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Reliability and Maintainability Evaluation of Solar Control Systems

March 1979

ARGONNE NATIONAL LABORATORY
Energy and Environmental Systems Division
Solar Reliability and Material Program

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RELIABILITY AND MAINTAINABILITY EVALUATION OF SOLAR CONTROL SYSTEMS

by

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Energy and Environmental Systems Division
Solar Reliability and Materials Program

March 1979

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Office of Solar Applications

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FOREWORD

This document is one of a series of documents that have been prepared by the ANL Solar Reliability and Materials Performance Program covering reliability, maintainability, and materials performance of solar heating and cooling systems.

The data that are used in the preparation of these documents are obtained primarily from the commercial solar demonstration sites sponsored by the U.S. Department of Energy. The ANL Solar Reliability and Materials Program is a major activity of the DOE National Solar Data Program managed by H. Jackson Hale.

Approved by:

P.S. Chopra

P.S. Chopra, Manager
ANL Solar Reliability and Materials Program

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SUMMARY

Control system problems affected the performance or reduced the effectiveness of 25 percent of the 47 DOE-sponsored solar heating and cooling sites that were reviewed. The reliability field information presented in this report indicates that most of the control system problems that have been encountered so far have been design related. The second major reason some of the DOE-sponsored solar-energy systems experienced operating difficulties was improper sensor calibration, location, and installation. Defective components caused some operating problems, but the incidence of these problems was approximately one-third that of the design-related problems.

After an introductory look at control systems and terminology, this report will present control problems in detail. Since the major control problem is design-related, a Failure Modes and Effects Analysis (FMEA) on two existing systems is presented. While the FMEA cannot be used to improve the design of these operational systems, the results can be used to critique the system and to indicate where improvements can be made in future systems.

Guidelines for design, sensor calibration, location, and installation are presented. In an appendix, the characteristics of various sensors that are applicable to solar-energy installations are presented.

1 INTRODUCTION

The Department of Energy (DOE) is conducting a demonstration program to evaluate the operating characteristics of liquid and air solar-energy systems so that reliable and cost effective heating and cooling systems can be developed. A survey of problem areas at 47 DOE-sponsored systems indicates that a major portion of the problems encountered so far have been related to controls.[1] (See Fig. 1.) Solar-energy control systems are a major problem area in part because variable energy sources and small temperature differences mean that they have to be more complex than the control systems used in conventional heating, ventilating, and air-conditioning systems (HVAC). In addition, some of the control components are new to the HVAC industry, and designers are not familiar with them. Using failure data obtained from the DOE-sponsored systems, this report describes the major control problems and addresses the question of how they can be reduced.

Because of the variety of control system configurations used on the DOE-sponsored heating and cooling sites, it is impossible to describe each system or design philosophy. The following section discusses the salient features of three basic control systems and presents the control system terminology used throughout the report.

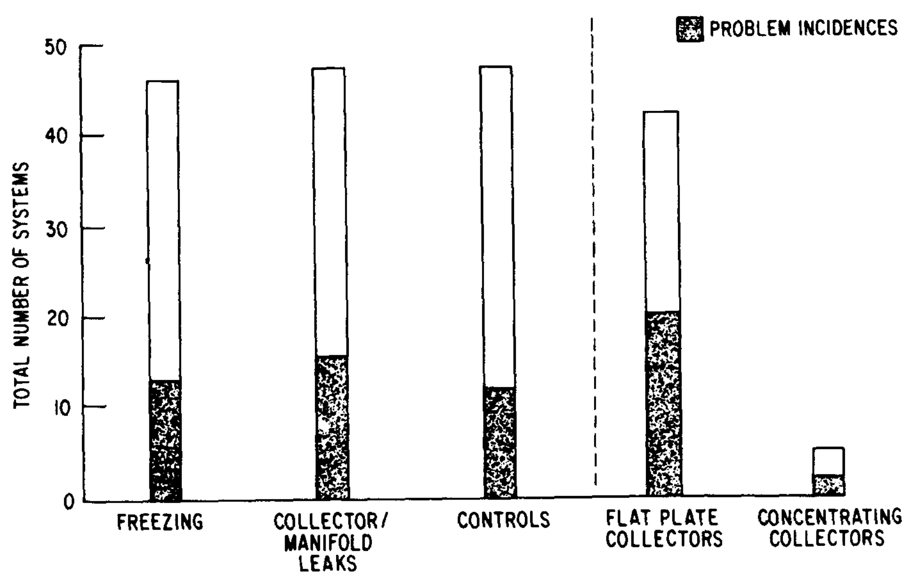


Fig. 1. Solar-Energy System Problem Incidences

1.1 THE THERMOSTAT AS A CONTROL SYSTEM

Figure 2 illustrates a common thermostat. To conserve energy during the winter months, the thermostat is set at 68°F. In control language, this specified temperature is referred to as the setpoint. If the house temperature drops below the setpoint, a feedback signal is generated. When the difference between the setpoint and the feedback (the error signal) reaches a value selected by the thermostat manufacturer, then the thermostat forces a system response and turns the furnace on. When the house temperature, as sensed at the thermostat, matches the thermostat setting, then the error signal cancels, and the system responds by shutting the furnace off.

Most thermostats include a thermometer or indicator to provide a visual check of the heating system's performance. If, during normal cyclic operation, the setpoint does not correspond with the thermometer, then the system is said to be out of calibration.

As a control system, the thermostat has three components: the sensor, the controller, and the actuator.

The Sensor

The sensor, a bimetallic strip, is attached to and wound around a movable shaft. This strip has a large coefficient of expansion and responds to temperature changes by either increasing or decreasing in length.

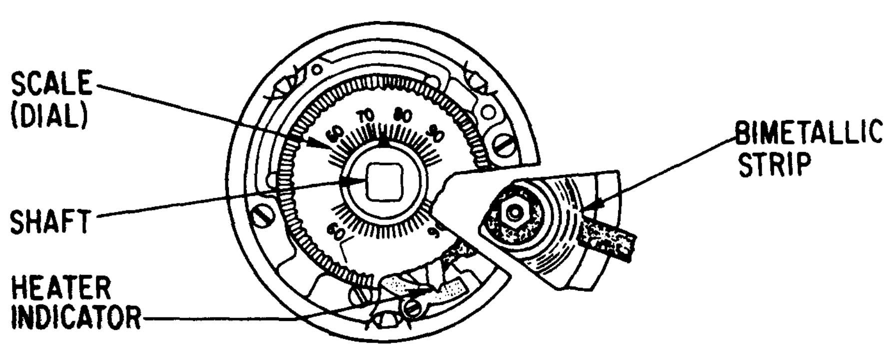


Fig. 2. Typical Heating Thermostat

The Controller

The shaft and body of the thermostat function as the controller. When the dial is set at a particular temperature, the shaft positions the free end of the bimetallic strip. This position is a result of two variables, the setpoint and the strip's coefficient of thermal expansion.

The Actuator

A mercury-filled relay is usually attached to the movable end of the bimetallic strip. This relay is the actuator. When the room temperature is at or above the setpoint, the relay contacts are dry. When the room temperature falls below the setpoint, the relay contacts are immersed in mercury, and the electrical circuit to operate the furnace is completed.

1.2 A SOLAR DOMESTIC HOT WATER CONTROL SYSTEM

The solar domestic hot-water (DHW) system illustrated schematically in Fig. 3 is another example of a control system. The collector coolant absorbs heat from the solar collectors, and a pipe carries the heated collector fluid to the DHW preheater tank. Pump P-1 moves the fluid from the collectors to the preheat tank and is operated by a differential temperature controller.

A differential temperature controller is activated by the temperature difference between two sensors. Its components are described in the sections that follow.

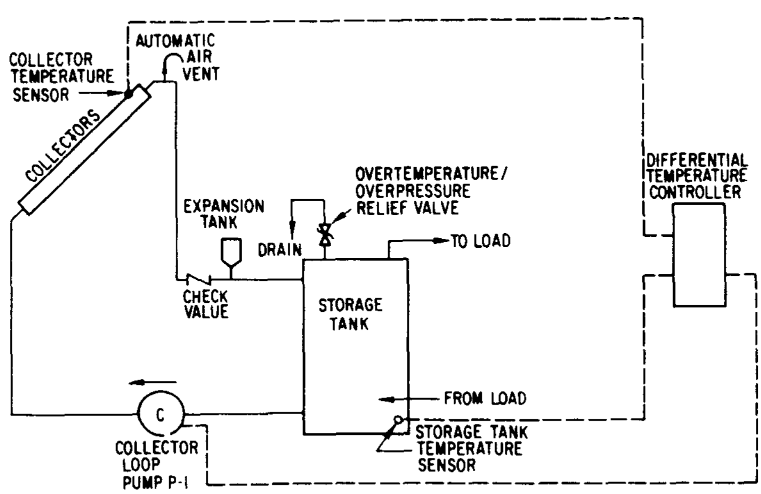


Fig. 3. Schematic of a Solar Domestic Hot Water System

The Sensors

Thermistors are the most common sensors used for temperature measurements on solar energy heating and cooling systems. These elements are manufactured from semiconducting material and their electrical resistance varies with the temperature. The dependence of the electrical resistance of a typical thermistor on the ambient temperature is illustrated in Fig. 4.

The Controller

The controller uses solid state components to measure the temperature difference between the solar collector array and the storage tank. If the temperature difference is large enough, for example, 9°F or greater, Pump P-1 is started and heat is transferred from the collector array to the storage tank. After the pump is running, the controller will maintain pump operation until the temperature difference drops to a predetermined shutoff value, such as 1.8°F.

Controllers can be ordered with optional control modes. For instance, the pump can be shut off to stop heat collection if the storage tank exceeds a maximum temperature. This operational mode should be included to prevent excessive hot water temperatures, thus eliminating the possibility of lifting safety relief valves and possible scalding incidents.

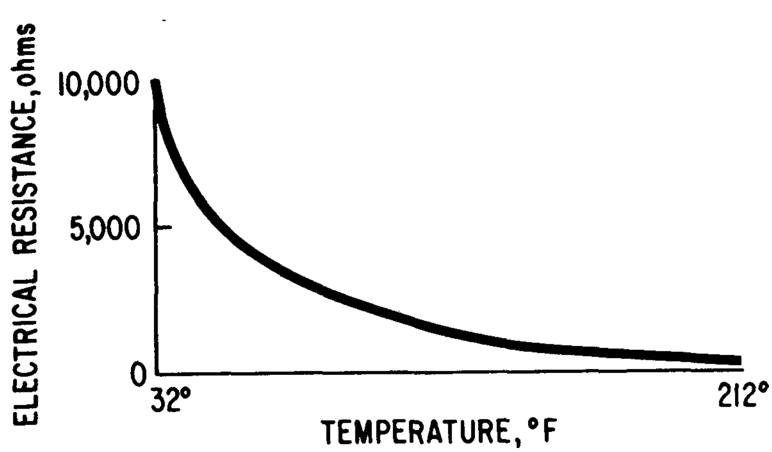


Fig. 4. Electrical Resistance of a Thermistor as a Function of Temperature

In areas of the United States where freezing temperatures seldom occur, water is often used as a collector fluid. In these systems, the controller can be used to start the pump and to circulate water through the collector for freeze protection.

The differential controller, in summary, is a specialized unit for solar-energy systems. The setpoint is a difference in temperatures. The feedback signal is the difference between two sensors, one mounted on the solar collector and the other mounted in the storage tank.

The Actuator

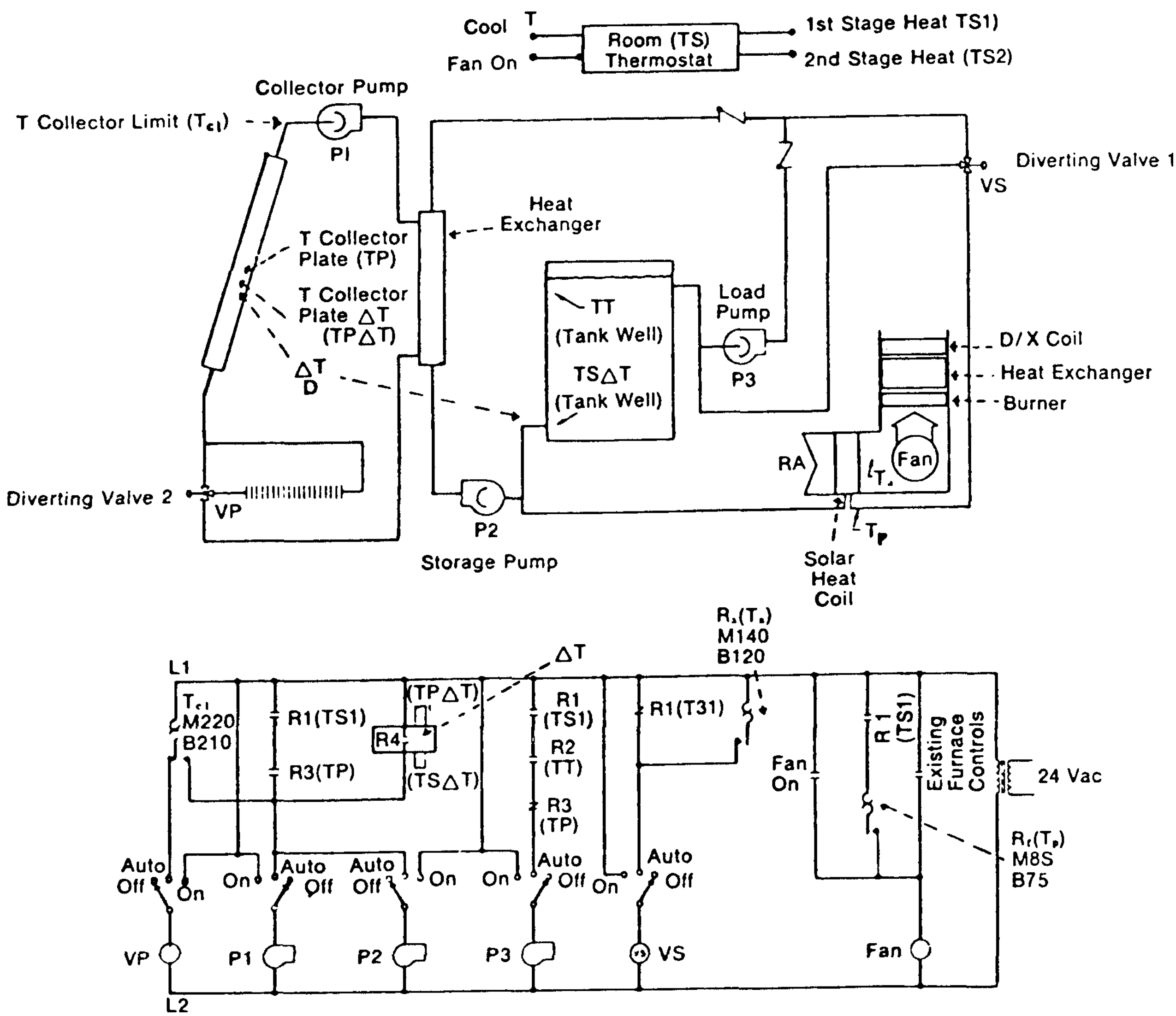
The actuator in a temperature differential controller is usually a relay assembly that starts and stops a pump or opens and closes a control valve. (This simple ON/OFF mode of control is common to the solar heating and cooling industry.) A relay can be either one of the newer, solid-state relay devices or a more conventional electromechanical unit. Both relay types are described in Appendix A.

A proportional output based on the temperature differential can be utilized to control pump speed or adjust control-valve settings. Proportional-output control actuators are not common in the solar-heating industry, but can be used to obtain more efficient energy collection. For example, the collector-loop pump speed can be proportionally controlled to maintain the desired differential temperature between the collector and the storage tank.

1.3 A SOLAR HEATING CONTROL SYSTEM

The solar heating control system is an extension of the solar domestic hot water system discussed in the previous section. Figure 5 presents a typical solar heating control schematic.[2] The collector array is in an isolated loop, and a heat exchanger is the interface between the collectors and the storage tank. Pumps P1 and P2 work together to remove heat from the collectors and store it in the storage tank. Pumps P1 and P2 are controlled by three different means:

- Relay R4 is contained within the differential controller and is activated by the temperature difference between the collector absorber plate and storage.



L_1, L_2 — Power in line voltage
R — Relay
M — Make contact temp
B — Break contact temp

Fig. 5. Typical Solar Heating Control Schematic

- Thermostat T_{c1} provides overtemperature protection for the collector and the collector fluid. When activated, this thermostat starts pump P1, and it opens three-way valve VP to divert the collector fluid through the heat rejector.

- Contacts for room thermostat TS1 and collector plate thermostat TP function to operate pumps P1 and P2 if there is a demand for a higher room temperature and the collector temperature is sufficient for the demand.

When a heating demand exists, and solar insolation is not available, P3 and the fan are activated, and heat is drawn from storage. In this mode, pump P2 is interlocked and cannot operate. If storage cannot meet the heating demand, P3 is interlocked, and the auxiliary heating unit supplies the load.

As can be seen in Fig. 5, the differential temperature controller is now part of the total control system. The solar heating system is more complex, and it has more components than the DHW system. The greater complexity is necessary to provide system flexibility, but as the number of components increases, the chance of a malfunction also increases.

2 CONTROL SYSTEM PROBLEMS

The reliability field information discussed in this section is based on a review of 47 DOE-sponsored solar heating and cooling systems. As shown in Fig. 1, approximately 25 percent of these solar energy systems experienced control system problems. These problems can be placed in five categories, and Fig. 6 is a frequency distribution of the control system problems experienced. These data indicate that each system that was affected had more than one control-related problem.

The effect of these problems on the solar energy control system is presented in Table 1. This information indicates:

30 percent of the failures caused a loss of solar energy*

27 percent of the failures caused the control system to enter an improper mode of operation

16 percent of the failures caused a loss of auxiliary energy

8 percent of the failures caused collector damage

8 percent of the failures caused spurious pump operation

The remaining 11 percent of the problems were recorded as miscellaneous. These problems ranged from fire hazard conditions, to lightning damage, to inadequate provision for control system maintenance.

2.1 DESIGN

Improper design is the major cause of solar-energy system control problems, and it occurs because solar heating and cooling control systems are more complex than conventional HVAC control systems. This additional complexity is required because the operating modes depend on variable insolation rates, intermittent demands from storage or collectors, control decisions based on small temperature differentials, and the successful integration of the auxiliary heating and cooling equipment into the operation of the system.

The major design-related problem area indicated in Table 1 is that the control system can enter an improper operating mode. For example, sometimes

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*Inability to collect when solar insolation is available or storage is depleted by operating the collector loop pump when insolation is not available.

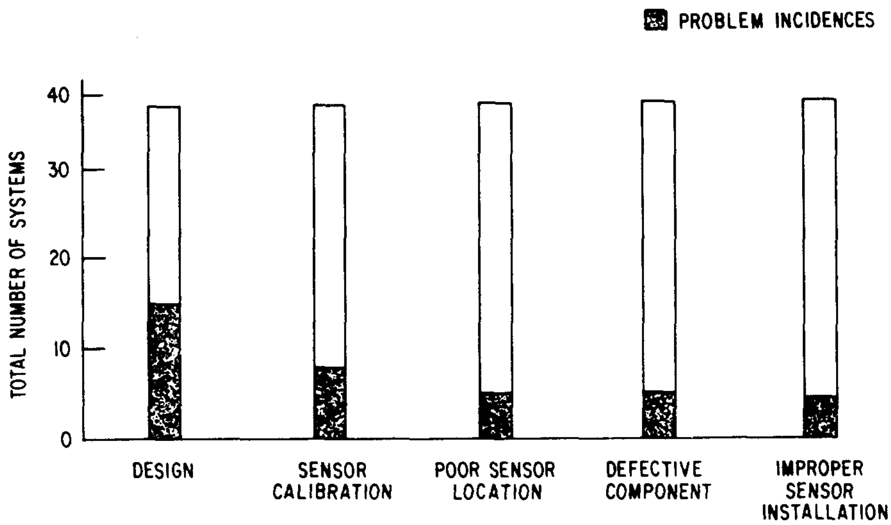

Fig. 6. Control-System Problem Incidences

Table 1. Listing of Control Problems and System Effects

	Problem				
System Effect	Design	Calib-ration	Defective Component	Sensor Location	Improper Sensor Installation
Loss of Solar Energy	1	4	3	3	0
Improper Oper-ating Mode	5	1	2	0	2
Loss of Auxil-iary Energy	4	1	0	1	0
Collector Damage	2	0	0	1	0
Spurious Pump Operation	2	1	0	0	0
Misc.	2	1	1	0	0

auxiliary boilers heated the thermal storage tank, or the auxiliary and solar heating systems operated simultaneously. These examples indicate that the truth tables for the control modes were either not developed or were improperly evaluated.

Control-system design problems can also cause a loss of energy from the auxiliary systems. For example, at one site, improperly controlled dampers exhausted the heated air instead of drawing in fresh air.

Freeze damage of the collector array can also result from improper control-system design. At one site, the contractor failed to provide a back-up power source to drive the freeze protection pump in case of a power failure. At another solar site, the control system design did not include a back-up for the water level switches, and water remained in the collector array when the ambient temperature was below freezing and insolation was not available.

Design problems can also degrade system performance and prevent solar energy from being collected when it is available. At one site, the control system designer specified an improper auxiliary boiler temperature, and the boiler expended unnecessary fuel in attempting to heat the storage tank to 180°F continuously.

2.2 CALIBRATION

Inadequate sensor calibration is the second largest cause of control problems in solar heating and cooling systems. This problem arises because of the small relative temperature differences that have to be detected for precise control. Unless the sensors are properly calibrated, appropriate control decisions cannot be made.

Calibration problems exist in conventional HVAC systems. However, these systems use relatively constant sources of energy such as gas or electricity, and the consequences of inadequate sensor calibration are not as severe as in solar heating and cooling systems.

Data from the DOE-sponsored solar heating and cooling systems indicated in Table 1 show that improper sensor calibration leads primarily to the loss of solar energy. In the majority of cases reviewed, solar energy was lost because of excessive pump cycling, continuous pump operation, or premature pump activation and operation during periods of low solar insolation.

Some calibration problems can be explained by the following example. Assume that a differential controller utilizing a 9°F temperature differential is used with uncalibrated or unmatched integrated-circuit temperature sensors to initiate solar collection.* The combination of the 9°F differential temperature setting and the uncalibrated sensors could start the collector loop pump when the actual temperature differentials were as low as 0.4°F or as high as 17.6°F. At either extreme, the system will not operate efficiently, and the thermal performance of the overall system will be degraded.

2.3 DEFECTIVE COMPONENTS

Defective components accounted for six of the recorded control system problems. On two of the solar heating and cooling systems, the temperature sensors could not withstand the collector environment; they failed and had to be replaced. At two other sites, the control system problems were caused by faulty differential temperature controllers. Spare units were available, and the systems were back in service within a few hours. Another control system problem was traced to the failure of a 120 volt circuit breaker that disabled the control system power supply. The system was down until a spare circuit breaker could be installed.

The remaining control systems that experienced defective component problems were built around an experimental microprocessor. Many of the components in these systems were one of a kind and had not undergone reliability testing before being installed.

2.4 SENSOR INSTALLATION AND LOCATION

Improper installation and sensor location together comprised 19 percent of the control system problems. This percentage is almost as large as the 22 percent attributed to calibration problems and again emphasizes that solar-energy systems must have accurate input data to perform efficiently. On a recent field trip, a collector temperature sensor was observed to be positioned loosely against the absorber plate and could not measure the absorber-plate temperature accurately. An adequate sensor-mounting assembly would improve the performance of such a system considerably.

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*See Appendix A.

Finally, it is important to locate sensors properly so that they can record what is happening. Poor placement of sensors is a common problem. For an example, see Fig. 7. In this system, the freeze protection sensor was affected by convection currents from the storage tank, and it indicated a temperature that was greater than ambient. Freeze protection was inadequate and problems developed. If the temperature sensor had been installed at least ten pipe diameters away from the elbow and towards the collectors, the effect of the convection currents would have been minimized.

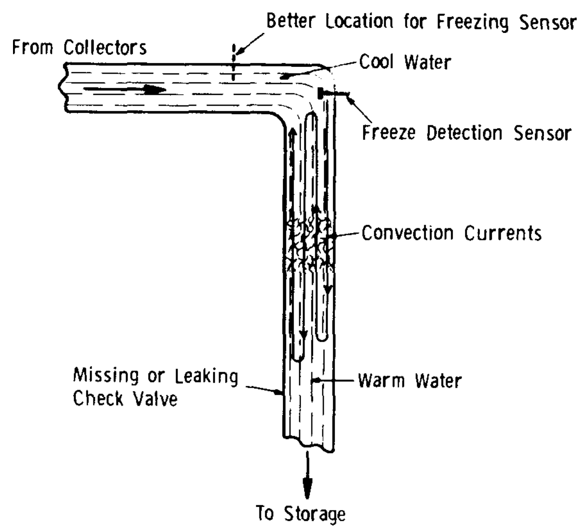

Fig. 7. Freeze Detection Sensor Location
Affects System Performance

Other problems can arise because the sensors are located in close proximity to auxiliary heat sources. As a result, these sensors indicate temperatures that are higher than the actual fluid temperature and the efficiency of the system is reduced.

3 CONTROL SYSTEM RELIABILITY EVALUATION

The Failure Modes and Effects Analysis (FMEA) method is the most adaptable technique for analyzing the reliability of solar-energy systems. The FMEA method was developed conceptually during the German V-1 rocket-development program in World War II. The method examines each component individually to determine the ways that the component can fail. The consequences of each mode of failure are then assessed with respect to the total system or environment, and the probability of failure is calculated for each failure mode.

The probability that a component failure will occur can be calculated as follows:

$$P_f = 1-e^{-\lambda T} \tag{1}$$

where:

P_f is the probability that the failure will occur
λ is the component failure rate expressed in failures per hour*
T is the time interval given in hours

The term $1-e^{-\lambda T}$ can be approximated by λT if λT is small. For instance, if $\lambda T = 0.01$, then $1-e^{-\lambda T} = 0.00995$ and the approximation is within 0.5 percent. If $\lambda T = 0.1$, then $1-e^{-\lambda T} = 0.09516$ and the approximation is within 5 percent.

The system failure probabilities are calculated by summing the component failure probabilities that lead to a specific type of failure. Examples of the calculation method are presented in the following sections.

3.1 SYSTEM ANALYSIS

Sections 3.1.1 and 3.1.2 summarize the FMEA results for two existing solar-energy systems. One system is part of the DOE-sponsored solar heating and cooling program and the other was designed, constructed, and operated by

*Occasionally λ will be expressed in failures per demand operation. In such cases, the exponential power (λT) is computed by multiplying the demand failure rate by the operational frequency.

NASA at the Langley Research Center in Hampton, Virginia.[3] Both systems use flat-plate solar collectors and are retrofitted to existing heating systems. The DOE-sponsored system has a domestic hot water heating loop, but the NASA configuration does not utilize solar energy for DHW.

The FMEA technique examines the effect of component failures on the system as a whole. As a result, the analysis can be correlated only to those problems discussed in Sec. 2 under the defective component category. This type of analysis could be extended to include problems such as sensor calibration, improper sensor location, and inadequate sensor installation. However, the probabilities of these events occurring are not well documented and have not been included.

3.1.1 Failure Modes and Effects Analysis of a Control System in the National Solar Heating and Cooling Program

The control system schematic for a DOE-sponsored heating and cooling site is shown in Fig. 8. From this schematic, the components of interest are identified and their failure modes are defined. The component failure rates were obtained from the Reactor Safety Study and this information is presented in Table 2.[4] This table also indicates the effect of a component failure on the system, and this information can be used for troubleshooting the system.

Table 3 summarizes the analysis for four failure events and these results are presented graphically in Fig. 11 on page 30. Although some of the failure probabilities are high, the relative ranking is more important than the absolute value. For example, the second event (failure to collect heat) and the third event (DHW malfunction) have a much higher probability of occurring than the first event (loss of heat from storage) or the fourth event (excessive DHW temperature). In particular, the third event is over thirty-three times more likely to occur than the fourth. Moreover, safety relief valves are required on DHW tanks so that if the fourth event occurs, the safety relief valve will lift before a scalding incident can occur.

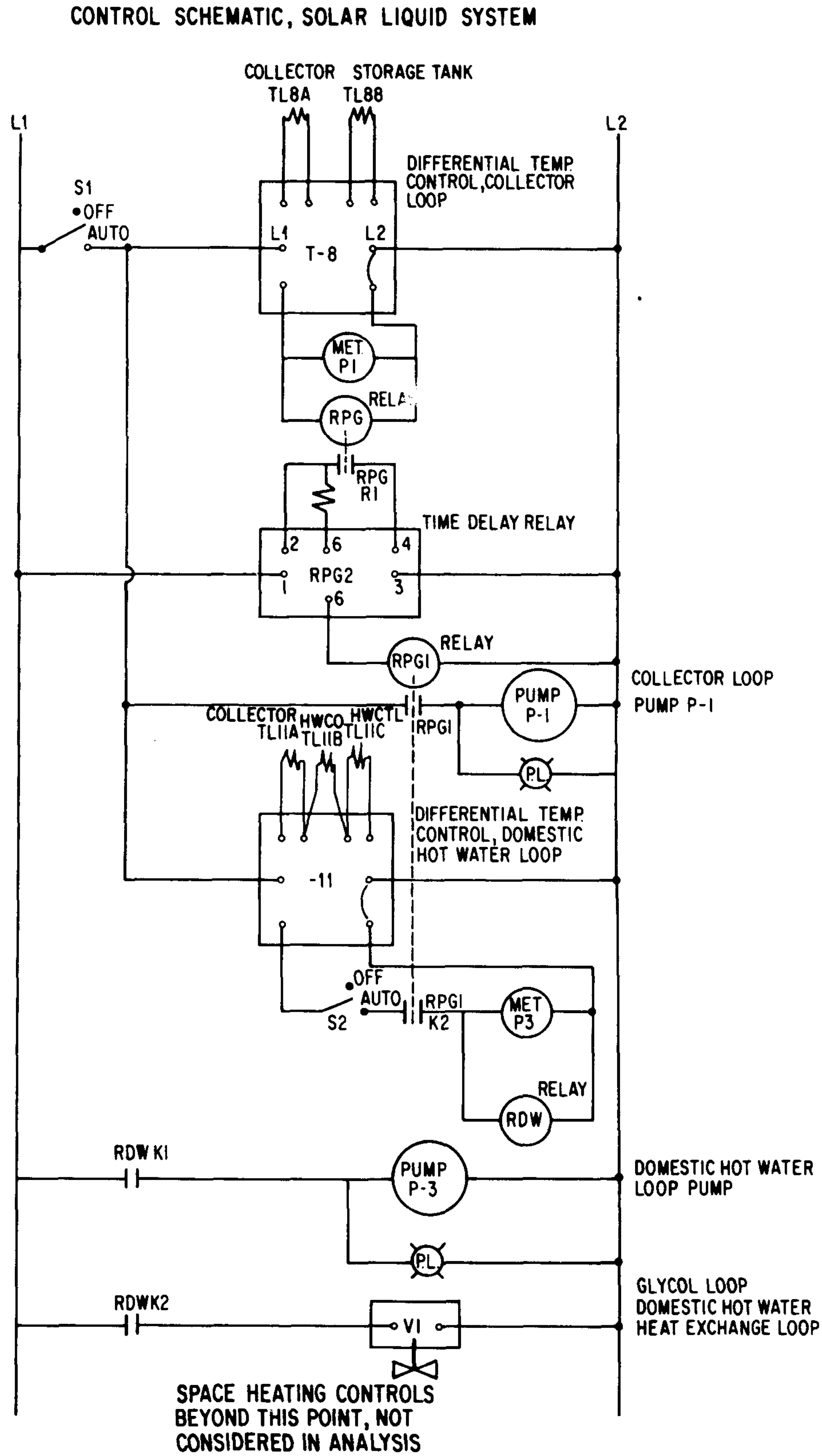

Fig. 8. Schematic of a Solar-Energy Control System

Table 2. National Solar Heating and Cooling Demonstration System Failure Modes and Effects Analysis Tabulation Sheet

Component	Failure Rate	Failure Mode	Effects
1. T18A thermistor for collector loop, pump controller T-8	3×10^{-6}/hr	1.1 Resistance decr.	1.1 Pump starts & runs continuously causing loss of stored heat through cold collectors.
	3×10^{-6}/hr	1.2 Resistance incr.	1.2 Pump will not start, therefore, solar energy cannot be collected.
2. TL8B thermistor for collector loop, storage tank, pump controller T-8	3×10^{-6}/hr	2.1 Resistance decr.	2.1 Same as 1.2
	3×10^{-6}/hr	2.2 Resistance incr.	2.2 Same as 1.1
3. Pump Controller T-8	1×10^{-6}/hr	3.1 Fails, causing RPG relay to actuate	3.1 Same as 1.1
	1×10^{-6}/hr	3.2 Fails, causing RPG de-energize	3.2 Same as 1.1
4. Relay RPG	3×10^{-7}/hr	4.1 Contacts closed	4.1 Same as 1.1
	1×10^{-4}/demand	4.2 Contacts open	4.2 Same as 1.2
5. Time-delay relay RPG-2	3×10^{-7}/hr	5.1 Contacts closed	5.1 Same as 1.1
	1×10^{-4}/demand	5.2 Contacts open	5.2 Same as 1.2

*Assume winter operating conditions with freezing nights, system operating in automatic mode.

Table 2. National Solar Heating and Cooling Demonstration System (Cont'd.)

	Component	Failure Rate	Failure Mode	Effects
6.	Relay RPG-1	3×10^{-7}/hr	6.1 Contacts closed	6.1 Same as 1.1
		1×10^{-4}/demand	6.2 Contacts open	6.2 Same as 1.2
7.	Pump P-1	3×10^{-4}/demand	7.1 Fails to run when required	7.1 Same as 1.2
8.	TL11A thermistor for domestic hot-water loop, collector temp. sensor	3×10^{-6}/hr	8.1 Resistance decr.	8.1 Valve V1 will open, and pump P-3 will run, only if solar heat is being collected (Controller T-8 is actuated).
		3×10^{-6}/hr	8.2 Resistance incr.	8.2 Valve V1 will remain closed, and pump P-1 cannot run. Domestic water-heating loop will not function.
9.	TL11B thermistor for domestic hot-water loop, hot-water tank high-temp., cutoff sensor	3×10^{-6}/hr	9.1 Resistance decr.	9.1 Domestic hot water will not be heated.
		3×10^{-6}/hr	9.2 Resistance incr.	9.2 Water temp. in hot-water tank may exceed safe limit.
10.	TL11C thermistor for domestic hot-water loop, hot-water tank temp.-difference sensor	3×10^{-6}/hr	10.1 Resistance decr.	10.1 Same as 8.2
		3×10^{-6}/hr	10.2 Resistance incr.	10.2 Same as 8.1

Table 2. National Solar Heating and Cooling Demonstration System (Cont'd.)

	Component	Failure Rate	Failure Mode	Effects
11.	Controller T-11, domestic hot-water control	1×10^{-6}/hr	11.1 Fails, causing relay RDW to actuate	11.1 Same as 8.1
		1×10^{-6}/hr	11.2 Fails, causing relay RDW to de-energize	11.2 Same as 8.2
12.	Relay RDW	3×10^{-7}/hr	12.1 Contacts closed	11.2 Same as 8.2
		1×10^{-4}/hr	12.2 Contacts open	12.2 Same as 8.2
13.	Pump Pump P-3	3×10^{-4}/hr	13.1 Pump fails to run when required	13.1 Same as 8.2
14.	Valve V1	1×10^{-3}/hr	14.1 Valve fails to open when required	14.1 Domestic water loop will not function.
		1×10^{-3}/hr	14.2 Valve fails to close when required	14.2 Minimal amount of heat is added to domestic hot water tank by convection. System appears to function well otherwise.

ANALYSIS NOT CARRIED PAST THIS POINT;
FURTHER ANALYSIS NOT CONSIDERED NECESSARY.

Table 3. National Solar Heating and Cooling Demonstration System Summary Sheet

Assumptions: One quarter year equals 2,500 hours (actually over the long run 1 year = 8,742 hours)

For demand calculations, assume approximately 500 demands per quarter year.

1. Summary of events causing a loss of heat from storage tanks:

   $\Sigma P_f = P_{f\ 1.1} + P_{f\ 2.2} + P_{f\ 3.1} + P_{f\ 4.1} + P_{f\ 5.1} + P_{f\ 6.1}$*

   $\Sigma P_f = 0.02$ per quarter year.

2. Summary of events causing failure to collect heat:

   $\Sigma P_f = P_{f\ 1.2} + P_{f\ 2.1} + P_{f\ 3.2} + P_{f\ 4.2} + P_{f\ 5.2} + P_{f\ 6.2} + P_{f\ 7.1}$

   $\Sigma P_f = 0.21$ per quarter year.

3. Summary of events causing domestic hot-water loop not to function:

   $\Sigma P_f = P_{f\ 8.2} + P_{f\ 9.1} + P_{f\ 10.1} + P_{f\ 11.2} + P_{f\ 13.1} + P_{f\ 14.1}$

   $\Sigma P_f \cong 1.0$ per quarter year.

4. One event is possible to cause the domestic hot water to exceed its safe temperature limit:

   $P_f = P_{f\ 9.2} = 0.0075$ per quarter year.

*The numbers used in this summary (1.1, 2.2, etc.) refer to the failure mode listing of Table 2.

3.1.2 Failure Modes and Effects Analysis of the Control System of the NASA Langley Solar Energy Heating System

This control system's electrical schematic is illustrated in Fig. 9, and Fig. 10 presents the hot water distribution system. In Table 4, the failure rate, mode, and effect information is compiled for all relevant system components. The calculations for the relevant failure events are summarized in Table 5.

The mathematical method for determining the failure probabilities from the FMEA data is identical to that used in Sec. 3.1.1. As was also the case in that analysis, the failure-rate data from the Reactor Safety Study may have overstated the numerical probabilities by a factor of 10 to 100.

For similar event categories, the NASA system exhibits failure probabilities comparable to those calculated for the DOE-sponsored system analyzed in Sec. 3.1.1. These results are presented in Fig. 11.

3.2 COMPARISON OF FMEA RESULTS FOR THE TWO SYSTEMS

The analysis results for the two control systems are summarized in Fig. 11. However, not all of the failure events can be compared. The domestic hot water loop failure events do not apply to the NASA system since it does not have a DHW loop. The storage-to-house-heating-mode failure and the loss-of-house heating event for the DOE-sponsored system were not included since this system has a more complex HVAC interface and the results would not be useful for this report.

As indicated in Fig. 11, both systems exhibit comparable failure probabilities for a loss of stored heat event (about 2 percent per quarter year). The NASA system is about five times more likely to suffer a failure-to-collect-heat event than the analyzed DOE-sponsored system. An examination of the analysis in Sec. 3.1 indicates that the difference in reliability is a result of components with large failure rates. In the NASA case, control valves V-1 and V-2 are the largest contributors. If these valves exhibited failure rates of an order of magnitude smaller (1×10^{-4}/hr), then both systems would exhibit comparable failure probabilities.

The general approach to improving both systems would be to reduce the number of components and improve the quality of the individual components as

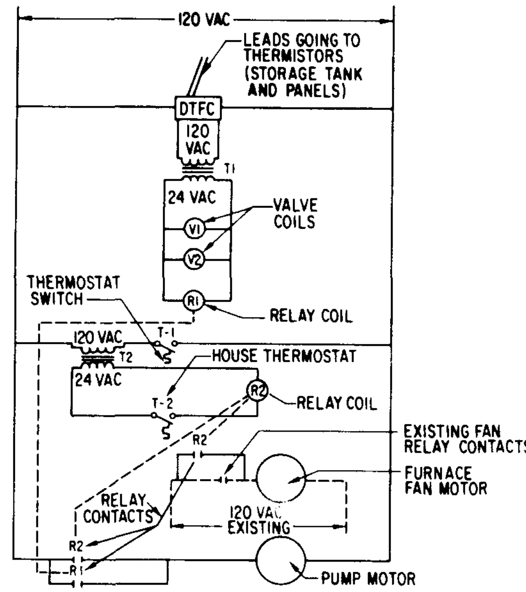

Fig. 9. Schematic of the NASA Langley Solar-Energy Control System

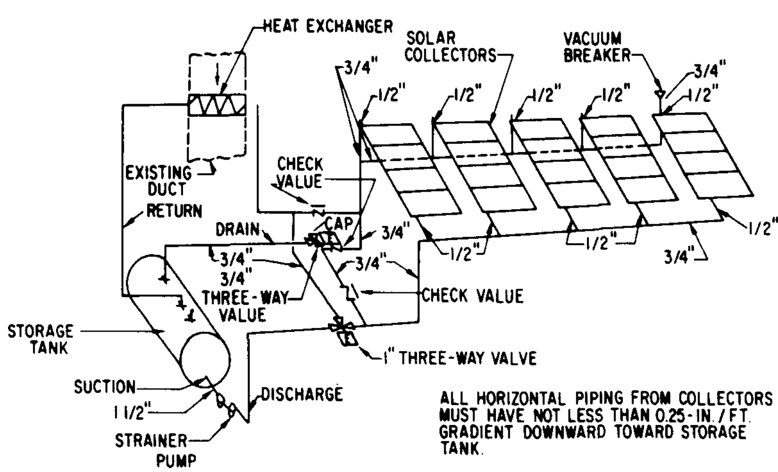

Fig. 10. Schematic of the NASA Langley Solar-Energy System

Table 4. NASA Langley System Failure Modes and Effects Analysis Tabulation Sheet

	Component	Failure Rate	Failure Mode	Effects
1.	Transformer T-1	1×10^{-6}/hr.	1.1 fails open	1.1 V1, V2 & R1 cannot operate. Solar energy cannot be collected.
		1×10^{-6}/hr.	1.2 fails shorted	1.2 Same as 1.1
2.	Transformer T-2	1×10^{-6}/hr.	2.1 fails open	2.1 T1, T2 & R2 cannot operate. Solar energy cannot be collected.
		1×10^{-6}/hr.	2.2 fails shorted	2.2 Same as 2.1
3.	Relay R-1	3×10^{-7}/hr.	3.1 contacts closed	3.1 Pump motor runs continuously-causes loss of stored heat.
		1×10^{-4}/demand	3.2 contacts open	3.2 Pump motor won't run to collect solar energy. Solar energy cannot be collected.
4.	Relay R-2	3×10^{-4}/hr.	4.1 contacts closed	4.1 Pump & furnace fan run continuously-causes loss of stored heat.
		3×10^{-7}/hr.	4.2 contacts open	4.2 Pump & furnace fan won't run. Loss of storage heat to house mode.
5.	Thermostat T-1	3×10^{-7}/hr.	5.1 contacts closed	5.1 Pump & furnace fan run when house heat called for by T-2. Loss of aux. heat into storage tank when storage heat is depleted.
		3×10^{-7}/hr.	5.2 contacts open	5.2 Pump & furnace fan won't run-loss of house heating.

Table 4. NASA Langley Failure Modes and Effects Analysis
Tabulation Sheet (Cont'd)

	Component	Failure Rate	Failure Mode	Effects
6.	Thermostat T-2	3×10^{-7}/hr.	6.1 contacts closed	6.1 Pump & furnace fan run until storage heat is depleted. Loss of storage heat.
		3×10^{-7}/hr.	6.2 contacts open	6.2 Pump & furnace fan will not run when house heat is required. Loss of house heating.
7.	Differential Temperature controller DTFC	1×10^{-6}/hr.	7.1 fails causing V1, V2 & R1 to actuate & remain actuated.	7.1 Pump runs continuously with valves V1 & V2 in solar collection mode. Loss of storage heat.
		1×10^{-6}/hr.	7.2 fails, causing V1, V2 & R1 to deactuate & remain deactuated.	7.2 Pump will not run in solar collection mode & valves V1 & V2 will not go into solar collection lineup. Solar energy cannot be collected.
8.	Thermistor 1 on solar collector	3×10^{-6}/hr.	8.1 Resistance decreases	8.1 Pump starts & runs continuously. Valves V1 & V2 go into solar collection lineup. Loss of storage heat.
		3×10^{-6}/hr.	8.2 Resistance increases	8.2 Pump will not run in solar collection mode. Valves V1 & V2 will not go into solar collection lineup. Solar energy cannot be collected.
9.	Thermistor 2 in storage tank	3×10^{-6}/hr.	9.1 Resistance decreases	9.1 Same as 8.2, solar energy cannot be collected.
		3×10^{-6}/hr.	9.2 Resistance increases	9.2 Same as 8.1, loss of storage heat.

Table 4. NASA Langley System Failure Modes and Effects Analysis
Tabulation Sheet (Cont'd.)

Component		Failure Rate	Failure Mode	Effects
10.	Valve V-1	1×10^{-3}/hr.	10.1 Failed in de-energized lineup storage to heating lineup.	10.1 Solar energy cannot be collected.
		1×10^{-3}/hr.	10.2 Failed in energized lineup solar collection mode	10.2 Loss of storage to house heating mode.
11.	Valve V-2	1×10^{-3}/hr.	11.1 Failed in de-energized lineup storage to heating lineup.	11.1 Solar energy cannot be collected.
		1×10^{-3}/hr.	11.2 Failed in energized lineup solar collection mode.	11.2 No effect.
12.	Pump	3×10^{-4}/demand	12.1 Fails to operate when required.	12.1 Solar energy cannot be collected, also loss of storage to house heating mode.

Table 5. NASA Langley System Summary Sheet

Assumptions: One quarter year equals <u>2,500 hours</u>

For demand calculations, assume approximately <u>500 demands per quarter year</u>

1. Summary of events causing a loss of heat from storage tank:

   $\Sigma P_f = P_f\ 3.1 + P_f\ 4.1 + P_f\ 6.1 + P_f\ 7.1 + P_f\ 8.1 + P_f\ 9.2^{*}$

   $\Sigma P_f = 0.019$ per quarter year

2. Summary of events causing failure to collect heat:

   $\Sigma P_f = P_f\ 1.1 + P_f\ 1.2 + P_f\ 2.1 + P_f\ 2.2 + P_f\ 3.2 + P_f\ 7.2 + P_f\ 8.2$

   $+ P_f\ 9.1 + P_f\ 10.1 + P_f\ 11.1 + P_f\ 12.1$

   $\Sigma P_f \overset{o}{=} 1.0$ per quarter year

3. Summary of events causing failure of storage to house-heating mode of operation:

   $\Sigma P_f = P_f\ 4.2 + P_f\ 10.2$

   $\Sigma P_f = 0.92$ per quarter year

4. Summary of events causing a failure of the system to prevent any house heating:

   $\Sigma P_f\ 5.2 + P_f\ 6.2$

   $\Sigma P_f = 0.0015$ per quarter year

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* The numbers used in this summary (3.1, 4.1, etc.) refer to the failure mode listing of Table 4.

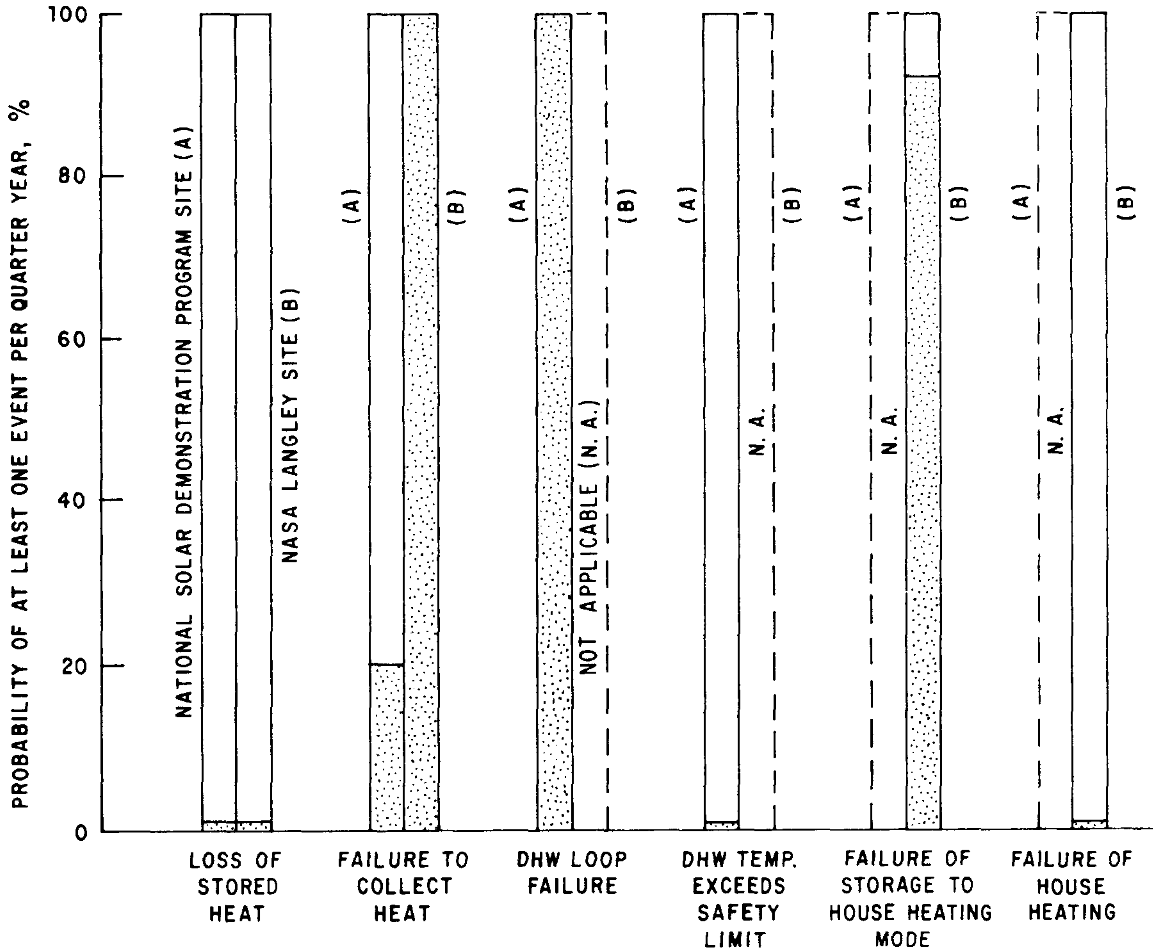

Fig. 11. Comparison of FMEA Results

much as possible. The practicality of such an approach is of course limited by minimal acceptable operating conditions and by economics.

In summary, FMEA results allow system reliability to be improved on the drafting board rather than in the field. Basic reliability criteria can be established for a system's design, thus permitting the designer to state the expected lifetime of the system and to establish preventive maintenance scheduling. In this manner, controls implementation and utilization can be improved to yield more efficient, reliable, and economical solar-energy systems.

4 GUIDELINES FOR SOLAR-ENERGY CONTROL SYSTEMS

4.1 DESIGN

The following guidelines can help the designer to eliminate some of the problems associated with solar-energy systems controls.

- Avoid custom-made components. They are expensive initially and difficult to replace later.

- Install adequate instrument indicators to verify operating properly.

- Check design criteria and calculations by monitoring system performance and by conducting adequate temperature surveys during the checkout phases of operation. On complex systems, temporary instrument-logging equipment should be used.

- Study modes of operation carefully and be sure that each mode is compatible with the others. Some examples of operating modes are:

  - Solar Energy to Storage
  - Solar Energy to Space Heating
  - Solar Energy to Domestic Hot Water (DHW) Heating
  - Solar Energy to Space Heating and to DHW Heating
  - Storage Energy to Space Heating
  - Storage Energy to DHW Heating
  - Storage Energy to Space Heating and DHW Heating

  If, for example, the solar-energy-to-storage mode is incompatible with the storage-energy-to-space-heating mode, the designer must ensure that these modes will not co-exist under any operating conditions. This type of problem has occurred under conditions that caused not only poor solar-energy system operation, but also large energy losses from the conventional HVAC system.

- Be sure that the controls are adequate to perform the task of managing the system's operation. Plan for flexibility with regard to possible future expansion or modification or both.

For maximum system performance and reliability, the controls must be designed to meet the overall system goals. For example, proper collector-to-storage tank temperature differences must be specified to assure net positive heat gain. If water is used in the collector loop, appropriate freeze-protection or draindown control modes must be established and thoroughly analyzed.

4.2 CALIBRATION

Sensor calibration is often overlooked by installers or maintenance personnel but it is critical to system performance, and an established maintenance and calibration schedule is essential. The HVAC maintenance contractor is the obvious candidate for establishing and implementing maintenance and calibration schedules, since the average building superintendent or homeowner will not have calibration equipment or experience.

A calibration program should be established through careful consideration of the following points:

- How frequently is calibration needed?
- What is the specification for each calibration item?
- What test instruments are necessary to perform an adequate calibration?
- What are the cost benefits for the maintenance service and how do they compare with alternate calibration schemes?

4.3 COMPONENTS

Solar equipment manufacturers comprise a broad spectrum in today's industry. Some companies are old-line equipment vendors marketing new equipment lines; others are new companies. Occasionally an established corporation will acquire a fledgling business and use its well-known name on a relatively untried product. In short, selecting a component for solar applications requires more attention to detail than selecting conventional HVAC components.

Equipment costs for solar controls components are not the major share of the total system cost, and a brief survey of specifications for various kinds of controllers indicates a small cost differential between a simple unit and a more complex control system. Since economizing on controls can diminish system performance and reliability, a small additional expenditure in the area of controls can improve system operation and, as a result, reduce the payback time.

4.4 SENSOR INSTALLATION AND LOCATION

High quality equipment is of little value unless sensors are properly located. For example, one demonstration site had a freezing incident because the freeze protection sensor was improperly located (see Table 1). In this instance, the sensor indicated a temperature of 80°F, while the actual fluid temperature was 22°F, and the system froze.

Proper sensor mounting is also very important. For example, a surface-mounted collector temperature sensor using fiberglass tape is unreliable for controls use. It can separate from the collector on an especially cold day, and, as a result, storage-tank energy will decrease because storage fluid will be pumped through cold solar collectors. In critical locations, adequate sensor fittings such as plugs, screw attachments, and immersion assemblies should always be used. Temperature sensors, in particular, require careful and precise installation

4.5 DOCUMENTATION

A solar control system must be easy to maintain. Equipment should be located and labeled so that maintenance can be performed as easily as possible. Here again, as in the area of reliability, good installation practices are important. A listing of likely problems and their associated causes can permit a less technically oriented person to isolate and repair failures that would normally require a service call. A well-written operating and maintenance manual that includes complete specifications for the control system should accompany any solar-energy system installation.

5 CONCLUSIONS

Control system problems caused operating difficulties or reduced the efficiency of 12 of the 47 DOE-sponsored heating and cooling sites that were reviewed. These problems arose because of the need to base control decisions on small temperature differences and the fact that the energy sources (storage and solar insolation) are time dependent. In addition, the auxiliary heating and cooling systems impose their own requirements on the control system design philosophy.

The design of a solar-energy control system usually requires the integration of many off-the-shelf components. Although each subassembly has been designed to meet specific requirements, the combination may not meet the overall system goals.

To determine whether the proposed control system will function properly before it is built, a truth table must be developed and verified. This aspect of the design process indicates that either the system operating modes are compatible or that two competing modes can be activated at the same time.

As a follow-on to the control system truth table, a reliability evaluation of the proposed configuration should be made. Failure Modes and Effects Analysis (FMEA) is an applicable technique because the designer can track the effect of a component failure on the system. A completed FMEA is also a troubleshooting guide and should be included as part of the operations manual.

The failure rate data for the FMEAs in this report were taken from the Reactor Safety Study. Although these data may overestimate the system failure probabilities, the system designer can obtain a relative ranking of the mode failure rates. This information permits the designer to make decisions that can improve the system reliability before the system is in place. For example, in one of the systems that was investigated, the high failure probabilities were linked to two control valves. If these valves were replaced with more reliable units, then both systems would exhibit comparable failure probabilities.

Control systems must have proper sensor inputs so that the appropriate control decisions can be made. The combined total of the sensor-related problems (installation, calibration, and location) was almost as large as the design-related problems. (See Table 1.) These sensor problems are the result of a lack of knowledge of the requirements of solar energy systems on the part of the HVAC contractors. As the industry becomes more aware of the need to measure small temperature differences accurately, and of the fact that the sensors must be placed the appropriate number of pipe diameters away from pipe bends, pumps or fans, the frequency of occurrence of the control sensor related problems will decrease.

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APPENDIX A

COMMERCIALLY AVAILABLE CONTROLS FOR SOLAR-ENERGY SYSTEMS

The solar-energy system designer has a wide range of control systems from which to select. This section discusses the major types of sensors, controllers, and actuators in common use. No attempt is made to compare products by brand name. Accuracies and costs are intended to be only approximate estimates; actual equipment prices and accuracies will vary from manufacturer to manufacturer. Because of the large variety of component and system types, only those types currently used on solar-energy systems in significant numbers or those that appear especially applicable have been considered.

A1 SENSORS

The selection of sensors and their installation is perhaps the most important and least appreciated aspect of control systems. No controller can produce the correct outputs unless it has accurate, reliable inputs from its sensors. The sensors considered here include those for measuring temperatures.

A1.1 Temperature Sensors

A standard mercury or alcohol household thermometer with an extended high-temperature capability makes an effective temperature sensor for local readout. Although thermometers can be used for troubleshooting, control requirements dictate the need for sensors to detect and transmit information to a remote location. Temperature sensors used in solar-energy systems include platinum resistance temperature devices, thermistors, thermocouples and thermopiles, and measuring devices that utilize integrated-circuit detectors.

Platinum Resistance Temperature Devices

A platinum resistance temperature device (RTD) is a wire-wound resistor made from carefully prepared platinum wire. The electrical resistance of the platinum wire, and therefore of the RTD, changes with a temperature in a predictable, repeatable, and linear manner. Therefore, the temperature of the RTD can easily be derived from measurements of the electrical resistance of the RTD.

RTDs, when properly calibrated, can be very accurate, to about ±0.18°F. However, they are moderately expensive (above $50 each). The system cost per RTD is increased because external circuitry is required to make the resistance measurements. Since typical RTD resistances at room temperature are near 100 ohms, compensation techniques must be utilized to eliminate errors due to cable resistance (1 to 10 ohms).

Thermistors

Thermistors, like RTDs, are devices with temperature-dependent resistances. However, thermistors are made of semiconductor materials, rather than platinum. They undergo a greater change in resistance for the same temperature change than an RTD does. The thermistor's resistance at room temperature can range from 1000-10,000 ohms. Therefore, the resistance of the cable is a small fraction of the sensor resistance and can usually be ignored. This simplifies the measuring circuit requirements.

Inexpensive thermistors (about $3) have the disadvantage of non-linear resistance vs. temperature curves. More expensive thermistors (about $20) are often linearized by additional internal components and are accurate to about ±1.8°F. Thermistors are the most commonly used temperature sensors in solar controls applications.

Thermocouples and Thermopiles

A thermocouple consists of two junctions, each formed by joining two dissimilar metals. An output voltage is produced that depends (1) on the difference between the temperatures of the junctions and (2) on the properties of the metals used in forming the junctions. Thermocouples can be used to a definite advantage if the desired measurement is a temperature difference rather than an absolute temperature.

If the output voltage is to indicate the absolute temperature of one junction, the temperature of the other junction must be accurately known. In many cases, thermocouple circuits appear to contain only one junction. In that case, the second junction is contained within the voltmeter (or controller) or is placed most effectively at the junction of the voltmeter terminals and the thermocouple wire. The voltmeter (or controller) will usually be designed to compensate automatically for the temperature of this second junction.

One disadvantage of thermocouples is their low voltage output, which requires expensive amplifiers and increases noise-pickup problems. This disadvantage can be overcome if several thermocouples are wired in series and located so that each thermocouple senses the same temperature. Then the output voltages of the individual thermocouples will add and will become less susceptible to noice pickup. Such an arrangement is called a thermopile. A variation on the thermopile can easily average any number of temperatures. All that is needed is that the individual thermocouples be located at the points where they can read the temperatures to be averaged.

Thermocouples are of moderate accuracy, about ±1.8°F, and moderate cost (about $20). Thermopiles are often slightly less accurate and more expensive. Thermocouples and thermopiles both require special care during installation to maintain their rated accuracy. Also, special thermocouple extension wire, made of the same material as the thermocouple, must be used. This adds to the total cost of the temperature-measuring system.

Integrated-Circuit Sensors

Recently, at least one manufacturer has begun marketing an integrated-circuit temperature sensor. The current that this sensor draws from an unregulated power supply is proportional to the sensor's absolute temperature. With no user calibration, the device is accurate to ±1.8°F. The integrated-circuit sensor is also relatively inexpensive (about $10). Because the output from the sensor is a current rather than a voltage, the problem of electrical noise pickup on long cables is greatly reduced. Any number of sensors can easily be wired in parallel to yield the average temperature sensed by the individual devices. These sensors are limited to a maximum operating temperature of 302°F. In general, this temperature limit is sufficient for most solar applications.

A1.2 Liquid Flowmeters

Liquid-flow rates are not used in most solar-energy systems as a control parameter. This is partly due to the high cost of accurate liquid flowmeters, which are not normally part of the permanent instrumentation.

Therefore, each type of flowmeter will be discussed only briefly here. The reader should be aware that most flowmeters measure volumetric flow, whereas the desired measurement is usually mass flow. The conversion can easily be made, but fluid density at the operating temperature must be known. Most liquid flowmeters must be carefully installed and periodically recalibrated to maintain their rated accuracies. Solids and gas pockets in the fluid can cause measurement errors or can damage most meters. Thus, filters and automatic gas vents are often necessary. Also, most flowmeters require a uniform, non-turbulent flow and therefore must be preceded and followed by flow-straightening sections of pipe. Liquid flowmeters basically fall into one of six categories: turbine, impact, differential-pressure, pitot, positive-displacement, and Vortex-shedding types.

Turbine Meters

Turbine meters consist of a propeller or turbine located in the flow stream. The rate of rotation of this turbine is linearly proportional to the volumetric flow rate. These meters can be very accurate (within about 2 percent) if properly installed and protected, but they are very expensive (about $800).

Impact Meters

Impact meters measure the force that the liquid exerts on a target inserted in the stream. The output from an impact flowmeter is proportional to the square of the flow rate. This limits the accuracy of these meters to about 5 percent, and the usable range to about 10 to 1, but they are much less costly than turbine flowmeters (about $100).

Differential-Pressure Flowmeters

Differential-pressure flowmeters measure the pressure drop across a calibrated nozzle and convert this pressure drop to flow rate. These meters have the advantage of relatively low pressure drop and do not increase the system pumping power requirements.

Pitot Tubes

Pitot tubes measure the pressure inside a tube caused by the fluid's impact on the open end of the tube. The pitot tube, therefore, measures fluid velocity, which must be converted to mass-flow rate.

Positive-Displacement Meters

Positive-displacement meters are also used occasionally, especially where integrated flow is needed. A positive-displacement meter, which is similar to the typical home water meter, operates by physically allowing only a fixed volume of liquid to flow through it for each revolution of a wheel. Turbulence does not degrade performance of positive-displacement meters, but these meters produce high pressure drops.

Vortex-shedding Flowmeters

Vortex-shedding flowmeters may be useful in solar applications in the future because of their potential for high reliability, moderate accuracy, and low cost.

A1.3 Air-Flow Sensors

The difficulty of measuring air-flow rates accurately virtually eliminates this instrumentation from all but research instrumentation systems. One major problem is that air flow through a duct is never uniform, and the measured flow rate depends on the location of the sensor in the duct.

The two most common types of air flowmeters are propeller anemometers, which resemble wind-speed indicators, and hot-wire anemometers. The hot-wire anemometer functions by heating a wire to a constant temperature and then measuring the electrical power required to maintain that temperature. The higher the air flow, the faster the wire loses heat, and the more electrical power is required to maintain the temperature of the wire. The electrical power is measured and converted to a flow rate.

Air flow can also be determined by measuring the pressure drop across a calibrated nozzle. However, the flow rate is not a linear function of pressure drop, and the air density must be known to make the conversion. The air density also depends on the temperature and on barometric pressure, so these parameters must be measured.

A1.4 Insolation Sensors

Solar insolation is best measured with a pyranometer. Most pyranometers contain a dark surface that is exposed to and heated by sunlight. A thermopile measures the difference in temperature between the dark surface and the ambient air. This thermopile output indicates the solar intensity. High-quality pyranometers are accurate to about 3 percent and cost about $1,000. Somewhat less expensive pyranometers may produce significant errors if not mounted in a horizontal plane.

Solar cells can also be used as inexpensive insolation-measuring devices. If the output of the cell is shorted, the current through it is proportional to the solar insolation. Such a cell is inexpensive and insensitive to mounting angles, but it requires individual calibration. The cell's spectral response is also limited, so that changes in the incident light spectrum will produce measurement errors.

A1.5 Position Sensors

Position sensors may be required on tracking collectors. A precision potentiometer is the usual position sensor. This is simply a resistor with a movable center tap. The center tap is connected to the collector directly or through an appropriate mechanical interconnection. A voltage is applied across the resistor, and the voltage at the center tap is measured. This measured voltage is proportional to the position of the center tap and therefore to the position of the collector. Precision potentiometers cost about $30 and are accurate to 0.1 percent. However, the mechanical link to the collector can add considerably to the cost and can degrade the final accuracy.

A1.6 Btu Meters

Btu meters (also called Q meters) measure both the temperature difference between two locations and fluid-flow rate. These data are then used to calculate the instantaneous energy collected or lost. The input-temperature and flow sensors used in Btu meters are the same general types of instruments discussed previously in this report, and the comments presented for those instruments apply to Btu meters as well.

A2 CONTROLLERS

Controllers vary widely in construction type and design philosophy. For the purposes of this report, controllers will be divided into local and remote types.

A2.1 Local Controllers

Local controllers are devices that sense a local parameter and operate a local control device. Generally, these local controllers do not require external electrical power. Examples include check valves and backdraft dampers (both of which limit flows to only one direction) and automatic air vents.

A2.2 Remote Controllers

Remote controllers sense remote parameters, control remote devices, or both. These controllers are usually electrical or pneumatic in nature, and sensing and actuator signals can be carried by electrical cables or pneumatic tubing. Controllers range from simple thermostats or a few relays to the complexity of a microcomputer.

Small controllers using relays, thermostats, and similar items are moderately reliable and relatively low in cost. They are also less likely to be damaged by lightning and power-line voltage spikes than electronic controllers. However, when complex control functions based on many possible input and output modes need to be performed, relay-based controllers quickly become large and unreliable.

Solid-state controllers are much smaller, more reliable, and consume less power than relay controllers in all but the simplest systems. However, unless proper precautions are taken, these controllers are subject to damage from electrical pulses on signal and power lines. In all but the simplest control systems, solid-state controllers are preferred to relay devices.

A3 ACTUATORS

Actuators are devices used by a controller to operate motorized dampers, and to control valves, pumps, and blowers, etc. The actuator allows low-power signals from the controller to actuate devices that consume relatively large amounts of power. The most common actuators are electromechanical relays, solid-state relays, and silicon-controlled-rectifier (SCR) motor-speed controllers.

A3.1 Electromechanical Relays

Electromechanical relays are the most common type of on-off actuator. Typically, a controller will energize a low-power relay, which applies 120 v ac power to the coil of a high-power relay. The contacts on the high-power relay then supply electrical current to the item to be controlled. The low-power relay can be a part of the controller if the controller is relay based. If the controller is solid-state based, the low-power relay can be included in the actuator.

A3.2 Solid-State Relays

Solid-state relays are the electronic equivalents of high-power electromechanical relays. Because solid-state devices have no moving parts, they are more reliable than electromechanical relays. They also can be operated directly by a solid-state controller, eliminating the need for a low-power relay in the actuator.

A3.3 SCR Controllers

If a controller must adjust the speed of a variable-speed fan or pump, neither an electromechanical nor a solid-state relay will be adequate. In that case, a solid-state SCR motor-speed controller must be used. The SCR controller accepts an input signal, which represents the desired speed of the controlled motor, from the solar-energy system controller. The SCR then applies the power needed to achieve this motor speed.

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