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QUICK LOOK REPORT FOR SEMISCALE MOD-2B TEST S-SG-4

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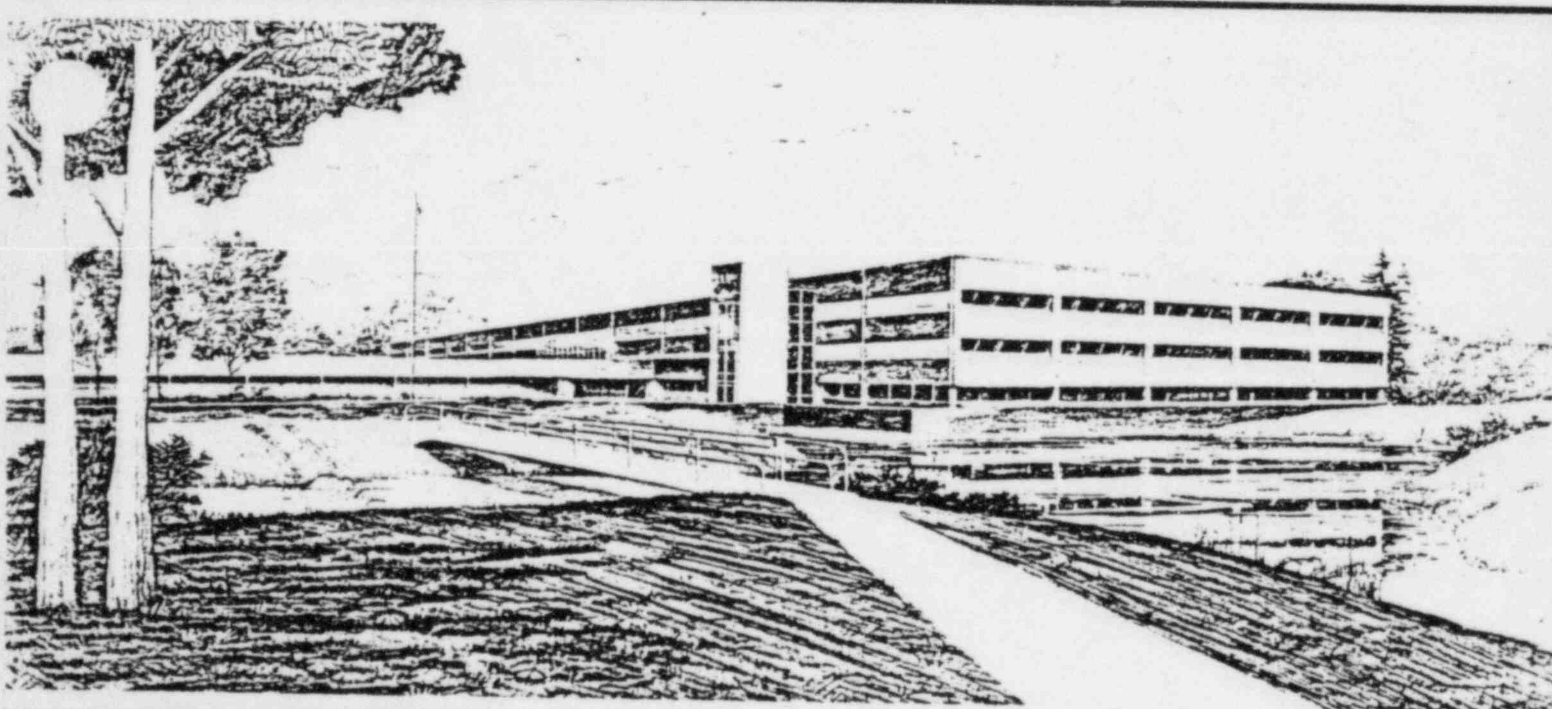

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QUICK LOOK REPORT FOR SEMISCALE MOD-2B TEST S-SG-4

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ABSTRACT

Results of a preliminary analysis of the seventh test performed in the Semiscale Mod-2B Steam Generator Tube Rupture Series are presented. Test S-SG-4 simulated a pressurized water reactor accident initiated by the double-ended offset shear of one cold side steam generator tube. The transient included a 600-second period during which only automatic plant protection systems responded to the initiating event. Main coolant pump trip, which is generally initiated at the safety injection signal (SIS), was delayed until 600 s. Pump trip was followed by a 200-second period during which no operator action or automatic plant response occurred, so that pump trip effects could be clearly assessed. Plant recovery commenced at 800 s with the initiation of intact loop steam and feed and pressurizer auxiliary spray. Safety injection (SI) was used throughout the transient to maintain primary system inventory. Pressurizer heaters were used to establish pressure control in the pressurizer and control the rate of primary depressurization. The test results provided a measured evaluation of the effect of delayed pump trip on tube rupture signatures, the effectiveness of auxiliary spray in filling the pressurizer and reducing primary pressure, and the effectiveness of pressurizer heaters in controlling primary pressure, with a liquid filled pressurizer. The test showed that the prescribed operator response was adequate to recover the Semiscale system from a one-tube rupture.

SUMMARY

This report presents a preliminary analysis of the Semiscale MOD-2B Steam Generator Tube Rupture Series (SG) Test S-SG-4. S-SG-4 is the seventh test of the SG series to be conducted. The test series is designed to study the effect of the number of tubes ruptured (break size), the location of the rupture (hot side or cold side of the steam generator) and the effect of limited operator responses to the accident following an initial 10-minute simulated identification period.

Test S-SG-4 simulated a pressurized water reactor transient initiated by a double-ended offset shear of one cold side steam generator tube. Data from this experiment will be examined to evaluate event signatures, event severities in Semiscale and recovery procedures, with the principal objective of providing data to benchmark computer code calculations.

Test S-SG-4 was designed in three parts: (a) an initial 600 s period in which only automatically functioning plant protection systems were assumed to operate, (b) a 200 s period with no operator actions or plant automatic responses to assess the effects of delayed pump trip, and (c) an operator controlled recovery consisting of pressurizer auxiliary spray, intact loop steam and feed, SI cycling, and pressurizer internal heater operation.

The signature of a single-tube rupture is characterized by a relatively rapid decrease of the primary coolant system pressure to a saturation condition in the hot legs as primary coolant system fluid flows through a simulated single-tube break into the broken loop steam generator secondary. Automatic protective actions that influence the pressure response during this early period are core scram and main steam isolation valve (MSIV) closure. Both are initiated by a low pressurizer pressure trip at 13.1 MPa (1900 psia). Main feedwater termination, auxiliary feedwater start, and safety injection start are all initiated on a safety injection signal (SIS) at a pressurizer pressure of 12.5 MPa (1814 psia). Main coolant pump trip was delayed until 600 s.

Part of the pressure response during this early period is a rapid increase in secondary pressure in both loops as primary-to-secondary heat transfer raises the pressure of the secondaries after MSIV closure. Accompanying this secondary pressure increase was a lifting of the atmospheric dump valve (ADV) in both the intact and broken loop steam generators. The broken loop ADV cycled frequently until 500 s as a significant amount of heat was transferred from primary to secondary. The primary pressure dropped to 7.0 MPa (1015 psia) followed by a gradual recovery as SI filled the pressurizer and compressed the steam space. Upon pump trip at 600 s there was very little vessel voiding and the primary tubes were full.

Cold side, one-tube rupture transients with pump trip at SIS (S-SG-8) and pump trip at 600 s (S-SG-4) were compared. The significant difference was considerably higher primary to secondary heat transfer in the broken loop steam generator with the pumps running. This resulted in lower primary pressure, SI flow exceeding break flow much earlier in time, higher vessel level, and an increasing pressurizer level.

The recovery procedure was initiated at 800 s, following a 600 s simulated operator diagnostic period and a 200 s period for assessment of pump trip effects. Pressurizer auxiliary spray and intact loop steam and feed were initiated simultaneously at 800 s. The pressurizer was completely filled with liquid at 1280 s and auxiliary spray was terminated. This operation also reduced primary pressure considerably. Intact loop steam and feed was continued throughout recovery reducing secondary pressure at an average predetermined rate of 2.76 MPa/hr (400 psia/hr), until the ADV was latched open at 6000 s. SI was cycled as necessary to keep the vessel and pressurizer collapsed liquid levels within specified bands. SI compression of the primary system was observed as primary pressure increased during SI operation. Pressurizer back-up and variable heaters, energized at 2.3 kW total power, were operated intermittently for 90 min., in an attempt to control primary pressure. They were not successful until the broken loop steam generator secondary completely filled with liquid. This increased the secondary pressure and effectively stopped break flow. The pressurizer warm-up heaters, supplying

13 kW total power, were effective in controlling primary pressure. A controlled primary depressurization at 2.76 MPa/hr (400 psia/hr), was accomplished for 1200 s and the test was terminated. The recovery procedures specified were successful in recovering the primary system from a cold side, one-tube rupture transient.

The initial transient response was well calculated by RELAP5. The calculation accurately showed the phenomena that occurred because of delayed pump trip, pump stoppage, pressurizer auxiliary spray operation, and SI operation. The failure to accurately calculate the break flow after SCRAM precluded calculating the correct response to internal pressurizer heater operation and resulted in poor event timing.

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1. INTRODUCTION

This report documents preliminary results from Semiscale Mod-2B test S-SG-4, the seventh experiment performed in the Semiscale Steam Generator Tube Rupture (SG) Test Series.[1] Test S-SG-4 was performed February 10, 1984. The test series includes experiments designed to investigate both tube rupture initiated transients and transients otherwise induced but concurrent with tube rupture. Data from these experiments will be examined to evaluate event signatures, event severities in Semiscale, and recovery procedures with the principle objective of providing data to assess computer code capability. Although inherent scaling distortions and facility limitations preclude interpreting the results of the SG Test Series as precise replications of pressurized water reactor response, the experiments are designed to provide thermal-hydraulic behavior that will be representative of PWR behavior. Subsequent references in this document on simulation of a full-scale PWR address the design of the experiment rather than the quantitative results.

Test S-SG-4 simulated a pressurized water reactor transient initiated by the double-ended offset shear of one cold side steam generator tube. The test simulated a one tube rupture transient with a delayed pump trip and a recovery scenario consisting of a combination of pressurizer auxiliary spray, pressurizer internal heaters, intact loop secondary steam and feed, and safety injection (SI). In the initial 600 s period only automatically functioning plant protection systems were assumed to operate. The tube rupture, which was simulated in the broken loop steam generator of the Semiscale system was the initiating event. Automatically occurring events during the first 600 s included main steam isolation valve closure, termination of main feedwater, auxiliary feedwater initiation, and start of safety injection. Coastdown of the main coolant pumps was initiated at 600 s followed by a 200 s period with no operator action so that the delayed trip affects could be determined. An operator induced recovery operation was initiated at 800 s after the break occurred (a time of 600 s is within the range of transient identification and response time that have occurred, or are expected to occur, in actual full scale plant transients).

An intact loop steam and feed was initiated at 800 s reducing the secondary pressure at a predetermined average rate of 2.76 MPa/hr (400 psig/hr) thereby increasing the secondary heat sink. Concurrently the pressurizer auxiliary spray was operated until the pressurizer was filled with liquid. The pressurizer back-up and variable heaters were then used in an attempt to return primary pressure control to the pressurizer and to control the primary depressurization rate below the specified maximum. Pressurizer back-up and variable heaters were unable to control primary pressure until the broken loop steam generator was filled, and break flow was essentially stopped. The warm-up heaters were then used to control primary pressure. The test was terminated after a 1200 s controlled depressurization had been observed.

A preliminary analysis of test S-SG-4 is presented in the following sections. Section 2 describes the system configuration and test conduct. Section 3 presents results from test data analysis. Section 4 presents a comparison of test data to the RELAP5 pretest analysis, and Section 5 summarizes conclusions drawn from the preliminary analysis.

2. SYSTEM CONFIGURATION AND TEST CONDUCT

2.1 System Configuration

The Semiscale Mod-2B system configuration is illustrated in Figure 1. The system is scaled from a reference four-loop PWR system based on the core power ratio, 2(MW)/3411(MW).[2,3] Component elevations, dynamic pressure heads, and liquid distribution were maintained as similar as practical. The two-loop test configuration consisted of the vessel with a 25-rod electrically heated core[a] with external downcomer, tube-and-shell steam generators and associated loop piping with circulation pumps. The broken loop (the loop in which the steam generator tube rupture occurs) is scaled to represent one loop of a four-loop PWR and the intact loop represents three loops of a four-loop PWR. The Semiscale Steam Generator Tube Rupture Experiment Operating Specification[1] gives more detail about the specific components.

Special modifications to the Semiscale Mod-2B system are incorporated to properly control and measure boundary conditions for the steam generator tube rupture series. These include condensing systems and catch tanks to accurately measure system mass flow rate from the steam generator secondaries, special effluent flow controls in the steam generator secondaries to give properly scaled steam relief flow rates, and a tube-rupture break assembly to simulate the primary to secondary flow path created by the tube rupture.

In both the intact and broken loops, a simulated power operated atmospheric dump valve (ADV) and a staged safety relief valve (SRV) system are situated on the main steam line. They represent scaled ADV and SRV flow capacities and operation.[3] The SRV orifice is designed to pass a scaled flow corresponding to only the first stage of relief of the SRV in a PWR (PWR SRV's typically have 5 stages of relief). The ADV orifice is

a. For test S-SG-4, only 21 rods were powered.

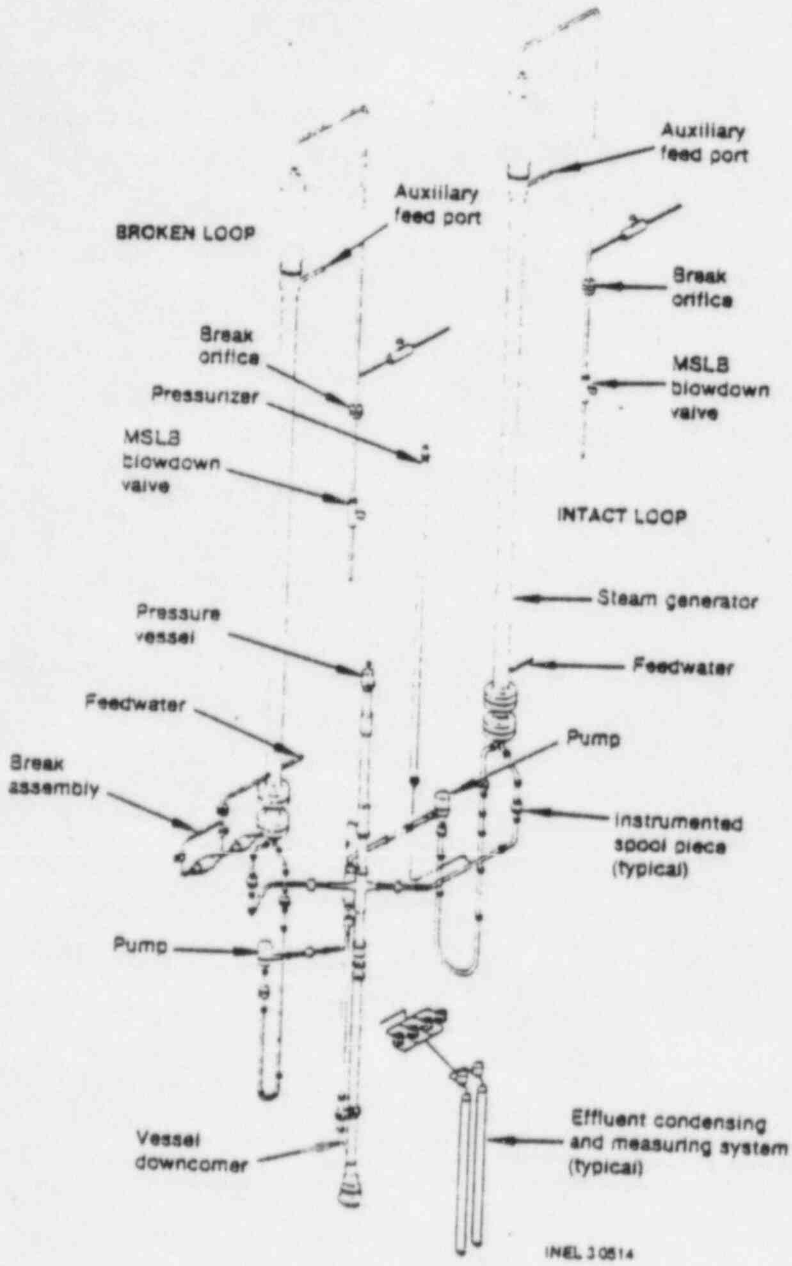


Figure 1. Semiscale Mod-2B system as configured for the SG test series.

designed to pass scaled flow corresponding to ADV operation in a PWR. In a PWR, the pressure relief setpoint for the ADV stage is encountered before the various multistaged SRV relief setpoints. Figure 2 shows the orientation used in Semiscale to simulate this operation in both the broken and intact loops. The parallel flow path arrangement allows ADV flow through the ADV block valve and orifice, and stage one SRV flow through the combination of both block valves and orifices. The block valves operate in an open or shut mode only, with the orifices controlling the flow rates. The ADV block valve opens automatically at the ADV pressure setpoint. If the pressure continues to rise after the ADV opens, the SRV block valve opens automatically at the SRV pressure setpoint. As the pressure decreases, the block valves close automatically, 69 kPa (10 psi) below their respective pressure setpoints. In Semiscale, the ADV relief setpoint is 5.85 MPa (836 psig) in the broken loop and 6.55 MPa (937 psig) in the intact loop. The first stage SRV relief setpoint is 5.94 MPa (849 psig) in the broken loop and 6.74 MPa (965 psig) in the intact loop.[a] Figures 3 and 4 show mass flow rate versus pressure for ADV and SRV operation for the broken and intact loops, respectively. The ADV can also be manually latched open during the recovery procedure with the SRV block valve shut.

The pressurizer PORV[b] provides a means of manually relieving primary system pressure from the top of the pressurizer. Semiscale uses a single valve with a flow control orifice to simulate the two PORV's of a full scale PWR. A 0.141 cm (0.055 in.) sharp edged orifice was sized to pass 0.03 kg/s (0.069 lb/s) at 16.2 MPa (2350 psia). The scaling criteria are presented in Appendix A of Reference 1. The pressurizer surge line hydraulic resistance was 1.8×10^{9} m^{-4} for test S-SG-4. Pressurizer internal heaters can be operated in the variable mode, backup mode or warmup mode. The variable and backup mode total power was 2.35 kW

a. The ADV and SRV relief setpoints were set to different, and artificially low, values for the two steam generators to ensure ADV operation during the transient. The scaling of these relief setpoints is discussed in detail in Reference 1.

b. The PORV was not used in S-SG-4.

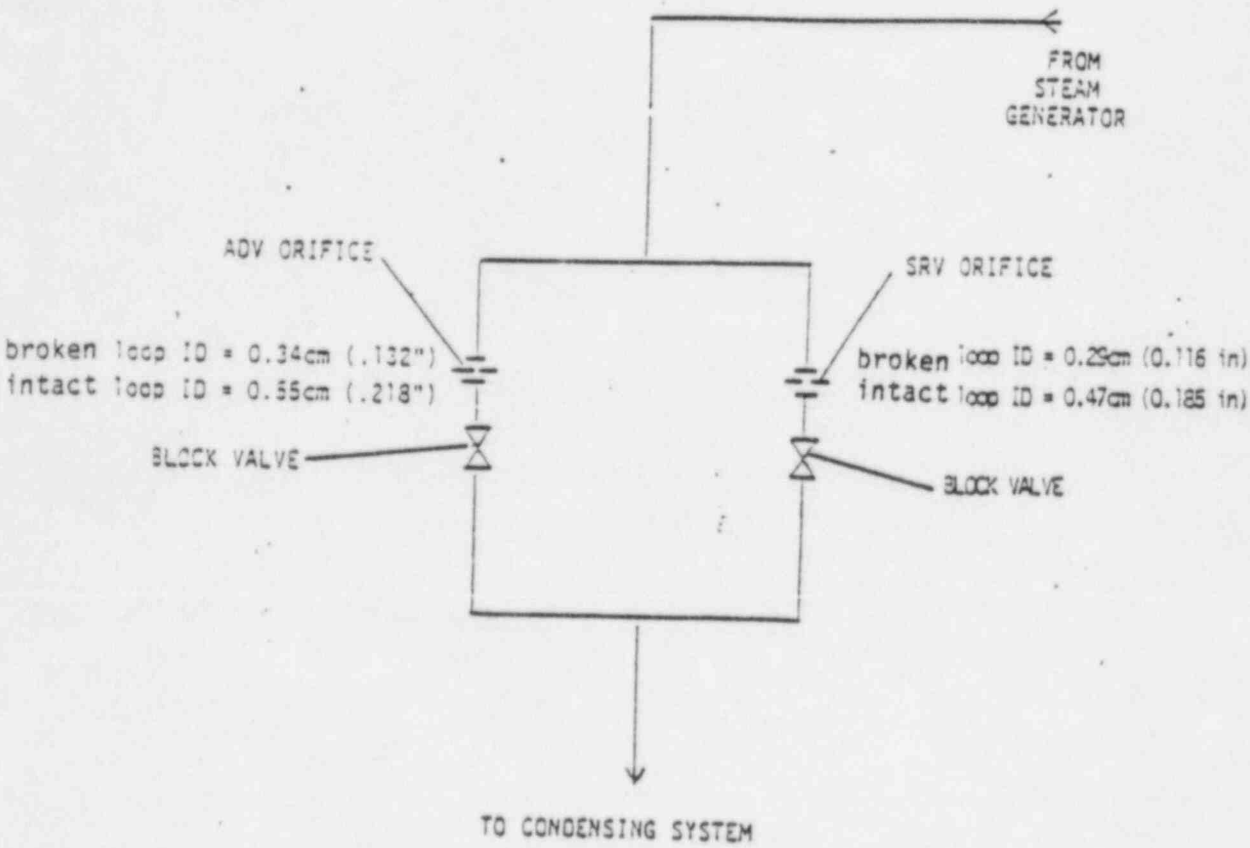


Figure 2. ADV and safety relief valve system.

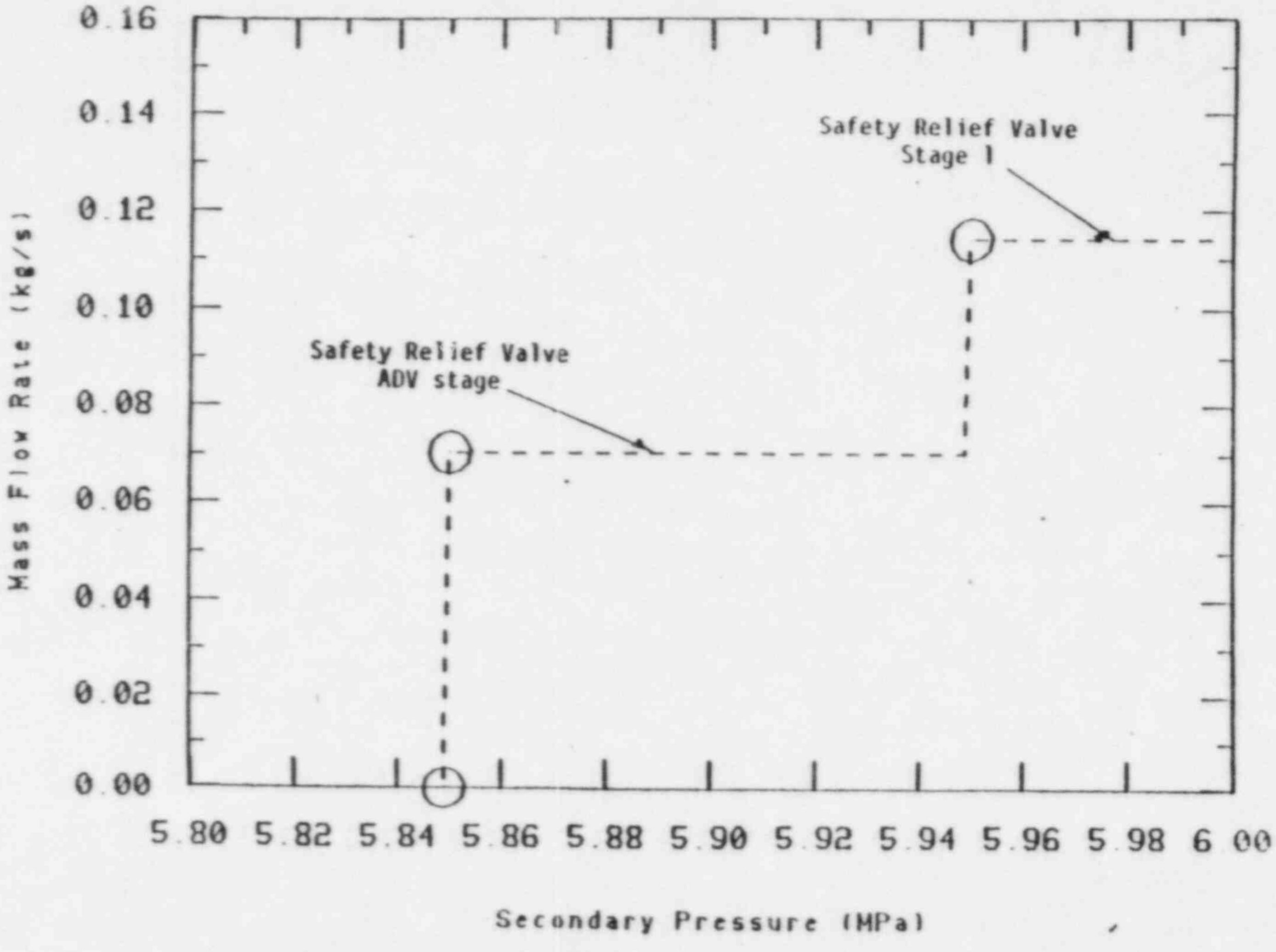


Figure 3. Broken loop steam generator safety relief valve operation.

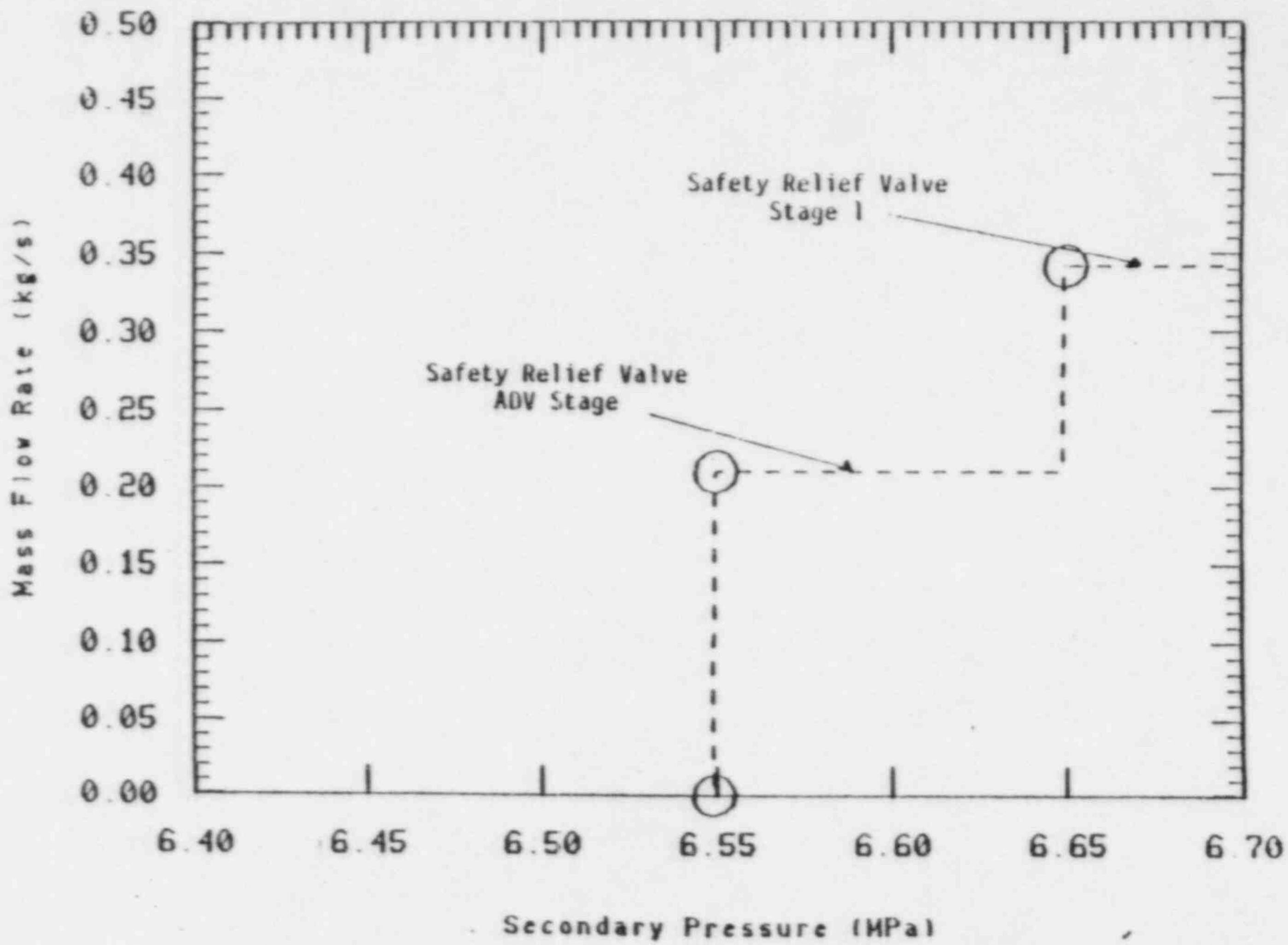


Figure 4. Intact loop steam generator safety relief valve operation.

and the warmup mode was 13.3 kW. Pressurizer auxiliary spray [296 K (73°F)] was introduced into the top of the pressurizer at a constant rate of 13.75 g/s (0.029 lbm/s) using positive displacement pumps.

The tube rupture break assembly connects the primary coolant system with the secondary side in the vicinity of the broken loop steam generator tube sheet (Figure 5). The break assembly can be connected to either the hot leg or cold leg side of the primary at the broken loop steam generator plenum, 57.1 cm (22.5 in) below the top of the tube sheet. The break assembly connects to the secondary at one location, 36.5 cm (14.4 in) above the top of the tube sheet on the cold leg side of the generator. For test S-SG-4, the break assembly was on the cold leg side of the primary. The break assembly consists of a break orifice and venturi flow meters to measure single phase break mass flow rate. The break orifice is an interchangeable symmetric conical flow tube as depicted in Figure 6. Figure 6 shows the dimensions for a 1-, 5-, and 10-tube break orifice. Test S-SG-4 used the 1-tube break orifice with a 0.079 cm (0.0308 in) ID. The flow tube was calibrated in single phase water and can be used to monitor break mass flow rate in both directions because of the symmetry of the flow tube.

Heat loss makeup in the Semiscale system is accomplished by using external heaters distributed fairly uniformly throughout the Semiscale system. These heaters are controlled by six separate power supplies including: vessel, hot legs, cold legs, intact loop pump suction, broken loop pump suction and pressurizer. The total power provided by these heaters is 44 kW. An additional 20 kW of heat loss makeup was provided by augmenting core power throughout the transient. Control of the heaters is as follows: If the maximum allowable temperature level [900 K (1160°F)] is reached on the inside surface of the pipe insulation, external power to that component is reduced by half. If the temperature trip limit continues to be exceeded, power to that component is terminated. Pressurizer external heaters were not used during S-SG-4. Power to the vessel upper head and upper plenum heater banks was terminated when the collapsed liquid level dropped to 20% full for the respective heater bank.

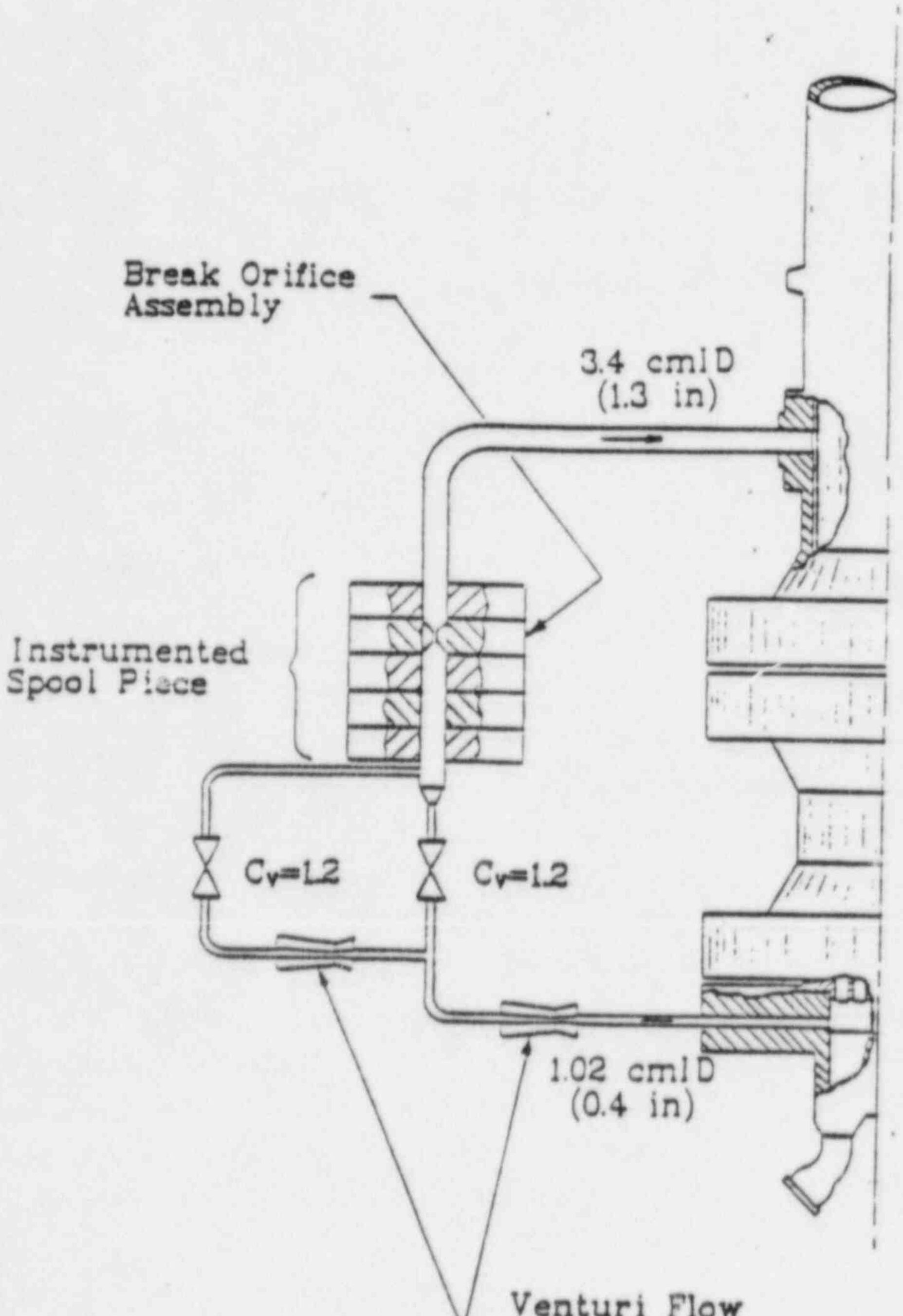
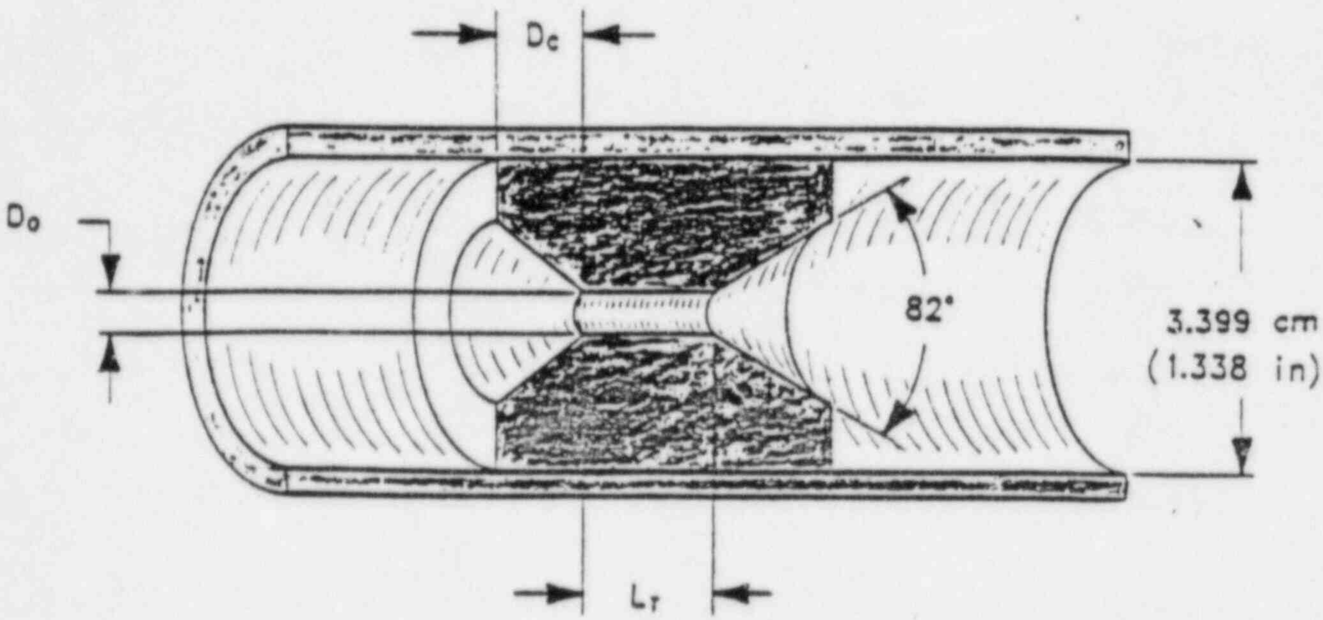


Figure 5. Semiscale tube-rupture break assembly.



TUBE RUPTURE	D_o		L_T		D_c	
	cm	in	cm	in	cm	in
1 TUBE	.079	.0308	.198	.078	1.473	.662
5 TUBE	.175	.0689	.439	.173	1.372	.709
10 TUBE	.249	.0975	.622	.245	1.270	.745

Figure 6. Semiscale conical break orifice.

2.2 Test Conduct

The system was filled with demineralized water and vented to ensure a liquid full system. Instrumentation was calibrated and zeroed as necessary. The system was heated to initial conditions using core power and forced flow with the primary coolant pumps running. Specified and measured initial conditions are listed in Table 1.

The test was initiated at t = 0 by opening a block valve in the break assembly allowing primary fluid to flow into the broken loop secondary. Table 2 contains a sequence of significant events for S-SG-4. The first 600 s involved automatically occurring events such as core scram, main steam isolation valve closure, auxiliary feedwater initiation and main feedwater termination. The initiating events for these actions were a low pressurizer pressure trip (13.1 MPa (1888 psig)) and SI signal (12.51 MPa (1803 psig)). The main coolant pump trip was delayed until 600 s after the tube rupture, followed by a 200-second period during which no operator action or automatic plant response occurred. Broken loop auxiliary feedwater was also terminated at 600 s. SI was used throughout the transient to maintain primary system inventory. Power to the pressurizer external heaters was terminated at t = 0. Power to the vessel upper head and upper plenum external heaters was terminated at t = 1140 s and t = 1250 s respectively, when the collapsed liquid level had dropped to 20% full for the respective heater bank.

The recovery procedure started at 800 s. This time period simulated the time required for operator identification of the tube rupture, plus 200 s for assessment of pump trip effects. Intact loop steam and feed using ADV operation and auxiliary feedwater began at 800 s. The ADV was operated to maintain a controlled 2.76 MPa/hr (400 psia/hr) secondary depressurization rate. By 6000 s the ADV was no longer able to maintain the specified depressurization rate and was latched open to produce the maximum cooling possible. Intact loop auxiliary feedwater was used throughout the steam and feed operation to maintain the secondary level. Pressurizer auxiliary spray was also initiated at 800 s in an attempt to reduce primary pressure and fill the pressurizer with liquid. The spray

TABLE 1. INITIAL CONDITIONS FOR TEST S-SG-4

	Specified	Measured
Primary cold leg flow rate (nominal)		
Broken loop	2.7 ℓ/s (43 gpm)	3.05 ℓ/s (48 gpm)
Intact loop	8.1 ℓ/s (128 gpm)	9.73 ℓ/s (154 gpm)
Pressurizer pressure	15.6 ± 0.14 (2250 ± 20 psig)	15.56 MPa (2244 psig)
Pressurizer liquid volume	0.0102 ± 0.0008 m^3 (0.36 ± 0.028 ft^3)	0.0098 m^3 (0.34 ft^3)
Core power	2.0 ± 0.01 MW	1.99 MW
Loop to loop cold leg fluid temperature differential	2.0 K (3.6°F)	1.4 K (2.5°F)
Core fluid temperature rise	37 ± 1.5 K (66.6 ± 3°F)	35.9 K (64.5°F)
Steam generator pressure		
Broken loop	5.55 ± 0.07 MPa (793 ± 10 psig)	5.52 MPa (788 psig)
Intact loop	5.55 ± 0.07 MPa (793 ± 10 psig)	5.43 MPa (775 psig)
Steam generator secondary fluid mass[a]		
Broken loop	100 + 40 - 20 kg (220 + 88 - 44 lbm)	83 kg[b] (183 lbm)
Intact loop	100 + 40 - 20 kg (220 + 88 - 44 lbm)	88 kg[b] (194 lbm)
Steam generator feedwater temperature	505 ± 3 K (450 ± 6°F)	504 K (447°F)
Primary leakage at t = 0	<0.006 kg/s (<0.0132 lbm/s)	0.0009 kg/s (0.002 lbm/s)

a. These values were determined from data acquisition system liquid levels following main steam isolation valve closure.

b. Measured with LIS+1117 + 51 for intact loop or LBS+1117 + 51 for broken loop.

TABLE 2. S-SG-4 SEQUENCE OF SIGNIFICANT EVENTS

Event	t (s)
Break flow initiated	0
PRZ internal heaters off	0
SCRAM, P_{PRZ} = 13.1 MPa (1888 psig)	141
MSIV closure (both loops)	141
Core Scram	141
SIS, P_{PRZ} = 12.51 MPa (1803 psig)	145
HPIS initiated (both loops)	145
Main feedwater secured (both loops)	145
Auxiliary feedwater started	
IL	145
BL	150
Main coolant pump trip	602
Auxiliary spray initiated	800
Intact loop steam and feed initiated	800
Auxiliary spray terminated	1280

	Time On (s)	Time Off (s)
SI Operation		1850
	2120	2520
	2680	2890
	3070	3280
	3480	3660
	5000	5740
	6180	6800
	7240	7830
	8270	8770
	9680	10,000

TABLE 2. (Continued)

	Time	
	On (s)	Off (s)
Pressurizer internal heater operation (BU and Var)	1280	1340
	3420	3540
	3700	5500
	5750	8960
	9050	9700
	10030	10,950

	Time	
	On (s)	Off (s)
Warm-up heater operation	8960	9040
Test termination 11,300 s		

consisted of 300 K (80°F) water injected into the top of the pressurizer at 13.75 g/s (0.029 lbm/s). At 1280 s the pressurizer was filled with liquid and auxiliary spray was terminated. Spray was not used again in this test.

Throughout the remainder of the test, SI was cycled to maintain a collapsed vessel level between 241 and 291 cm (95 and 115 in.) and a collapsed pressurizer level between 80 and 250 cm (31.5 and 98 in.). The first five SI cycles, listed in Table 2, were based on vessel level requirements and the last five were based on pressurizer level requirements.

The pressurizer back-up and variable heaters were operated six times between 1200 and 11,000 s, in an attempt to establish primary pressure control in the pressurizer and maintain primary pressure at 5.8 + 0, -0.07 MPa (829 + 0, -10 psig). The back-up and variable heaters were ineffective and the warm-up heaters were energized between 8960 and 9050 s. The back-up and variable heaters were then operated to maintain pressure for 600 s followed by a controlled primary depressurization, of 2.76 MPa/hr (400 psig/hr), for 1200 s. The test was terminated 11,300 s after the tube rupture.

3. RESULTS

This section discusses the overall thermal-hydraulic response of the Semiscale system during Test S-SG-4. Test S-SG-4 was a simulation of a double-ended offset-shear of one steam generator tube on the cold side of the steam generator near the tube sheet. The discussion is organized into the early response section (0 to 800 s) and the recovery section (800 to 11,300 s). The recovery section is divided into four areas: the overall system response to the combined operator actions, the effects of pressurizer auxiliary spray operation, the effects of intact loop steam and feed operation, and the combined effects of SI and pressurizer internal heater operation.

3.1 System Behavior--Tube Rupture Signature Early in Time with Delayed Pump Trip (0 to 600 s)

The occurrence of a one-tube rupture event during normal operation in a PWR has a very distinctive signature response as shown in the comparison of primary and secondary pressure in Figure 7. The tube rupture, occurring in the broken loop steam generator, initiated the transient at 0 s. Primary fluid originally at 15.56 MPa (2256 psia) flowed through the conical flow tube break orifice into the broken loop steam generator originally at 5.52 MPa (800 psia). The loss of mass from the primary loop caused a fairly steady primary depressurization until the low pressurizer pressure setpoint of 13.1 MPa (1900 psia) was achieved at about 141 s. Prior to achieving the low pressurizer pressure trip, both the broken and intact loop steam generator pressures remained fairly constant as core power was removed via normal secondary steaming conditions with the primary loop pumps running (see Figure 8). The energy addition to the broken loop secondary from break flow was small enough to cause a negligible pressure rise during this period.

At the pressurizer low pressure trip point, two prominent events occurred which greatly affected the depressurization rate: the core power was scrammed to the ANS decay power curve and the main steam isolation valves were closed on the steam generators. Upon MSIV closure, the heat

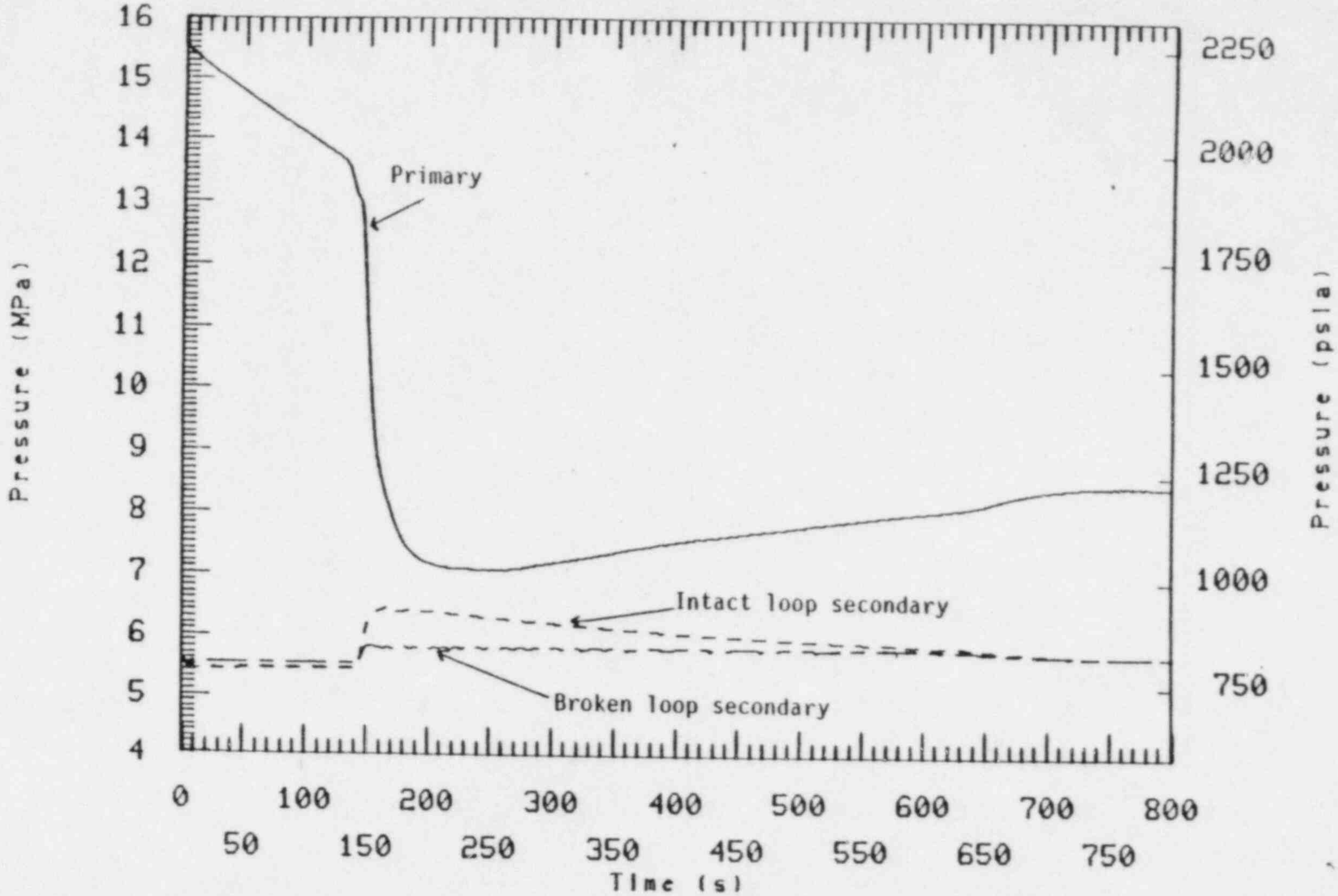


Figure 7. Comparison of primary and secondary pressure during a cold side one tube rupture transient (S-SG-4).

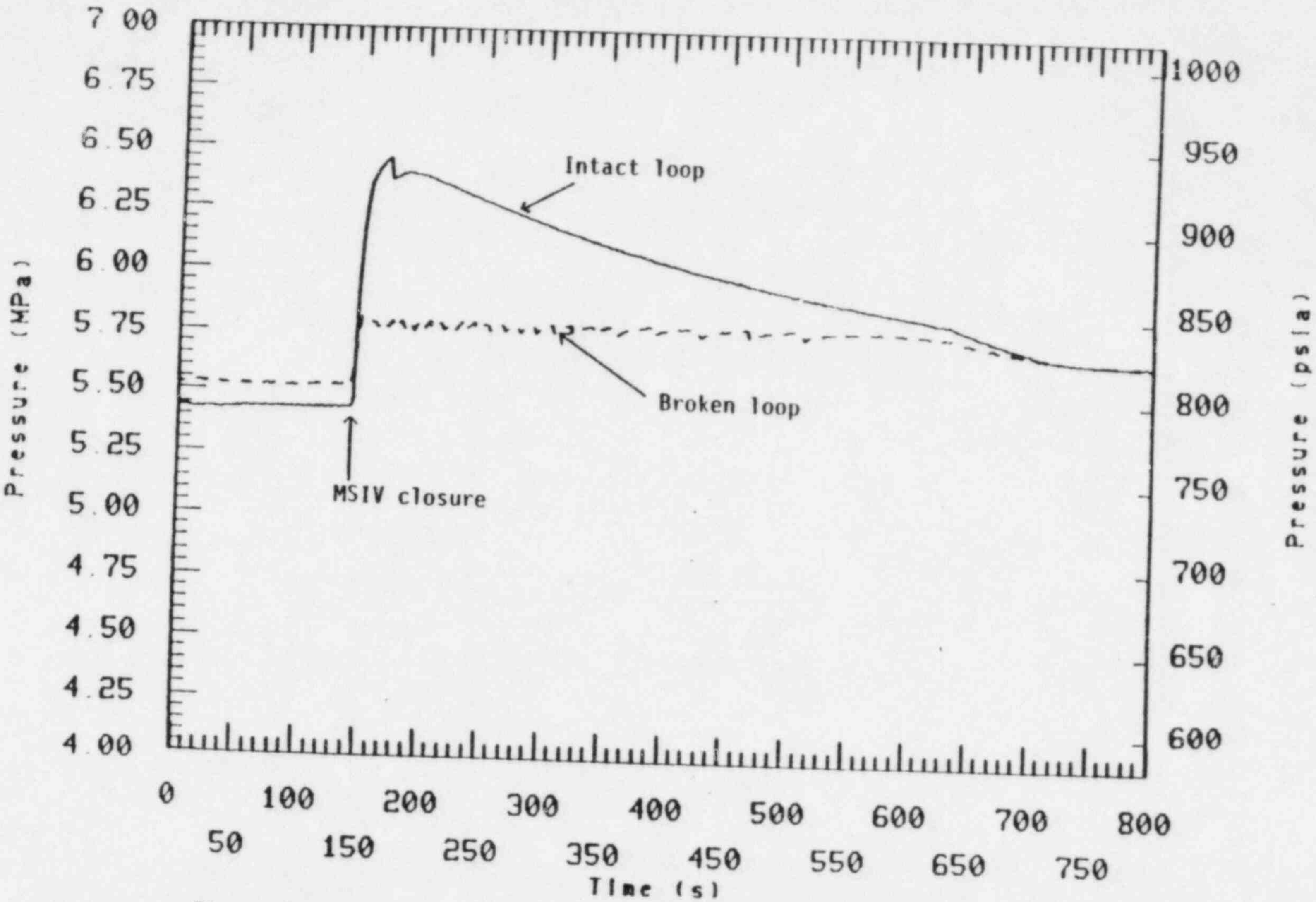


Figure 8. Comparison of broken loop and intact loop secondary pressure during a cold side, one-tube rupture transient (S-SG-4).

transfer to both the broken and intact loop steam generator secondaries caused a rapid pressurization of the secondaries as shown in Figure 8. The secondary pressure in the intact loop steam generator achieved the ADV setpoint of 6.55 MPa (950 psia) cycling the ADV twice. The broken loop secondary pressure achieved the ADV setpoint of 5.85 MPa (848 psia) initiating the ADV cycling. The ADV cycled 23 times as significant heat was being transferred from the primary.

Following the core scram at 13.1 MPa (1900 psia), the system pressure showed an increased depressurization rate as the system liquid shrunk due to primary to secondary heat transfer (see Figure 7). The safety injection signal was achieved at 12.51 MPa (1814 psia): and terminated power to the primary coolant pumps, started SI flow, terminated main feedwater and started auxiliary feedwater to the secondaries. No major change in depressurization rate occurred from these events as their effects were overshadowed by core scram. Eventually, the primary system depressurization was sufficient for the hot leg fluid to reach a saturation condition at about 180 s (Figure 9).

Primary pressure remained above both secondary system pressures for the entire 600 s period, causing a primary-to-broken loop secondary mass flow, as shown in Figure 10. As long as break flow exceeded total SI flow primary system mass inventory depleted. Figure 11 shows the pressurizer collapsed liquid level essentially depleted after the initial 120 s. By 155 s SI flow exceeded break flow and the primary inventory started to recover. SI flow filled the primary system voids and by 400 s was reestablishing a level in the pressurizer. Filling of the pressurizer with liquid compressed the steam space resulting in a gradual, pressure rise in the primary system. The pressure increase produced the subcooled hot leg conditions illustrated in Figure 9.

Prior to the primary pump coastdown, at approximately 650 s, there was no precise level measurement in the vessel, downcomer, or primary U-tubes. During pump operation the differential pressure measurements were influenced by frictional pressure drops and velocity effects. The pumps were tripped at 600 s and typical natural circulation flow[4] was then

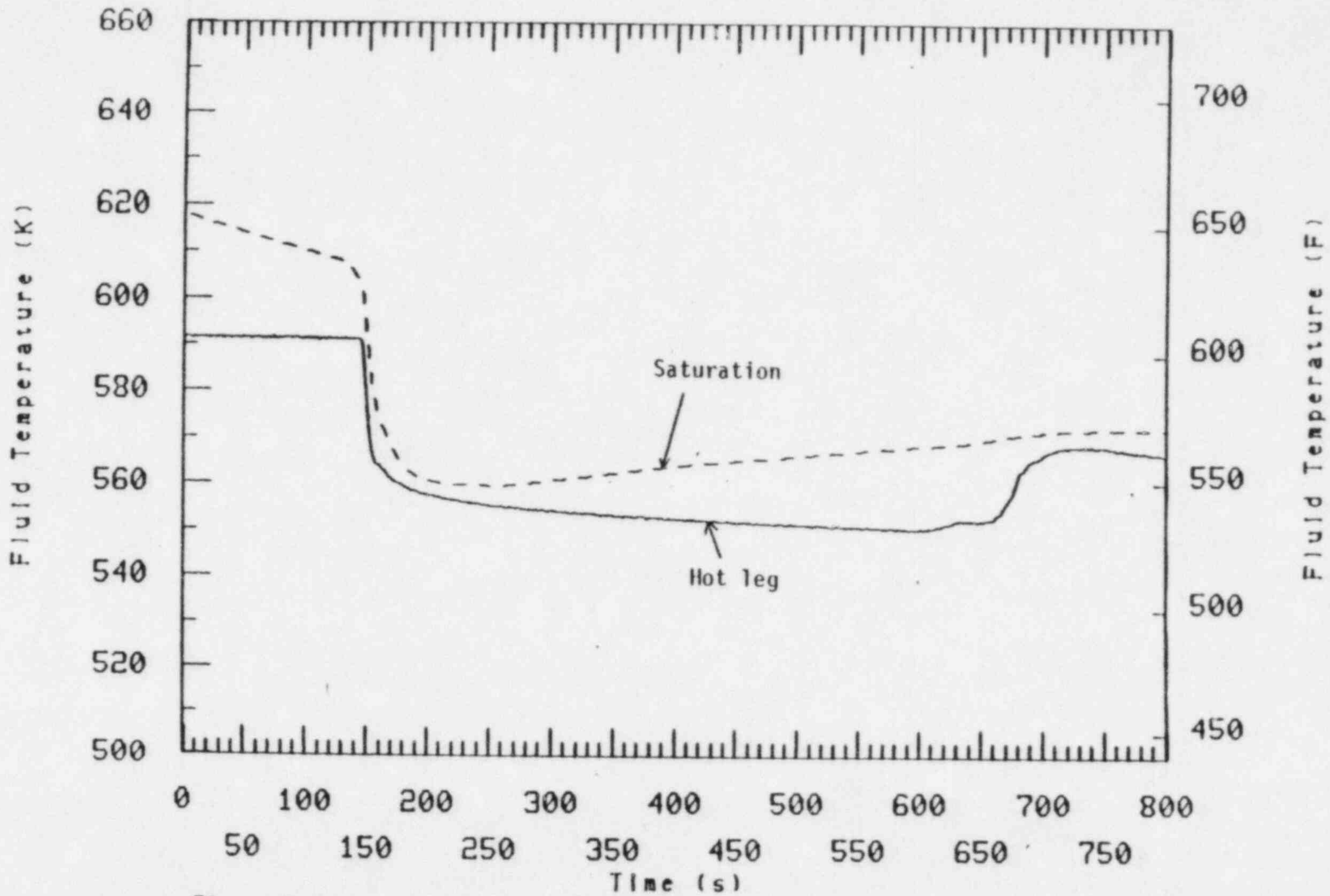


Figure 9. Comparison of fluid temperature and saturation temperature for a cold side, one-tube rupture transient (S-SG-4).

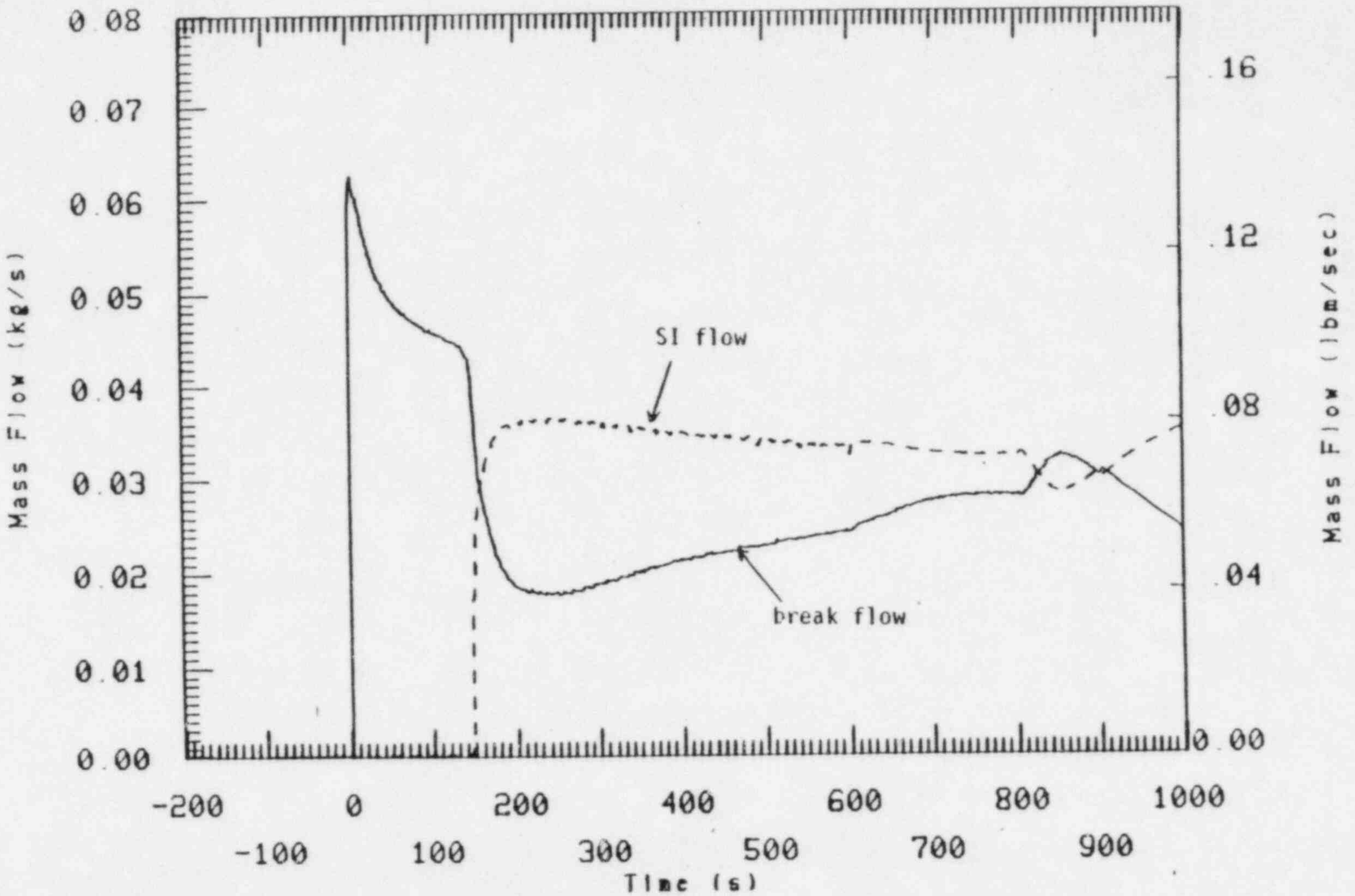


Figure 10. Comparison of break flow and SI flow during a cold side, one-tube rupture transient (S-SG-4).

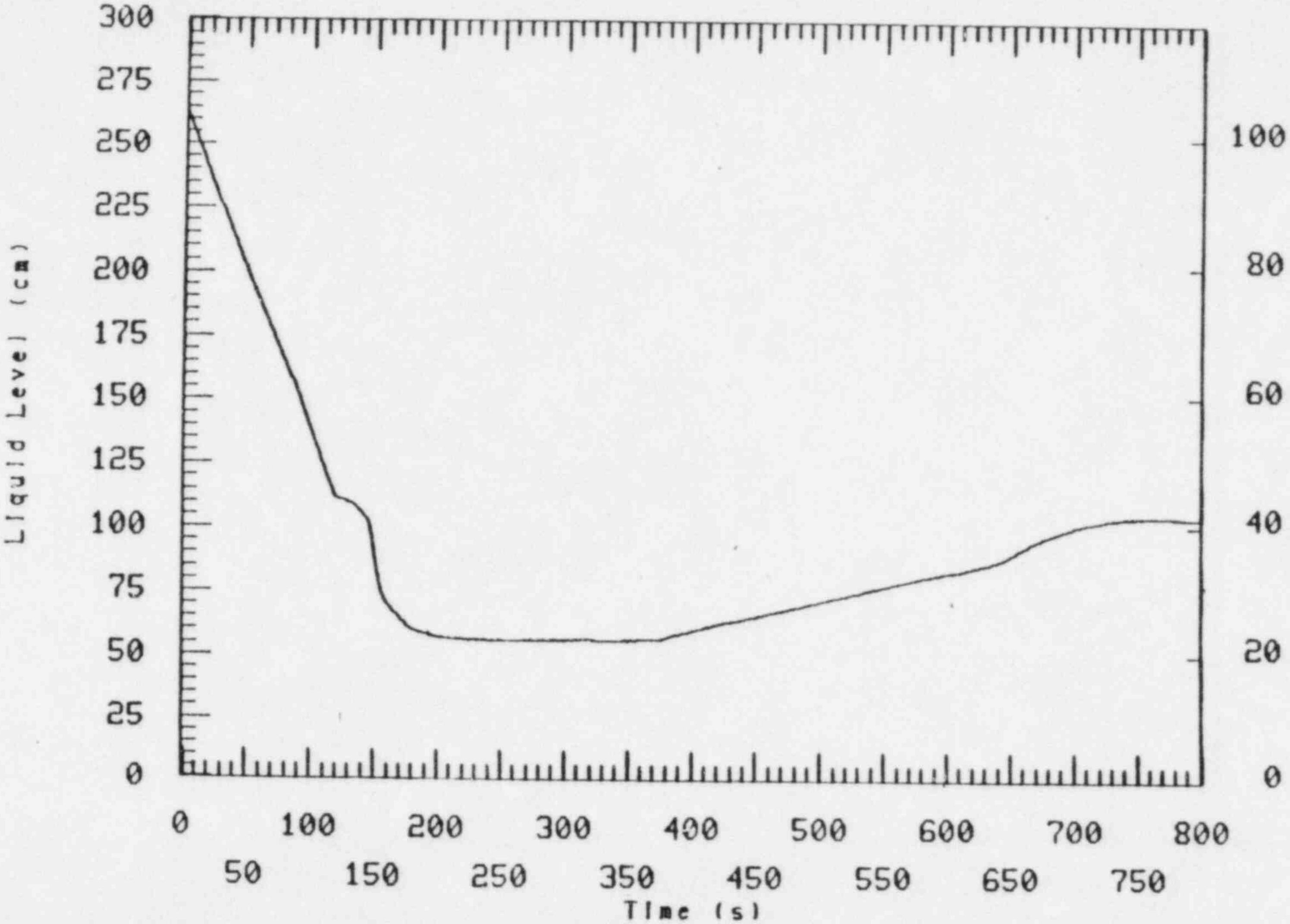


Figure 11. Pressurizer collapsed liquid level during a cold side, one-tube rupture transient (S-SG-4).

established as shown in Figure 12. At this time there was very little voiding in the vessel upper head, Figure 13, and the primary U-tubes remained full of liquid. Upon pump trip, the hot leg fluid again saturated, primary flow momentarily stopped, and primary to secondary heat transfer was minimized. The resulting steam production in the vessel caused a slight pressure rise in the primary system. The pressure then stabilized as natural circulation flow was established, effectively removing core decay heat.

During the initial 600 s, the steam generator collapsed liquid level was affected by ADV flow and auxiliary feed flow in the intact loop; and break flow, ADV flow, and auxiliary feed flow in the broken loop. Figure 14 shows the collapsed liquid level in both the intact and broken loop secondaries. Following main steam isolation valve closure, the liquid level settled to a pool-type condition of about 800 cm (315 in.) in the intact loop steam generator and about 950 cm (374 in.) in the broken loop steam generator. The broken loop steam generator collapsed liquid level continued to increase until about 600 s. Figure 15 shows that the break flow dominated the broken loop mass balance. There was a slight increase in intact loop steam generator liquid level during the initial 600 s period (Figure 14) as auxiliary feed flow added mass with little depletion due to ADV operation (see Figure 16).

A number of comparisons can be made between tests S-SG-4 and S-SG-8,[5] which also was a one-tube, cold side break test. The only difference in the first 600 s of these tests was a change in the timing of main coolant pump trip. In S-SG-8 the pumps were tripped at SIS, which occurred 154 s after the tube rupture. In S-SG-4 the pumps were tripped 600 s after the tube rupture. Figure 17 shows the primary pressures for the two tests. The pressures follow the same trend until the pumps are tripped in S-SG-8 at 154 s. At this time, in S-SG-8, primary to secondary heat transfer is minimized, steam is produced in the vessel, and the primary pressure recovers. The pressure then drops slowly as natural circulation removes core decay heat. In S-SG-4 the pressure drops about 1.8 MPa (260 psia) lower than in S-SG-8 and slowly recovers as SI compresses the primary system. This lower pressure is produced by a

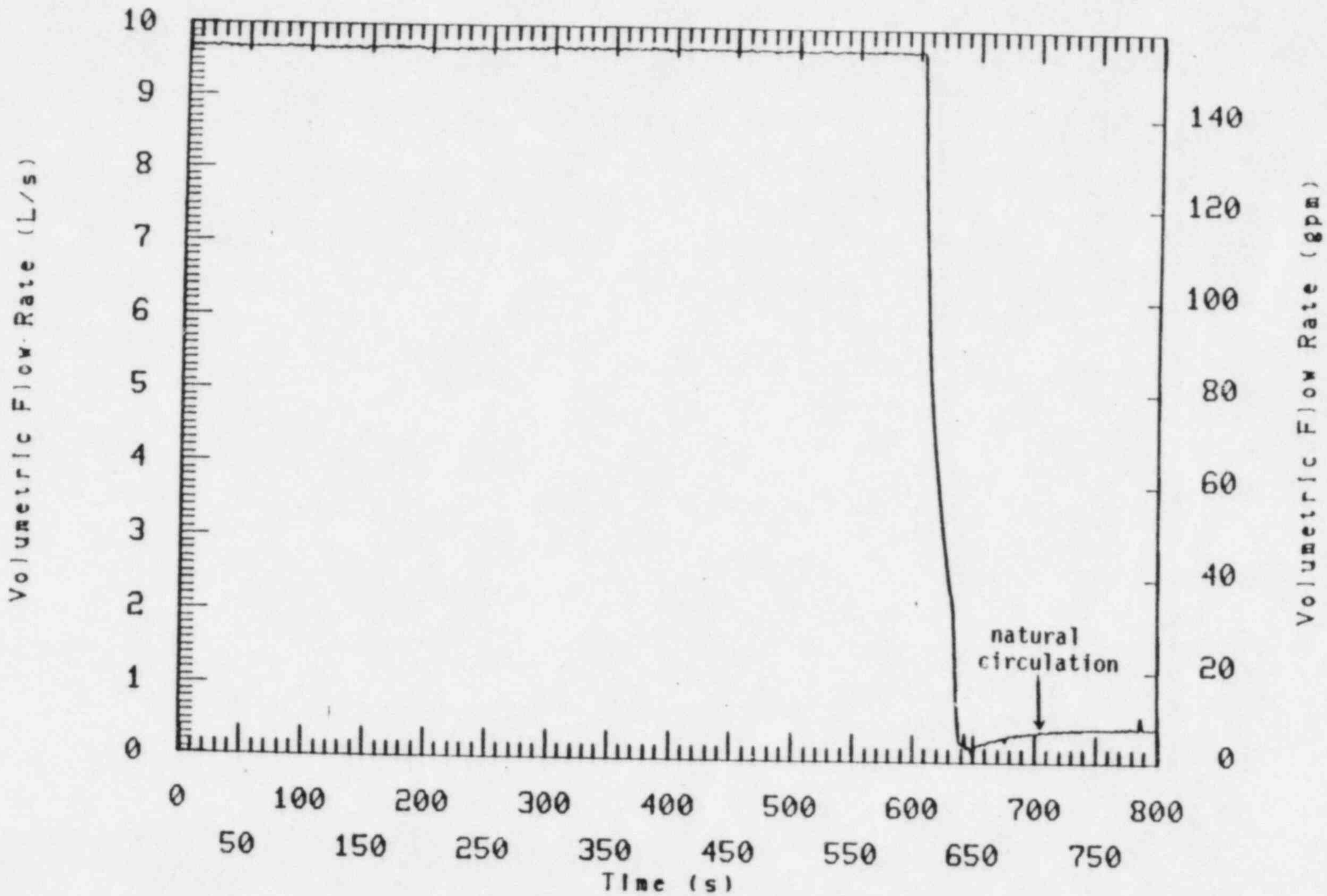


Figure 12. Change to natural circulation in the intact loop during a cold side, one-tube rupture transient (S-SG-4).

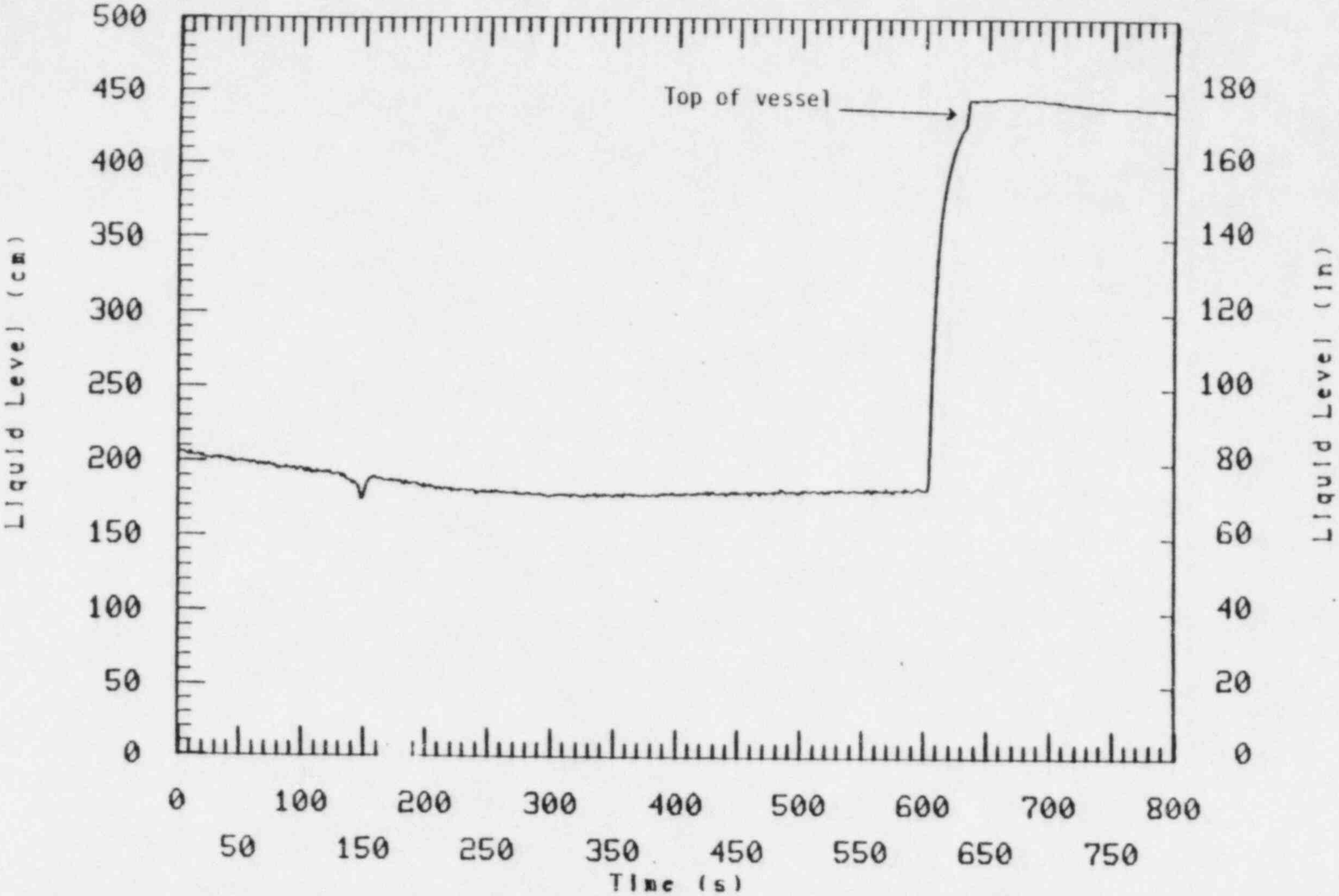


Figure 13. Vessel collapsed liquid level during a cold side, one-tube rupture transient (S-SG-4).

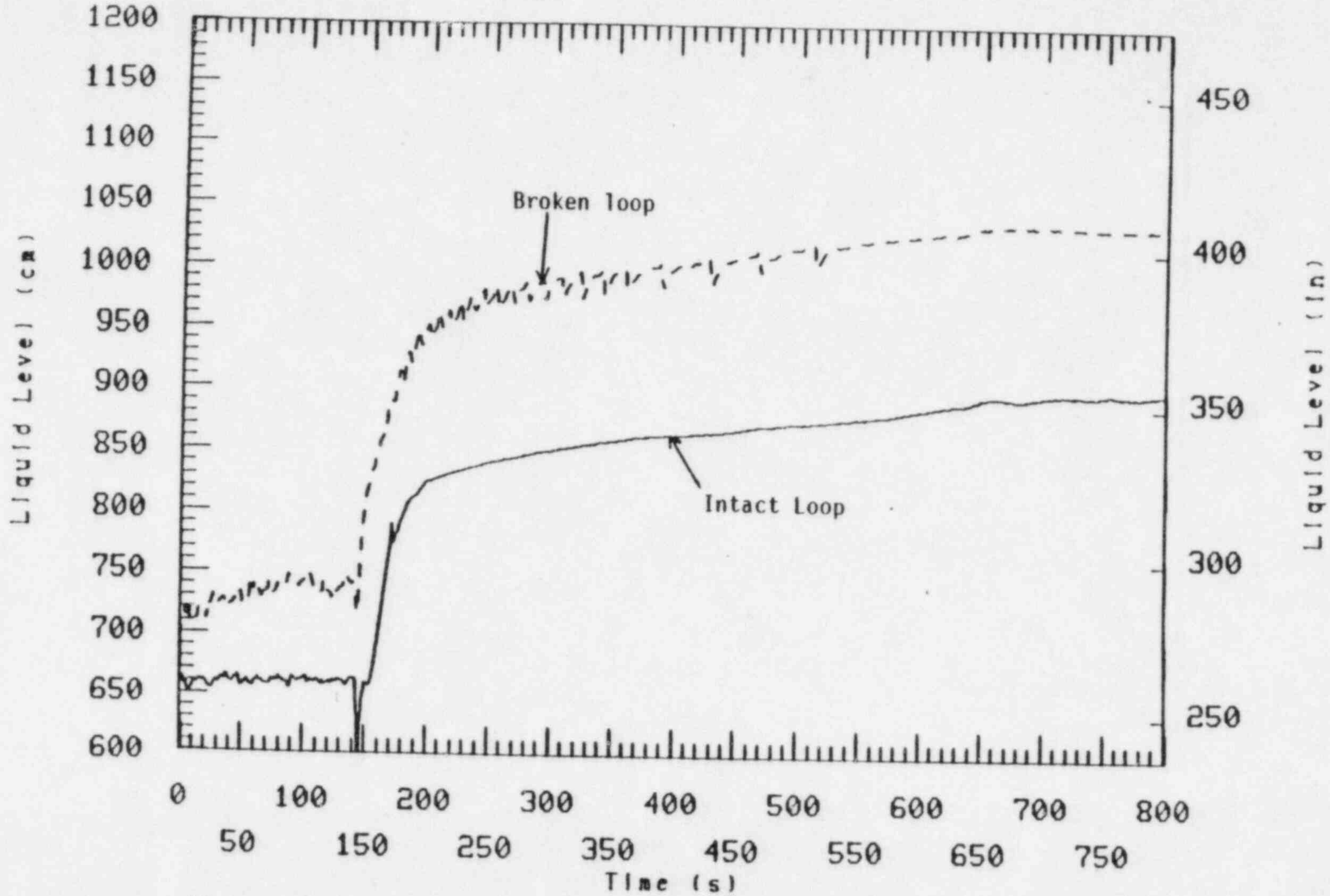


Figure 14. Collapsed liquid level in the broken and intact loop secondary during a cold side, one-tube rupture transient (S-SG-4).

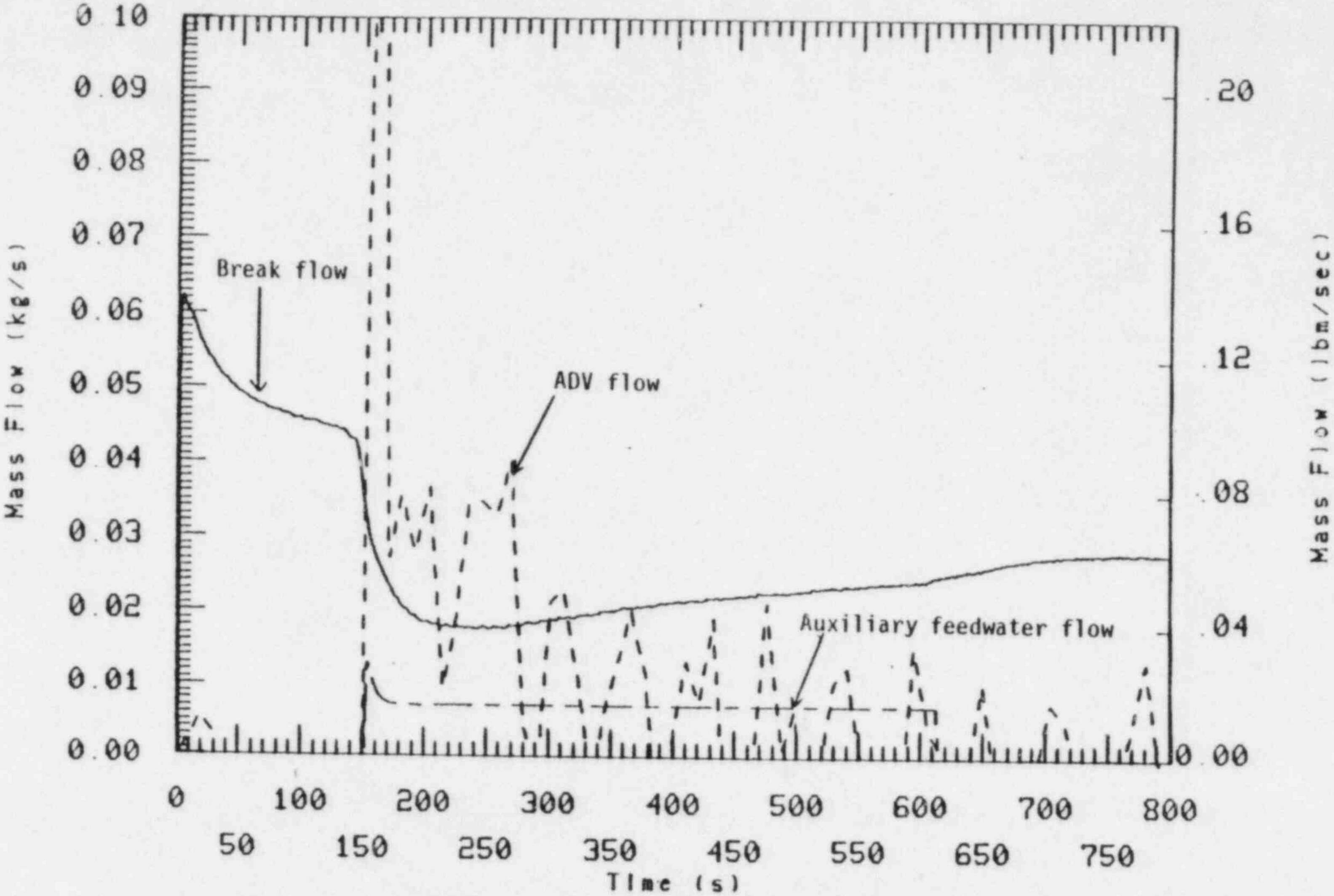


Figure 15. Comparison of break flow, ADV flow, and auxiliary feed flow in the broken loop steam generator during a cold side, one-tube rupture transient (S-SG-4).

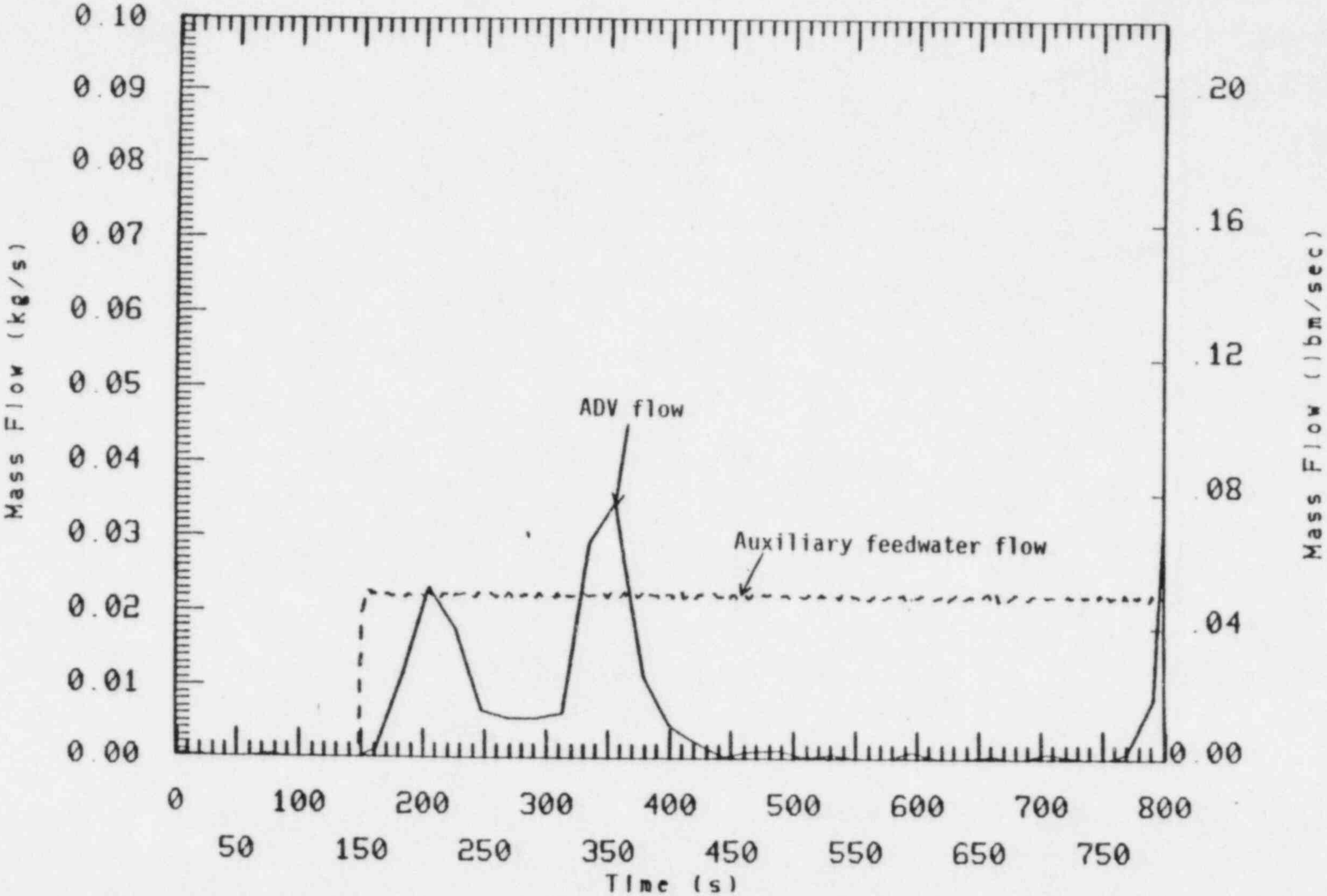


Figure 16. Comparison of auxiliary feed and ADV flow in the intact loop secondary during a cold side, one-tube rupture transient (S-SG-4).

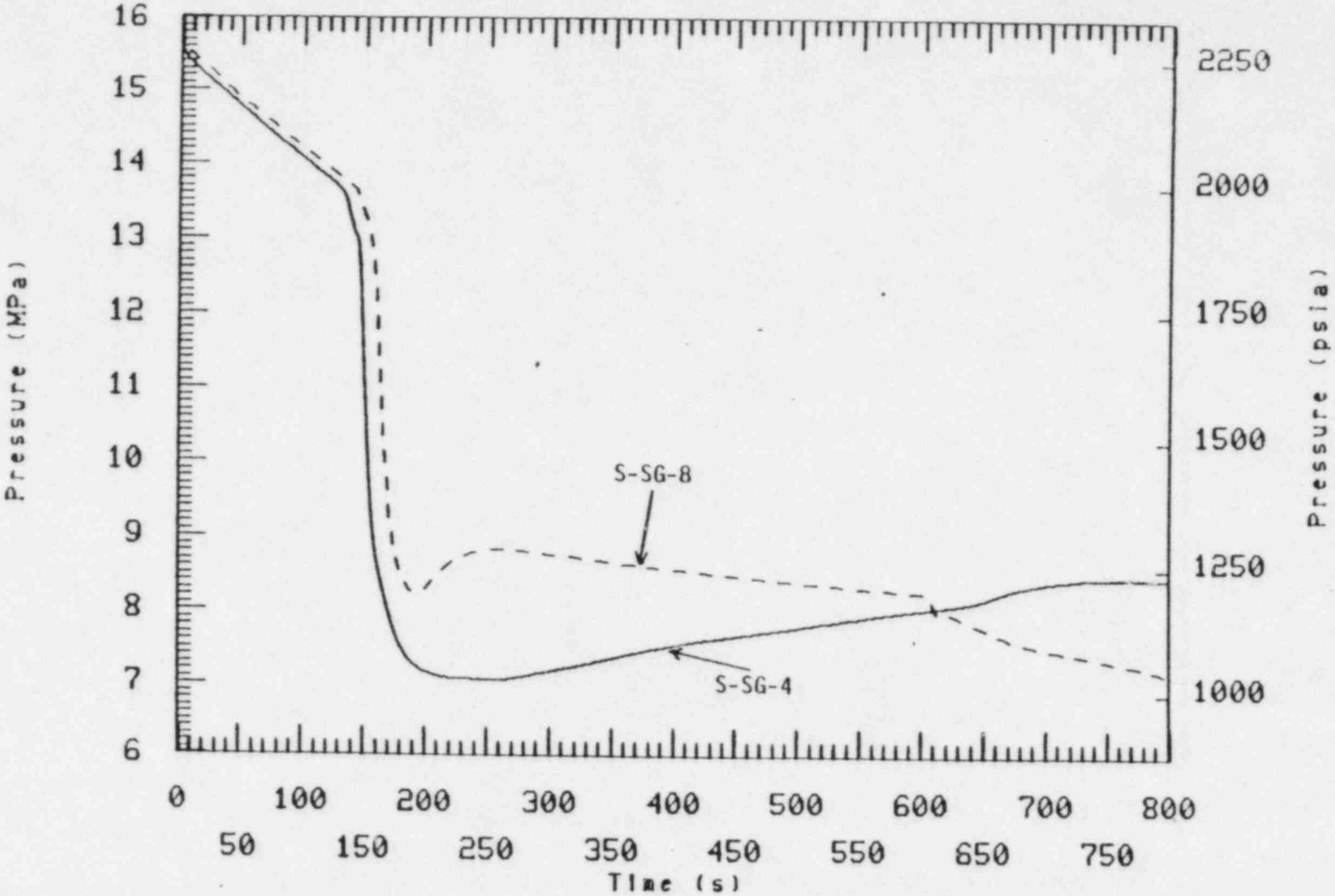


Figure 17. Comparison of primary pressure for early pump trip (S-SG-8) and delayed pump trip (S-SG-4) during a cold side, one-tube rupture transient.

significantly higher heat transfer rate from primary to secondary in the broken loop steam generator during S-SG-4, Figure 18. Pump flow rates greatly exceeded natural circulation flow rates and produced much higher convective heat transfer coefficients in S-SG-4. This resulted in greater secondary energy removal, lower primary system fluid temperatures, and corresponding lower primary pressure.

The pressurizer empties at the same rate in both tests as shown in Figure 19. However, the level recovers early in S-SG-4 while the pressurizer remained empty through 600 s in S-SG-8. This level recovery is a result of SI flow exceeding break flow much earlier in S-SG-4. Pump operation enhanced primary to secondary heat transfer producing a lower primary pressure, as described above, which resulted in reduced break flow and increased SI flow. This combination produced much less severe primary fluid conditions in S-SG-4 than S-SG-8.

Figure 20 shows a comparison of secondary pressures for S-SG-4 and S-SG-8. The intact loop secondary pressure falls significantly lower in S-SG-4 than in S-SG-8. This results from a much lower primary to secondary heat transfer in the intact loop in S-SG-4, as shown in Figure 21. The reduced primary to secondary heat transfer is the result of a much smaller primary to secondary temperature difference in S-SG-4, Figure 22. The primary pressure and temperature fell to a point very close to the intact loop secondary and therefore only minimal energy was transferred. Conversely, the broken loop secondary pressure remained much higher in S-SG-4 than S-SG-8. The broken loop secondary pressure, in S-SG-4, rose to the ADV setpoint upon MSIV closure and stabilized there as the ADV frequently cycled controlling the secondary pressure. The higher secondary pressure and ADV cycling reflected the much higher primary to secondary heat transfer rate in the broken loop in S-SG-4 as was shown in Figure 18.

The different behavior of the intact and broken loop steam generators in S-SG-4 resulted form the different ADV setpoints. The intact loop

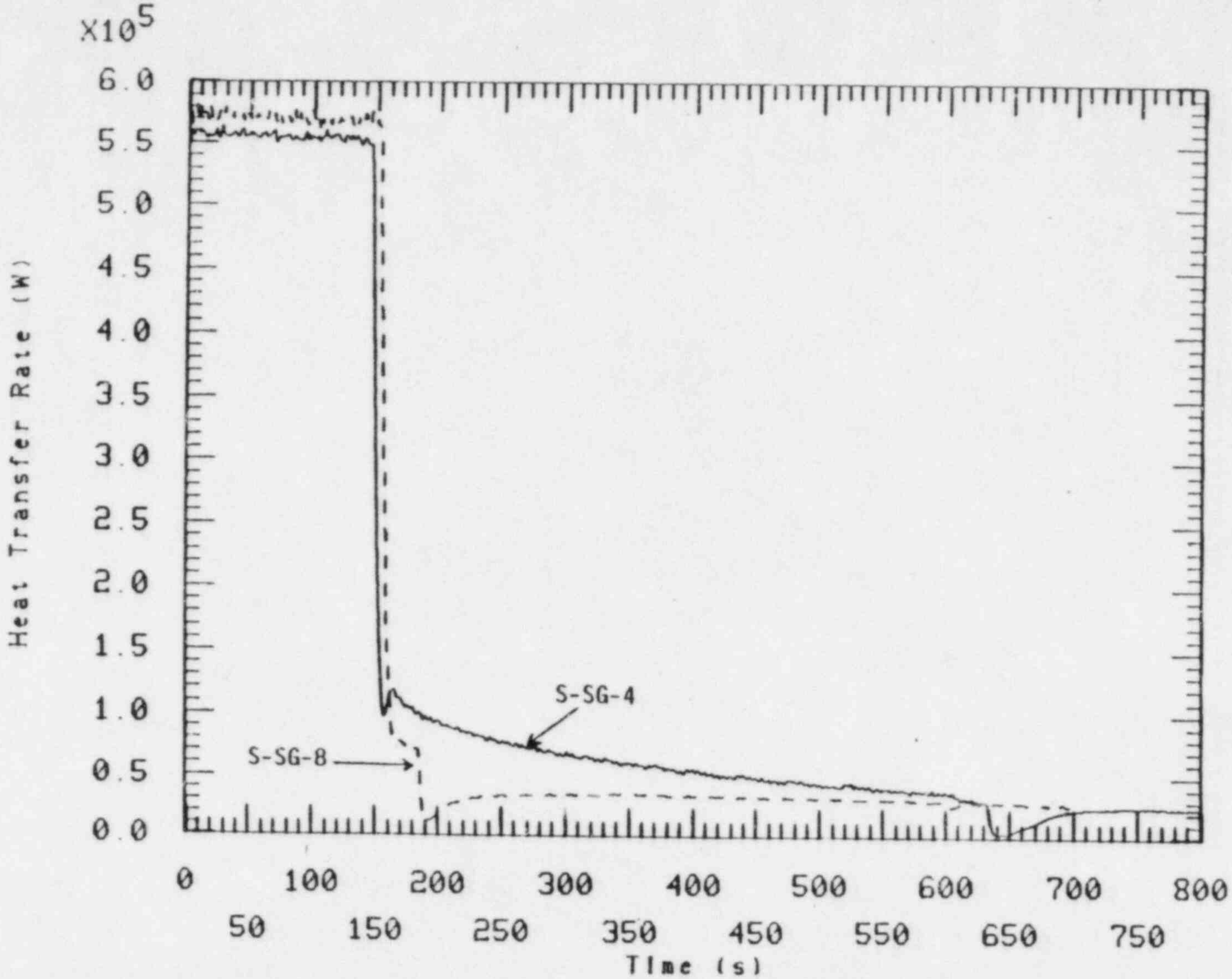


Figure 18. Comparison of primary to secondary heat transfer in the broken loop steam generator for early pump trip (S-SG-8) and delayed pump trip (S-SG-4) during a cold side, one-tube rupture transient.

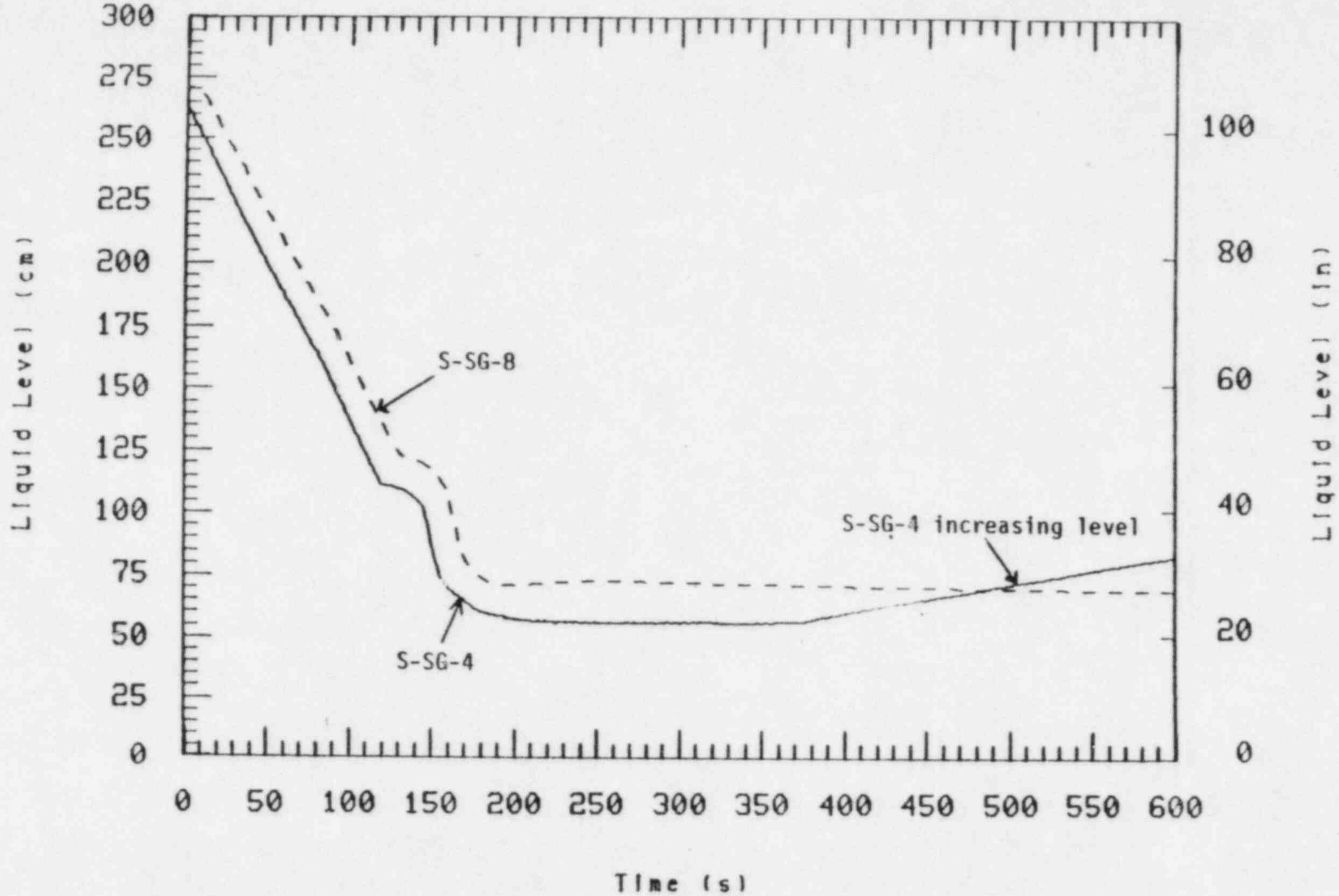


Figure 19. Comparison of pressurizer collapsed liquid level for early pump trip (S-SG-8) and delayed pump trip (S-SG-8) during a cold side, one-tube rupture transient.

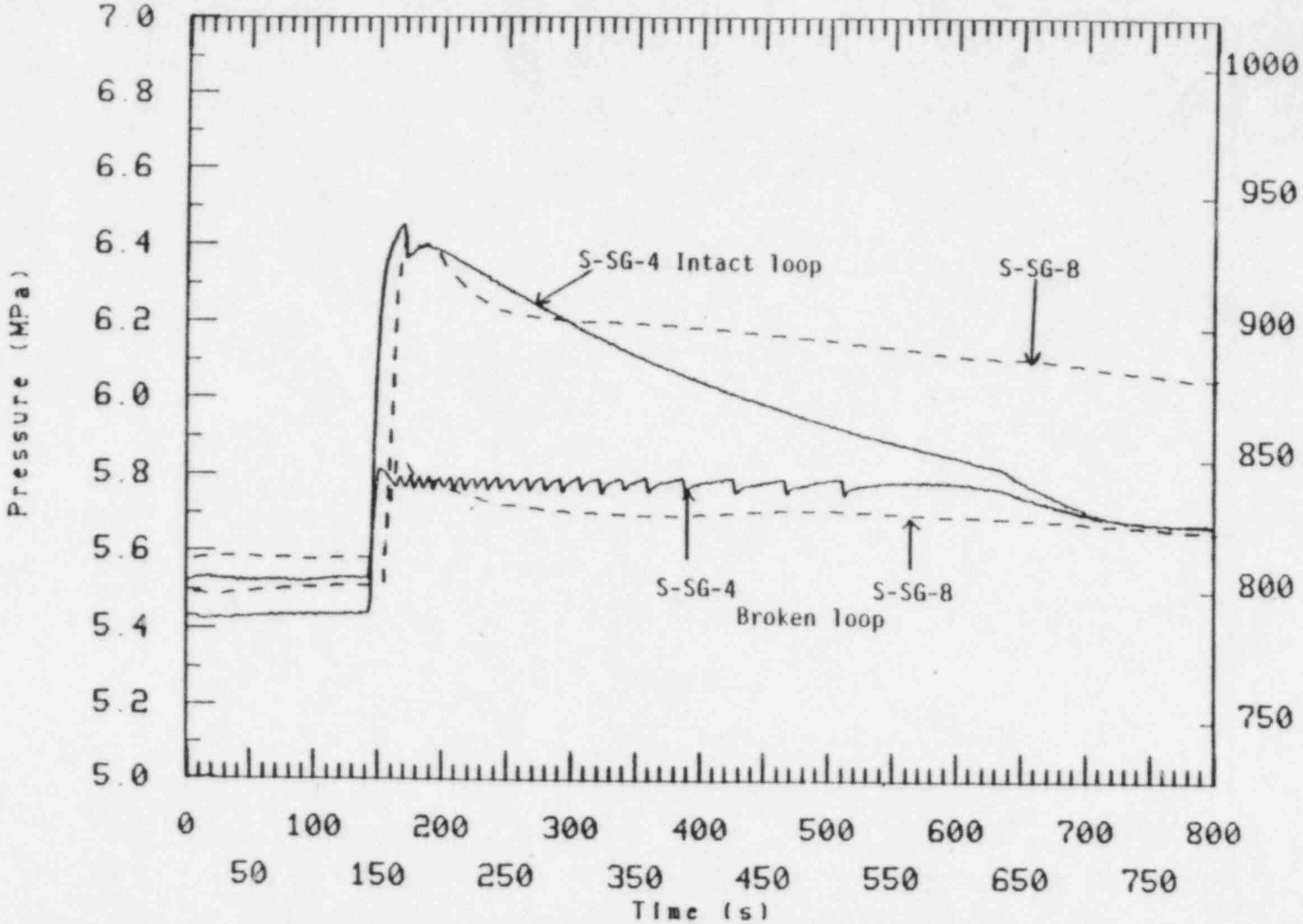


Figure 20. Comparison of intact loop and broken loop secondary pressures for early pump trip (S-SG-8) and delayed pump trip (S-SG-4) during a cold side, one-tube rupture transient.

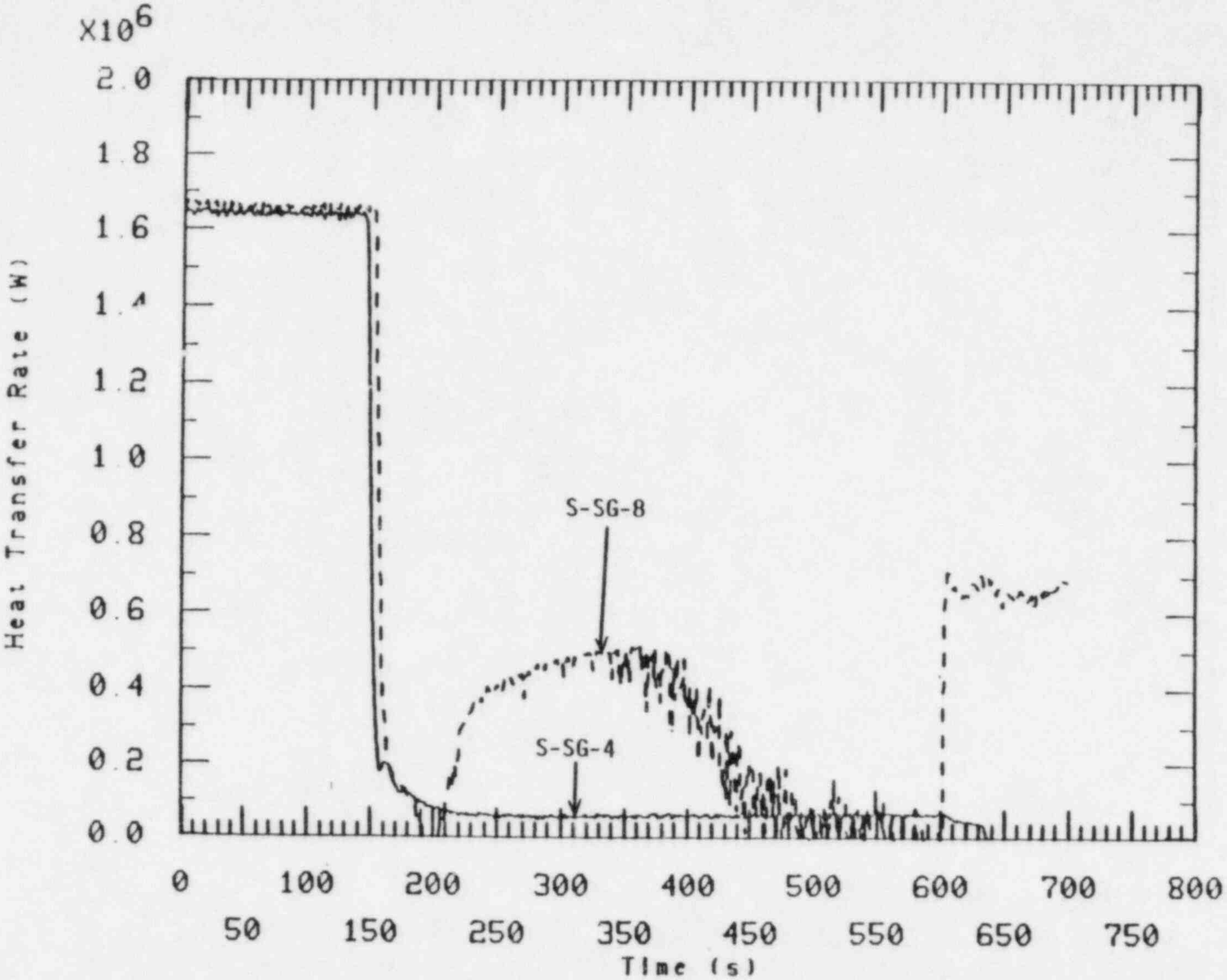


Figure 21. Comparison of primary to secondary heat transfer in the intact loop steam generator for early pump trip (S-SG-8) and delayed pump trip (S-SG-4) during a cold side, one-tube rupture transient.

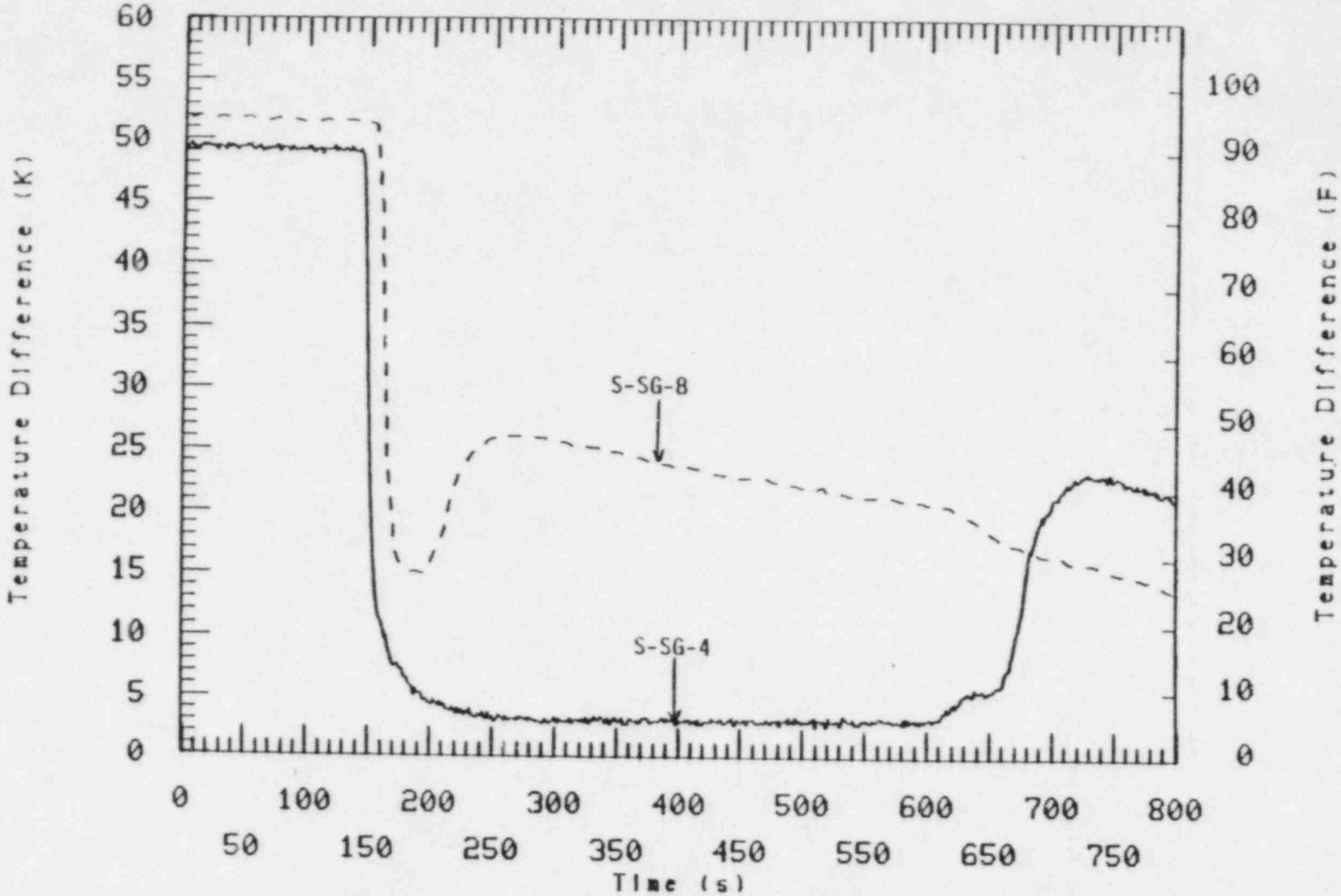


Figure 22. Comparison of intact loop primary to secondary temperature difference for early pump trip (S-SG-8) and delayed pump trip (S-SG-4) during a cold side, one-tube rupture transient.

setpoint was 6.55 MPa (950 psia)[a] which was just below the minimum pressure reached in the first 600 s. The primary and secondary fluids were at about the same temperature and therefore only a small amount of energy was transferred in the intact loop steam generator. The broken loop ADV setpoint was 5.85 MPa (848 psia). The broken loop secondary, at saturated fluid conditions, was approximately 20 K (36°F) below the primary fluid temperature. This temperature difference resulted in considerable primary to secondary heat transfer, in the broken loop, while the pumps operated.

The overall result of the delayed pump trip was to produce a less severe primary fluid condition during the diagnostic stage of the transient. The vessel level was higher and a pressurizer level had been restored. The primary fluid was cooler and less primary fluid had escaped througn the tube rupture. The broken loop ADV, however, passed much more fluid to the atmosphere. The difference in secondary behaviors was a result of a Semiscale scaling distortion in that the intact and broken loop secondaries had different ADV setpoints.

3.2 Recovery Phase Signature

The system recovery in S-SG-4 involved pressurizer auxiliary spray, intact loop steam and feed, SI cycling, and pressurizer internal heater operation. Recovery in this case meant the establishment of primary pressure control in the pressurizer and a controlled primary depressurization of 2.76 MPa/hr (400 psia/hr) for 1200 s.

Recovery commenced at 800 s with the simultaneous operation of pressurizer auxiliary spray and intact loop steam and feed. Spray operation was terminated at 1280 s, when the pressurizer became liquid solid. Intact loop steam and feed continued until test termination at 11,300 s. SI was used as needed throughout the recovery to maintain

a. The ADV setpoints and their scaling criteria are discussed in Appendix A of Reference 1.

primary system inventory. The pressurizer internal heaters were used intermittently from 1200 s until test termination in an attempt to control primary pressure.

3.2.1 Overall System Response to the Combined Recovery Methods (800-11,300 s)

The overall response to the combined recovery methods was a rapid depressurization, resulting from auxiliary spray operation, followed by a gradual pressure drop as environmental heat loss and intact loop steam and feed subcooled the primary system (Figure 23). SI cycling was characterized by periodic increases in the vessel or pressurizer levels, shown in Figure 24,[a] as well as small primary pressure increases resulting from compression of the primary system. The intact loop steam and feed operation reduced the secondary pressure at the specified rate until 6000 s when the ADV was latched open to achieve maximum cooldown (Figure 25). The intact loop secondary inventory showed a general decline as auxiliary feedwater could not balance the steaming rate as shown in Figure 26. The broken loop pressure dropped (Figure 25) due to environmental heat loss, and an ADV leak, until about 8500 s when the secondary filling started compression of the steam space (Figure 26). SI operation compressed the secondary until liquid solid, raising the pressure to the ADV setpoint. The ADV cycled until SI was terminated, followed by a gradual decline in the secondary pressure. Pressurizer back-up and variable heaters were ineffective in controlling primary pressure until the broken loop secondary filled reducing break flow. The warm-up heaters cycled once between 8960 and 9040 s, and were effective in controlling primary pressure.

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a. Pressurizer zero level is referenced to the bottom of the pressurizer vessel. Vessel zero level is referenced to the cold leg centerline.

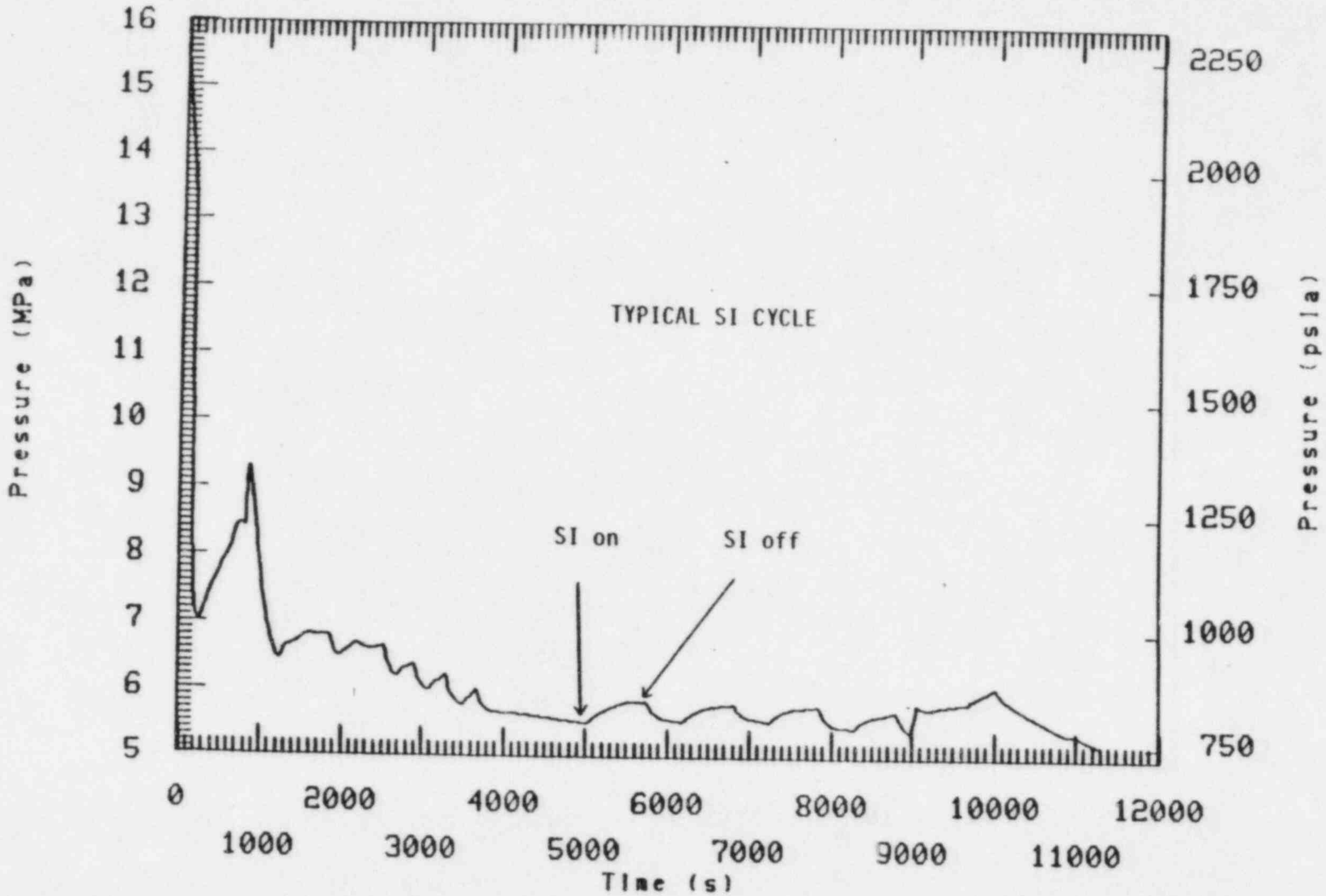

Figure 23. Primary pressure during a cold side, one-tube rupture transient (S-SG-4).

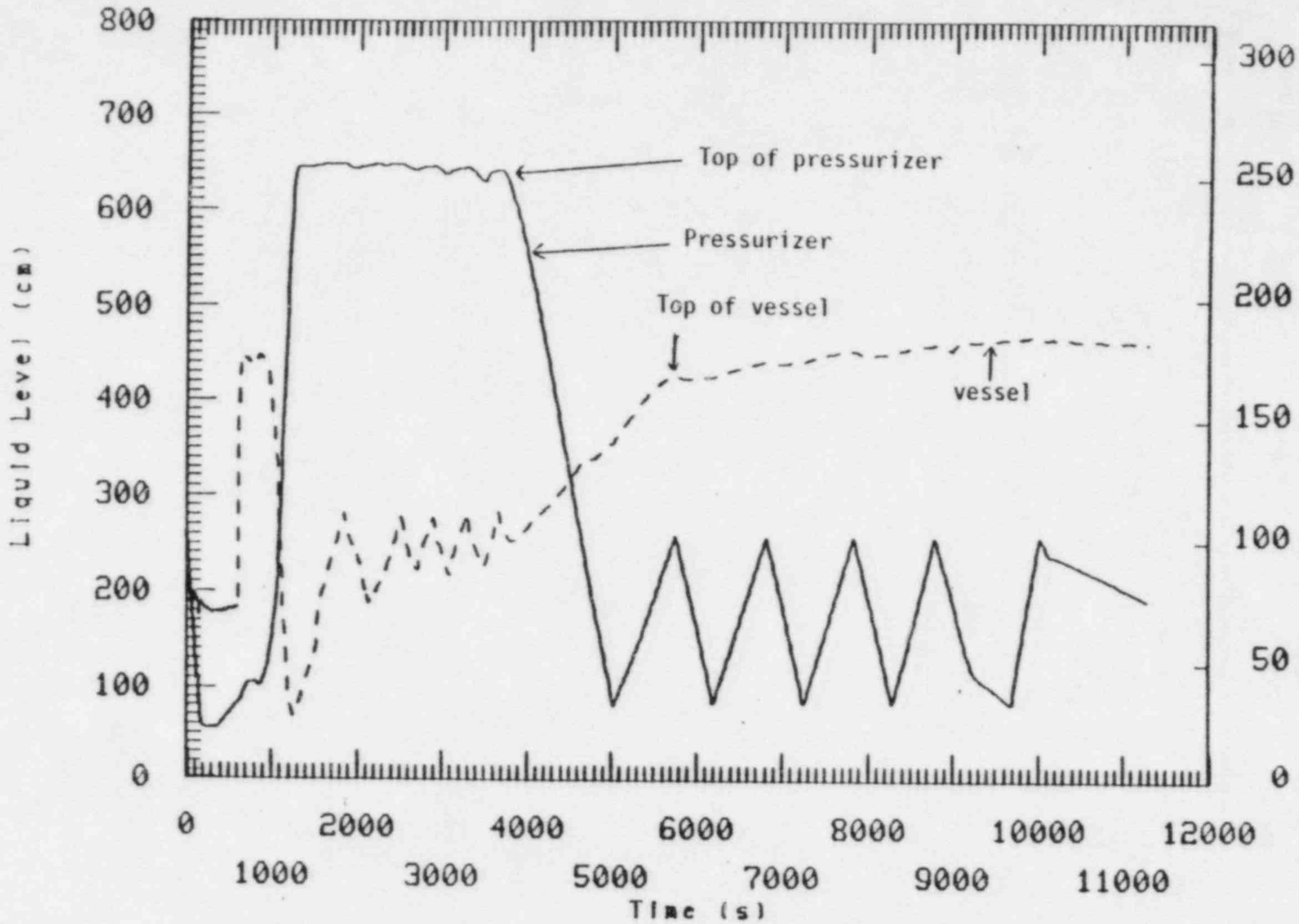

Figure 24. Pressurizer and vessel collapsed liquid level during a cold side, one-tube rupture transient (S-SG-4).

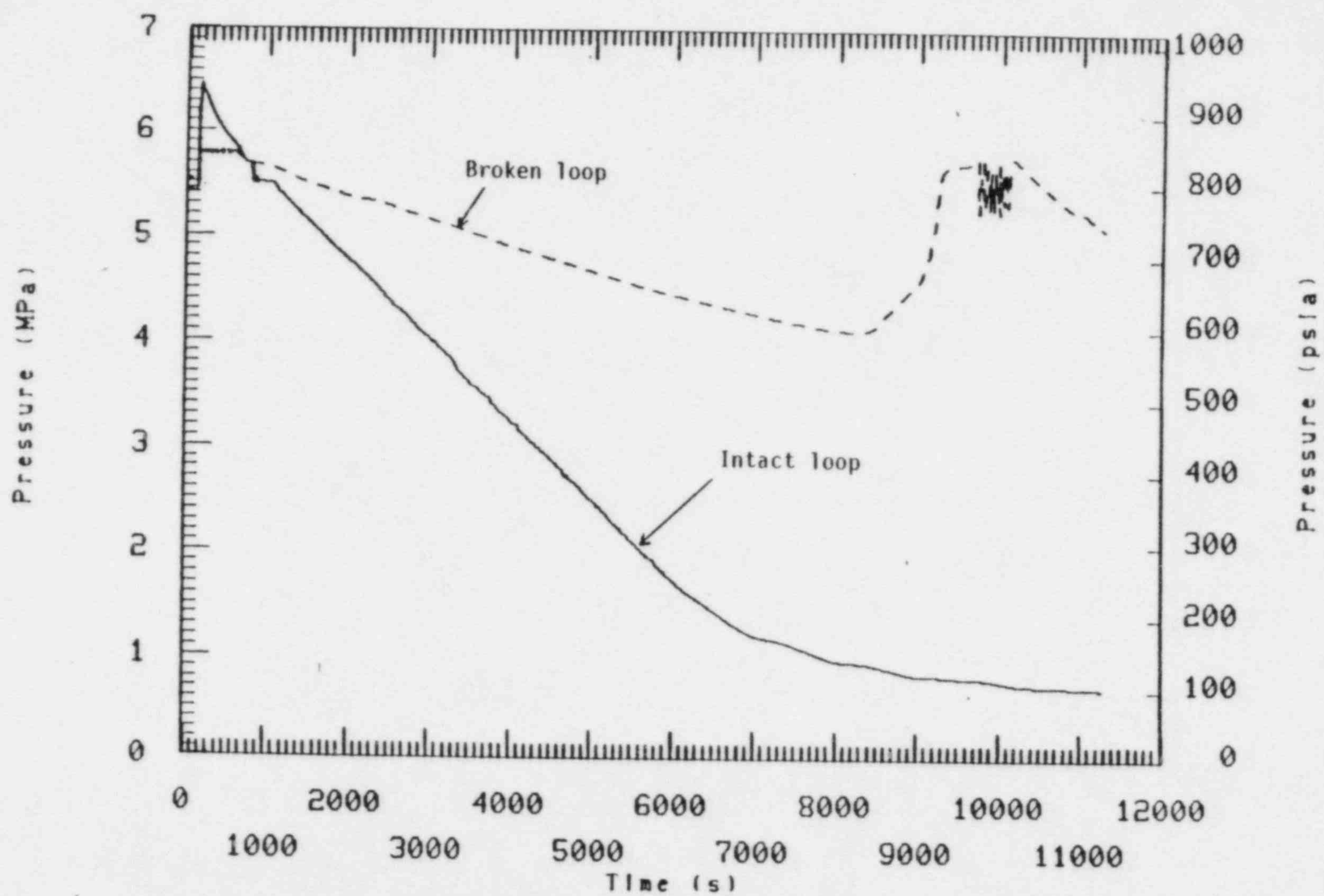

Figure 25. Comparison of intact and broken loop steam generator secondary pressures during a cold side, one-tube rupture transient (S-SG-4).

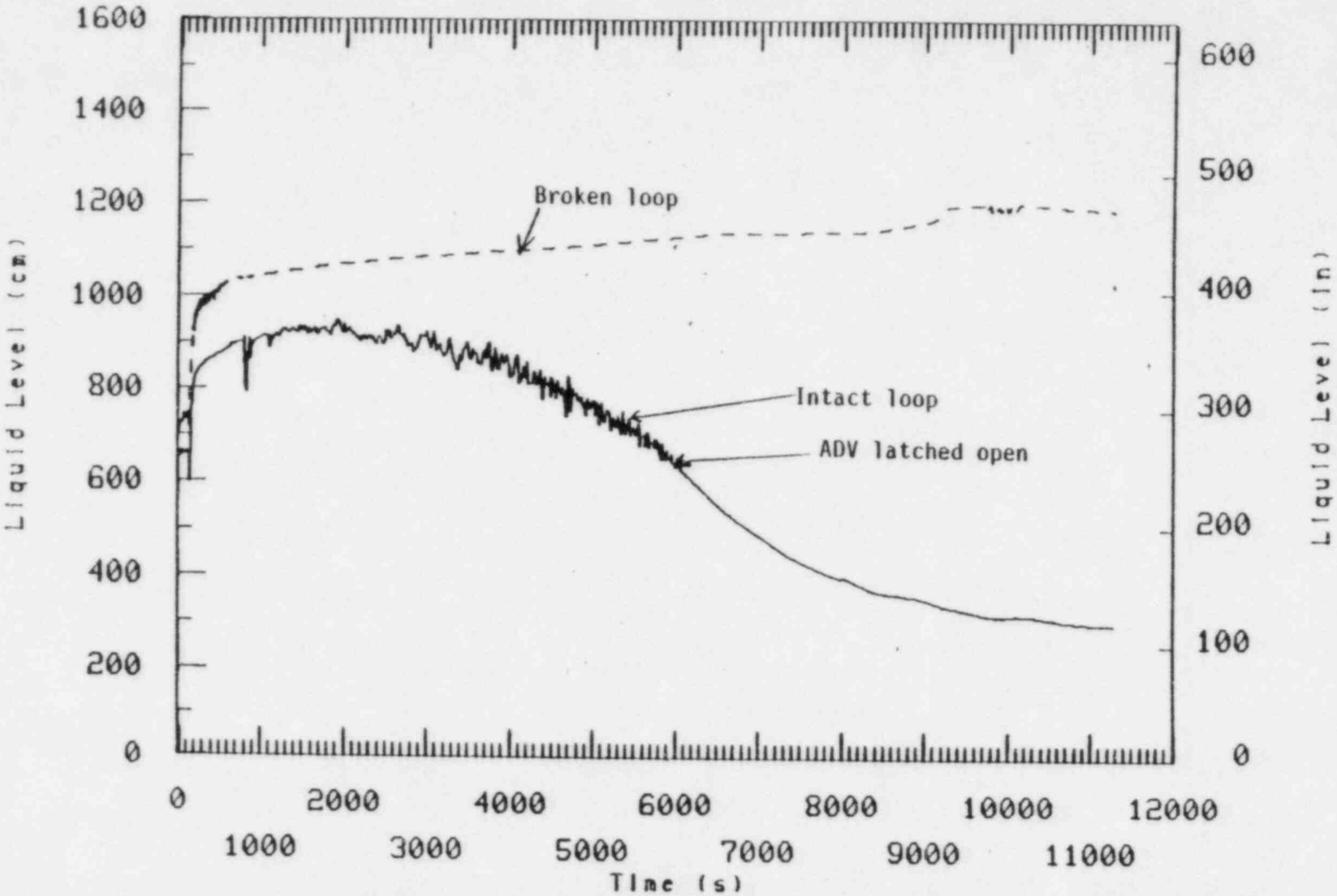

Figure 26. Comparison of intact and broken loop steam generator collapsed secondary levels during a cold side, one-tube rupture transient (S-SG-4).

3.2.2 Pressurizer Auxiliary Spray Operation (800 to 1280 s)

Pressurizer auxiliary spray operation was initiated at 800 s and consisted of injecting 300 K (80°F) water at 13.75 g/s (0.030 lbm/s) into the top of the pressurizer. The spray initially caused a rapid pressure increase in the primary system (Figure 27) as the spray was vaporized by striking the hot thermal shield at the top of the pressurizer. This thermal shield is a metal liner in the top of the pressurizer designed to prevent thermal shock to the pressurizer walls resulting from impinging cold spray. As the thermal shield and walls cooled, (Figure 28), the spray condensed the pressurizer steam bubble resulting in a localized low pressure region in the pressurizer. The flow of primary fluid into the pressurizer and out of the vessel is reflected in their changing levels shown in Figure 29. Spray was terminated at 1280 s, when the pressurizer became liquid solid, and was not used again in this test. Primary pressure dropped until spray was terminated, then rose as SI flow compressed the primary system.

3.2.3 Intact Loop Steam and Feed Operation (800 to 11,300 s)

An intact loop steam and feed operation consisting of steaming through the ADV and feeding with auxiliary feedwater was initiated 800 s after the tube rupture in an attempt to increase the secondary heat sink. The ADV was operated to maintain a constant secondary depressurization of 2.76 MPa/hr (400 psia/hr) (Figure 25). This rate was specified to maintain minimal thermal stresses on the plant and is a typical full scale plant cooldown rate.[6] By 6000 s the secondary had cooled to a point where the specified depressurization rate could not be maintained. The ADV was then latched open to achieve the maximum cooldown possible. The objective of the steam and feed operation was to cool the primary system and provide a mechanism for a controlled primary depressurization. The operation was successful in cooling the primary with significant subcooling shown in Figure 30. A controlled primary depressurization was also accomplished between 10,000 and 11,300 s, aided by the considerable heat sink of the intact loop steam generator, Figure 31.

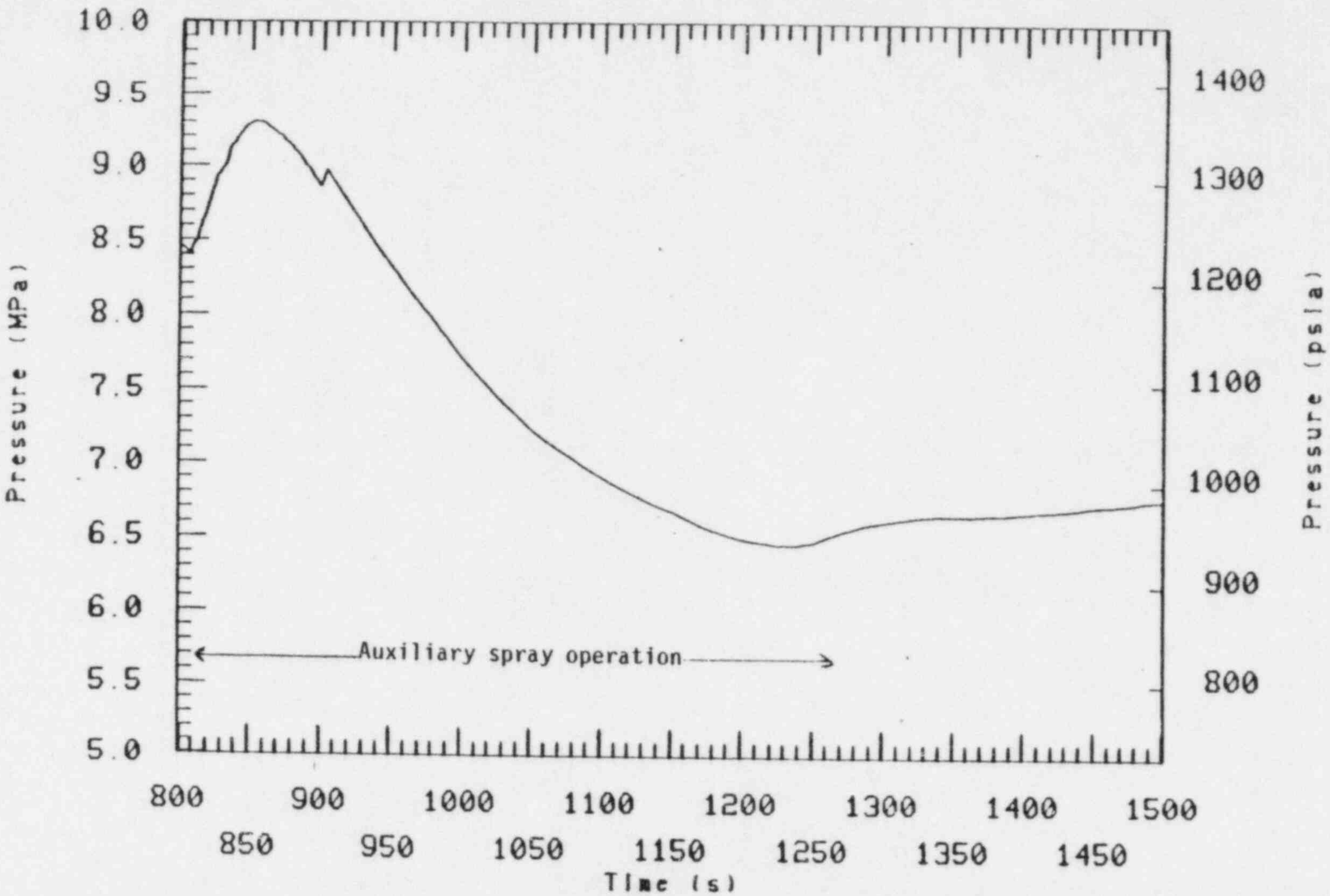

Figure 27. Pressurizer pressure during a cold side, one-tube rupture transient (S-SG-4).

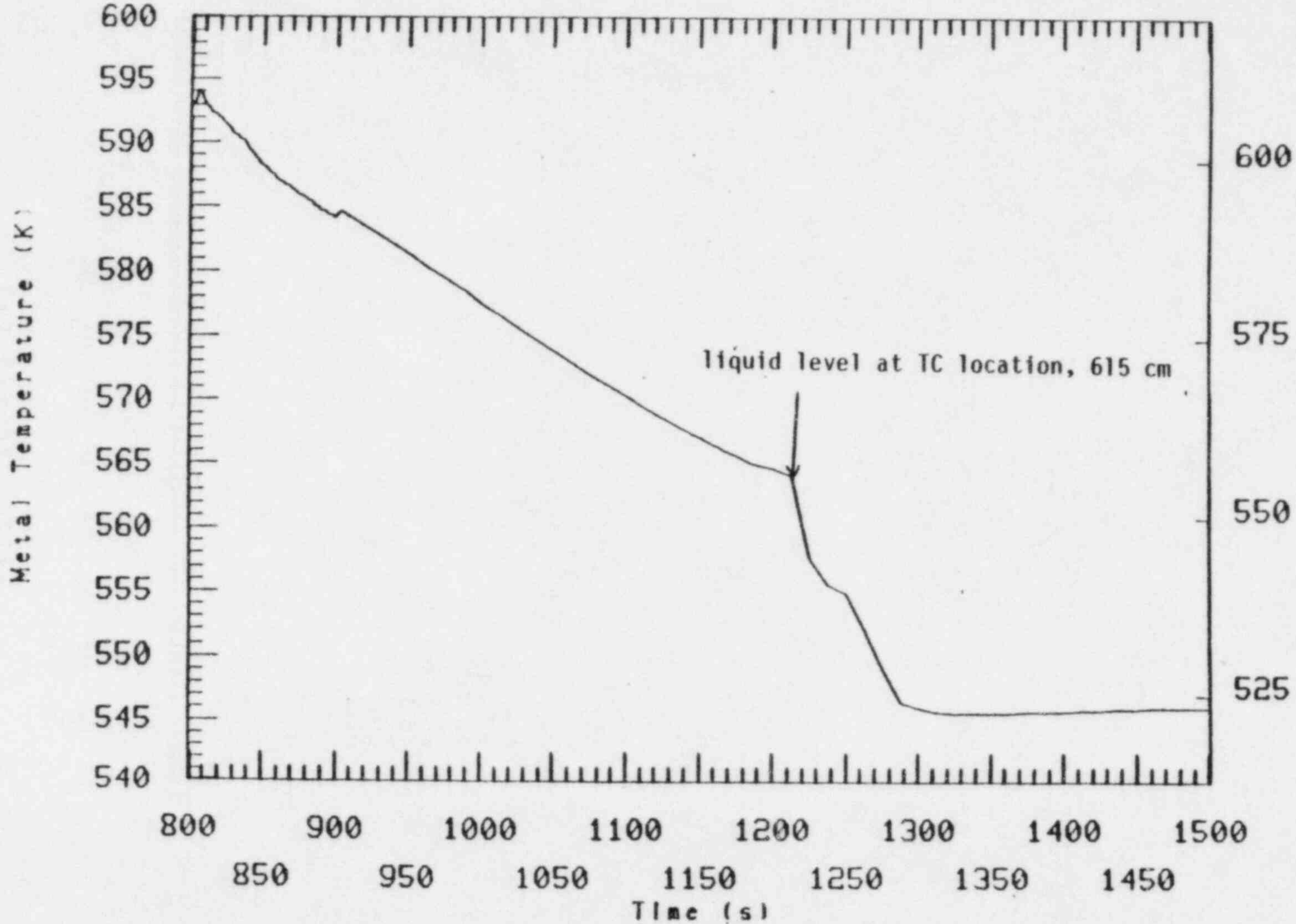

Figure 28. Pressurizer metal temperature during a cold side, one-tube rupture transient (S-SG-4).

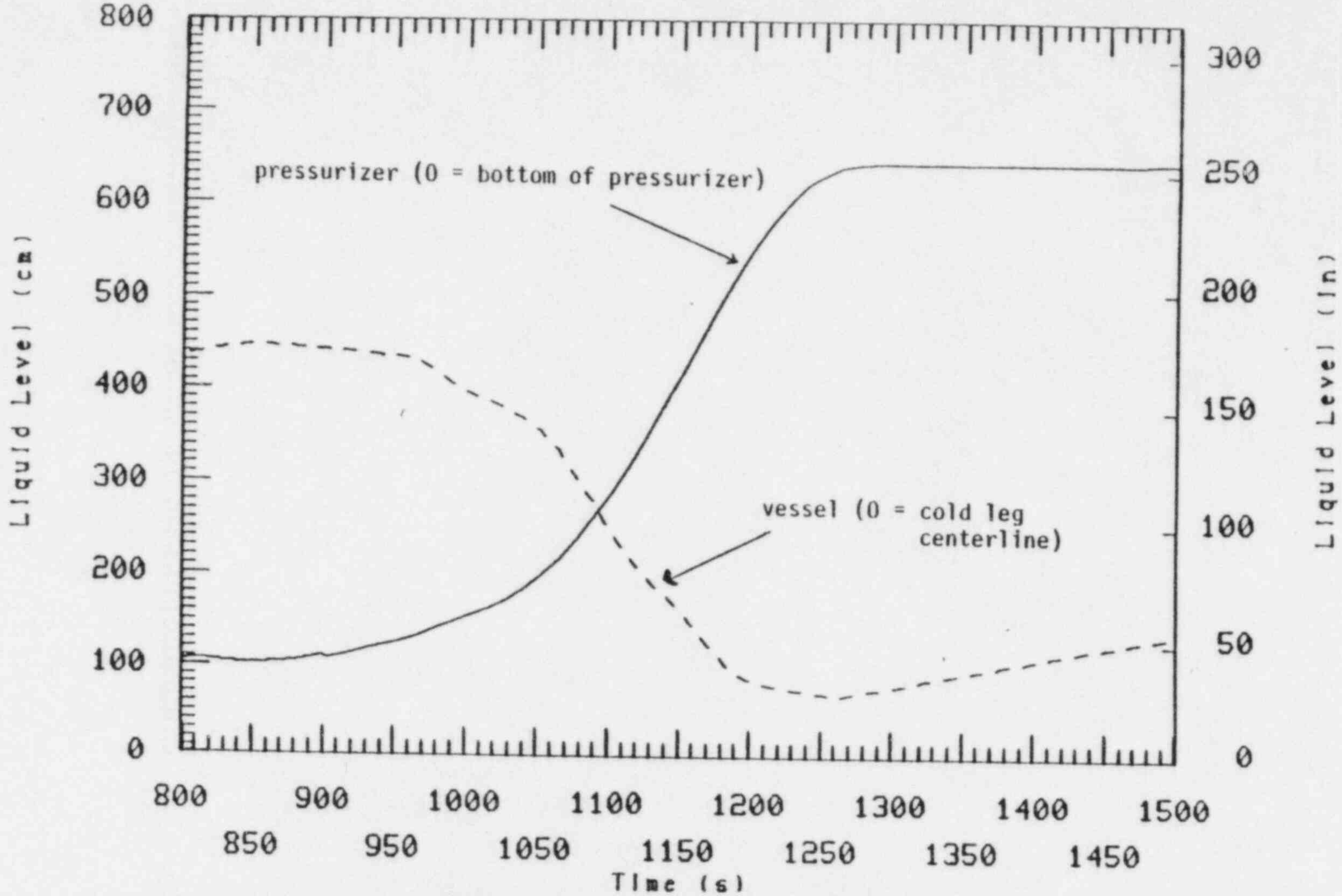

Figure 29. Pressurizer and vessel collapsed liquid level during a cold side, one-tube rupture transient (S-SG-4).

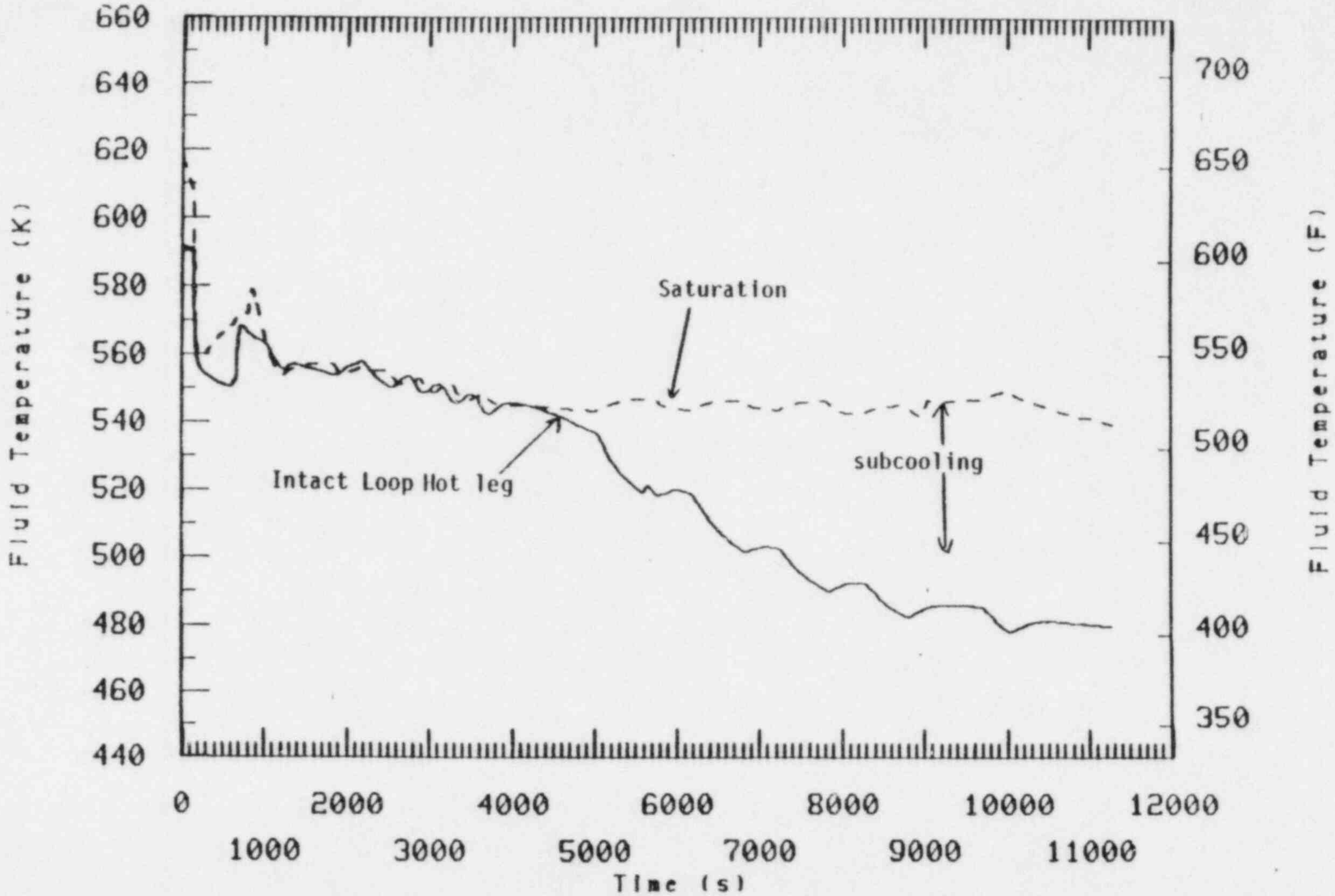

Figure 30. Comparison of fluid temperature and saturation temperature during a cold side, one-tube rupture transient (S-SG-4).

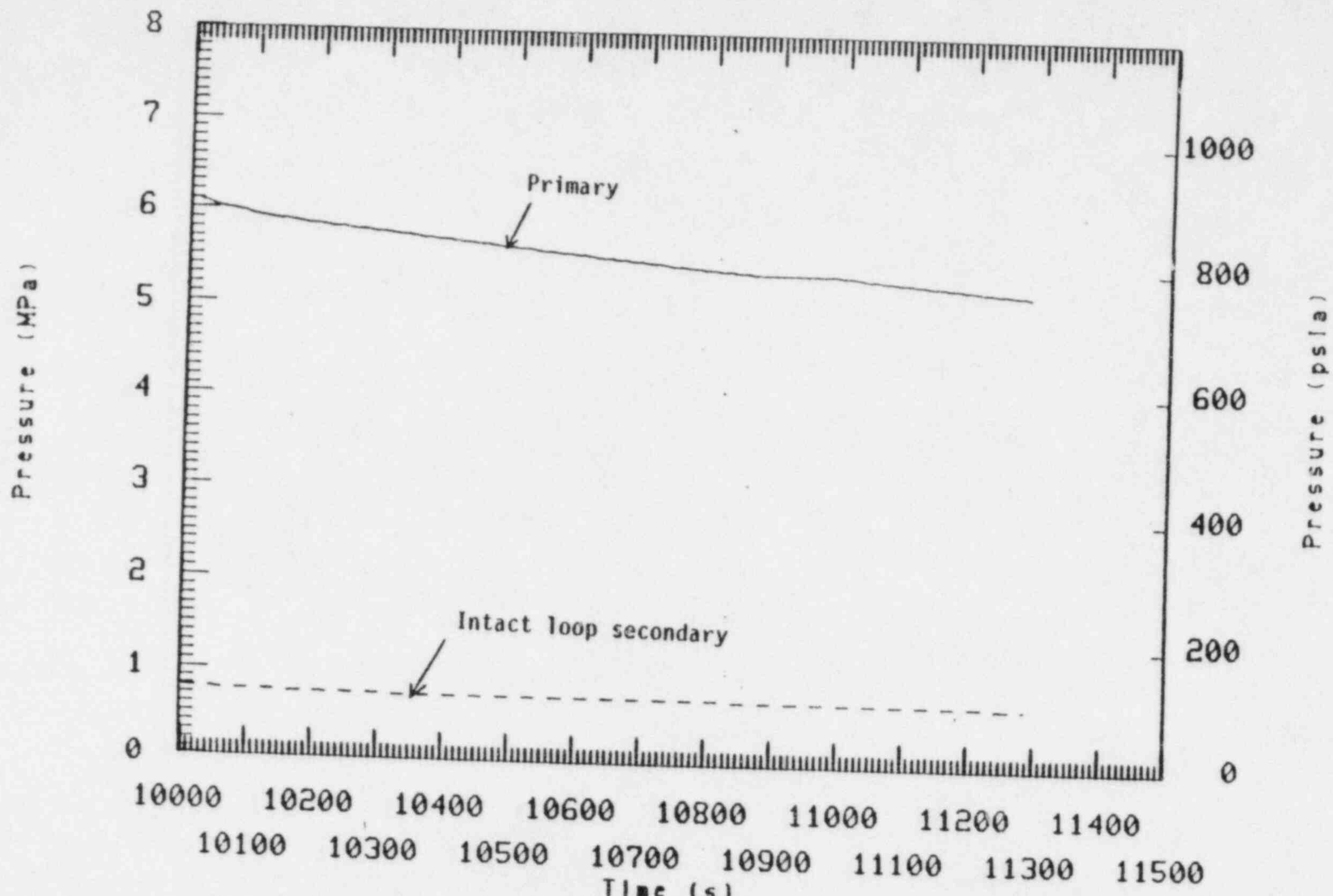

Figure 31. Comparison of primary and intact loop secondary pressure during a cold side, one-tube rupture transient (S-SG-4).

3.2.4 Effects of Combined SI Cycling and Pressurizer Internal Heater Operation on Primary Pressure (800 to 11,300 s)

SI was used throughout recovery to maintain primary system inventory, while the pressurizer internal heaters were used in an attempt to establish primary pressure control in the pressurizer. SI was cycled during recovery to maintain vessel level between 241 and 291 cm (95 and 115 in.), and pressurizer level between 80 and 250 cm (31.5 and 98 in.). SI was first initiated at SIS and was terminated after the pressurizer had filled and the vessel level established. The following four cycles, as listed in Table 2, were necessary to maintain vessel level, see Figure 32. The last five SI cycles (Table 2) were to maintain pressurizer level (Figure 33).

The pressurizer back-up and variable heaters were operated six times in an attempt to maintain primary pressure at 5.8 + 0, -0.07 MPa (841 + 0, -10 psia). The first heater cycle was initiated when auxiliary spray reduced primary pressure below 5.8 MPa (841 psia). SI compression then raised primary pressure which terminated heater operation. The following three heater operations had no observable effect on primary pressure as shown in Figure 34. During these heater operations vessel or pressurizer level fell requiring SI operation. SI operation filled and compressed the primary system, raised the primary pressure, and resulted in a pressurizer heater trip. When the specified levels had been reestablished, SI was shut off, primary pressure fell (Figure 34) and the pressurizer heaters were restarted, initiating the cycle again. Twice during the fourth heater cycle SI was cycled without compressing the primary to 5.8 MPa (841 psia), and the heaters were left operating.

The pressurizer back-up and variable heaters could not control primary pressure because more energy was lost with fluid exiting the pressurizer than the heaters could supply. Steam generated at the heater rods is minimal and cannot compensate for the volume loss due to break flow. Figure 35 compares break flow to the flow out of the pressurizer. As the break flow continues, the pressurizer drained and SI operation was necessary to reestablish the level. SI filling compressed the primary, raised the pressure and sustained the break flow. Figure 36 compares the

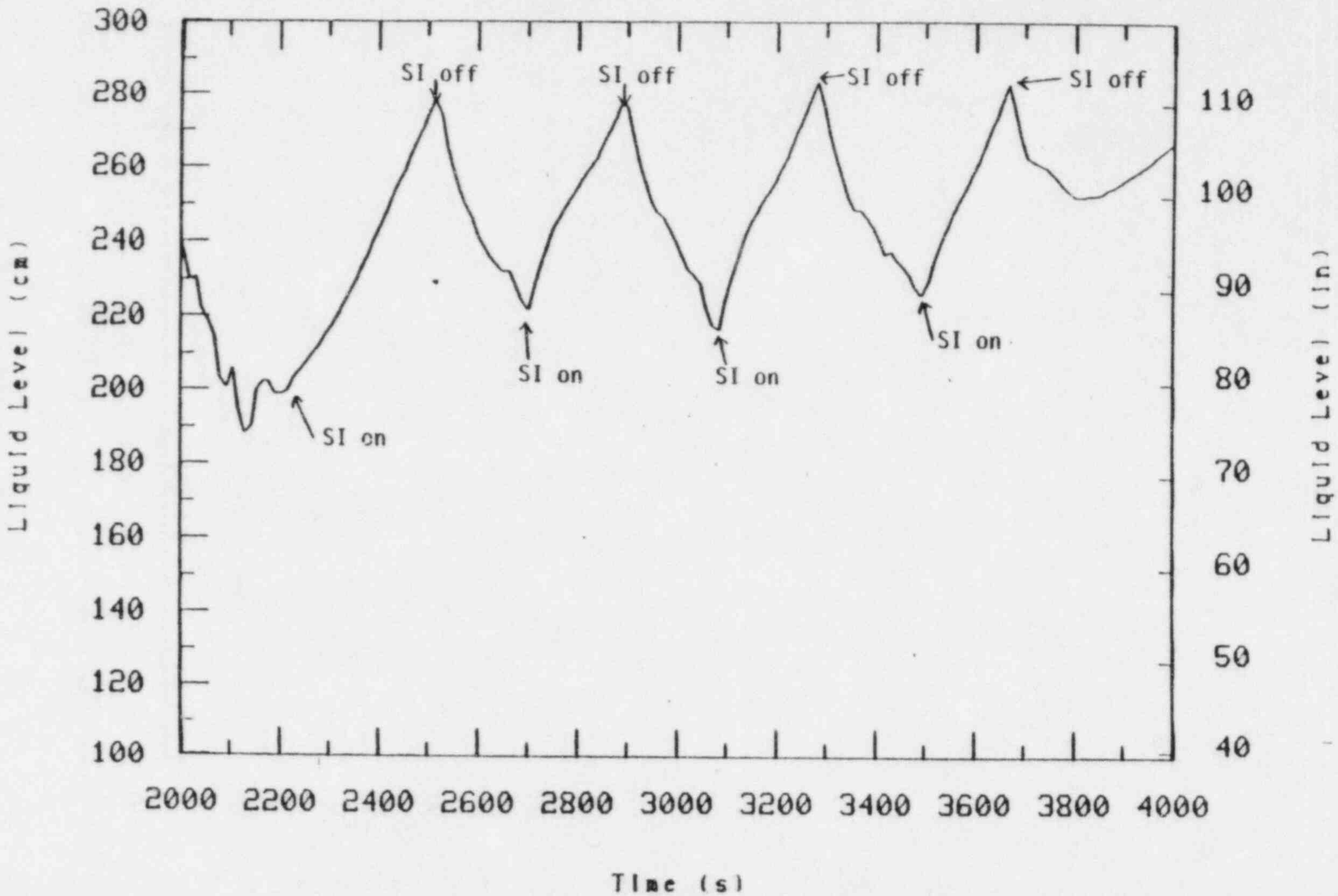

Figure 32. Vessel collapsed liquid level during a cold side, one-tube rupture transient (S-SG-4).

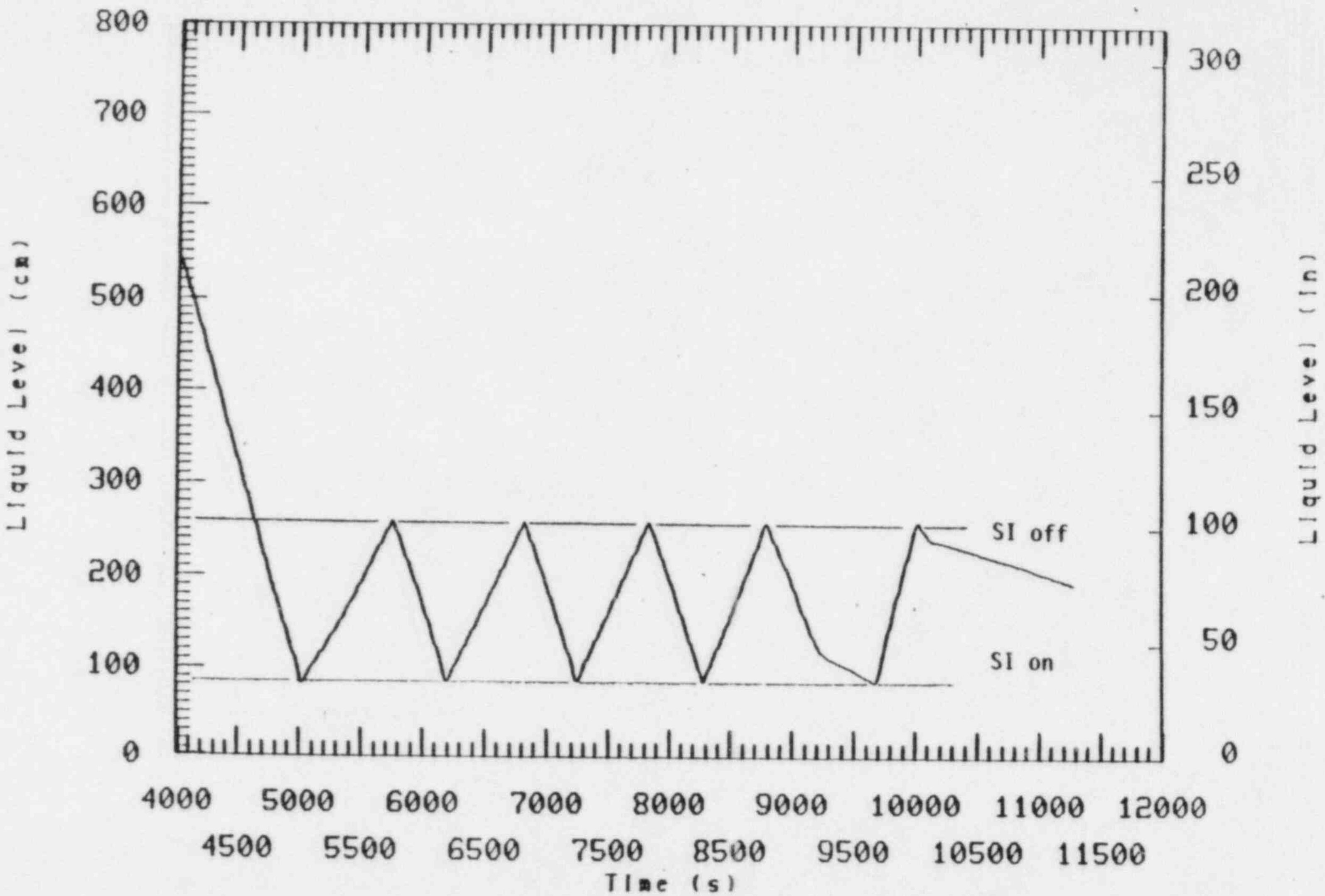

Figure 33. Pressurizer collapsed liquid level during a cold side, one-tube rupture transient (S-SG-4).

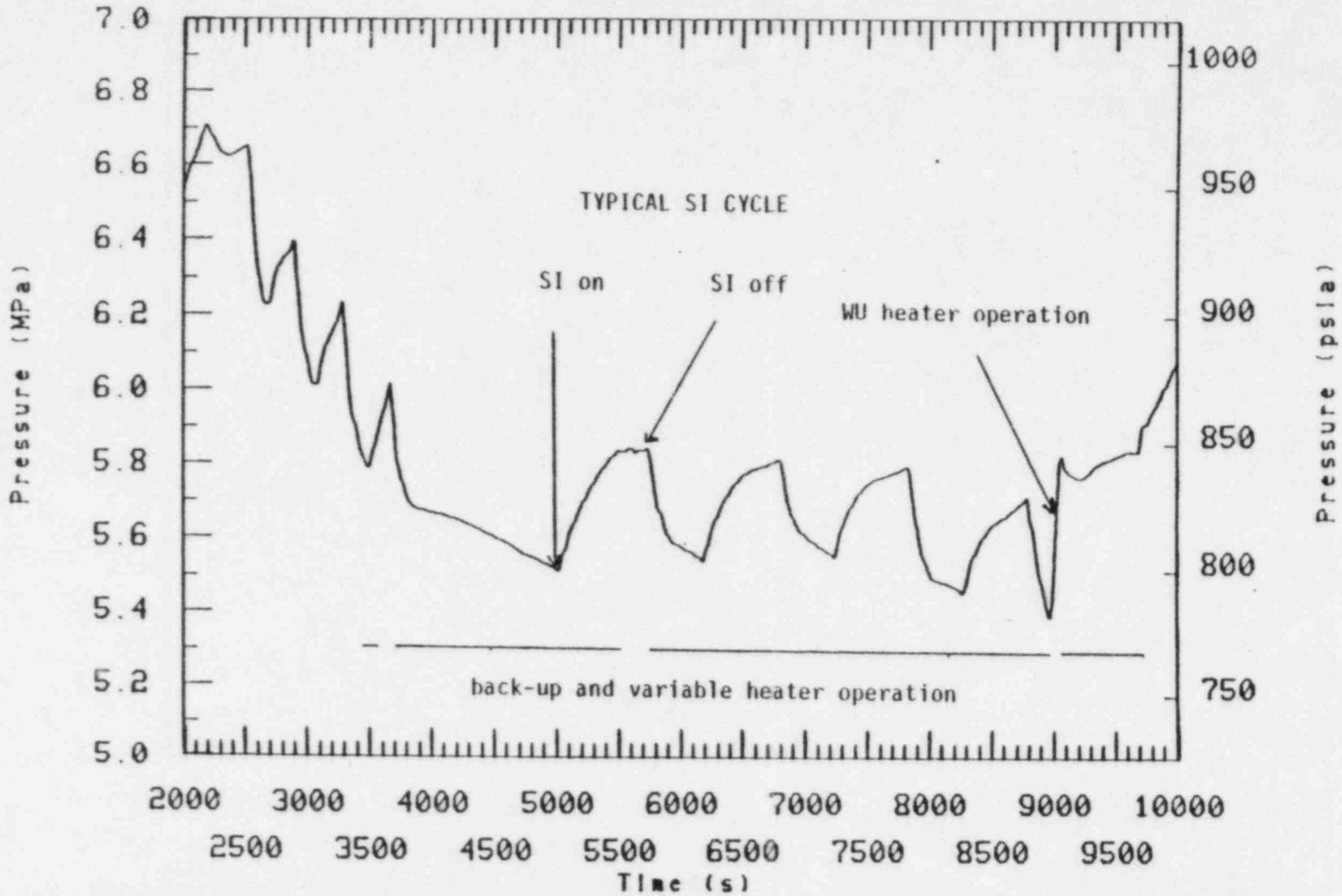

Figure 34. Pressurizer pressure during a cold side, one-tube rupture transient (S-SG-4).

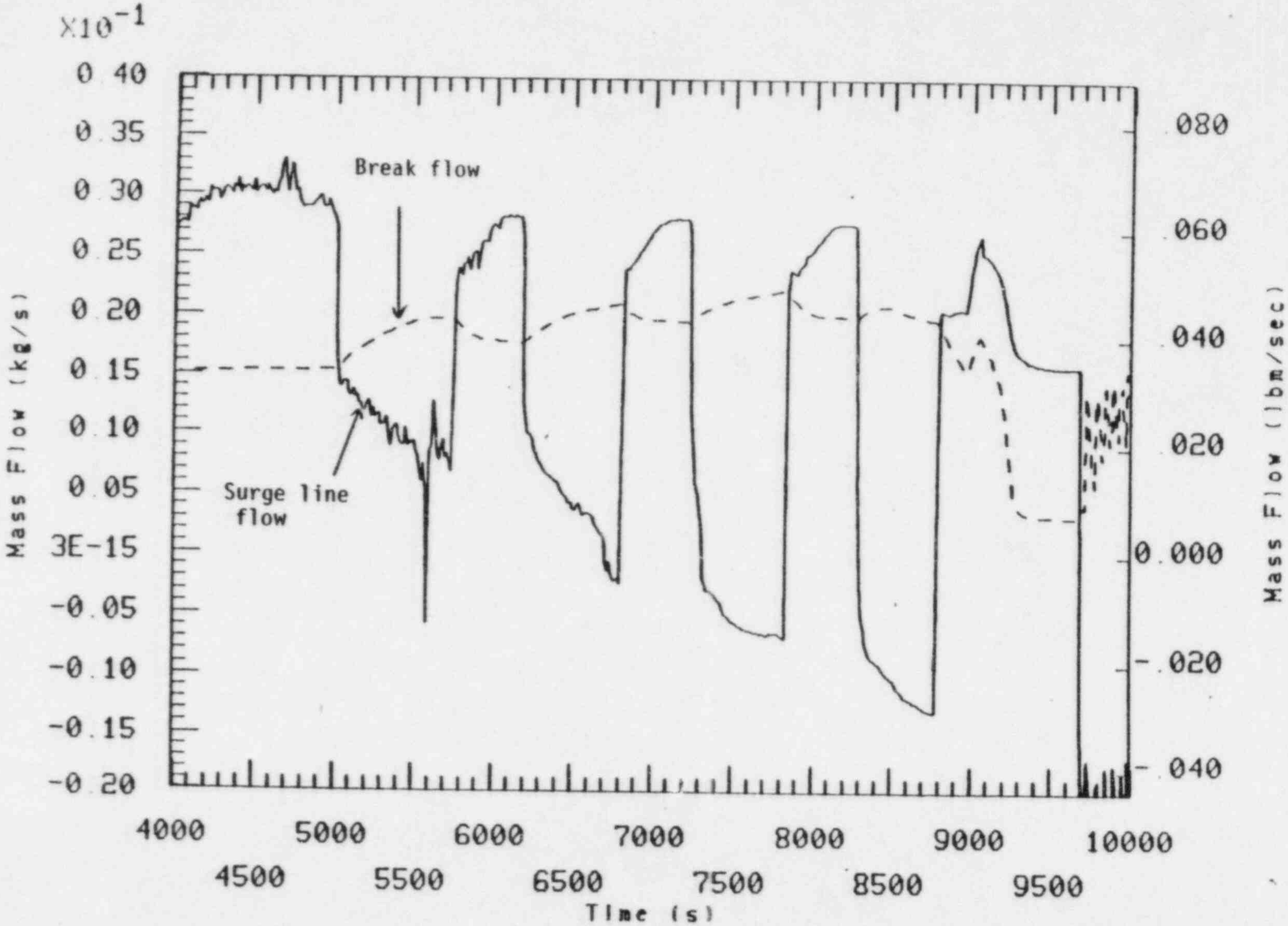

Figure 35. Comparison of break flow, surge line flow, and SI flow during a cold side, one-tube rupture transient (S-SG-4).

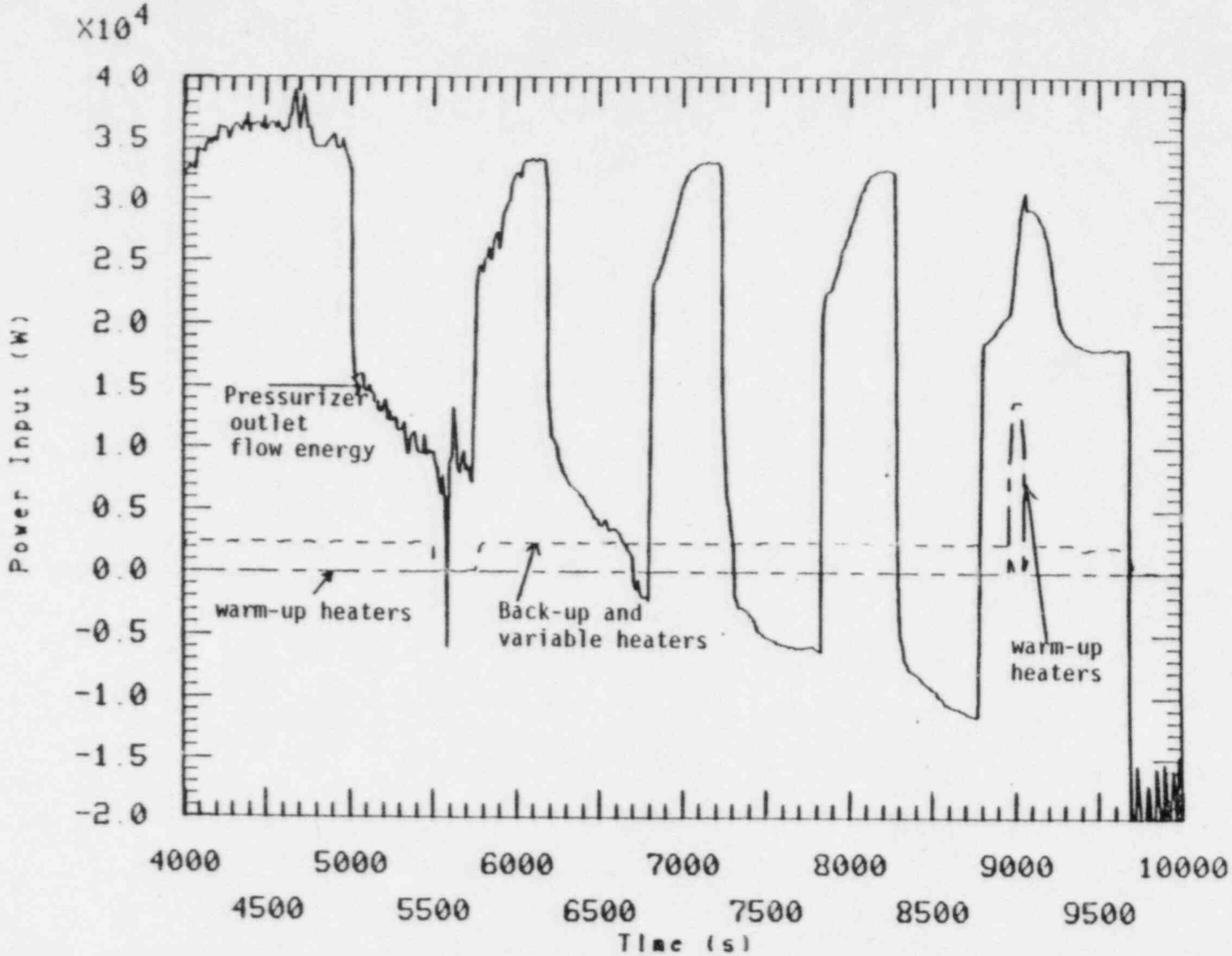

Figure 36. Comparison of pressurizer internal heater power and pressurizer outlet flow energy during a cold side, one-tube rupture transient (S-SG-4).

energy lost by mass flow out of the pressurizer and energy addition from pressurizer heaters. This net energy loss from the pressurizer is why the heaters could not control primary pressure.

The pressurizer warm-up heaters were effective in controlling primary pressure because of their considerably higher energy input. The 13 kW energy addition produced enough steam at the heater rods to compensate for the volume loss due to break flow. After the warm-up heaters had established primary pressure, the back-up and variable heaters were again energized between 9050 and 9700 s. Coincident with this was the filling and pressurizing of the broken loop secondary at approximately 9250 s, Figure 37. This secondary pressure rise essentially stopped break flow and the pressurizer level drop slowed considerably, Figure 38. The back-up and variable heaters were then able to control primary pressure. SI was cycled on at 9680 s on a low pressurizer level signal, compressing the now hydrodynamically coupled primary and broken loop secondary systems. This pressure rise tripped the broken loop ADV as is evidenced in Figure 37 until SI was terminated. After SI was terminated, a controlled primary depressurization, using back-up and variable heater power, was accomplished and the test was terminated.

This combined recovery period showed that the pressurizer back-up and variable heaters are not able to control primary pressure during a one-tube rupture transient. Only when the break flow is stopped are they effective. However, warm-up heaters are capable of controlling primary pressure during a one-tube break. SI was capable of maintaining primary inventory and was the most significant factor in primary pressure control during this test.

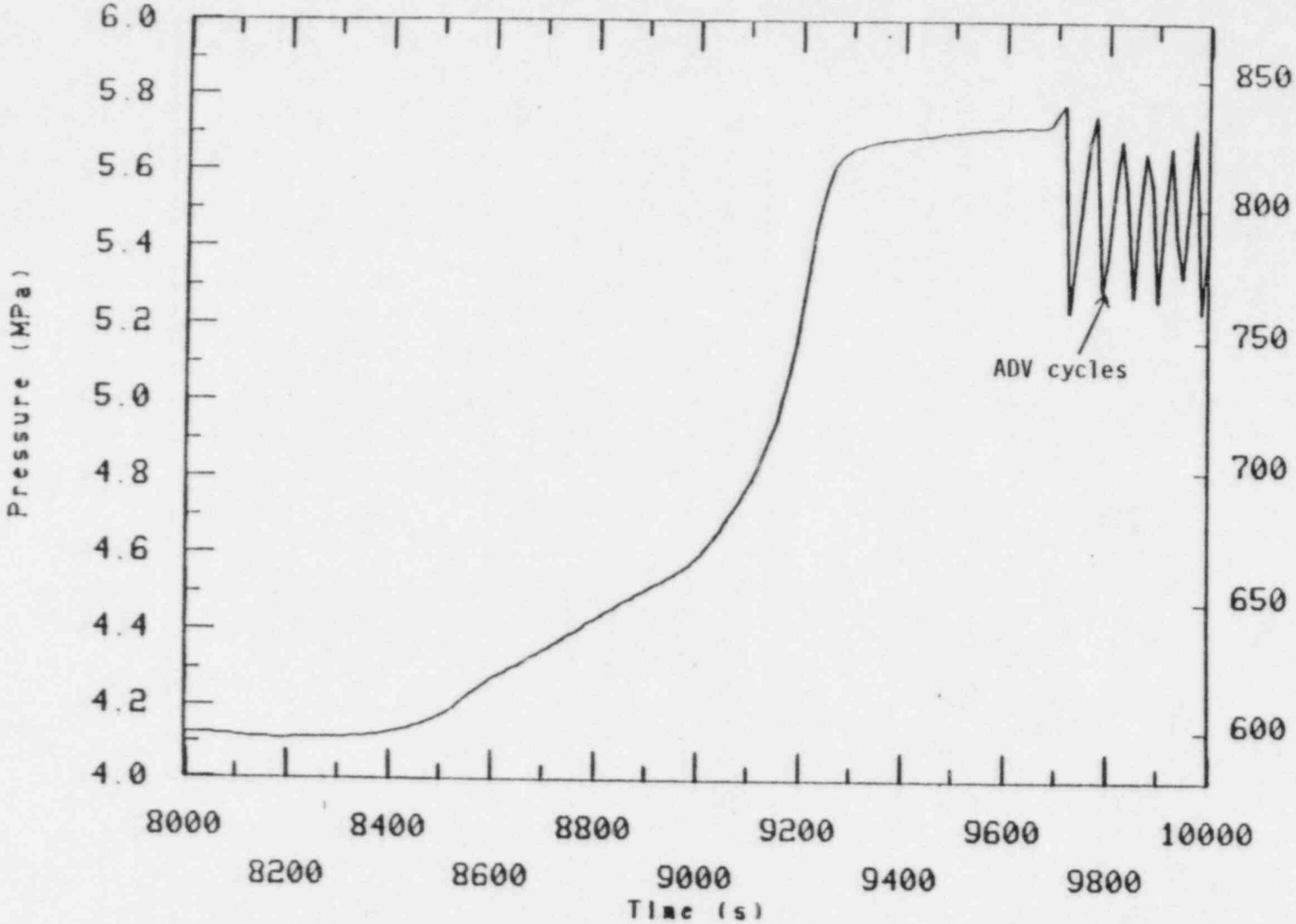

Figure 37. Broken loop secondary pressure during a cold side, one-tube rupture transient (S-SG-4).

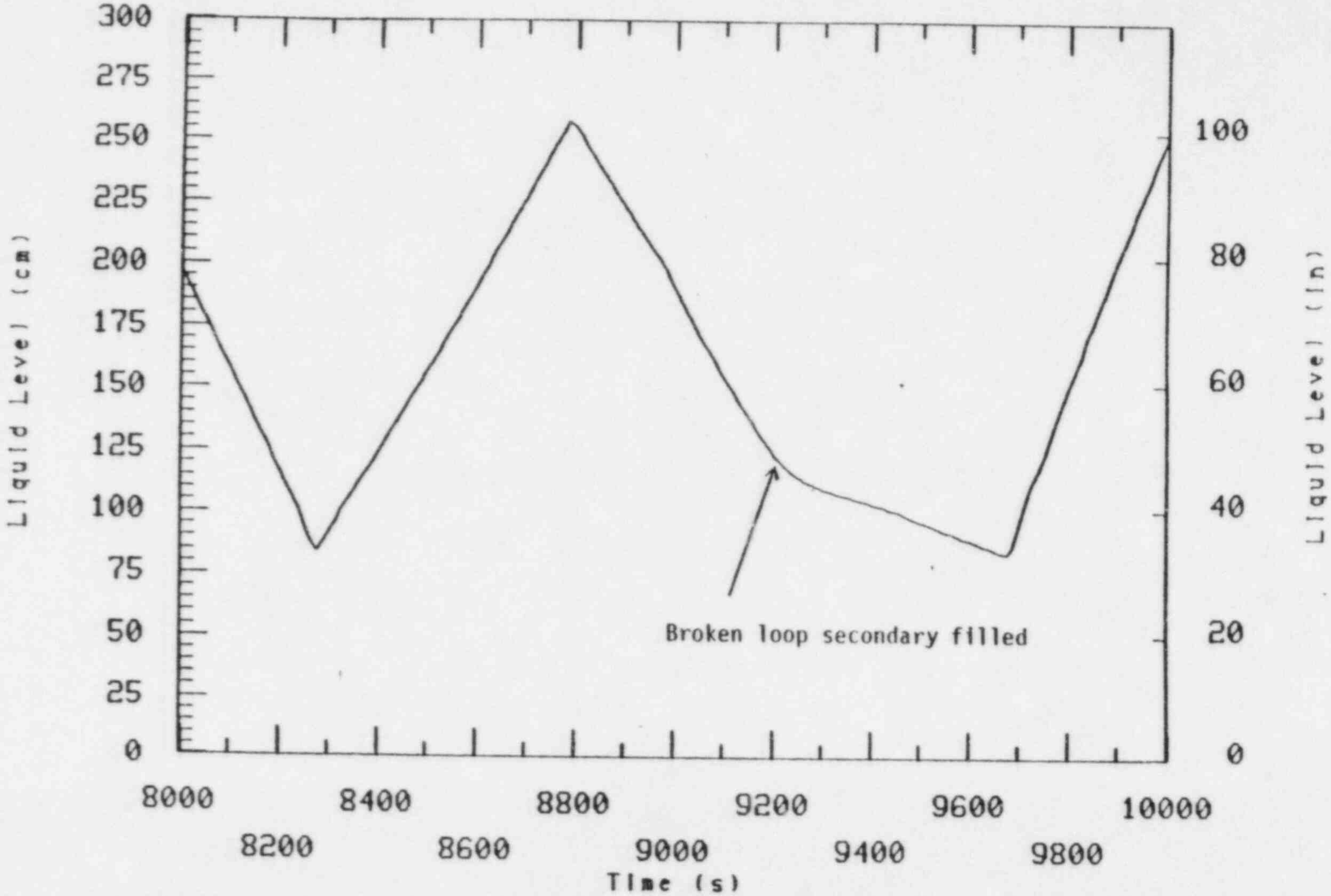

Figure 38. Pressurizer collapsed liquid level during a cold side, one-tube rupture transient (S-SG-4).

4. COMPARISON TO THE PAD CALCULATION

This section compares the test results to the PAD calculation[7] for Test S-SG-4. In general, the phenomena that occurred during the test were well calculated by RELAP5. However, the break flow was not well calculated after SCRAM. This resulted in major differences between the PAD calculation and the test when the pressurizer heaters were turned on.

4.1 Differences in Initial and Boundary Conditions

A comparison of the measured and calculated initial conditions is shown in Table 3. Although the measured secondary masses are within the specifications, they are 17 and 12% lower than the masses used in the broken loop and intact loop secondaries in the calculation. Neither these differences, nor any other slight differences in the initial conditions, would cause significant differences between the calculated and measured transient responses.

However, differences in the external heater powers contributed to some of the differences in the transient response. The power supplied to the various external heaters initially is shown in Table 3. Adding the core power, 19.2 kW more power was input to the primary coolant system (PCS) in the PAD calculation than in the test. However, the PAD calculation modeled the passive cooling system for the intact loop primary coolant pump, which removes 20 kW at full flow (0.0 kW when the pumps are stopped), while the active cooling system used in the test removes 4.3 kW at all flow rates. The net excess heat input modeled by RELAP5 was, therefore, 3.5 kW prior to SCRAM (Table 4). This is insignificant compared to the 2.0 MW of core power. After SCRAM the core power drops to decay heat levels and any excess heat addition or loss becomes more significant. Prior to tripping the pumps and after SCRAM the PAD calculation modeled approximately 15.0 kW net excess heat loss compared to the test. This contributed to the larger calculated depressurization (Figure 39) of the PCS after SCRAM. After tripping the pumps the active cooling system continues to remove 4.3 kW in the test, while the passive cooling system drops to zero. As a result, the PAD calculation modeled between 5.0 and 9.0 kW net additional heat input

TABLE 3. CALCULATED AND MEASURED INITIAL CONDITIONS

	Measured	Calculated
Primary cold leg flow rate		
Broken loop	3.05 ℓ/s (48 gpm)	3.41 ℓ/s (54 gpm)
Intact loop	9.73 ℓ/s (154 gpm)	9.6 ℓ/s (152 gpm)
Pressurizer pressure	15.56 MPa (2244 psig)	15.52 MPa (2238 psig)
Pressurizer liquid volume	0.0098 m^3 (0.34 ft^3)	0.0092 m^3 (0.32 ft^3)
Core power	1.985 MW	2.0 MW
Loop to loop cold leg fluid temperature differential	1.4 K (2.5°F)	0.7 K (1.3°F)
Core fluid temperature rise	35.9 K (64.5°F)	37.0 K (67°F)
Steam generator pressure		
Broken loop	5.52 MPa (788 psig)	5.50 MPa (786 psig)
Intact loop	5.43 MPa (775 psig)	5.45 MPa (778 psig)
Steam generator secondary fluid mass		
Broken loop	83 kg (183 lbm)	100.7 kg (221.3 lbm)
Intact loop	88 kg (194 lbm)	100.8 kg (221.3 lbm)
Steam generator feedwater temperature	504 K (447°F)	505 K (450°F)
Primary leakage at t = 0	0.0009 kg/s (0.002 lbm/s)	0.006 kg/s (0.013 lbm/s)
External heater power		
Vessel	20.07 kW	20.0 kW
Hot legs	7.33 kW	8.0 kW
Cold legs	3.23 kW	3.3 kW
I.L. pump suction	8.78 kW	8.5 kW
B.L. pump suction	4.20 kW	8.0 kW
Pressurizer	0.0 kW	0.0 kW
TOTAL	43.61 kW	47.8 kW

TABLE 4. CALCULATED AND MEASURED SEQUENCE OF EVENTS

Event	Measured t(s)		Calculated t(s)	
Break flow initiated	0.0		0.0	
SCRAM, P_{PRZ} = 13.1 MPa				
MSIV closure (both loops)	141		121.9	
Core Scram	141		121.9	
	141		121.9	
SIS, P_{PRZ} = 12.51 MPa	145		126.4	
HPIS initiated (both loops)	145		126.4	
Main feedwater secured (both)	145		126.4	
Auxiliary feedwater started				
IL	145		126.4	
BL	150		126.4	
Main coolant pump trip	602		600.0	
Auxiliary spray initiated	800		800.0	
IL steam and feed initiated	800		800.0	
Auxiliary spray terminated	1280		1273.1	
SI Operation	On	Off	On	Off
	145	1850	126	1142
	2120	2520	1246	1394
	2680	2890	1482	1578
	3070	3280	1722	1810
	3480	3660	1970	2054
	5000	5740	2306	2398
	6180	6800	2788	2824
	7240	7830	4206	4617
	8270	8770		
	9680	10000		
Pressurizer internal heater operation (back-up and variable)	1280	1340	3128	3848
	3420	3540	3956	4202
	3700	5500		
	5750	8960		
	9050	9700		
	10030	10950		
Warm-up heater operation	8960	9040	--	--
Test termination		11300		5649

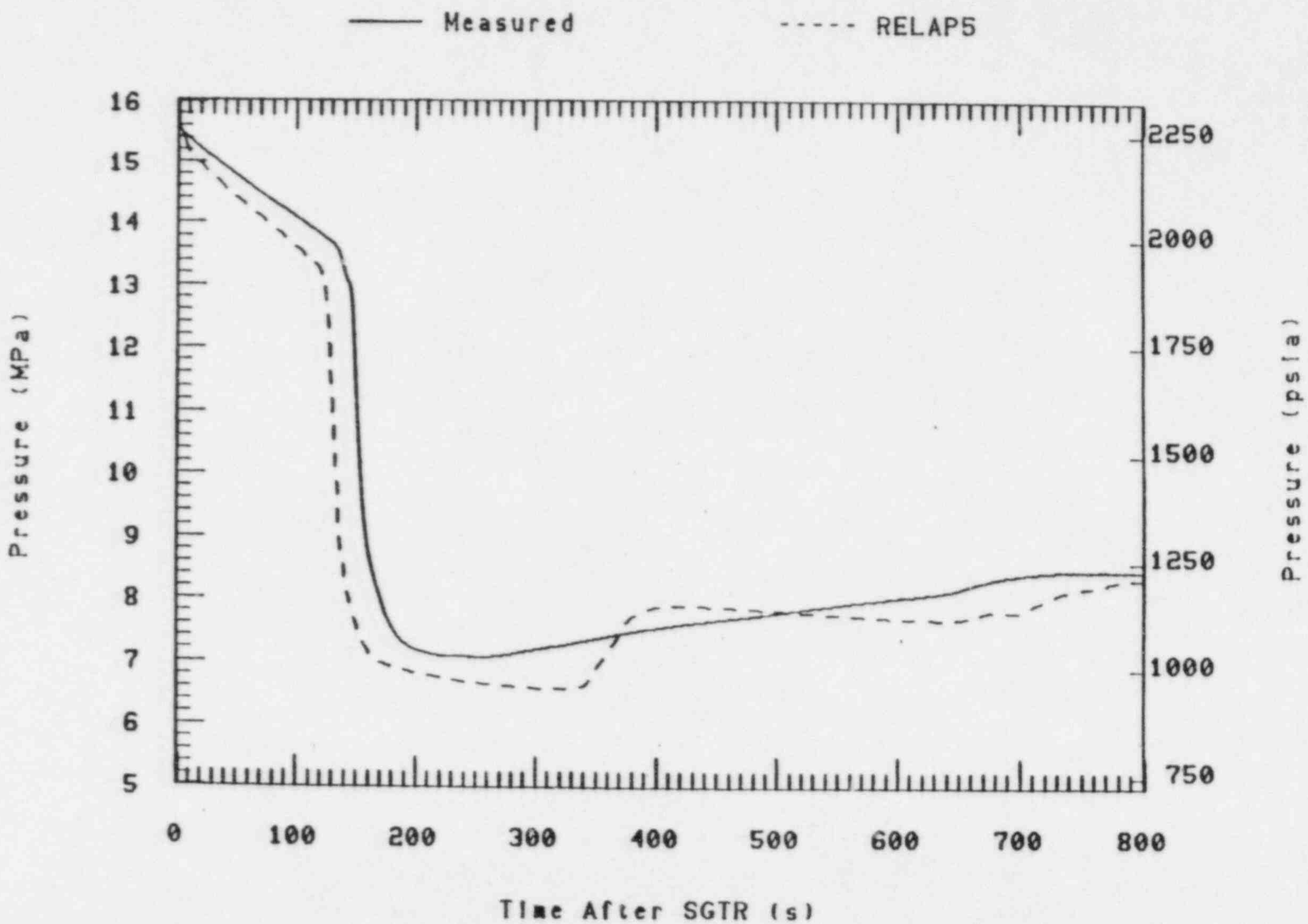

Figure 39. RELAP5 comparison of pressurizer pressure (0 - 800 s).

after tripping the primary coolant pumps. The effects of the heat loss on the different operations performed during the transient are discussed in the following sections.

Figure 40 compares the secondary pressures for the first 800 s of the transient. It is apparent the ADV setpoints were lower in the test (although within specifications) than in the PAD calculation. These lower setpoints did not adversely affect the transient response and are of little significance, even though the intact loop ADV opened in the test but not in the calculation. More important is the mechanism by which the core heat is removed from the system: steaming out the ADV's. RELAP5 calculated not only the first 800 s, but also the remainder of the intact loop steam generator steam and feed operation, very well.

The one major phenomenon that was not calculated well by RELAP5 was the break flow (Figure 41). Prior to SCRAM the break flow was well calculated as a total of 6.8 kg flowed out the break in the test and 6.4 kg in the calculation. After SCRAM, however, the calculated break flow is approximately half the observed flow even though the primary pressure is about the same (Figure 39). The lower ADV setpoint contributes to this disparity, although its effect is probably small. After cycling to relieve pressure the ADV in the broken loop steam generator did not properly reseat. The resulting leak lowered the secondary pressure (Figure 42) and thereby worsened the already poor break flow comparison. Break flow probably had a more significant effect on the transient response to HPIS operation and pressurizer internal heater operation. The effects of the break flow during these operations are discussed in the following sections.

4.2 Delayed Pump Trip (0-800 s)

Two of the major objectives of Test S-SG-4 were to determine the effects of delayed primary coolant pump trip and to determine the effects of pump trip. An additional 200 s with no operator action was inserted into the test at the 600 s point specifically to study the effects of pump trip. As described in Section 3.1 the delayed pump trip resulted in the primary-to-secondary heat transfer coefficients being maintained at their

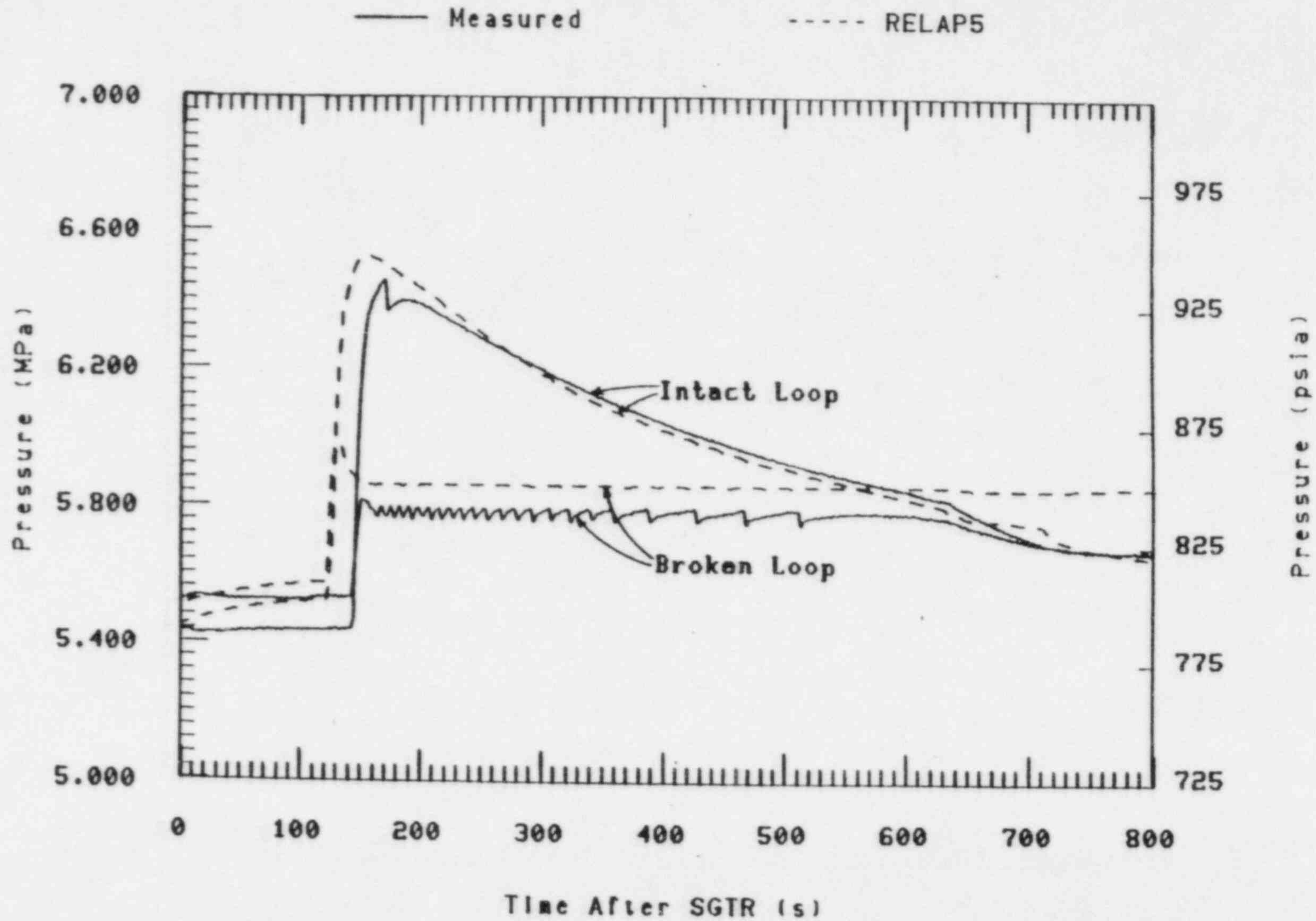

Figure 40. RELAP5 comparison of secondary pressure (0 - 800 s).

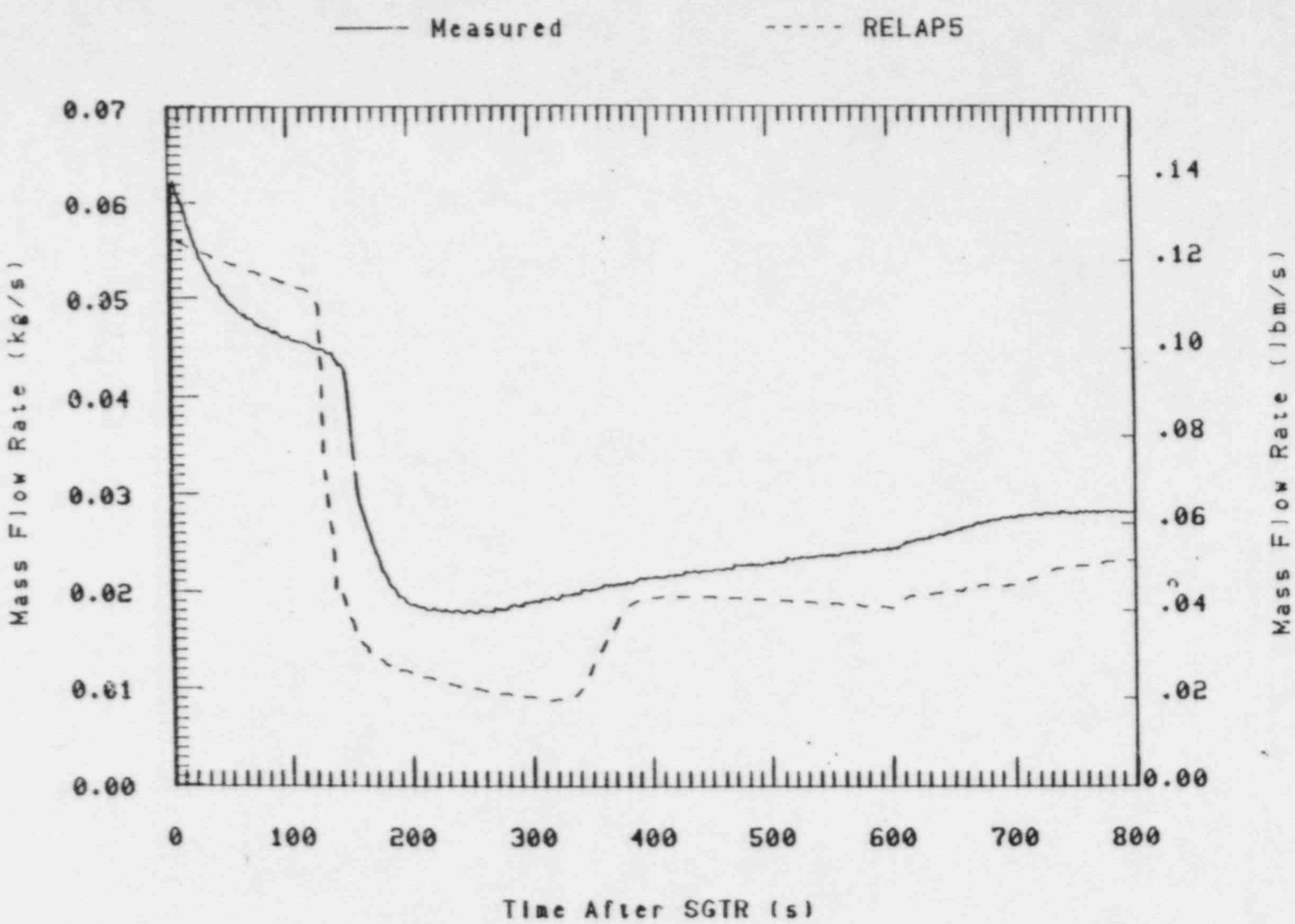

Figure 41. RELAP5 comparison of break flow (0-800 s).

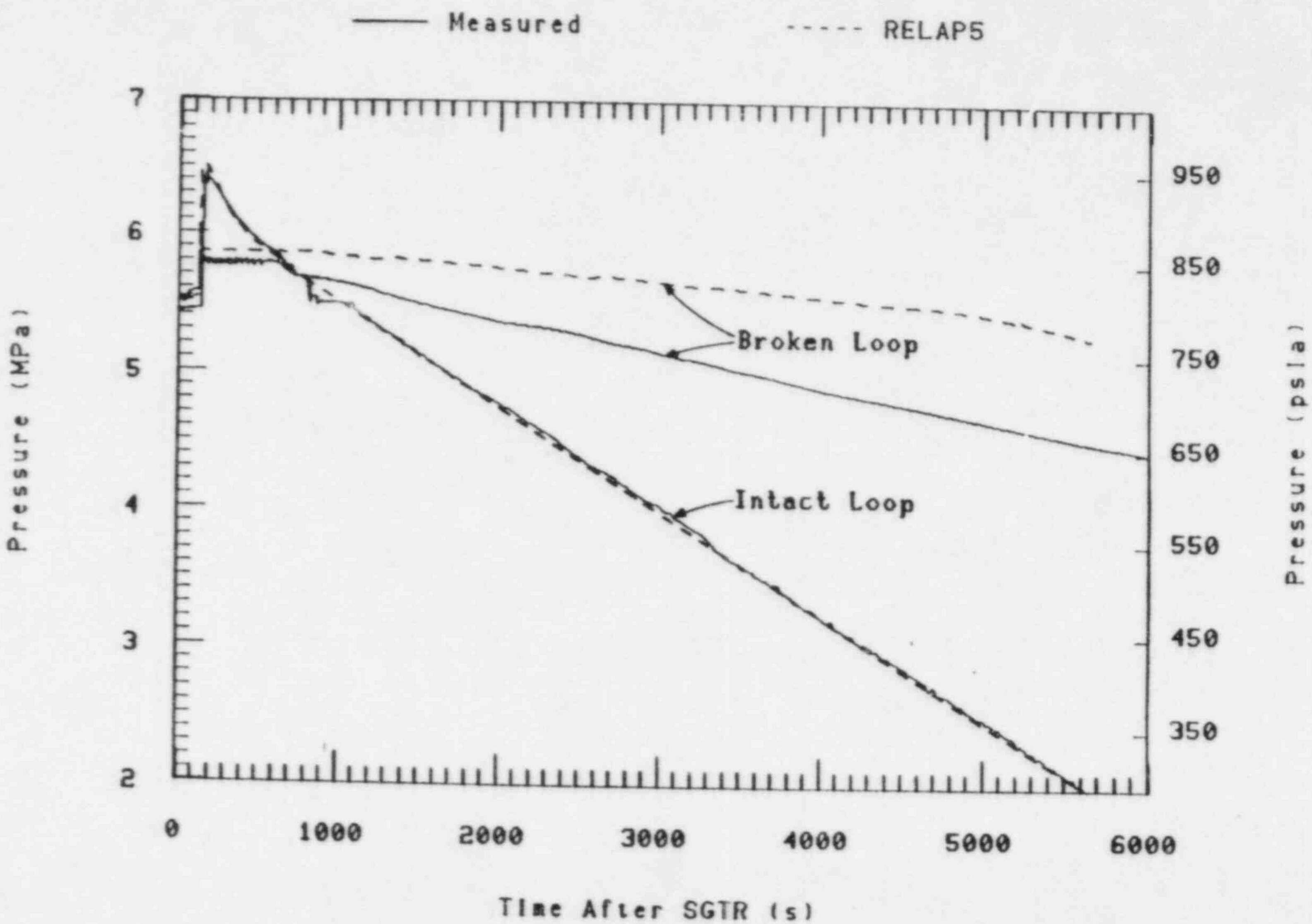

Figure 42. RELAP5 comparison of secondary pressure (0 - 6000 s).

high, forced convection values for a longer time. As a result, the PCS depressurized approximately 1.0 MPa (145 psi) lower than in Test S-SG-8. RELAP5 correctly calculated this greater depressurization (Figure 39) as well as the change in heat transfer in the two loops after SCRAM (Figure 43).

Prior to SI initiation, the primary system mass inventory was depleted by break flow. RELAP5 correctly calculated the pressurizer emptying and the rate at which the pressurizer emptied (Figure 44). When SI flow exceeded break flow the primary system inventory began to recover. At about 370 s in both the calculation and the test the pressurizer began to refill. Filling the pressurizer with liquid compressed the steam space resulting in a pressure rise in the primary system. RELAP5 calculated this pressure rise in a stair-step fashion[7] as the liquid level crossed volume boundaries. The pressure at 800 s was, however, correctly calculated.

The primary coolant pumps were tripped at 600 s and natural circulation flow was then established. Upon pump trip in both the calculation and the test, the primary flow momentarily stopped, causing steam to form in the core and a slight pressure rise in the primary system.

4.3 Pressurizer Spray Operation (800-1280 s)

Recovery operations commenced at 800 s with the operation of pressurizer auxiliary spray and initiation of steam and feed in the intact loop steam generator. When the spray was initiated in the test the liquid impinging on the hot pressurizer thermal shield was turned to steam causing a rapid pressurization of the primary system (Figure 45). RELAP5 cannot calculate this phenomenon. The liquid from the spray enters the top modeled pressurizer volume and mixes with the fluid there. Energy is then transferred from the hot pressurizer wall to this homogenized fluid and not just the liquid from the spray. As a result the rapid pressurization is not calculated by RELAP5.

The continued use of auxiliary spray quickly reversed the pressurization causing a rapid depressurization. In both the calculation

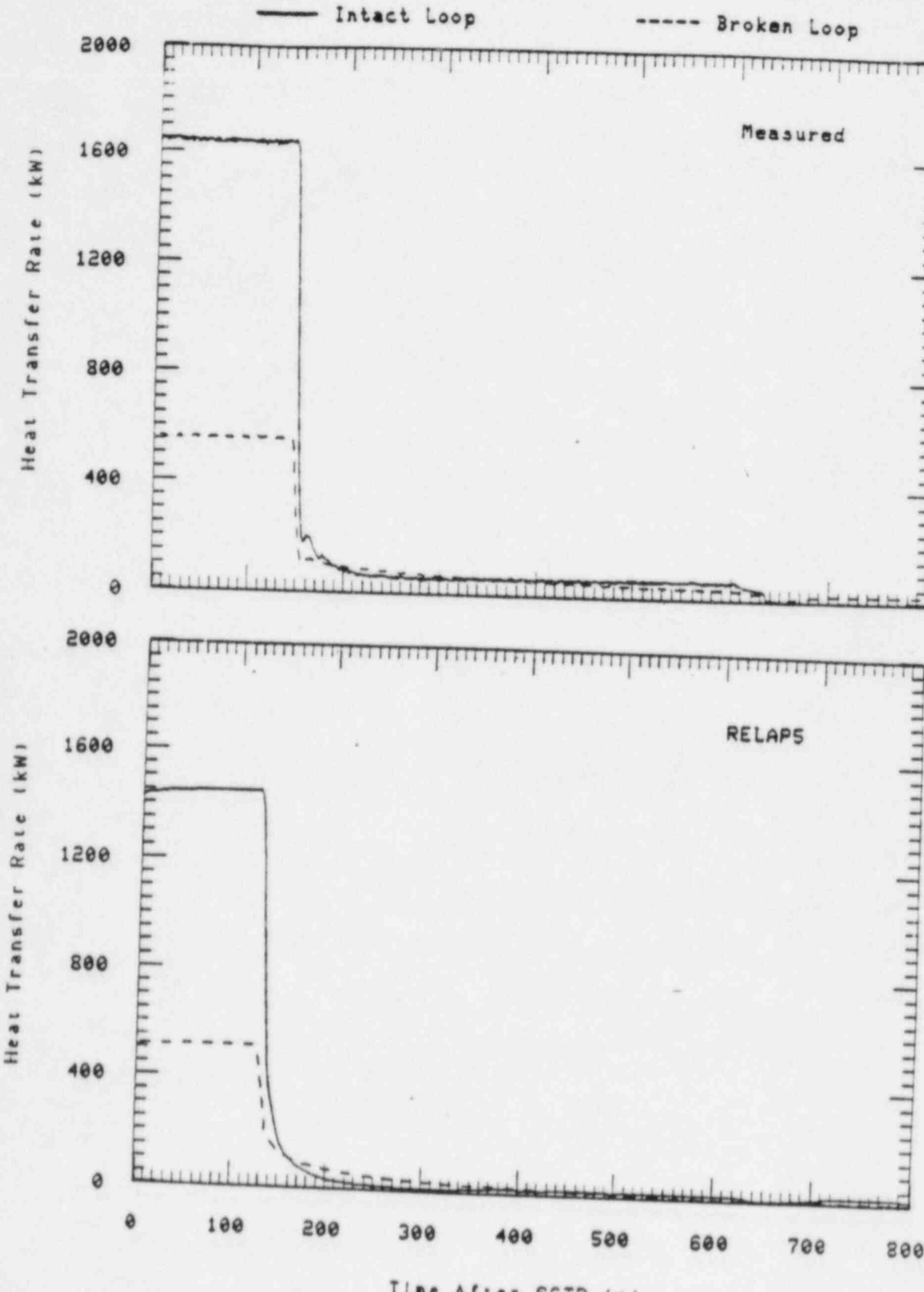

Figure 43. RELAP5 comparison of primary-to-secondary heat transfer rates (0 - 800 s).

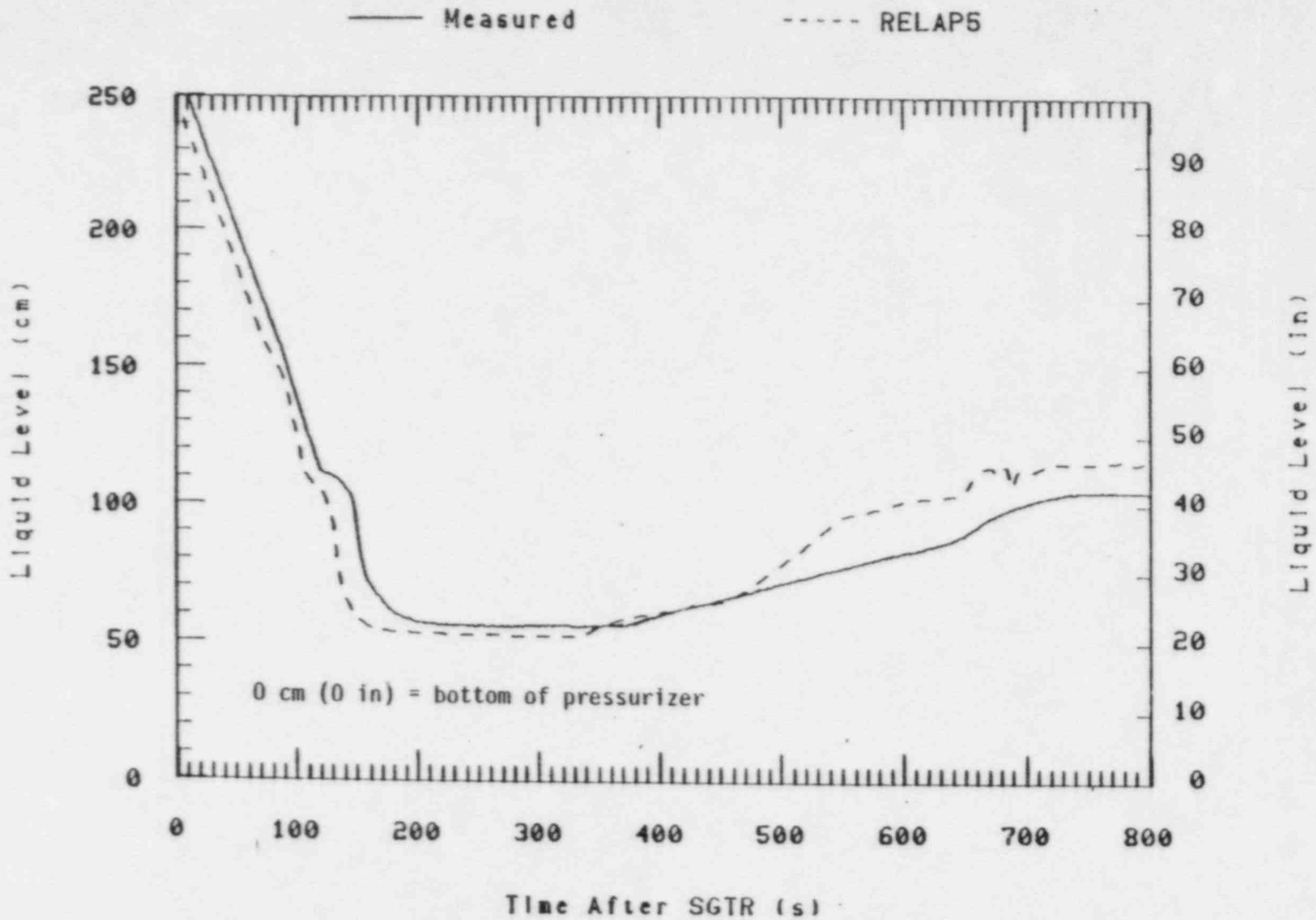

Figure 44. RELAP5 comparison of collapsed pressurizer liquid level (0 - 800 s).

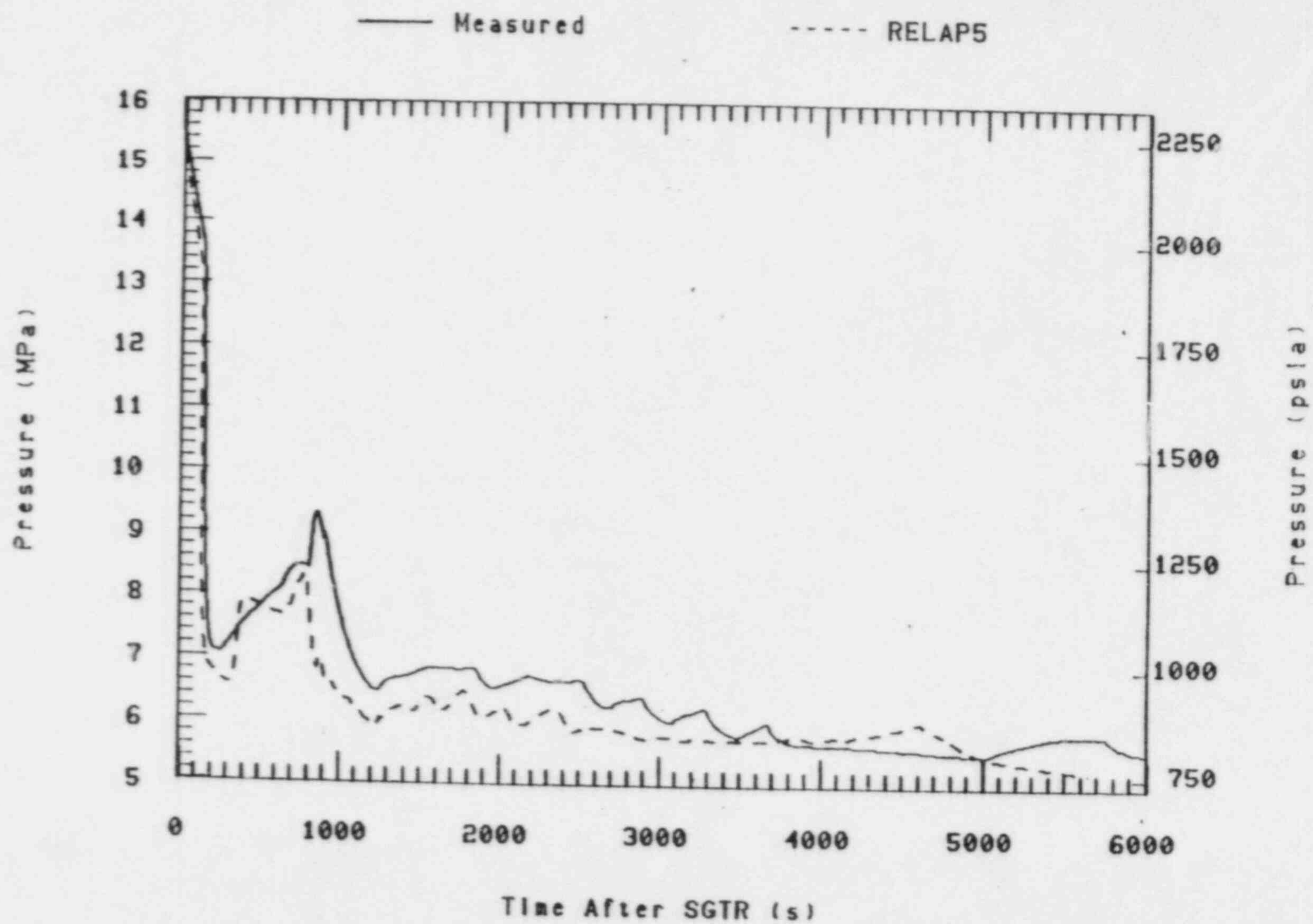

Figure 45. RELAP5 comparison of pressurizer pressure (0 - 6000 s).

and the test the local low pressure in the pressurizer drew more mass from the primary system than was injected by SI. This mass loss combined with the mass loss via the break caused the vessel level (Figure 46) to drop. The vessel level dropped enough in the test that the upper head external heaters had to be turned off. This was not calculated by RELAP5. However, RELAP5 accurately calculated the fill rate of the pressurizer as a result of auxiliary spray operation (Figure 47). The lower vessel level observed in the test was the result of the larger break flow in the test than calculated.

4.4 Pressurizer Internal Heater Operation

The objective in powering the pressurizer internal back-up and variable heaters was to restore primary pressure control to the pressurizer. Pressure control can only be restored if there are no voids in the primary system except in the pressurizer, and the mass forced out of the pressurizer is greater than the break flow plus an additional amount that compensates for volume shrink with SI off. With the smaller calculated break flow, the conditions for restoring pressure control occurred earlier in the calculation than in the test.

In both the calculation and the test all the voids were removed from the primary system except for the pressurizer (5700 s in the test, 3700 s in the calculation). However, while RELAP5 calculated the voids to be filled from the liquid forced out of the pressurizer, liquid from both the pressurizer and SI flow was required to collapse the voids in the test. Since SI had been used to maintain the upper head level in both the calculation and the test, the extra mass required to collapse the voids in the test was primarily the result of the larger break flow. The larger shrinkage in the test was insignificant compared to the larger break flow.

Despite the larger break flow in the test, RELAP5 calculated very nearly the same rate of mass flow out the pressurizer forced by the internal heaters, operating between 3700 and 5500 s in the test and between 3120 and 3848 s in the calculation (Figure 48). The upper head was calculated to fill faster, by 5700 s in the test and 3700 s in the

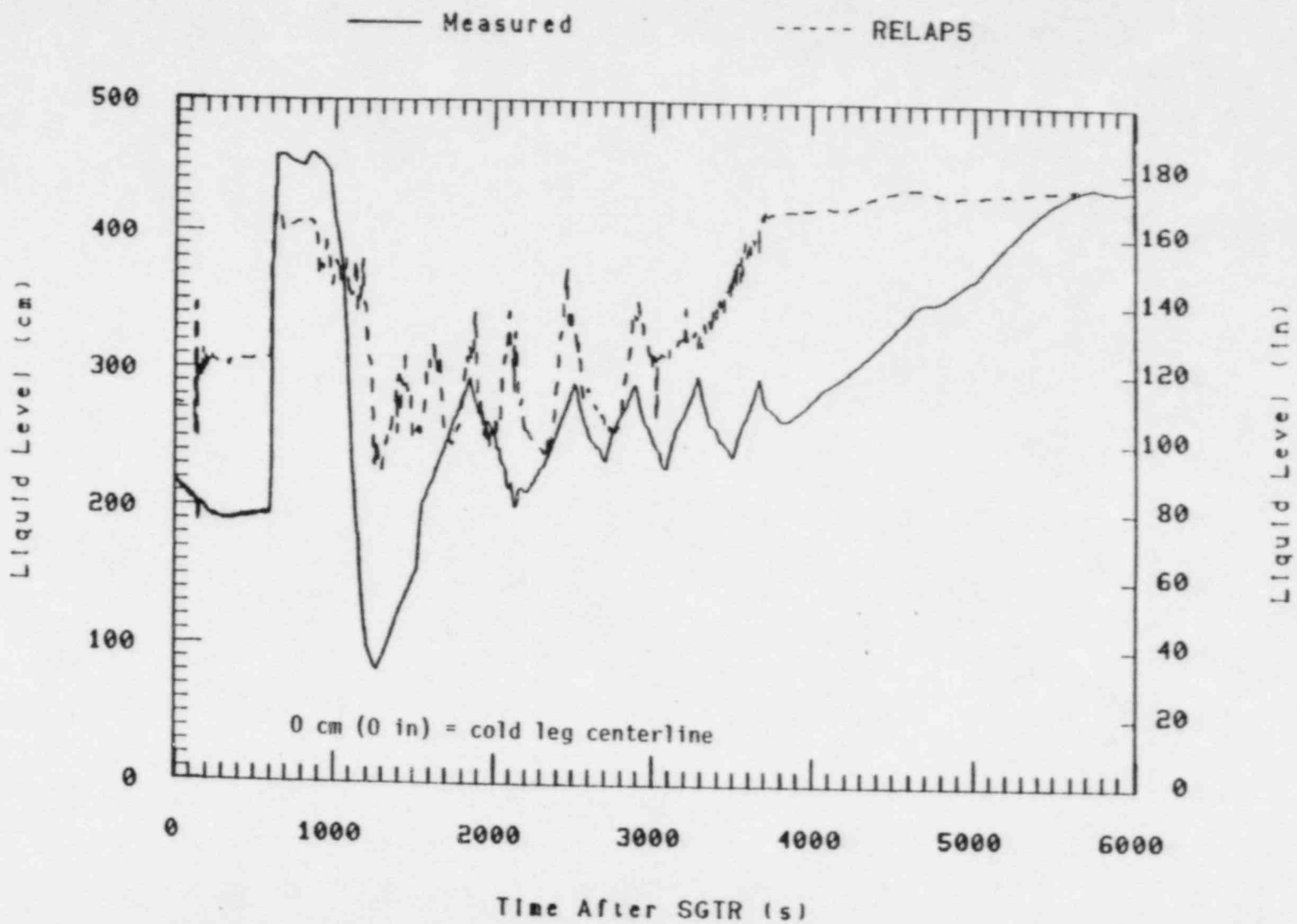

Figure 46. RELAP5comparison of collapsed vessel liquid level, +421 -13 (0 - 6000 s).

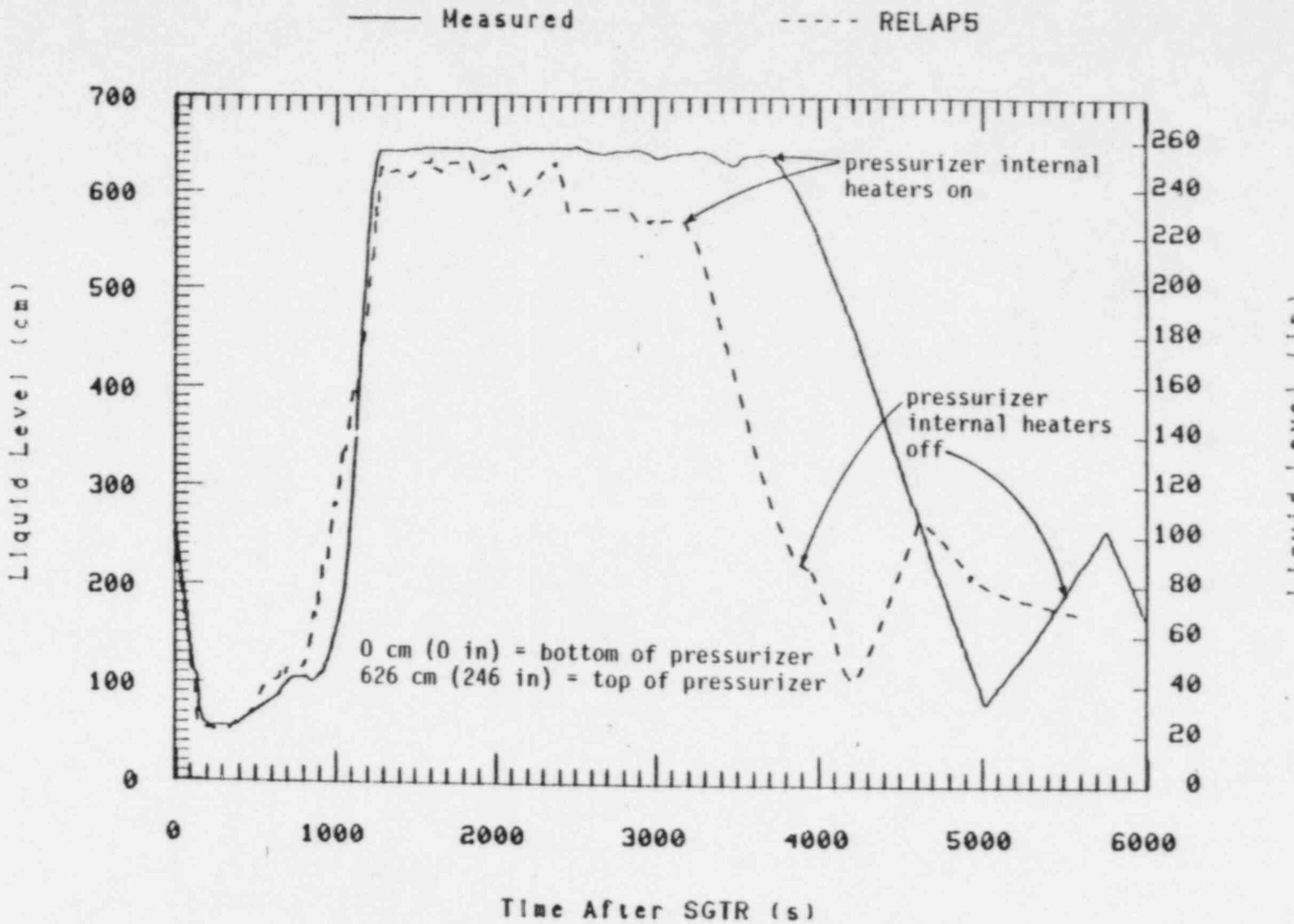

Figure 47. RELAP5 comparison of collapsed pressurizer liquid level (0 - 6000 s).

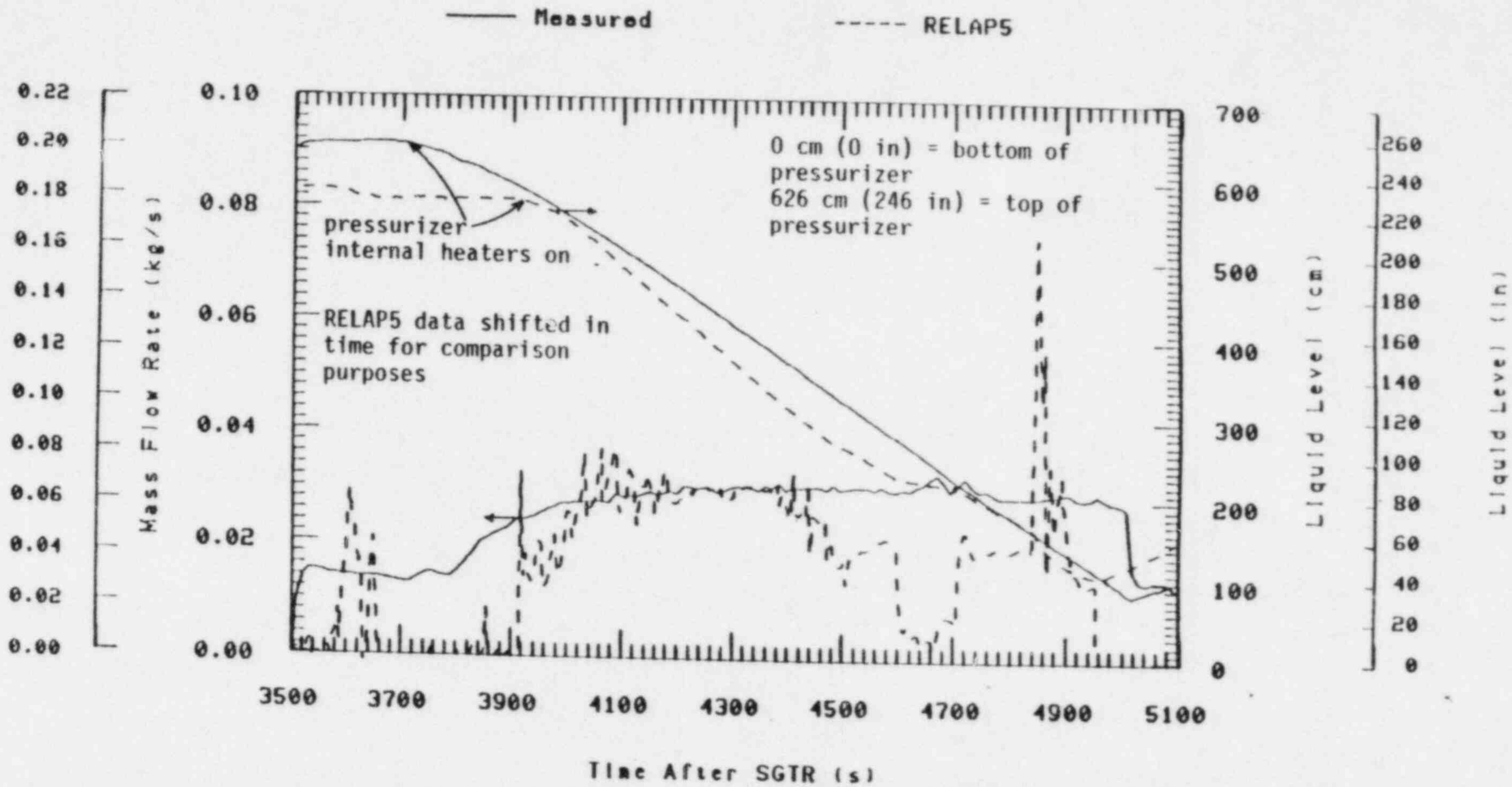

Figure 48. RELAP5 comparison of pressurizer surge line flow and collapsed pressurizer level during pressurizer heater operation, SI off.

calculation (Figure 49), because of the lower calculated break flow (Figure 50). Also the upper head was fuller in the calculation at heater initiation because the lower break flow had not depleted the primary as quickly after previous SI operation. As a result, liquid remained in the pressurizer when the upper head became liquid solid in the PAD calculation. This, combined with the lower break flow, enabled RELAP5 to calculate the restoration of pressure control to the pressurizer before the low level SI setpoint [80 cm (31.5 in)] was reached. This did not happen in the test. Because of the larger break flow, pressurizer pressure control was not restored until the broken loop steam generator was liquid full, and the break flow was thereby reduced.

4.5 SI Operation

As discussed in the previous section, when the primary is liquid solid, except for the pressurizer, and more mass is injected than flows out the break, the primary pressure rises. SI flow, then, always causes the pressure to rise after the primary system is liquid solid. RELAP5 correctly calculated this phenomenon (Figure 51), although the pressurizer level increased faster (Figure 52) due to the lower break flow.

In summary the initial transient response was well calculated by RELAP5. The calculation accurately showed the phenomena that occurred because of delayed pump trip, pump stoppage, pressurizer auxiliary spray operation, and SI operation. The failure to accurately calculate the break flow precluded calculating the correct response to internal pressurizer heater operation. Also, fewer calculated SI flow cycles were necessary prior to heater operation due to the lower calculated break flow. Posttest analysis will include an indepth study of the system response to boundary conditions such as break flow and heat loss.

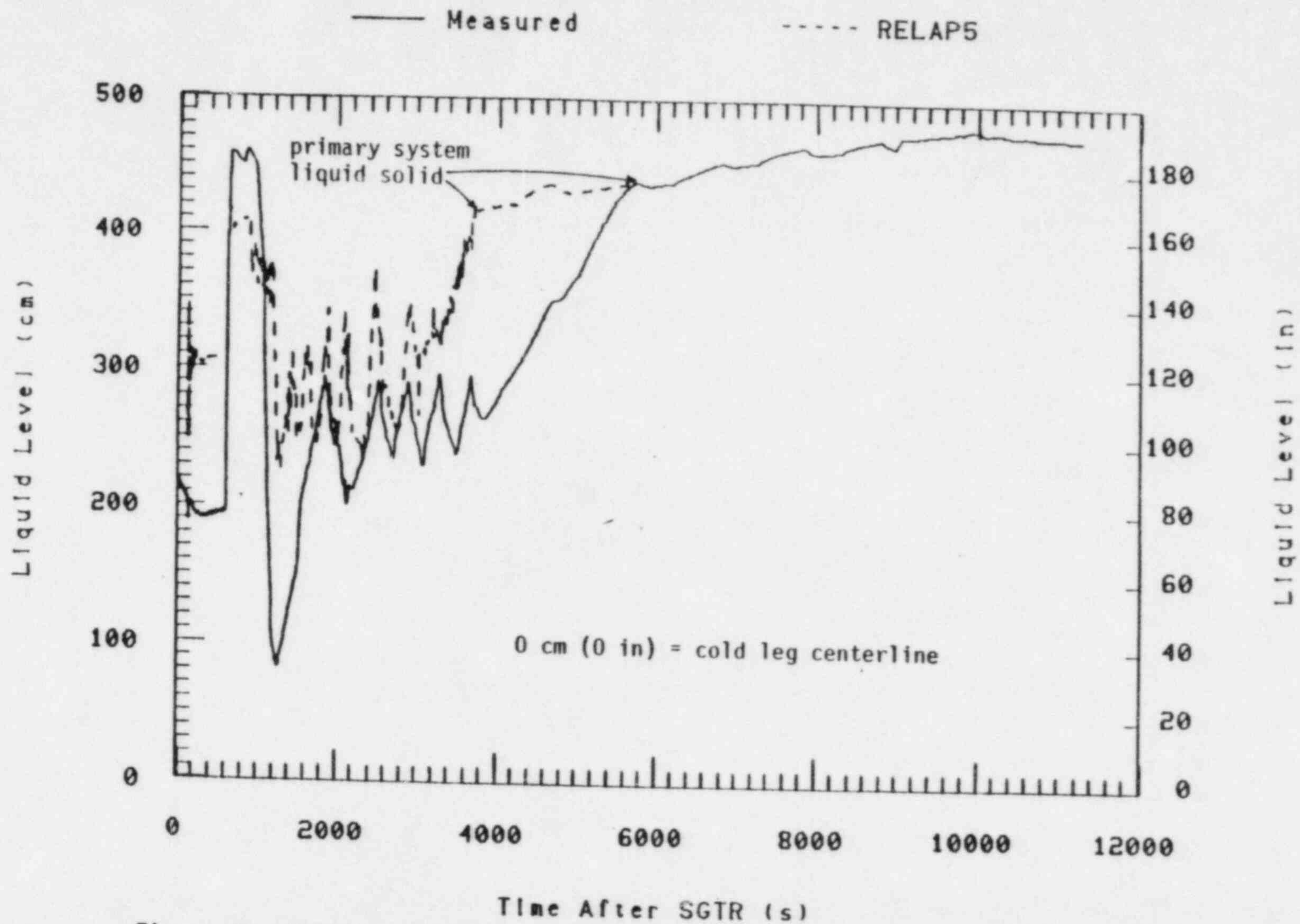

Figure 49. RELAP5 comparison of collapsed vessel liquid level, +421 -13 (0 - 12000 s).

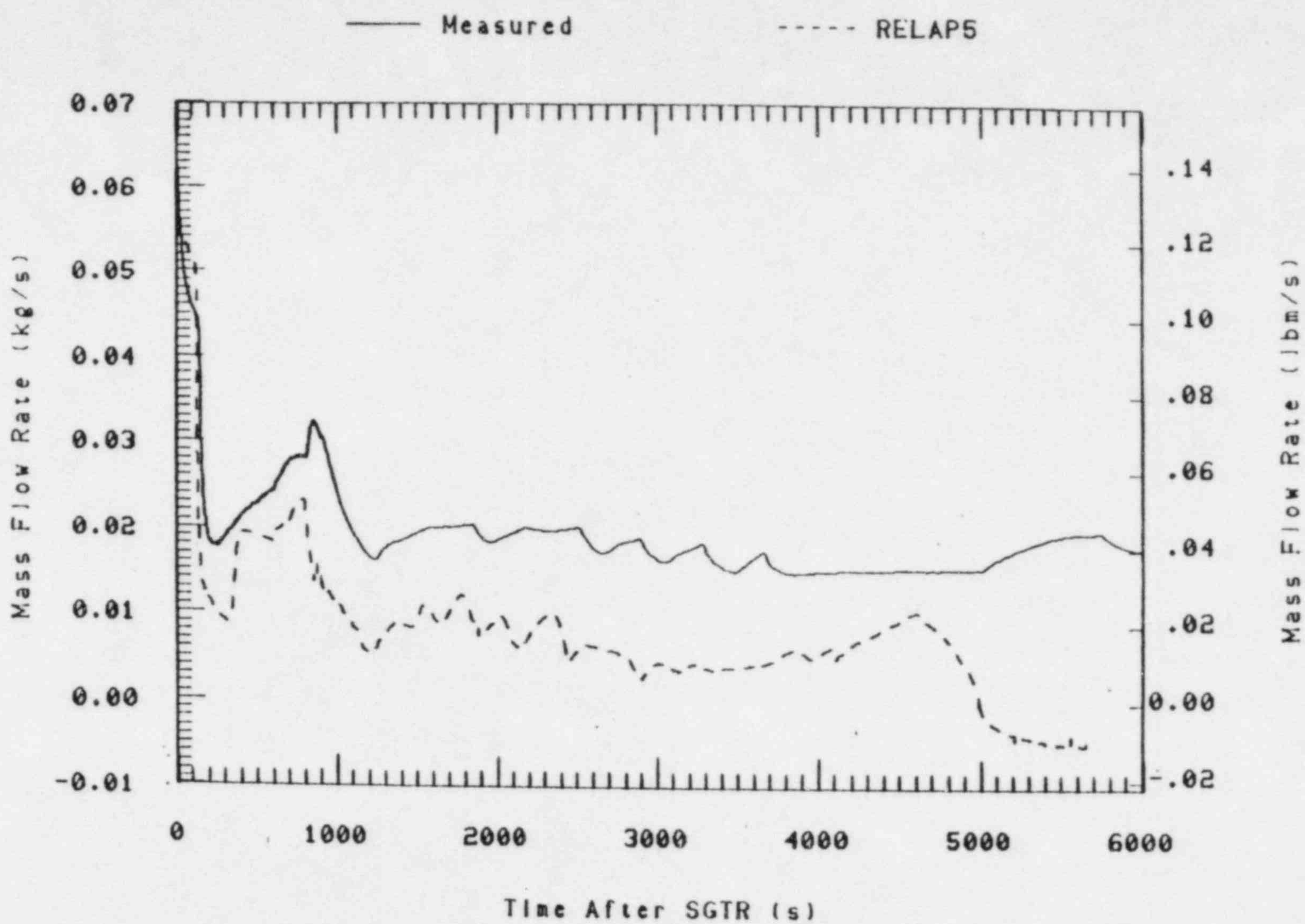

Figure 50. RELAP5 comparison of break flow (0 - 6000 s).

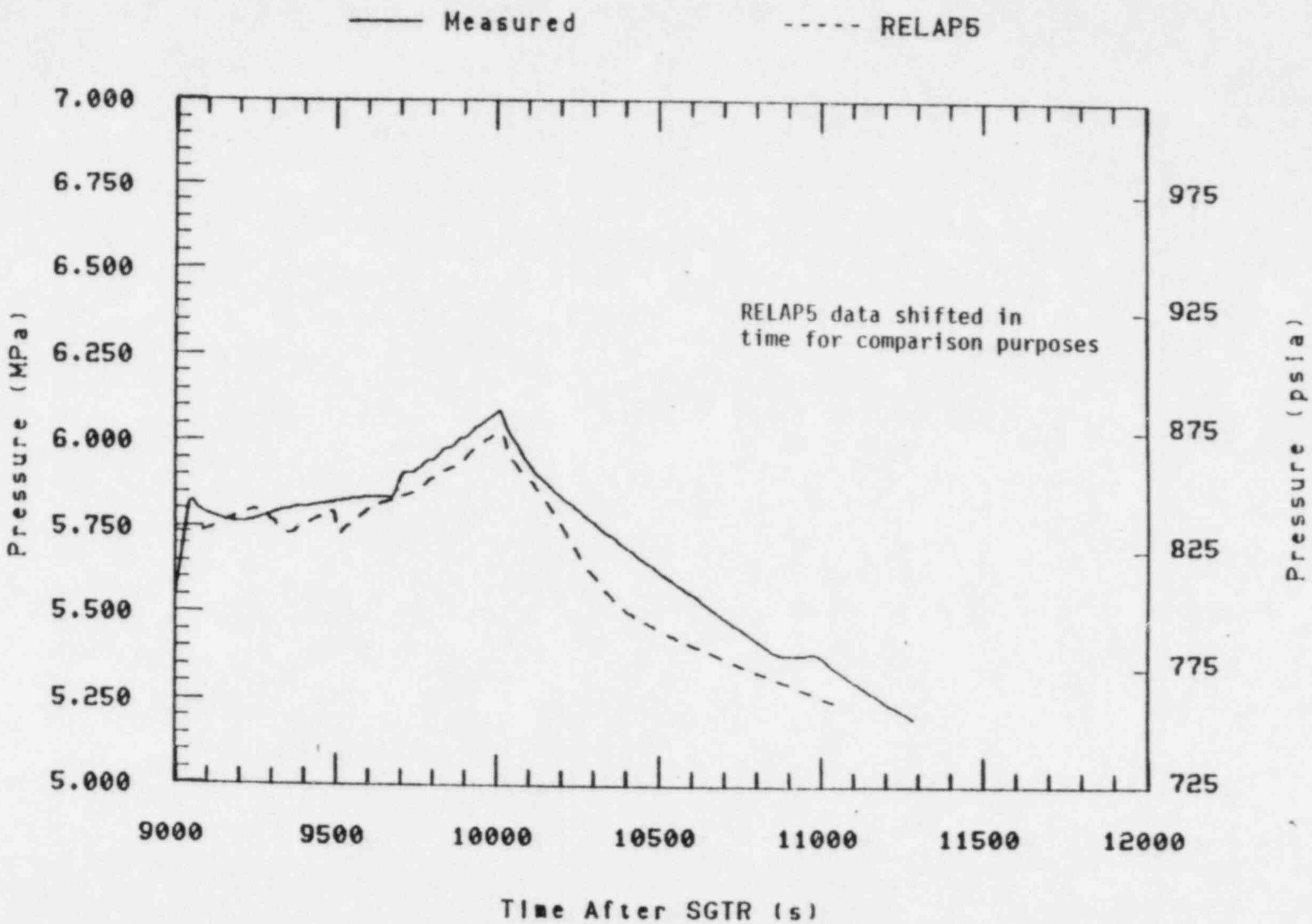

Figure 51. RELAP5 comparison of pressurizer pressure during SI operation and pressurizer heaters off.

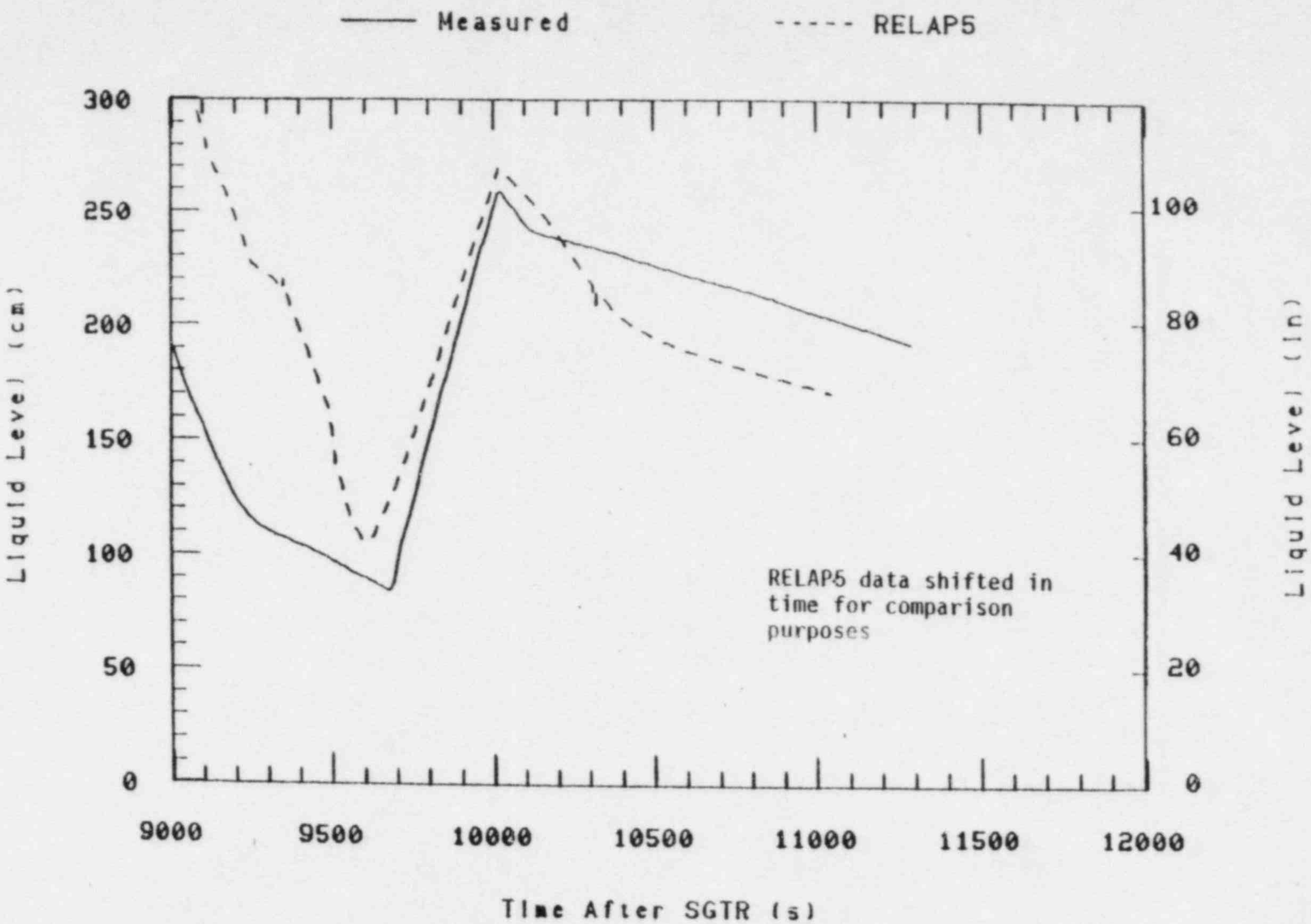

Figure 52. RELAP5 comparison of collapsed pressurizer liquid level during SI operation and pressurizer heaters off.

5. CONCLUSIONS

The following conclusions have been drawn based on a preliminary analysis of test S-SG-4, and a brief comparison of delayed pump trip (S-SG-4) and early pump trip (S-SG-8).

1. Delaying pump trip resulted in the following response.

   - Primary pressure falls to a lower level early in the transient.

   - Primary to secondary break flow is lowered.

   - The primary system is not voided significantly and a pressurizer level is established early in the transient.

   - More energy is transferred from the primary to secondary systems, resulting in subcooling of the hot legs while the pumps operate.

2. Delayed pump trip caused more secondary coolant release through the broken loop ADV.

   - Increased heat transfer from the primary to the broken loop secondary raised secondary pressure opening the ADV frequently during the early part of the transient.

3. Pump trip results in a primary system pressure recovery.

   - Tripping the pumps at SIS or at 600 s produces a primary pressure recovery resulting from reduced primary to secondary heat transfer.

4. Pressurizer auxiliary spray produced significant depressurization in the primary system.

   - Condensation of steam in the pressurizer reduced the pressure until the pressurizer filled with liquid.

5. Intact loop steam and feed effectively cooled the primary system.

   - The loop hot legs were subcooled early in the transient.

   - A controlled depressurization was achieved while maintaining subcooled primary fluid conditions.

6. Pressurizer back-up and variable heaters were not able to control primary pressure during a single-tube break.

   - Backup and variable heaters could not compensate for flow out the pressurizer and tube rupture.

   - The warm-up heaters produced enough steam to compensate for flow out of the pressurizer.

   - Stopping break flow by pressurizing the broken loop steam generator allowed heater pressure control.

7. SI was the dominant factor in primary pressure control.

   - SI filling repressurized the primary during early portion of the transient.

   - SI filling dominated any pressurizer heater effects.

8. RELAP5 accurately calculated the phenomena that occurred for most of the operations during the test.

   - Well calculated were the phenomena that occurred because of delayed pump trip, pump stoppage, pressurizer auxiliary spray operation, and SI operation.

9. RELAP5 failed to accurately calculate the break flow which had a significant effect on the transient response.

   - Fewer SI cycles were calculated prior to internal pressurizer heater operation.

   - The response to the internal pressurizer heater operation was not well calculated.

   - The timing of the important events was poor.

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16. ABSTRACT *(200 words or less)* Results of a preliminary analysis of the seventh test performed in the Semiscale Mod-2B Steam Generator Tube Rupture Series are presented. Test S-SG-4 imulated a pressurized water reactor accident initiated by the double-ended offset shear of one cold side steam generator tube. The transient included a 600-second period during which only automatic plant protection systems responded to the initiating event. Main coolant pump trip, which is generally initiated at the safety injection signal (SIS), was delayed until 600 s. Pump trip was followed by a 200-second period during which no operator action or automatic plant response occurred, so that pump trip effects could be clearly assessed. Plant recovery commenced at 800 s with the initiation of intact loop steam and feed and pressurizer auxiliary spray. Safety injection (SI) was used throughout the transient to maintain primary system inventory. Pressurizer heaters were used to establish pressure control in the pressurizer and control the rate of primary depressurization. The test results provided a measured evaluation of the effect of delayed pump trip on tube rupture signatures, the effectiveness of auxiliary spray in filling the pressurizer and reducing primary pressure, and the effectiveness of pressurizer heaters in controlling primary pressure, with a liquid filled pressurizer. The test showed that the prescribed operator response was adequate to recover the Semiscale system from a one-tube rupture.

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