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ABSTRACT

The Solar Energy Research Institute has been involved in testing active component reliability and control systems. Six test loops were constructed to thermally cycle drain valves, check valves, air vents, vacuum breakers, tempering valves, and polybutylene piping. Results showing poor reliability of some of the components and limited performance of others lead to a better understanding of certain failures in the field and present designers with realistic expectations for these components. The seven SDHW control systems tested included thermistors, switches, RTDs, IC sensors, and controllers. Serious reliability problems included sensor degradation or failure from high temperatures, and controllers that did not meet specifications. As much as 50% of collected energy can be lost because of sensor degradation, and auxiliary energy requirements can increase by 250%.

INTRODUCTION

This paper presents an overview of the active component and control system testing and analysis performed at the Solar Energy Research Institute since 1981. Failure mechanisms of components and reliability problems of control systems are identified, tests performed are described, and results and recommendations are summarized. Greater detail of component and control system selection, test plans, results, and recommendations are given in the final reports [1-5]. An extensive literature search was conducted to provide guidance for the control system laboratory tests. Much has been written about control systems, but little laboratory testing has been done to determine performance and reliability. High failure rates in installed systems document the serious and widespread nature of the problem, but field data are lacking.

COMPONENT RELIABILITY TESTING AND RESULTS

Drain Valves

One common type of active solar energy system uses electrically actuated valves to protect the collector array and outdoor piping from freezing. For various reasons, drain out systems have acquired a reputation for being unreliable. Though the operating principles of the automatic drain valves evaluated are similar, the specific designs are very different. One uses a brass construction with a polymer piston (Type I), another is a thermoplastic design (Type II), and the third uses a rotating disk with copper and brass construction (Type III).

All of the drain valves underwent a static pressure test, and then one drain valve from each manufacturer underwent a thermal cycling test while a second underwent an infrequent cycling test.

Inspecting and photographing the valves revealed no noticeable defects. The three Type I brass valves and the six Type II thermoplastic valves passed the static-pressure test. In the Type III valves, water readily poured from the collector port through the drainport when the valve was energized (in the fill mode). The manufacturer said that the valve needed to be under pressure to operate properly. Under pressure, it passed the static-pressure test. An additional problem was detected by the internal parts being at line voltage, which revealed an electrical short in the heat motor.

All the drain valves entrained air in the cycling loop during filling. It is good practice to install an air vent on the storage tank to prevent accumulation of air in the tank from frequent cycling.

At the end of the testing only two of the originally installed valves were still operable. However, even these two leaked significantly at cold water temperatures. This might have resulted from thermal setting of the seals. At moderate and high temperatures the leaks ceased. These were dismantled and showed signs of seal wearing, but very little accumulation of scale.

The high number of failures is surprising and is probably attributable to the 93°C (200°F) operating temperatures. However, the operating temperatures did not exceed the maximum temperature rating of any of the valves. Additionally, these conditions are not unrealistic for summertime operation when owners are on vacation.

The results show that failure for Type II is not dependent on the number of drain fill cycles, but rather on operating time or operating temperature. Even though some of the drain valves were not regularly cycled between fill and drain modes, they did cycle automatically to prevent overheating and reduce energy consumptions. The Type II drain valves had corrosion of internal metal parts such as retaining rings, a severely cracked plastic shaft holder, and seals that had deformed. Catastrophic failures were caused by failure of the plastic piston, possibly from thermal stress and fatigue. The manufacturer has recently withdrawn this drain valve from the market.

Though the manufacturer of the Type III drain valves had a testing program, it was not as long as this one. Our results are consistent with their field experience. They identified the problem as an unsuitable lubricant on a plunger to move the rotating disk. This was consistent with an inspection of one of the failed valves. However, another valve had significant scale on the rotating disk that was worn from the rotation. It appeared that the scale may have caused the disk to bind, preventing operation.

These test results are comparable with field results in a recent report [6] where seven of 18 drain valves failed within two years of operation; five failed in the first six months.

Air Vents and Vacuum Breakers

Air vents in solar energy systems eliminate air in a circulation loop or tank that is pressurized relative to the ambient pressure. Vacuum breakers facilitate draining by admitting air into the system. Though these components are most frequently used in drain out systems, which drain and fill frequently, they are also used in other system types to reduce the initial filling time and future draining time when the heat transfer fluid is replaced or removed for system maintenance. These devices are placed at the highest point in the system, usually just above the collector array.

Air vents and vacuum breakers are generally installed outdoors and therefore subject to freezing and icing of the ports. If the valve stem and body are not insulated, then the water inside the valve may freeze, preventing the release or admittance of air. This can lead to inability of the system to drain in sufficient time to prevent freezing. The ports to vent air or admit air are fairly small and may be easily clogged by scale or other debris. Because of the high potential for failure, these valves were selected for testing.

The five air vents, five vacuum breakers, and four combination air vent/vacuum breakers ordered did not have any obvious defects or deficiencies. The valves varied in design from all plastic to all metal construction. All of the air vents and combination valves sprayed water upon filling. This keeps the outlet port clean, but still presented an inconvenience, if not danger, with hot water, which could be sprayed on people, equipment, and roofs. The air vents have a small cap over the outlet port to protect the port and allow the water to be sprayed in a particular direction. However, after repeated fillings, some caps began to unscrew and spray water in undesirable directions. A thermoplastic jacket over three of the combination valves directed spray immediately downward and protected the outlet ports from dust, ice, and snow accumulation. The literature accompanying the all metal combination valve stated that it deliberately allowed an amount of water to flow through it to keep it free of scale and debris. Of the five air vents, four vacuum breakers, and three combination valves tested, none failed during the thermal cycling test.

Significant scaling occurred around the outlet ports of some of the air vents. However, the water pressure was sufficient to maintain an adequate hole through the scale. After the thermal cycling test, all the valves were dismantled. Significant scaling was observed inside the body of the metal construction air vents, which might lead to valve failure. One vacuum breaker was severely rusted and stuck in one position. Another one from the same company had no rust and moved freely. The thermoplastic combination valves had no significant scaling inside the valve body.

Check Valves

Check valves, common plumbing components that prevent or restrict flow in one direction, are used in nearly every active and many thermosyphon solar energy systems, except the drain back system. Check valves are useful in two types of service within solar energy systems. The first use is as an isolation valve to prevent pressurized water from flowing into an unpressurized drain. In this manner, it replaces a solenoid valve in drain out systems, where it must hold line water pressure. In general, check valves seal better with higher differential pressures because of the greater force holding them shut. The other major use is to prevent reverse thermosyphoning in systems that do not drain when the pump is off. In this case, a check valve must seal very tightly under a very low differential pressure.

Two basic types of check valves are used in solar energy systems, swing check valves and spring-loaded check valves. The swing check valve has a disk or flapper that allows flow in only one direction. It must be installed very carefully so that gravity does not cause the weight of the disk itself to keep the valve open. This is particularly important when only a small differential pressure is available to shut the check valve. The spring-loaded check valve has a spring to force the check valve to close. It can generally be installed in any direction since the spring will keep it closed. Flow in the proper direction must have sufficient force to push the check valve open. Although this check valve is more versatile to install, it has a higher pressure drop through it. Tests were developed for each of the two check valve uses.

Three swing check valves and three spring-loaded check valves were included in the high differential pressure test. No catastrophic failures were noted during the 11,308 cycles. However, leaking was observed through all the spring-loaded check valves after 7800 cycles. Significant scaling observed in all of these valves after the test was caused by the wet/dry cycling that deposits minerals that adhere to the metal surfaces. Apparently the scaling led to leakage of the spring-loaded check valves.

Three swing check valves and three spring-loaded check valves as well as one visual floating type check valve were included in the low differential pressure test. The float in the visual check valve repeatedly became lodged in an O-ring under flow conditions and was eliminated from further testing. The variable results of this test reveal that a check valve may not perform consistently in the same way. It was not unusual for a check valve to leak heavily during one test and not leak during the next. Evidently, the check valve seats differently and can either seal well or poorly. The swing check valve appears to seal somewhat better, sealing well 11 out of 16 tests (69%). This is neither a good result nor conclusive due to the small sample size. However, it is indicative that these valves do not seal well against natural convective currents.

Dye traveled through the valves at high rates. This can be a great source of heat loss by circulating a significant amount of water through the collector array on a cold night over 16 hours. Since the flow rate is slow, the temperature drop could be substantial, effectively rejecting much of the previously collected energy. This is particularly of concern for one tank system that uses auxiliary energy to maintain the storage tank temperature because it can increase the auxiliary energy usage as well as lose collected solar energy. After testing, these check valves were dismantled and inspected. There was no significant scaling since the valves were always wet.

Tempering Valves

Tempering (or mixing) valves are conventional plumbing valves and are not unique to the solar energy industry. A tempering valve prevents the water delivered to the load from exceeding a specified temperature, referred to as the set point, which is maintained by mixing or tempering the hot water with cold water. These devices for domestic usage are not designed for accuracy, but first to prevent scalding and the second to conserve energy by limiting the temperature of the delivered water to temperature insensitive appliances, such as washing machines and dishwashers.

After the valves operated for a suitable period of time, their performance was determined with tank temperatures of 49°C (120°F), 71°C (160°F), and 93°C (200°F) with the tempering valves set to 49°C (120°F) and 60°C (140°F). No tempering valves failed to temper the hot water during testing. If the tempering valves were inoperative overnight with no flow, the next morning the top ones were very hot (from natural convection) while the bottom ones were close to room temperature. Therefore, the tempering valves were flushed accordingly before each test to simulate a period of inactivity.

Instructions and design guidelines state that tempering valves should be placed below the top of the storage tank. This may be to prolong the life of the tempering valve since it would undoubtedly be at a lower temperature. However, tests showed that this also results in temperatures 23°C (41°F) in excess of the set point.

The tempering valves responded quickly, approaching the set point within 20 seconds of operation. The top tempering valves seldom overshot the set point. Being flushed with hot water prior to the test, they produced colder water. The bottom mounted valves consistently exceeded the set point, particularly at higher tank temperatures, to the point of being dangerous for the few seconds it takes to reach steady-state.

The results of the steady-state performance tests showed significant variations between the tempering valves. In general, the temperature of the tempered water was sensitive to flow rate at the lower flow rates but not at the higher flow rates. It does not appear that there are any obvious effects on the steady-state performance from the location of the tempering valve with respect to the top of the storage tank.

The most significant criterion for a tempering valve is that it not exceed the set point excessively. At a tank temperature of 71°C, none of the tempering valves exceeded the 49°C set point significantly. However, at higher tank temperatures, the accuracy of the tempering valves changed dramatically. These temperatures should not be encountered frequently, but even at these high temperatures they provide a great deal of tempering, reducing the 93°C water to about 60°C. At low storage tank temperatures the tempering valves reduce the outlet water temperature significantly below the set point. This may be a problem in a solar energy system used without an auxiliary system (such as during the summer) and when the tank temperature is low.

Perhaps the most important result for the solar energy system owner is that the tempering valve output is very sensitive to the tank temperature. Since the temperature of a solar energy system varies fairly rapidly over a reasonably large temperature range, the output from the tempering valve will vary greatly throughout the day and year. Because of the nature of these devices, they are not very accurate nor can they be expected to be so at their low cost. If a tempering valve appears to malfunction, then the range of storage tank temperatures should be considered before suspecting tempering valve failure.

After 18,832 cycles, the tempering valves were dismantled. The cause of the significant scaling observed on the mechanisms and parts is not known since these valves did not experience wet/dry cycling.

Polybutylene Piping

The use of polybutylene pipe instead of copper for domestic solar systems could reduce the cost of system piping [7]. Polybutylene pipe costs less than copper pipe and is easier to install due to its flexibility and use of compression fittings, which should allow more rapid, lower cost installation. However, a potential drawback of polybutylene pipe is its temperature limitation as well as some question regarding the long-term integrity of the mechanical fittings when subjected to elevated temperature. Polybutylene pipe is suitable for solar energy systems containing water, glycols, or silicone oils but not organic heat transfer fluids.

The total length of the polybutylene pipe in the test loop was about 10 m. The pipe was sized (nominal 19 mm, 3/4 inch) to allow draining without the need for a vacuum breaker. Numerous fittings (couplers, tees, elbows, valves) were incorporated into the system. All fittings were attached using copper compression rings. Elastomeric, expanded polyethylene and rigid polyurethane insulations provide additional support for the pipe, which sagged considerably at elevated temperatures. The loop continued to operate successfully without leaks or other signs of deterioration after completing 24,000 cycles over 5 months.

SDHW CONTROL SYSTEM TEST RESULTS

Seven SDHW control systems were purchased to evaluate their performance and failure modes in a controlled laboratory environment [4]. The tests were not intended to be exhaustive but rather to provide insight into the operation and failure mechanisms of these control systems. The seven chosen were commonly used "on/off" control systems and among the less expensive. They included all of the functions of a controller for an antifreeze system and also draindown valves control. Proportional controllers were not evaluated.

Each control system underwent six tests: a sensor temperature response characterization, a sensor stagnation test, a controller function test, a controller environmental exposure test, a controller vibration test, and a controller inspection and high-potential test. All of the testing was performed with calibrated instruments traceable to the National Bureau of Standards. These tests did not account for installation errors such as improperly locating the sensors.

Sensor Temperature Response Characterization

Control systems often come with two types of sensors: thermistors, which turn the pump on and off, and thermal switches (also called snap switches), which act as limit devices for freeze protection, over-temperature protection, and to prevent the pump from operating at night. This test measured the resistance response of the thermistors to temperature over the range of 12° to 80°C and determined the temperatures at which the switches opened and closed.

Two control system manufacturers used 3000-ohm thermistors, and four used 10,000-ohm thermistors. Resistances for six temperatures (12°, 25°, 40°, 55°, 70°, and 80°C) were measured for each thermistor.

The thermistors agreed closely with each other at temperatures higher than 60°C, but showed a significant spread at temperatures lower than 30°C. The 3000- and 10,000-ohm thermistors had about a 2°C spread near 0°C. Because freeze protection may be controlled by thermistor output, it is important to correct for these temperature response differences. Thermistor self-heating during the test increased their temperatures by approximately 1°C, which should be accounted for in controller design.

All of the freeze-protection switches activated (opened) within 1°C of their published specifications and four of the five deactivated (closed) 2° to 4°C below their published specification. The other switch closed within the specifications. Other switches, used for over-temperature protection and to prevent night-time operation, deviated between 0° and 5°C from their published specifications. These switches are not designed as precision sensors and deviations such as these will not cause serious problems.

Sensor Stagnation Test

Fifteen thermistors were attached to a metal plate and maintained at 204°C, the stagnation temperature of a well-designed collector, for 224 continuous hours. All five of the 3000-ohm thermistors and one of the 10,000-ohm thermistors failed the stagnation test because the resistance response to temperature changed more than the uncertainty of the measurement process. Two of the 10,000-ohm thermistors were slightly affected by the test, and the remaining seven 10,000-ohm thermistors passed the test without any significant change in performance.

Four of the five freeze-protection switches and the switch to prevent night-time pump operation, all of which might be mounted in a collector, were maintained at 204°C for 96 continuous hours. Only one freeze-protection switch changed sufficiently to warrant concern, and its change would cause freeze protection to activate at warmer temperatures preventing any freeze-related damage. The switch designed to prevent pump operation below a collector temperature of 26.7°C failed during the initial temperature response characterization and was replaced. The replacement switch catastrophically failed the stagnation test by remaining closed throughout the test. If this switch failed open, it would prevent operation of the collector pump; in the failed closed position it would not affect operation of the collector pump but would also not prevent nighttime circulation.

Controller Function Test

Each controller was tested to determine its performance as a function of storage-tank temperature. Accurate decade resistance boxes were used to simulate sensor inputs; the decade resistance box was about 1 ohm. The results were very repeatable at the time of testing and varied only about 5 ohm from day to day.

All the controllers tested, except for one, deviated significantly beyond the uncertainty limits of the specified turn-on differential. Several deviated from the turn-off differential specified by their manufacturer, showing either a lack of quality control or possibly a lack of understanding for proper system control. Errors in the turn-off differential can result in collection loss at start-up and shut-down and on partly cloudy days, as well as to pump cycling. It can also cause inefficient collection or heat loss if the turn-off differential becomes negative.

Controller Environmental Exposure Test

Each controller was placed in an environmental chamber for 24 hours at 80°C and 25% relative humidity, the maximum relative humidity at this temperature. Since a greater relative humidity was desired, the temperature was decreased to 66°C, which resulted in a relative humidity of 70%. The controllers were then kept at these conditions for 142 hours. The controller function test was repeated during and after the exposure. One failed in the pump-on position during the exposure test but returned to its previous performance after drying. The high temperature and humidity significantly affected the performance of another controller. The differentials of the other controllers changed between 0.1° and 0.5°C, which, when combined with the sensor degradation, can be significant.

Controller Vibration Test

SDHW controllers are frequently mounted on pumps. The cyclical nature of the pump operation and the constant vibration of the controller caused by pump operation may lead to failure of the controller. One controller was subjected to this vibration for 112 continuous hours, which had no significant effect on its performance. Because of equipment limitations, only one controller was tested in this manner. However, other controllers with different structural design may experience failure from vibration, and controllers sensitive to temperature may experience changes in performance or failure from the heat transferred from the pump motor, which can become very hot.

Controller Inspection and High-Potential Test

Each controller underwent a high-potential (5000 VDC) test before and after the environmental test to determine DC current leakage of the electrical power circuit and to evaluate the controller electrical integrity. The results of the test, show cause for concern about the long-term electrical reliability and durability of two controllers, which could withstand a potential of only 100 volts and 400 volts, respectively.

Visual inspection of the controllers before and during the tests revealed mislabeled wires, a moveable jumper that broke, inaccessible fuses, soldered fuses or no fuse, an unlabeled switch, a broken trace on the circuit board that was repaired by soldering across a bare wire, and a soldered pad that was coming off the circuit board.

SENSOR THERMAL CYCLING TEST RESULTS

A new group of 17 thermistors and 11 thermal switches were tested in 1984 [8]. Instead of being subjected to a constant high temperature as in the earlier test, they were subjected to thermal cycling for nearly five weeks --12 hours at a collector stagnation temperature of 204°C and 12 hours cooling down to room temperature. Initial characterization of the five 3000-ohm and the twelve 10,000-ohm thermistors revealed about a 2°C spread in their response at lower temperatures.

Five weeks of thermal cycling followed the post-stagnation sensor recharacterization. Three of the 10,000-ohm thermistors failed catastrophically from the thermal cycling, two changed response by about 4°C at lower temperatures, three changed between 0.5° and 1.5°C, and four changed less than 0.5°C. Above about 41°C (nominal 5000 ohms) all of the nine working 10,000-ohm thermistors were within 1.5°C of their original response.

The 11 freeze protection switches were exposed to the same temperature cycling as the thermistors. Four were initially within their published specifications for both opening and closing, three were within only one specification, two did not meet either specification, and two did not come with specifications. These deviations would probably not lead to either system failure or cycling. After the thermal cycling two were within their specifications (as they were initially), two met only one specification, one did not meet either specification, and four failed. Three of the four failed switches and all five 3000-ohm thermistors failed because of a control failure that caused them to be exposed to 238°C.

EFFECT OF SENSOR DRIFT

As previously reported, testing at SERI has demonstrated that sensors can change their temperature-resistance response or can catastrophically fail. Catastrophic failure will lead to continual pump operation, no pump operation, or possible erratic pump operation, as well as possible failure of the freeze protection and distribution systems. However, the effect of sensor drift or degradation on system performance is not well known and depends on the system configuration and sensor location. Thermistors degrade from exposure to high temperatures, thus, the collector sensor is more susceptible to degradation than the storage tank sensor. Sensors are also not uniformly affected by high temperatures and thermal cycling, therefore, it cannot be concluded that sensors drift together, canceling the effects of degradation.

Sensor response can drift such that a negative temperature differential is needed to turn the pump off. That is, the pump will stop only when the collector outlet temperature is lower than the storage tank temperature. Therefore, the pump will cease to operate only when there is sufficient heat loss between the storage tank sensor and collector outlet sensor to cause a sufficient drop in temperature of the circulating fluid. If the ambient temperature drops quickly, then the collector sensor will cool quickly because of the high thermal losses from the collector, and the pump will turn off. However, if the ambient temperature drops slowly, then the storage tank will keep the sensor warm while the storage tank temperature also drops. In this case, the pump can stay on for extended periods of time and cause significant energy loss from storage. The ambient air temperature required to turn off the pump, as a function of the system parameters and storage tank temperature, can be calculated from an energy balance on the collector.

The effect of sensor degradation on the annual performance of a solar domestic hot water system was determined by computer simulations using TRNSYS 10.0 for four locations: Albuquerque, N. M.; Fort Worth, Tex.; Madison, Wis.; and Washington, D.C. Annual sensitivity runs were made in which both the differential-on temperature and the differential-off temperature were varied over the ranges of interest.

The results of these simulations reveal the degree of the problem resulting from control sensor degradation. The net annual collected energy is not nearly as dependent on the differential-off temperature when it is positive as when it is negative. The selection of the differential-off set point is straightforward and should be selected to avoid pump cycling, to prevent operation of the pump when the value of the collected energy is less than the cost of collecting it, and to impede the set point from drifting below zero because of sensor degradation.

Differential-off temperatures below -2.8°C can reduce the net collected energy by as much as 50% of the energy collected at a differential-off temperature of 0°C. Sensor degradation that results in a differential-off temperature of only -2.8°C can cause the pump to operate almost continuously, resulting in a loss of previously collected energy and extra parasitic costs due to inefficient operation of the pump.

Reliable switches are available, but some are likely to fail under prolonged thermal cycling. Control system manufacturers should select switches for use based on results from thorough and realistic tests to prevent catastrophic failures that might lead to severe freeze damage.

The effect of sensor degradation and controller inaccuracy can be very significant if it leads to a negative differential-off temperature, which can result in control instabilities that lead to excess pump operation and loss of collected energy (as much as 50%) by nighttime operation. Previous reports have identified control systems as a major problem without specifying the actual consequences. This may be one of the major reliability problems as well as a prime reason why systems are delivering less energy than expected. Controller manufacturers should select sensors capable of withstanding collector stagnation temperatures and should thoroughly test them to determine degradation effects.

Standard testing methods to provide guidelines for the solar industry should be developed for control systems, including electronic controllers, thermistors, switches, and other types of sensors. Although some of these components are used for conventional (nonsolar) equipment, they need to be able to withstand the particular conditions of a solar system, such as thermal cycling and collector stagnation conditions.

CONCLUSIONS

Testing of key components currently used in solar energy systems successfully identified several weaknesses. Many of the drain valves tested showed significant problems, including scaling, leaking, and catastrophic failure. The air vents accumulated significant amounts of scale internally and around the air parts, but continued to operate, and water sprayed in undesirable directions during filling. The check valves tested did not stop natural convection and some leaked when used as isolation valves between line and atmospheric pressure. The performance of tempering valves was highly dependent of the storage tank temperature and to a lesser degree dependent on flow rate through the valve. The polybutylene piping did not show any effects of degradation from the thermal cycling. These results lead to a better understanding of system reliability in the field, component selection, and can lead to the future development of test procedures for these components.

The SDHW control systems tested were common low-cost control systems. Though industry and users appear, at times, to be satisfied with SDHW controllers, the controllers did not meet their own standards. The type of 3000-ohm thermistor used is still of insufficient quality to be used in active solar energy systems. The failures experienced are not a result of the nominal resistance rating but rather from the construction of the thermistor.

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