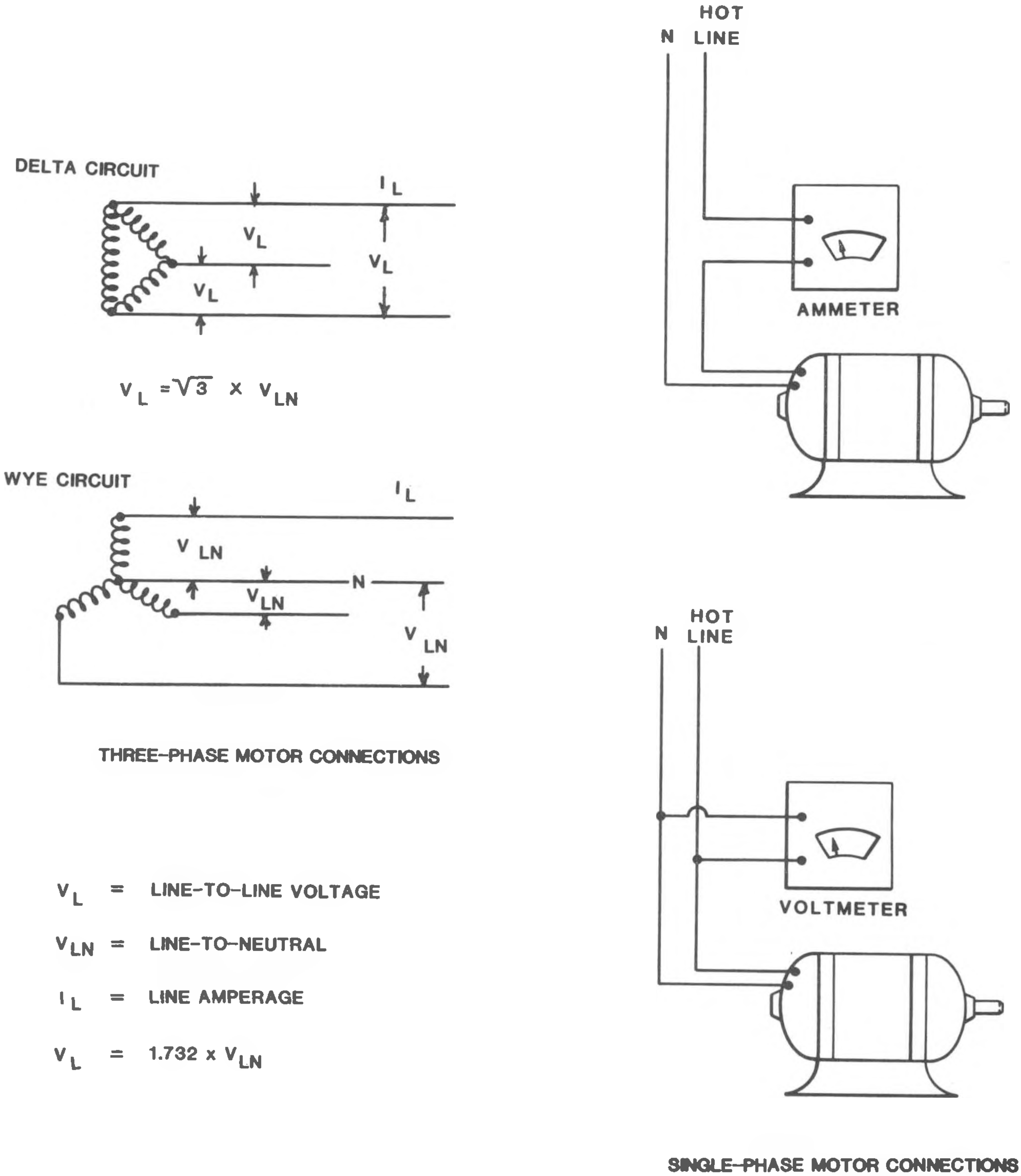


Fig. B.3 Ammeter and voltmeter connections into three-phase and single-phase motor circuits

- It may be difficult, if not impossible, to obtain manufacturer data on motor efficiency at different operating points.

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

$$COE = P_c C_e, \quad \text{(B.4)}$$

where

COE = operating cost in \$/h,

P_c = power consumed by the pump in kW, and

C_e = electrical energy cost in \$/kWh.

The power consumed by the pump is obtained from field measurement or can be calculated from Eqs. B.1, B.2, or B.3.

Step 3: Determine the maximum rate of solar energy collection

Energy transported to storage is expressed as

$$Q_c = MC(\Delta T), \quad \text{(B.5)}$$

where

Q_c = rate of solar energy collection

M = mass flow rate,

ΔT = difference between the temperature in the storage tank and the temperature of the liquid leaving the collectors, and

C = specific heat.

If, and only if, water is the heat-transport medium, Eq. B.6 gives the rate of solar energy collection in Btu/h:

$$Q_c = 500\ W(\Delta T), \tag{B.6}$$

where

W = flow of water through the collector loop in gal/min, and

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 must 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 the table do not include the standby-heater losses. These losses depend on the size of the tank and tank location (such as 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 (ηs)	
Auxiliary Fuel	Typical DHW Heater	Tankless Coil Heater
Gas	0.5-0.75	-
Oil	0.5-0.7	0.4[a]
Electricity	1.0	-

[a]Private communication, J. Meeker, Northeast Solar Energy Center.

The cost benefit of the solar energy collected is

$$C_b = C'_b(\Delta T), \text{ and} \tag{B.7}$$

$$C'_b = Q_c \times C_a/\eta_s(\Delta T), \tag{B.8}$$

where

C_b = cost of solar energy collected in \$/h,

C'_b = cost of solar energy collected per degree of temperature difference in \$/(°F·h), and

C_a = cost of auxiliary energy used in \$/Btu.

η_s = seasonal efficiency

Step 5: Determine low-temperature differential set point

The ideal T is at the point where cost to operate the solar-energy-collection system is equal to the cost of solar energy collected:

$$COE = C_b = C'_b(\Delta T), \text{ or} \tag{B.9}$$

$$\Delta T = (COE)/C'_b \tag{B.10}$$

The value of ΔT calculated by 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.

Sample Calculation of Low-Temperature Differential Set Point

Assume a collector loop using 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 \$4/10^6 Btu. During field testing, system power consumption was measured with a wattmeter and found to be 120 W (i.e., 0.12 kWh/hour-of-operation). The cost of one kWh is \$0.07. Then the calculation proceeds as follows.

$$COE = P_c C_e = 0.12\ (0.07) = \$0.008/\text{h}$$

$$C_a = \$4 \times 10^{-6}/\text{Btu}$$

$$Q_c = 500\ (1.5)(\ T) = 750\ \Delta T$$

$$C'_b = \frac{Q_c \times C_a}{\eta_s(\Delta T)} = \frac{750}{0.7} \times 4 \times 10^{-6} = \$0.00429/°\text{F}\cdot\text{h}$$

$$T = (COE)/C'_b = \frac{0.008}{0.00429} = 1.9°\text{F}\ (1.0\ °\text{C})$$

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