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Failure Testing of Active Solar Energy Components

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PREFACE

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SUMMARY

Objective

The objective of this testing was to determine operating characteristics and failure modes of drain valves, air vents, vacuum breakers, check valves, tempering valves, and polybutylene piping used in solar energy space and domestic water heating systems.

Discussion

Drain Valves

Conclusions: Many of the drain valves tested showed significant problems, including catastrophic failures. Scaling inside drain valves might render them inoperative.

Recommendations: Manufacturers should implement more thorough internal testing of randomly selected drain valves. Manufacturers should reexamine the temperature stability of their drain valve components and, if necessary, either upgrade the components or derate the temperature limitations. To prevent excessive drain valve degradation, designers should include overtemperature protection in solar energy systems. Valves should be thoroughly inspected before shipment.

Air Vents and Vacuum Breakers

Conclusions: Air vents can create a safety hazard by spraying hot water in undesirable directions. Valves can build up scale inside and on the outlet port.

Recommendations: Test the valves at realistically low ambient temperatures with realistic pipe lengths. Determine if scaling inside the valve body and on the outlet port can lead to valve failure.

Check Valves

Conclusions: Check valves used to prevent natural convection do not have very consistent performance. Check valves can leak under both high and low differential pressures. Check valves are not suited to preventing natural convection.

Recommendations: Determine suitable ways of preventing natural convection losses. Determine the effectiveness of "heat traps." Determine if convective cells can be sustained inside small-diameter tubing (12.7 mm [1/2 inch] and 19 mm [3/4 inch]).

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SECTION 1.0

INTRODUCTION

The objective of this task was to determine failure mechanisms that limit the lifetime of active solar energy systems and to provide recommendations to improve system reliability. Components with suspected or unknown failure rates were identified, test plans were written and reviewed, and the tests were conducted. This report will devote a section to each component tested, including a description of that component, the test plan, the test results, and recommendations. The test results reveal failure mechanisms but do not lead to statistical failure rates because of the small sample size.

We identified the following candidates for testing: (1) draindown valves, (2) vacuum breakers, (3) air vents, (4) check valves, (5) tempering valves, (6) polybutylene pipe, (7) pipe insulation, (8) storage tank liners, and (9) control systems. Of the nine components identified, the first six were tested in this study because they were either suspected of having high failure rates or their reliability was not known. Pipe insulation, storage tank liners, and control systems were considered important items to test but were not included because of time and fiscal constraints of the task. Although we did not test control systems, we identified six areas of concern regarding control systems: determining the effects of electromagnetic interference (EMI), accuracy and reliability of solid-state and proportional controllers, effects of pump vibration for pump-mounted controllers, pump motor overheating from proportional controllers, and sensor testing. EMI was identified as a potentially serious problem, but was not included in the testing because elaborate testing apparatus was required. Reference 1 discusses laboratory testing of control systems, while three recent reports [2,3,4] discuss field reliability experience with residential active solar energy systems. Among the recommendations of Kendall et al. [2] was a study of the reliability of air vents and check valves; we included both in this study. ESG, Inc. [3] showed that draindown valves have a failure rate; we also tested these valves in this study.

These tests were intended to identify failure mechanisms and not to rate brand name components. The manufacturers' names have been omitted intentionally. The cycling times and storage tank temperatures were controlled automatically by a minicomputer with the ability to restart automatically after a loss of power. Storage tank temperatures and number of cycles were displayed on the CRT and printed hourly. Electromechanical counters also recorded the number of cycles. The computerized control system verified valve position and tank temperatures every four seconds.

SECTION 2.0

DRAIN VALVES

2.1 BACKGROUND

One common active solar energy system uses electrically actuated valves to protect the collector array and outdoor piping from freezing. Historically, these systems, called drainout (also called draindown or freeze-dump) systems, used two or more solenoid valves to isolate the collector loop from city water pressure and to drain water from the collector array and piping; at the same time they isolate the storage tank from the drain-line to prevent draining the stored hot water (see Figure 2-1). Solenoid valves are designed to change position frequently. In many drainout systems, draining occurs only when low temperatures are detected, and therefore, the solenoid valves may remain in the fill or circulating position for months at a time. This long period of inactivity can lead to the accumulation of dirt and scale on the seals and overheating of the solenoid coil. When conditions require the valve to change position to permit drainage of the system, it can stick in place or fail to close completely. For these reasons, drainout systems have acquired a reputation for being unreliable. Additionally, large solenoid valves (such as 15-W valves) may use more electrical energy than the pump [5].

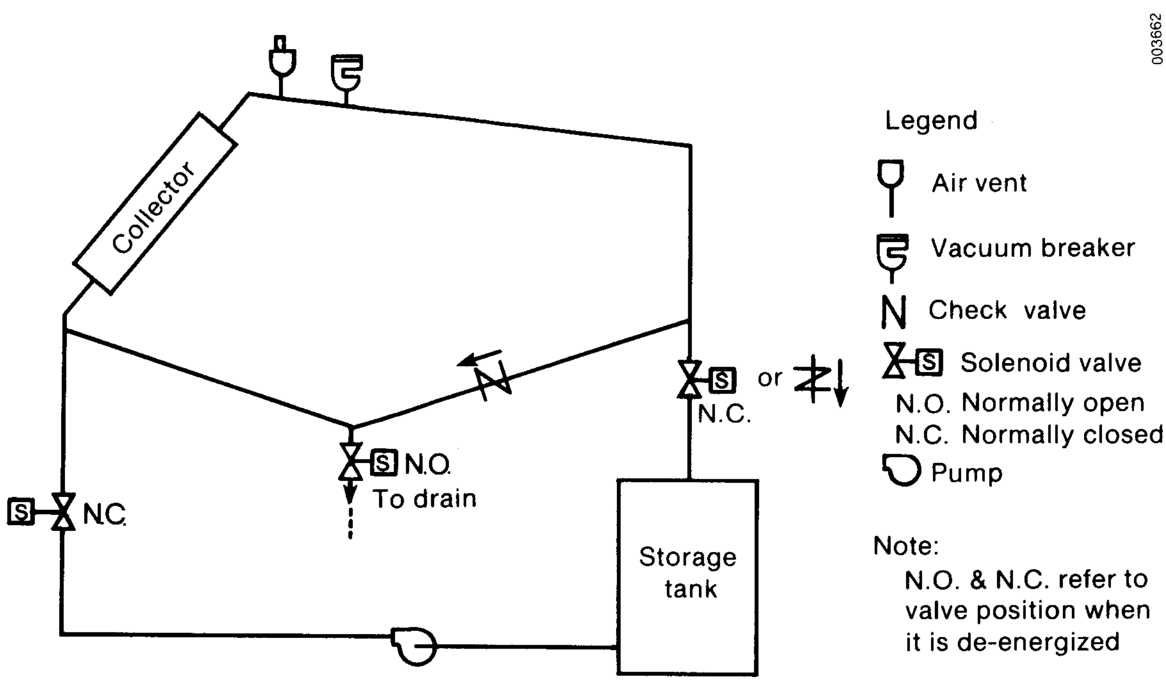

Figure 2-1. Schematic of Drainout System with Solenoid Valves

As with other active solar energy systems, drainout systems have both advantages and disadvantages. The foremost favorable aspects include good heat transfer (because a heat exchanger is not required and water is used); no need for a special heat transfer fluid to protect against freezing or boiling (resulting in potentially lower initial and maintenance costs); and lower capital cost because of fewer components. Several manufacturers have identified these advantages and are trying to capitalize on them. They have been designing or are attempting to design drainout valves that are reliable and energy efficient. They have also reduced the initial and installation cost by combining the functions of several solenoid valves into one valve, as shown in Figure 2-2.

We identified four manufacturers of drain valves and ordered three drain valves from each manufacturer. Two sets we received were identical except for labeling, and the original manufacturer was identified. The general operating principle of all three types is similar. Electric resistance heat is applied to a "heat motor" containing a mixture (such as wax and copper particles) that has a very high coefficient of thermal expansion. The expansion drives a shaft that eventually opens and closes the ports. Because of the thermal mass of the heat motor, only periodic heating is required to keep the valve in position. This cycling results in lower energy consumption, prevents overheating of the motor, and causes the valve to cycle minutely many times in the fill position even though it does not return to the drain position. Heating the motor positions the valve to fill the system. When draining is required, the electrical circuit is opened and a spring pushes the valve back to the drain position. In this manner, the valve is "failsafe" and will drain upon loss of power.

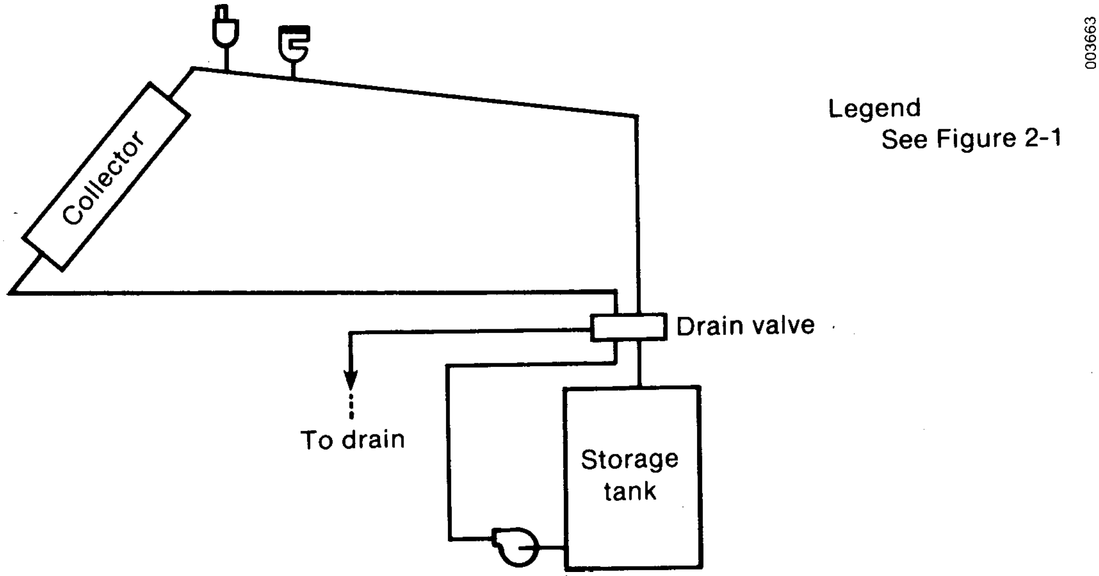

Figure 2-2. Schematic of Drainout System with Drain Valve

Though the operating principles are similar, the three types of drain valves tested are very different in design. One type uses a brass construction with a polymer piston (Type I), the second is built with a thermoplastic body (Type II), and the third uses a rotating disk with copper and brass construction (Type III). Table 2-1 summarizes the drain valve labels, types, and tests.

Two manufacturers require an air vent and vacuum breaker at the high point of the system. The third manufacturer claims there is positive draining with their drain valve even if the air vent and vacuum breaker fail because two drain ports are used: one to drain water and the other to admit air into the collector loop. Literature from one manufacturer recommends that an additional air vent be placed on the tank since some air will be entrained in piping because the riser and downcomer pipes are of different lengths. Another manufacturer verbally recommended the use of an air vent on the storage tank.

We conducted a static pressure test on all the drain valves. Then one drain valve from each manufacturer was subjected to a thermal cycling test and one to an infrequent cycling test. These tests are discussed in detail in Appendix A.1.

Table 2-1. Drain Valve Description and Tests

Label[a]	Type[b]	Test[c]
DV1	II	Infrequent cycling
DV2	II	Thermal cycling
DV3	II	Infrequent cycling
DV4	I	Static pressure only
DV5	I	Thermal cycling
DV6	I	Thermal cycling
DV7	II	Thermal cycling
DV8	II	Thermal cycling
DV9	II	Infrequent cycling
DV10R	III	Thermal cycling
DV11R	III	Thermal cycling
DV12R	III	Thermal cycling
DV13RR	III	Infrequent cycling
DV14RR	III	Thermal cycling

[a]DV10,11,12 are not listed because they failed the static pressure test.

[b]Type I, brass body with polymer piston; Type II, thermoplastic body with polymer piston; Type III, copper/brass body and rotating disk.

[c]All drain valves underwent static pressure test except those marked with an "R" or "RR."

2.2 TEST RESULTS

2.2.1 Static Pressure Test

The drain valves were inspected and photographed. No obvious initial defects were noted. The static test proved to be more difficult than anticipated. Often it was a test of the integrity of unions or detection of air bubbles. Although none of the unions provided with the drain valves were defective, numerous unions obtained locally had pinhole leaks at 1310 kPa (190 psig). Several drain valves had to be tested repeatedly to obtain reliable results. 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 drain port when the valve was energized (in the fill mode). The manufacturer said that the valve needed to be under pressure to operate properly. DV12 was the only Type III drain valve that passed the static-pressure test. An additional problem with the Type III drain valves was that the internal parts were at line voltage, which revealed an electrical short in the heat motor. The manufacturer stated that experimental drain valves had been sent inadvertently and promptly replaced them (DV10R,11R,12R). The replacement valves were not pressure tested prior to installation due to time limitations.

2.2.2 Thermal Cycling and Infrequent Cycling Tests

We observed through a visual flowmeter that all the drain valves entrained air 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.

Table 2-2 is a list of the major events that occurred during the testing, and Table 2-3 summarizes the drain valve failures. The high number of failures is surprising and is suspected to have been caused by high operating temperatures. However, the operating temperatures did not exceed the maximum temperature rating of the valves. Maximum temperatures are likely to occur when owners are on vacation, and the load is very low or nonexistent.

At the end of the testing only two of the originally installed valves (DV5 and 6) were still operable. Even these two leaked significantly (about 1.4 L/h or 0.4 gal/h) at cold water temperatures. This problem might have resulted from thermal setting of the seals. At moderate and high temperatures the leaks ceased. We dismantled the valves after the tests; these valves had worn seals but very little accumulation of scale.

DV2 and 8 operated for 4785 cycles before failure. If a system cycles an average of four times per day, these drain valves should operate for just over three years. However, a closer examination of Table 2-2 shows that this extrapolation is not justified. The drain valves from the same manufacturer that were not cycled (DV3 and 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 temperature. Even though some of the drain valves were not regularly cycled between fill and drain modes, they were cycled automatically to prevent overheating and reduce energy consumption. Inspection of the Type II drain valves revealed corrosion of internal metal parts such as retaining rings, severely cracked plastic shaft holders, and deformed seals.

Table 2-2. Summary of Major Drain Valve Events

Date (1983)	Valve Number	Counts	Comments
7/18	All	—	Testing began.
8/ 2	DV8	866	Operating slowly.
8/ 5	DV9	a	Leaking from shaft seal.
8/16	DV2	2132	Leaking from shaft seals.
	DV8	2132	Leaking, actuator not totally closing.
8/17	DV10R,11R	—	Arrived and installed.
8/19	DV3	a	Leaking, shaft housing severely cracked.
	DV2	2351	Water draining into electric cord.
	DV10R,11R	2351	Put into service.
8/23	—		Power outage.
8/31	DV8	3377	Continuous leaking in drain mode.
9/12	DV10R	4454	Failed in fill position after 1103 cycles.
9/16	DV8	4785	Failed. Allowed water pressure into drain line, blew off drain hose.
	DV2,9	4785	Unplugged to prevent catastrophic failure. Considered failed due to excessive leaking through shaft seal.
	DV3	a	Actuator moves only part way to drain position. Unplugged to prevent catastrophic failure. Considered failed due to excessive leaking through shaft seal.
	DV1	a	Installed. Replacement for DV3.
	DV7	4788	Installed. Replacement for DV2.
	DV12R	4788	Installed. Replacement for DV10R.
9/19	DV12R	5048	Leaking through drain port on filling.
9/22	DV12R	5337	Very slow to drain (11 minutes).
9/23	DV12R	5400	Failed. Slow to drain. Continual, steady leak (2 L/h) through drain port, at 612 cycles.
10/12	DV7	6635	Periodic leak through drain port and through shaft seal.
	DV7	6671	Failed. Allowed water pressure into drain line, blew off drain hose, at 1183 cycles.
	DV1	a	Leaking badly through shaft seal. Taken out of service.

Table 2-2. Summary of Major Drain Valve Events (Concluded)

Date (1983)	Valve Number	Counts	Comments
10/18	DV14RR	7108	Installed. Replaced DV12R. Leaks through drain port during fill cycle.
	DV13RR	a	Installed. Replaced DV11R.
10/19	DV5,6,14RR	7144	Leaking through shaft seal with cold water circulation.
	DV14RR	7144	No longer leaking through drain port.
10/20	DV5,6,13RR, 14RR	7322	No leaks at higher temperatures.
11/ 1			Cold water test.
	DV5	8300	Leaks significantly through shaft seal in fill position.
	DV6	a	Leaks significantly through shaft seal.
11/ 7	DV5,6,13RR 14RR	9003	Operating properly at higher temperatures.
12/ 1	All	9518	Test stopped.
	DV5		9518 cycles.
	DV14RR		2410 cycles.
	DV6		135 days.
	DV13RR		135 days.

[a]These drain valves were used for the infrequent cycle test and were cycled only during an operational test or during a power failure.

Table 2-3. Drain Valve Failures

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

[a]Infrequent cycle test.

Catastrophic failures were caused by failure of the plastic piston, possibly from thermal stress and fatigue. The manufacturer of this valve has recently withdrawn it from the marketplace.

Though the manufacturer of the Type III drain valves (DV10R, 11R, 12R) had a testing program, it was not as extensive as this one. However, our results are consistent with their field experience. They identified one problem as an unsuitable lubricant on a plunger designed to move the rotating disk. This was consistent with an inspection of one of the failed valves (DV10R). Another valve (DV12R) had significant scale on the rotating disk that was worn from the rotation. The scale may have caused the disk to bind, preventing operation. DV11R also had accumulated a significant amount of scale around the disk and ports. The manufacturer has since replaced or repaired drain valves in the field. They sent three more replacement valves, and we installed two of them (DV13RR and 14RR). These replacement valves operated until the loop was shut down (about 2000 cycles over two months) without significant problems. The valves leaked slightly during the initial periods of operation with cold water circulating, but they did not leak at higher temperatures or at cold water operation later. After the testing, they were dismantled and examined. We observed scaling on the metal components, apparently from water evaporating when the valve is in the drain position, which caused mineral deposits to adhere to the metal components.

These test results are consistent with the field experience reported in Ref. 3; in that case 7 of 18 drain valves failed within two years of operation and 5 failed in the first six months.

2.3 RECOMMENDATIONS

Based on this testing, we recomend that manufacturers of draindown valves should:

- Implement more thorough internal testing of randomly selected drain valves, particularly to determine the effects of cycling, high operating temperatures, and scale
- Reduce the maximum operating temperature for thermoplastic drain valves
- Recommend overtemperature protection of the solar energy system to protect the drain valve
- Thoroughly inspect valves before shipment to prevent shipping of experimental or prototype valves.

SECTION 3.0

AIR VENTS AND VACUUM BREAKERS

3.1 BACKGROUND

Air vents are used in solar energy systems to eliminate air in a pressurized circulation loop or tank. Vacuum breakers facilitate draining by admitting air into the system. Although both of these components are often used in drainout systems, which drain and fill frequently, they are also used in antifreeze systems to reduce the initial filling time and future draining time when the heat transfer fluid is replaced or removed for system maintenance. Air vents and vacuum breakers are placed at the highest point in the system, usually just above the collector array. Air vents generally have a float that drops when air enters the chamber and rises as pressurized water refills it. Vacuum breakers have a seal (such as a ball or plate) that is forced shut by the pressurized water. When a valve is opened to drain the system, the pressure is released, the vacuum breaker opens, and air is allowed into the system, which causes rapid draining.

Air vents and vacuum breakers are generally used outdoors and are therefore subject to freezing and icing of the ports. If the valve stem and body are not insulated, the water inside the valve may freeze and prevent release or admittance of air. Blockage of the ports can preclude the draining of the system in sufficient time to prevent freezing. The ports that vent or admit air are fairly small and can be easily clogged by scale or other debris. Because of the high potential for failure, air vents and vacuum breakers 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 (three thermoplastic valves from one company and a metal valve from another company) were ordered. The test procedures are discussed in detail in Appendix A.2.

3.2 TEST RESULTS

3.2.1 <u>Thermal Cycling Test</u>

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 to keep the outlet port clean. However, spraying water is still an inconvenience, if not a danger, because hot water could be sprayed on people, equipment, and roofs. Air vents have a small cap over the outlet port to protect the port and to 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 water to flow through it to keep it free of scale and debris. Too much water flowed out of the valve for the laboratory setup; however, that amount of water may be acceptable for an outdoor installation. The valve was therefore removed and not fully tested. In all, five air vents, four vacuum breakers, and three combination valves were tested. None of the valves were noted to have 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 opening in spite of the scale. After the thermal cycling test, all of the valves were dismantled. We observed significant scaling 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 from the same company had no rust and moved freely. The thermoplastic combination valves had no significant scaling inside the valve body.

3.2.2 Low Ambient Temperature Test

This test proceeded without difficulty. The systems drained and filled properly at both tank temperatures and ambient air temperatures between -18° and -6° C (-1° and 22° F). In one case, the dry ice was left on the air vent for about four hours to create a temperature of -16° C (2° F). The system filled and drained properly. The final test included removing the enclosure, air vent, and vacuum breaker and plugging the openings. Surprisingly, the thermoplastic drain valve (Type II) filled and drained the loop without difficulty, possibly because of such short piping runs in the test apparatus (2 m). This does not mean that drainout systems do not require air vents and vacuum breakers. The results revealed that this test method is inconclusive and cannot be used to generate information about air vents and vacuum breakers at low temperatures.

3.3 RECOMMENDATIONS

Based on these test results, we recommend that:

- A more realistic test is needed to determine the reliability of air vents and vacuum breakers operating at low ambient air temperatures.
- Scaling inside metal air vents and vacuum breakers should continue to be monitored to determine if it leads to valve failure.
- Scaling on the outside requires continued attention to see if it results in blockage of the outlet port.

SECTION 4.0

CHECK VALVES

4.1 BACKGROUND

Check valves are common plumbing components used to prevent flow or restrict flow to one direction. They are used in nearly every active and thermosyphon solar energy system; the notable exception is the drainback system. Check valves are used in two types of service in solar energy systems. The first use is as an isolation valve to prevent pressurized water from flowing into an unpressurized drain. Thus check valves have been used to replace solenoid valves in drainout systems as shown in Figure 2-1. The check valve must hold line water pressure to accomplish this task. In general, check valves seal better at higher differential pressures because there is greater force holding the check valve shut.

The other major use is in systems that do not drain when the pump is off (for example, antifreeze, recirculation, thermosyphon, and some drainout systems). In active systems the hot storage tank is usually located below the collector array. As the ambient temperature drops, the collector cools and the cold fluid in the collector sinks while hot fluid in the storage tank rises. In essence, a natural convection circulation loop is established. Designers install a check valve above the storage tank to prevent this natural circulation. The check valve must seal very tightly under a very low differential pressure.

Two types of check valves used in solar energy systems are 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 keep the disk open, particularly 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 close the check valve. It can generally be installed either horizontally or vertically since the spring will keep it closed. Flow in the proper direction must have sufficient force to open the check valve. Although this check valve is more versatile to install, it has a higher pressure drop through it. We developed tests for each of the two check valve uses; they are discussed in detail in Appendix A.3. We ordered six swing check valves (CV7 to 12) with Teflon seals and six spring-loaded check valves (CV1 to 6) from two manufacturers.

4.2 TEST RESULTS

Inspection of the check valves did not reveal any defects.

4.2.1 High Differential Pressure Test

We conducted a high differential pressure test on three swing check valves (CV7,8,9) and three spring-loaded check valves (CV1,2,6). No catastrophic failures were noted during 11,308 cycles. However, all the spring-loaded check valves leaked after 7800 cycles. Significant scaling was present in all of these valves after the test. The scaling is probably due to wet/dry cycling, which deposits minerals that adhere to the metal surfaces. Apparently the scaling led to leakage of the spring-loaded check valves.

4.2.2 Low Differential Pressure Test

We conducted a low differential pressure test on three swing check valves (CV10,11,12) and three spring-loaded check valves (CV3,4,5), as well as one visual floating check valve. 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.

The variable results of this test (Table 4-1) reveal that check valves may not perform consistently. The first test was performed after 74 cycles. Two spring-loaded check valves (CV3,5) and one swing check valve (CV10) leaked slightly, while the other spring-loaded check valve (CV4) and the other two swing check valves (CV11,12) did not leak. 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 in various positions and can seal either well or poorly. The swing check valve appears to seal somewhat better, sealing well in 11 out of 16 tests (69%). Although these test results are not conclusive because of the small sample size, they indicate that these valves do not always seal well against natural convective currents.

With a stop watch we estimated a heavy dye migration flow rate of 0.06 m/s (0.2 fps) or 0.5 L/min (0.1 gpm) for a nominal 1/2-in. pipe. Much heat can be lost by circulating 363 L (96 gal) through the collector on a cold night over a period of 16 hours. Since the flow rate is slow, the temperature drop could be substantial, effectively dissipating much of the previously collected energy. This effect is particularly important for one-tank systems that use auxiliary energy to maintain the storage tank temperature, because loss of heat can increase the auxiliary energy usage as well as lose collected solar energy. The delivery of hot water to the collectors by natural convection can warm the collector sensor and cause the control system to cycle the pump at night.

After the tests, we dismantled and inspected these check valves. There was no significant scaling since the valves were always wet.

Table 4-1. Low Differential Pressure Check Valve Test Results

Check Valve	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

4.3 RECOMMENDATIONS

Spring-loaded check valves appear to leak under high differential pressure and may drain hot water from the storage tank. The amount of leakage should be quantified and the effect on system performance determined. Check valves under low differential pressure appear to be unsuited to stopping natural convection. We recommend the following actions:

- Better methods of eliminating natural convective loops besides using check valves must be found, including examining the effectiveness of "heat traps," which are plumbing arrangements designed to reduce convection by plumbing vertically downward by a heat source or storage tank before plumbing vertical or horizontal runs.
- It should be determined how convective cells operate within a single tube; hot liquid appears to rise in the center of the tube while cold liquid drops along the tube wall. (This was demonstrated in the tempering valve [TV] test discussed in Section 5.0; the top mounted TVs were hot to the touch while the TVs mounted lower than the tank top were cool after long periods of no flow.)

SECTION 5.0

TEMPERING VALVES

5.1 BACKGROUND

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 setpoint, is maintained by mixing or tempering the hot water with cold water. The mixing is accomplished by using a thermally sensitive element (such as a bimetallic spring, wax, or refrigerant) that expands and contracts when temperatures change and thereby controls the cold and hot water ports. These devices for domestic usage are not designed to be very accurate. They are designed first to prevent scalding and second to conserve energy by limiting the temperature of the delivered water to appliances that accept water temperatures higher than required, such as washing machines and dishwashers.

Six tempering valves were ordered, two from each of three manufacturers. All six had all-metal housings and an adjustable setpoint on top. Two tests were performed that were the same except for the sampling rate. The purpose of the first test was to determine the transient response of the tempering valves, while the second test was to determine their steady-state response. The test procedure for the tempering valves is discussed in detail in Appendix A.4.

5.2 TEST RESULTS

No tempering valves failed to temper the hot water during testing. We observed that if the tempering valves were inoperative overnight with no flow, the next morning the top ones (TV1,4,5) were very hot (from natural convection) while the bottom ones (TV2,3,6) were at about room temperature. We flushed all the tempering valves before each test to simulate a period of inactivity.

The results in this section are presented as a function of time and hot-water flow rate. Because of the test setup, measuring the hot water flow rate presented a convenient method of comparing results. For a given tempering valve setpoint, tank temperature, and controlled hot-water flow rate, the mixed temperature from the various tempering valves could be readily compared. The cold water flow rate could not be controlled because the tempering valve controlled the amount of cold water necessary to temper the water properly.

Figures 5-1 and 5-2 show typical time-dependent results for the tempering valves for two different tank temperatures. The tempering valves approached the setpoint within 20 seconds of operation. However, the response time of the thermocouple measuring the tempered water was also about 20 seconds, which means that the tempering valves may have approached the setpoint sooner and also that the thermocouple may not have registered the temperature excursions properly. The extremes might have been further from the steady-state temperature. Note that the temperature at bottom tempering valves surpasses the 60°C (140°F) setpoint and then drops. Instructions and design guidelines state that tempering valves should be placed below the top of the storage tank. This location may prolong the life of the tempering valve since it would undoubtedly be at a

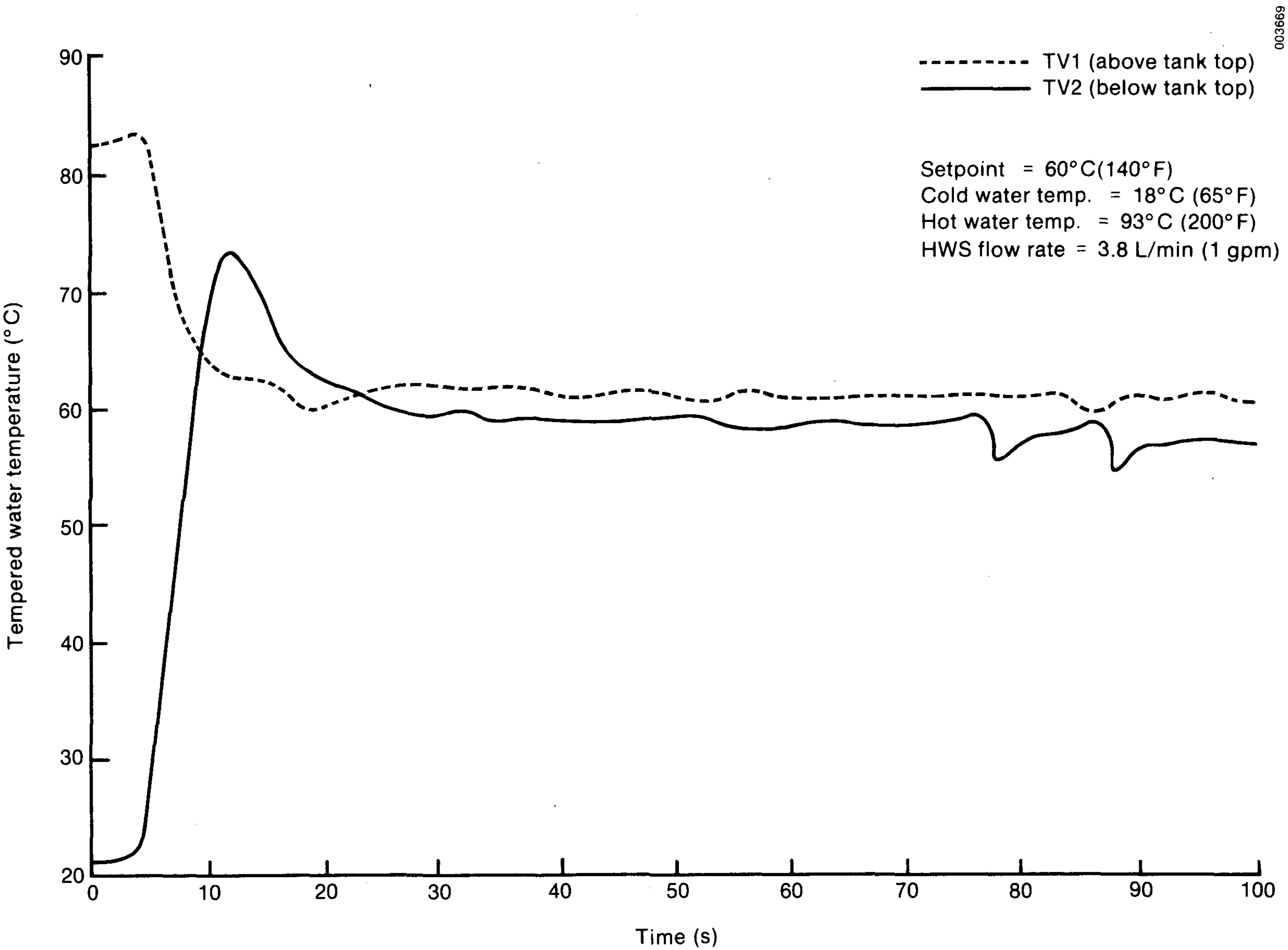

Figure 5-1. Transient Responses of TV1 and TV2

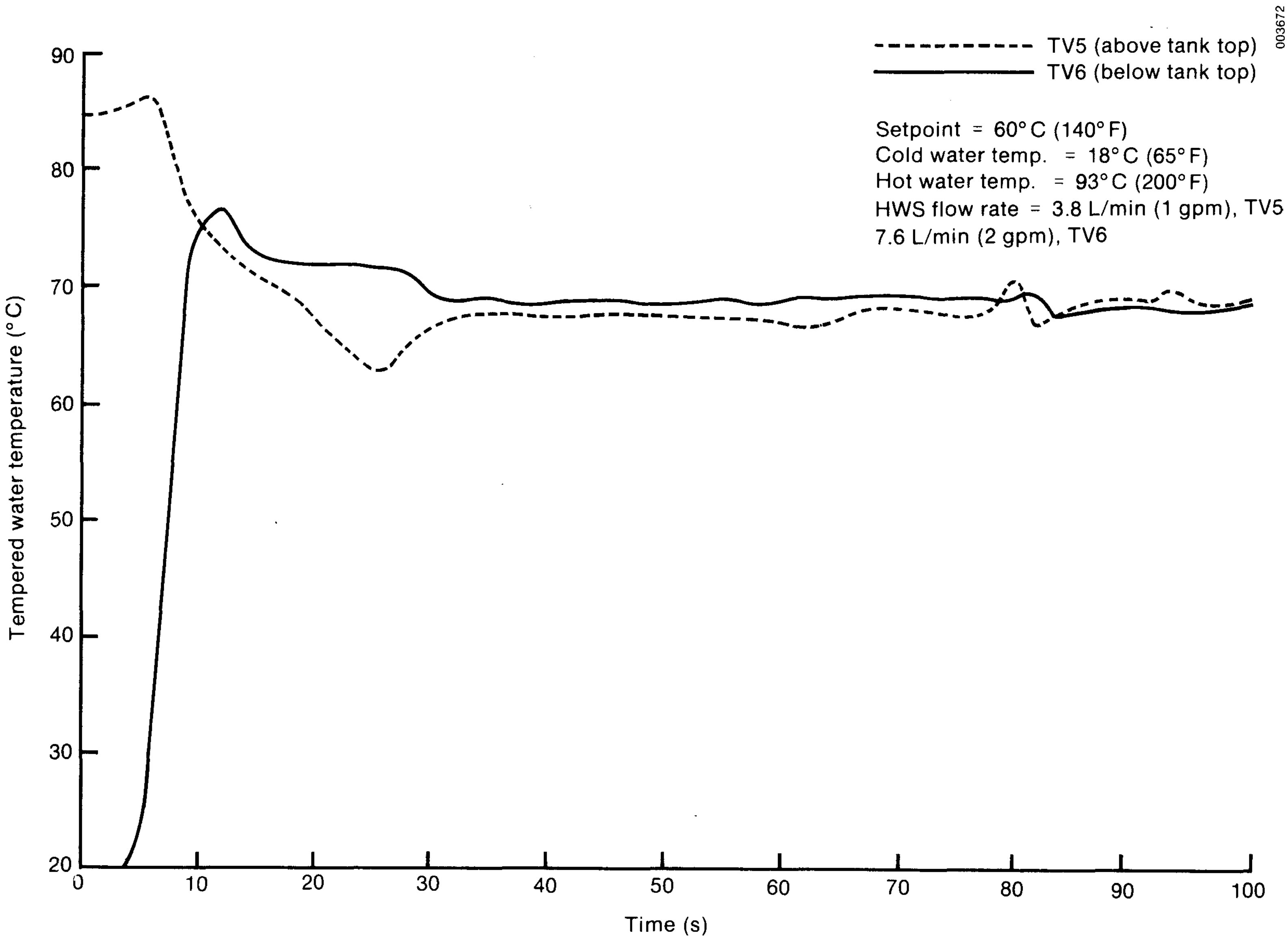

Figure 5-2. Transient Responses of TV5 and TV6

lower temperature. However, it also results in temperatures 23° C (41° F) in excess of the setpoint (TV2, tank 93° C, setpoint 60° C). This potential for safety hazard must be considered when designing and installing a tempering valve.

Tables 5-1 and 5-2 present the temperature extremes detected by the thermocouple for each transient test. The top tempering valves seldom surpassed the setpoint. Since they had been flushed with hot water prior to the test, they produced colder water. The worst case was TV5 with a setpoint of 49° C (140° F) and a tank temperature of 93° C (200° F)—it momentarily dropped 7° C (13° F) below the setpoint. However, this was an isolated case. The bottom-mounted valves consistently exceeded the setpoint, 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 response test are presented in Figures 5-3 through 5-8. As shown by these figures, performance varied tremendously between tempering valves. In general, the temperature of the tempered water was sensitive to the flow rate at lower flow rates but not at higher flow rates. Figure 5-9 shows a comparison of all the tempering valves over the flow range at one setpoint and one tank temperature. Observe that 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. A comparison of TV1 with TV2 (Figures 5-3 and 5-4), TV3 with TV4 (Figures 5-5 and 5-6), and TV5 with TV6 (Figures 5-7 and 5-8) reveals that although there are differences between tempering valves from the same manufacturer, they generally follow the same trends and performance. From the same comparisons 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 5-3 summarizes the operating ranges for each valve at each setpoint. Perhaps the most significant criterion for a tempering valve is that it not exceed the setpoint excessively. At a tank temperature of 71° C (160° F), none of the tempering valves exceeded the 49° C (120° F) setpoint significantly (see Figures 5-3 through 5-8). However, at higher tank temperatures, the accuracy of the tempering valves changed dramatically. These temperatures should not be encountered frequently, but when they are a great deal of tempering still occurs, reducing the 93° C (200° F) water to about 60° C (140° F). At low storage tank temperatures the tempering valves reduce the outlet water temperature significantly below the setpoint. This may be a problem when a solar energy system is used without an auxiliary system (such as during the summer) and the tank temperature is low.

With the setpoint at 60° C (140° F), TV1, 2, 3, and 4 provide reasonably tempered water at high storage tank temperatures. However, at a storage tank temperature of 71° C (160° F), the outlet water is 6°-8° C (10°-15° F) below the desired water temperature. The lower outlet temperatures can be significant if appliances such as a dishwasher require a minimum temperature to provide proper service. The delivery of water cooler than the tank temperature may activate the electric booster heater in a dishwasher even though there is sufficient solar heated water in the storage tank. TV5 and 6 provided the acceptable water temperature at a tank temperature of 71° C (160° F) but did not adequately temper the water at a tank temperature of 93° C (200° F).

Perhaps the most important result from the tempering valve tests is that output temperature from the tempering valve is very sensitive to the tank temperature. Since the temperature of a solar energy system may vary rapidly and widely, the output from the

Table 5-1. Time Dependent Tempering Valve Extremes (49° C Setpoint)

Tempering Valve	Hot Water Flow Rate (L/min)	Tank Temperatures (° C) 49			71			93		
		Initial	Extreme	Steady	Initial	Extreme	Steady	Initial	Extreme	Steady
Top										
1	3.8	45	37	37	64	46	49	65	60	60
	9.6	46	37	37	63	46	49	60	57	58
4	3.8	42	35	35	59	44	44	76	59	59
	9.6	45	36	36	58	43	44	64	57	57
5	3.8	46	37	37	59	46	48	62	60	60
	9.6	45	39	39	63	46	47	71	59	59
Bottom										
2	3.8	19	37	37	21	51	50	23	61	54
	9.6	19	38	38	19	52	51	24	67	54
3	3.8	18	37	36	21	49	45	26	56	56
	9.6	18	38	36	20	51	44	28	64	55
6	3.8	18	37	37	18	50	49	23	64	60
	9.6	18	39	39	20	53	49	41	63	59

Table 5-2. Time Dependent Tempering Valve Extremes (60° C Setpoint)

Tempering Valve	Hot Water Flow Rate (L/min)	Tank Temperatures (°C) 49 Initial	49 Extreme	49 Steady	71 Initial	71 Extreme	71 Steady	93 Initial	93 Extreme	93 Steady
Top										
1	3.8	45	45	45	61	50	51	83	60	61
	9.6	47	45	45	64	50	51	91	60	60
4	3.8	43	43	46	60	50	50	88	59	60
	9.6	47	45	45	65	50	50	88	59	60
5	3.8	46	45	45	62	55	58	85	61	68
	9.6	46	46	46	64	55	59	88	68	68
Bottom										
2	3.8	19	44	44	20	62	53	23	73	57
	9.6	19	45	45	24	62	53	21	83	58
3	3.8	20	44	44	20	58	50	22	70	59
	9.6	20	44	44	21	61	50	40	70	59
6	3.8	19	45	45	19	61	60	20	76	68
	9.6	19	46	46	20	62	60	19	85	69

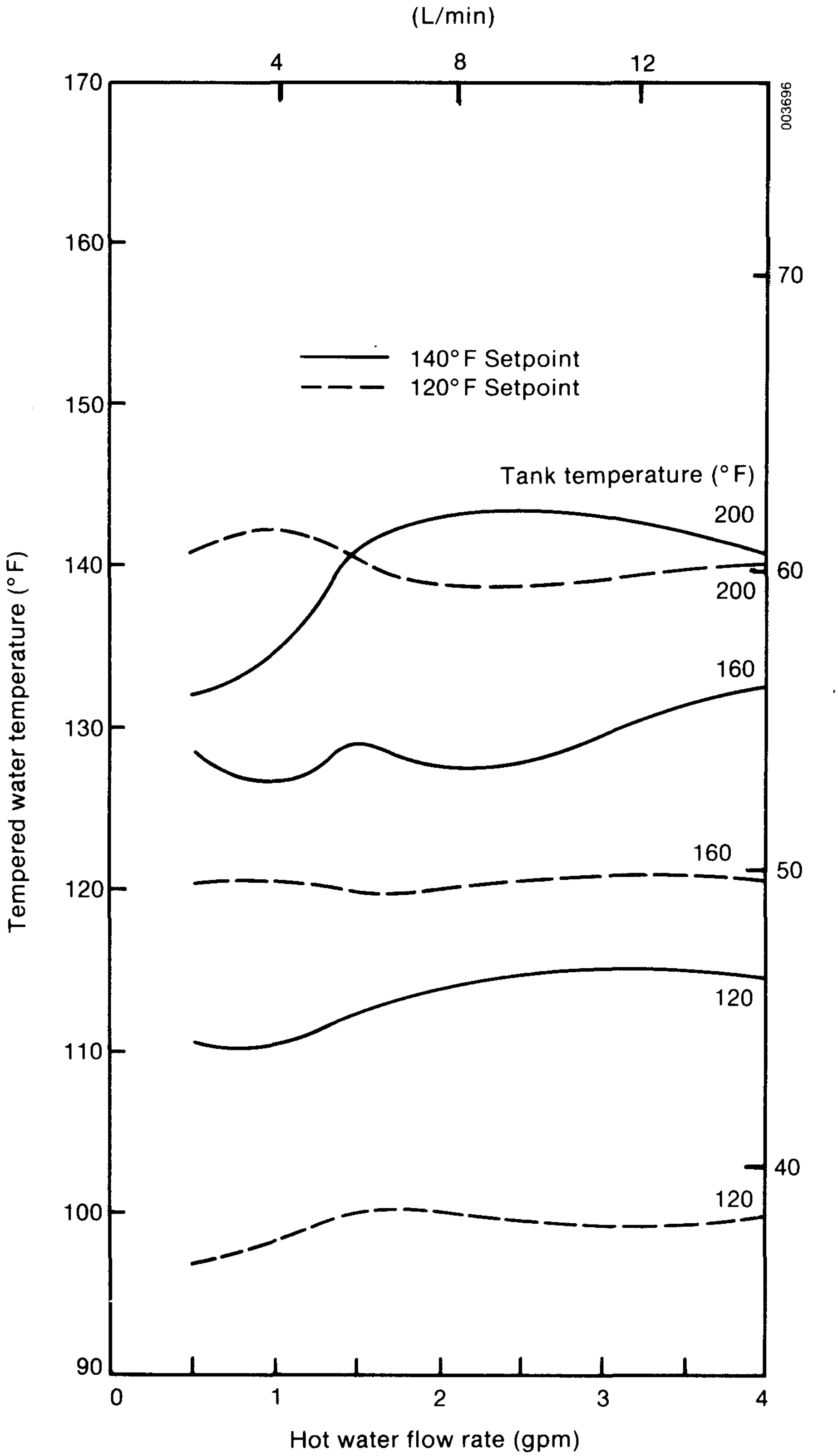

Figure 5-3. Tempering Valve 1, Top

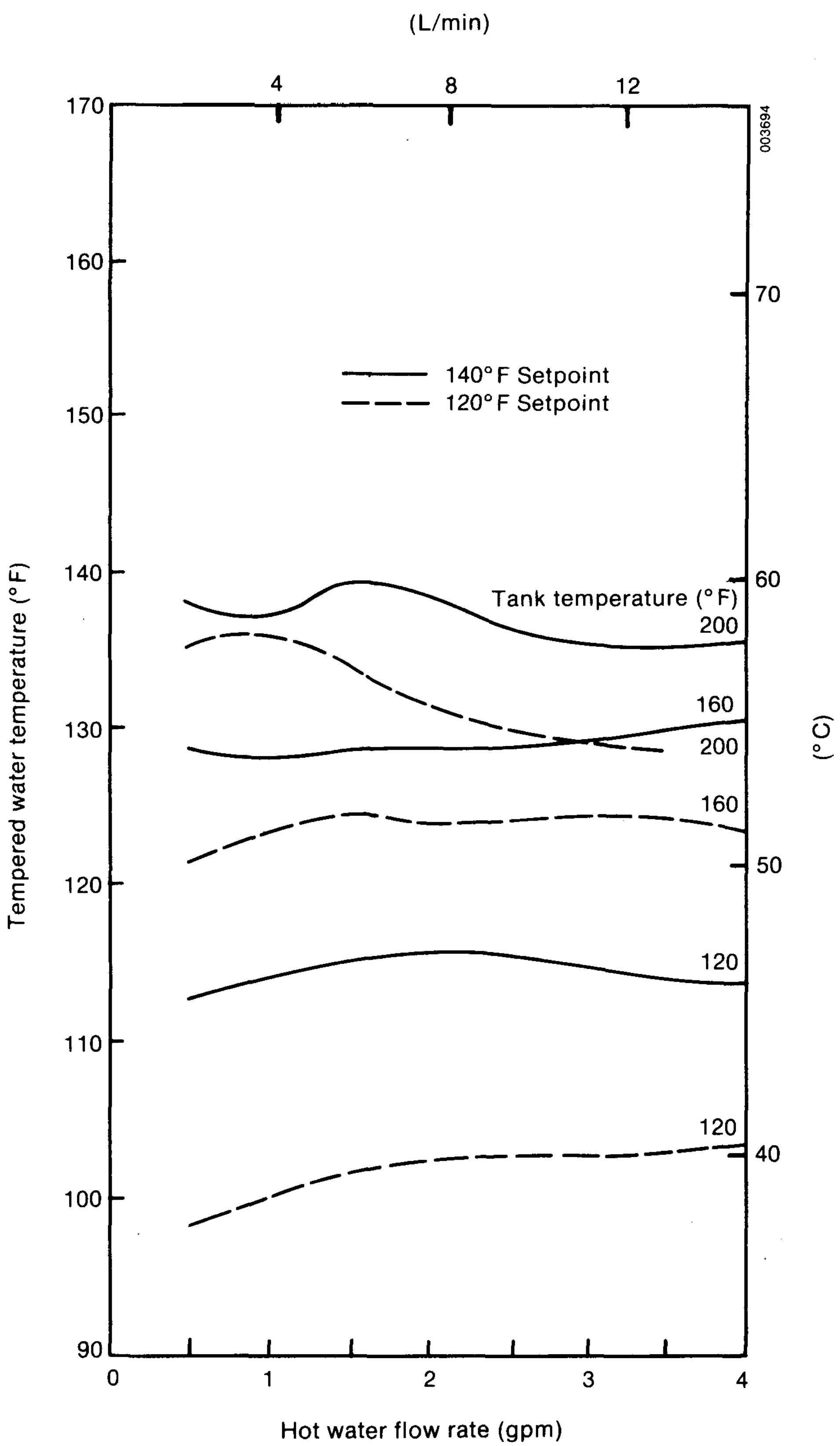

Figure 5-4. Tempering Valve 2, Bottom

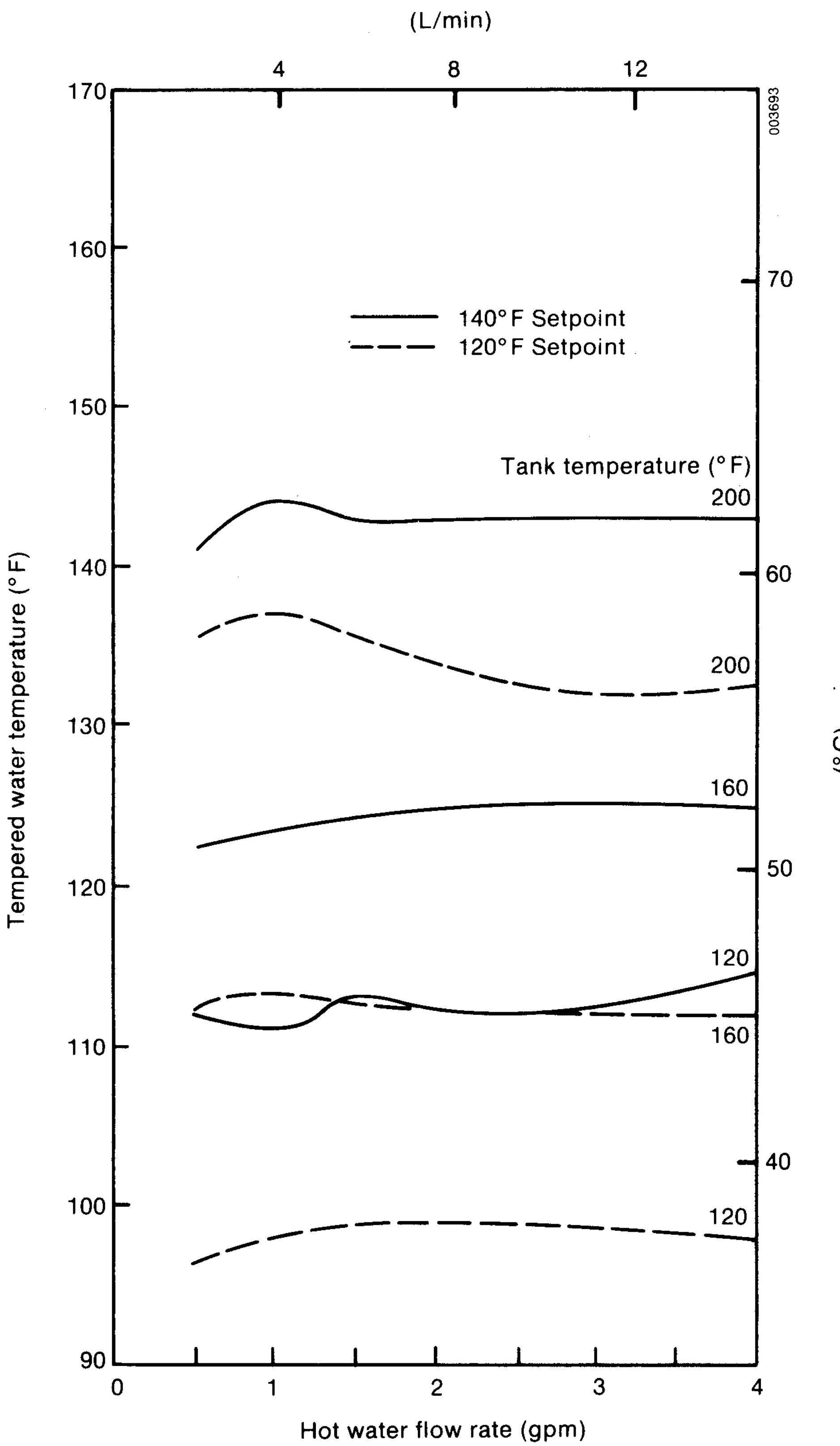

Figure 5-5. Tempering Valve 3, Bottom

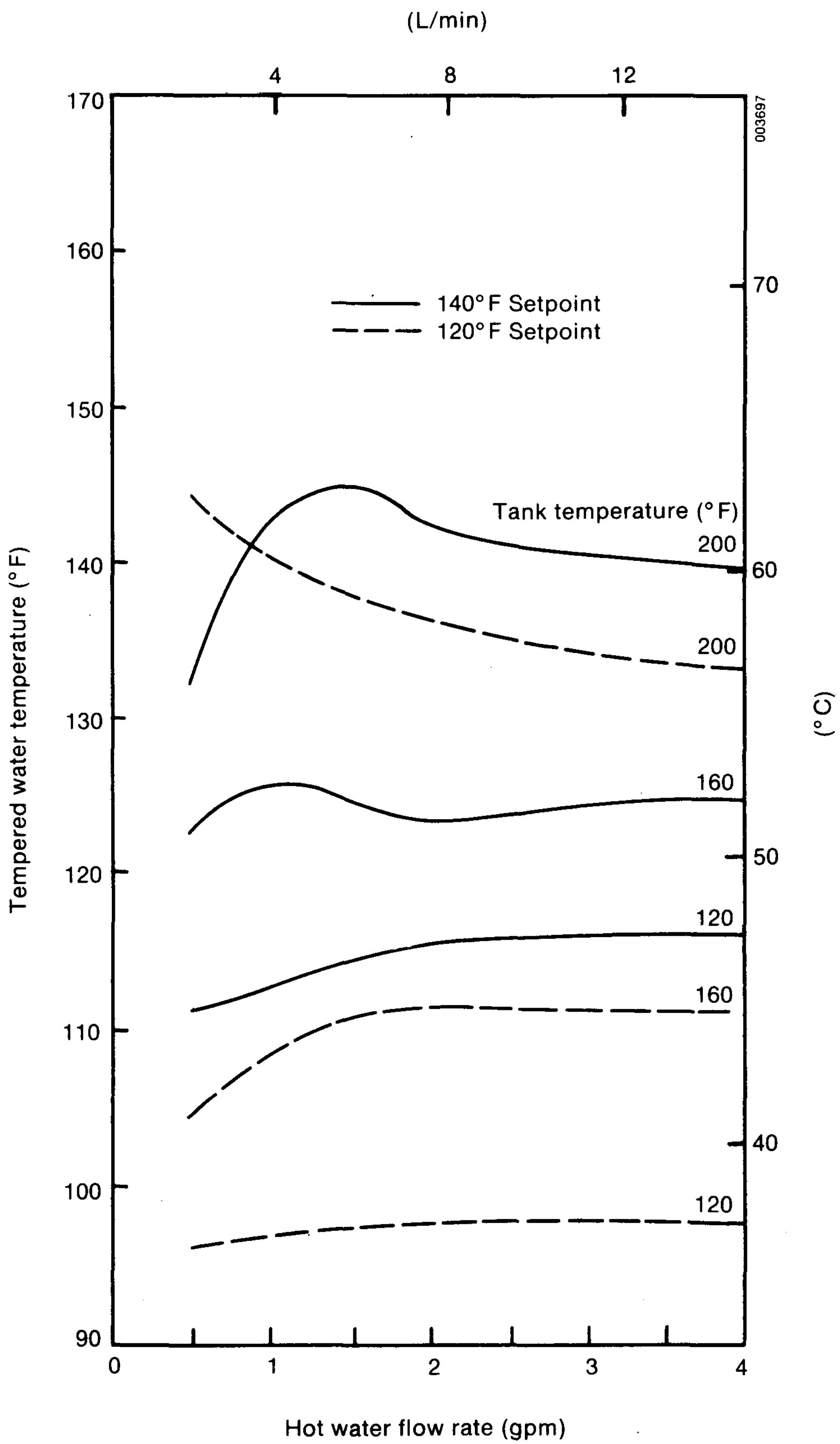

Figure 5-6. Tempering Valve 4, Top

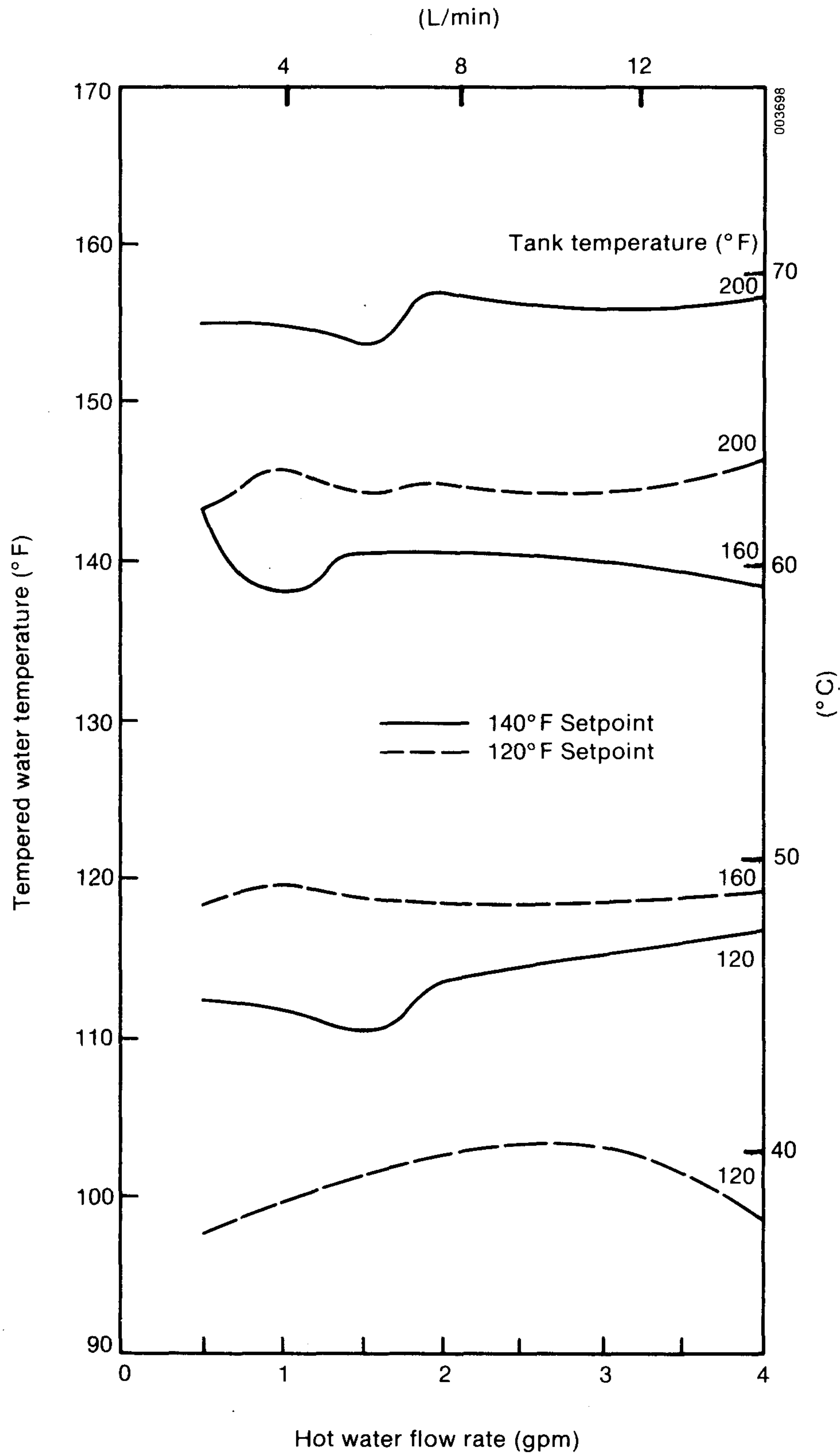

Figure 5-7. Tempering Valve 5, Top

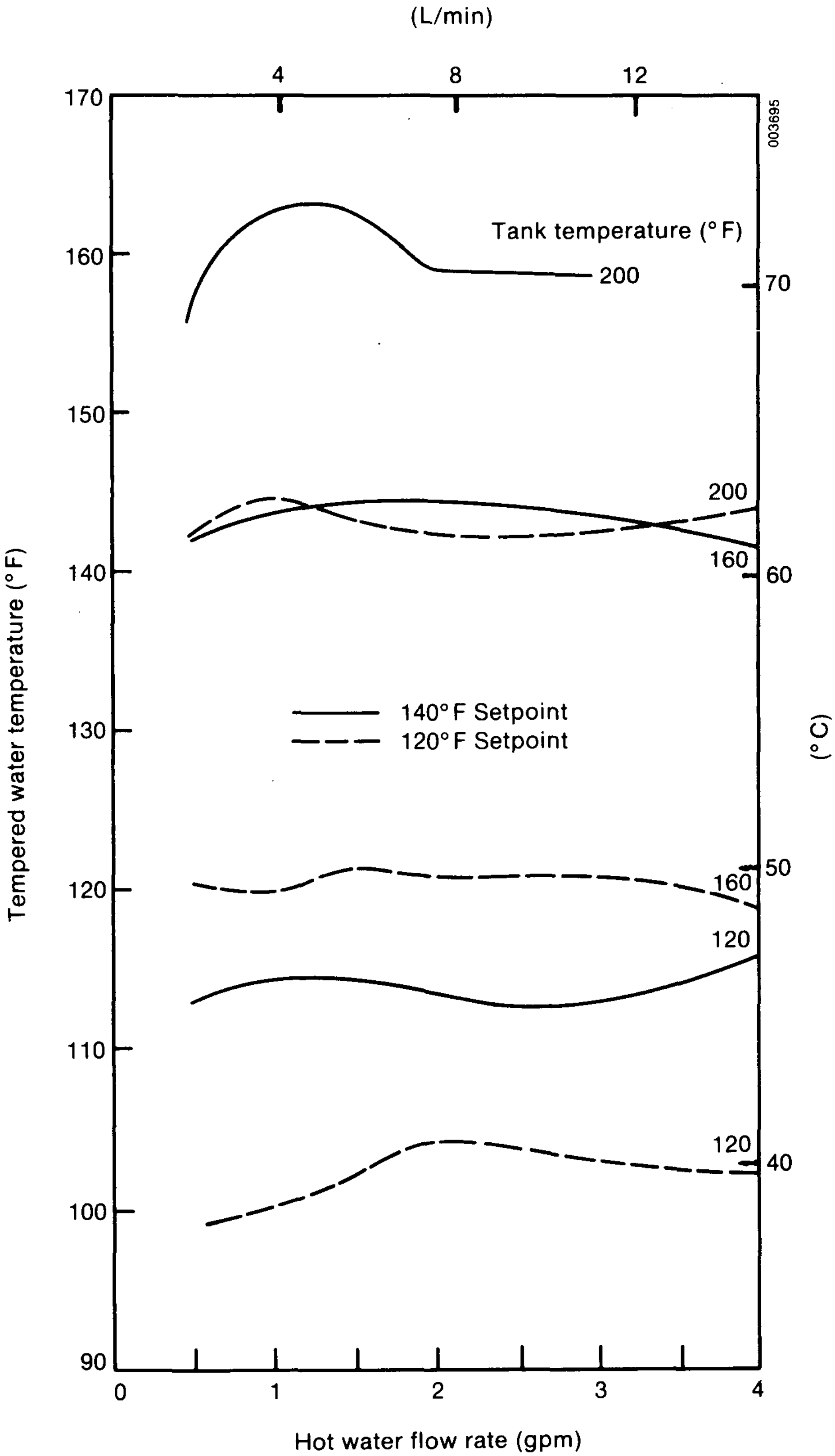

Figure 5-8. Tempering Valve 6, Bottom

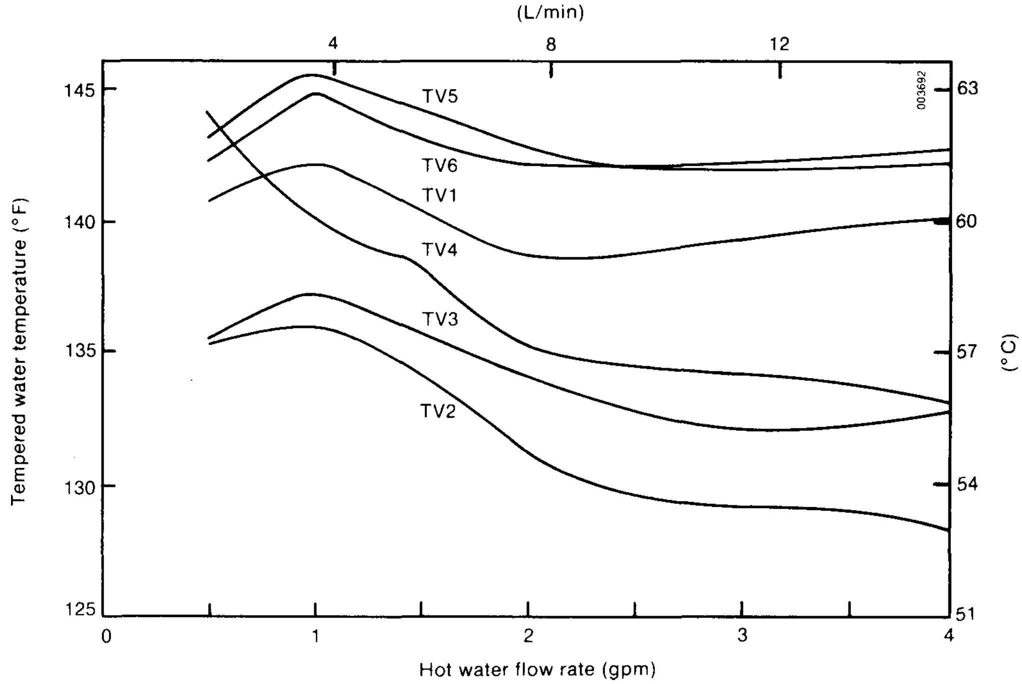

Figure 5-9. Comparison of all Tempering Valves at 49° C (120° F) Setpoint and 93° C (200° F) Tank Temperature

tempering valve will vary greatly throughout the day and year. These devices should not be expected to deliver a constant water temperature over a wide range of source temperatures at their low cost. If a tempering valve appears to malfunction, the range of storage tank temperatures might cause the fluctuations rather than tempering valve failure.

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

5.3 RECOMMENDATIONS

- Homeowners using appliances that require a minimum temperature for proper operation should periodically measure the water temperature rather than depend on the tempering valve markings.
- Users should be aware that the tempering valves may not temper the water properly at high storage tank temperatures. When high storage tank temperatures occur frequently, such as during the summer, the user may want to lower the tempering valve setpoint temperature to prevent scalding.
- Users should be aware that excessively hot water temperatures may occur during each initial use of a tempering valve.

Table 5-3. Performance Ranges of Individual Tempering Valves

Tempering Valve	Set Point							
	49° C (120° F)				60° C (140° F)			
	Low[a]		High[b]		Low[c]		High[d]	
	°C	°F	°C	°F	°C	°F	°C	°F
1	35.9	96.6	61.2	142.2	43.5	110.3	61.8	143.2
2	36.8	98.2	57.8	136.0	44.8	112.6	59.5	139.1
3	35.7	96.3	58.5	137.3	44.0	111.2	62.3	144.1
4	35.6	96.1	62.3	144.1	44.1	111.4	62.7	144.9
5	36.6	97.9	63.1	145.6	44.1	111.4	69.4	156.9
6	37.2	99.0	62.6	144.7	44.9	112.8	72.7	162.9

[a]Tank temperature at 49° C (120° F), hot water flow rate at 1.9 L/min (0.5 gpm).

[b]Tank temperature at 93° C (200° F), TV4 hot water flow rate at 1.9 L/min (0.5 gpm), all others at 3.8 L/min (1 gpm).

[c]Tank temperature at 49° C (120° F), TV2 and 4 hot water flow rate at 1.9 L/min (0.5 gpm), TV1 and 3 at 3.8 L/min (1 gpm), TV5 at 5.7 L/min (1.5 gpm), and TV6 at 11.3 L/min (3 gpm).

[d]Tank temperature at 93° C (200° F), TV3 and 6 hot water flow rate at 3.8 L/min (1 gpm), TV2 and 4 at 5.7 L/min (1.5 gpm), TV5 at 7.6 L/min (2 gpm), and TV1 at 11.3 L/min (3 gpm).

SECTION 6.0

POLYBUTYLENE PIPING

6.1 BACKGROUND

The use of polybutylene pipe instead of copper for domestic solar systems could reduce the cost of system piping [6] for several reasons. First, polybutylene pipe costs less than copper pipe. Second, it is more flexible than copper pipe and thus easier to install. Also, it accepts compression fittings, which should allow more rapid installation than soldering, heat fusion, or adhesive fitting. However, one potential drawback of polybutylene pipe is its temperature limitation. A second is the integrity of the mechanical fittings when subjected to elevated temperature.

Some properties of polybutylene compared to copper and steel are listed in Table 6-1. Polybutylene pipe is manufactured to conform to ASTM Standard D 3309, which specifies that pipe and associated fittings should 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); minimum burst pressure at this temperature is 2.21 MPa (320 psi). The pipe should also be capable of withstanding thermal cycling between 16° and 82°C (60°F and 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 that the pipe's average burst pressure was 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 at the collector outlet. This is a considerable constraint for closed, nondraining systems, where it is not desirable to vent the collector liquid, and for closed drainback systems, where it is desirable to prevent outside air from entering the system.

Polybutylene fittings are available for pipes 1 in. in diameter and larger. Such fittings are fusion welded. Acetal fittings were available in smaller sizes but are no longer recommended by one manufacturer for use with polybutylene pipe. For smaller pipe sizes in closed loops, copper fittings with compression rings are used.

The test procedure for the polybutylene piping is discussed in detail in Appendix A.5.

6.2 TEST RESULTS

The total length of the polybutylene pipe was about 10 m (33 ft). The pipe was sized (nominal 3/4 in.) to allow draining without the need for a vacuum breaker. Numerous fittings (couplers, tees, elbows, and valves) were incorporated into the system. All fittings were attached by copper compression rings installed with a simple crimping tool.

Table 6-1. Some Properties of Polybutylene[a], Copper, and Steel

Property	Polybutylene		Copper		Steel	
Density in kg/m^3 (lb/ft^3)	912	(56.9)	8910	(556)	7870	(491)
Specific heat in J/kg °C (Btu/lb °F)	1880	(0.45)	385	(0.092)	447	(0.107)
Thermal expansion coefficient in 10^{-6} m/m °C (10^{-6} ft/ft °F)	150	(83)	17	(9.3)	12	(6.7)
Thermal conductivity 0°-100° C, in W/m °C (Btu/ft h °F)	0.22	(0.13)	389	(225)	52	(30)
Tensile strength in MPa (1000 psi)	28	(4)	220	(32)	450	(65)
Melting point in °C (°F)	126	(254)	1082	(1980)	1516	(2760)
Cost in \$/m (\$/ft)[b]	1.02	(0.31)	2.20	(0.67)	-	-

[a]Compiled from Modern Plastics Encyclopedia, Guide to Plastics.

[b]Nominal 3/4-in. diameter.

Fabrication of the polybutylene test loop was rapid, and the loop satisfactorily tested for leaks. The loop was insulated with elastomeric, expanded polyethylene, and rigid polyurethane insulations. The insulation provided 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 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 tested to its burst pressure with water at 13° C (55° F). The results are shown in Table 6-2.

Table 6-2. Polybutylene Pipe Pressure Test

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

6.3 RECOMMENDATIONS

- Screening tests should be performed in accordance with "Standard Practice for Screening Polymeric Containment Materials for the Effects of Heat and Heat Transfer Fluids in Solar Heating and Cooling Systems" (ASTM E862-82) and, if warranted, pursue the use of polybutylene piping in solar energy systems by building prototype systems and operating them in the field.
- Rigid insulation installed on hot pipes must be cut a little shorter than the pipes to avoid imposing large tensile stresses in the pipe as it cools.
- Flexible insulation should be compressed to allow for thermal expansion and used at expansion joints to prevent insulation gaps at high temperatures.

SECTION 7.0

CONCLUSIONS AND RECOMMENDATIONS

Tests of some key components currently used in solar energy systems successfully identified several weaknesses.

7.1 DRAIN VALVES

Conclusions

Many of the drain valves tested showed significant problems, such as severe leaking around seals, catastrophic failure of pistons, improper selection of plunger lubricant, and scaling on metal components of one type of drain valve. Two of the three types tested showed severe problems; one type had a 100% failure rate. The manufacturer of this valve withdrew it from the market after we discussed the test results with him. The manufacturer of the valve with high failure rates apparently was still revising and improving the valve while it was being marketed. This valve also had severe accumulation of scale, which could lead to binding of the disk and valve failure in areas of high mineral content water. The third type tested did not have any serious problems.

Recommendations

Manufacturers should implement more thorough long-term internal testing of randomly selected drain valves to determine failure modes and reliability of their components. This will lead to more reliable drain valves.

Manufacturers should reexamine the temperature stability of their drain valve components and, if necessary, either upgrade the components or derate the temperature limitations.

To prevent excessive drain valve degradation, system designers should include overtemperature protection in solar energy systems.

Valves should be thoroughly inspected and tested before shipment.

7.2 AIR VENTS AND VACUUM BREAKERS

Conclusions

Several of the metal air vents created a safety hazard, as well as an inconvenience, when the protective cap would rotate upon filling and spray hot water in undesirable directions.

The metal valves had scale build-up inside the valve body and on the outlet port.

Recommendations

Test the valves at a realistically low ambient temperatures with realistic pipe lengths.

Determine if scaling inside the valve body and on the outlet port can lead to valve failure.

7.3 CHECK VALVES

Conclusions

The check valves leaked under both high and low differential pressures.

Check valves used to prevent natural convection had very inconsistent performance. They sometimes sealed well and sometimes leaked severely.

The check valves tested did not prevent natural convection in our test loops. The spring-loaded check valves leaked during 75% of the tests, while the swing check valves leaked about 30% of the time. Overall, the check valves did not stop natural convection in more than 50% of the tests.

Recommendations

Determine suitable ways of effectively preventing natural convection losses.

Determine the effectiveness of "heat traps" in which pipe is plumbed vertically downward before any horizontal or vertical pipe runs.

Determine if convective cells can be sustained inside small-diameter tubing (12.7 mm [1/2 inch] and 19 mm [3/4 inch]), which would confirm natural convection loops within individual pipes.

7.4 TEMPERING VALVES

Conclusions

The outlet temperature is a strong function of storage tank temperature and a weak function of flow rate. Hence, solar energy system users cannot expect a constant outlet temperature since the storage tank temperature varies significantly.

Tempering valves mounted below the top of the tank can be expected to initially provide significantly hotter water than the setpoint if the tank is very hot.

There is no apparent effect on tempering-valve steady-state operation from placing the tempering valve either below or above the top of the storage tank.

Recommendations

Users requiring a certain hot water temperature should periodically measure it, perhaps installing a temperature gauge by the outlet of the tempering valve.

Users should reduce the tempering valve setting if the storage tank reaches high temperatures, such as during the summer, and increase the setting when the tank is cold.

7.5 POLYBUTYLENE PIPING

Conclusions

The polybutylene pipe tested had burst pressures averaging 3.7 MPa (540 psi) after 24,000 cycles of hot water, cold water, and draining. It appears to be suitable for use in hot water systems that operate below 93°C (200°F) and offers potential for substantial cost reductions in installed pipe compared with copper pipe.

Recommendations

Screening tests should be performed on polybutylene pipe in accordance with "Standard Practice for Screening Polymeric Containment Materials for the Effects of Heat and Heat Transfer Fluids in Solar Heating and Cooling Systems" (ASTM E862-82). If warranted a prototype system with polybutylene piping should be built and tested.

Insulation must be installed carefully because of the high coefficient of thermal expansion of polybutylene.

SECTION 8.0

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APPENDIX A

TEST PROCEDURES

The following test procedures were developed at SERI, generally in the absence of standard test methods for equipment used in solar applications. They are not intended to be test standards or qualification tests but were designed specifically to determine the failure modes of various solar components in this task or to determine the performance of these components.

A.1 DRAIN VALVE TESTS

A.1.1 Static Pressure Test

The objective of this test was to determine if any obvious manufacturing defects existed and whether the seals seated properly. We tested each drain valve prior to installation in the drain valve loop. Upon delivery, the drain valves were labeled, carefully inspected, and photographed (see Form 1 in Appendix B). The test setup is shown in Figure A-1. We used the following test procedure:

1. Install the drain valve in the test setup.
2. Energize the drain valve, opening the top ports.
3. Open valve V1.
4. Fill the drain valve with room-temperature water, taking care to eliminate entrained air.
5. De-energize the drain valve.
6. Pressurize the drain valve to 1.5 times its rated operating pressure.
7. Close valve V1.
8. Record the pressure (see Form 2 in Appendix B) for one hour.
9. If the pressure drops less than 10%, drain valve is considered to seat properly.
10. After testing, remove the drain valve.

A.1.2 Thermal Cycling Test

The objective of this test was to determine the effects of frequent thermal cycling on the drain valves. One valve from each manufacturer was subjected to this test. The test loop is shown in Figure A-2.

1. Install one drain valve from each manufacturer after successfully passing the static pressure test in the thermal cycling test loop.
2. Wire the valves to the control relays.
3. Set the tank temperature to 93°C (200°F).

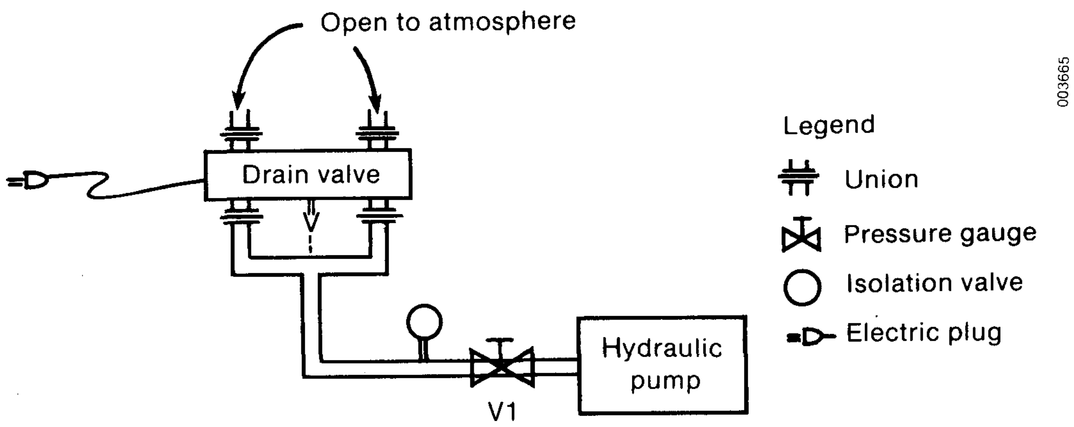

Figure A-1. Drain Valve Static Pressure Test Setup

4. Automatically cycle the drain valves, 15 minutes on, 15 minutes off.
5. Record the date, valve number, counter, operational status, flow rate, ambient temperature, storage tank temperature, and pressure daily (see Form 3 in Appendix B).
6. Use petcocks to confirm that the drain valves fill and drain properly.
7. If drain valve fails, remove, inspect, photograph, and document failure.
8. Continue test until drain valves fail.

A.1.3 Infrequent Cycling Test

The objective of this test was to determine if drain valves are susceptible to failure if they are maintained in the fill position for extended time periods. Drain valves that drain only when low temperatures are encountered are subject to this condition.

1. After the drain valves have successfully passed the static pressure test, install one drain valve from each manufacturer in the test loop (see Figure A-2).
2. Wire the drain valves to a continuous power source.
3. Post a sign at power source, "Do Not Turn Off."
4. Observe drain valves daily, recording significant events.
5. After three months of continuous power, de-energize and evaluate drain valve.

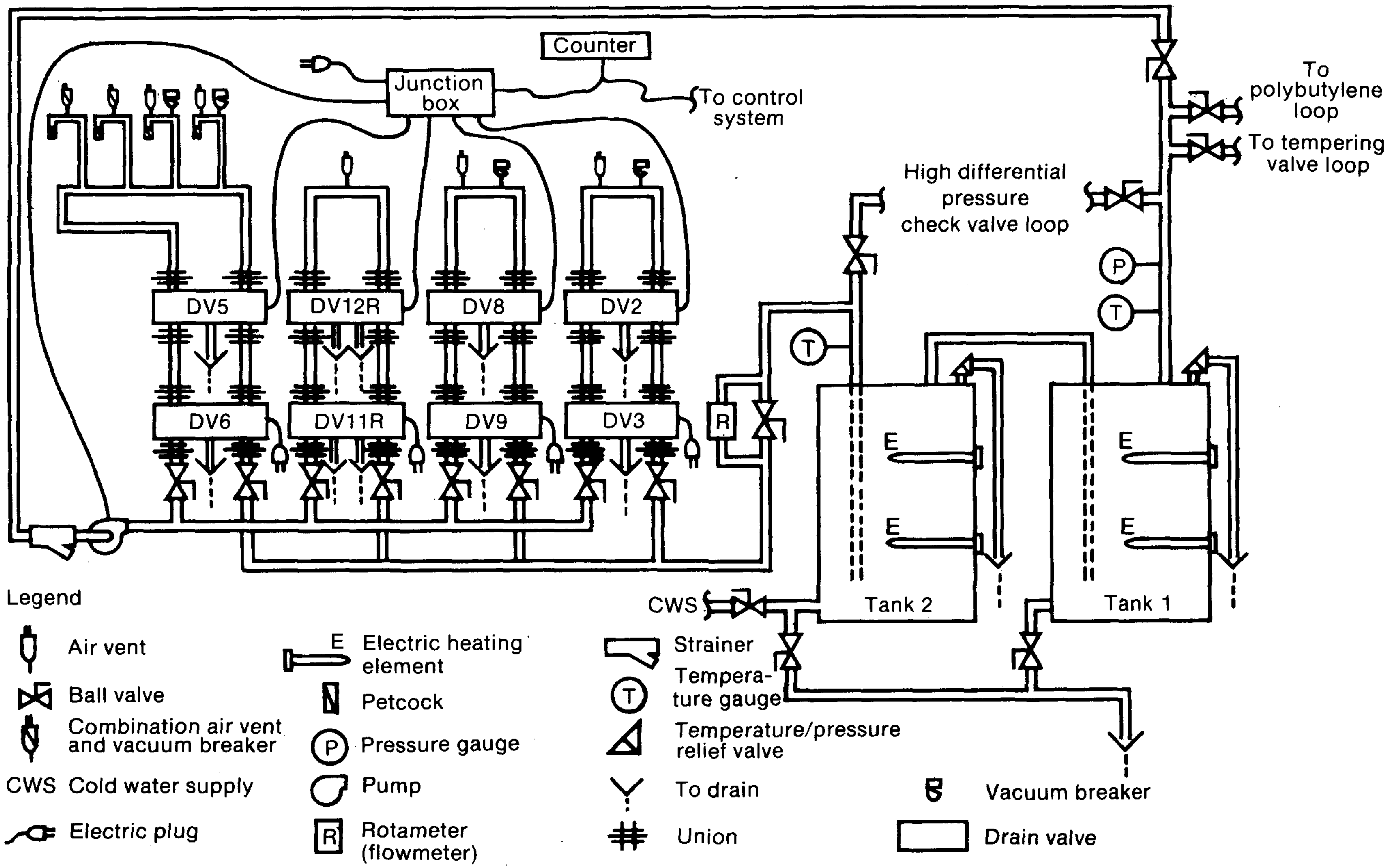

Figure A-2. Schematic of Drain Valve, Air Vent, and Vacuum Breaker Test Loop

A.2 AIR VENT AND VACUUM BREAKER TESTS

A.2.1 Thermal Cycling Test

The valves were labeled, inspected, and photographed. They were installed in the thermal cycling loop (Figure A-2) and operated in conjunction with the drain valves, so that these valves completed a full cycle of operation every 30 minutes. The valves were externally inspected and their operation confirmed regularly. Petcocks were installed near the valves to permit manual air venting and vacuum breaking to ensure proper operation.

A.2.2 Low Ambient Temperature Test

This test was intended to evaluate proper air venting and vacuum breaking when the air vent and vacuum breaker (or combination air vent/vacuum breaker) were subject to freezing ambient temperatures. The following procedure was used with the storage tank at 38° C (100° F), and then at 16° C (60° F).

1. De-energize the drain valve that allows circulation to the valve to be tested.
2. Ensure that the loop has drained.
3. Enclose the valve to be tested (see Figure A-3).
4. Place dry ice in the enclosure, ensuring that none is on the valve.
5. Cover the enclosure, making sure that the thermometer is reading the temperature of the air and not the dry ice.
6. Wait until the air temperature in the enclosure stabilizes between -18° and 0° C (0° F and 32° F).
7. Record the valve number, time, and air temperature in the enclosure (see Form 4 in Appendix B).
8. Energize the drain valve, refilling the loop.
9. Record the time required to fill the loop and the air temperature in the enclosure.
10. If the loop does not fill within 15 minutes, note this and repeat the test from the beginning twice. Otherwise, go to the next step.
11. Wait until the air temperature in the enclosure stabilizes.

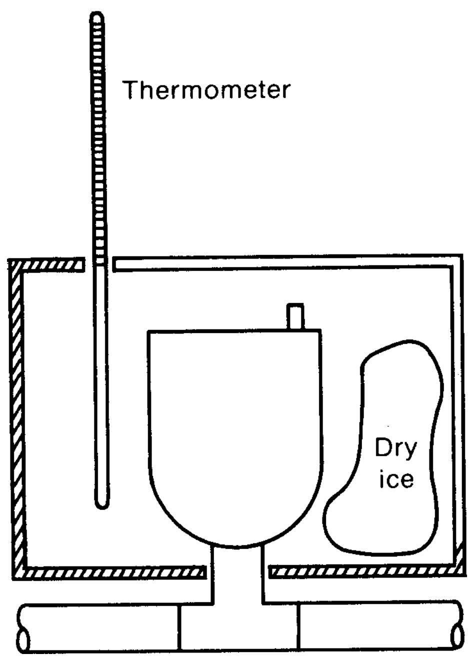

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Figure A-3. Air Vent/Vacuum Breaker Low Ambient Test Setup

12. Record the time and air temperature in the enclosure.
13. De-energize the drain valve.
14. Record the time and air temperature in the enclosure upon draining.
15. If the loop does not drain within 15 minutes, note this and repeat the test twice.
16. Inspect the valve and note any observations.

A.3 CHECK VALVE TESTS

A.3.1 High Differential Pressure Test

The purpose of this test was to determine the ability of check valves to function as shutoff valves in drainout systems. The check valves were labeled, inspected, photographed, and installed in the thermal cycling loop as shown in Figure A-4. Two solenoid valves were used to control the loop. A normally open (N.O.)* solenoid was used to control flow to a drain, and a normally closed (N.C.)* solenoid was used to shut off pressure from the upstream side of the solenoid. When the N.C. solenoid closed and the N.O. solenoid opened, water pressure forced the check valve closed. Any leaking could be observed in a clear section of the drain piping. The cycle for the test loop at 93°C (200°F) consisted of circulation for 9 minutes and then no circulation and a high differential pressure for 1 minute. The ambient and storage tank temperature, tank pressure, flow rates, cycles, and observations were recorded daily (see Form 3 in Appendix B).

A.3.2 Low Differential Pressure Test

The purpose of this test was to determine if check valves are sufficient to prevent natural convective flows such as those caused by density gradients in a collector-storage loop.

The check valves were labeled, inspected, photographed, and installed in a separate loop with visual indicators as shown in Figure A-5. Because the visual indicators could withstand only limited pressure, the loop was maintained at atmospheric pressure. After the check valves were installed and the loop filled, the storage tank thermostat was set to 77°C (170°F). The fluid was circulated for 15 minutes and then was turned off for 15 minutes. The ambient and storage tank temperatures, flow rate, cycles, and observations were recorded daily. The ability of the check valves to prevent natural convection was determined periodically.

The following procedure was used to check the sealing capability of the check valves:

1. Ensure that the loop is thermally equilibrated.
2. Stop the pump.
3. Record the time, counts, and temperatures (top of tank, top of loop, bottom of cold leg) (see Form 5 in Appendix B).

---

*N.O. and N.C. refer to the valve position when it is de-energized.

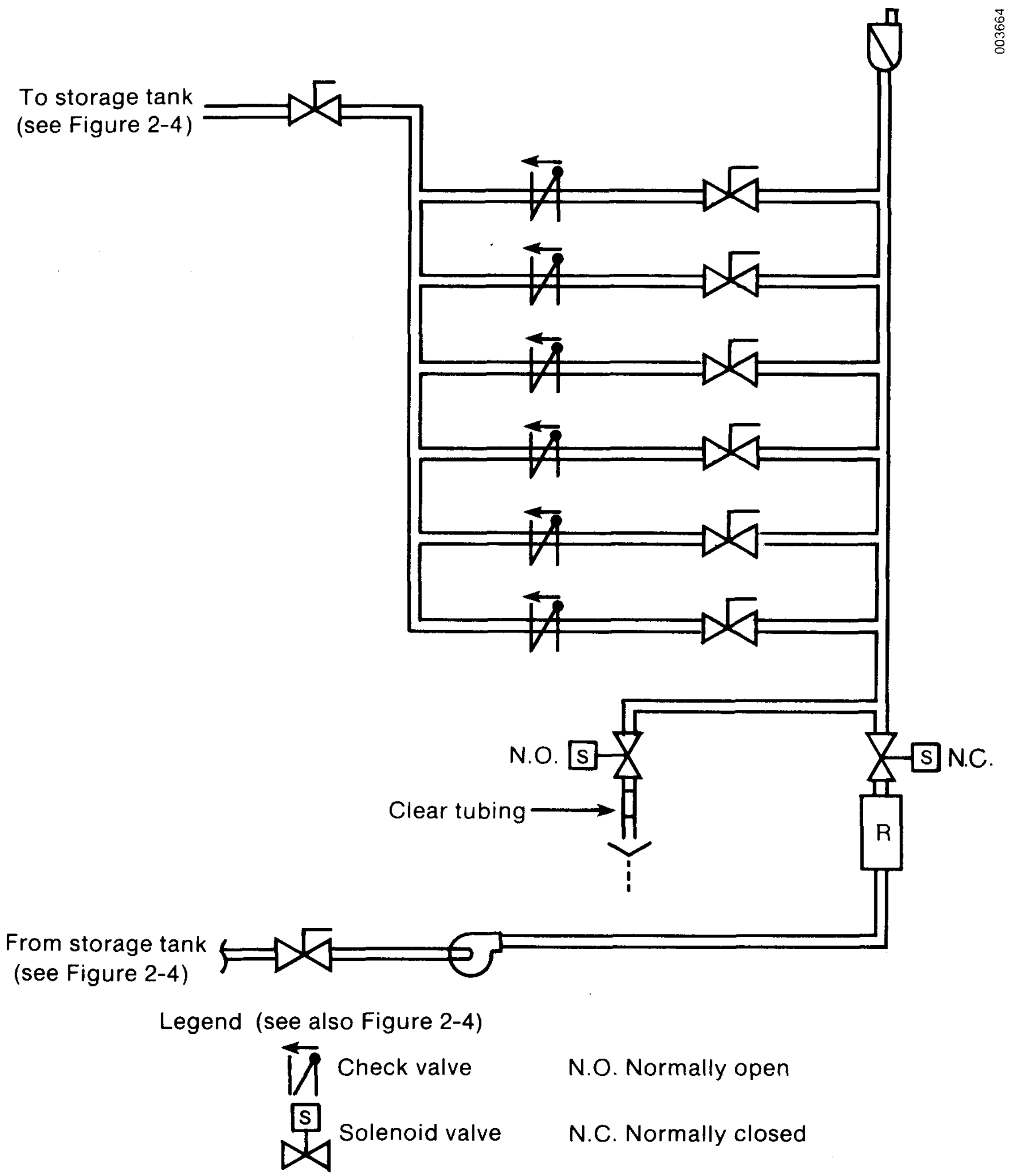
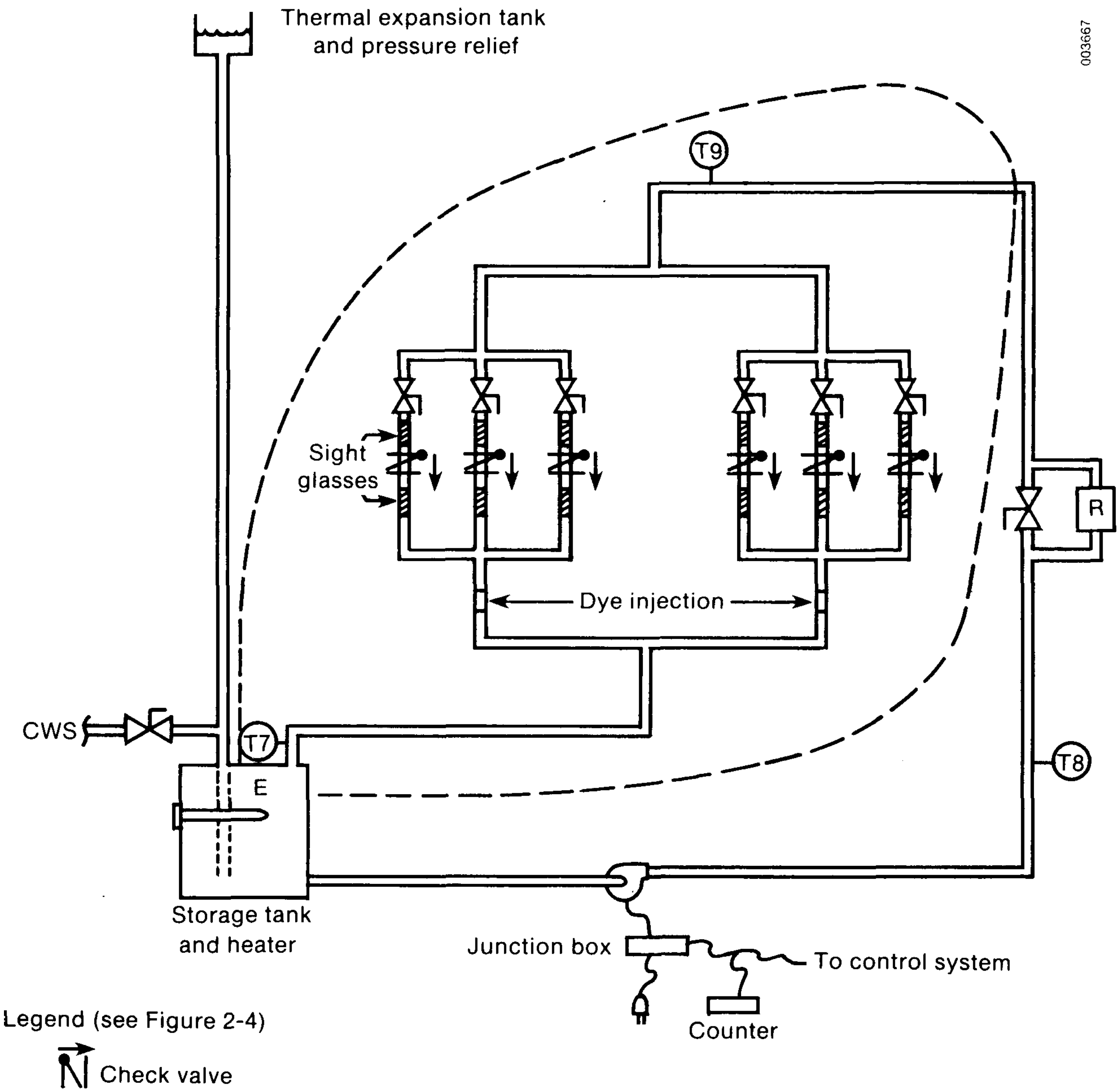


Figure A-4. High Differential Pressure Test Setup for Check Valves



NOTE:
1) Storage tank piping inside "———" is heavily insulated. Other piping uninsulated.
2) Swing check valves installed horizontally, spring-loaded check valves installed vertically

Figure A-5. Low Differential Pressure Test Setup for Check Valves

4. Slowly inject dye beneath the check valves, ensuring that air does not enter the pipe.
5. Record the time and progress of the dye.
6. Shut off leaking check valves.
7. Continue until temperatures reach steady state.
8. If necessary, flush loop to eliminate dye.
9. Test each valve twice.

A.4 TEMPERING VALVE TESTS

The objective of this test was to determine the performance and reliability of tempering valves for domestic use. Upon delivery, the tempering valves were labeled, inspected, photographed, and then installed in the thermal cycling loop as shown in Figure A-6. The tempering valves were subject to flow for 30 seconds in every ten minutes. After the valves operated for a suitable period of time, their performance was determined using the following procedure for tank temperatures of 49°, 71°, and 93°C (120°, 160°, and 200°F) with the tempering valves set to 49° and 60°C (120° and 140°F).

1. Set the storage tanks to the desired temperature and circulate the water to ensure good mixing.
2. Adjust the setpoint of the tempering valve to be tested.
3. Close the isolation valves to each tempering valve.
4. Close valves V1 and V2 to direct water through flowmeters.
5. Open the solenoid valve to the drain.
6. If the tempering valve is mounted above the tank, flush it with hot water before each test. If it is mounted below the tank, flush it with cold water.
7. For the first test (transient response test), record the temperatures of cold, hot, and tempered water every 2 seconds until a steady mixed water temperature is reached, maintaining the hot water flow rate at 3.8 L/min (1 gpm). Repeat the test for a hot water flow rate of 7.6 L/min (2 gpm). For each test record the final cold water flow rate.
8. For the second test (steady-state response test), record the temperatures of the cold, hot, and tempered water every 10 seconds until a constant mixed water temperature is reached for hot water flow rates of 1.9, 3.8, 5.7, 7.6, 11.3, 15.1 L/min (0.5, 1, 1.5, 2, 3, 4 gpm) (see Form 6 in Appendix B).
9. Monitor the tank temperature carefully to ensure that it does not decrease during the test. Flush the tempering valves before each test to start each individual test from the same reference point.

A.5 POLYBUTYLENE PIPING TESTS

The objective of this test was to determine the integrity of polybutylene pipe under conditions common to active solar energy systems. The polybutylene piping was plumbed in a configuration using multiple elbows, tees, and valves, as shown in Figure A-7. A thermal cycling test was performed as follows:

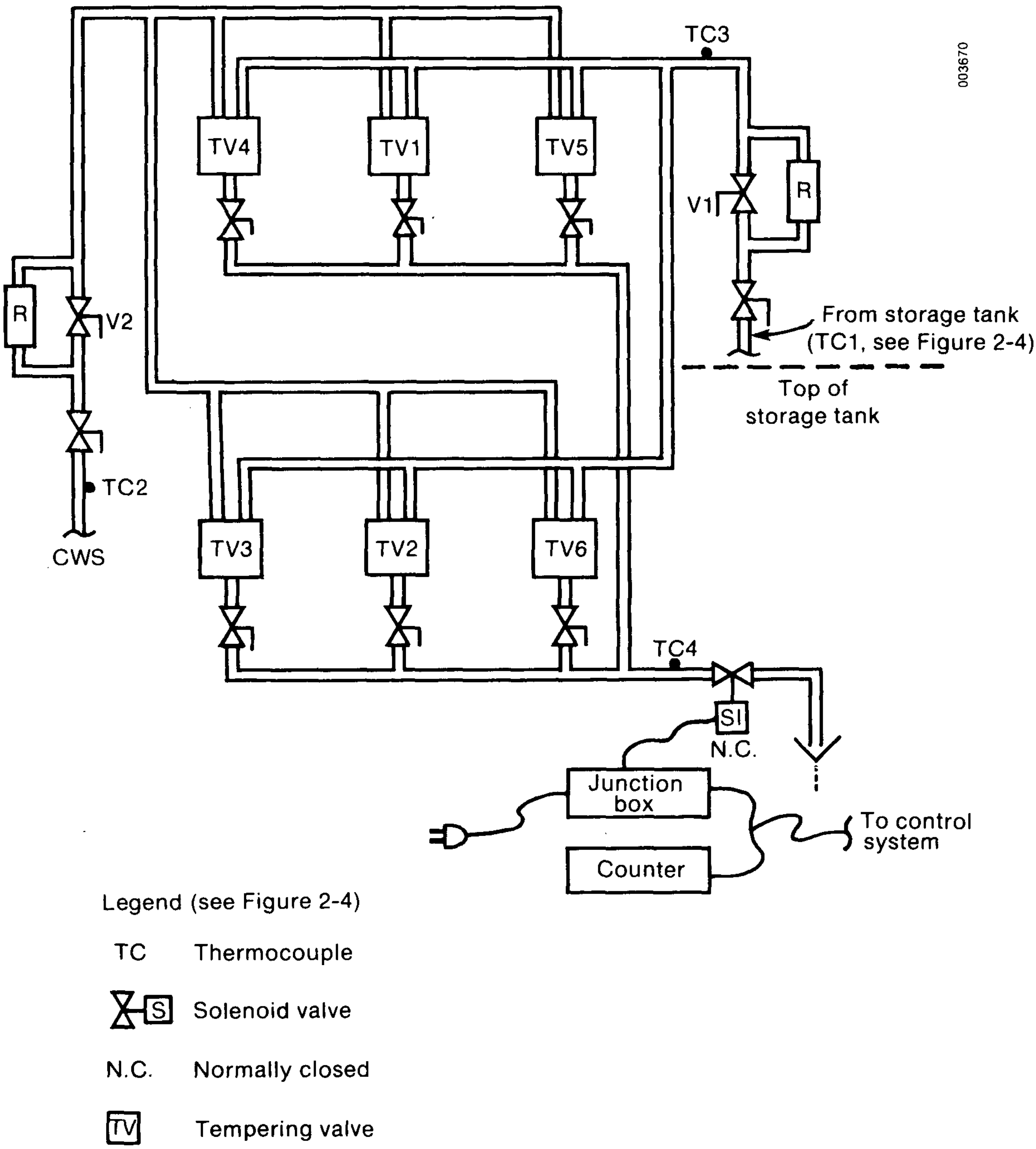


Figure A-6. Tempering Valve Test Setup

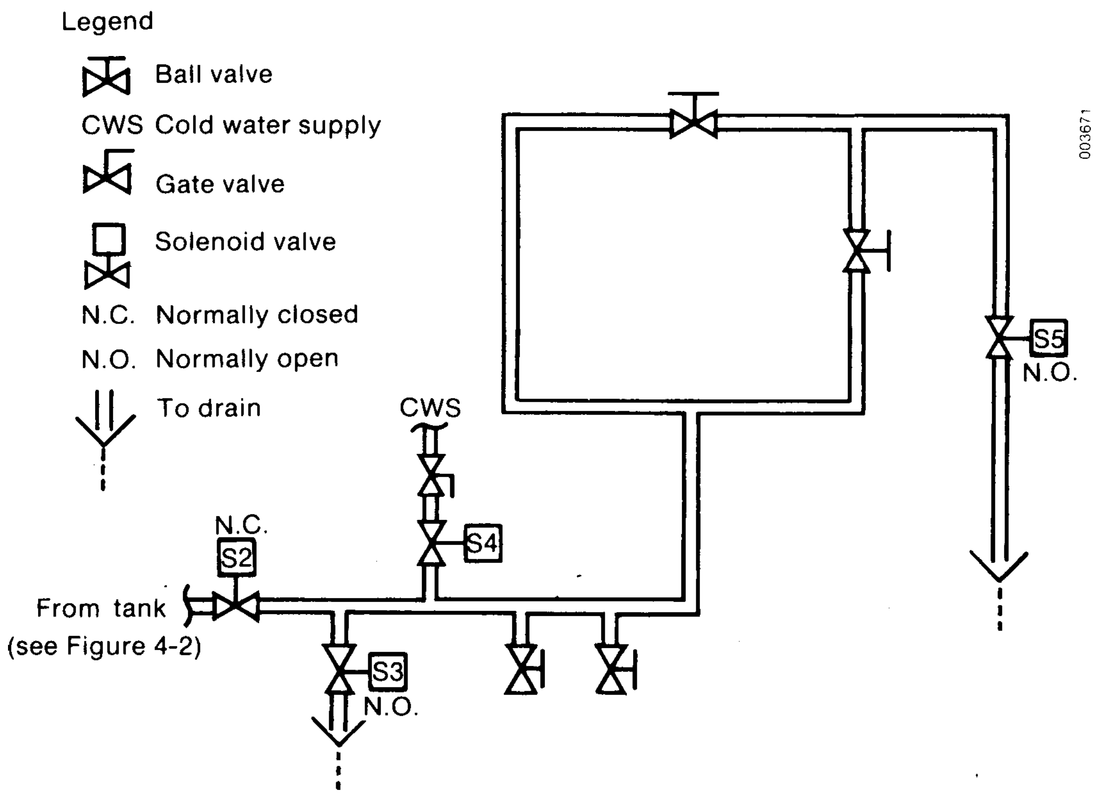


Figure A-7. Schematic of Polybutylene Pipe Test Loop

1. At the start of a cycle, the solenoids are at their failsafe positions with the hot water inlet line solenoid (S2) closed, the cold water inlet line solenoid (S4) closed, and the loop inlet (S3) and outlet (S5) solenoid drain valves open.
2. Open valve S2 and close valve S3 to allow hot water to flow through the system for 1 minute.
3. Close outlet valve S5 to allow the system to reach temperature equilibrium over 2-1/2 minutes.
4. Drain the system by opening valves S3 and S5, and closing valve S2.
5. Rapidly cool the system by allowing cold water to flow through the loop for 2 minutes after opening valve S4 and closing drain S3.
6. Repeat the cycle with hot water at 93°C (200°F) displacing the cold water by closing valve S4 and opening valve S2.

This procedure is to test the system at over-design conditions. The loop will complete a cycle every 8 minutes. Quickly closing solenoids subject the system to mechanical shock at water pressures of 0.65 MPa (80 psig), while rapid interchanges of hot and cold water create large thermal stresses.

APPENDIX B

SAMPLE TEST FORMS USED IN EXPERIMENTS

Form 1

Valve Labels and Observations

Label	Manufacturer	Comments

003673

Form 2

Static Pressure Test

Valve	Pressure (psi) at Time (min)										Comments
	0	1	2	5	10	20	30	40	50	60	

003674

Form 3

Daily Log Sheet

TEST:
Drain valves (DV)
Air vents (AV)
Vacuum breakers (VB)
Combination valves (CA)
High ΔP check valves (HCV)
Low ΔP check valves (LCV)

Date	Valve (Type & #)	Counter (Counts)	Status (O = Oper) (N = Nonoper)	Flow (gpm)	Amb. Temp. (°F)	Tank Temp. (°F)	Tank Press. (psig)	Comments (Initials)

003675

Form 4

Low Ambient Air Temperature Test

Date ______________________

Tester ______________________

Tank Temperature ______________________

DV	CV	AV	Time	Low Air Temperature	Activity[1]	Comments

003682

[1]Activity:
1) DV energized
2) Loop filled
3) DV de-energized
4) Loop drained

Form 5

Check Valve Low ΔP Test

Date ____________________

Counter ____________________

Valve ____________________

Tester ____________________

Time	T7 (°F)	T8 (°F)	T9 (°F)	Comments

003681

Form 6

Tempering Test Valve

Date____________________

Counter____________________

Valve____________________

Tester____________________

T(Set) (120°, 140°F)	T(Tank) T1 (°F)	T(Cold) T2 (°F)	T(Hot) T3 (120°, 140°, 160°, 180°)	T(Mix) T4 (°F)	Flow Cold (gpm)	Flow Hot (gpm)	Length of Test (min)	Comments

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