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ABSTRACT

Component and system reliability of active solar energy systems continues to be a major concern of designers, manufacturers, installers, and consumers. Six test loops were constructed at the Solar Energy Research Institute in Golden, Colorado, to thermally cycle active solar energy system components. Drain valves, check valves, air vents, vacuum breakers, tempering valves, and polybutylene pipe were included in the testing. Test results show poor reliability of some of the components and limited performance from others. The results lead to a better understanding of certain failures in the field and present designers with realistic expectations for these components.

1. INTRODUCTION

The objective of this task was to determine failure mechanisms that limit the lifetime of active solar energy systems and to recommend solutions. The final report discusses the details of component selection, test plans, testing, results, and recommendations (1). This paper summarizes the results of those tests. The test results reveal failure mechanisms but do not lead to definite failure rates due to the small sample size.

It is important to understand that these tests are intended to identify failure mechanisms and not to rate brand name components. The manufacturers' names have been omitted intentionally. When appropriate and possible, test results have been sent to the manufacturer and the results discussed with them. The cycling times and storage tank temperatures were controlled automatically with the ability to restart automatically after a loss of power. Storage tank temperatures and number of cycles were displayed on the screen and printed hourly. Electromechanical counters also recorded the cycles. The computerized control system verified valve position and tank temperatures every four seconds.

2. 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.

Four manufacturers of automatic drain valves were identified, and three drain valves from each manufacturer were ordered. Upon arrival of the valves, two were found to be identical except for labeling, and the original manufacturer was identified.

Though the operating principles 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.

The drain valves were inspected and photographed without any defects being noticed on any of them. The three Type I brass valves (DV4,5,6) and the six Type II thermoplastic valves (DV1,2,3,7,8,9) passed the static-pressure test. The third set, Type III, (DV10,11,12) presented some problems. 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, DV12 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. The manufacturer stated that the wrong drain valves had been sent and promptly replaced them. The replacement valves were not pressure tested prior to installation due to time limitations.

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

Table 1 summarizes the drain valve failures. 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.

At the end of the testing only two of the originally installed valves (DV5,6) were still operable. However, even these two leaked significantly (about 1.4 l/h or 0.4 gal/h) 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.

DV2 and 8 operated 4785 cycles before failure. If a system cycles an average of four times per day, one might expect these drain valves to operate for just over three years. However, a closer examination of Table 1 shows that this extrapolation is not justified. The drain valves from the same manufacturer that were not cycled (DV3,9) failed at the same time. The leaks from these drain valves develop at about the same time and increased at similar rates, irrespective of cycling. These results show that failure for Type II is not dependent on the number of drain fill cycles, but rather on operating time and/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. Inspection of the Type II drain valves revealed 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 (DV10R, 11R, 12R) 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 (DV10R). However, another valve (DV12R) 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. DV11R also had accumulated tremendous scale around the disk and ports. This manufacturer has since replaced or repaired drain valves in the field. They sent two more replacement valves that were installed (DV13RR and 14RR). These replacement valves operated until the loop was shut down (about 2000 cycles over a period of two months) without significant problems. During the initial periods of operation with cold water circulating, the valves leaked slightly but they did not leak at higher temperatures or at cold water operation later. After the testing they were dismantled and revealed scaling on the metal components. This is apparently from water evaporating when the valve is in the drain position, resulting in mineral deposits that adhere to the metal components.

These test results are comparable with field results in a recent report (2) where seven of 18 drain valves failed within two years of operation; five failed in the first six months.

3. AIR VENTS AND VACUUM BREAKERS

Air vents are used in solar energy systems to eliminate air in a circulation loop or tank that is pressurized relative to the ambient pressure. Vacuum breakers are used to facilitate draining in these systems 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. These valves may be obtained individually or as one combination air vent/vacuum breaker valve.

Five air vents (from three companies), five vacuum breakers (from two companies), and four combination air vent/vacuum breakers (thre thermoplastic valves from one company and a metal valve from another company) were ordered. An inspection of the valves did not reveal 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 had the important purpose of keeping the outlet port clean, but still presented an inconvenience, if not danger with hot water, in that water 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. The amount of water flowing out of it was too much for our laboratory set-up; however, it may be acceptable for an outdoor installation. It was therefore removed and not fully tested. In all, five air vents, four vacuum breakers, and three combination valves were 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 in the future. 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.

4. CHECK VALVES

Check valves are common plumbing components used to prevent or restrict flow in one direction. They are used in nearly every active and many thermosyphon solar energy system, the notable exception being 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 has been used to replace a solenoid valve in drain out systems. The check valve must hold line water pressure to accomplish this task. In general, check valves seal better with higher differential pressures because of the greater force holding the check valve 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 other type, 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.

Six check valves were ordered from two manufacturers; three swing check valves (CV7 to 12) with Teflon seals from one and three spring-loaded check valves (CV1 to 6) from the other. Inspection of the check valves did not reveal any defects. Three different colors (copper, silver, and black) of springs were used in the spring-loaded check valves.

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 was observed in all of these valves after the test. This is due to 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. Meriam 1000 Green Fluid Concentrate mixed with hot water was used as a visual flow indicator. Table 2 shows the results of the tests. The variable results of this test reveal that a check valve may not perform consistently in the same way. The first test was performed after 74 cycles with two spring-loaded check valves leaking slightly (CV3,5) and one swing check valve leaking slightly (CV10). The other spring-loaded check valve (CV4) and other two swing check valves (CV11,12) did not exhibit any signs of leaking. It was not unusual for a check valve to leak heavily during one test and not leak during the next. For example, over a period of six weeks, CV12 was tested five times. The first, second, and fourth test showed no leakage, while the third and fifth showed heavy leakage. Evidently, the check valve seats differently and can either seal well or poorly. The swing check valve appears to seal somewhat better, sealing well eleven out of sixteen 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. Visual indications with a stop watch lead to an estimate of 0.06 m/s (0.2 fps) or 0.5 L/m (0.1 gpm) for a 1.3 cm (1/2 in.) pipe. This can be a great source of heat loss by circulating 363 L (96 gal) through the collector array on a cold night over a period of 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.

5. TEMPERING VALVES

Tempering (or mixing) valves are conventional plumbing valves and are not unique to the solar energy industry. The purpose of a tempering valve is to prevent the water delivered to the load from exceeding a specified temperature. That temperature, referred to as the set point, is maintained by mixing or tempering the hot water with cold water. These devices for domestic usage are not designed to be very accurate. Their first purpose is 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. It was observed that 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 (TV2, Tank 93°C, Set point 60°C).

The tempering valves responded quickly, approaching the set point within twenty 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 worst case was DV5 with a set point of 49°C and a tank temperature of 93°C where it momentarily dropped 7°C below the set point. However, this was an isolated case. 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. TV5 and 6 (from the same manufacturer) and TV3 and 4 (from the same manufacturer) in general performed comparably, while TV1 and 2 (from the same manufacturer) performed somewhat differently. The tests also revealed that though there are differences between tempering valves from the same manufacturer, they do generally follow the same trends and performance. From the same tests 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.

Table 3 summarizes the operating ranges for each valve at each set point. Perhaps 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. Hopefully these temperatures will 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 the tank temperature is low.

With the set point at 60°C TV1 through 4 provide reasonably tempered water at high storage tank temperatures. However, at a storage tank temperature of 71°C, the outlet water is 6°-8°C below the desired water temperature. This can be significant if appliances, such as a dishwasher, require a minimum temperature to provide proper service. If this happens, the electric booster heater in the dishwasher may activate even though there is sufficient solar heated water in the storage tank. TV5 and 6 provided the approximate proper water temperature at a tank temperature of 71°C but did not adequately temper the water at a storage tank temperature of 93°C.

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. Significant scaling was observed on the tempering mechanisms and parts. The cause of this is not known since these valves did not experience wet/dry cycling.

6. POLYBUTYLENE PIPING

The use of polybutylene pipe instead of copper for domestic solar systems could reduce the cost of system piping (3). 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 manufactured to conform to ASTM Standard D 3309, which specifies that pipe and associated fittings have a minimum burst pressure of 3.03 MPa (440 psi) at 23°C (73°F). Furthermore, the pipe and fittings should be capable of continuous operation at 82°C (180°F), and minimum burst pressure at this temperature is 2.21 MPa (320 psi). The pipe should also be capable of withstanding thermal cycling between 16°C (60°F) and 82°C (180°F) for a minimum of 1000 cycles when subjected to an internal pressure of 0.69 MPa (100 psi). Manufacturers' and other data not incorporated into an ASTM standard specify a continuous operating requirement of 82°C (180°F) at 0.69 MPa (100 psi). Tests conducted by the National Sanitation Foundation on polybutylene pipe at 99°C (210°F) showed an average burst pressure of 1.9 MPa (275 psi) and that the pipe could sustain a pressure of 1 MPa (150 psi) continuously for 18 months without failure.

Polybutylene pipe is suitable for solar energy systems containing water, glycols, or silicone oils but not organic heat transfer fluids. To prevent sag, the pipe should be supported about every 0.45 to 0.55 m (1.5 to 1.75 ft). One manufacturer recommends connecting the polybutylene pipe to the collector with 2 m (6 ft) of copper pipe to prevent exposure of the polybutylene pipe to collector stagnation temperatures. The manufacturer also recommends that a pressure/temperature relief valve set at 99°C (210°F) be located near the collector outlet. This is a considerable constraint for closed, nondraining systems where it is undesirable to vent the collector liquid, or for closed drain back systems where it is desirable to prevent outside air from entering the system.

Fusion welded polybutylene fittings are available for pipe sizes one inch and larger. Acetal fittings are available in smaller sizes but are suitable only for use in conventional once-through domestic hot and cold water systems and are not recommended for recirculating hydronic or solar systems where corrosion of the acetal can be a problem. For smaller pipe sizes in closed loops copper fittings with compression rings are used.

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 installed with a simple crimping tool.

Fabrication of the polybutylene test loop was very rapid, and the loop satisfactorily tested for leaks. The loop was insulated with elastomeric, expanded polyethylene and rigid polyurethane insulations. The insulation provides additional support for the pipe, which sagged considerably at elevated temperatures. The large thermal expansion coefficient presented some problems in installing insulation. Nonrigid insulation was compressed to allow for thermal expansion. Rigid insulation required the incorporation of flexible insulation at expansion joints to prevent the formation of gaps. The loop continued to operate successfully without leaks or other signs of deterioration after completing 24,000 cycles over a period of five months.

After thermal cycling, the test loop was pressure tested with water at 13°C (55°F). The results are shown in Table 4.

7. 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. The caps on the air vents did not remain in one position and permitted spraying of water in undesirable directions during filing. 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.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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TABLE 1
DRAIN VALVE FAILURES

DV	Time to Failure (days)	Cycles to Failure
10,11,12	0	0
12R	7	612
10R	26	1103
1	28	(not cycled)
7	28	1183
2,8	60	4785
3,9	60	(not cycled)
11R	60	(not cycled)

TABLE 2
LOW-DIFFERENTIAL PRESSURE
CHECK VALVE TEST RESULTS

CV	Number of Tests	Frequency Distribution of Dye Migration: Clear	Slight	Medium	Heavy
3	6	0	2	0	4
4	5	3	2	0	0
5	5	1	2	2	0
10	5	4	1	0	0
11	6	4	1	0	1
12	5	3	0	0	2
Summary					
Spring-Loaded	16	4	6	2	4
Swing	16	11	2	0	3

TABLE 3
PERFORMANCE RANGES OF INDIVIDUAL
TEMPERING VALVES

T.V.	Set point 49°C: Low(1) °C	49°C: High(2) °C	60°C: Low(3) °C	60°C: High(4) °C
1	35.9	61.2	43.5	61.8
2	36.8	57.8	44.8	59.5
3	35.7	58.5	44.0	62.3
4	35.6	62.3	44.1	62.7
5	36.6	63.1	44.1	69.4
6	37.2	62.6	44.9	72.7

(1)Tank temp. at 49°C, hot water flow rate at 1.9 L/m.
(2)Tank temp. at 93°C, TV4 hot water flow rate at 1.9 L/m, all others at 3.8 L/m.
(3)Tank temp. at 49°C, TV2,4 at hot water flow rate of 1.9 L/m, TV1,3 at 3.8 L/m, TV5 at 5.7 L/m, and TV6 at 11.3 L/m.
(4)Tank temp. at 93°C, TV3,6 at hot water flow rate of 3.8 L/m, TV2,4 at 5.7 L/m, TV5 at 7.6 L/m, and TV1 at 11.3 L/m.

TABLE 4
POLYBUTYLENE PIPE PRESSURE TEST

Test	Specimen	Pressure at Failure MPa	(psi)	Comments
1	Whole loop	3.5	(500)	Pipe separated from elbow.
2	Whole loop	3.7	(540)	Pipe split on straight length.
3	2.6 m (8') length	3.7	(540)	Pipe split.
4	1.0 m (3') length	4.0	(580)	Pipe split.
5	1.6 m (5') length	4.1	(600)	Pipe split.