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QUICK LOOK REPORT FOR SEMISCALE MOD-2B TEST S-SG-5

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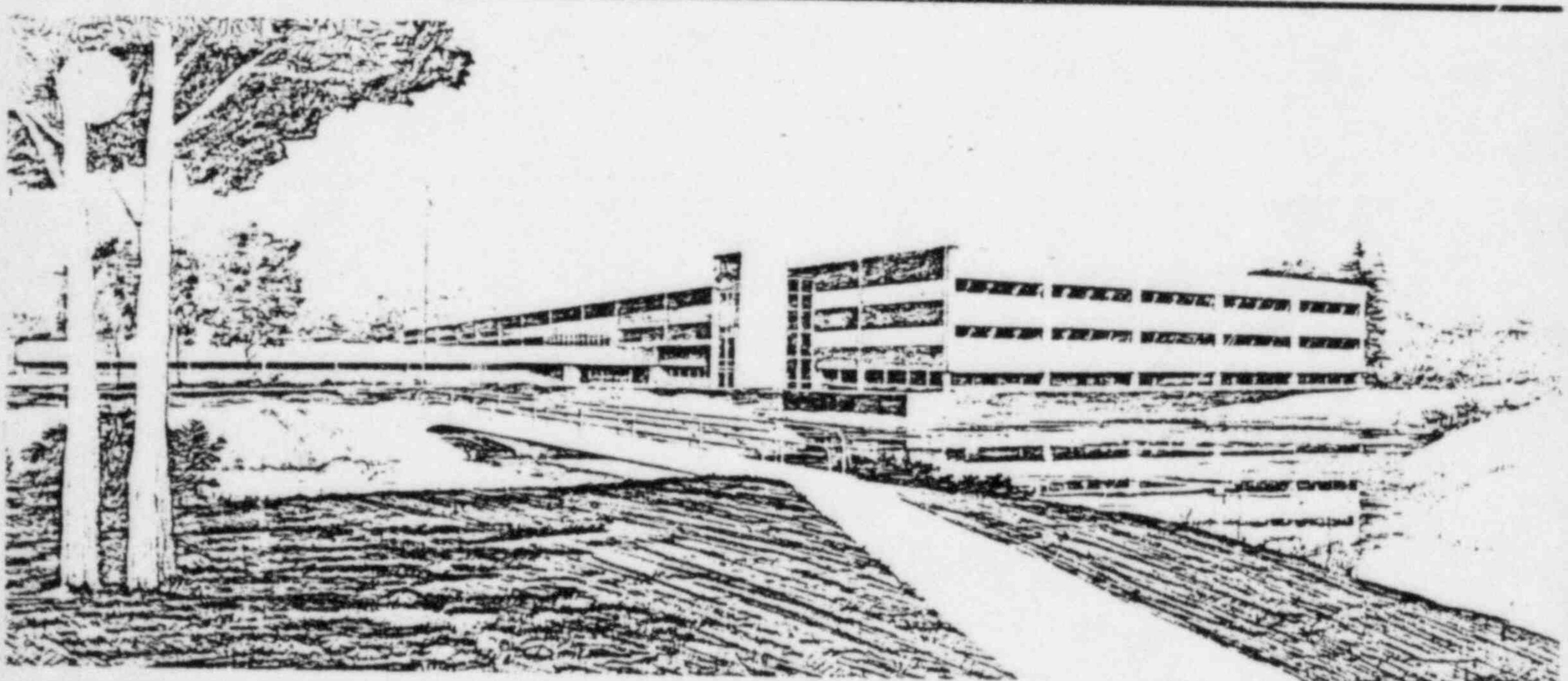

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QUICK LOOK REPORT FOR SEMISCALE MOD-2B TEST S-SG-5

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ABSTRACT

Results of a preliminary analysis of the third test performed in the Semiscale Mod-2B Steam Generator Tube Rupture Series are presented. Test S-SG-5 simulated a pressurized water reactor accident initiated by a double-ended offset shear of five hot side steam generator tubes. The transient included an initial 80-second period during which only automatic plant protection system response to the initiating event occurred. This period was followed by an operator-induced recovery procedure to establish an early steam and feed condition in both the unaffected and affected loop steam generators. The early secondary cooldown terminated at 600 s and was followed by use of SI and pressurizer heaters to maintain system inventory and recover primary system pressure control in the pressurizer. The test results provided a measured evaluation of the effectiveness of an early secondary steam and feed on reducing primary system pressure, the effect of high pressure injection system operation on recovering primary system inventory and pressure control, and the effectiveness of pressurizer heaters in controlling primary system pressure. The test showed that the prescribed limited operator response was adequate to recover the Semiscale system from a simulated five-tube rupture.

SUMMARY

This report presents a preliminary analysis of the Semiscale MOD-2B Steam Generator Tube Rupture Series (SG) Test S-SG-5. S-SG-5 is the third 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-5 simulated a pressurized water reactor transient initiated by a double-ended offset shear of five hot side steam generator tubes. 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 validate computer code capability.

Test S-SG-5 was designed in three parts: (a) an initial 80 s period in which only automatically functioning plant protection systems were assumed to operate, (b) an early steam and feed in both steam generator secondaries for 520 s, followed by (c) an operator controlled recovery period including an unaffected loop steam generator steam and feed, pressurizer heater operation, and termination of safety injection (SI).

The signature of this five-tube rupture was characterized by a relatively rapid decrease of the primary coolant system pressure to saturated conditions in the hot legs as primary coolant system fluid flowed through a simulated five-tube break into the affected loop steam generator secondary. Automatic protective actions that influenced the pressure response during this early period were core scram and main steam isolation valve (MSIV) closure. Both were initiated by a low pressurizer pressure trip at 13.1 MPa (1900 psia). Main coolant pump trip, feedwater termination, auxiliary feedwater start, and safety injection start were all initiated on a safety injection signal at a pressurizer pressure of 12.5 MPa (1814 psia). Part of the pressure response during this early period was a rapid increase in secondary pressure in both loops as

primary-to-secondary heat transfer raised 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 affected and unaffected steam generators. The five-tube break flow was sufficient to leave the vessel upper head collapsed liquid level near the hot legs at the end of 600 s. Following the attainment of saturation conditions in the hot legs, the primary and secondary system pressures remained fairly constant as safety injection (SI) fluid entered the primary and break flow left the primary system to the affected loop steam generator secondary. Decay heat was removed by natural circulation.

An early steam and feed condition was established at SCRAM + 60 s in both the affected and unaffected loop steam generator secondaries. This represented an attempt to cool the primary system before significant flow into the affected loop steam generator occurred.

The recovery procedure in S-SG-5 was initiated at 600 s to simulate a period for operators to identify the tube rupture. Operator response at 600 s included operating the unaffected loop ADV in an attempt to depressurize the unaffected loop secondary and thus increase the loop heat sink. SI was turned off after establishing acceptable levels in the vessel and pressurizer to control primary pressure and terminate atmospheric release from the affected loop generator. Pressurizer heaters were used to control system pressure within a specified band, after which the test was terminated.

Overall system response to the combined recovery methods, including unaffected loop steam and feed, SI cycling, and pressurizer heater operation, was to slowly fill the affected loop secondary, the vessel, and the pressurizer with SI. After establishing level, compression from SI caused the primary and the affected loop secondary pressures to rise above the ADV setpoint. SI was then cycled as necessary to control system pressure below the affected loop ADV setpoint, until the pressurizer high level trip was reached. Pressurizer heaters were finally used to control pressure in a specified band below the affected loop ADV setpoint.

A comparison of the system pressure response for the cold side and hot side five-tube rupture experiments (S-SG-2 and S-SG-5, respectively) shows similar responses except for the timing of events. A slightly higher break flow in the cold side rupture, due to higher density in the cold leg, produced early pressurizer emptying. No phenomenological differences were noted.

Comparisons between the pretest best-estimate RELAP5 calculation and test data are presented in this report. The calculated and measured initial conditions agreed well. For most of the transient, comparisons of the calculated and measured responses show good qualitative agreement. Underprediction of the break flow did however cause the primary pressure to be overpredicted and the filling of the affected loop steam generator to occur later than observed in the test. The calculated and measured primary pressure response to the operation of the pressurizer internal heaters was significantly different. Operation of the pressurizer internal heaters was able to control the primary pressure during the recovery phase of the transient in the calculation, but was unable to in the test prior to restarting SI. The reason for this difference in pressure response is believed to be due to differences in calculated and test pressurizer fluid conditions.

ACKNOWLEDGEMENT

The authors thank G. G. Loomis and K. E. Sackett for their assistance in preparing this report.

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FIGURES

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1. INTRODUCTION

This report documents preliminary results from Semiscale Mod-2B test S-SG-5, the third experiment performed in the Semiscale Steam Generator Tube Rupture (SG) Test Series.[1] 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 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-5 simulated a pressurized water reactor transient initiated by a double-ended offset shear of five hot side steam generator tubes. The test was designed in three parts, an initial 80 s period in which only automatically functioning plant protection systems were assumed to operate, followed by an operator induced secondary steam and feed of both steam generators, and a subsequent operator controlled recovery period, which included steaming and feeding of the unaffected loop steam generator secondary, cycling of safety injection (high pressure injection and charging pumps), and operation of pressurizer heaters to control primary pressure. Automatic signals started safety injection (SI), closed main steam isolation valves, turned off main feedwater, started auxiliary feedwater, tripped the main coolant pumps, and shut off pressurizer heaters. An early secondary cooldown was initiated at 82 s (SCRAM + 60 s), and consisted of steaming both the unaffected and affected loop secondaries through their respective atmospheric dump valves (ADVs) and feeding with auxiliary feedwater. This procedure simulated optimum use of the secondary heat sinks to depressurize and cool the primary system, when minimum contamination of the secondaries had occurred. Recovery operations were initiated at 600 s after the occurrence of the break. (A time of 600 s is

within the range of transient identification and response times that have occurred, or are expected to occur, in actual plant transients.) The S-SG-5 recovery included steaming the unaffected loop secondary system through the ADV and feeding with auxiliary feedwater. The ADV was cycled in an attempt to maintain primary pressure at 5.6 ± 0.14 MPa (812 ± 20 psia). SI was used during recovery to fill the primary pressure vessel, the affected loop secondary, and the pressurizer to an acceptable level for pressurizer heater operation. SI was then cycled to control primary system pressure. Pressurizer heaters were used to maintain the primary system pressure at 5.6 ± 0.14 MPa (812 ± 20 psia). The test was terminated when primary pressure control had been demonstrated.

A preliminary analysis of test S-SG-5 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 with external downcomer, tube-and-shell steam generators and associated loop piping with circulation pumps. The affected loop (the loop in which the steam generator tube rupture occurs) is scaled to represent one loop of a four-loop PWR and the unaffected 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 effluent 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 unaffected and affected 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 designed to pass scaled flow corresponding to ADV operation in a PWR. On 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 affected and unaffected loops. The parallel flow path arrangement allows

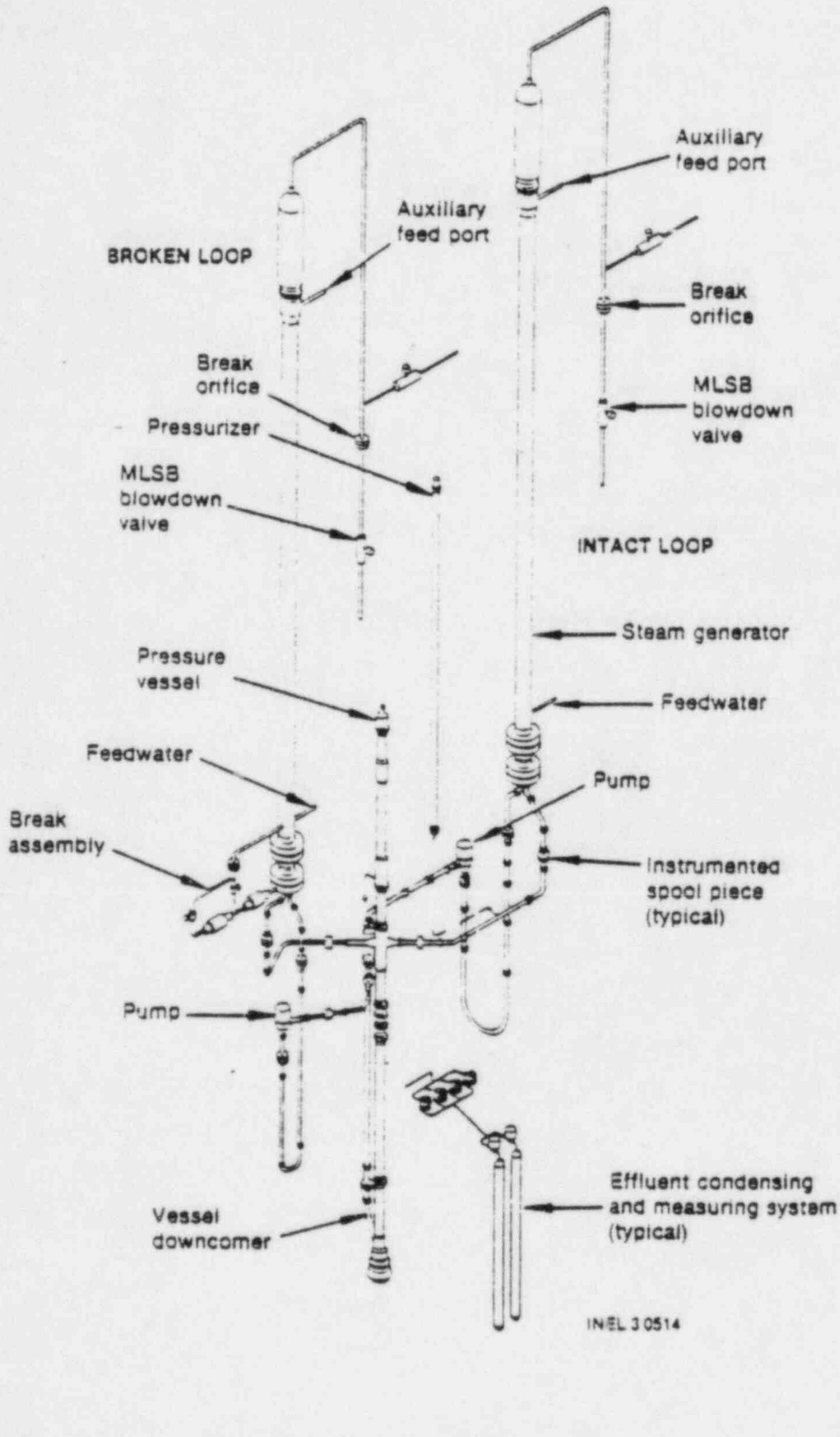

Figure 1. Semiscale Mod-2B system as configured for the SG test series.

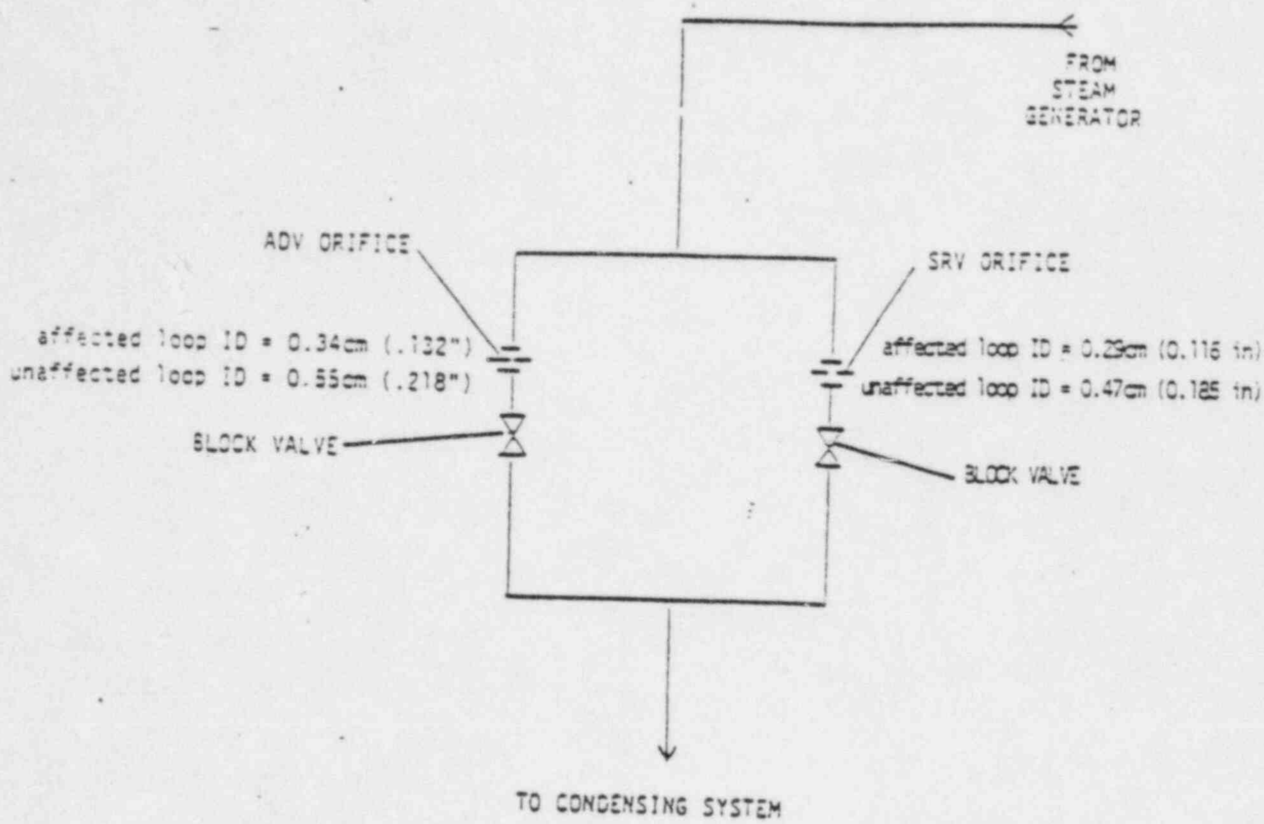

Figure 2. ADV and [illegible] relief valve system.

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 (848 psia) in the affected loop and 6.55 MPa (949 psia) in the unaffected loop. The first stage SRV relief setpoint is 5.94 MPa (861 psia) in the affected loop and 6.74 MPa (977 psia) in the unaffected loop.[a] Figures 3 and 4 show mass flow rate versus pressure for ADV and SRV operation for the affected and unaffected loops, respectively. The ADV can also be latched open manually during the recovery procedure with the SRV block valve shut.

The pressurizer PORV 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 tube rupture break assembly connects the primary coolant system with the secondary side in the vicinity of the affected loop steam generator tube sheet (see 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

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

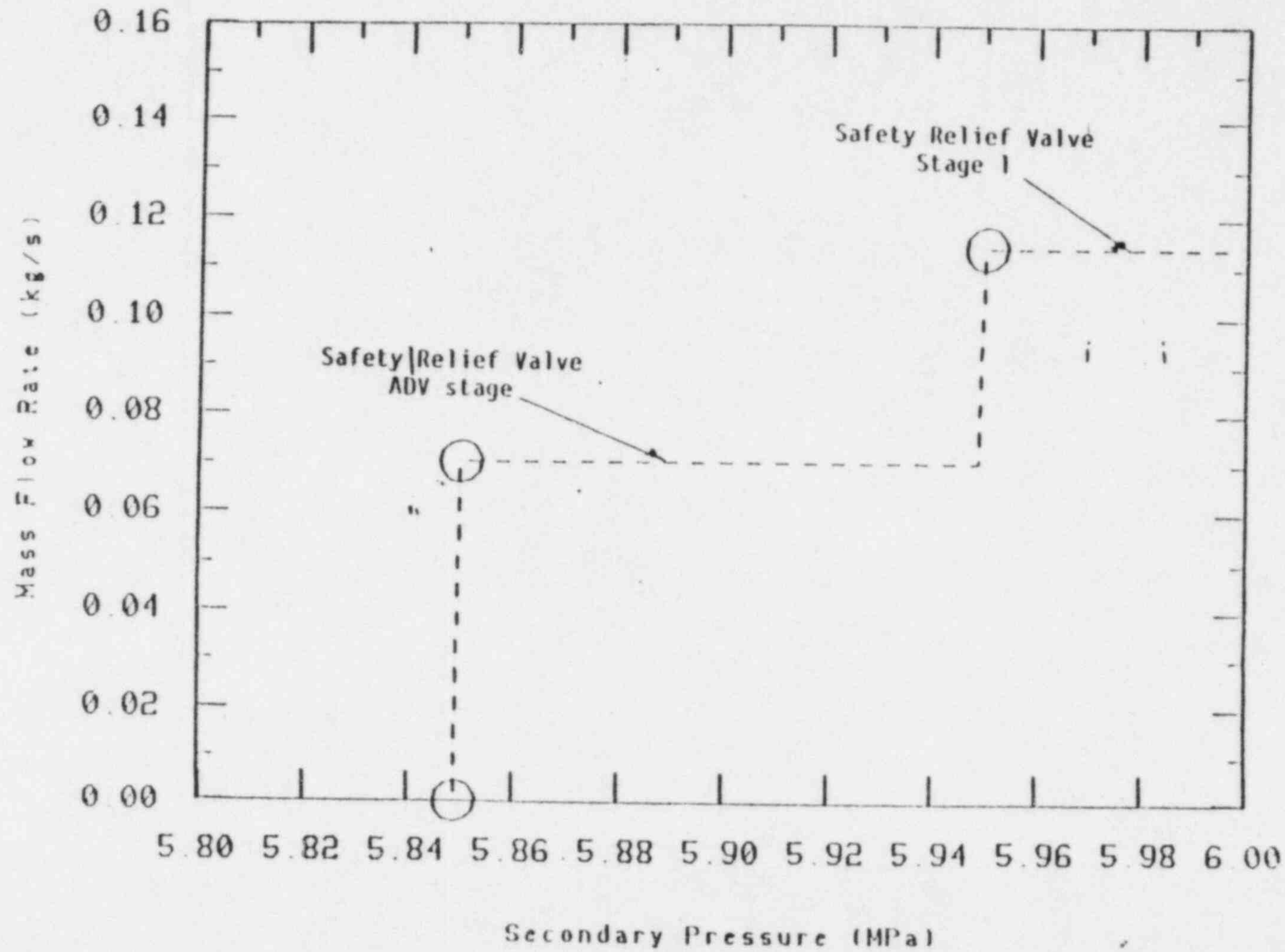


Figure 3. Broken loop steam generator safety relief valve operation.

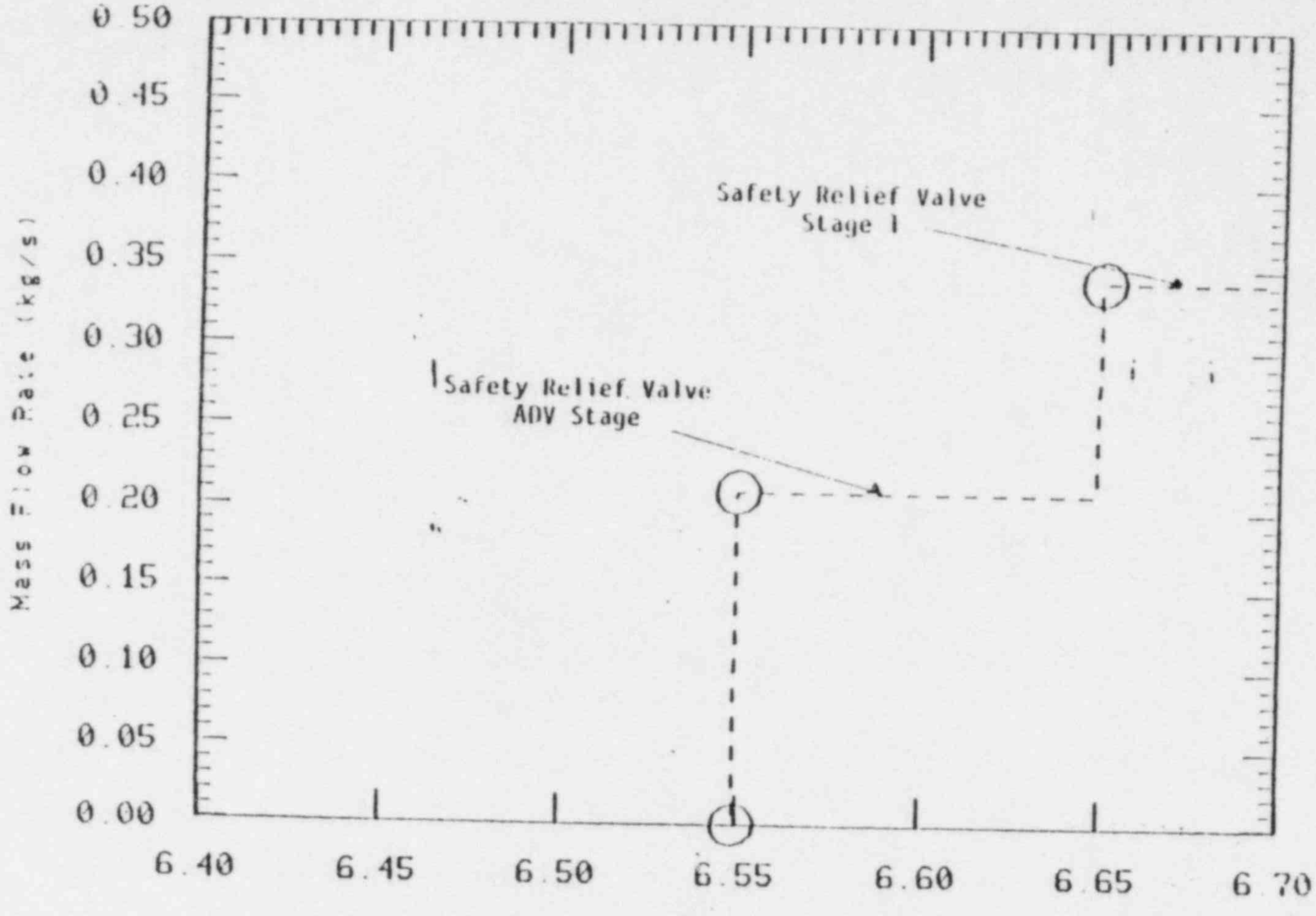


Figure 4. Intact loop steam generator safety relief valve operation.

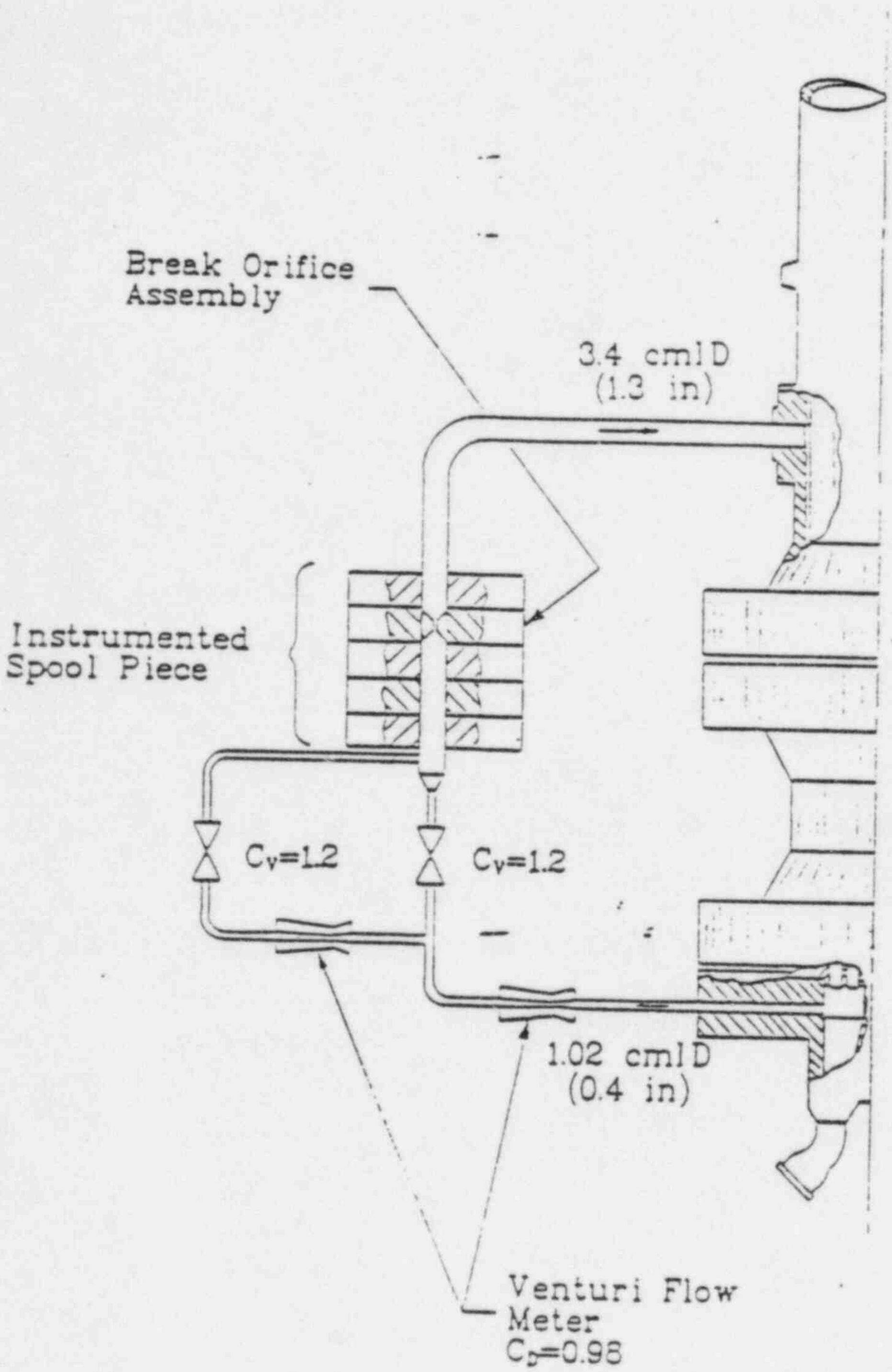
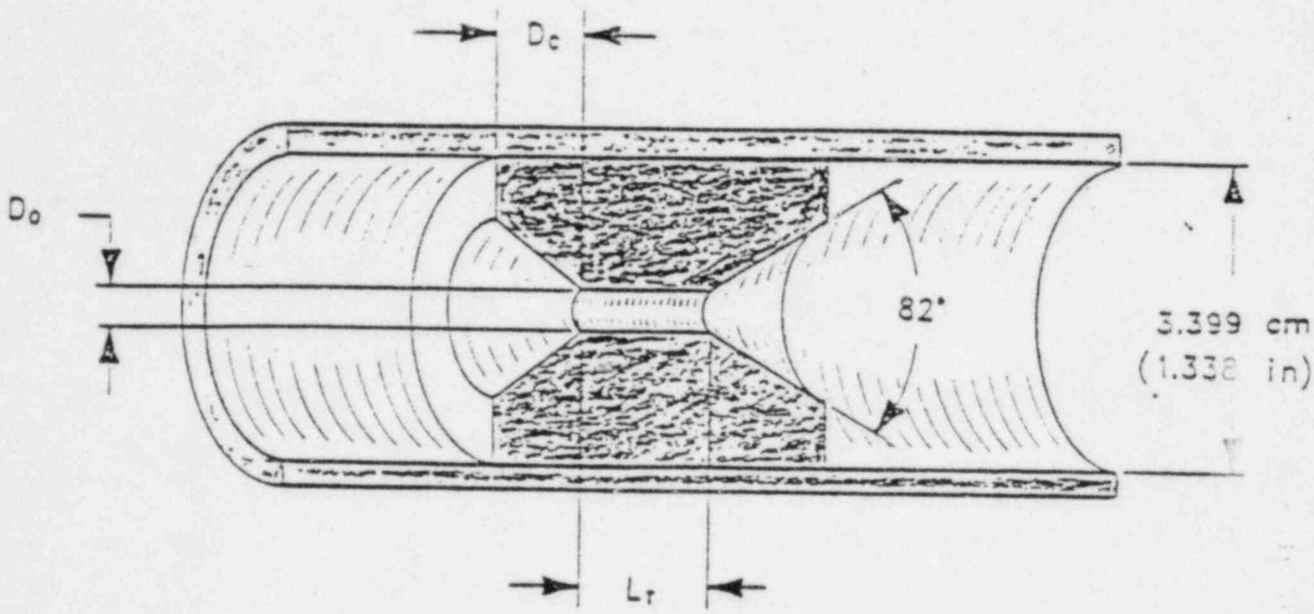


Figure 5. Semiscale tube-rupture break assembly.

generator. For test S-SG-5, the break assembly was on the hot 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-5 used the 5-tube break orifice with a 0.175 cm (0.0689 in) ID. The flow tube was calibrated in single phase water and can be used to monitor break mass flow rate.

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, unaffected loop pump suction, affected loop pump suction and pressurizer. The total power provided by these heaters is about 47 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) 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 in S-SG-5. Power to the vessel upper head and upper plenum heater banks was terminated when the indicated liquid level fell below 20% of full for the portion of the vessel covered by the particular heater.

Pressurizer internal heaters were used in the following manner during the S-SG-5 recovery in an attempt to maintain primary system pressure control in the pressurizer. Three types of pressurizer heaters were used, back-up heaters, variable heaters, and warm-up heaters. The back-up heaters were operated in an on/off mode only, supplying a total maximum power of 1170 watts from 2 heater rods. These heaters were controlled automatically to energize when the primary pressure decreased to 15.5 MPa (2253 psia) and to turn off when pressure returned to 15.7 MPa (2273 psia). The variable heaters supplied up to 1185 watts total power from 2 heater rods. The controller was set to maintain primary pressure at 5.6 ± 0.14 MPa (812 ± 20 psia). These heaters were energized at



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.

5.6 MPa (812 psia), and as the primary pressure decreased, the power increased to a maximum at 5.46 MPa (792 psia). As the pressure rose, power was reduced until it was terminated at 5.74 MPa (832 psia). Warm-up heaters were controlled manually and supplied up to 14 kW total power from 6 rods.

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 affected loop secondary. Table 2 contains a sequence of significant events for S-SG-5. The first 82 s involved automatically occurring events such as core scram, main steam isolation valve closure, auxiliary feedwater start and main feedwater stop, main coolant pump trip and HPIS/charging flow initiation. The initiating events for these actions were a low pressurizer pressure trip (13.1 MPa (1900 psia)) and SI signal (12.51 MPa (1814 psia)). A time of SCRAM + 60 s (82 s after tube rupture) was the initiating event for the early cooldown of both the affected and unaffected loop secondaries. This cooldown involved steaming of both secondaries through their respective ADV's and feeding with auxiliary feedwater. The recovery procedure for S-SG-5 involved intact loop steam and feed, operation of the pressurizer heaters, and cycling of SI. SI included both high pressure injection flow and charging pump flow as described in Reference 1.

The recovery procedure started at 600 s, the simulated time required for operator identification of the tube rupture. Unaffected loop auxiliary feed was controlled by maintaining the secondary water level between 800 and 1050 cm (315 and 413 in.). Affected loop auxiliary feed was terminated at 600 s in an attempt to isolate the secondary. The unaffected loop ADV was cycled to maintain the secondary pressure at the level

TABLE 1. INITIAL CONDITIONS FOR S-SG-5

	Specified	Measured
Primary Cold Leg Flow Rate (Nominal)		
Affected Loop	2.7 ℓ/s (43 gpm)	3.28 l/s (52 gpm)
Unaffected Loop	8.1 ℓ/s (128 gpm)	9.65 l/s (153 gpm)
Pressurizer Pressure	15.6 ± 0.14 (2250 ± 20 psig)	15.47 MPa (2230 psig)
Pressurizer Liquid Volume	0.0102 ± 0.0008 m^3 (0.36 ± 0.028 ft^3)	0.0094 m^3 (0.33 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)	0.2 K (0.36°F)
Core Fluid Temperature Rise	37 ± 1.5 K (66.6 ± 3°F)	38.35 K (69°F)
Steam Generator Pressure		
Affected Loop	5.55 ± 0.07 MPa (793 ± 10 psig)	5.62 MPa (802 psig)
Unaffected Loop	5.55 ± 0.07 MPa (793 ± 10 psig)	5.47 MPa (780 psig)
Steam Generator Secondary Fluid Mass[a]		
Affected Loop	100 + 40, - 20 kg (220 + 88, - 44 lbm)	94.3 kg[b] (208 lbm) 114.6 kg[c] (253 lbm) 92.2 kg[d] (203 lbm)
Unaffected Loop	100 + 40, - 20 kg (220 + 88, - 44 lbm)	105.6 kg[b] (233 lbm) 129.4 kg[c] (285 lbm) 106.4 kg[d] (235 lbm)
Primary Leakage at t = 0	<0.006 kg/s (<0.0132 lbm/s)	0.003 kg/s (0.006 lbm/s)

a. These values were determined from data acquisition system levels following main steam isolation valve closure. Initial conditions were established using process indicated levels which have a high uncertainty in a steaming condition; however the specified process levels where achieved prior to test initiation.

b. Measured with LIS 1117 + 51 for unaffected loop or LBS 1117 + 51 for affected loop.

c. Measured with LIS 1117 + 836 for unaffected loop or LBS 1117 + 836 for affected loop.

d. Measured with LIS 1117 + 825 for unaffected loop or LBS 1117 + 825 for affected loop.

TABLE 2. SEQUENCE OF EVENTS FOR TEST S-SG-5

Specified Criteria	Actual Time (s)	Event
0 s	0	Break flow initiated
0 s	1	Pressurizer internal heaters off
P_{PRZ} = 13.1 MPa (1888 psig)	18	SCRAM
SCRAM	20	Core power shut off
SCRAM	20	MSIV closure
P_{PRZ} = 12.5 MPa (1803 psig)	22	SIS
SIS	22	Main feedwater secured
SIS	22	Auxiliary feedwater initiated
SIS	22	SI turned on
SIS	24.5	Pumps off
SCRAM + 60 s	82*	Unaffected loop--ADV latched open
SCRAM + 60 s	82	Affected loop--ADV latched open
600 s	600	Unaffected loop--ADV cycled to maintain P_s = 3.25 ± 0.14 MPa
600 s	600	Affected loop--ADV closed Affected loop--Auxiliary feed secured
	4700	Affected loop secondary filled, ADV cycling initiated
$\dot{m}_{ADV} = \dot{m}_{SI}$	6300	SI terminated: LL_{PRZ} changing very slowly ($\dot{m}_{ADV} = \dot{m}_{SI}$). Affected loop ADV cycling terminated

TABLE 2. (continued)

Specified Criteria	Actual Time (s)	Event
$75 \leq LL_{prz} \leq 382$ cm	7300-7500	SI cycled to control pressure
	8400-8500	SI cycled to control pressure shut off on LL_{prz} high level
$P_p = 5.6 \pm 0.14$ MPa	7200-8800	Pressuzier internal heaters (back-up, variable)--On
	8800-9000	Pressurizer warmup heaters energized @ 14 kW
	9000-end	Pressurizer heaters cycling to control pressure

* The early secondary steam and feed was an operator induced action. The 2 second delay to 82 s was caused by the difference between process and data system measurements, and operator response time.

established by the early cooldown, 3.3 MPa (482 psia). Safety injection flow was filling the primary vessel, the affected loop steam generator secondary through the break, and the pressurizer. The vessel and the affected loop secondary were filled at 4700 s, and the pressurizer liquid level was rising, compressing the steam space. This compression caused a primary pressure rise that exceeded the affected loop ADV setpoint and resulted in ADV cycling. Concurrently, the unaffected loop ADV was operated in an attempt to cool the primary system and reduce the primary pressure to 5.6 MPa (812 psia).

Safety injection was terminated at 6300 s, after pressurizer and vessel level requirements were satisfied, to reduce primary pressure and stop the atmospheric release. The primary pressure dropped below the affected loop relief setpoint, and ADV cycling was terminated. Vessel and pressurizer levels remained stable while the primary pressure dropped to the initiation point for pressurizer heater operation. The pressurizer back-up and variable heaters were energized at 7200 s to control primary pressure. The pressure continued to drop and SI was operated between 7300 and 7500 s to reestablish primary system pressure. Once again the pressurizer heaters were unable to maintain primary system pressure within the specified band. SI was started again at 8400 s and terminated on pressurizer high level criteria at 8500 s, without having reestablished primary pressure. SI was not operated again. The primary pressure dropped slowly while the effect of back-up and variable heaters was examined. At 8800 s the back-up and variable heaters were shutoff, and the warm-up heaters were energized at a maximum power of 14 kW. By 9000 s, primary pressure had been established in the specified band and the warm-up heaters were shut off. The back-up and variable heaters were then used successfully to maintain primary pressure. The test was terminated after stabilizing pressure with pressurizer heaters for 15 min.

3. RESULTS

This section discusses the overall thermal-hydraulic response of the Semiscale system during Test S-SG-5. Test S-SG-5 was a simulation of a double-ended offset-shear of five steam generator tubes on the hot side of the steam generator near the tube sheet. The discussion is organized into four areas: the initial response to automatically occurring events (0 to 82 s), the early secondary steam and feed (82 to 600 s), the recovery period involving operator actions (600 to 9900 s) and a comparison of the response for a 5-tube cold side (Test S-SG-2)[4] and 5-tube hot side (Test S-SG-5) break experiment.

3.1 System Behavior--Tube Rupture Signature Early in Time (0 to 82 s)

The occurrence of a 5-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 affected loop steam generator) initiated the transient at 0 s. Primary fluid originally at 15.47 MPa (2243 psia) flowed through the conical flow tube break orifice into the affected loop steam generator originally at 5.6 MPa (803 psia). The loss of mass from the primary loop caused a fairly steady primary depressurization until about 12.5 s, at which time a marked increase in the depressurization rate occurred. This increase in depressurization rate is thought to be due to a reduction in the free surface area of the fluid in the pressurizer. The resulting reduction in flashing led to a more rapid depressurization (see Reference 4, Appendix A for details). The primary depressurization following this point was fairly steady until the low pressurizer pressure setpoint of 13.1 MPa (1900 psia) was achieved at about 20 s.

Prior to achieving the low pressurizer pressure trip, both the affected and unaffected loop steam generator pressures remained fairly constant as core power was removed via normal secondary steaming conditions

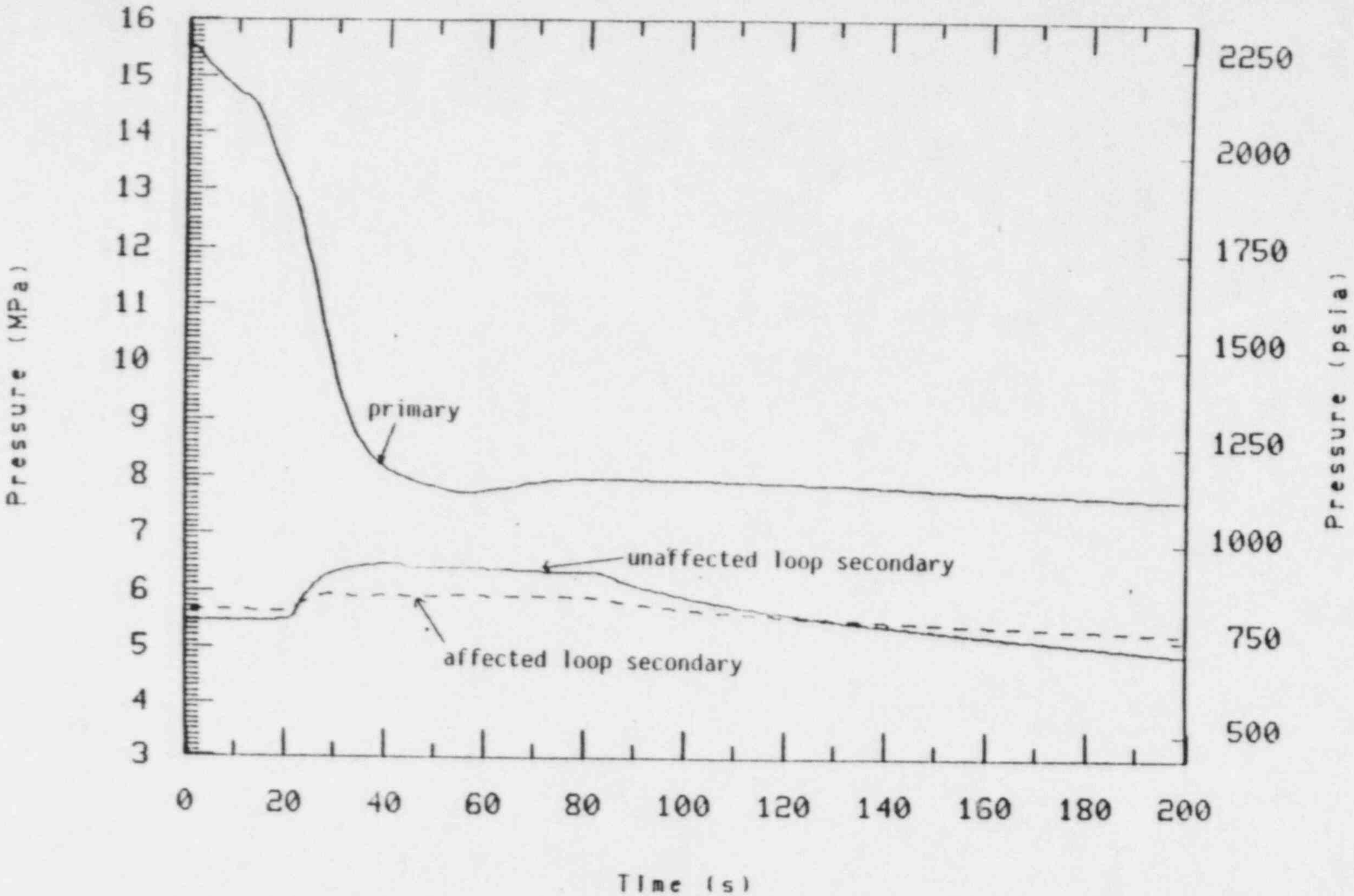


Figure 7. Comparison of primary and secondary pressure during a hot side five tube rupture transient, (S-SG-5).

with the primary loop pumps running (see Figure 8). The energy addition to the affected loop secondary from break flow had a negligible effect on secondary pressure during this period.

At the low pressurizer 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 transfer to both the affected and unaffected loop steam generator secondaries caused a rapid pressurization of the secondaries as shown in Figure 8. The secondary pressure in the unaffected loop steam generator achieved the ADV setpoint of 6.55 MPa (950 psia) cycling the ADV once. The affected loop secondary pressure achieved the ADV setpoint of 5.85 MPa (848 psia) and cycled twice during this early period.

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 initiated:
(a) terminating power to the primary coolant pumps, (b) starting SI flow, and (c) terminating main feedwater and starting auxiliary feedwater to the secondaries. No major change in primary depressurization rate occurred from these events as their effects were overshadowed by the effect of core scram.

Following pump trip and coastdown, the loop flow reduced to typical natural circulation values[5] as shown on Figure 9. The termination of pump flow and subsequent transition to natural circulation resulted in reduced heat transfer from primary to secondary. This was illustrated by a decrease in secondary pressure in both loops. Eventually, the primary system depressurization was sufficient for the hot leg fluid to reach a saturation condition at about 40 s (Figure 10). Flashing in the system then caused a major reduction in the depressurization rate. The primary pressure made a slight recovery between 55 and 75 s. This repressurization

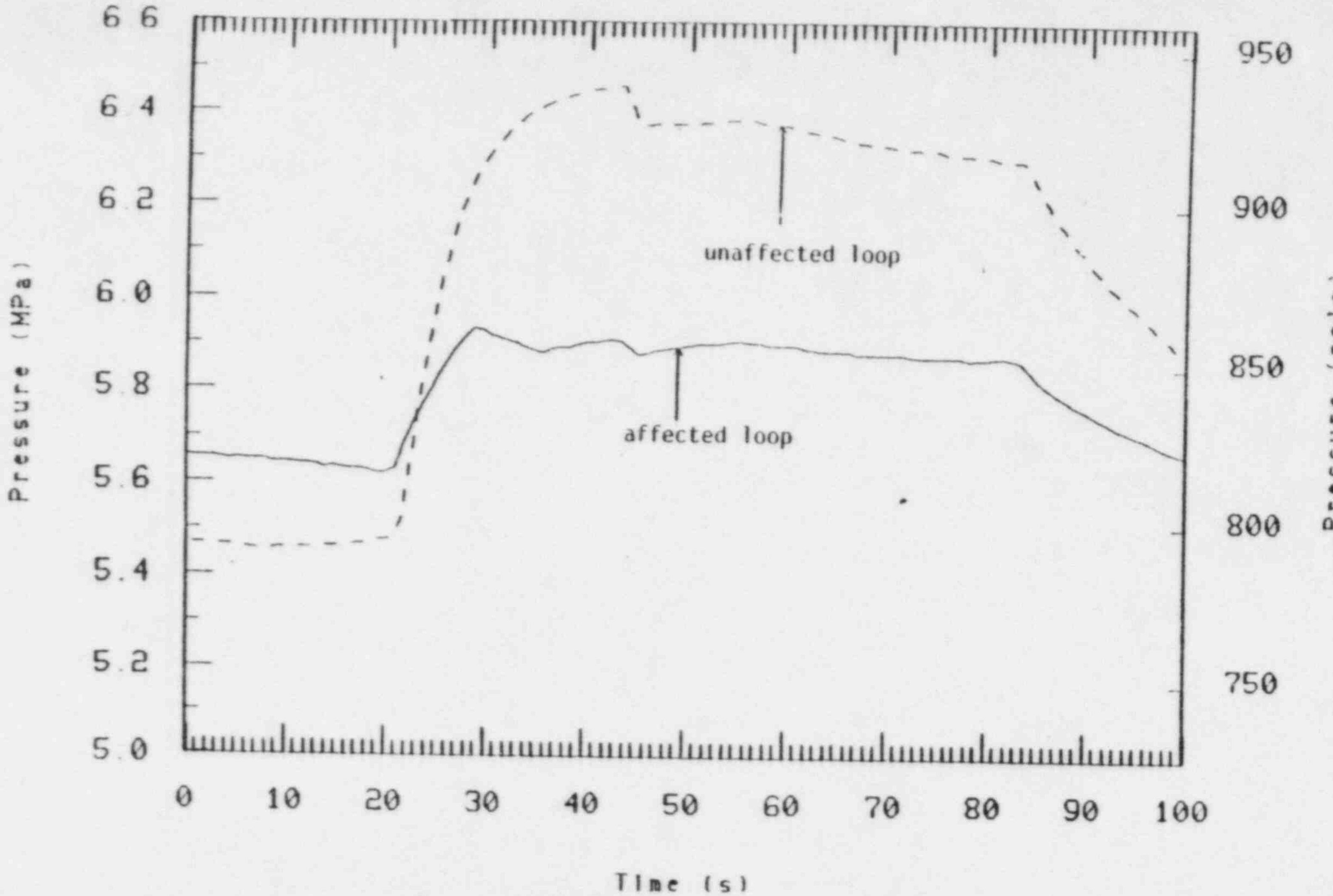


Figure 8. Comparison of affected loop and unaffected loop secondary pressure during a hot side, five-tube rupture transient (S-SG-5).

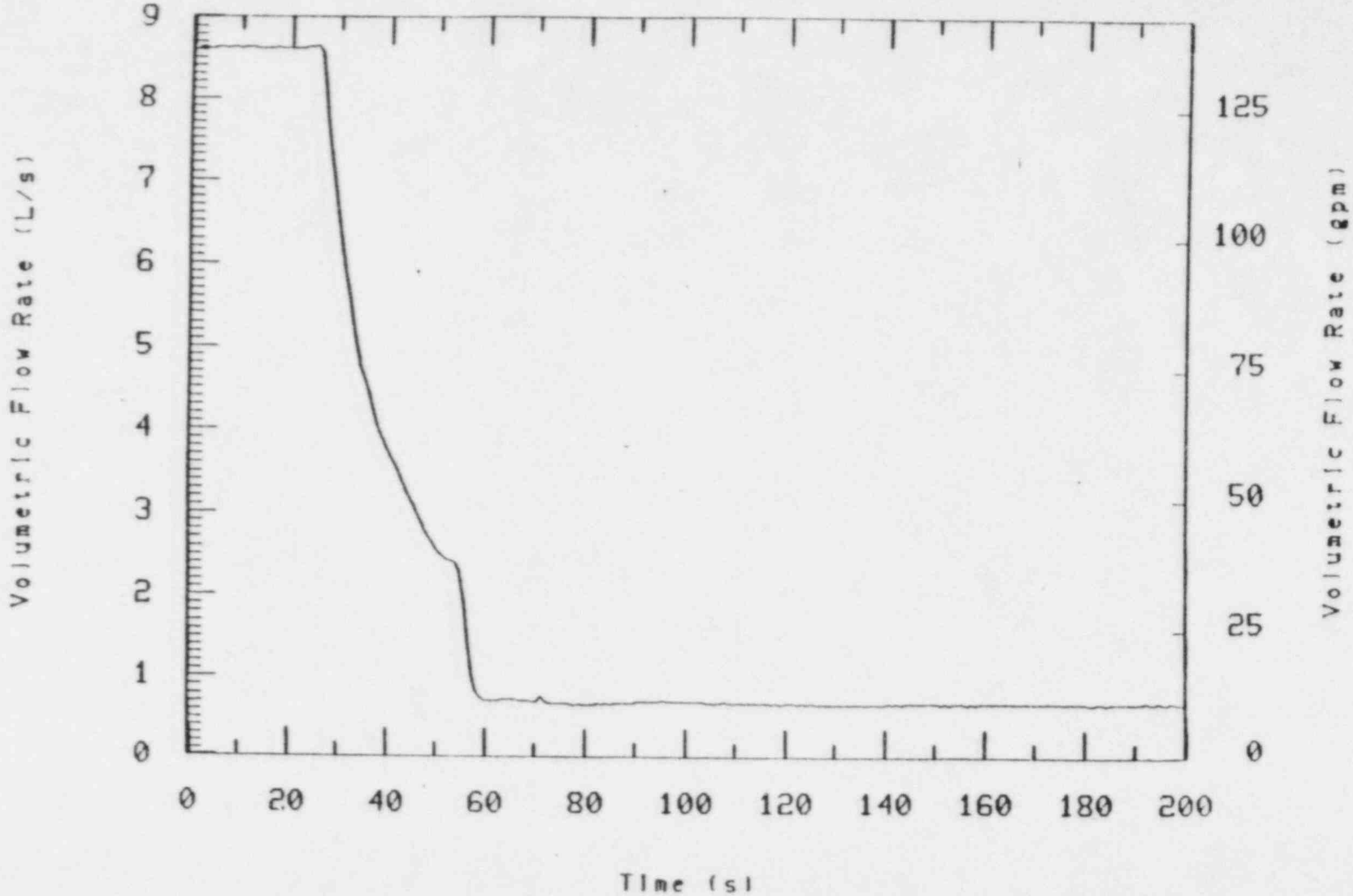


Figure 9. Change to natural circulation in the unaffected loop during a hot side, five-tube rupture transient (S-SG-5).

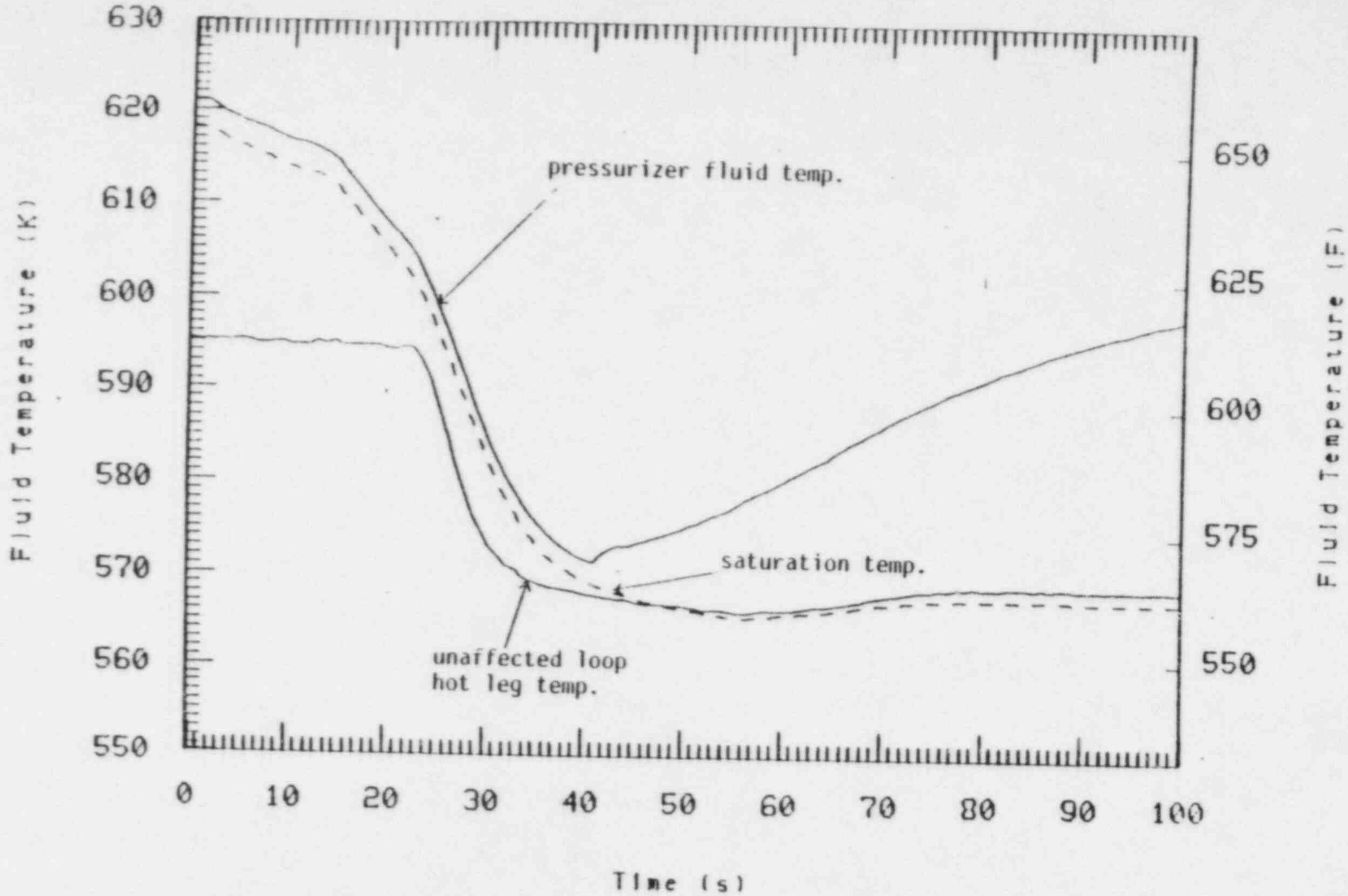


Figure 10. Comparison of fluid temperatures and saturation temperature for a hot side, five-tube rupture transient (S-SG-5).

was likely caused by superheated steam in the pressurizer (Figure 10), flashing in the reactor vessel, and reduced heat transfer to the secondaries.

Primary pressure remained above both secondary system pressures for the entire 82 s period, causing a primary-to-affected loop secondary mass flow as shown on Figure 11. As long as break flow exceeded total SI flow, primary system mass inventory depleted. Figure 12 shows the pressurizer collapsed liquid level essentially depleted after the initial 50 s.

3.2 Early Cooldown Response

An early cooldown of both the affected and unaffected steam generator secondaries was initiated at SCRAM + 60 s, which occurred 82 s after the tube rupture. This cooldown consisted of steaming through both secondary ADVs and feeding with auxiliary feedwater for approximately 520 s. Early cooldown was emphasized during the diagnostic period, using the secondary heat sinks when they would be least contaminated. ADV operation produced an immediate pressure drop in the secondaries of both loops. The unaffected loop secondary pressure dropped quickly, increasing the heat sink and hastening the primary depressurization. The affected loop pressure dropped less rapidly due to the mass addition and energy injected by the break flow (see Figure 13). The primary system pressure dropped very slowly for the first 100 s of the cooldown and then dropped rapidly as the vessel liquid level dropped below the upper head, causing the vessel upper head and upper plenum external heaters to turn off.

Steaming in the unaffected loop caused a level[a] decrease in the secondary as the ADV mass flow rate exceeded that of auxiliary feedwater flow rate (see Figure 14). The liquid level[a] in the affected loop

a. The indicated level in the secondaries during steaming was influenced by frictional pressure drops, boiling effects, and velocity effects on the differential pressure measurement. Therefore the indicated level is incorrect until the secondaries were isolated after 600 s.

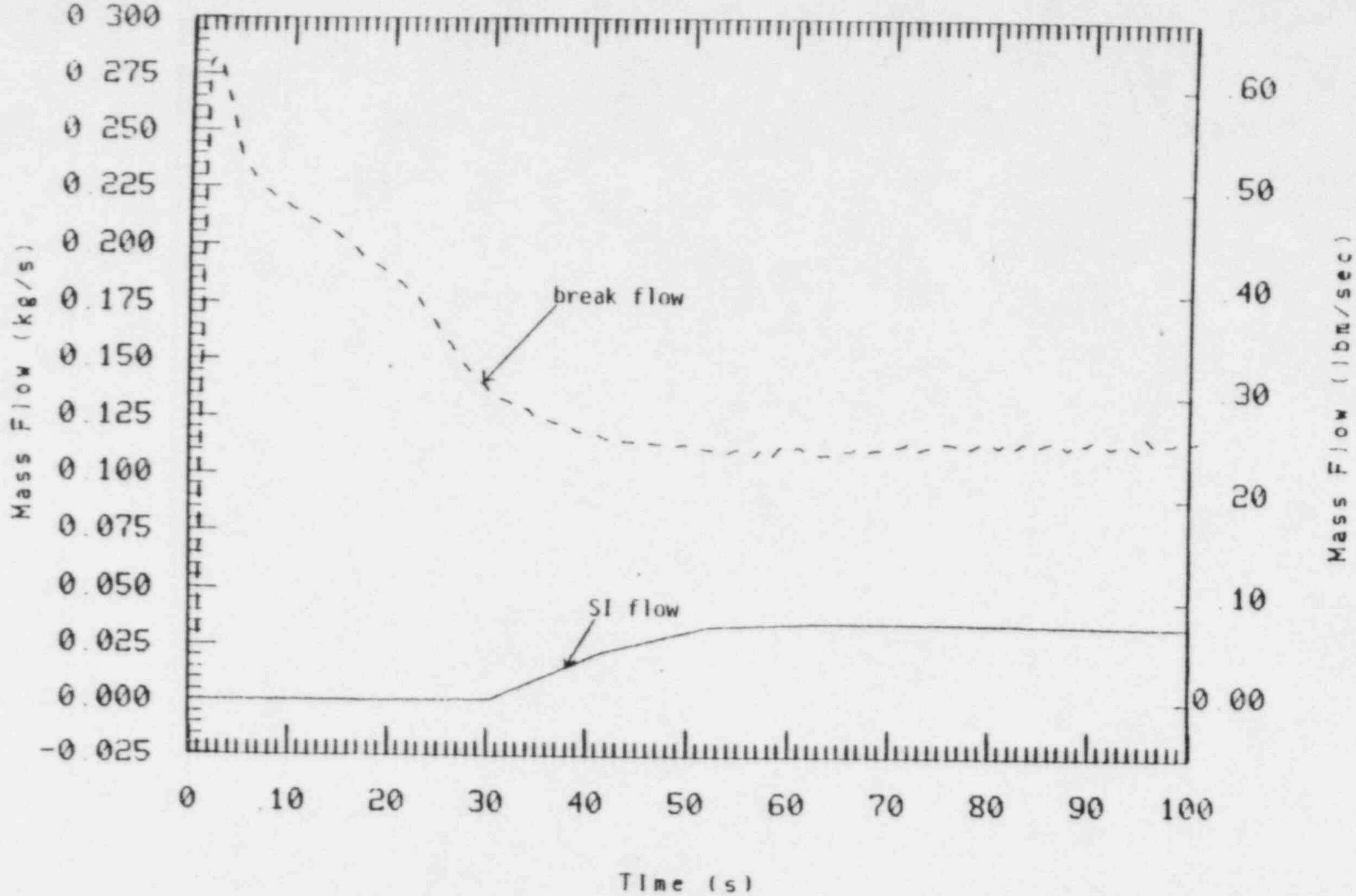


Figure 11. Comparison of break flow and SI flow during a hot side, five-tube rupture transient (S-SG-5).

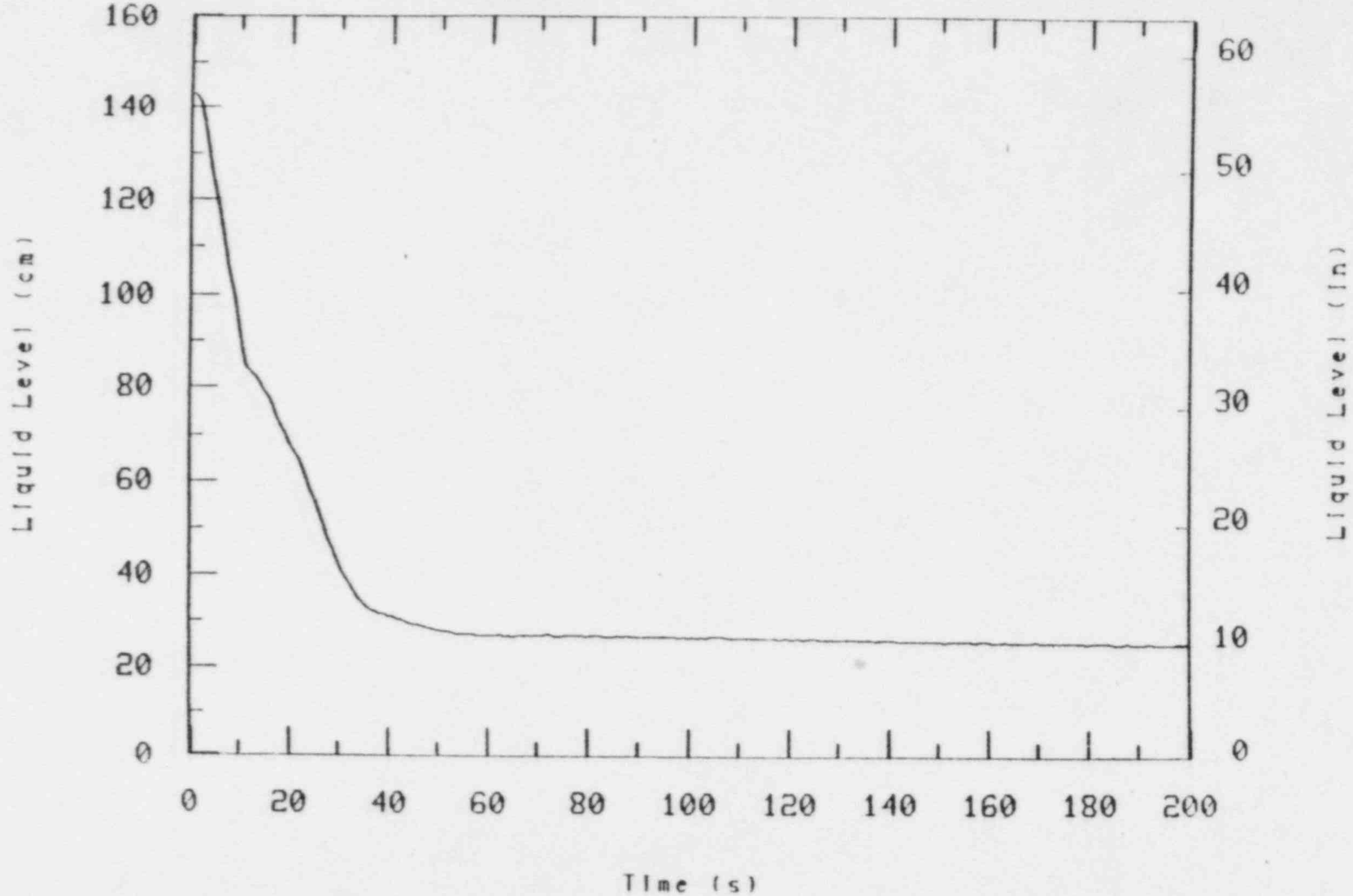


Figure 12. Pressurizer collapsed liquid level (LPRZ+632+30) during a hot side, five-tube rupture transient (S-SG-5).

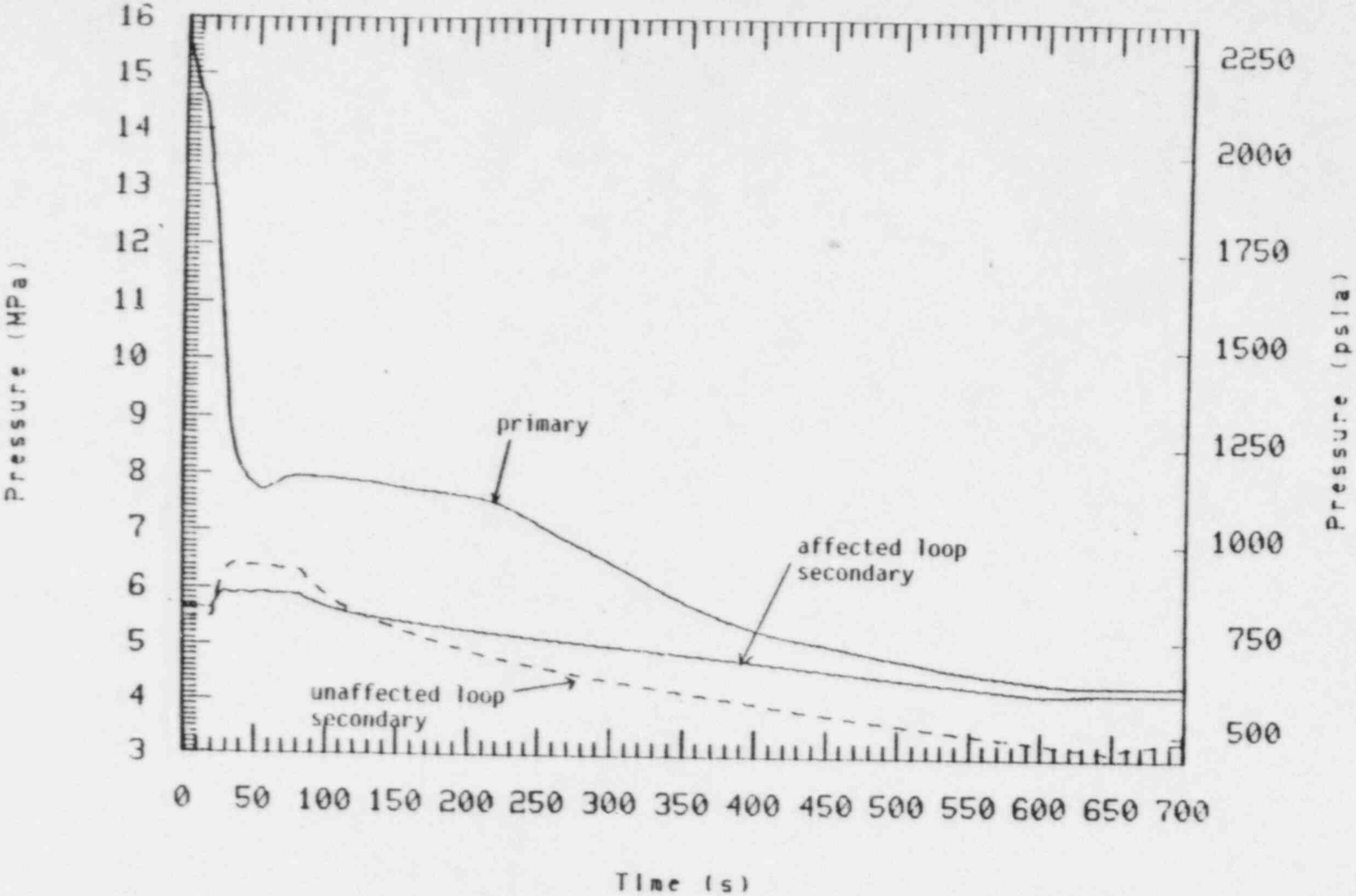


Figure 13. Comparison of primary and secondary pressure during a hot side, five-tube rupture transient (S-SG-5).

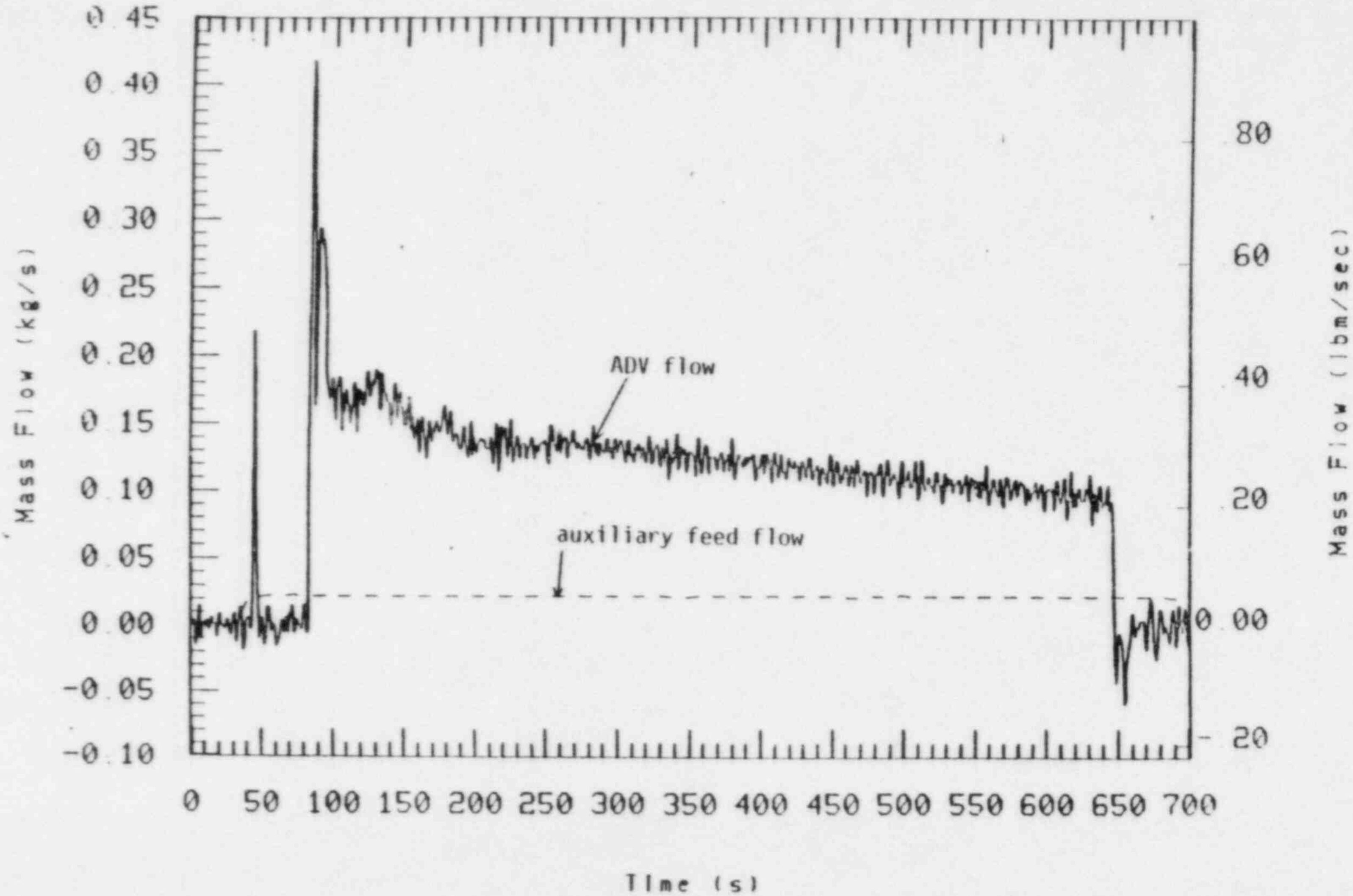


Figure 14. Comparison of auxiliary feed and ADV flow in the unaffected loop secondary during a hot side, five-tube rupture transient (S-SG-5).

remained fairly constant during the cooldown with ADV flow being equaled by the combined auxiliary feedwater flow and break flow, as shown in Figure 15.

Safety injection flow was maintained throughout the early cooldown in an attempt to maintain system inventory. However, the pressurizer level did not recover (see Figure 12), and the vessel level fell to about the level of the hot leg as shown in Figure 16. Primary to secondary break flow persisted throughout the early cooldown, depleting the system inventory, until 550 s, when the SI flow exceeded the break flow (Figure 17).

Two-phase natural circulation[5] was first observed at about 250 s, when a sharp increase was noted in cold leg flow (see Figure 18). Figure 19 shows considerable voiding in the cold leg from 250 to about 1200 s, when the flow rates return to single-phase natural circulation levels.

At the end of the early cooldown period (600 s), the primary and secondary pressures were well below the affected loop relief setpoint. The pressurizer had emptied and the vessel liquid level was about 95 cm (37.4 in.) above the top of the core. Primary-to-secondary break flow was small and SI was operating to fill the system. From this condition, recovery operations were initiated.

3.3 Recovery Phase Signature

The system recovery in Test S-SG-5 involved unaffected loop secondary steam and feed, safety injection operation, and pressurizer heater operation. Recovery in this case meant the termination of break flow, the establishment of acceptable levels in the vessel and pressurizer, and the maintenance of primary pressure below the affected loop relief setpoint for 15 minutes, using pressurizer heaters.

Recovery operation commenced at 600 s by terminating the affected loop auxiliary feedwater and closing the ADV. The unaffected loop was placed in a controlled steam and feed mode to maintain the secondary pressure

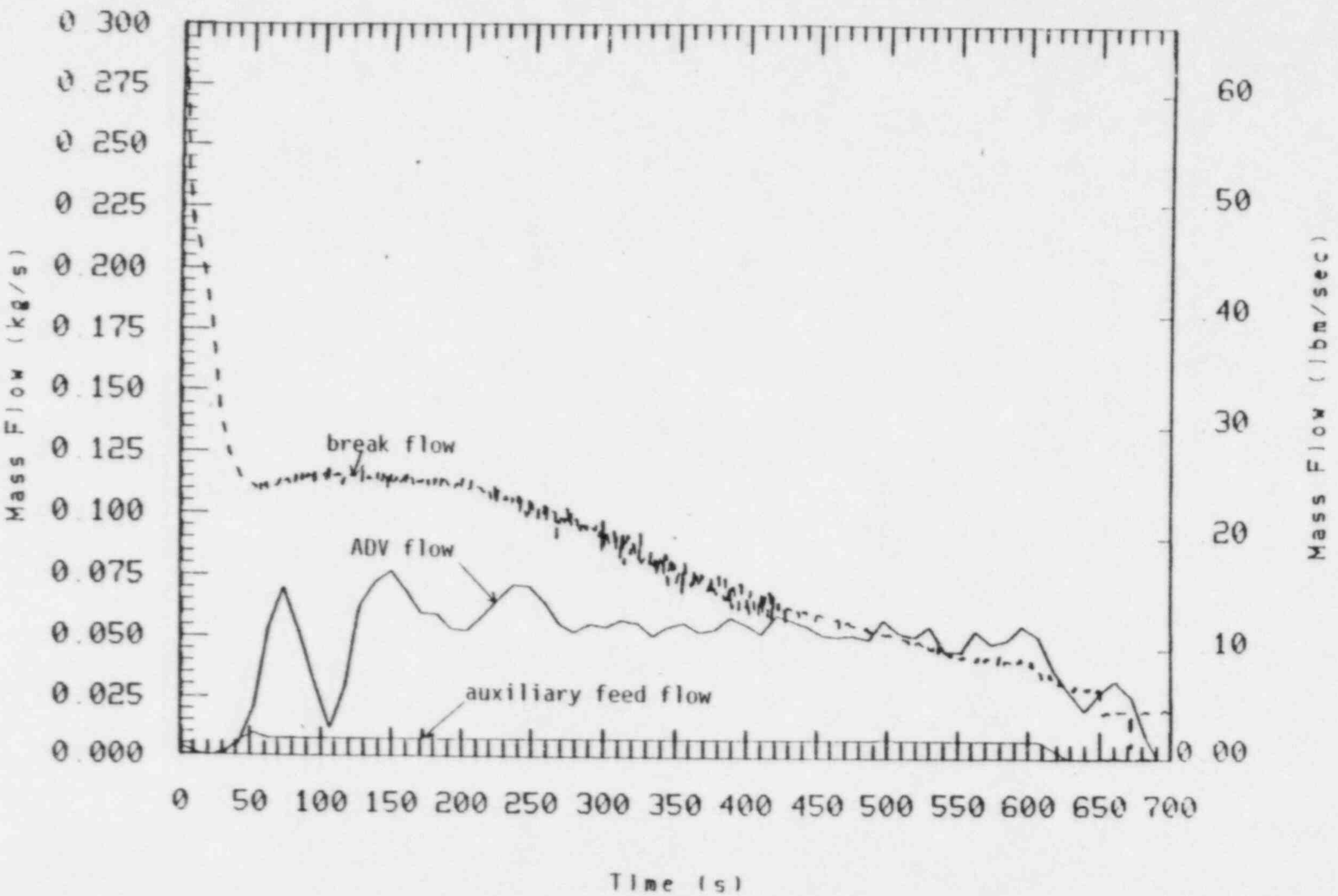


Figure 15. Comparison of break flow, ADV flow, and auxiliary feed flow in the affected loop steam generator during a hot side, five-tube rupture transient (S-SG-5).

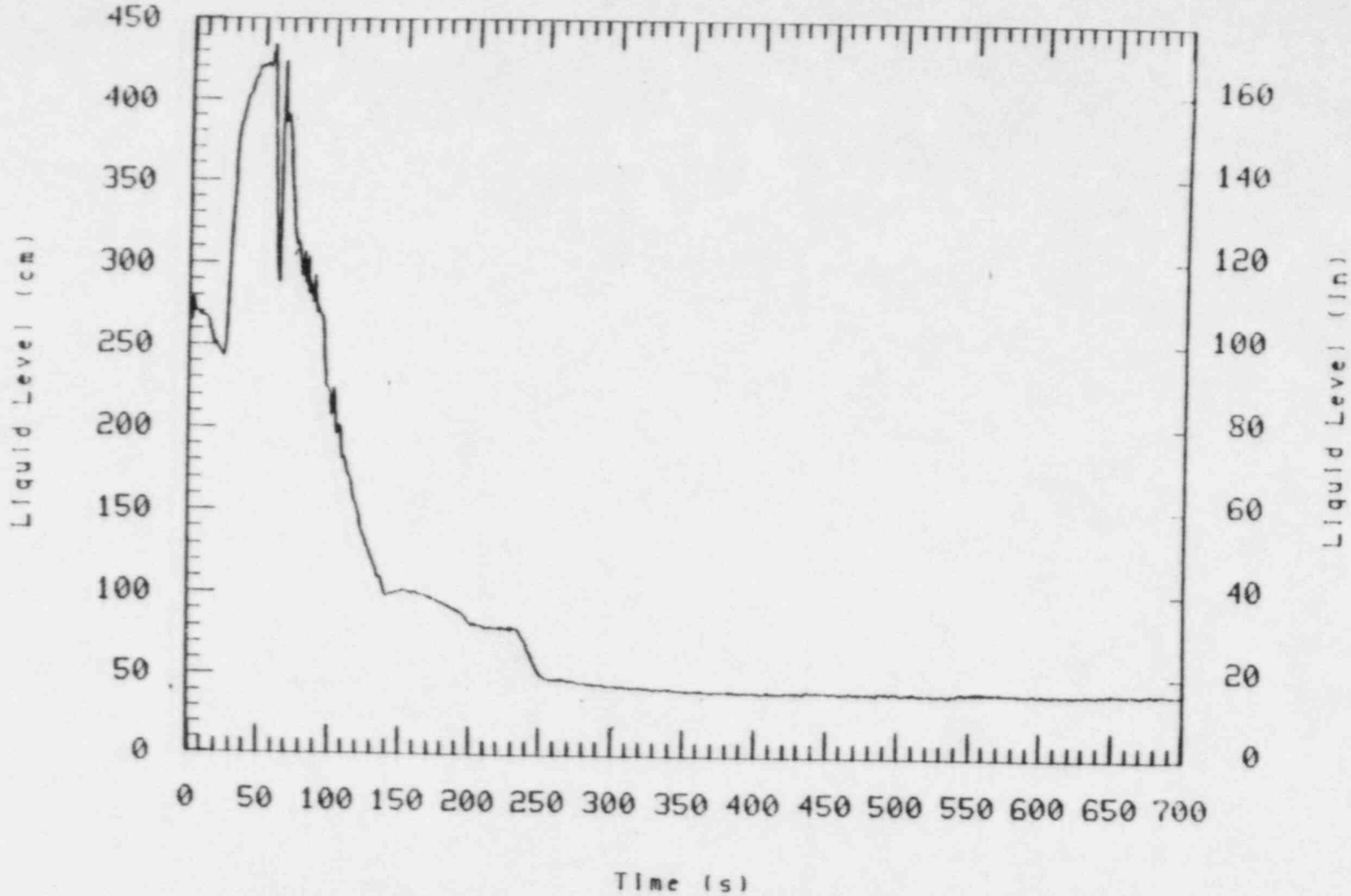


Figure 16. Vessel upper head collapsed liquid level (LV+421-13m) during a hot side, five-tube rupture transient (S-SG-5).

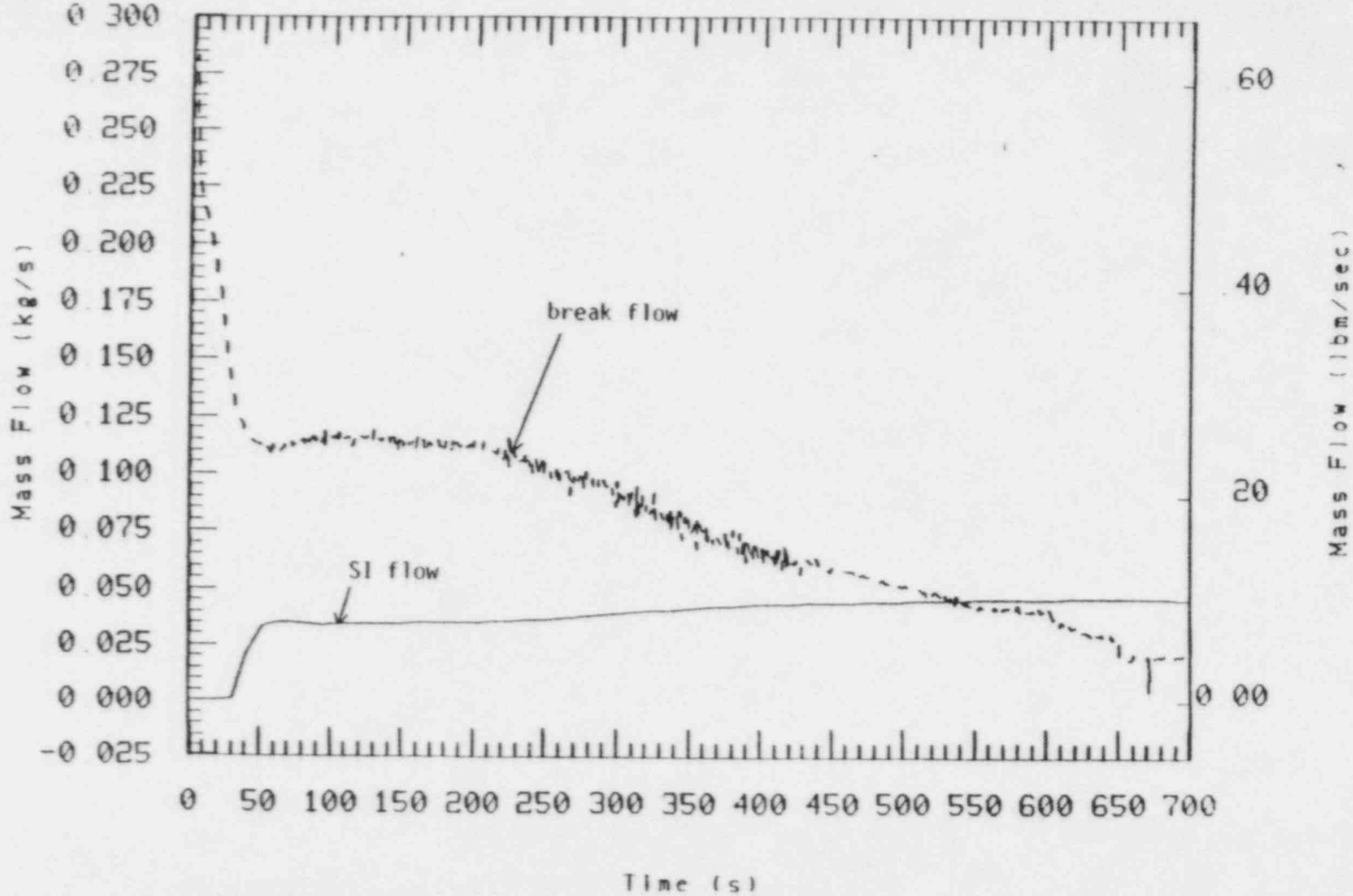


Figure 17. Comparison of break flow and SI flow for a hot side, five-tube rupture transient (S-SG-5).

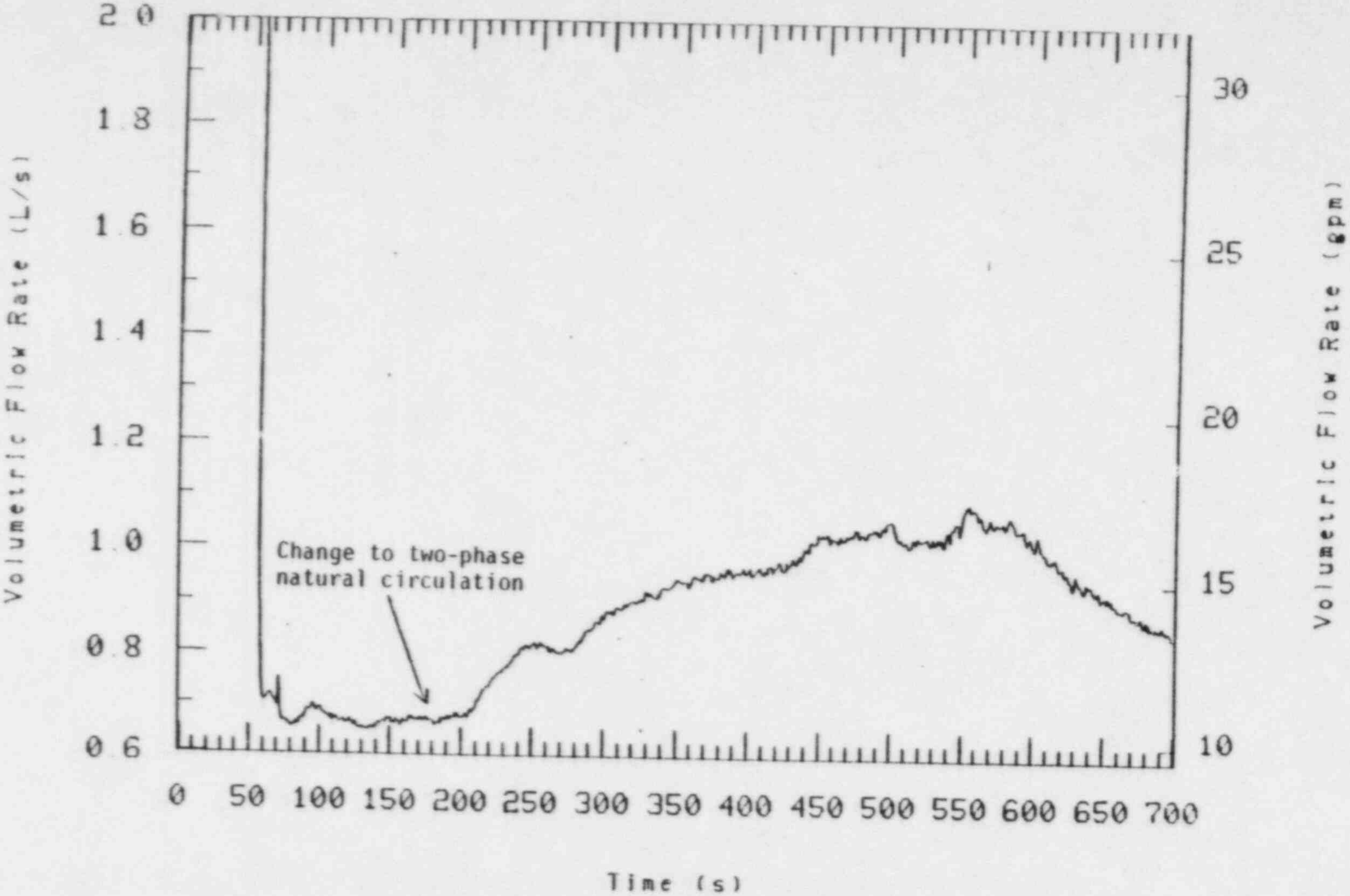


Figure 18. Change to two-phase natural circulation in the unaffected loop during a hot side, five-tube rupture transient (S-SG-5).

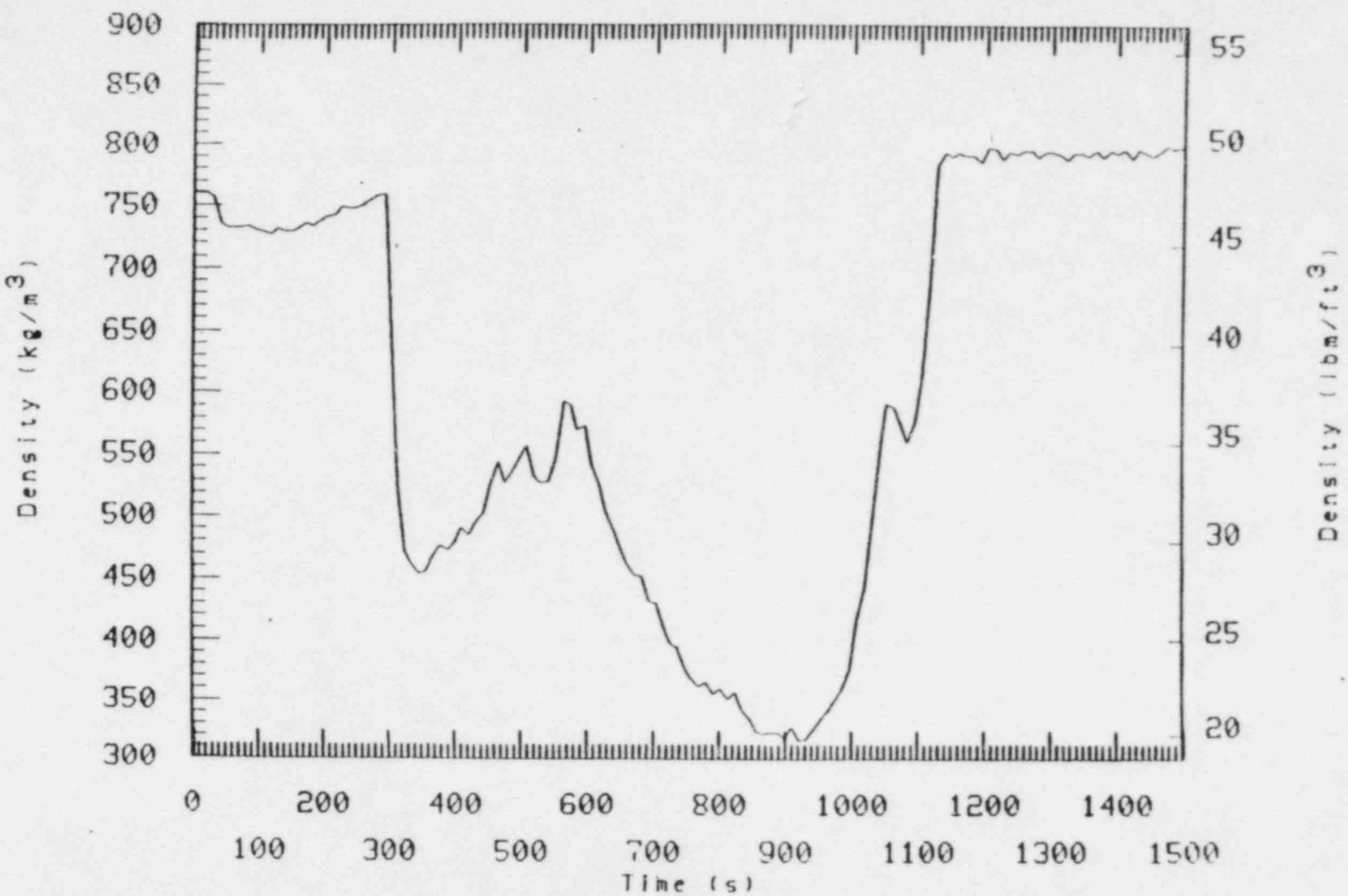


Figure 19. Fluid density in the unaffected loop, cold leg during a hot side, five-tube rupture transient (S-SG-5).

achieved at 600 s, thereby providing an enhanced heat sink to hasten primary depressurization. Safety injection was used to fill the voids in the primary system. Pressurizer variable and back-up heaters were used as needed to maintain primary pressure at 5.6 ± 0.14 MPa (812 ± 20 psia). Warm-up heaters were used to re-establish pressure only after SI was no longer available and back-up and variable heaters were shown to be ineffective. The test was terminated when the primary pressure had been stabilized by pressurizer heaters for 15 min in the specified band.

3.3.1 Effect of SI on System Recovery

At 600 s the vessel was highly voided, the pressurizer had drained, and the affected loop secondary still had a large steam space. SI operation maintained the primary system pressure slightly above the secondaries, resulting in break flow filling the affected loop secondary. SI and break flow were essentially identical while the secondary was filling, as shown in Figure 20. Vessel and pressurizer levels did not increase until the affected loop secondary had been filled to the point of compressing a small steam space, raising the secondary pressure (Figure 21) and forcing SI to fill the primary system. Vessel and pressurizer levels are shown in Figure 22, illustrating their simultaneous filling. The pressurizer filled much slower than the vessel due to the superheat in the steam space resisting compression as the pressurizer level rose.

The vessel and affected loop secondary became essentially liquid solid at 4300 s, as exhibited by the close coupling of the two system pressures shown in Figure 23. This coupling was lost when the affected loop ADV cycled, reducing pressure, but redeveloped as soon as ADV cycling was terminated. This illustrates that the pressures are coupled when depressurization moves slowly, as with SI filling and heat loss depressurization. However, coupling is lost in a rapid transient such as ADV cycling. Therefore, the rate of change dictates the degree of coupling.

SI pressurized the system to a point exceeding the affected loop relief setpoint, resulting in ADV cycling, initiated at 4200 s (see Figure 21). At this point a quasi-steady state condition existed between

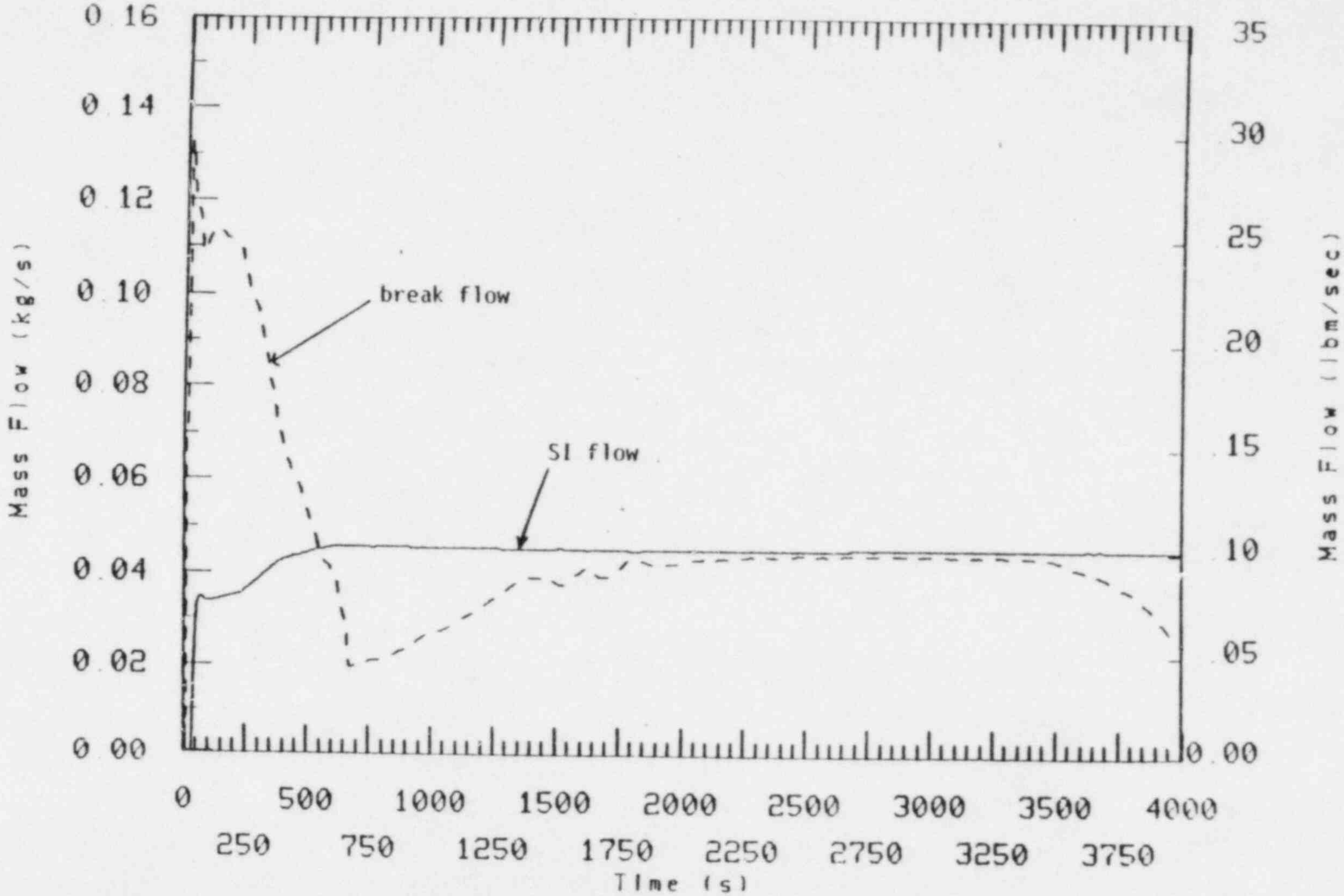


Figure 20. Comparison of break flow and SI flow during a hot side, five-tube rupture transient (S-SG-5).

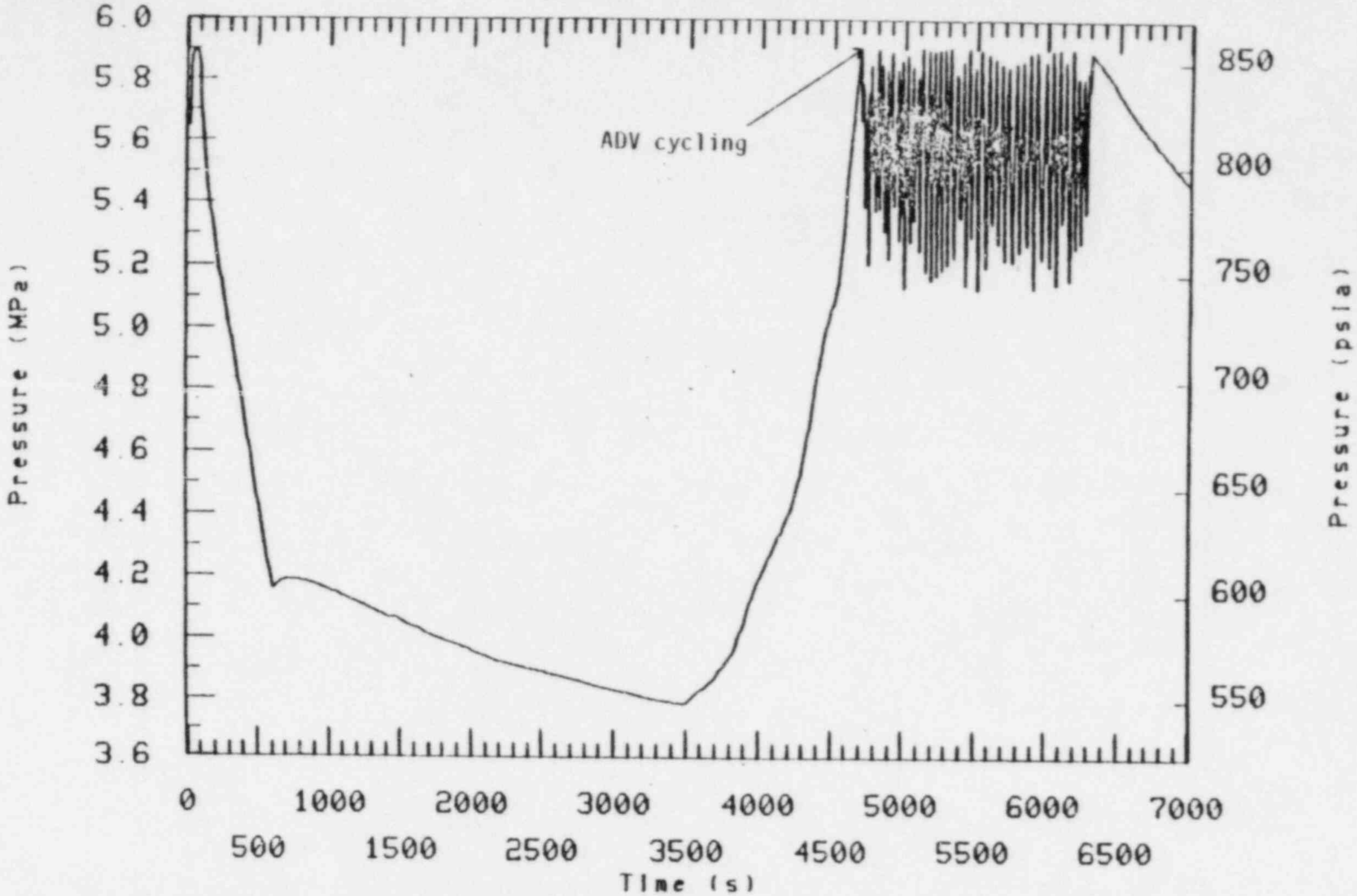


Figure 21. Affected loop secondary pressure during a hot side, five-tube rupture transient (S-SG-5).

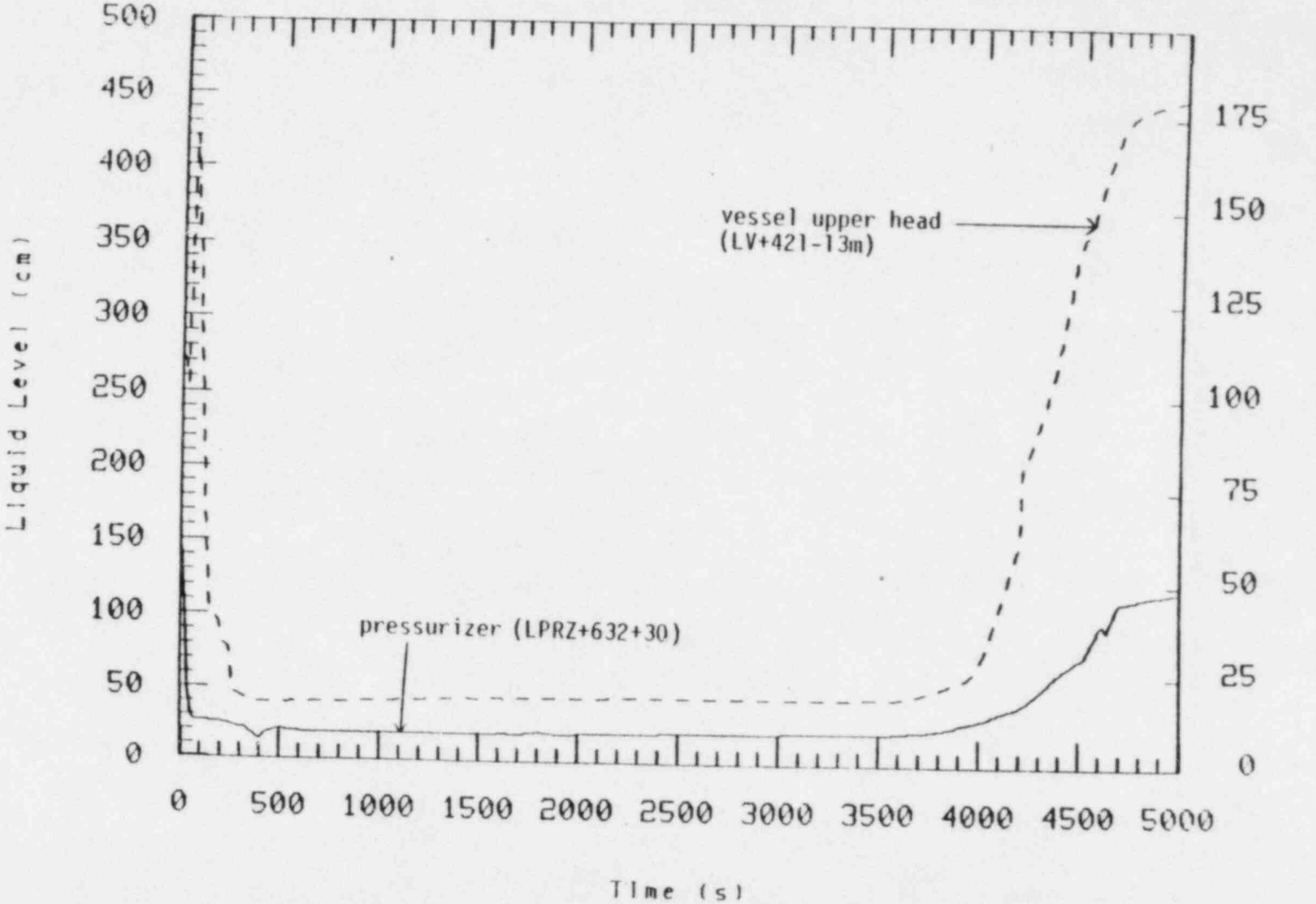


Figure 22. Comparison of vessel upper head and pressurizer collapsed liquid level during a hot side, five-tube rupture transient (S-SG-5).

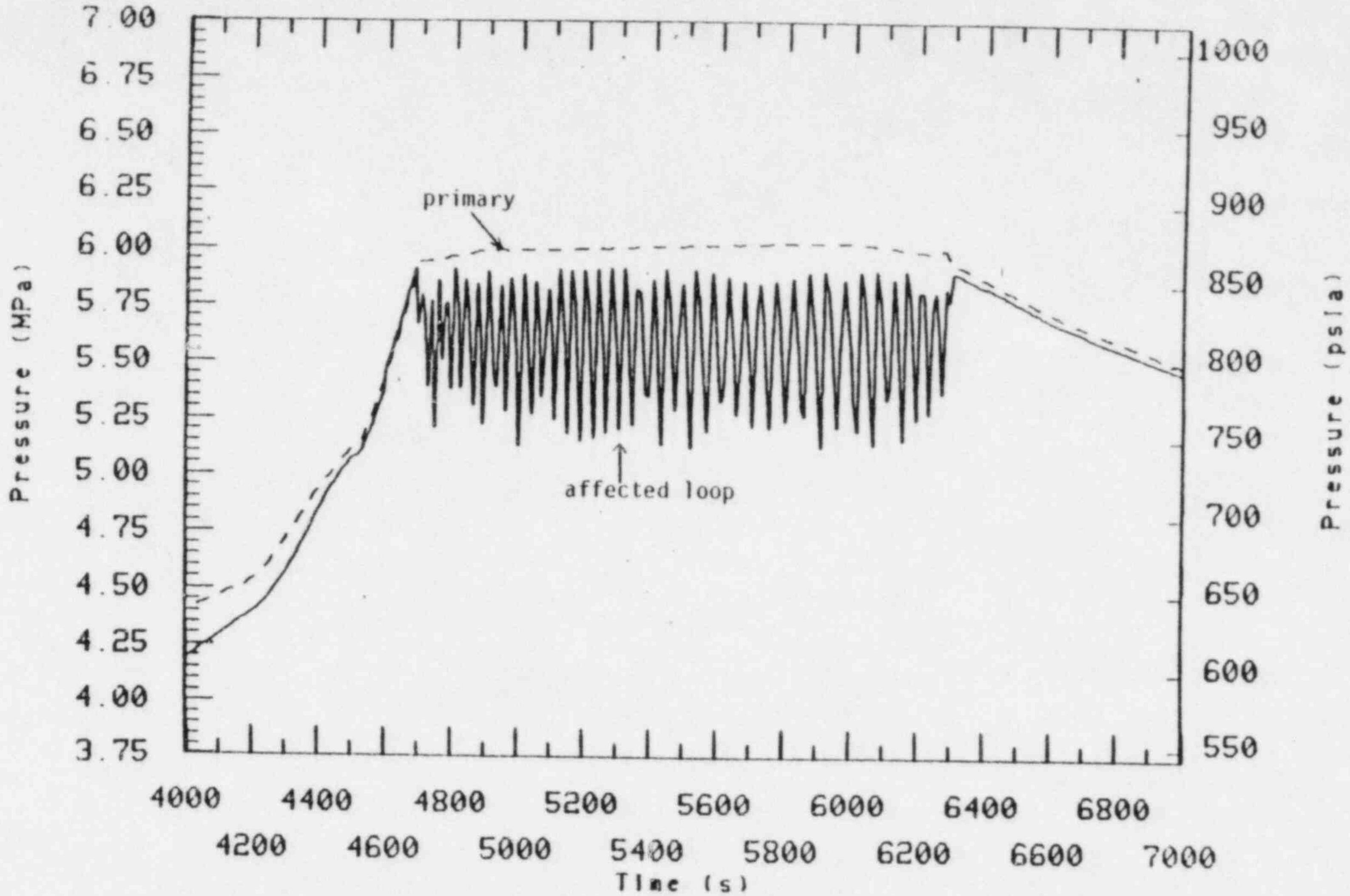


Figure 23. Comparison of primary and affected loop secondary pressure during a hot side, five-tube rupture transient (S-SG-5).

SI and break flow as shown in Figure 24, with primary pressure steady at 5.9 MPa (860 psia). The pressurizer liquid level rise slowed at 4700 s as SI was pumping against the compressed steam space, Figure 25.

This quasi-steady state condition was not encouraging recovery of the system, as the atmospheric discharge had been reestablished, and primary pressure remained above the affected loop relief setpoint (Figure 23). Since level had been regained in the pressurizer, SI was terminated at 6300 s. Immediately the primary pressure fell below the affected loop relief setpoint, terminating ADV flow and recoupling the primary and secondary pressures. Primary pressure continued to fall, hastened by the unaffected loop heat sink. The unaffected steam generator had been operated in a steam and feed mode in an attempt to bring primary pressure to 5.6 MPa (812 psia), as shown in Figure 26.

Levels in the vessel and the pressurizer remained stable after SI termination. However, after cycling SI at 7300 s and 8400 s, pressurizer level rose to the high level SI trip point as shown in Figure 27, while the vessel remained full. SI had been cycled to bring the primary pressure within the specified band, and had succeeded in doing so until the high level trip was reached. Figure 28 shows the effect of SI cycling on primary pressure late in the transient, with a nearly liquid solid system.

3.3.2 Effect of Pressurizer Heaters on System Recovery

Pressurizer heater operation was specified to maintain primary pressure at 5.6 ± 0.14 MPa (812 ± 20 psia). The intent was to regain primary system pressure control in the pressurizer below the affected loop relief setpoint, so that a controlled cooldown and depressurization could then proceed. Figure 29 shows the timing of pressurizer heater operation late in the transient. Figure 28 illustrates the effect on primary pressure. Pressurizer back-up and variable heaters were energized with 2300 W at 7200 s. Heater operation was unable to maintain system pressure and SI was cycled twice to return the pressure to the specified band. SI could not be used after the last cycle due to a high level in the pressurizer and primary pressure continued to fall. Warm-up heaters,

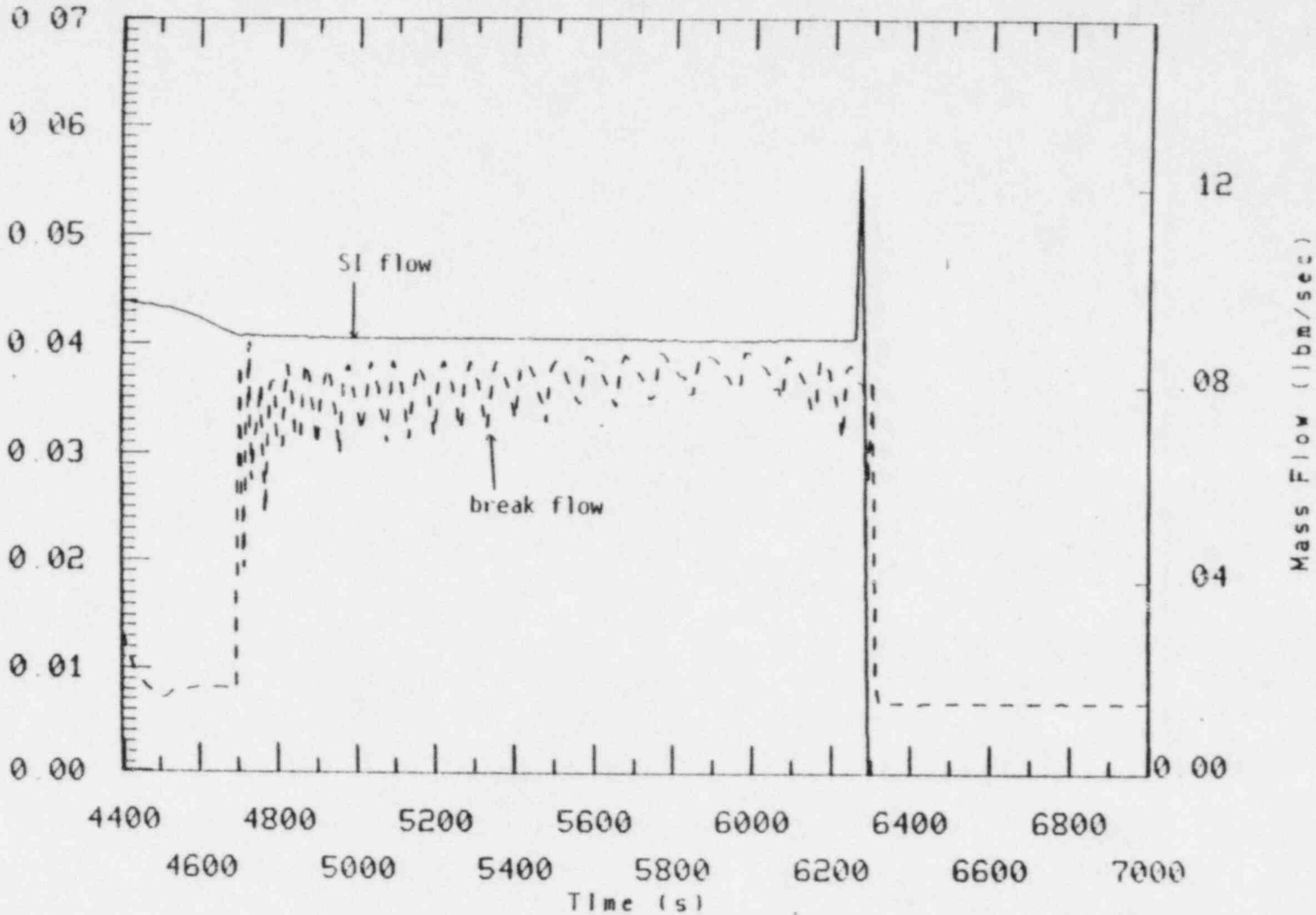


Figure 24. Comparison of break flow and SI flow during a hot side, five-tube rupture transient (S-SG-5).

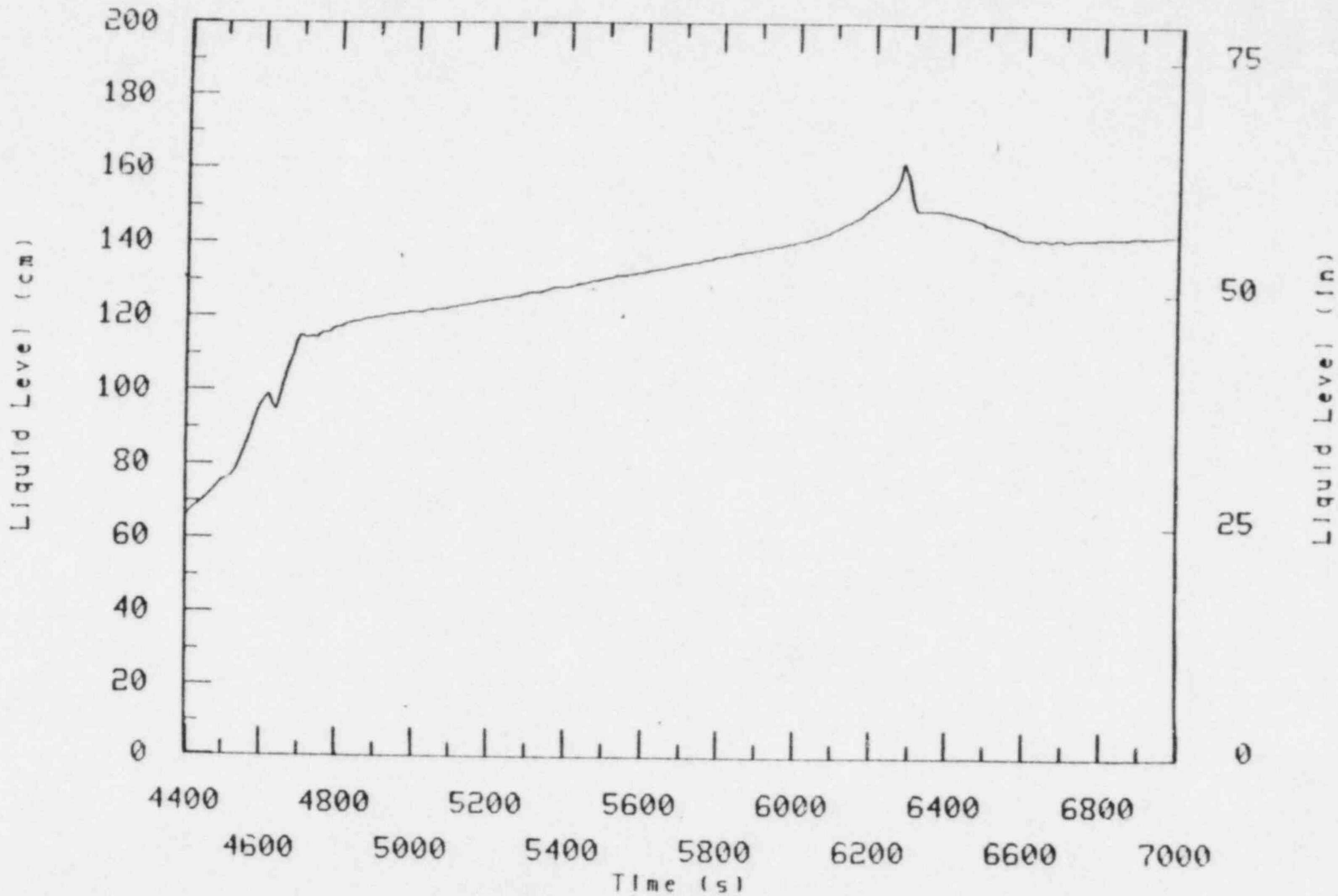


Figure 25. Pressurizer collapsed liquid level during a hot side, five-tube rupture transient (S-SG-5).

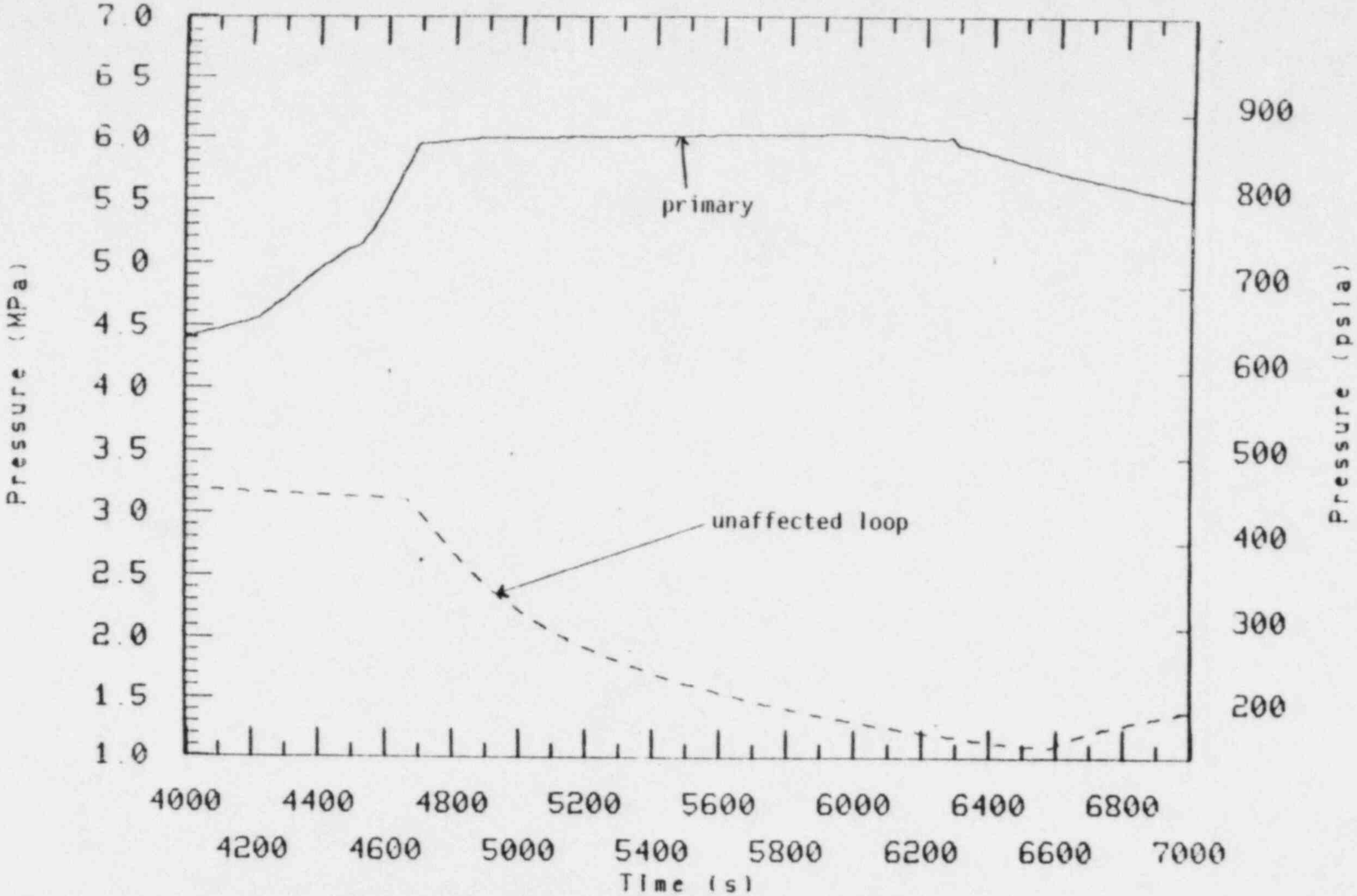


Figure 26. Comparison of primary and unaffected loop secondary pressure during a hot side, five-tube rupture transient (S-SG-5).

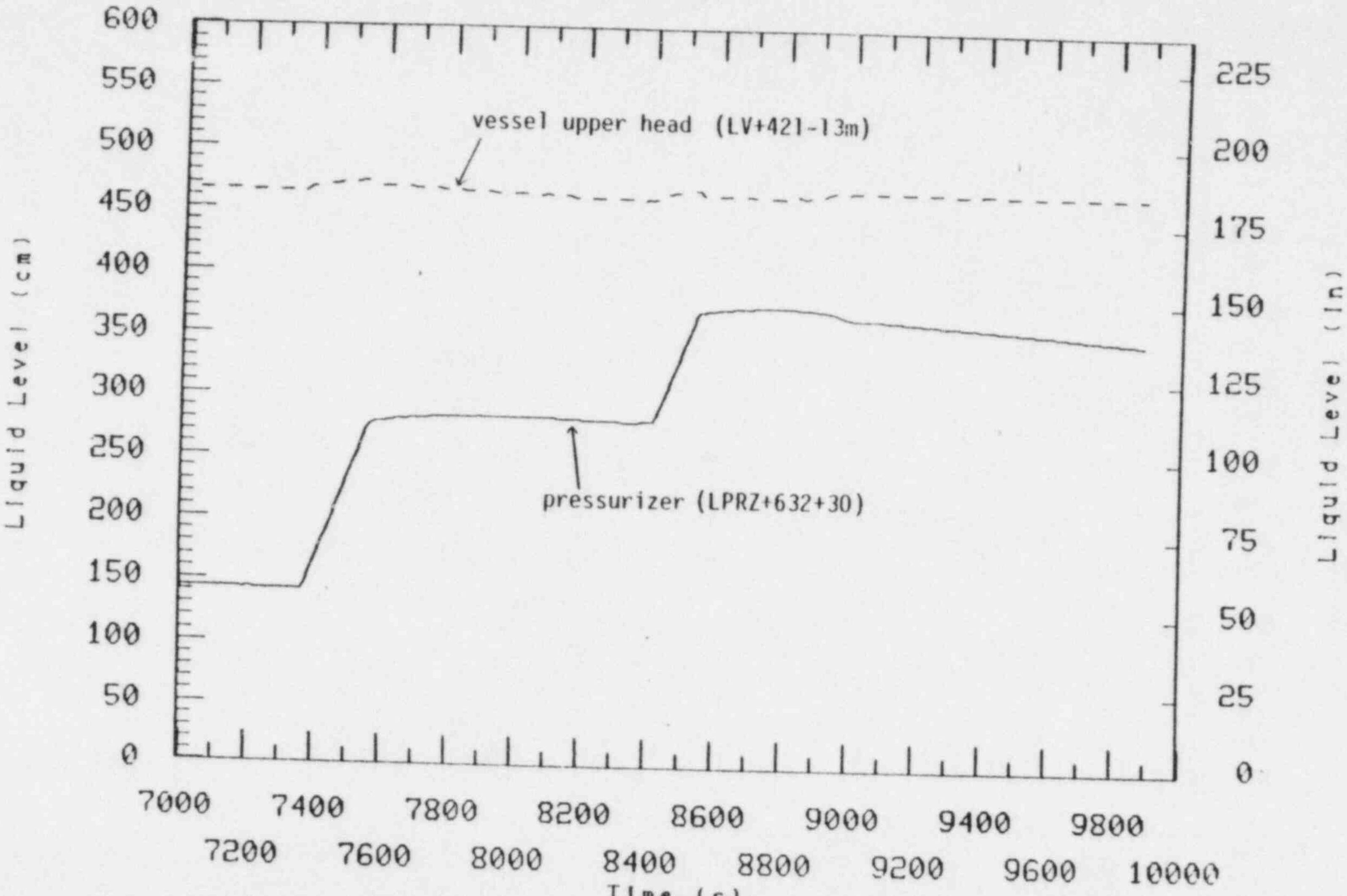


Figure 27. Comparison of vessel upper head and pressurizer collapsed liquid levels during a hot side, five-tube rupture transient (S-SG-5).

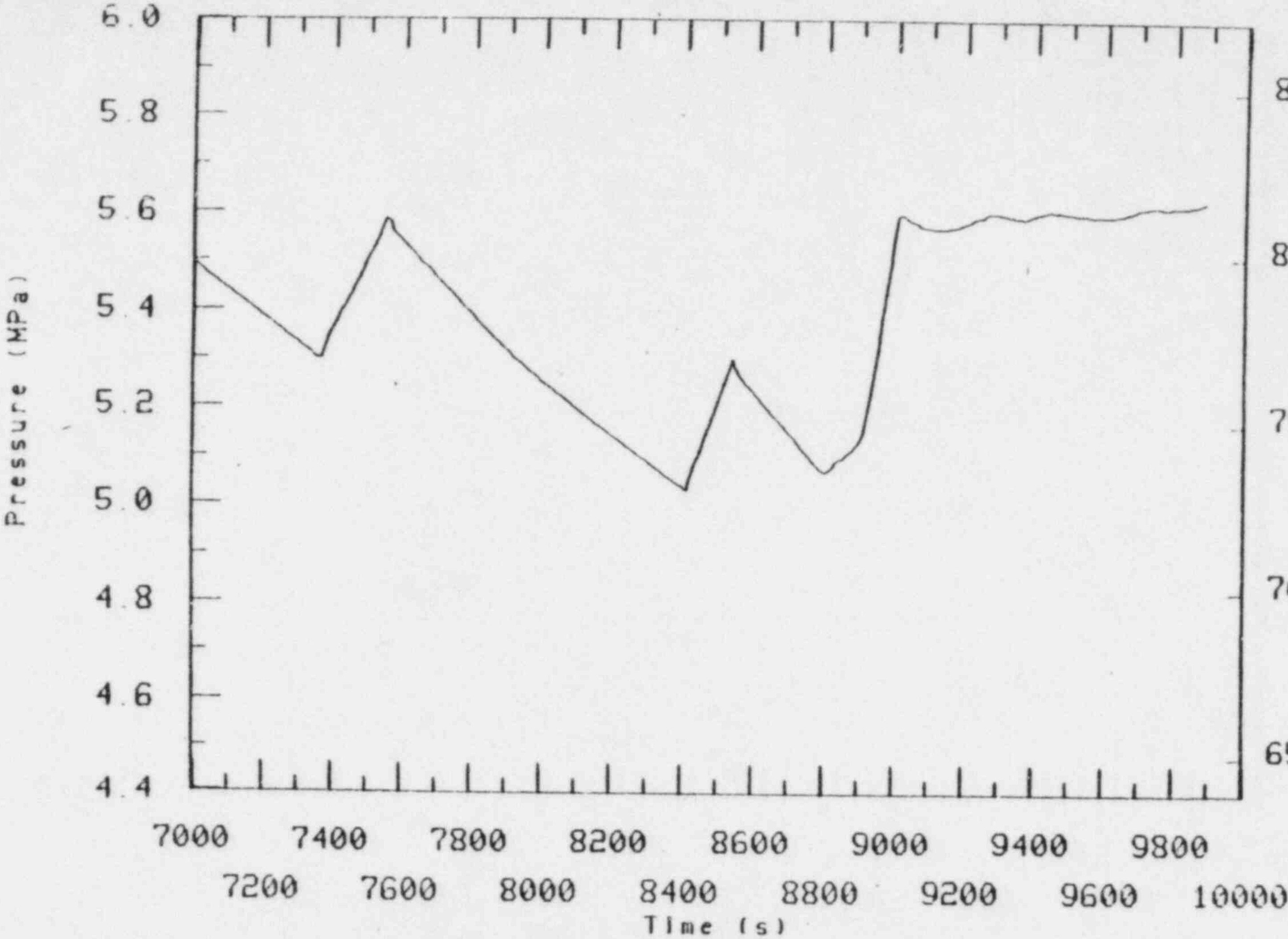


Figure 28. Primary pressure during a hot side, five-tube rupture transient (S-SG-5).

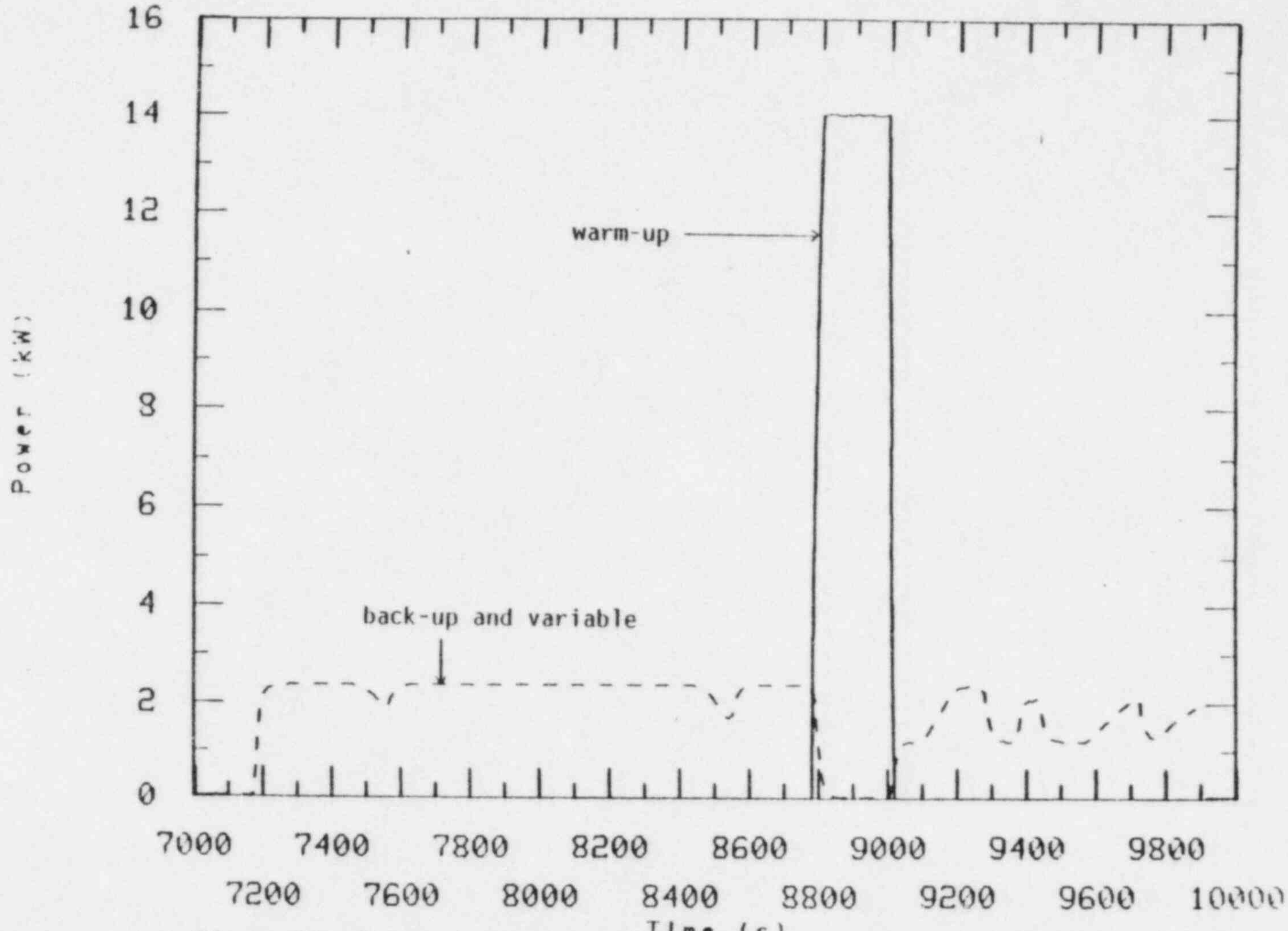


Figure 29. Pressurizer variable, back-up and warm-up heater power during a hot side, five-tube rupture transient (S-SG-5).

energized at 14 kW, were then used to return pressure to the desired band. After the warm-up heaters were turned off back-up and variable heaters were used successfully to control system pressure. Cycling of the variable heaters is indicated in Figure 29 after 9000 s, and their effect on primary pressure is evident in Figure 28.

Back-up and variable heaters were ineffective when initially used, but were effective after the warm-up heaters had warmed the fluid. Throughout the transient subcooled water had been injected into the pressurizer, as shown in Figure 30. Back-up and variable heaters supplying 2355 W were making up environmental heat loss and heating the subcooled water, but were unable to produce flashing. However, when the warm-up heaters were used, enough energy was applied to heat all the liquid to a saturated condition. The back-up and variable heaters were then able to make up heat loss and flash the liquid to control pressure.

3.4 Comparison of System Response for a 5-Tube Cold Side and 5-Tube Hot Side Tube Rupture Experiment

This section compares the early-in-time response (0-82 s) of system pressures and mass inventories for the cold side (S-SG-2) and hot side (S-SG-5) five-tube rupture experiments. Operator actions after 600 s were significantly different in the two tests, precluding further comparison. Initial conditions in the two tests were nearly identical and automatic actions during this time were exactly the same. Figure 31 shows that the primary system pressure was very close for both tests. Break flow was somewhat higher in the cold side break (S-SG-2) due to the higher density in the cold leg (see Figure 32). The higher break flow resulted in the pressurizer emptying more quickly, and is illustrated by the occurrence of an elbow in the pressurizer collapsed liquid level at 12.5 s in S-SG-2 and 14.5 s in S-SG-5, Figure 33.

An early steam and feed of both secondaries was initiated at 82 s in S-SG-5, while both secondaries were essentially isolated for the first 600 s of S-SG-2. Figure 34 compares primary pressure for the first 700 s

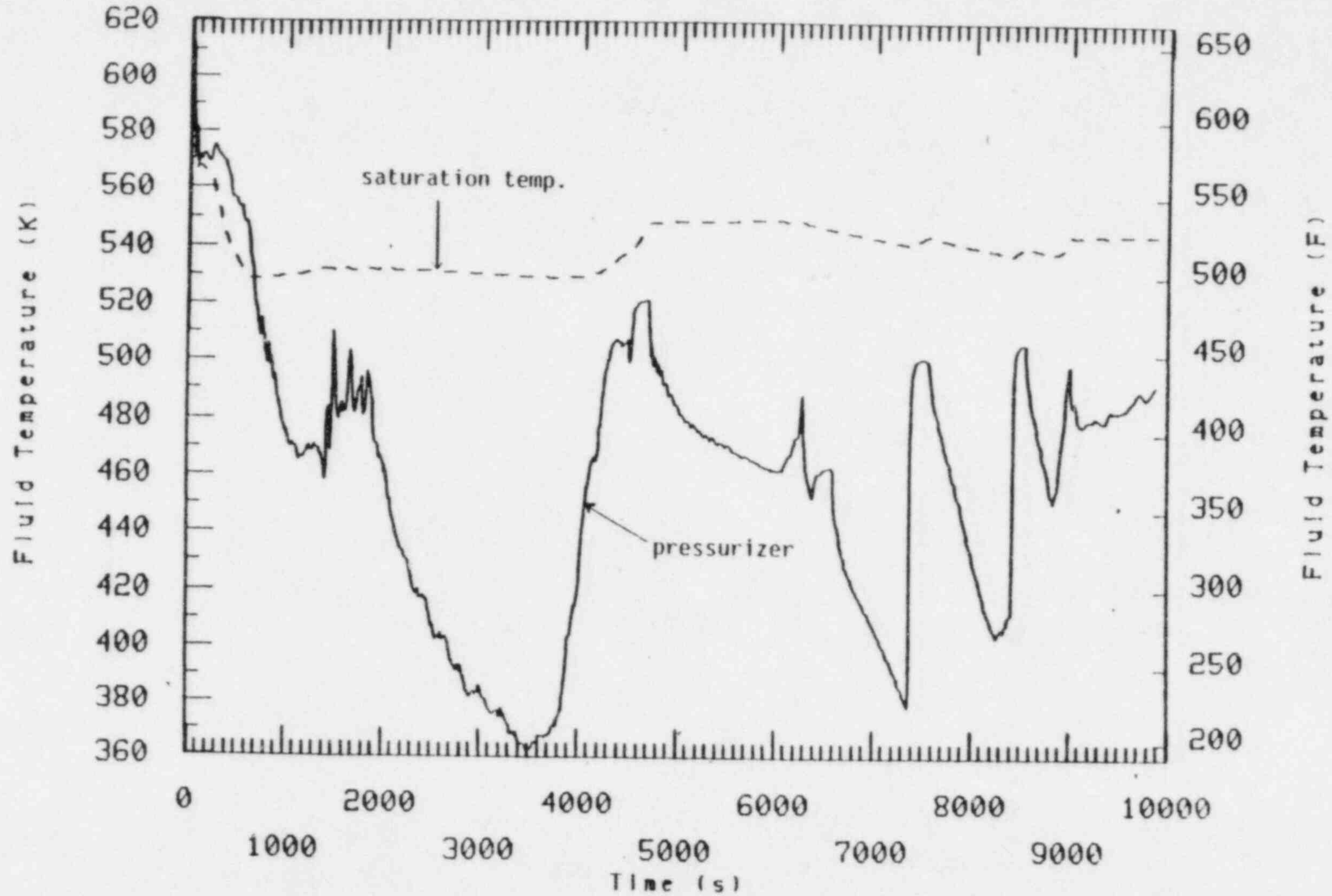


Figure 30. Comparison of fluid temperature and saturation temperature during a hot side, five-tube rupture transient (S-SG-5).

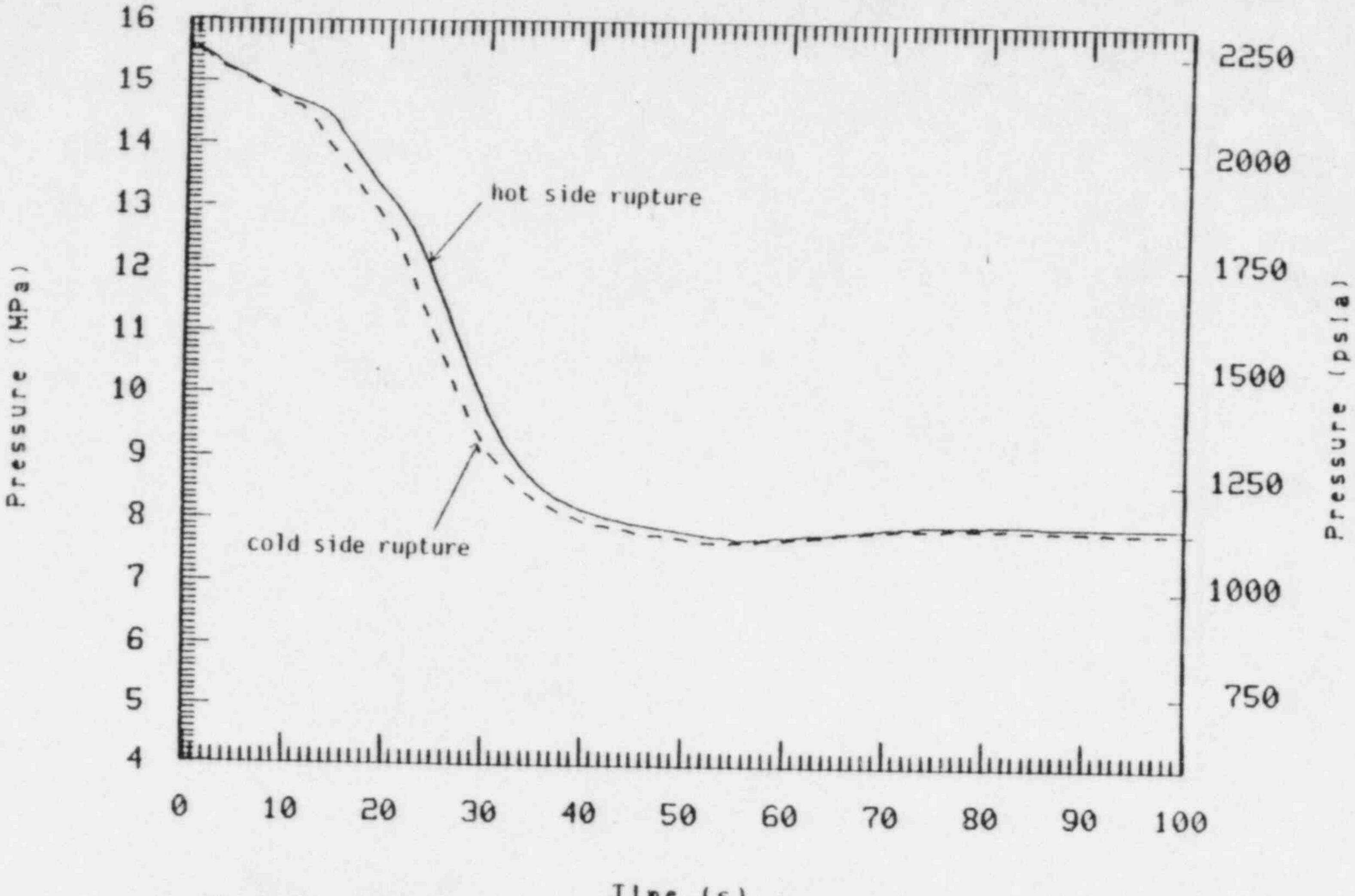


Figure 31. Comparison of primary pressure for a cold side (S-SG-2) and hot side (S-SG-5), five-tube rupture transient.

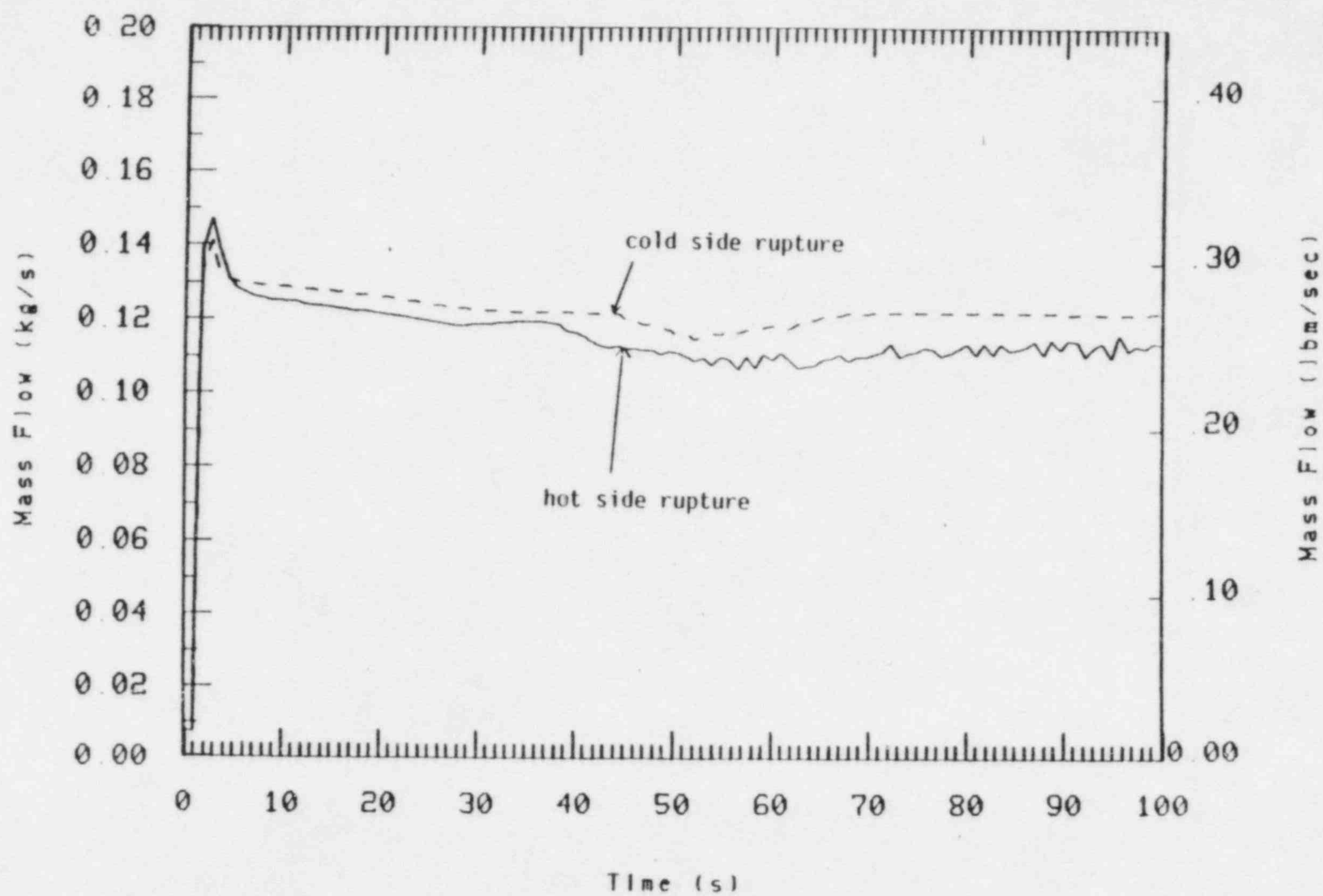


Figure 32. Comparison of break flow for a cold side (S-SG-2) and hot side (S-SG-5), five-tube rupture transient.

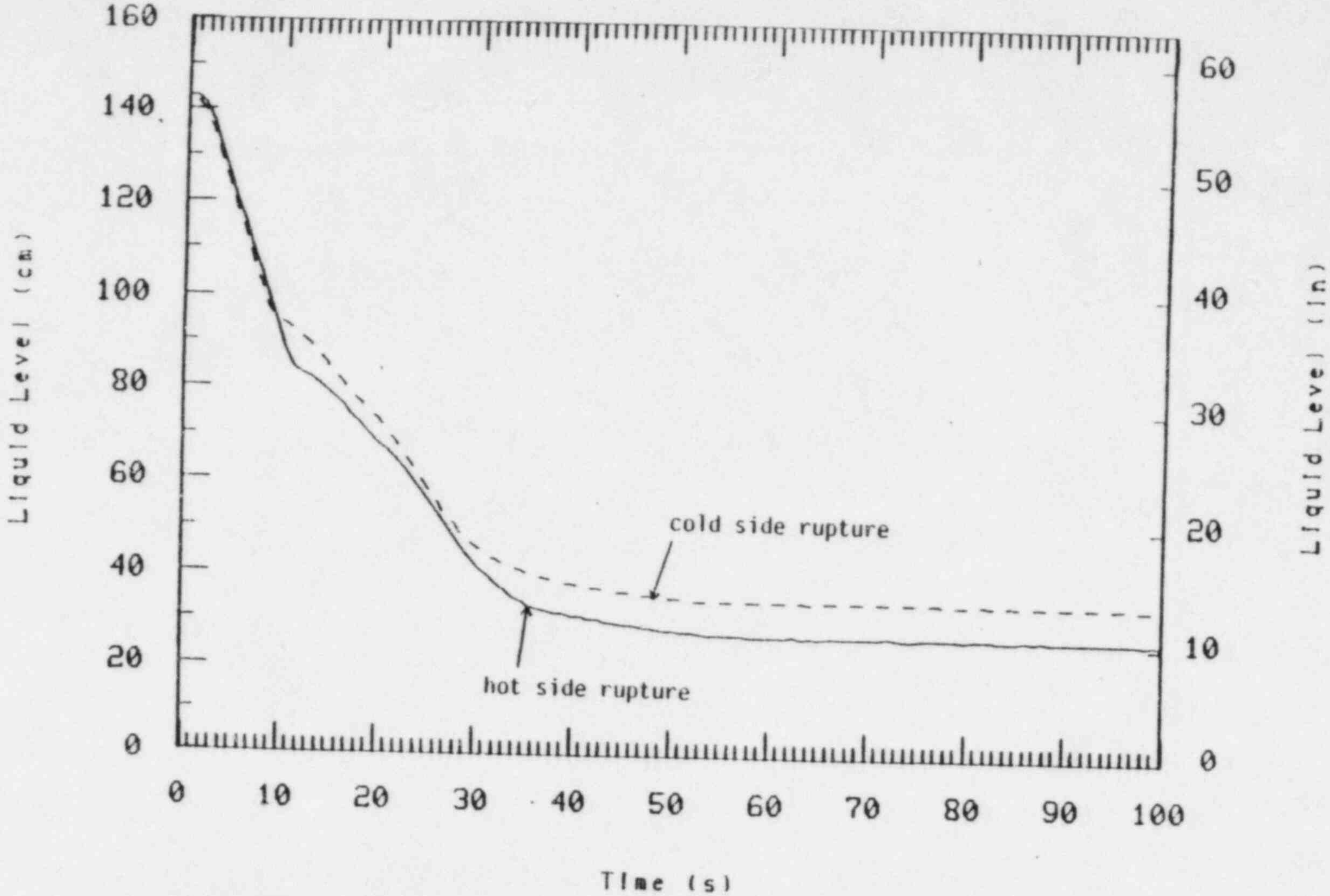


Figure 33. Comparison of pressurizer collapsed liquid level for a cold side (S-SG-2) and hot side (S-SG-5), five-tube rupture transient.

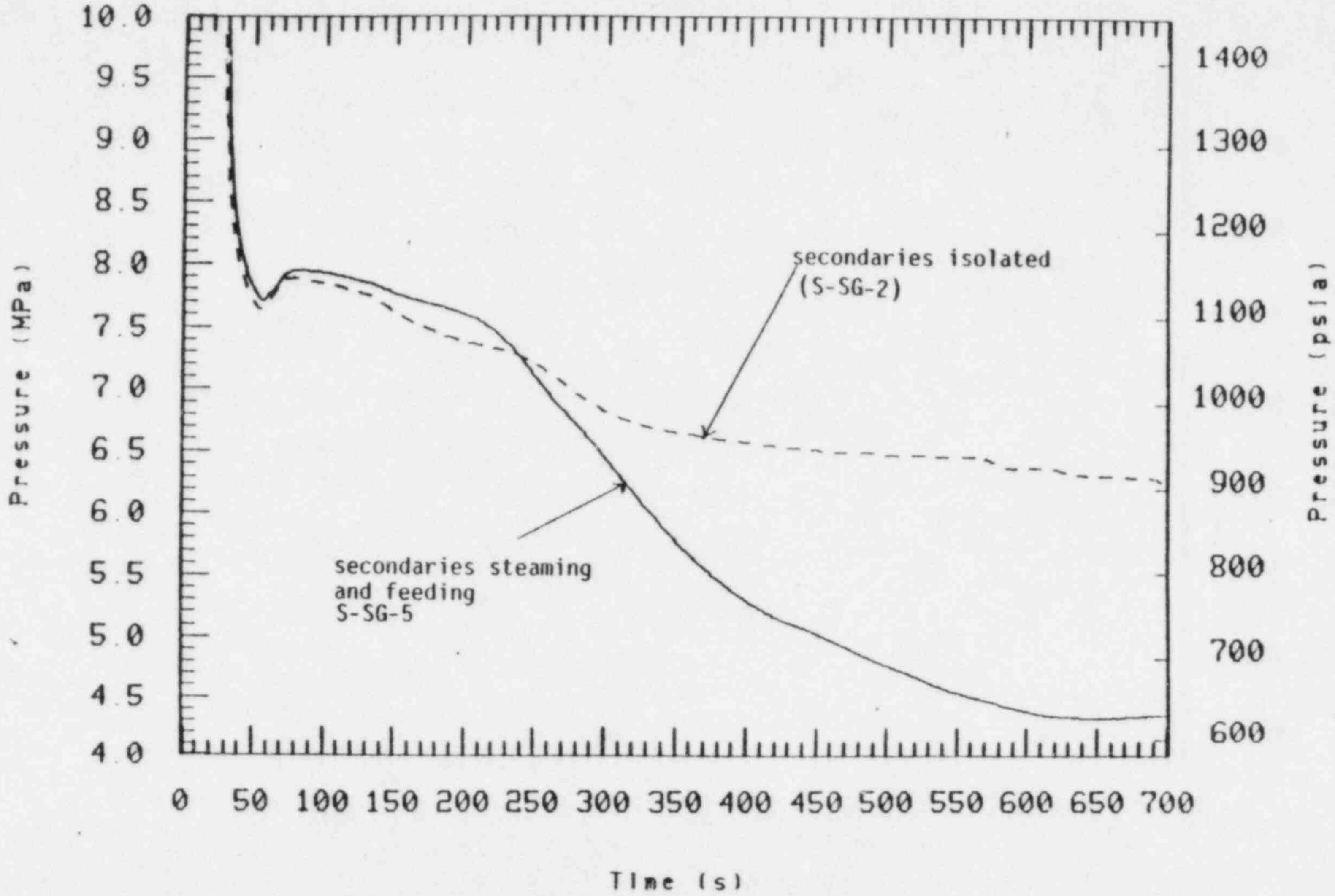


Figure 34. Comparison of primary pressure for a cold side (S-SG-2) and hot side (S-SG-5), five-tube rupture transient.

of the two tests. The effectiveness of early steam and feed in reducing primary pressure is evident. Primary pressure in S-SG-5 drops well below that in S-SG-2 and below the affected loop ADV setpoint.

In general the early system response was very similar between the two tests, the slight difference in break flow being the predominant difference. Early steam and feed was very effective in reducing primary pressure.

4. COMPARISON OF PRETEST CALCULATION TO TEST DATA

This section compares the S-SG-5 test results to the best-estimate calculation documented in the S-SG-5 Pretest Analysis Document.[1,a] Because the recovery procedures followed in the test and the calculation diverged at the point that SI flow was restarted in the test at 7300 s, comparisons are only presented up to this point. In the RELAP5 calculation the SI was not restarted after being turned off initially. The effect of differences between calculated and actual SI operation on subsequent transient response was considered significant enough as to preclude any meaningful direct comparisons with test data beyond 7300 s.

Discussion of the calculated and test results comparisons are presented in the following three sections: Operator Diagnostic Period (Section 4.1), Plant Recovery (Section 4.2), and Conclusions and Recommendations (Section 4.3). Table 3 compares the actual and calculated sequence of events.

4.1 Operator Diagnostic Period

Discussed in this section are calculated and test results comparisons for the period starting at time zero through 600 s. Table 4 presents the actual and calculated initial conditions. All of the calculated and actual initial conditions agreed well enough that the subsequent transient responses were not influenced by any differences, with the exception of the pressurizer liquid volume. Although the initial pressurizer liquid volume was within specified tolerances, the influence of the difference between calculated and actual initial pressurizer liquid volume was to delay the pressurizer emptying time relative to that observed. Consequently, due to the influence of pressurizer emptying on primary coolant system pressure, the calculated time to SCRAM and SIS was delayed relative to actual.

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a. The best-estimate calculation presented in the S-SG-5 Pretest Analysis Document utilized an adiabatic boundary on the inner pressurizer wall.

TABLE 3. COMPARISON OF ACTUAL AND CALCULATED SEQUENCE OF EVENTS

Event	Time (s)	
	Actual	Calculated
Break flow initiated	0	0
Pressurizer internal heaters off	1	N/A
SCRAM	20	28.8
MSIV closure	20	28.8
SIS	22	32.8
Main feedwater secured	22	32.8
Auxiliary feedwater initiated	22	32.8
HPIS turned on	22	32.8
Pumps tripped	55	62
IL--ADV latched open	82	88.8
BL--ADV latched open	82	88.8
IL--ADV cycled to maintain $P = 3.25 \pm 0.14$ MPa	600	--
IL--ADV cycled to maintain $P_s = 2.44$ MPa $\pm$ 0.138 MPa	--	--
BL--ADV closed	600	600.0
BL--Auxiliary feed secured	--	600.0
BLSG filled, ADV cycling initiated	4700	5050
HPIS terminated: LL_{prz} changing very slowly ($\dot{m}_{ADV} = \dot{m}_{HPIS}$). BLSG ADV cycling terminated	6300	8450
Pressurizer internal heaters initially used to control P_p @ 5.6 MPa	7200	8900
End of comparison	7800	10000

TABLE 4. COMPARISON OF ACTUAL AND CALCULATED INITIAL CONDITIONS

Parameter	Actual	Calculated
Pressurizer pressure	15.47 MPa (2243 psia)	15.50 MPa (2248.1 psia)
Core temperature differential	38.35K (69°F)	36.0K (64.8°F)
Core inlet temperature	556.6K (542.2°F)	559.2K (546.9°F)
Cold leg fluid temperature loop-to-loop difference	0.2K (0.36°F)	1.46K (2.63°F)
Primary flow rates		
Intact loop cold leg	9.65 ℓ/s (153 gpm)	9.60 ℓ/s (152.2 gpm)
Broken loop cold leg	3.28 ℓ/s (52 gpm)	3.47 ℓ/s (55 gpm)
Initial core power	1.988 MW	2.0 MW
Pressurizer liquid volume	0.0094 m^3 (0.33 ft^3)	0.0102 m^3 (0.36 ft^3)
Pressurizer steam volume	.03021 m^3 (1.067 ft^3)	0.02941 m^3 (1.0386 ft^3)
SG secondary pressure		
Intact Loop	5.47 MPa (793 psia)	5.55 MPa (805 psia)
Broken Loop	5.62 MPa (815 psia)	5.54 MPa (804 psia)
SG secondary water mass		
Intact loop	100.4 kg (221 lbm)	103.0 kg (227.1 lbm)
Broken loop	113.8 kg (251 lbm)	100.8 kg (222.2 lbm)
Primary coolant system leakage	0.003 kg/s (0.006 lbm/s)	0.0053 kg/s (0.0117 lbm/s)

Figure 35 compares the calculated and actual pressurizer pressure. During the first 50 s, the test data showed that the primary depressurized more rapidly than in the calculation, and in general the pressurizer pressure was underpredicted during the entire diagnostic period. The RELAP5 calculation used an adiabatic boundary on the inner wall of the pressurizer, thereby eliminating heat transfer from the pressurizer wall to the fluid. The effect of not modeling this heat transfer is probably the principal reason for underprediction of the pressurizer pressure. The influence of modeling pressurizer wall-to-fluid heat transfer will be quantified in posttest analyses.

The calculated and actual steam generator secondary pressures for both the unaffected and affected loops are presented in Figures 36 and 37. Major trends of the test data were predicted (e.g., peak pressure in both steam generators). The depressurization rate was overpredicted however in both loops. The calculated and measured integrated ADV flow rates (Figures 38 and 39) were in good agreement.

4.2 Plant Recovery Phase

Discussed in this section are the results of calculated and test results comparisons for the plant recovery phase of the transient. The test data presented in this section for comparison with the RELAP5 calculated results extend from 600 to 7300 s. At 7300 s in the test SI was restarted. The RELAP5 calculated results presented extend from 600 to 10000 s.

Figure 40 compares the measured and calculated pressurizer pressures. Good agreement was achieved during the period from 600 to 2000 s. However, from 2000 s to the point that the affected steam generator fills with liquid, the calculated results overpredicted the data. The overprediction of the pressurizer pressure is due to an underprediction of the break flow (Figure 41 presents the integrated break mass flow rate) during this period. Therefore, less primary coolant system voiding and a less effective steam generator heat sink was calculated for the affected loop. The relative effectiveness of the calculated and measured affected loop

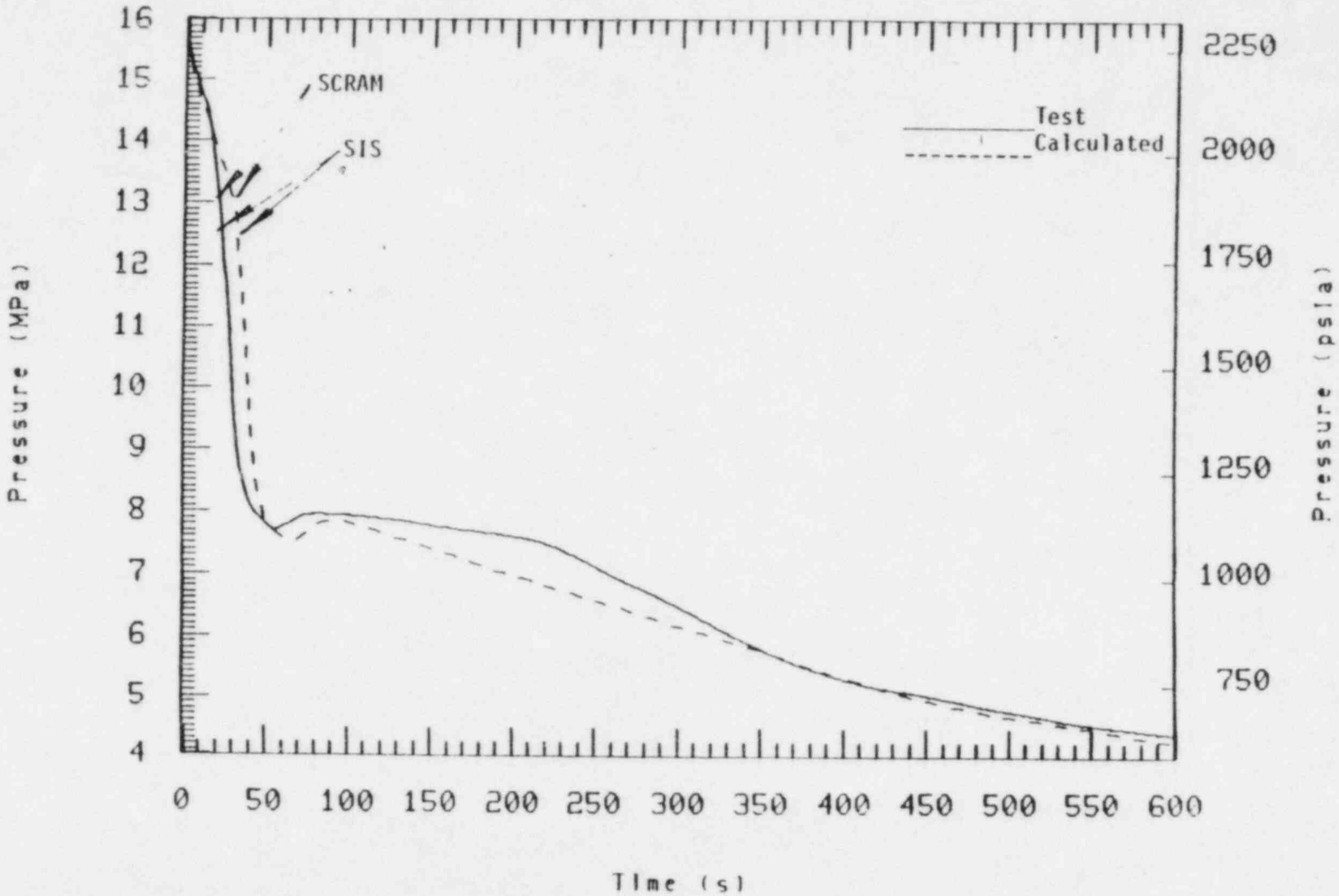

Figure 35. Comparison of test and calculated pressurizer pressure (0 to 600S).

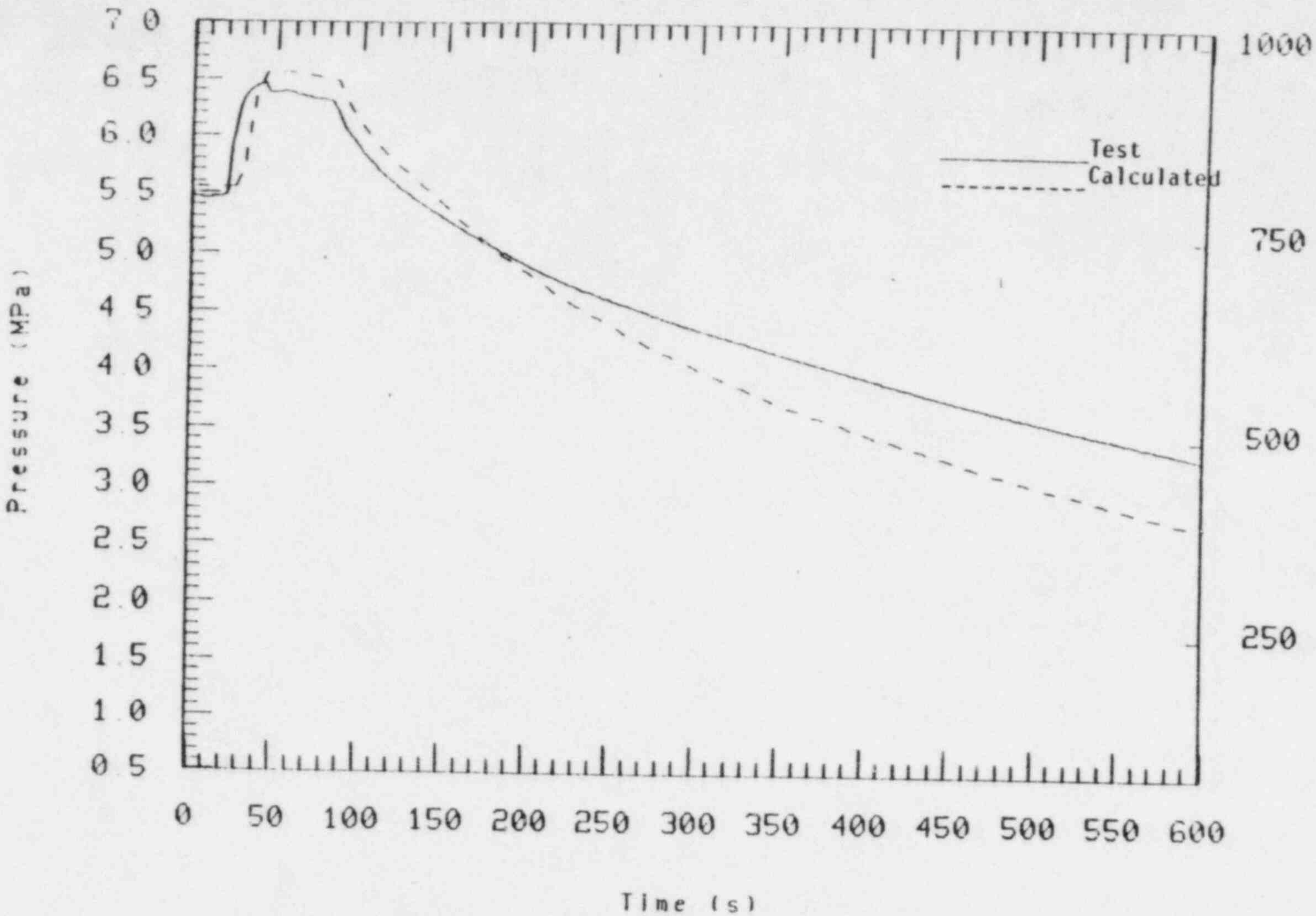

Figure 36. Comparison of test and calculated unaffected steam generator pressure (0 to 600S).

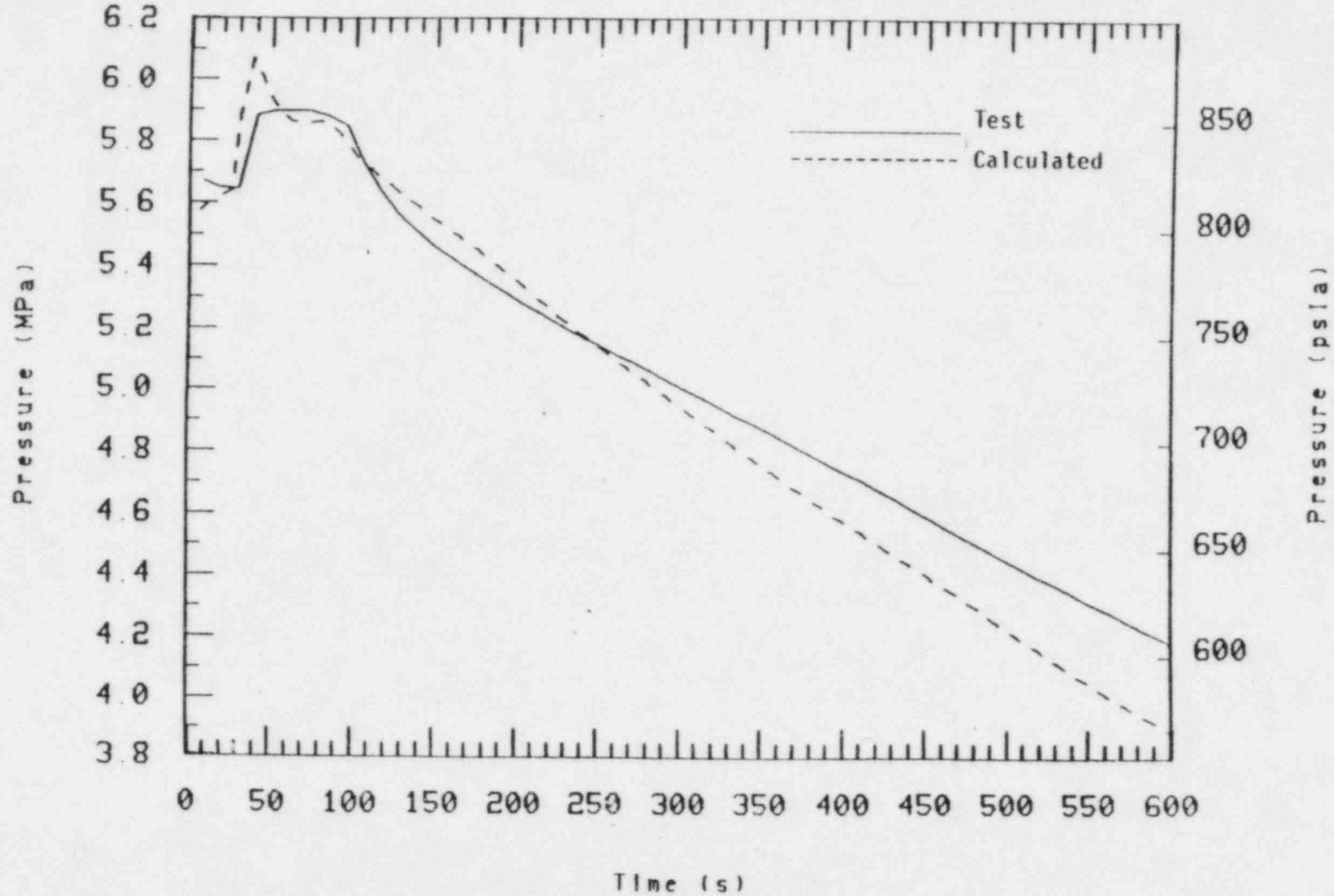

Figure 37. Comparison of test and calculated affected steam generator pressure (0-600S).

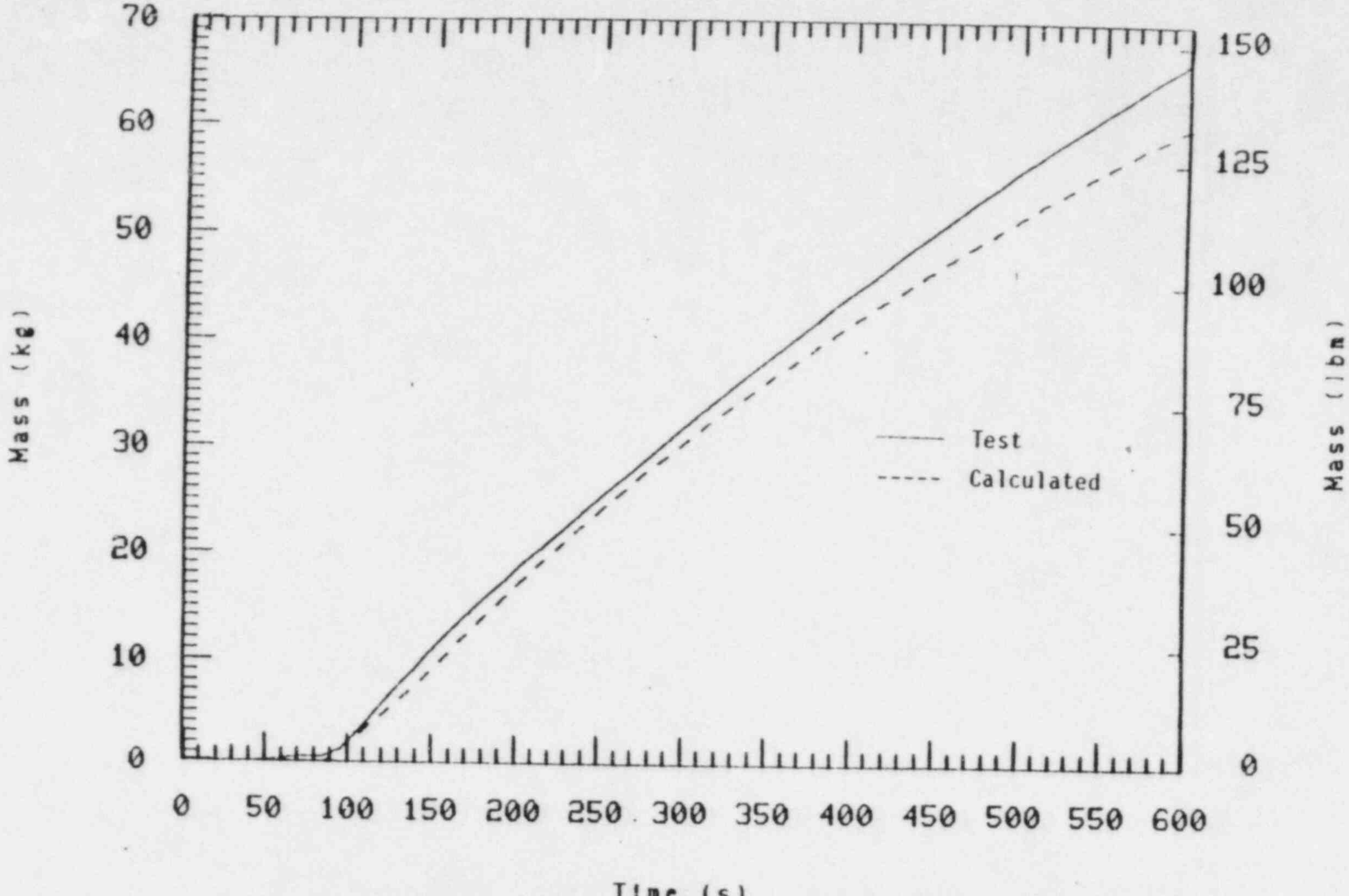

Figure 38. Comparison of test and calculated unaffected steam generator ADV integrated mass flow rate (o to 600 s).

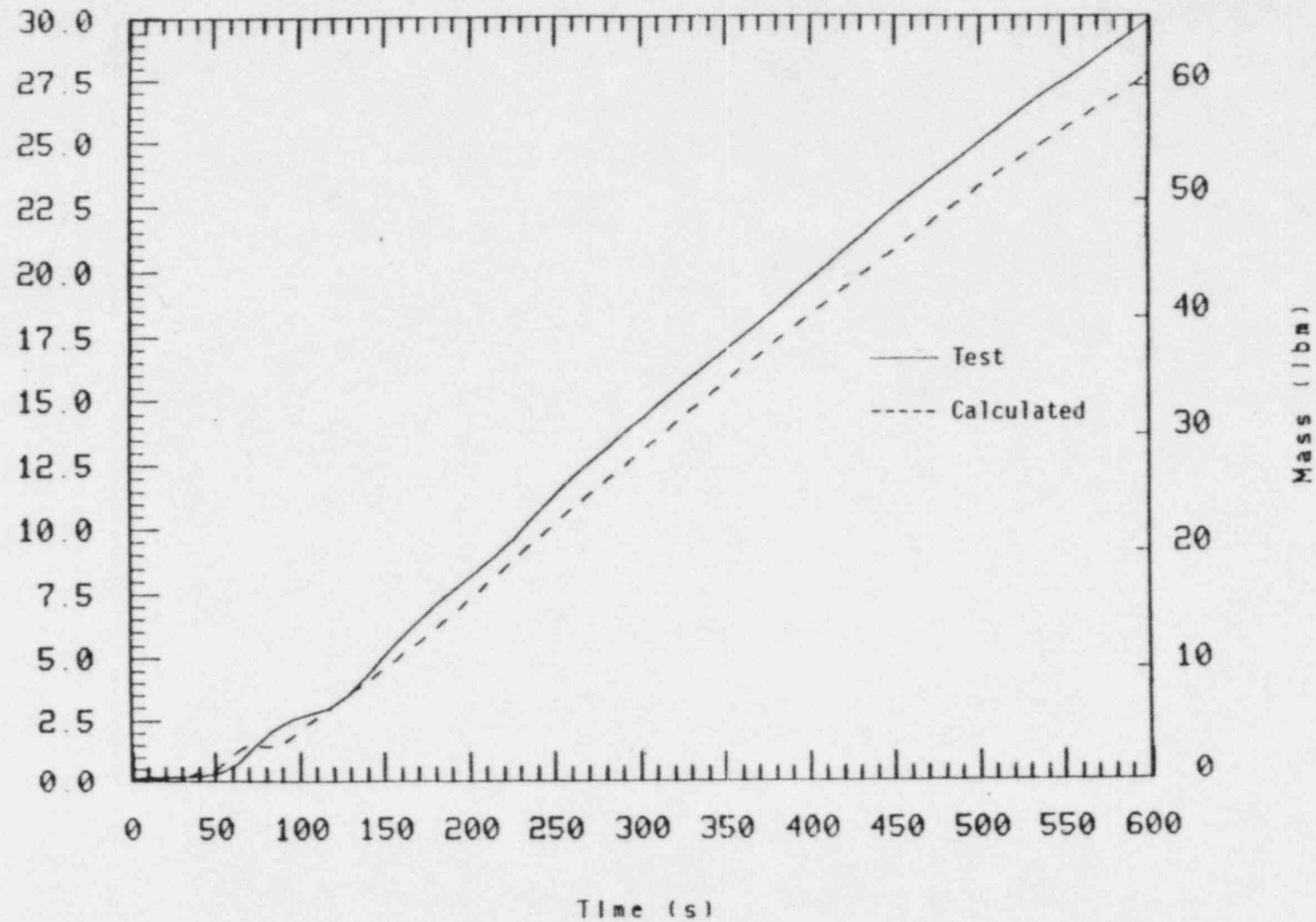

Figure 39. Comparisons of test and calculated affected steam generator ADV integrated mass flow rate (0 to 600 s).

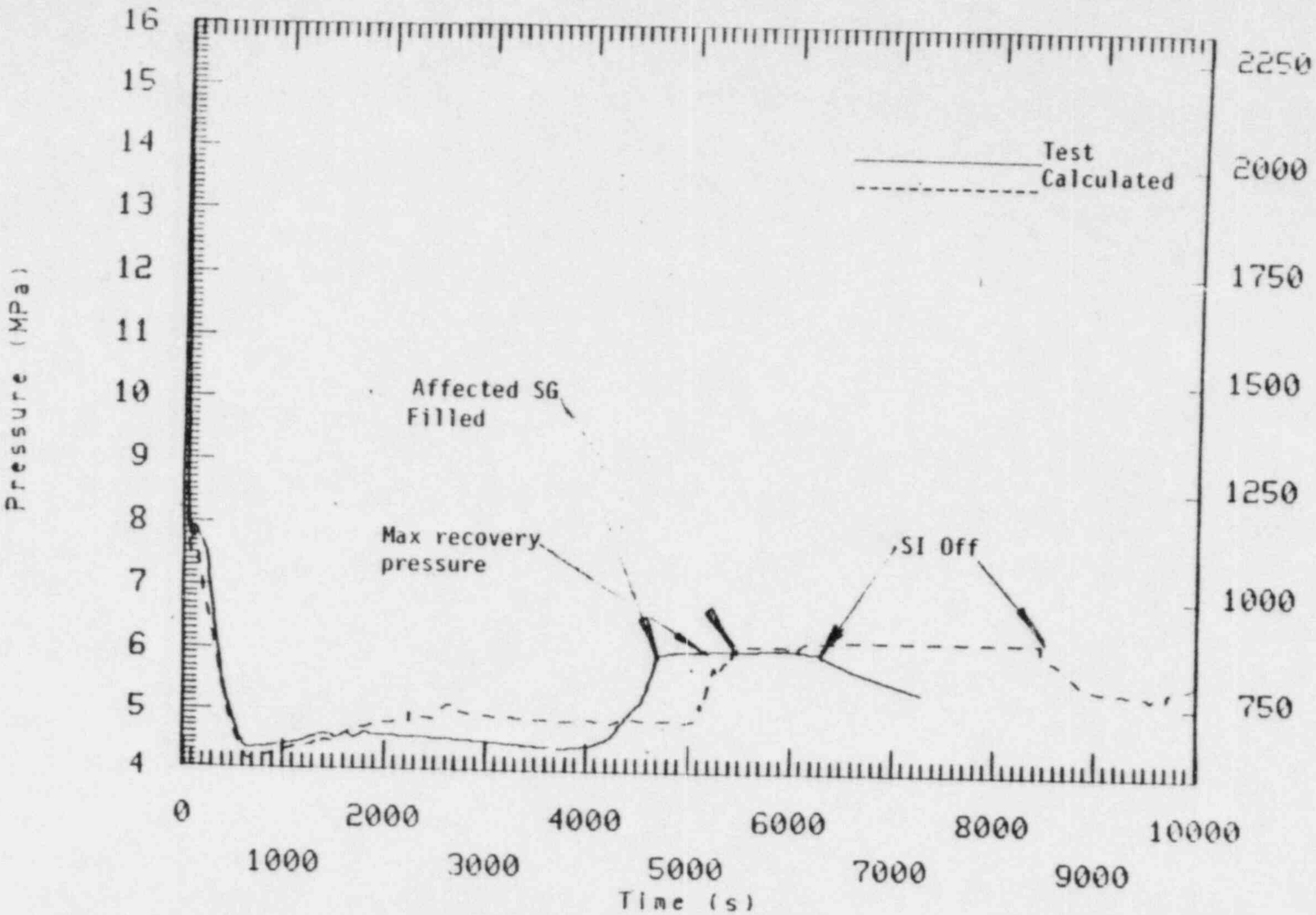

Figure 40. Comparison of test and calculated pressurizer pressure (0 to 10000S) .

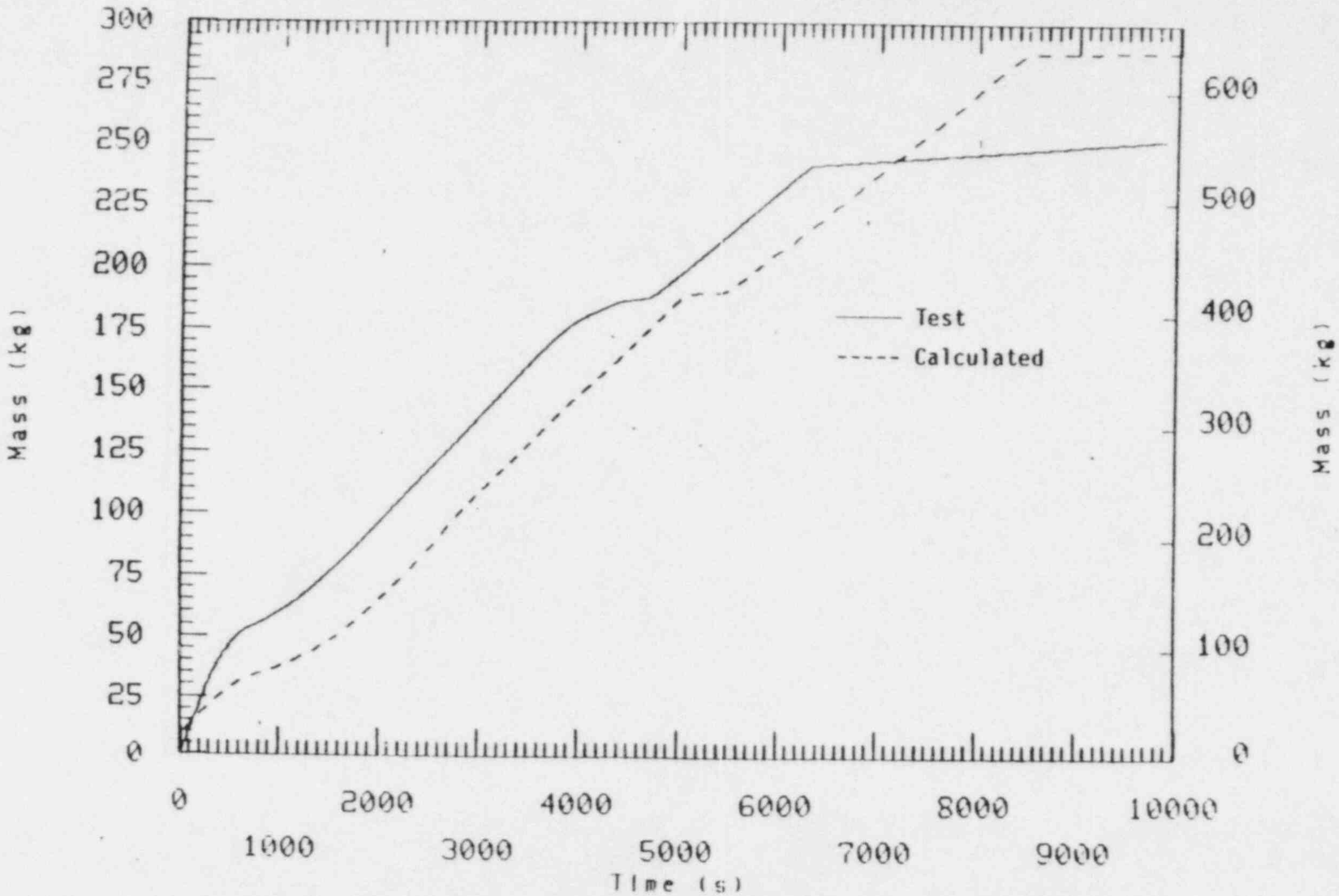

Figure 41. Comparison of test and calculated integrated break mass flow rate (0 to 10,000 s).

steam generator heat sink is indicated by the pressure responses (Figure 42). The measured affected steam generator pressure (and the associated fluid temperature which is near saturation) was lower than that calculated, and is an indication that the heat sink is more effective than that calculated. The unaffected steam generator pressure (Figure 43) was underpredicted during this same period. This was a result of the calculated and measured unaffected steam generator pressures being controlled at the value reached at 600 s.

The affected steam generator filled with liquid at 4700 s; filling was calculated to occur at 5300 s. The reason for this difference is the higher break mass flow in the test relative to that calculated. After the affected steam generator filled and pressurized to the ADV relief setpoint (Figure 42) the calculated and measured pressurizer pressure rose to the maximum pressure reached during the recovery phase (approximately 6.0 MPa (870 psi)).

In the test SI was turned off when the affected steam generator ADV flow equalled the SI flow. In the calculation SI was turned off when the pressurizer level reached 381 cm (150 in). The primary pressure, both calculated and measured, then decreased below the affected steam generator ADV relief setpoint. At this point (7200 s) in the test control of the pressurizer pressure at 5.6 MPa (812 psia) was unsuccesfully attempted by operating the pressurizer internal heaters. In the calculation at 8900 s the pressurizer internal heaters were operated and successfully controlled the pressurizer pressure at 5.6 MPa (812 psia).

Differences between the calculated and measured pressurizer pressure response to the operation of the internal heaters is probably due to differences between the respective pressurizer fluid temperatures. This is indicated by the fact that the net energy input to the pressurizer (environmental heat loss minus pressurizer internal heater power) is approximately equal to that calculated. The reasons associated with the difference in pressurizer pressure response to operation of the internal heaters will be investigated further in posttest analyses.

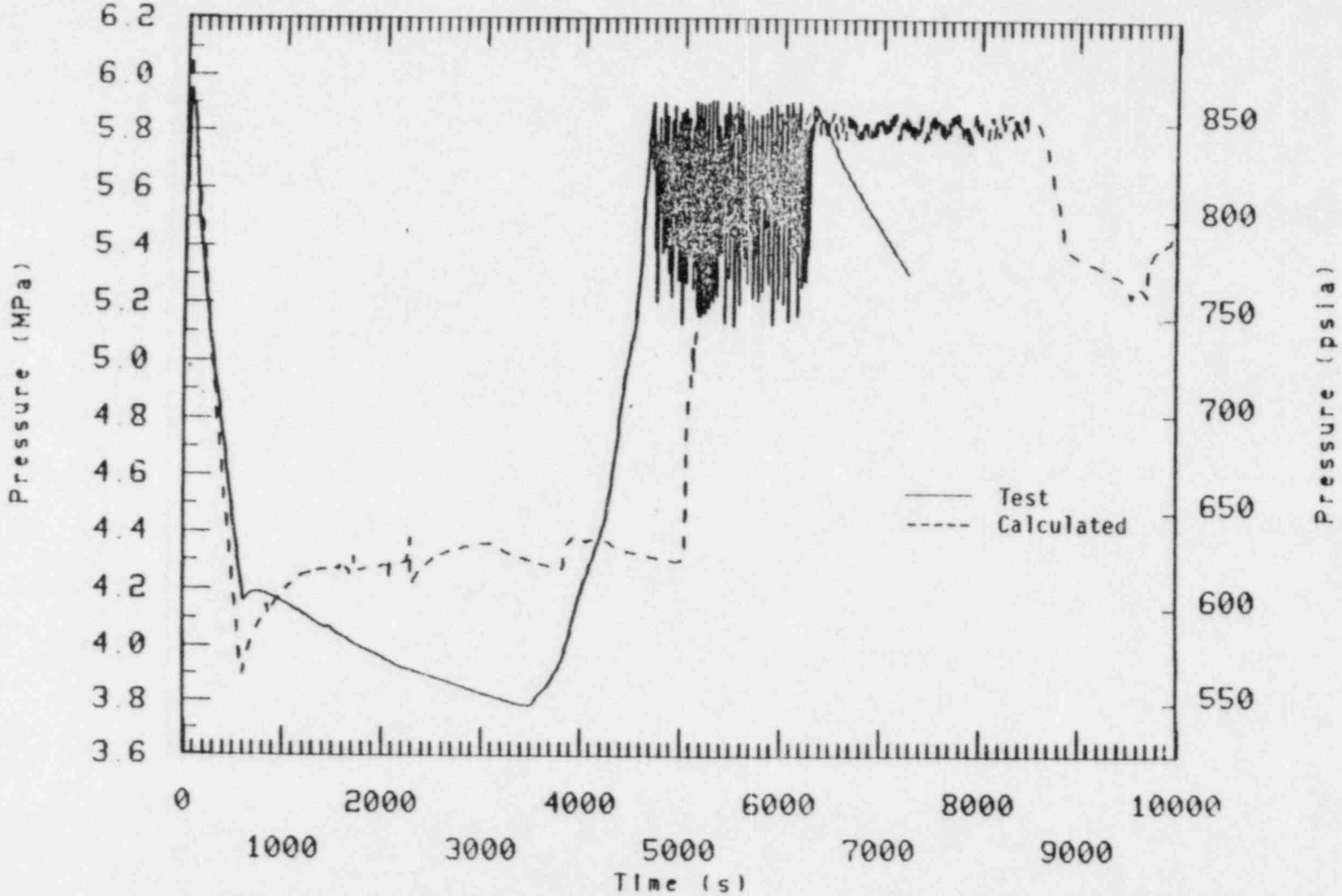

Figure 42. Comparison of test and calculated affected steam generator pressure (0 to 10000 s).

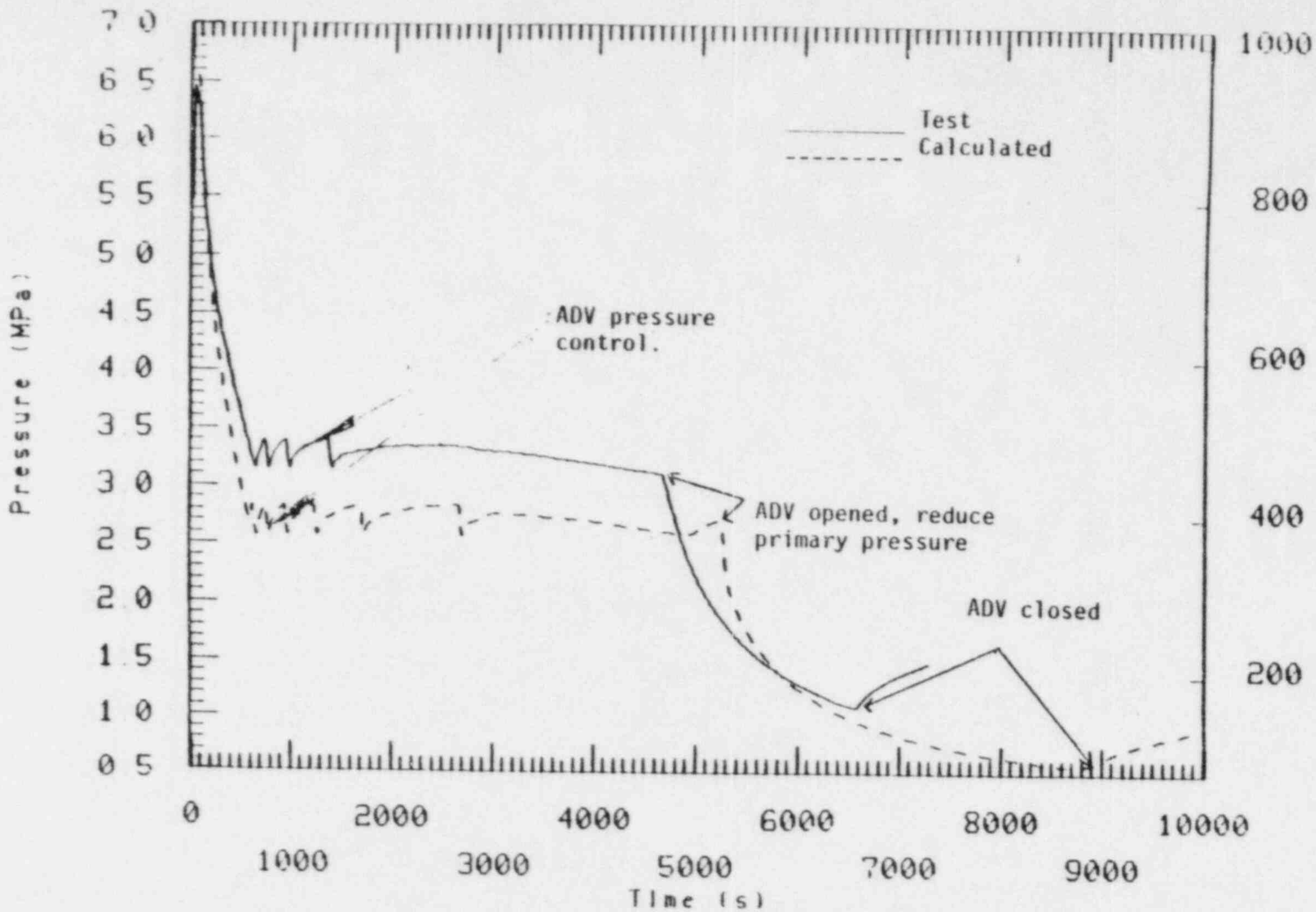

Figure 49. Comparison of test and calculated unaffected steam generator pressure (0 to 10000S).

4.3 Summary and Recommendations

In general, the calculated transient signature compared reasonably well with the test data. The major differences are the underprediction of the break flow which affected the magnitude and timing of the primary and secondary pressure response. The accuracy of the break flow calculation may be improved by benchmarking the model to test data. The best-estimate RELAP5 pretest calculation utilized an adiabatic boundary on the inner wall of the pressurizer. Although it is believed that this modeling approach did not significantly compromise agreement between calculated and measured test responses, it is recommended that a mechanistic pressurizer boundary be added to the model. This model should then be used in conjunction with the current best-estimate modeling approach during posttest analyses to quantify the differences between the responses calculated using the two modeling approaches.

5. CONCLUSIONS

The following conclusions have been drawn based on a preliminary analysis of S-SG-5, and a brief comparison of cold side (S-SG-2) and hot side (S-SG-5) five tube rupture experiments.

1. The combined effect of early secondary cooldown, unaffected loop steam and feed, SI operation, and pressurizer heater operation was sufficient to recover the Semiscale system from a steam generator, five-tube hot side rupture.

   Recovery included the establishment of specified levels in the vessel and pressurizer, termination of atmospheric release, and maintenance of primary pressure at 5.6 ± 0.14 MPa (812 ± 20 psia) using pressurizer heaters.

2. The early secondary steam and feed, initiated in both steam generator secondaries, was effective in cooling the system.

   The primary and secondary pressures at the end of steam and feed were well below the affected loop ADV setpoint, thereby terminating release. Comparison of S-SG-2 and S-SG-5 showed greatly reduced primary pressure directly resulting from the secondary steam and feed.

3. Safety injection was successful in re-establishing liquid levels and controlling primary system pressure.

   SI filled the vessel, affected loop secondary, and the pressurizer to specified levels. SI operation effectively maintained primary system pressure, and early termination of SI was essential to eliminating atmospheric release through the affected loop ADV.

4. Pressurizer heaters were ultimately successful in controlling primary system pressure, and recovering pressurizer pressure control.

   Warm-up heater operation was required to warm the fluid in the pressurizer before the back-up and variable heaters were effective.

5. Location of the rupture on the hot side rather than the cold side affected timing of some events, however no phenomenological differences were noted.

   Higher fluid density in the cold leg produced slightly higher break flows resulting in a faster pressurizer drain and depressurization.

6. The RELAP5 pretest calculation agreed qualitatively with test data for most of the transient.

   Differences in calculated and measured break flow indicate that the model should be benchmarked to test data. In addition, differences between the calculated and measured primary pressure response to operation of the pressurizer internal heaters indicate the need for additional study of the controlling phenomena and a subsequent assessment of the pressurizer model's capability to calculate this phenomenon.

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16. ABSTRACT (200 words or less)

Results of a preliminary analysis of the third test performed in the Semiscale Mod-2B Steam Generator Tube Rupture Series are presented. Test S-SG-5 simulated a pressurized water reactor accident initiated by a double-ended offset shear of five hot side steam generator tubes. The transient included an initial 80-second period during which only automatic plant protection system response to the initiating event occurred. This period was followed by an operator-induced recovery procedure to establish an early steam and feed condition in both the unaffected and affected loop steam generators. The early secondary cooldown terminated at 600 s and was followed by use of SI and pressurizer heaters to maintain system inventory and recovery primary system pressure control in the pressurizer. The test results provided a measured evaluation of the effectiveness of an early secondary steam and feed on reducing primary system pressure, the effect of high pressure injection system operation on recovering primary system inventory and pressure control, and the effectiveness of pressurizer heaters in controlling primary pressure. The test showed that the prescribed limited operator response was adequate to recover the Semiscale system from a simulated five-tube rupture.

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