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QUICK LOOK REPORT FOR SEMISCALE MOD-2B TEST S-SG-3

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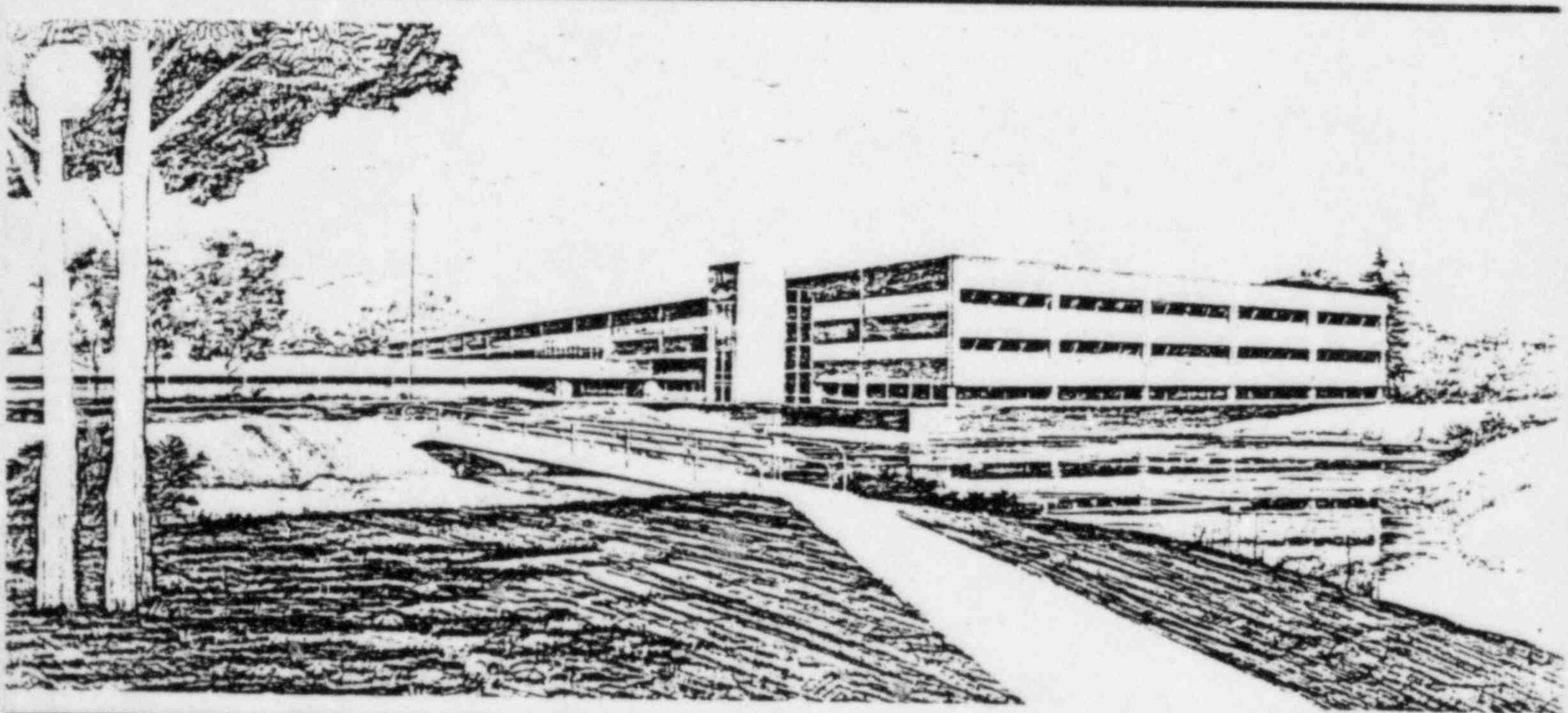

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QUICK LOOK REPORT FOR SEMISCALE MOD-2B
TEST S-SG-3

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ABSTRACT

Results of a preliminary analysis of the sixth test performed in the Semiscale Mod-2B Steam Generator Tube Rupture Series are presented. Test S-SG-3 simulated a pressurized water reactor accident initiated by a double-ended offset shear of ten cold side steam generator tubes. The transient was characterized by five distinct phases of operation. Phase 1 involved an initial 600 s period during which only automatic plant protection system response to the initiating event occurred. Phase 2 included an operator induced recovery involving pressurizer auxiliary spray to reduce system pressure below broken loop ADV setpoints. This pressure reduction was aided by intact loop generator feed and steam. Phase 3 involved using pressurizer heaters to subcool the system by increasing primary pressure. Phase 4 used the intact loop pump to redistribute the system fluid energy and promote core cooling. Finally, phase 5 involved a combination of pressurizer spray, intact loop pump flow, SI, pressurizer heaters, and intact loop generator feed and steam to establish a subcooling margin and to slowly depressurize the primary system. These procedures were all accomplished without sufficient core uncovery to cause a core rod heatup.

SUMMARY

This report presents a preliminary analysis of the Semiscale Mod-2B Steam Generator Tube Rupture Series (SG) test S-SG-3. S-SG-3 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 operator responses to the accident following an initial 10-minute simulated identification period.

Test S-SG-3 simulated a pressurized water reactor transient initiated by a double-ended offset shear of ten cold side steam generator tubes. Data from this experiment will be examined to evaluate event signatures, event severities in Semiscale and recovery procedures, and provide data to assess computer code capability.

Test S-SG-3 was primarily designed to investigate the effectiveness of pressurizer auxiliary spray to depressurize the primary system. An additional objective was to examine the effectiveness of using the combined methods of pressurizer auxiliary spray, pressurizer internal heaters, safety injection, main coolant pump flow, and intact loop generator feed and steam to obtain an acceptable primary fluid subcooling margin and depressurization rate. To accomplish these objectives test S-SG-3 was designed in five parts: (a) an initial 600 s period in which only automatically functioning plant protection systems were assumed to operate, (b) an initial recovery period using pressurizer spray and intact loop feed and steam to depressurize the system below broken loop ADV setpoints, (c) a period of repressurization to establish subcooling using pressurizer internal heaters and auxiliary spray, (d) a period involving a redistribution of primary fluid using the intact loop pump, pressurizer heaters and auxiliary spray, and (e) a period of establishing primary fluid subcooling and a depressurization using pressurizer internal heaters, pressurizer auxiliary spray, intact loop pump operation, intact loop steam generator feed and steam, and SI.

The ten-tube rupture signature was characterized by a relatively rapid decrease of the primary coolant system pressure to saturated conditions in

the hot legs as primary fluid flowed through the break to the broken loop secondary. Automatic protective actions that influenced the pressure response during this early period were core scram and main steam isolation valve (MSIV) closure. 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 intact and broken loop steam generators. The ten tube break was sufficient to leave the vessel collapsed liquid level 10 cm (3.9 in) below the top of the core at the end of 600 s. This amount of vessel voiding is a direct result of a break flow higher than safety injection during this period.

The overall system response of the 10 tube rupture transient was compared to other Semiscale 1 and 5 tube rupture transients and the results were found to be similar. The 1, 5, and 10 tube rupture transients all exhibited the same primary and secondary pressure response with the timing of events being the main difference. The most fundamental difference between the one-tube, five-tube, and ten-tube rupture transient was the relationship between break flow and SI. The break flow was much higher in relationship to the SI flow for the five and ten tube rupture transients resulting in more extensive vessel voiding at the end of 600 s. Vessel collapsed level was 15 cm (5.9 in) above the top of the core for the 5 tube case, 10 cm (3.9 in) below the top of the core for the 10 tube case and about 530 cm (209 in) above the top of the core for the 1-tube case.

The Semiscale system was successfully recovered from a 10 tube rupture transient using a four phase recovery scenario based on emergency operating procedures for a US PWR. Recovery procedures started after phase 1 (0 to 600 s) which was a time assumed for operator identification of the ten tube rupture transient.

At 600 s, phase 2 began by initiating pressurizer auxiliary spray in an attempt to depressurize the primary pressure significantly below the broken loop ADV setpoint. Auxiliary pressurizer spray alone was capable of reducing the primary pressure to the broken loop ADV setpoint; [5.85 MPa

(836 psig)]. However further reduction of primary pressure to a desired value of 5.6 MPa (800 psig) was not possible in a timely manner (within a predetermined 900 s period). Therefore the intact loop secondary ADV was latched open briefly and the primary pressure was quickly reduced to a predetermined value of 5.6 MPa (800 psig). This predetermined value was set so that there would be consistency between test data and pretest computer calculations.

Phase 3 involved using the pressurizer internal heaters and auxiliary spray to pressurize the primary system and thus subcool the primary fluid. Pressurizer variable and backup heater operation (2.35 kW) alone when combined with auxiliary spray were not sufficient to raise the system pressure from 5.6 MPa (800 psig) to 5.85 MPa (836 psig) as desired. However, warm-up heaters (13.3 kW) combined with auxiliary spray, pressurized the primary to 5.85 MPa (836 psig). There was a net increase in the vessel liquid inventory during this spray and heater operation as well as an increase in primary fluid subcooling.

During phase 4 the overall effect due to intact loop pump operation was to cause a lowering of primary system pressure and cause a termination of SI on a high pressurizer level trip. The lowering of primary system pressure was caused by mixing of subcooled cold leg and saturated hot leg fluid thus collapsing voids in the system. Because the voids were collapsed in the mixing operation, SI flow was able to fill the pressurizer to the high pressurizer level trip point [381 cm (150 in)] since the pressurizer represented one of the few voids left in the system.

Phase 5 combined intact loop pump operation, pressurizer auxiliary spray and internal heater operation, a latched open ADV and SI to cause an increase in system fluid subcooling [from 5 to 37 K (9 to 67°F)]. The reduction in primary fluid temperature due to an increased heat sink provided by the latched open ADV was the main contributor to loop fluid subcooling. Once 37 K (67°F) fluid subcooling in the loop had been achieved, an attempt was made to control the primary pressure on a 0.172 MPa/5 min (25 psi/5 min) depressurization rate using the pressurizer

internal heaters as necessary. It was necessary to leave the heaters off for most of this depressurization period as the system depressurization rate was slower than specified.

The system response during the operator diagnostic period, pressurizer auxiliary spray use; and initial intact loop steam generator feed and steam operation were well predicted by RELAP5. The calculated response to the internal pressurizer heaters and intact loop pump restart were not well predicted which resulted in poor event timing agreement.

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FIGURES

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1. INTRODUCTION

This report documents preliminary results from Semiscale Mod-2B test S-SG-3, the sixth experiment performed in the Semiscale Steam Generator Tube Rupture (SG) Test Series.[1] Test S-SG-3 was performed January 18, 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-3 simulated a pressurized water reactor transient initiated by a double-ended offset shear of ten cold side steam generator tubes. The test basically simulated a ten tube rupture transient with a recovery scenario consisting of a combination of pressurizer auxiliary spray and internal heater power, intact loop secondary feed and steam, safety injection (SI), and main coolant pump operation. The test consisted of five distinct phases. Phase 1 was an initial 600 s period in which only automatically functioning plant protection systems were assumed to operate. The tube rupture, which was simulated in the broken loop of the Semiscale system was the initiating event. Automatically occuring events during the first 600 s included main steam isolation valve closure, termination of main feedwater, auxiliary feedwater initiation, coastdown of the main coolant pumps, and start of safety injection. A four phase recovery operation was initiated at 600 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).

Starting at 600 s, phase 2 involved using pressurizer auxiliary spray aided by intact loop secondary feed and steam to bring the primary pressure down below the broken loop secondary atmospheric dump valve (ADV) trip point thus isolating the broken loop generator secondary from atmospheric release.

Upon achieving a primary pressure below the broken loop ADV setpoints, the primary pressure was increased to the broken loop ADV setpoint using pressurizer internal heaters and pressurizer spray (for pressurizer level maintenance) to establish a subcooling margin (phase 3).

Phase 4 involved turning on the intact loop pump (at initial operating speed) to redistribute system fluid energy and increase core cooling capability.

Phase 5 included intact loop secondary steam and feed (latched open ADV), pressurizer internal heater operation, SI, pressurizer auxiliary spray and main coolant pump operation to subcool the primary system fluid and then promote a slow (0.172 MPa/5 min (25 psi/5 min)) primary depressurization.

A preliminary analysis of test S-SG-3 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-3, only 21 rods were powered.

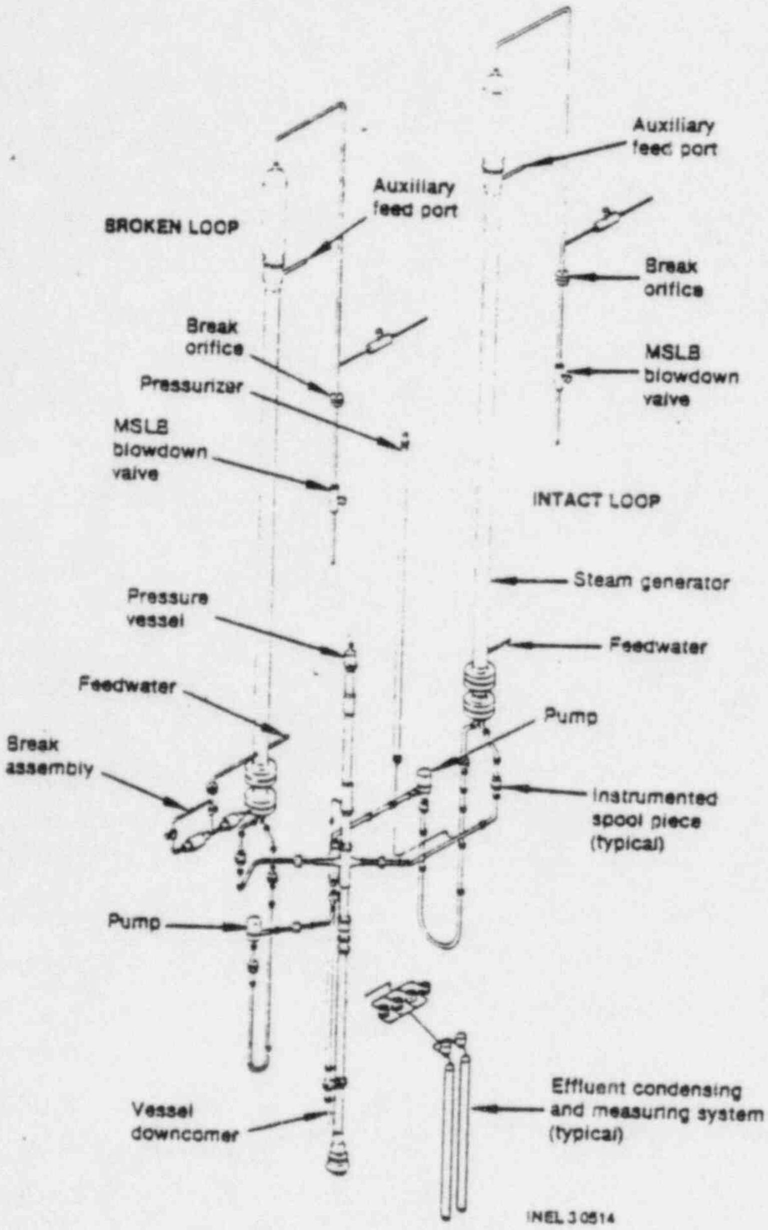

Figure 1. Semiscale Mod-2B system as configured for the SG test series.

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 inact 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 $1.8 \times 10^{9}\ m^{-4}$ for test S-SG-3. 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

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a. The ADV and SRV relief setpoints were set to different, and artifically 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 on S-SG-3.

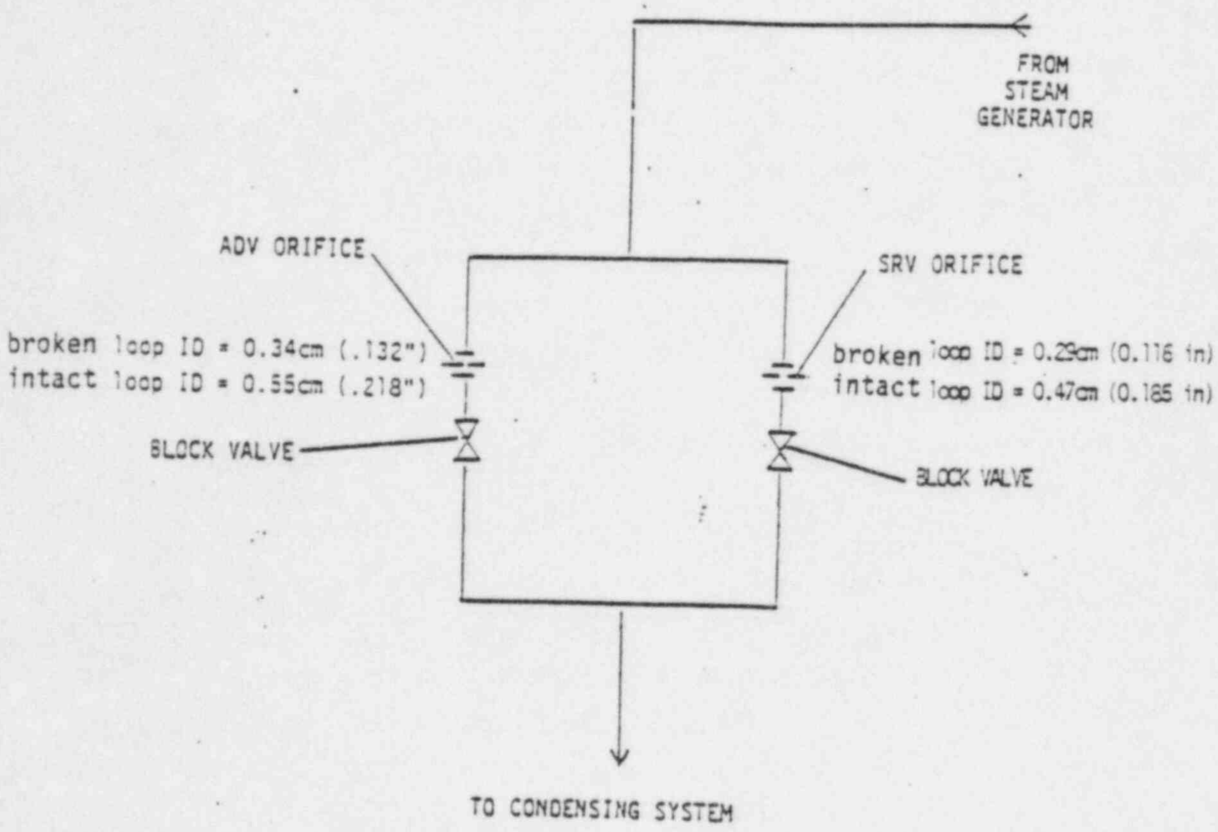


Figure 2. ADV and safety relief valve system.

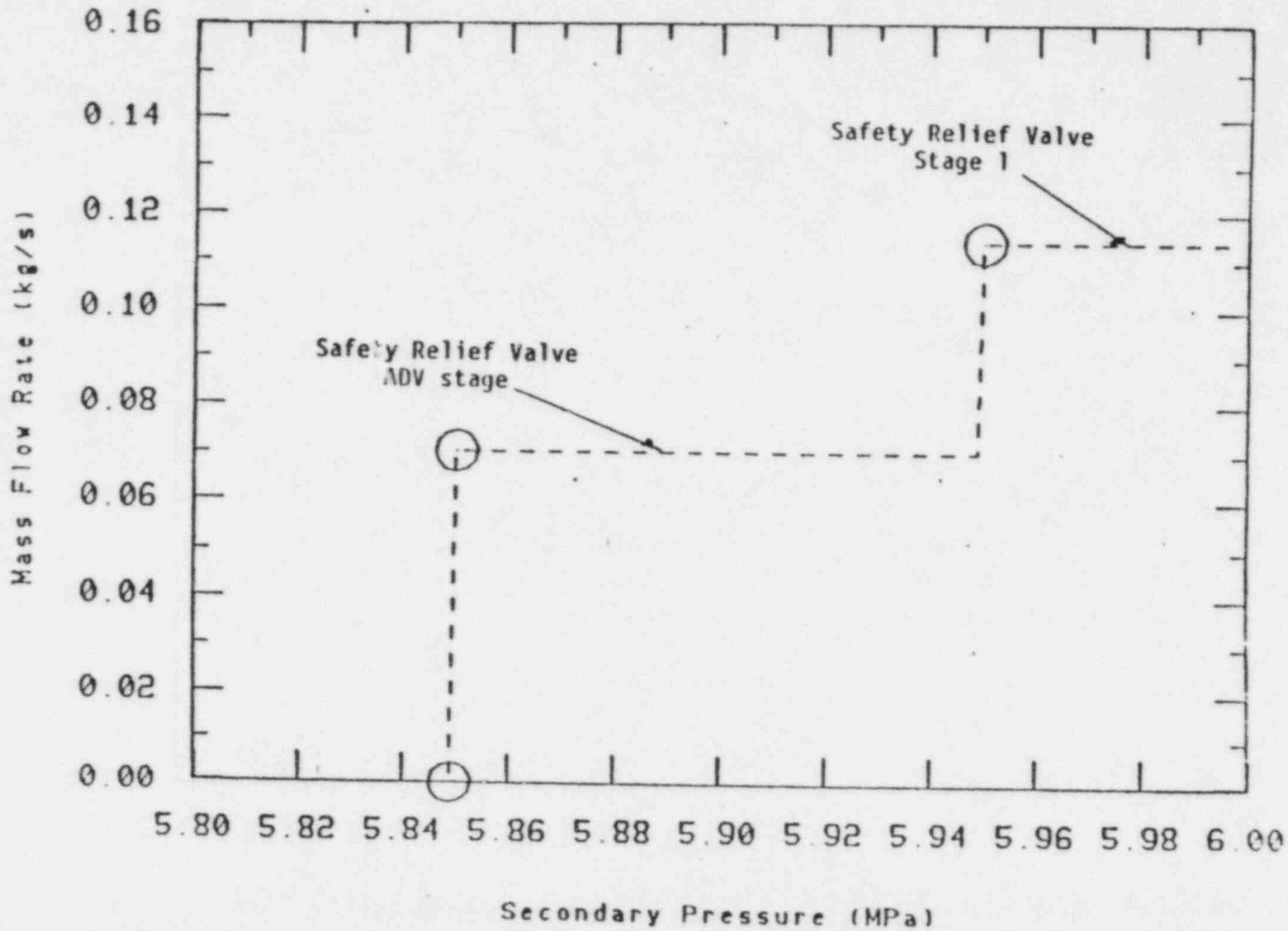


Figure 3. Broken loop steam generator safety relief valve operation.

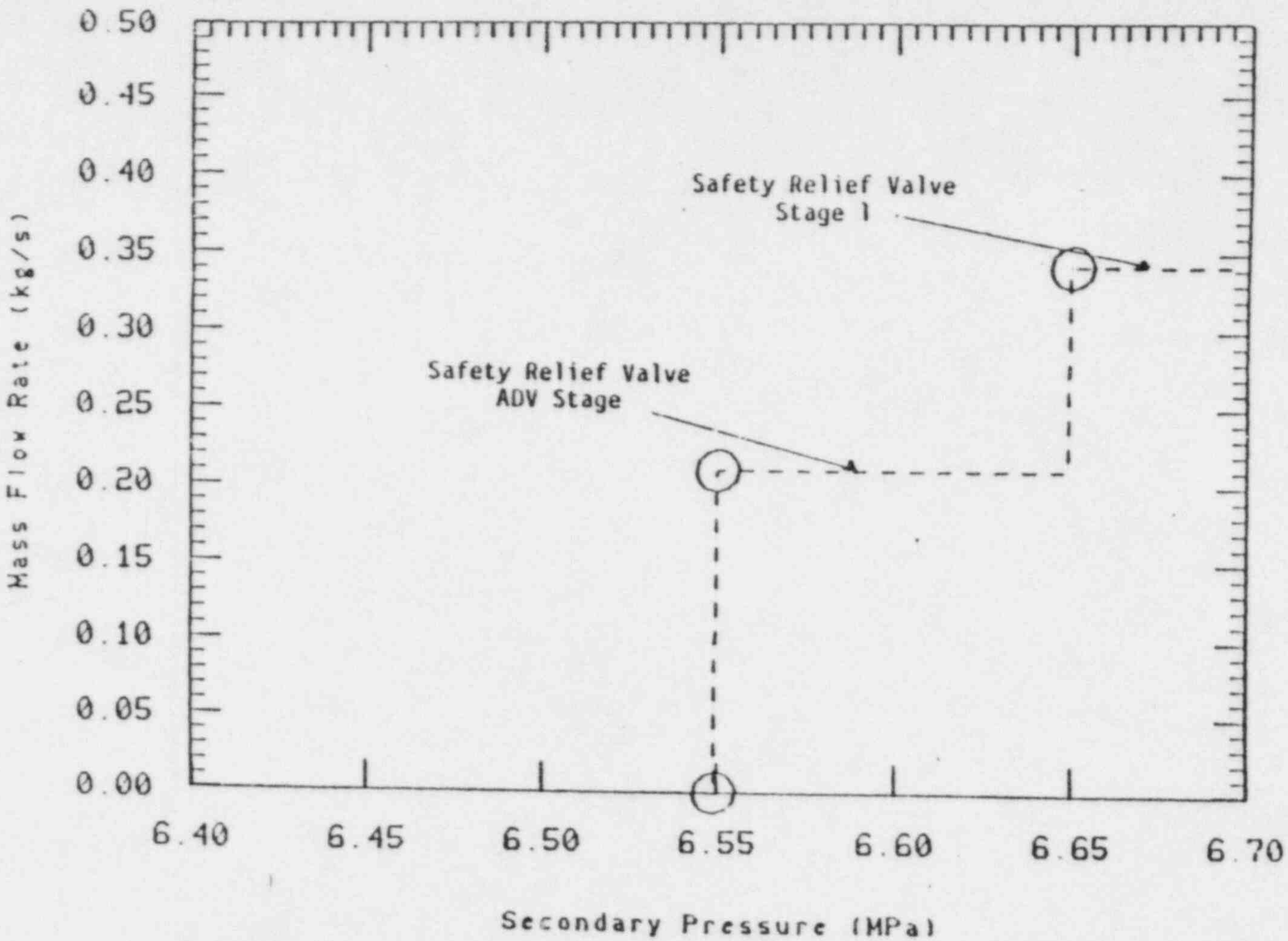


Figure 4. Intact loop steam generator safety relief valve operation.

and the warmup mode is 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-3, 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-3 used the 10-tube break orifice with a 0.249 cm (0.0975 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, unaffected loop pump suction, affected loop pump suction and pressurizer. The total power provided by these heaters is 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 (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-3. Power to the vessel upper head and upper plenum heater banks was terminated just before the transient initiation because rapid vessel voiding was anticipated.

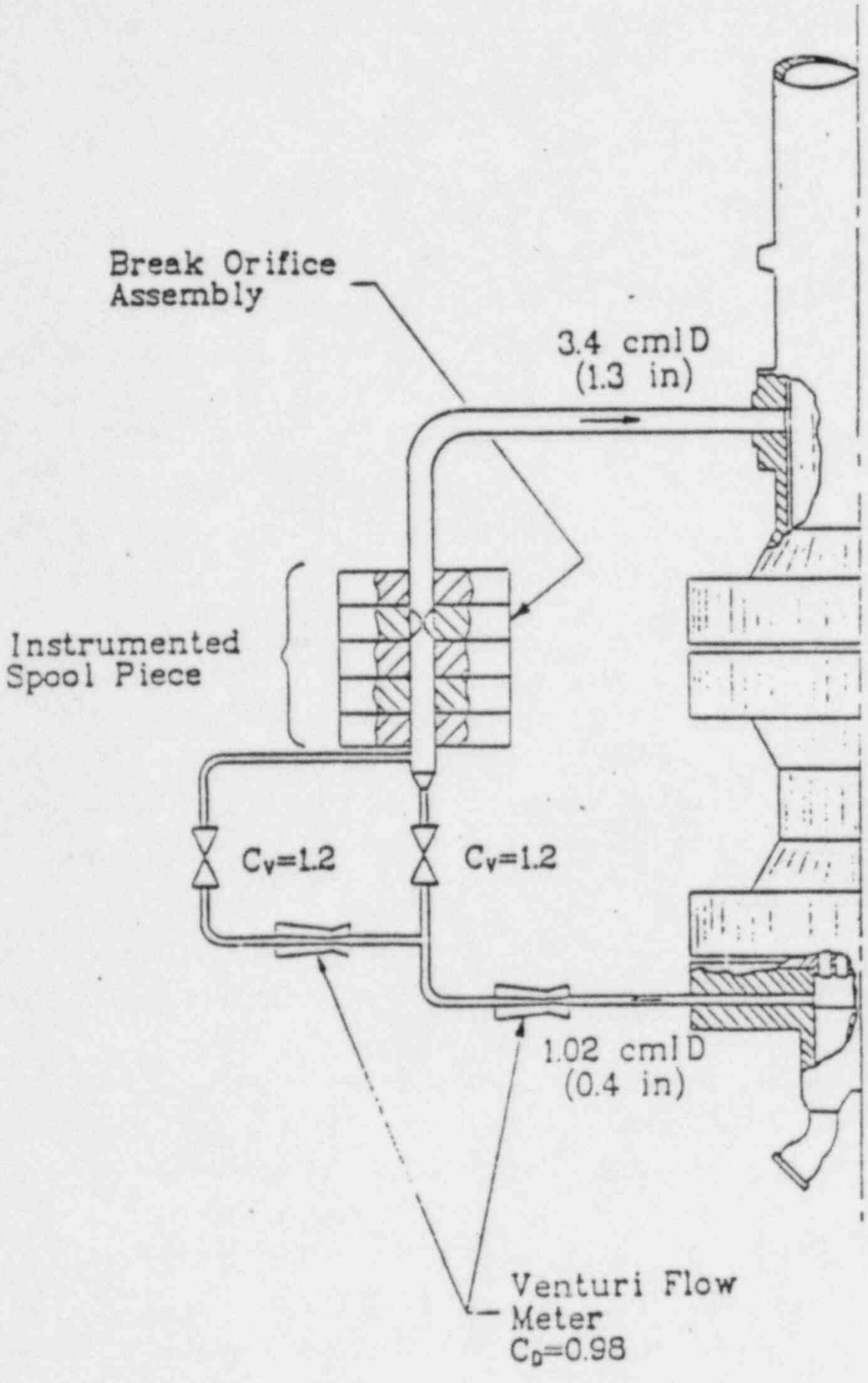
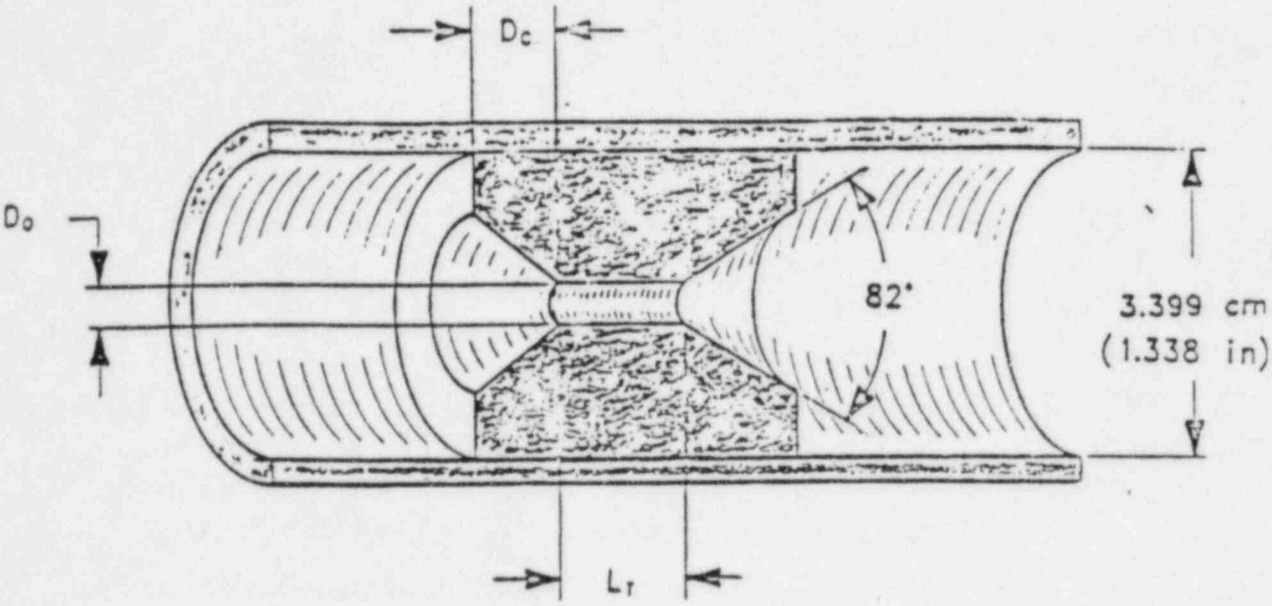


Figure 5. Semiscale tube-rupture break assembly.



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.

Test S-SG-3 consisted of five phases including automatically occurring events and manually operated recovery procedures. 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-3. The first 600 s (phase 1) involved automatically occurring events such as core scram, main steam isolation valve closure, SI initiation, auxiliary feedwater start and main feedwater stop, and main coolant pump trip. 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)). Power to the pressurizer external heaters and vessel upper head and upper plenum external heaters was terminated at t = 0.

At 600 s, a four phase recovery operation was intiated including pressurizer auxiliary spray, pressurizer internal heaters, intact loop secondary feed and steam and intact loop pump operation. First, at 600 s, phase 2 began when pressurizer auxiliary spray was operated at 13.75 g/s (0.029 lbm/s) in an attempt to reduce the primary pressure to 5.6 MPa (800 psig). The pressurizer spray was operated to maintain the hot collapsed pressurizer level between 240 and 260 cm (95 and 102 in) once the level reached 250 cm (98 in). After pressurizer auxiliary spray was operated for a preselected period of 900 s, the intact loop ADV was latched open until the primary pressure reached 5.6 MPa. Upon reaching 5.6 MPa primary pressure the ADV was closed. This operation was designed to bring the primary pressure down below the broken loop (the loop with the ruptured tubes) secondary ADV setpoint (5.85 MPa (836 psig)) thus effectively isolating the broken loop secondary from atmospheric release. SI was operated during phase 2 to maintain the hot collapsed pressurizer liquid

TABLE 1. INITIAL CONDITIONS FOR TEST S-SG-3

	Specified	Measured
Pressurizer pressure	15.6 ± 0.14 MPa (2250 ± 20 psig)	15.45 (2240 psig)
Pressurizer liquid volume	0.0102 ± 0.0008 m^3 (0.36 ± 0.028 ft^3)	0.0106 m^3 (0.37 ft^3)
Core power	2.0 ± 0.01 MW	1.99 MW
Loop to loop cold leg fluid temperature differential	2.0K (3.6F)	0.1K (0.18F)
Core fluid temperature rise	37 ± 1.5K (66.6 ± 3°F)	37.5K (67.5°F)
Steam generator pressure		
Broken loop	5.55 ± 0.07 MPa (793 ∓ 10 psig)	5.50 MPa (785 psig)
Intact loop	5.55 ∓ 0.07 MPa (793 ∓ 10 psig)	5.52 MPa (788 psig)
Steam generator secondary fluid mass[a]		
Broken loop[b]	100 + 40 - 20 kg (220 + 88 - 44 lbm)	93 kg (204 lbm)
Intact loop[c]	100 + 40 - 20 kg (220 + 88 - 44 lbm)	88 kg (194 lbm)
Primary leakage	<0.006 kg/s (<0.0132 lbm/s)	0.0031 kg/s (0.0069 lbm/s)

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

b. Measured with differential pressure cell LBS+1117+51.

c. Measured with differential pressure cell LIS+1117+51.

TABLE 2. SEQUENCE OF SIGNIFICANT EVENTS FOR TEST S-SG-3

Specified Criteria	Actual Time(s)	Event
		Phase 1
0 s	0	Break flow initiated
P_{PRZ} = 13.1 MPa (1888 psig)	16.4	SCRAM
SCRAM	17.1	Core power on ANS decay
SCRAM	16.9	MSIV closure
P_{PRZ} = 12.5 MPa (1803 psig)	18.1	SIS
SIS	18.1	Main feedwater secured
SIS	18.9	Auxiliary feedwater initiated
SIS	20.0	Pumps coastdown initiated
SIS	19.1	Safety injection on
		Phase 2
600 s--pressurizer spray aided by intact loop ADV operation to lower primary pressure below broken loop secondary pressure	600	Pressurizer spray started to reduce system pressure to 5.6 MPa (800 psig). Spray cycled to maintain pressurizer level betweeen 240 to 260 cm (95 to 102 in), SI on to maintain pressurizer level between 75 and 381 cm (30 and 150 in)
	1500/ 1518	Intact loop ADV opened/closed
	1518	P_p = 5.6 MPa (800 psig)
		Phase 3
Pressurize the primary to 5.85 MPa (836 psig) using pressurizer heaters	1518	Turn on pressurizer variable and backup heaters; pressurizer spray cycled several times to maintain pressurizer level between 75 and 250 cm (30 to 98 in), SI on to maintain pressurizer level between 75 and 381 cm (30 and 150 in)

TABLE 2. (continued)

Specified Criteria	Actual Time(s)	Event
	Phase 3 (continued)	
	2408	Turn on warmup heaters
	3635	P_p = 5.85
	Phase 4	
Redistribute system fluid energy using intact loop pumps	3667	Intact loop pump on to initial conditions
	3740	Primary pressure reached a minimum value
	3997	SI turned off on high pressurizer level
	4567	Primary pressure recovered and stabilized after reaching minimum value
	Phase 5	
Use intact loop ADV, intact loop pump, pressurizer spray, SI, and pressurizer heaters to subcool and depressurize the system in controlled manner	4567	Latch open intact loop ADV
	6730	37.2 K (67°F) subcooling reached; start 1200 s depressurization period; SI cycled to maintain pressurizer level between 75 to 100 cm (30 to 39 in). Pressurizer spray cycled to maintain pressurizer level between 75 to 250 cm (30 to 98 in)
	7220	Pressurizer heaters off
	8000	Test terminated (subcooling 29.4 K (53 F)

level between 75 and 381 cm (30 and 150 in). If the level reached 381 cm (150 in) SI was terminated until the level dropped to 75 cm (30 in) at which point SI was restarted.

Phase 3 began when the primary pressure first reached 5.6 MPa and involved pressurizing the primary system to 5.85 MPa (836 psig) using pressurizer internal heaters to pressurize and effectively subcool the primary system. First an attempt was made to pressurize the primary system using variable and backup heaters (nominally 2.35 kW total). After a preselected 900 s period of varible and backup mode without effective pressurization the warmup mode heaters, (total nominally 13.3 kW) were activated eventually resulting in pressurizing the primary system to 5.85 MPa (836 psig). The pressurizer spray was operated during this period to maintain the pressurizer hot collapsed level between 75 and 250 cm (30 and 98 in). If the level reached 250 cm the spray was terminated until the level dropped to 75 cm. SI was operated during phase 3 the same as phase 2.

Phase 4 began when the primary pressure reached 5.85 MPa by turning on the intact loop pump to the initial speed. After the primary pressure dropped to a minimum (due to cold leg fluid mixing with hotter regions of the system) the primary pressure was allowed to float from its minimum value to a quasi steady pressure for a preselected 900 s period at which time phase 5 began. During phase 4 the pressurizer variable and backup heaters (2.35 kW) were on if the hot collapsed level was above 75 cm (30 in) and the spray and SI was operated as in phase 3.

Phase 5 involved latching open the intact loop ADV to stimulate system subcooling[a] while maintaining the intact loop secondary level with auxiliary feedwater between 800 and 1050 cm (315 and 413 cm). If the secondary level fell below 250 cm (98 in) the ADV was shut until the level recovered to 400 cm (157 in). The pressurizer spray was operated as in

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a. Subcooling was defined as saturation temperature minus the average the intact and broken loop hot leg temperatures.

phase 4 and SI was operated to maintain the hot collapsed pressurizer level between 75 and 100 cm (30 and 39 in). The system was subcooled to 37 K (67°F) using the ADV operation at which time an attempt was made to depressurize the system for 1200 s using the variable and backup pressurizer heaters as a main point of control. If the primary depressurization was higher than 0.172 MPa/5 min (25 psi/5 min) the heaters were left on and if the depressurization was slower than 0.172 MPa/5 min (25 psi/5 min) the heaters were turned off. The test was terminated after 1200 s of this depressurization operation.

3. RESULTS

This section discusses the overall thermal-hydraulic response of the Semiscale system during test S-SG-3. The discussion is organized into two areas: (a) the initial response to automatically occurring events (phase 1 0-600 s) including a comparison of S-SG-3 (10 tube break) with SG-7 (5 tube break)[4] and SG-8 (1 tube break)[5] and (b) a four phase recovery period involving operator actions.

3.1 System Behavior--Tube Rupture Signature Early in Time (Phase 1, 0 to 600 s)

The occurrence of a 10-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 15.45 MPa (2228 psig) flowed through the conical flow tube break orifice into the broken loop steam generator originally at 5.50 MPa (785 psig). The loss of mass from the primary loop caused a fairly steady primary depressurization until about 17 s, at which time a marked increase in the depressurization rate occurred. At about 17 s the low pressurizer pressure setpoint of 13.1 MPa (1888 psia) was achieved which initiated two prominent events 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 both steam generators. The large decrease in system pressure following core scram at 17 s was due to dropping core power and the primary liquid shrinking due to primary to secondary heat transfer. Upon MSIV closure, the heat transfer to both the broken and intact loop steam generator secondaries caused a rapid pressurization of the secondaries as shown in Figure 8. The

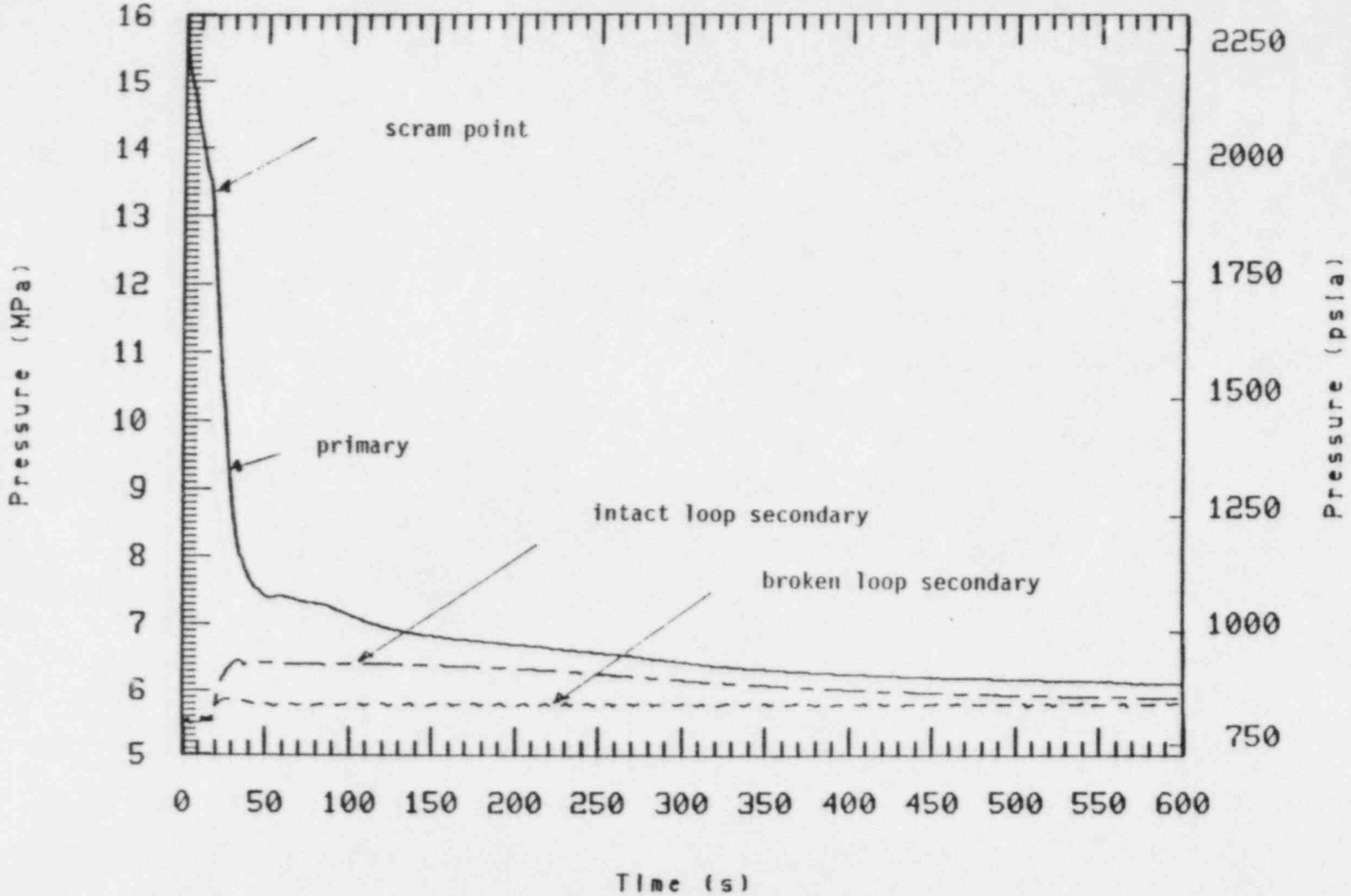

Figure 7. Primary and secondary pressure during a 10-tube rupture transient (S-SG-3).

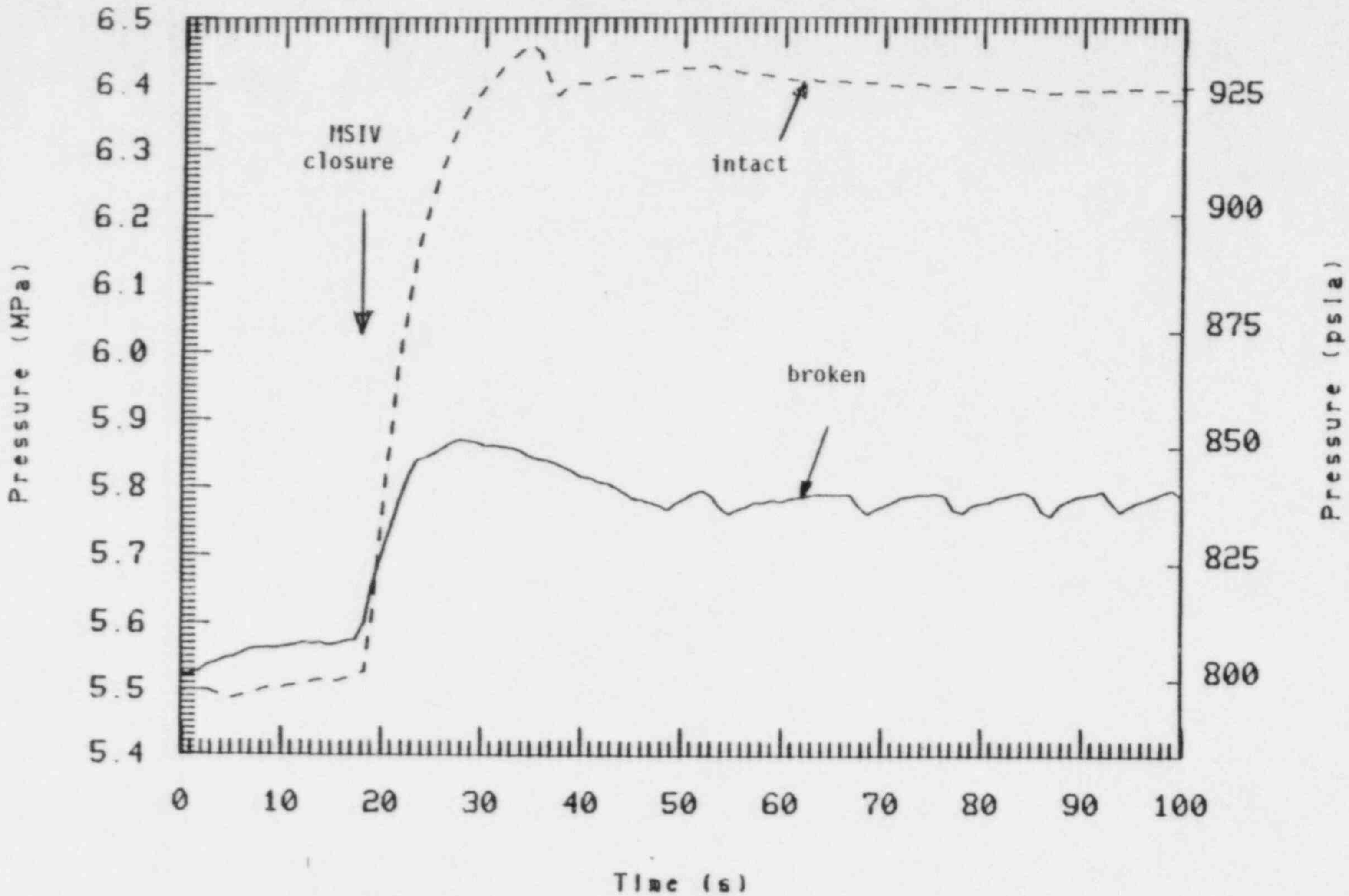

Figure 8. Intact and broken loop secondary pressure during a 10-tube rupture transient (S-SG-3).

secondary pressure in both generators briefly reached the ADV setpoints [6.55 MPa (938 psig)] in the intact loop and 5.85 MPa (836 psig) in the broken loop).[a]

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 (Figure 8). The energy addition to the affected loop secondary from break flow had a negligible effect on secondary pressure during this period because it was overpowered by the overall primary to secondary heat transfer.

The safety injection signal was achieved at 12.5 MPa (1803 psig) and initiated: (a) termination of power to the primary coolant pumps, (b) termination of main feedwater and starting auxiliary feedwater to the secondaries, and (c) starting safety injection (SI). 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 flows reduced to typical natural circulation values[6] 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 in the intact loop as evidenced by a slight decrease in intact loop secondary pressure (see Figure 8). Eventually, the primary system depressurization was sufficient for the hot leg fluid to reach a saturation condition at about 35 s (Figure 10). Flashing in the system then caused a major reduction in the depressurization rate (Figure 7). The primary pressure made a slight recovery between 50 and 60 s. This repressurization was mainly caused by superheated steam in the pressurizer (Figure 10) and reduced heat transfer to the broken loop secondary, aided by flashing in the reactor vessel.

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a. On Figure 8 the intact loop ADV operated at a slightly lower pressure than 6.55 MPa (938 psig) because the ADV was set to process instruments which read slightly lower than the experimental data measurements. However, a lower setpoint does not effect system or signature response.

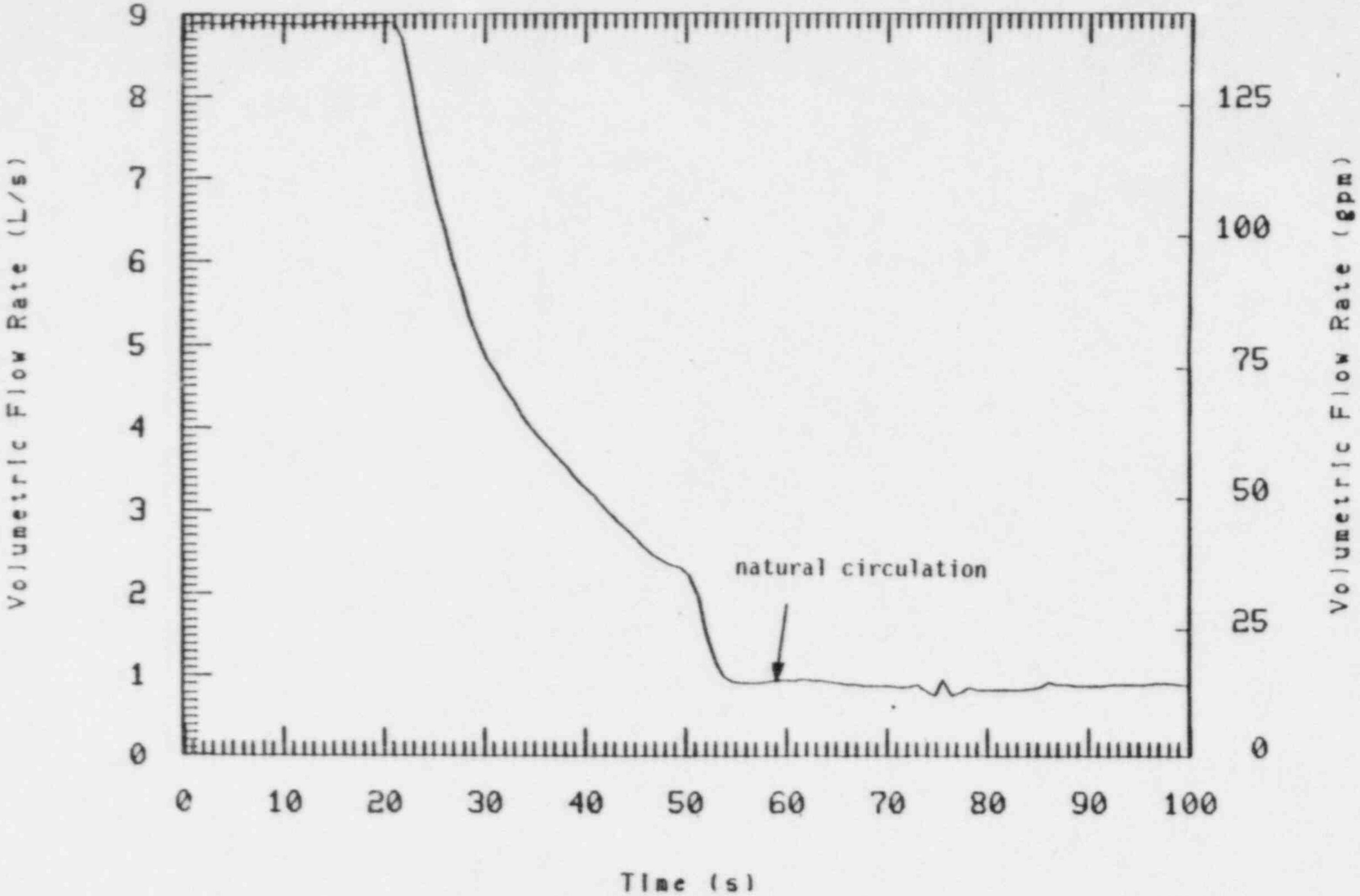

Figure 9. Intact loop cold leg volumetric flow during a 10-tube rupture transient (S-SG-3).

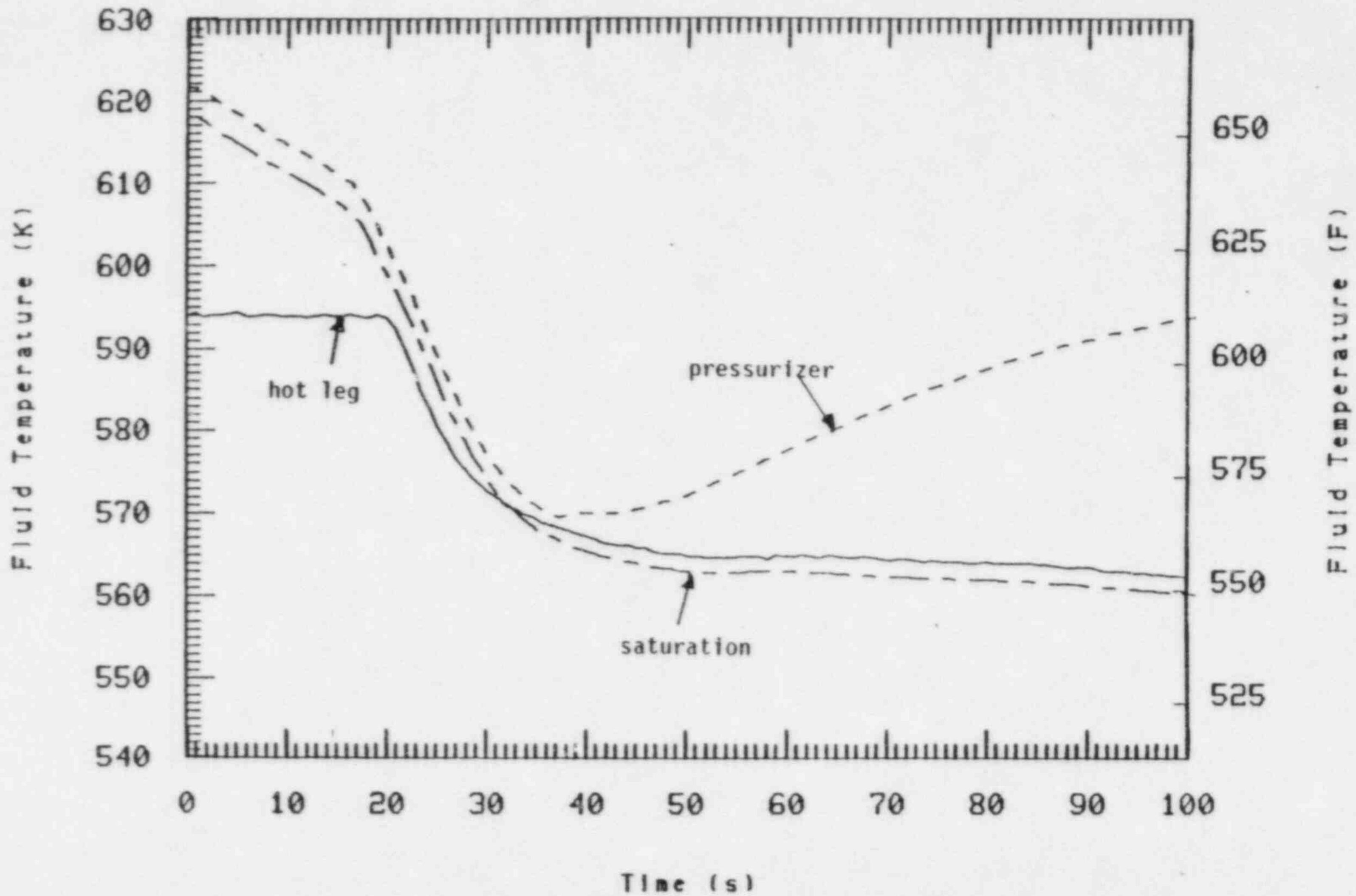

Figure 10. Intact loop hot leg and pressurizer fluid temperatures with the saturation temperature during a 10-tube rupture transient (S-SG-3).

Primary pressure remained above both secondary system pressures for the entire 600 s period (Figure 7) and caused a primary-to-broken loop secondary mass flow as shown in Figure 11. Figure 12 shows the pressurizer collapsed liquid level essentially depleted after 30 s.

With a 10 tube break considerable vessel voiding occurred during the initial 600 s period as shown on Figure 13. At 600 s the collapsed level was about 10 cm (3.9 in) below the top of the core. This is a direct consequence of the break flow being higher than SI flow during the initial 600 s period as shown on Figure 11.

The effect of break spectrum (1, 5 or 10 tube ruptured) on vessel voiding during the early operator diagnostic period is presented in the following section.

3.1.1 Comparison of System Response for a One, Five, and Ten Tube Rupture (0-600 s)

This section compares the early in time response (0-600 s) of system pressures and mass inventories for a one-tube (S-SG-8), five-tube (S-SG-7), and ten-tube (S-SG-3) rupture experiment. Initial conditions for the three experiments were nearly identical including initial pressurizer collapsed liquid level.

The overall system response of one-tube, five-tube, and ten-tube rupture are quite similar as shown on Figure 14. All three experiments show the same rapid primary depressurization (corresponding to core scram) to the hot leg saturation condition. However the timing of events are quite different. Prior to core scram (16.4 s for the ten-tube case (S-SG-3), 32 s for the five-tube case (S-SG-7), and 146 s for the one-tube case (S-SG-8)), the depressurization rate increased proportionally with increasing number of tubes ruptured. The depressurization rate was 0.0128 MPa/s (8.8×10^{-5} psi/s) for one tube, 0.065 MPa/s (4.9×10^{-4} psi/s) for five tube and 0.120 MPa/s (8.2×10^{-4} psi/s) for ten tubes. The repressurization following saturation attainment occurring in the primary is more pronounced for the one tube break than for either

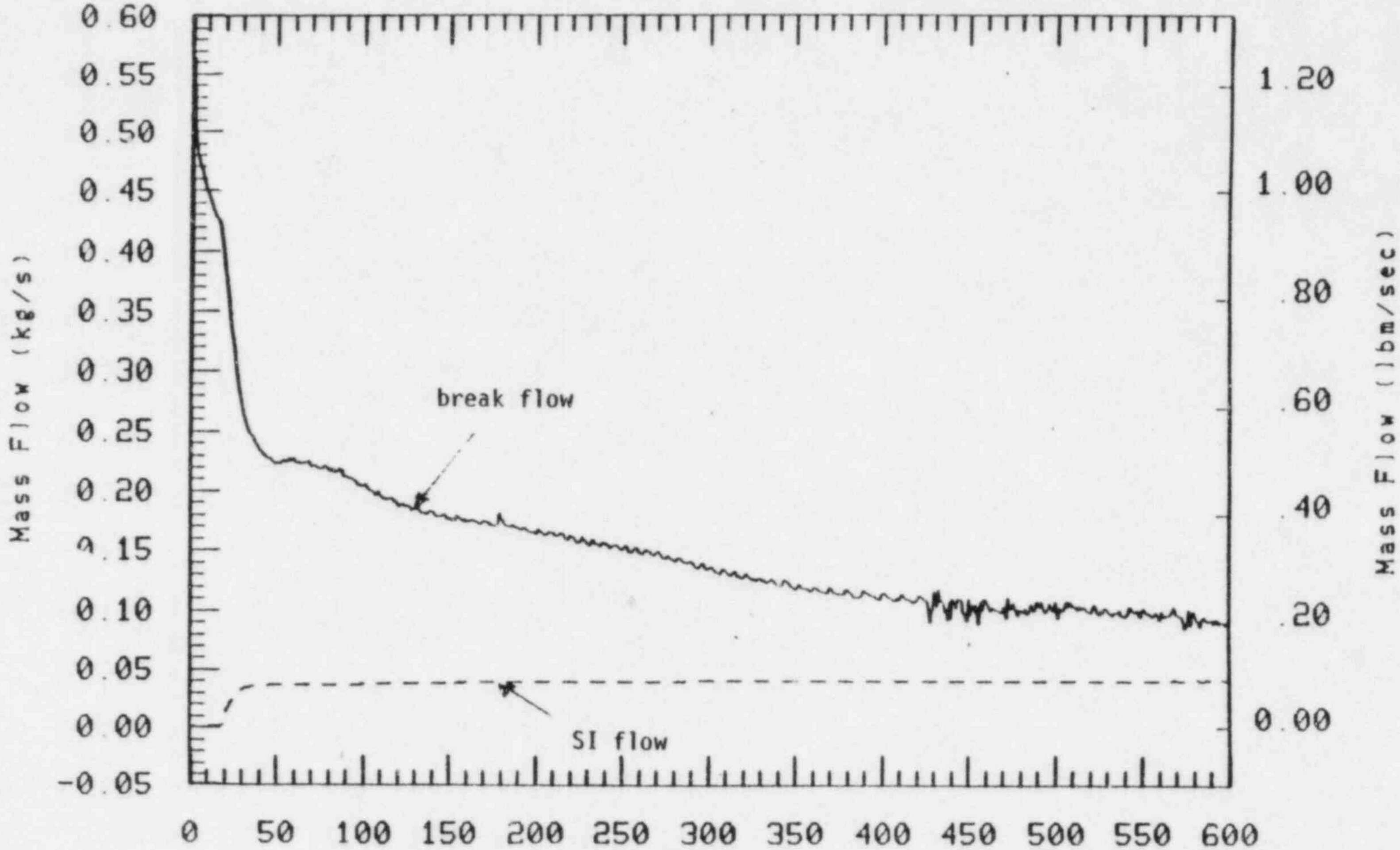

Figure 11. Break flow and SI flow during a 10-tube rupture transient (S-SG-3).

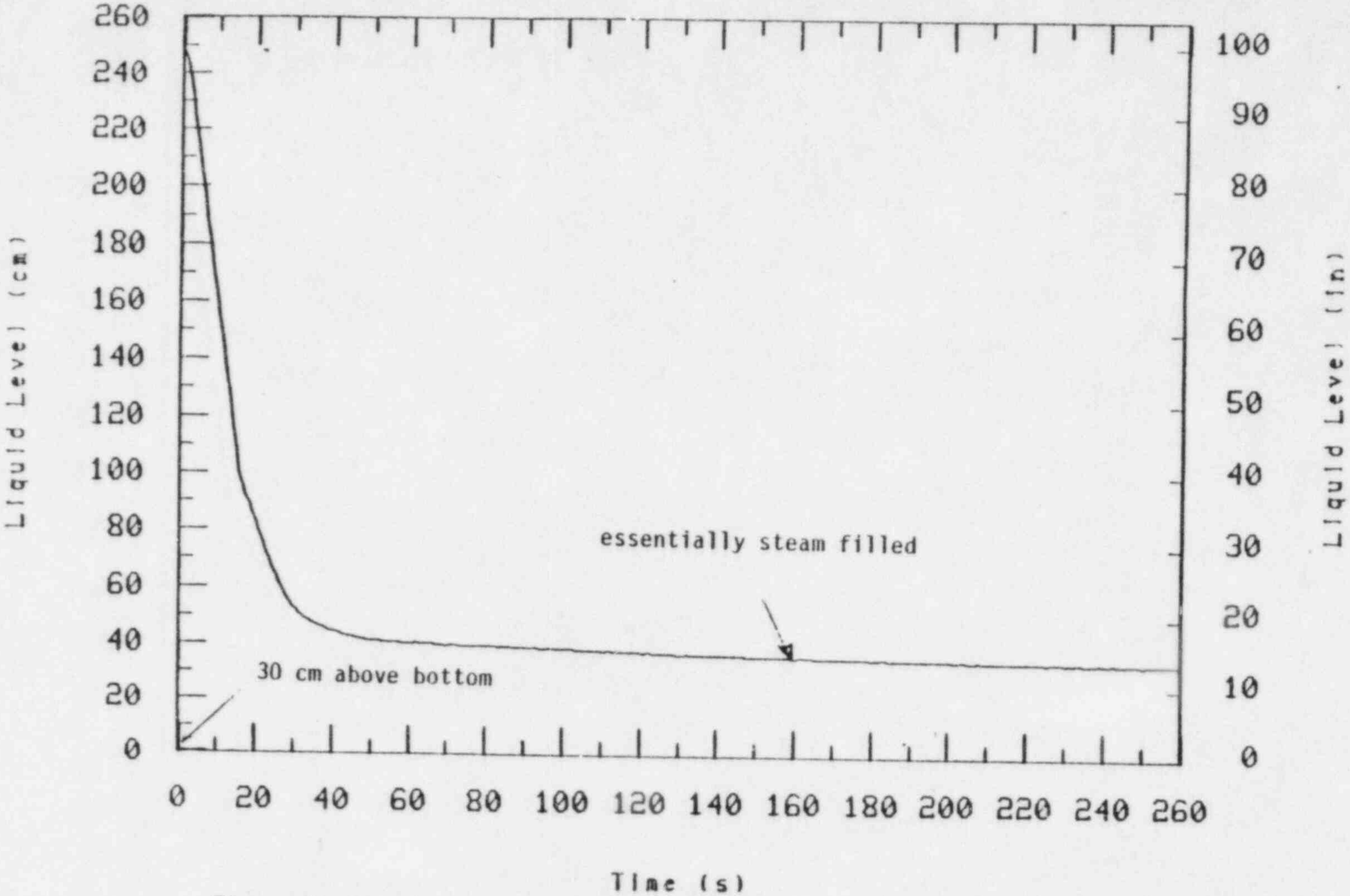

Figure 12. Pressurizer collapsed liquid level during a 10-tube rupture transient (S-SG-3).

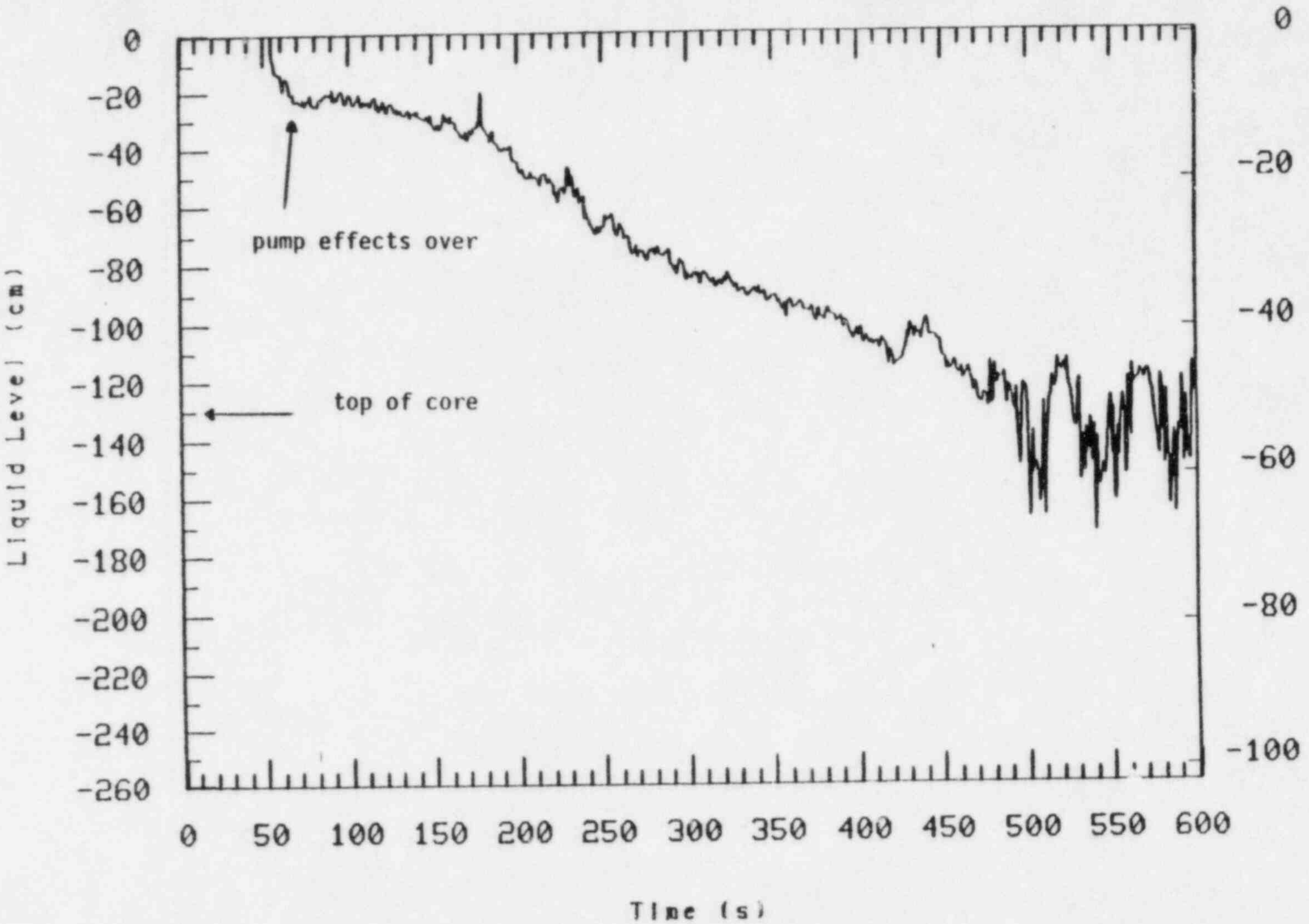

Figure 13. Lower vessel collapsed liquid level during a 10-tube rupture transient (S-SG-3).

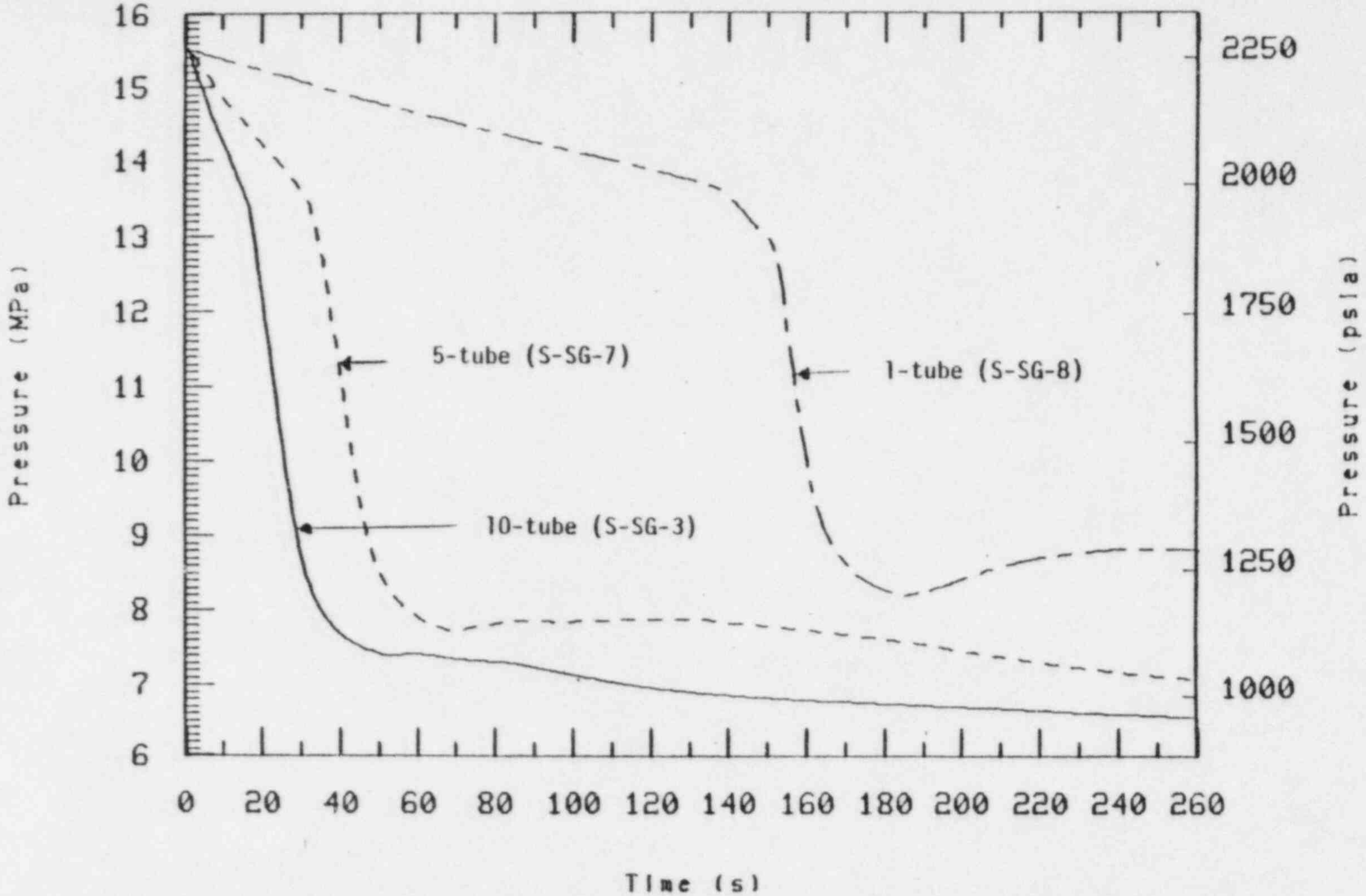

Figure 14. Comparison of primary pressure for a 1- 5 and 10-tube rupture transient.

the five or ten tube break. This is attributed to a higher break flow (Figure 15) for the larger number of tubes ruptured dominating the pressurization effects including pressurizer steam superheat, change from forced to natural circulation in the loop and boiling in the core. The similarity in response for the break spectrum was also seen in pressurizer collapsed liquid level (Figure 16) and the secondary pressurization in the steam generators (Figure 17).

The fundamental difference between the one-tube, five-tube, and ten-tube rupture was the relationship between break flow and SI flow. The break flow was much higher in relation to the SI flow for the five and ten tube ruptures resulting in more extensive vessel voiding as shown in vessel upper head collapsed level (Figure 18).

Comparison of the lower vessel collapsed level[a] for the five and ten tube case (Figure 19) shows slightly more voiding for the ten tube case than the five tube case at the end of the 600 s period. Both levels were near the top of the core at 600 s (15 cm above the core for the 5-tube case and 10 cm below the top of the core for the 10-tube case).

3.2 System Recovery

The Semiscale system was successfully recovered from a 10 tube rupture transient using a four phase recovery scenario based on Zion Emergency Operating Procedures.[7] The first recovery phase, phase 2, involved using pressurizer auxiliary spray and intact loop ADV operation to reduce the system pressure below broken loop ADV setpoints. Phase 3 involved pressurizing the system with pressurizer internal heaters to establish subcooling in the primary system. Phase 4 used the intact loop primary pump to redistribute system fluid energy and provide forced circulation cooling. Phase 5 combined intact loop pump flow, intact loop secondary ADV

a. The measurement is valid only after the pumps had coasted down and natural circulation established.

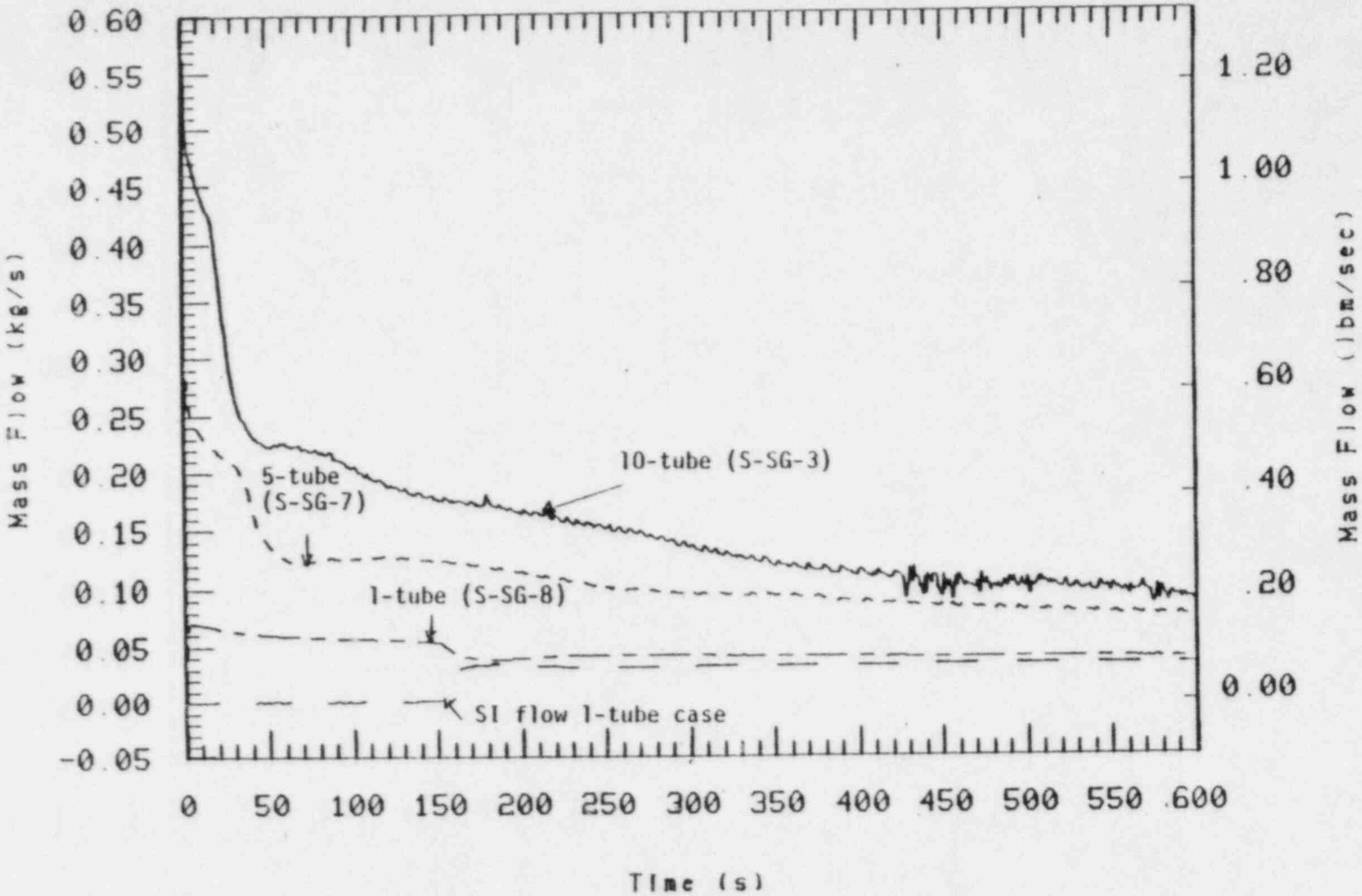

Figure 15. Comparison of break flow and SI flow for a 1-5 and 10-tube rupture transient.

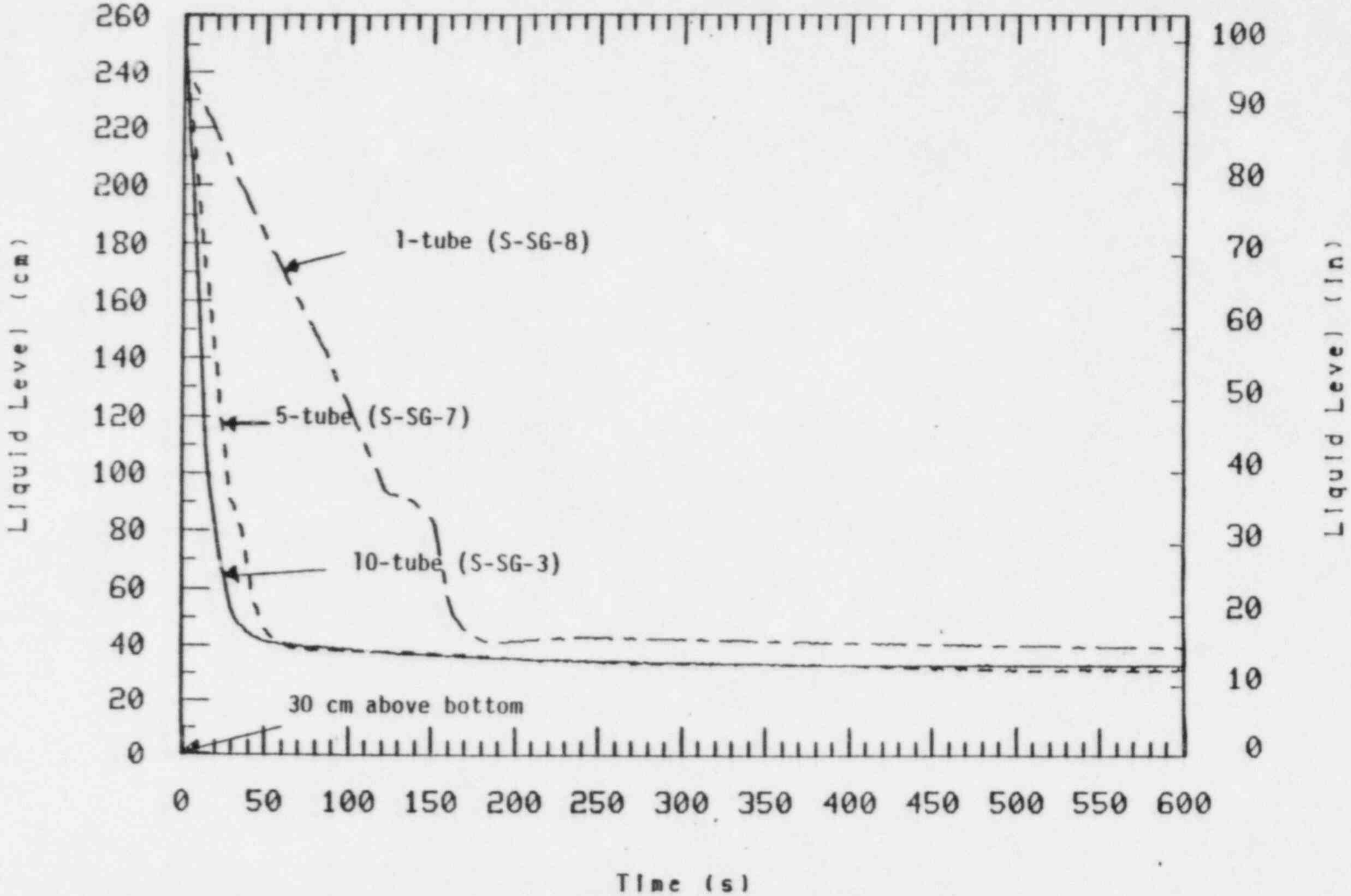

Figure 16. Comparison of pressurizer collapsed level for a 1-5 and 10-tube rupture transient.

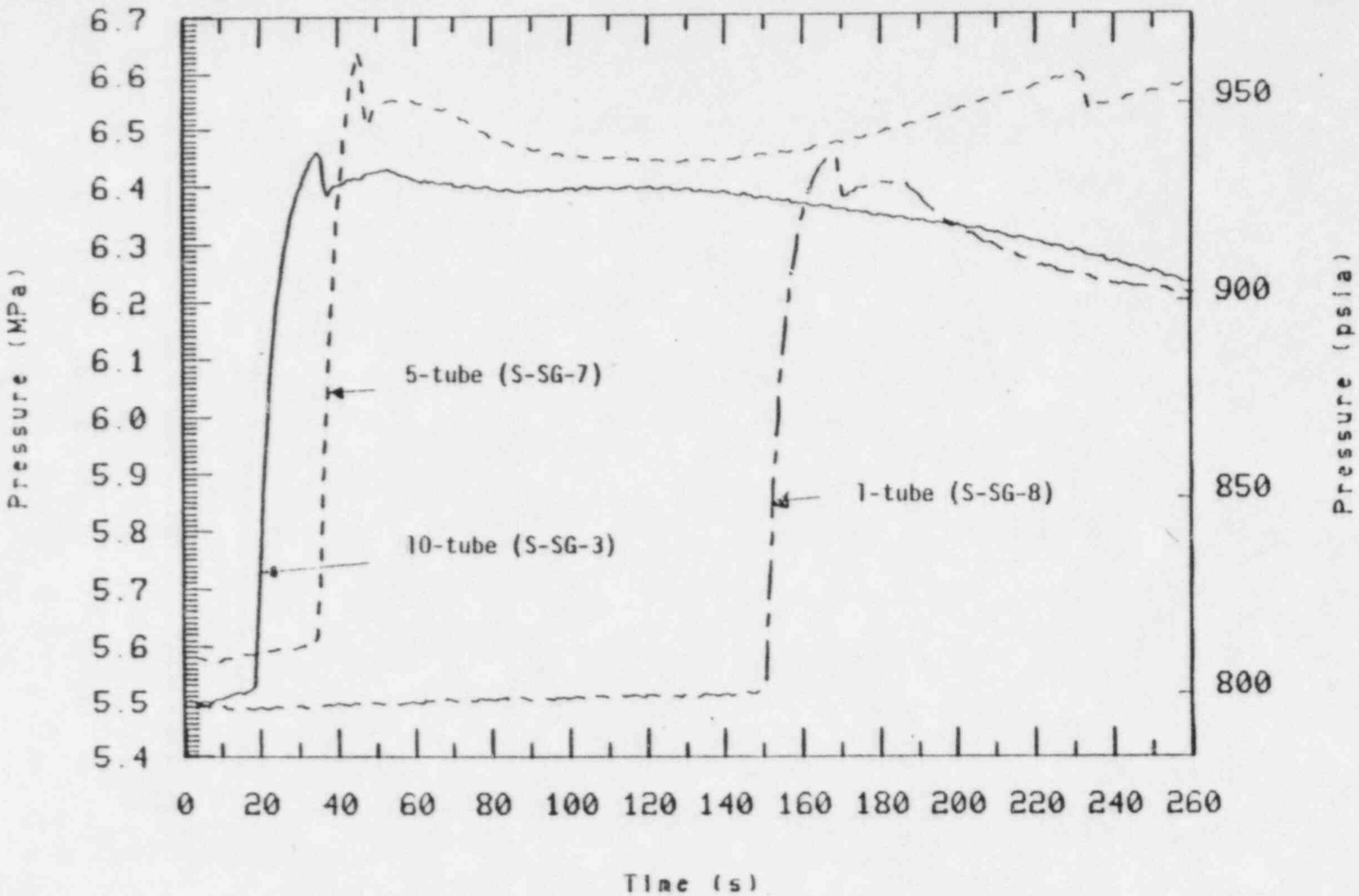

Figure 17. Comparison of intact loop secondary pressure for a 1-5 and 10-tube rupture transient.

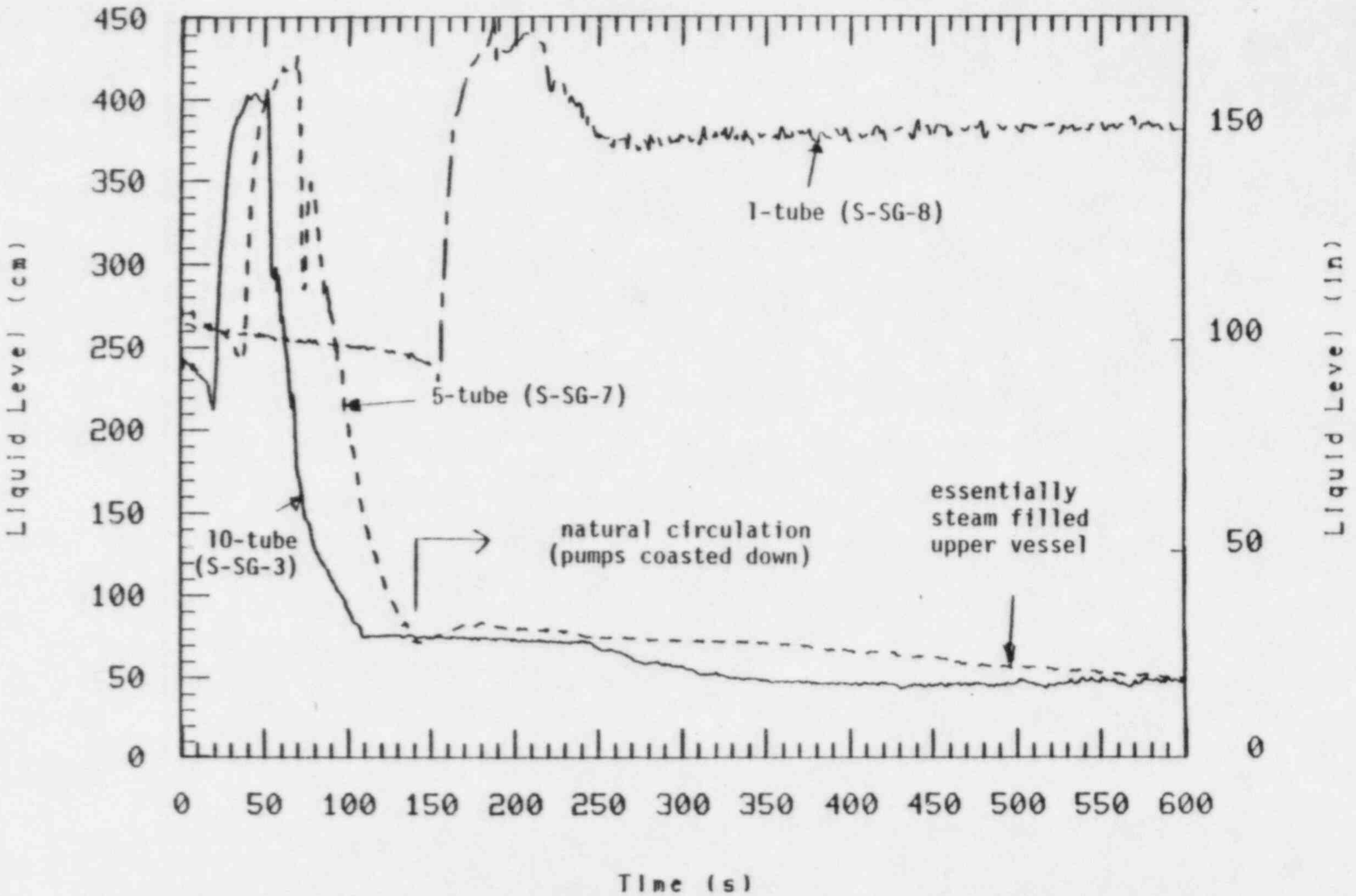

Figure 18. Upper vessel collapsed liquid level for a 1-5 and 10-tube rupture transient.

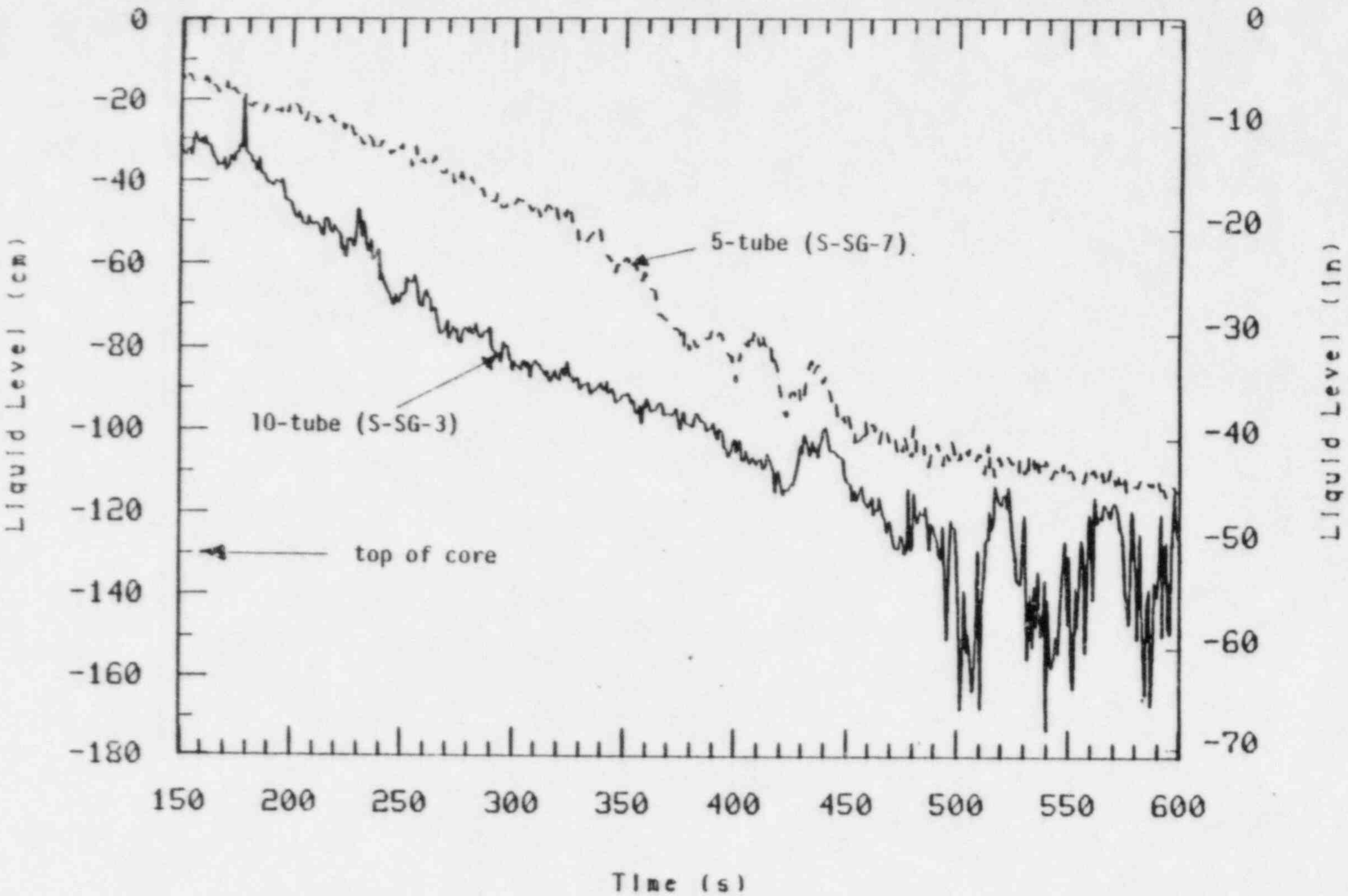

Figure 19. Lower vessel collapsed liqiud level for a 5 and 10-tube rupture transient.

operation, pressurizer auxiliary spray and internal heaters power and SI to subcool the system and then promote a slow depressurization. Figure 20 shows an overall primary system pressure plot delineating the various phases encountered. The entire recovery period shows a general trend of decreasing primary system pressure.

3.2.1 Use of Pressurizer Auxiliary Spray and Intact Loop ADV--(Phase 2)

Pressurizer auxiliary spray aided by intact loop secondary ADV operation was a sufficient operator response to lower the system primary pressure significantly below the broken loop ADV setpoint of 5.85 MPa (836 psig) thus isolating the broken loop secondary from atmospheric release. Figure 21 shows the primary pressure during phase 2 with a general downward trend in pressure during the spray period with a sharp decrease in primary pressure corresponding to a brief period of latched open intact loop ADV operation at 1500 s. Auxiliary spray alone was sufficient to bring the primary pressure to the ADV setpoint pressure of 5.85 MPa (836 psig) after about 250 s as shown in Figure 21. Except for the period when the intact loop ADV was latched open (1500 s), the reduction in primary pressure is attributed to a collapse of steam in the pressurizer due to condensation as cold spray contacts the steam. The initial primary pressurization following the initiation of spray at 600 s is attributed to cold water flashing upon contact with hot pressurizer walls. Eventually the walls were cooled by the spray (see Figure 22) and the primary pressure was reduced due to condensation.

The spray was cycled on pressurizer level as shown on Figure 23. If the spray reached a hot collapsed pressurizer level of 250 cm (98 in) the spray was then cycled between 240 cm (94 in) and 260 cm (102 in). To be consistant with pretest computer calculations, a preselected 900 s period of spray operation was allowed to reduce the primary pressure to 5.6 MPa (800 psig). If after 900 s the primary pressure had not reached 5.6 MPa intact loop secondary feed and steam using a latched open ADV was to be employed as shown in Figure 21.

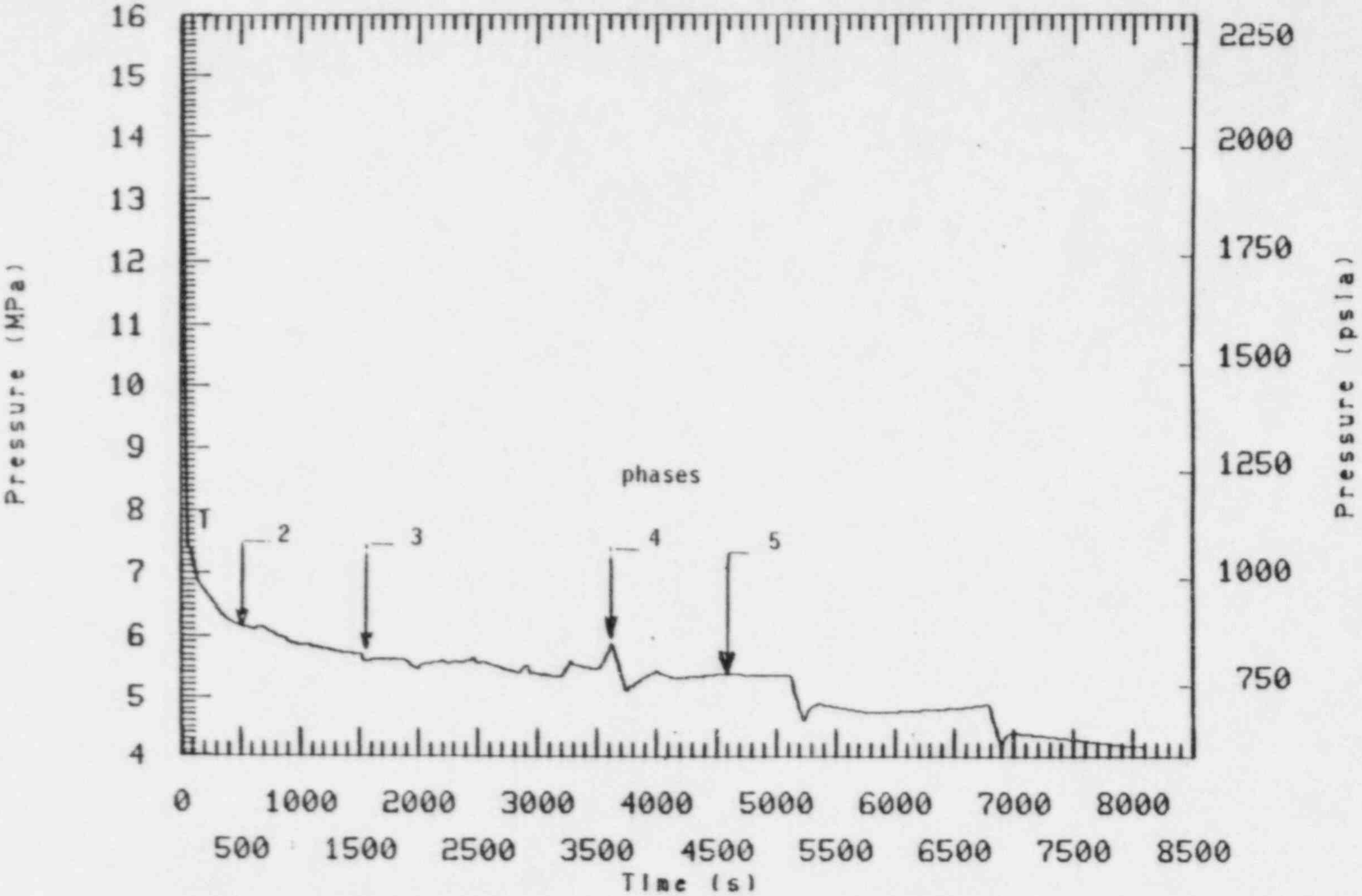

Figure 20. Primary pressure during the recovery phase for a 10-tube rupture transient (phase 1-5) (S-SG-3).

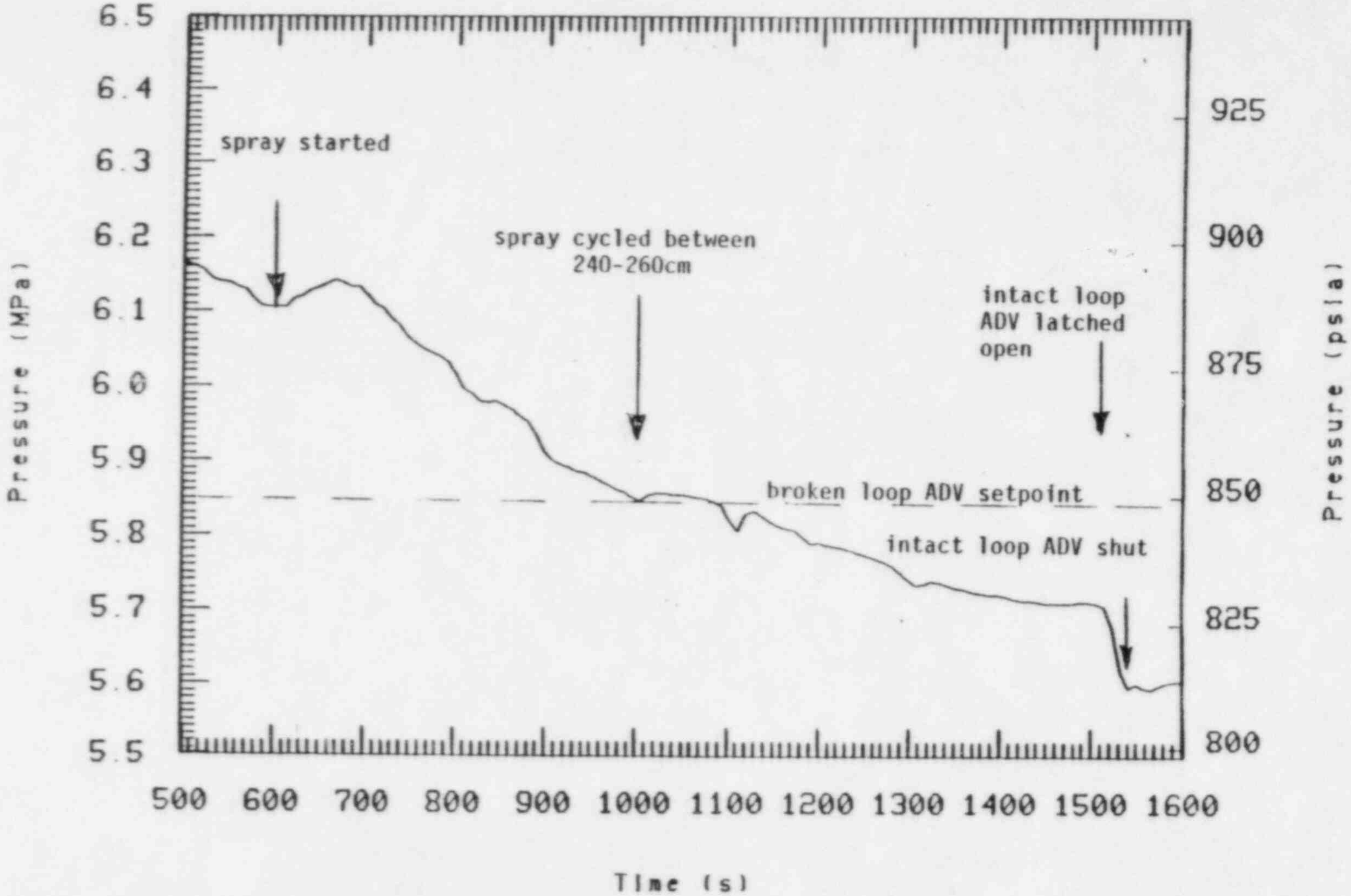

Figure 21. Primary pressure during pressurizer auxiliary spray and intact loop ADV operation (phase 2) (S-SG-3).

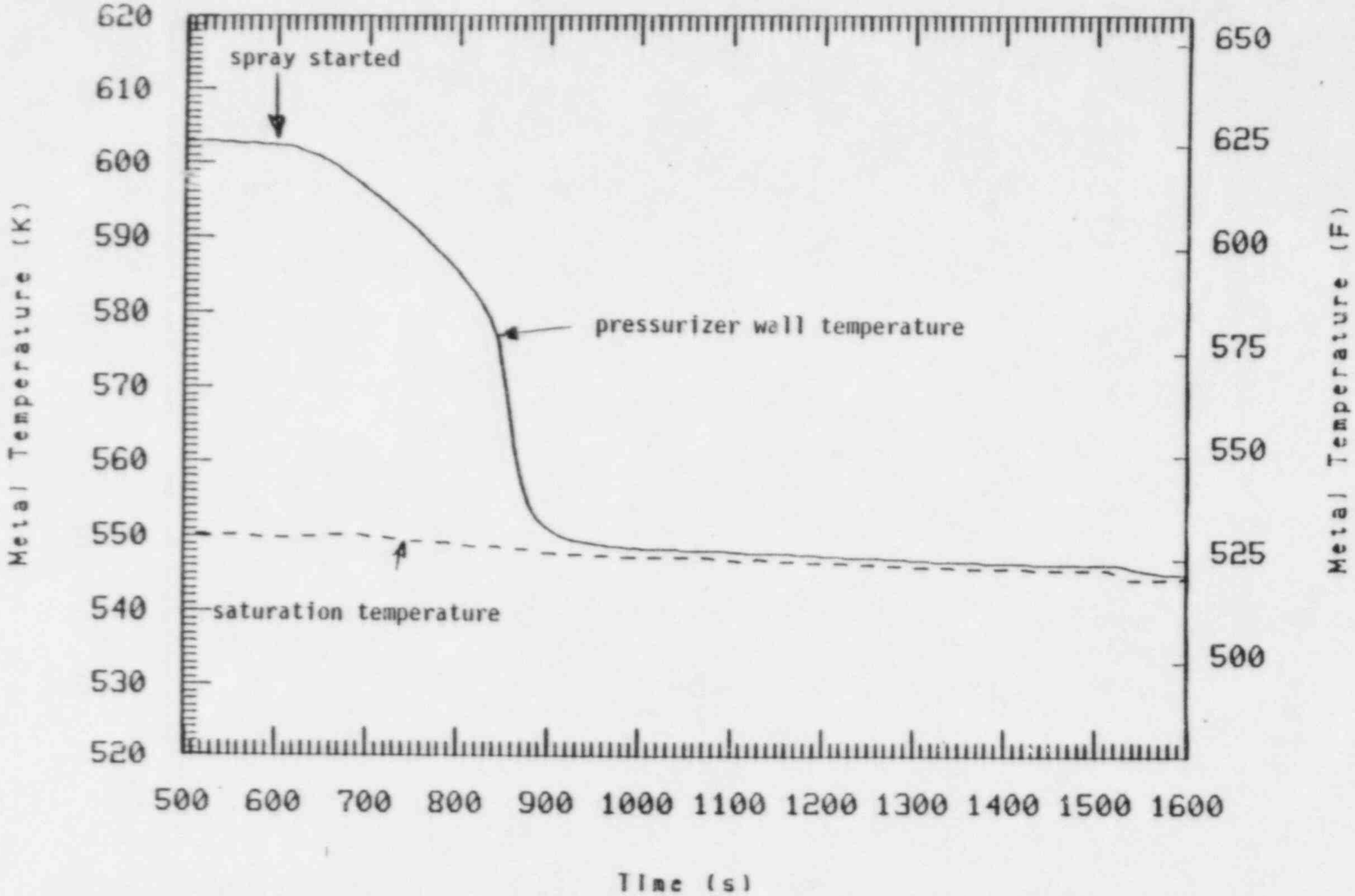

Figure 22. Pressurizer metal temperature and saturation temperature during pressurizer auxiliary spray (phase 2) (S-SG-3).

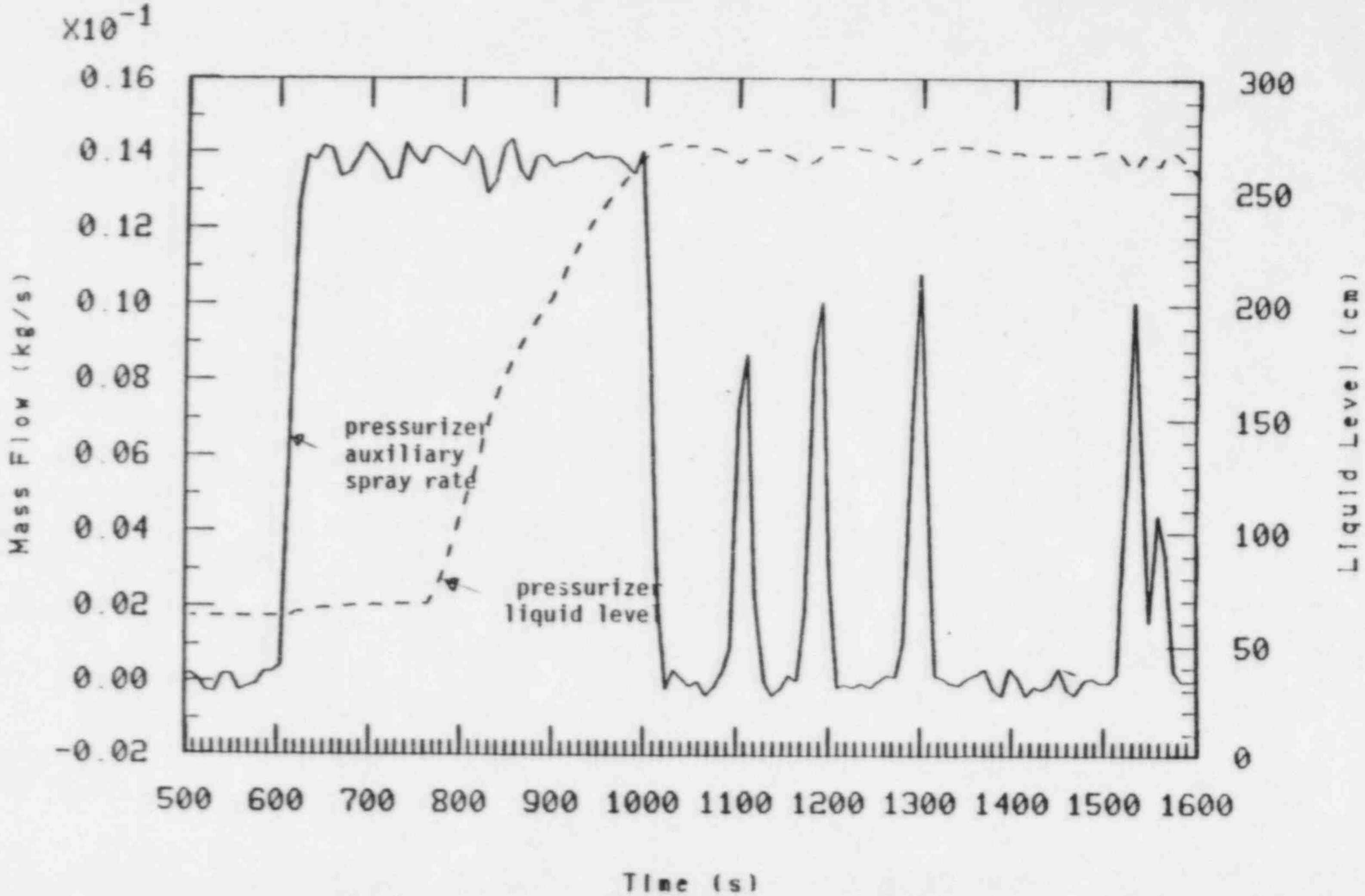

Figure 23. Comparison of pressurizer auxiliary spray rate and pressurizer collapsed level (phase 2)(S-SG-3).

During the time period between 600 and 1000 s approximately 5.4 kg of auxiliary spray entered the pressurizer corresponding to a level increase of only about 140 cm from the bottom, and yet, the level increased to 250 cm during this time period (see Figure 23). Figure 24 shows a relatively stable vessel level during the time period 600 to 1000 s which indicates the remainder of the mass entering the pressurizer came from other parts of the system such as the pump suction (see Figure 25). Use of spray did not cause a large change in vessel collapsed liquid level except for one cycle of spray operation occurring just before 1100 s as shown on Figure 24. Referring to Figure 21 just prior to 1100 s the spray condensed enough steam in the pressurizer to cause a relatively rapid primary system depressurization which led to flashing in the core and a core collapsed level depression. There was no core rod heat up associated with this level depression. The reason for this isolated core level depression will be examined in posttest analysis.

In summary, auxiliary pressurizer spray alone was capable of reducing the primary pressure to the broken loop ADV setpoint (5.85 MPa (836 psig)). Continued cycling of spray (on pressurizer level) and intact loop ADV operation was sufficient to reduce the primary pressure further to a preselected value of 5.6 MPa (800 psig).

3.2.2 Pressurization of the Primary System Using Pressurizer Internal Heaters--(Phase 3)

During phase 3, the competing effects of condensation induced pressure reduction due to pressurizer auxiliary spray and the boiling induced pressure increase due to pressurizer internal heater operation combined to increase the primary pressure from 5.6 MPa (800 psig) at the start of phase 3 to 5.85 MPa (836 psig) at the end of phase 3. Without the spray during phase 3, the pressurizer level would have depleted below the heaters which would have precluded heater operation. Figure 26 shows the primary pressure response with the periods of spray and heater operation indicated. Each introduction of spray cuased a primary pressure reduction and each termination of spray caused a primary pressure increase. The scenario called for variable and back up heater operation (2.35 kW total)

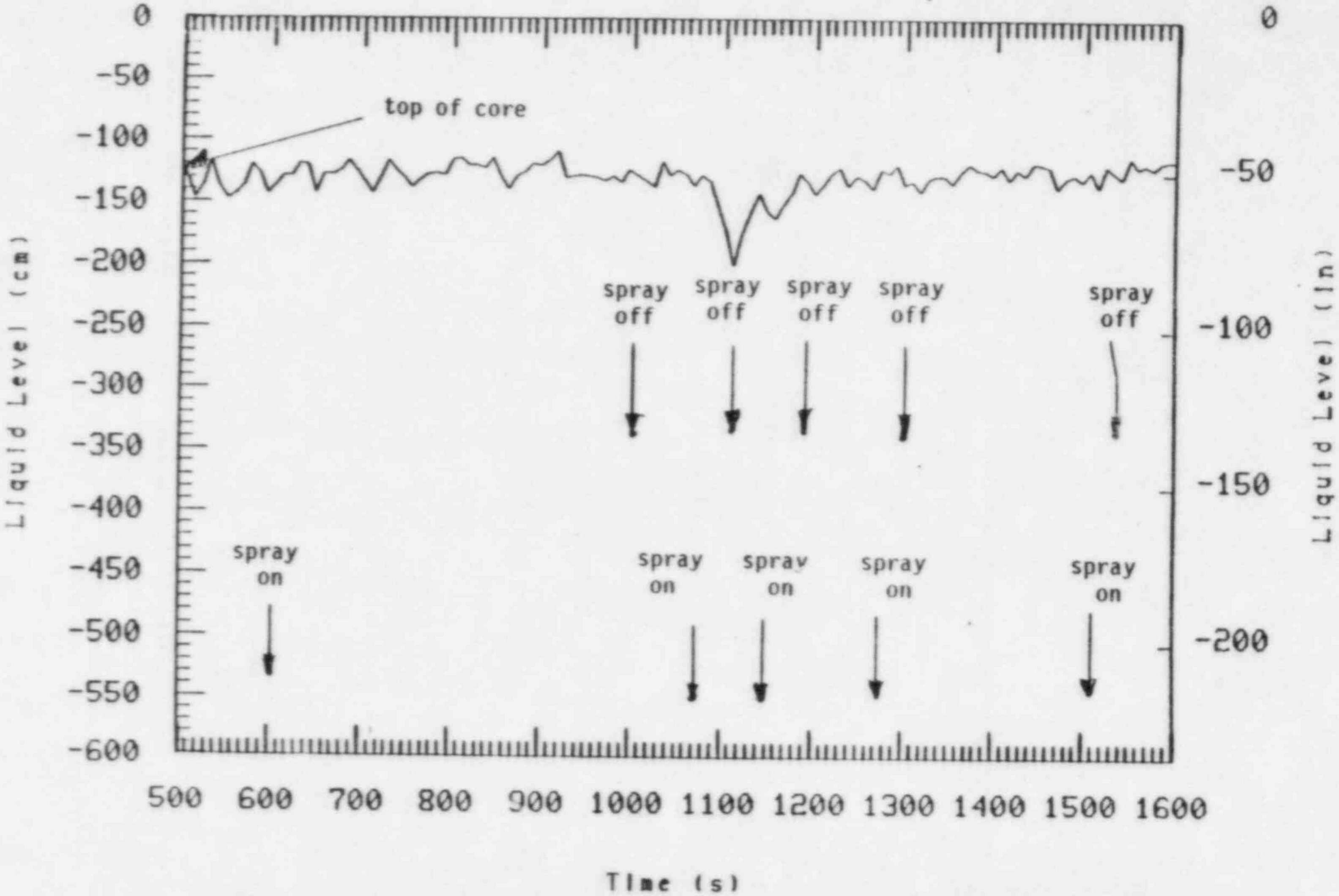

Figure 24. Lower vessel collapsed level during pressurizer auxiliary spray (phase 2)(S-SG-3).

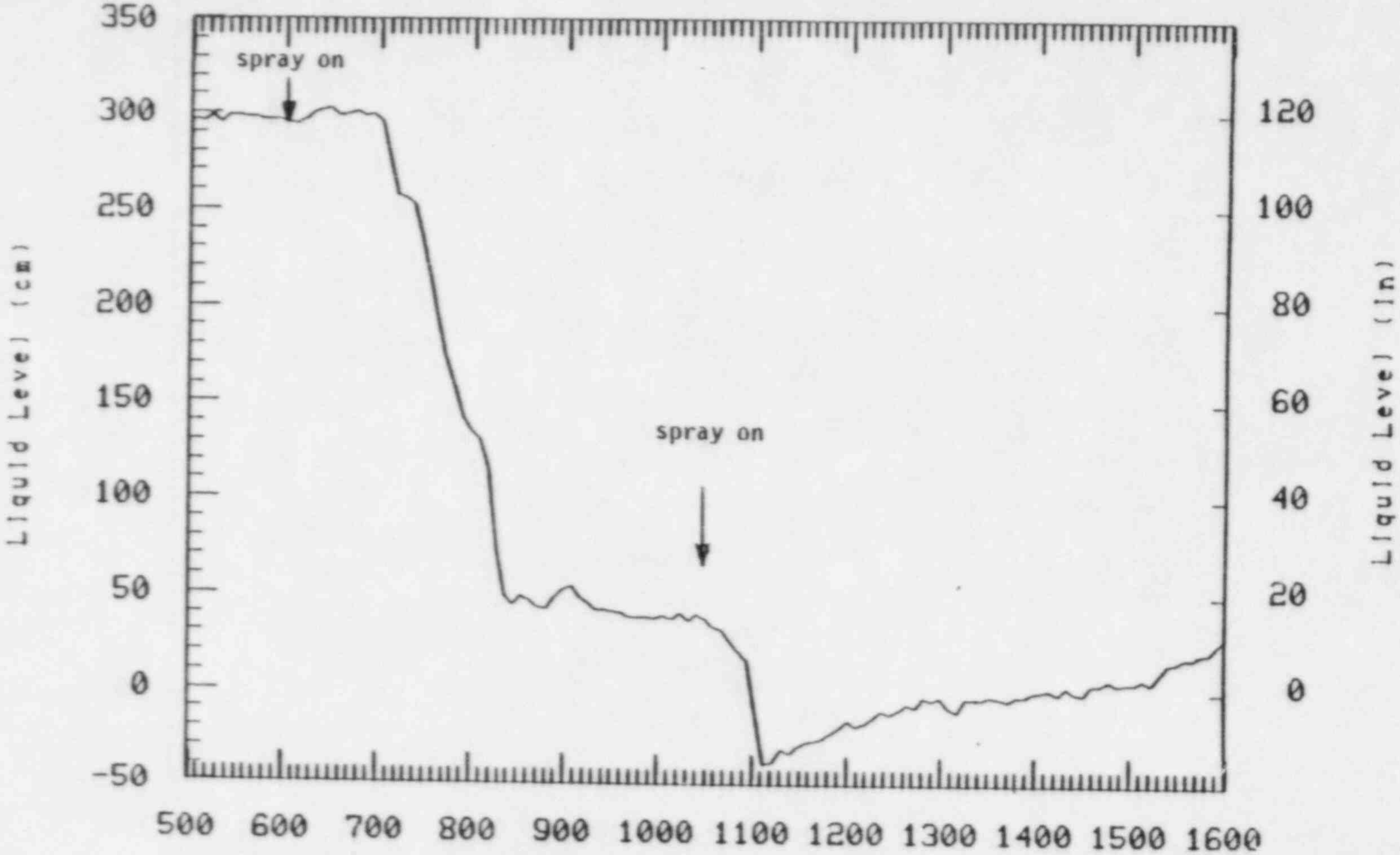

Figure 25. Intact loop pump suction collapsed level during pressurizer auxiliary spray (phase 2)(S-SG-3).

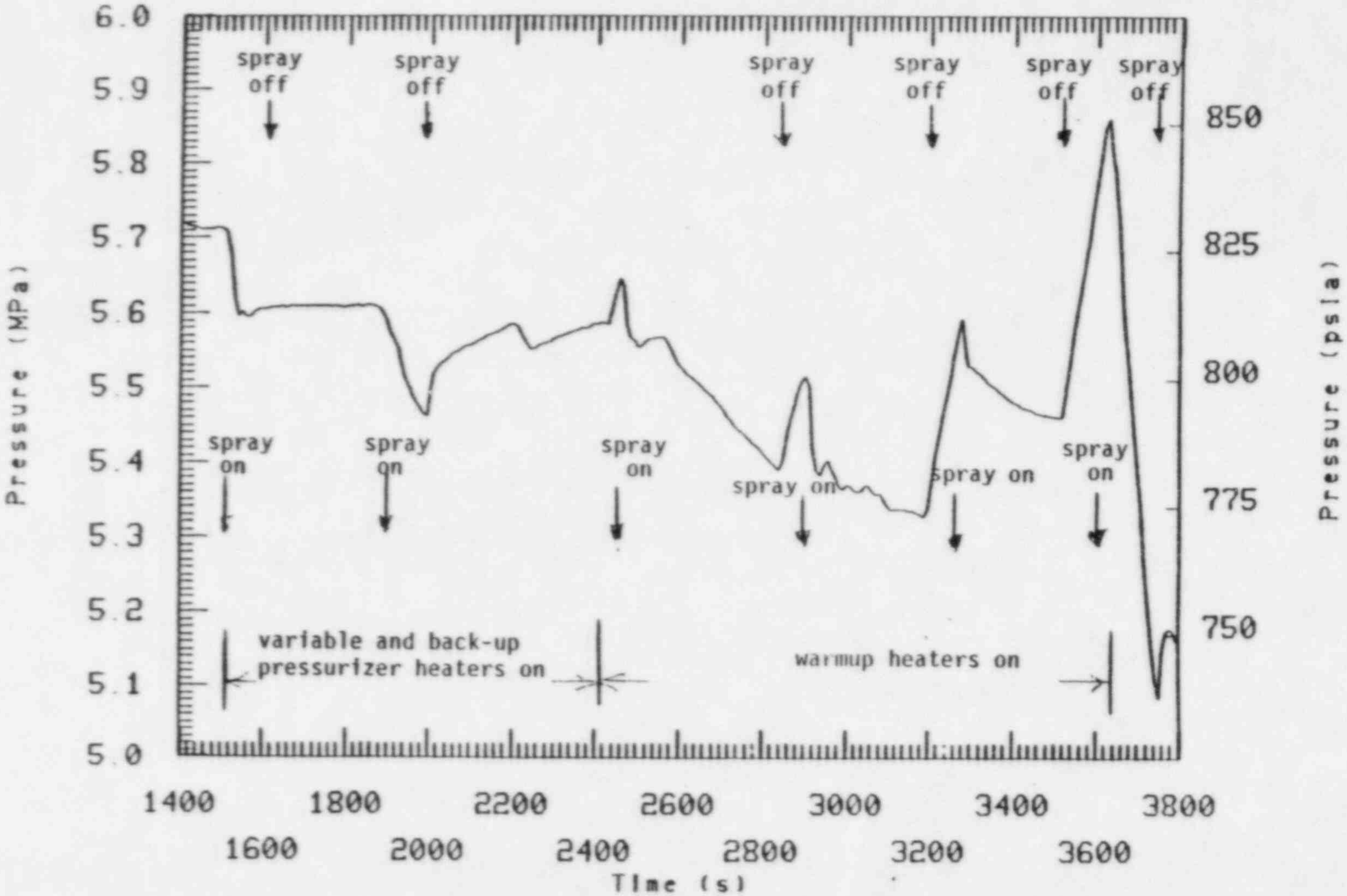

Figure 26. Primary pressure during pressurizer heater operation (phase 3)(S-SG-3).

for a preselected 900 s to be followed by warm-up heater operation (13.3 kW). As shown on Figure 26 variable and backup heater operation alone were not sufficient to overcome the competing effects of spray with the net result that the system would not pressurize to the desired 5.85 MPa (836 psig) primary system pressure. However, eventually the warm-up heater operation starting at 2408 s was sufficient to overcome the effects of the spray and the system was pressurized to 5.85 MPa (836 psig). Pressurizing the system was designed to increase the system subcooling as shown on Figure 27 which shows the hot leg became slightly subcooled by 4 K (7.2°F). Pressurizer spray was operated to maintain the hot collapsed pressurizer level between 75 and 250 cm (30 and 98 in) above the bottom of the pressurizer as shown on Figure 28. Cycling the spray with continued heater operation caused a net outward flow of pressurizer fluid to the primary loop during each period when spray was off (see Figure 28). The pressurizer level decreased when spray was off due to an increase in the pressurizer steam bubble which forced water into the primary loop. As a result the core collapsed liquid level showed a general increase during this operation as shown in Figure 29.

The final increase in pressure to 5.85 MPa (836 psig) starting at about 3500 s occurred during warmup heater operation (13.3 kW) without spray. In the absence of spray, variable and backup heater operation alone could have increased the primary pressure to the desired 5.85 MPa (836 psig) only if the pressurizer level could have been maintained above the heater rods. Predetermined scenario limitations (for pretest computer calculation consistency and to insure aadequate spray effects) kept the pressurizer level below 250 cm (98 in). Had this predetermined upper level trip been higher it might have been possible to pressurize the primary system to 5.85 MPa (836 psig) with variable and backup heaters alone. This could have been accomplished during a longer period without spray as the pressurizer level would have fallen from a higher trip level to the low level spray start point of 75 cm (30 in).

In summary, pressurizer variable and backup heater operation alone when combined with auxiliary spray were not sufficient to raise the system primary pressure from 5.6 MPa (800 psig) to 5.85 MPa (836 psig) as

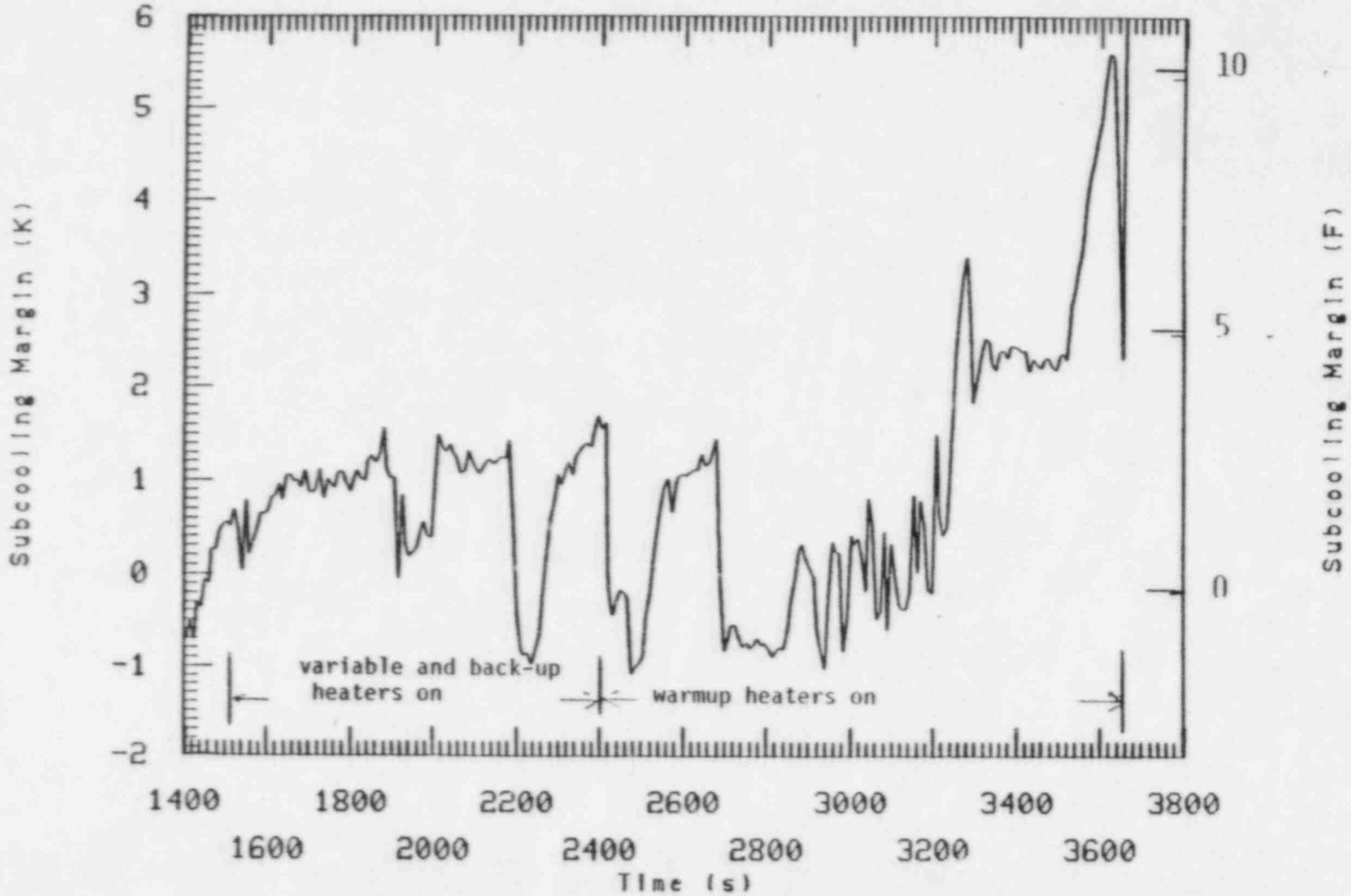

Figure 27. Primary subcooling during heater operation (phase 3)(S-SG-3).

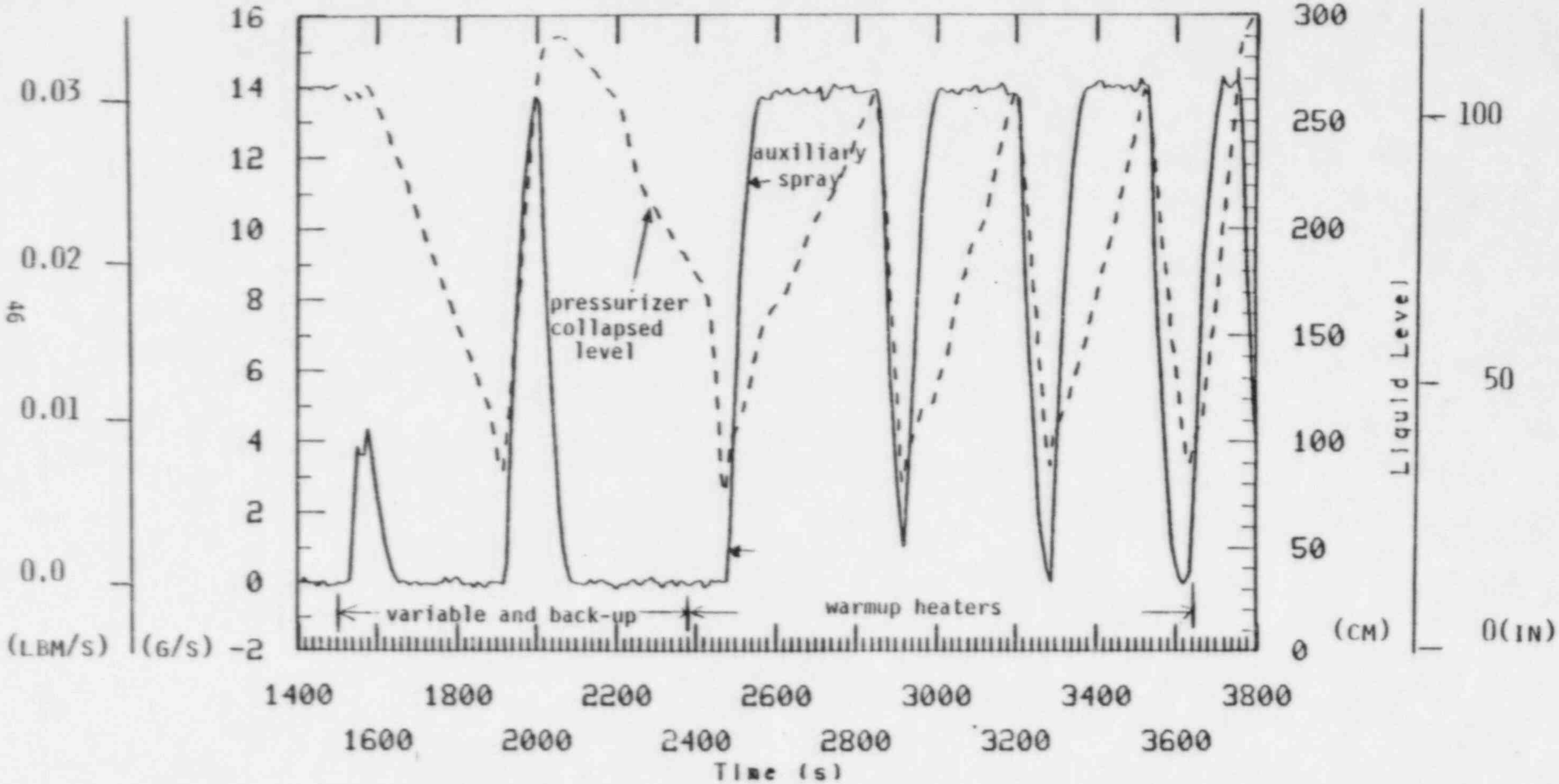

Figure 28. Comparison of pressurizer auxiliary spray rate and pressurizer collapsed liquid level during pressurizer heater operation (phase 3)(S-SG-3).

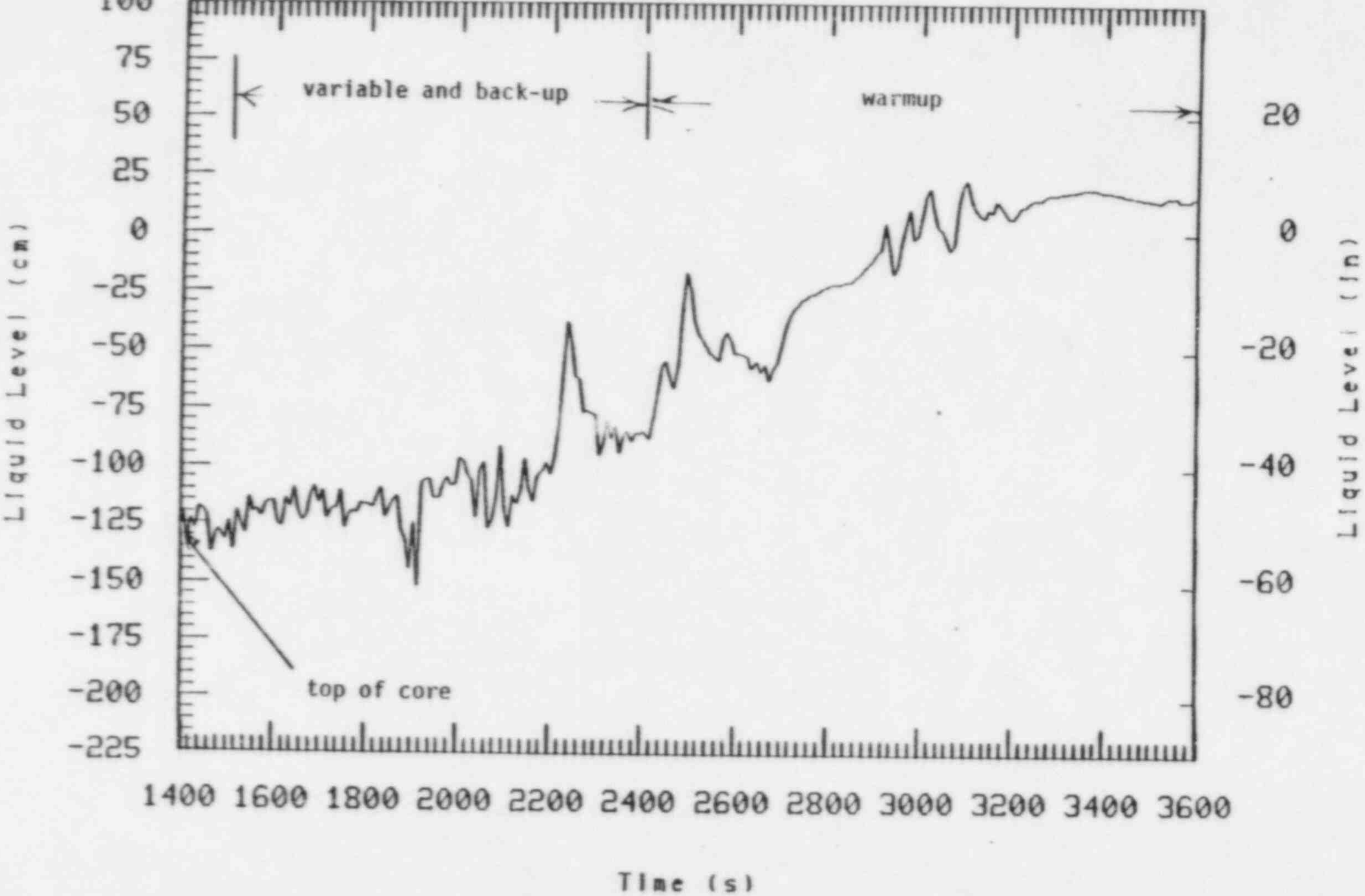

Figure 29. Lower vessel collapsed level during pressurizer heater operation (phase 3)(S-SG-3).

desired. However, pressurizer warm-up heaters combined with auxiliary spray pressurized the primary to 5.85 MPa (836 psig). There was a net increase in the vessel liquid inventory during this spray and heater operation as well as an increase in primary fluid subcooling.

3.2.3 Redistribution of System Fluid Energy Using Intact Loop Pump--(Phase 4)

During phase 4, operating the intact loop pump was a sufficient operation to redistribute system fluid energy and thus lower primary pressure. In addition, the redistribution of fluid energy changed the void content sufficiently in the system to cause the pressurizer level to reach the SI shutoff trip (381 cm (150 in). Cold fluid existing in the pump suction, downcomer, and cold leg were forced by the pump operation to mix with hotter regions of the system which contained voids. The colder subcooled water caused a collapse of voids which reduced the primary pressure. Figure 30 compares the primary pressure and pump speed showing an immediate decrease in primary pressure with an increase in pump speed as subcooled fluid in the cold leg mixed with saturated fluid in the hot leg. Figure 31 compares the hot leg, cold leg, and saturation fluid temperature showing the mixing effect occuring immediately when the intact loop pump was turned on to the initial operating speed. Both the cold leg fluid which had been about 200 K (360°F) subcooled, mixed with the essentially saturated hot leg fluid to produce a fairly uniform primary fluid temperature in both the hot and cold legs. The subcooling of 10 K (18°F) is shown in Figure 31.

SI was terminated for the first time in the recovery phases on a high pressurizer level trip (after 600 s of pump operation) as shown in Figure 32. Prior to the pump operation (phase 2, phase 3) the combined effects of SI and pressurizer auxiliary spray were not sufficient to fill the pressurizer past 250 cm as the amount of voids throughout the loop were sufficient to absorb SI flow when spray was terminated. However, after the pump operation, the fluid energy redistribution resulted in fewer voids and the pressurizer represented the largest void in the system to absorb SI flow. Therefore, once spray was terminated (at about 3750 s on Figure 32)

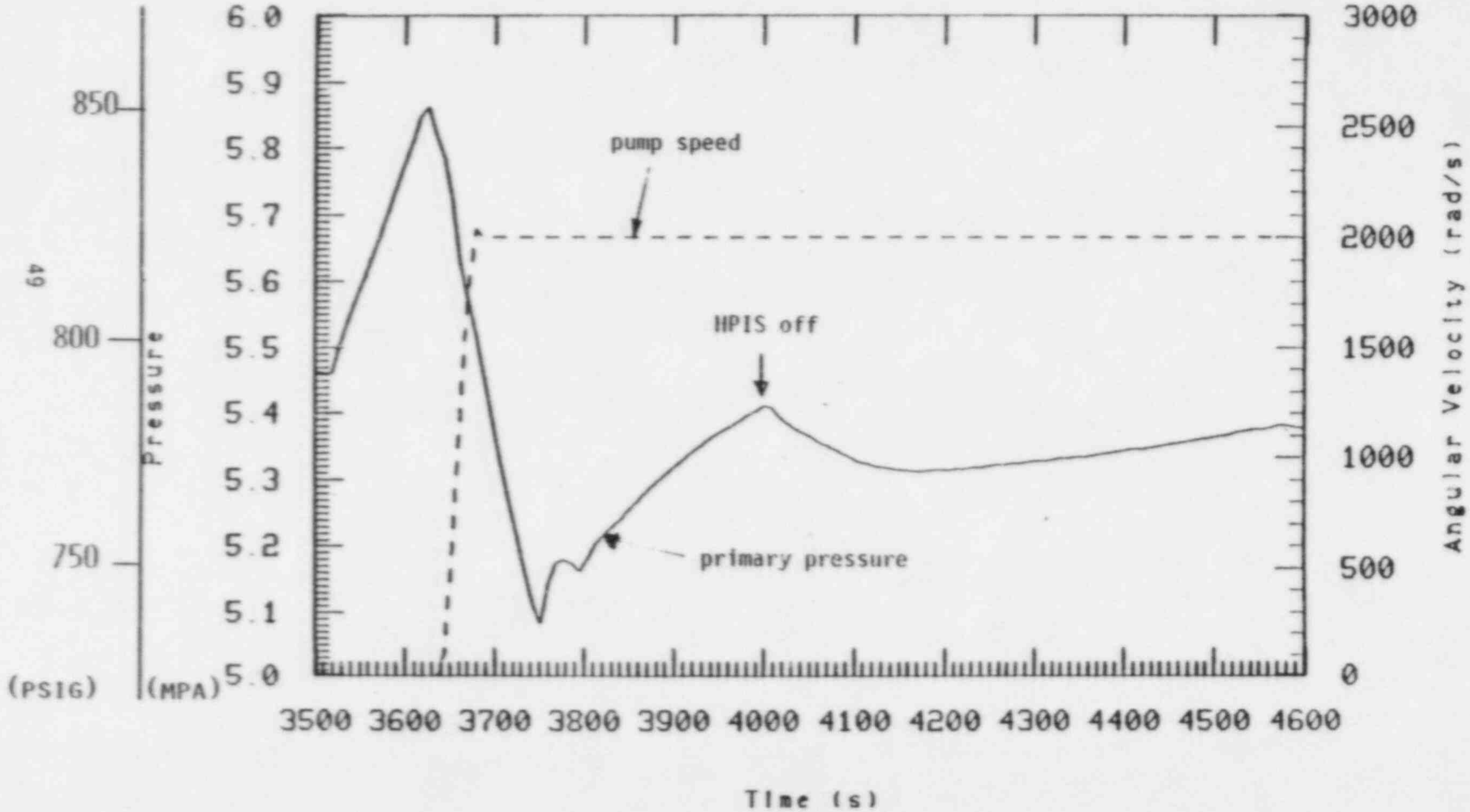

Figure 30. Primary pressure and intact loop pump speed during initial loop pump operation (phase 4)(S-SG-3).

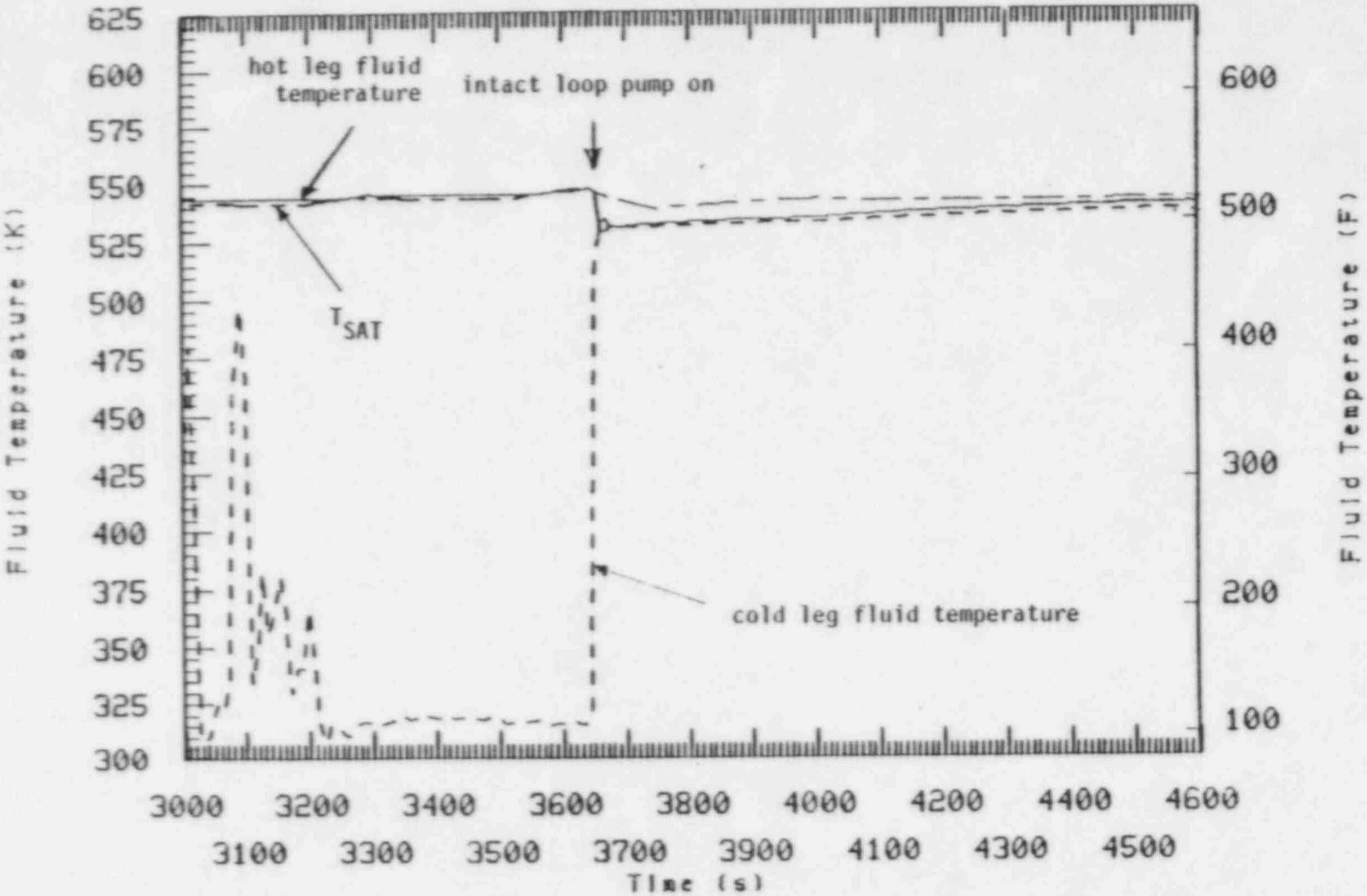

Figure 31. Comparison of intact loop hot leg and cold leg fluid temperature and saturation temperature during intact loop pump operation (phase 4)(S-SG-3).

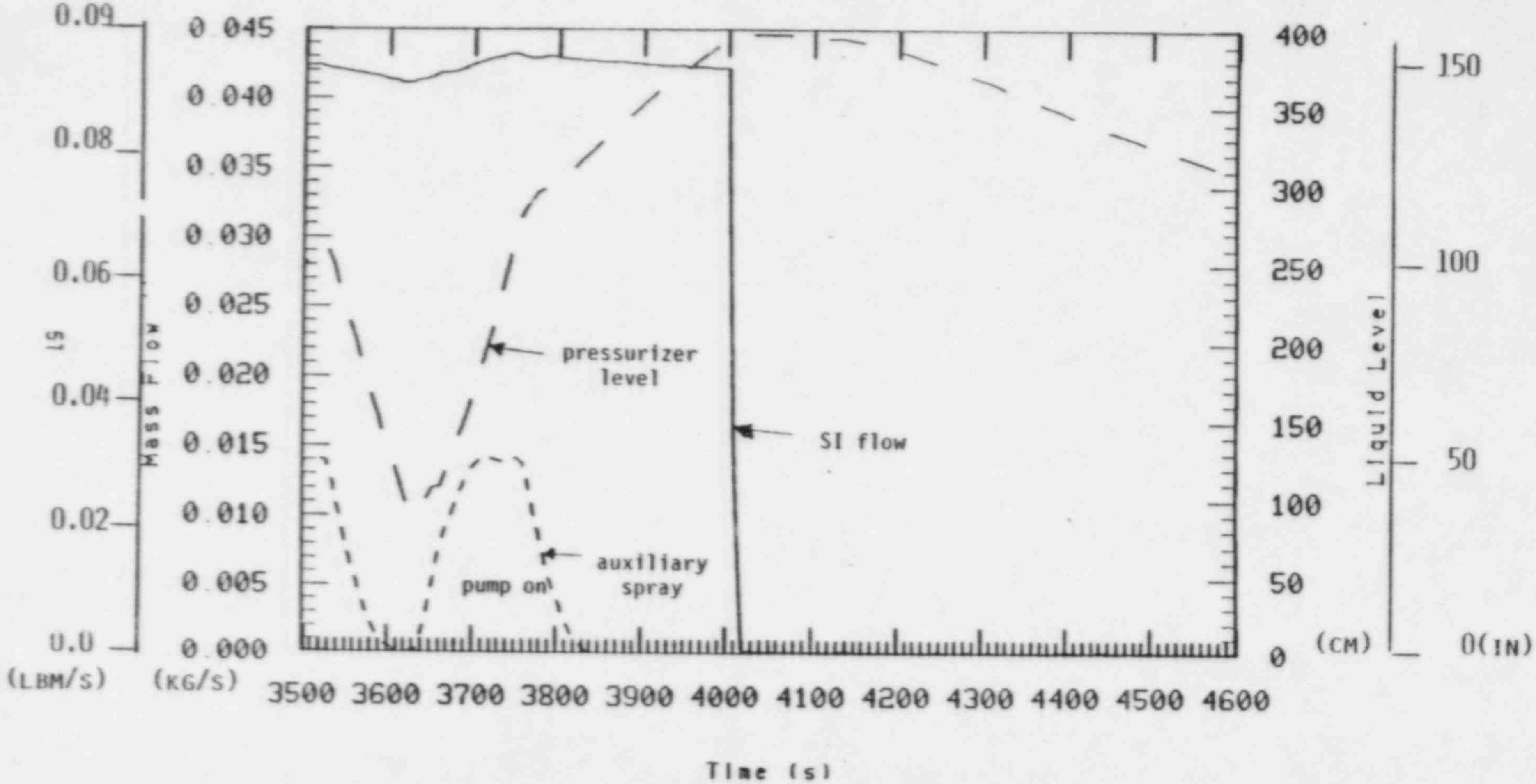

Figure 32. Comparison of auxiliary spray, SI flow, and pressurizer collapsed level during intact loop pump operation (phase 4)(S-SG-3).

SI continued to fill the pressurizer until the trip point was reached at about 4000 s. The effects of SI on system pressure are demonstrated on Figure 30 which shows a primary system pressurization prior to SI shutoff and a primary depressurization due to a positive break flow (Figure 33) following SI termination. The slight increase in primary system pressure which occurred toward the end of phase 4 (4200 to 4600 s) is attributed to continued pressurizer internal heater operation (variable and backup) which had been on throughout phase 4.

In summary, the overall effect due to pump operation was to cause a decrease of primary system pressure and to cause the SI to be terminated on a high pressurizer level trip. The lowering of primary system pressure was due to mixing of subcooled cold leg and saturated hot leg fluid thus collapsing voids in the system. Because the voids were collapsed in the mixing operation, SI flow was able to fill the pressurizer to the high pressurizer level trip point because the pressurizer represented one of the few voids left in the system for the SI flow to occupy.

Following SI termination on high pressurizer level, the system pressure decreased as the pressurizer level decreased due to positive break flow.

3.2.4 Combined Effects of Intact Loop ADV Operation, Pump Flow, Pressurizer Auxiliary Spray, Pressurizer Internal Heater Operation, and SI Flow--(Phase 5)

Phase 5 involved the combined effects of all previously used recovery techniques (phases 2, 3, and 4) to first subcool the system fluid and then to cause a slow (0.172 MPa/5 min) (25 psi/5 min)) primary depressurization.

At 4567 s the intact loop ADV was latched open causing an increase in intact loop secondary heat sink as shown in Figure 34. There was no appreciable effect on primary pressure due to the ADV operation. However, the effect of pressurizer spray to depressurize the primary is clear. The main affect of the ADV operation combined with intact loop pumped flow was to cause an increase in primary fluid subcooling as shown in Figure 35

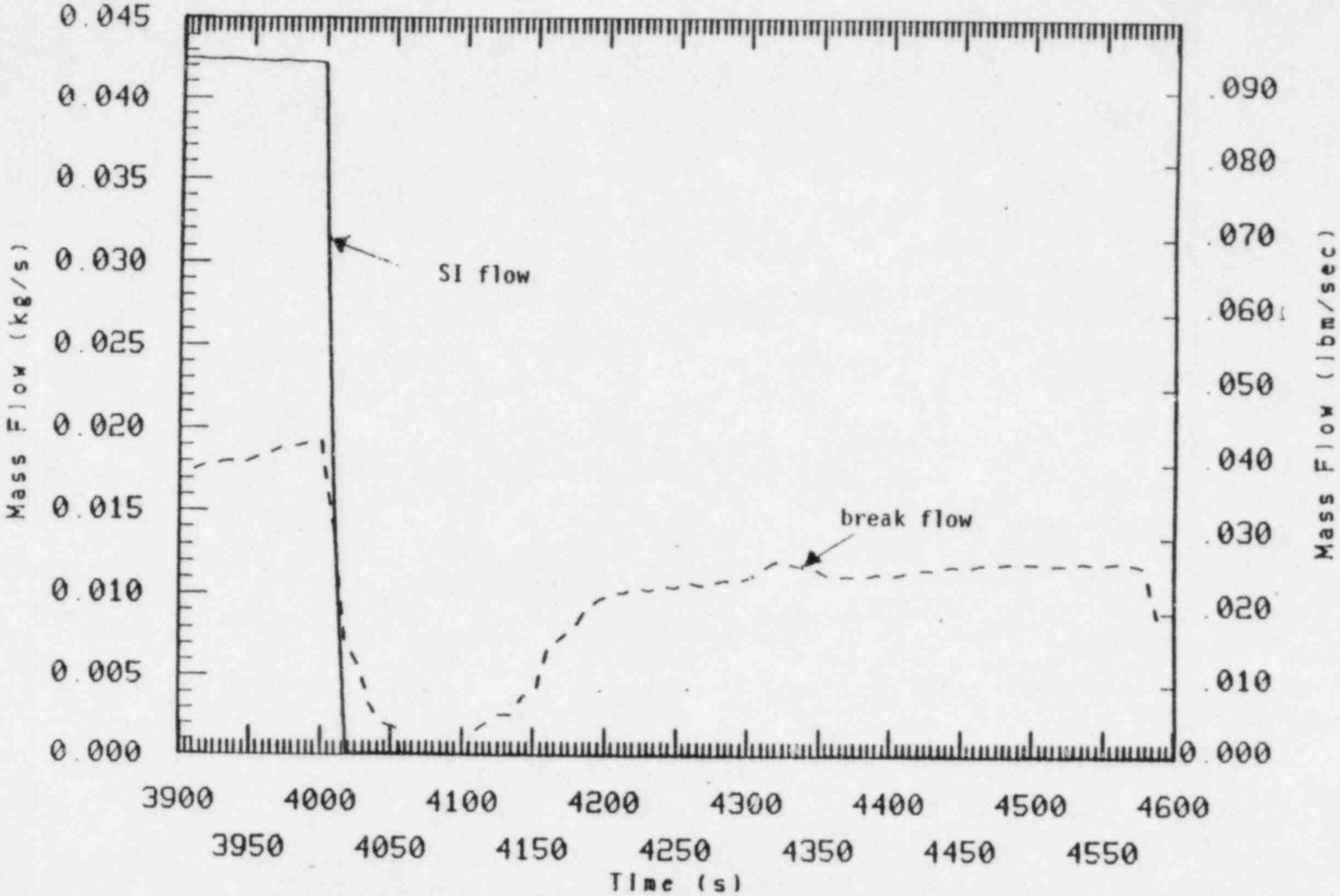

Figure 33. Comparison of SI flow and break flow during intact loop pump operation (S-SG-3).

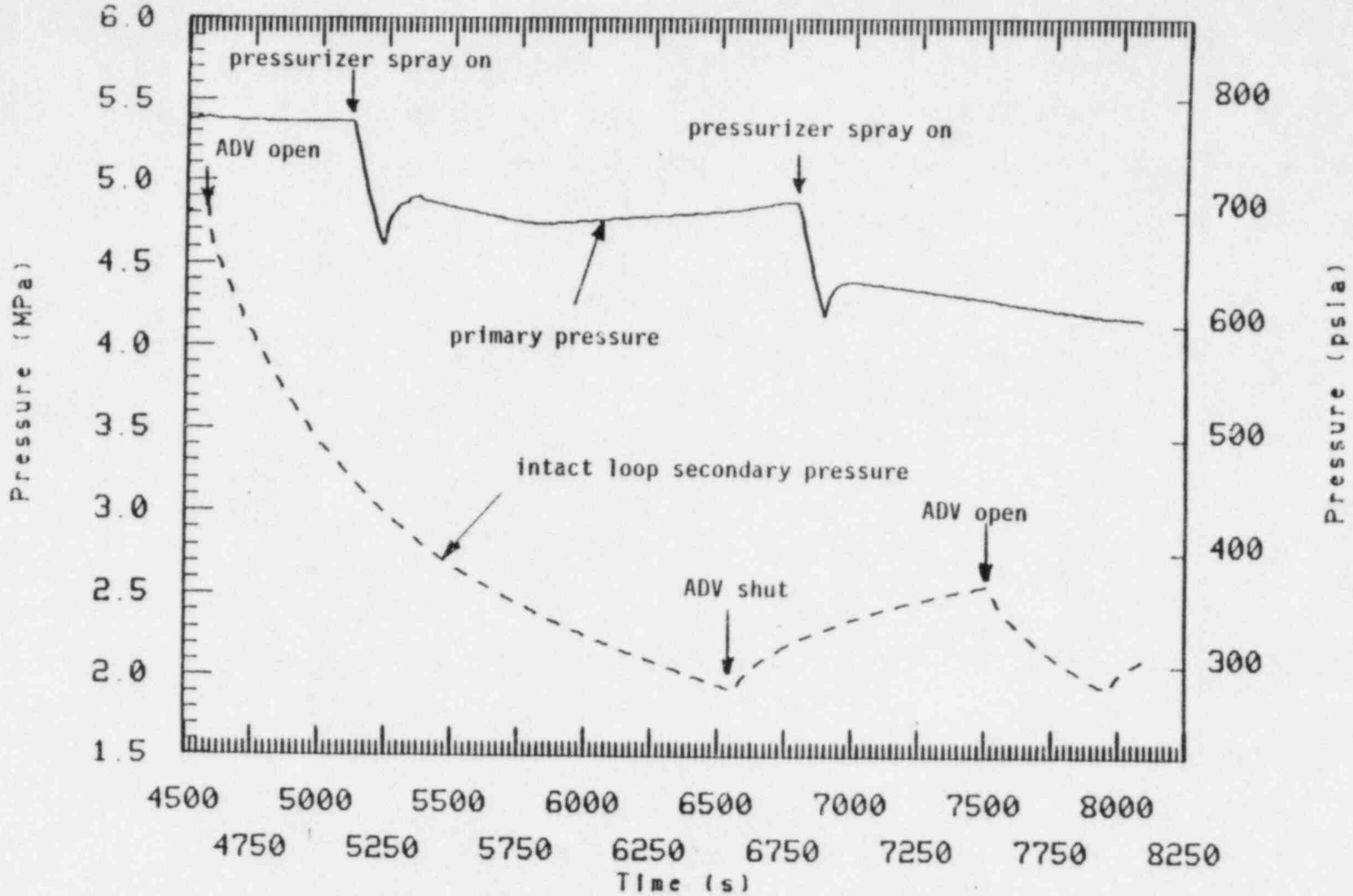

Figure 34. Comparison of primary and intact loop secondary pressure during latched open intact loop ADV operation (phase 5)(S-SG-3).

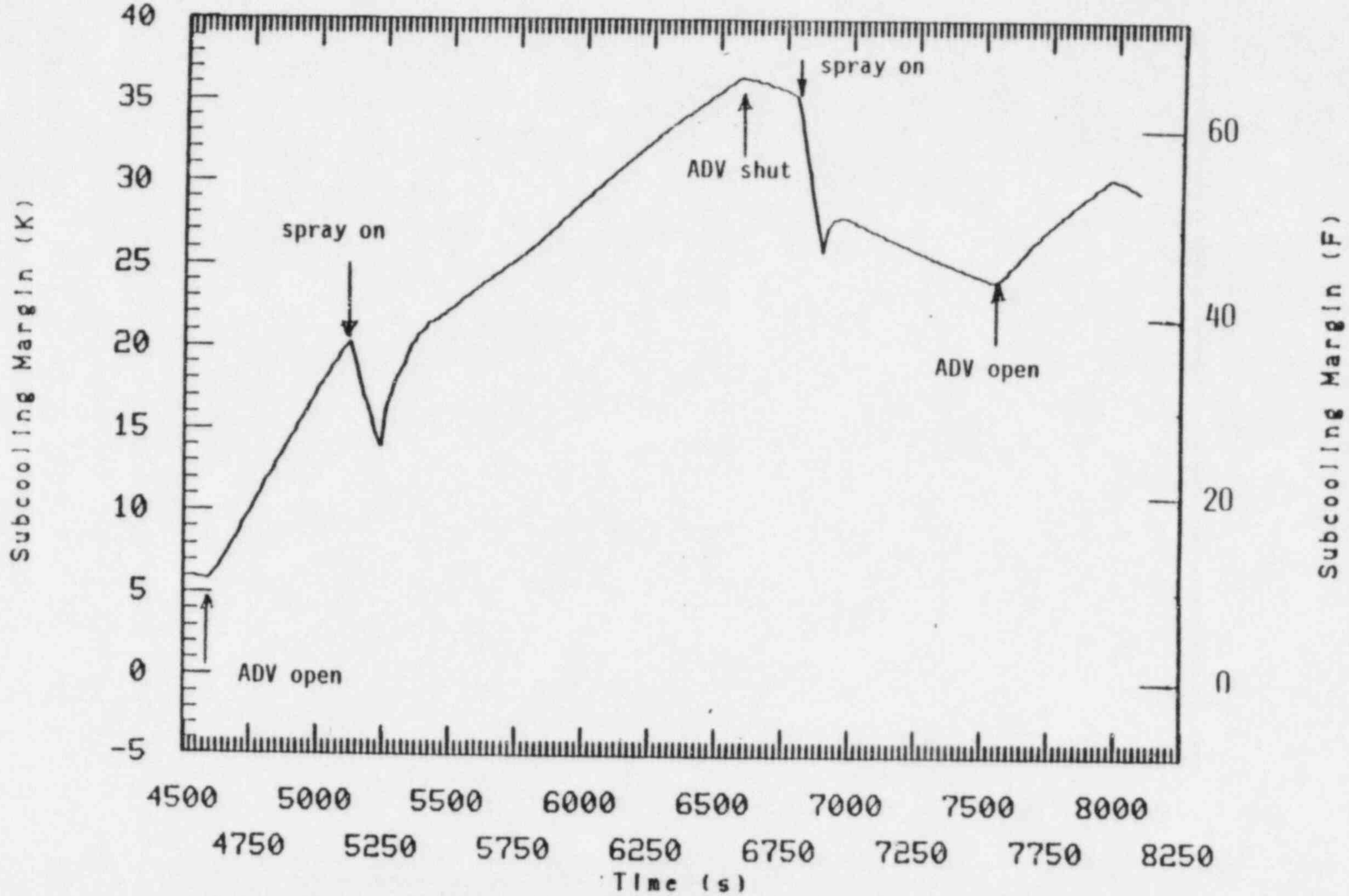

Figure 35. Primary fluid subcooling during latched open intact loop ADV operation (phase 5)(S-SG-3).

[from 5 to 37 K (9 to 67°F)]. Each spray operation reduced the system subcooling corresponding to reductions in primary pressure. Had the pressurizer spray been turned off while the pressurizer internal heaters remained on the subcooling margin in the system would have increased faster. When the intact loop secondary collapsed liquid level fell to 250 cm, the operators were required to shut the ADV until the level increased due to auxiliary feedwater to 400 cm, at which time, the ADV was latched open again. Shutting the ADV at about 6600 s on a low secondary level, stopped the increase in the subcooling margin which had occurred due to an increasing heat sink. Once the secondary level had increased to 400 cm the ADV was again latched open (7550 s) which again increased the subcooling margin.

Starting at a predetermined subcooling margin of about 37 K (6820 s) a 1200 s period of primary depressurization was began to attempt to bring the primary pressure down at 0.172 MPa/5 min (25 psi/5 min) as shown on Figure 36. This was attempted by using (a) the pressurizer internal heaters [variable and backup (2.35 kW)] as the main point of control, (b) operating pressurizer auxiliary spray on pressurizer level trips [on at 75 cm (30 in) off at 250 cm (98 in)], (c) SI operated on pressurizer level trip [75 cm and 100 cm (30 and 39 in)], and (d) continued intact loop ADV operation. While these actions occurred, intact loop pump operation continued. If the primary pressure was below the desired 0.172 MPa/5 min (25 psi/5 min) depressurization rate the pressurizer internal heaters (variables and backup) remained on and if the rate was above the specified value the heaters were turned off. At 7220 s the pressurizer heaters were required to be turned off as shown in Figure 36 and remained off for the rest of the experiment because the primary system depressurized slower than the required rate.

SI flow was on only occasionally for phase 5 to maintain the pressurizer hot collapsed level between 75 and 100 cm (30 and 39 in) as shown on Figure 37. As mentioned previously, pressurizer spray cycled to maintain the level between 75 and 250 cm (30 and 98 in) as shown on Figure 38. However, following termination of spray at about 6750 s, the pressurizer level continued to fill due to back flow through the break from

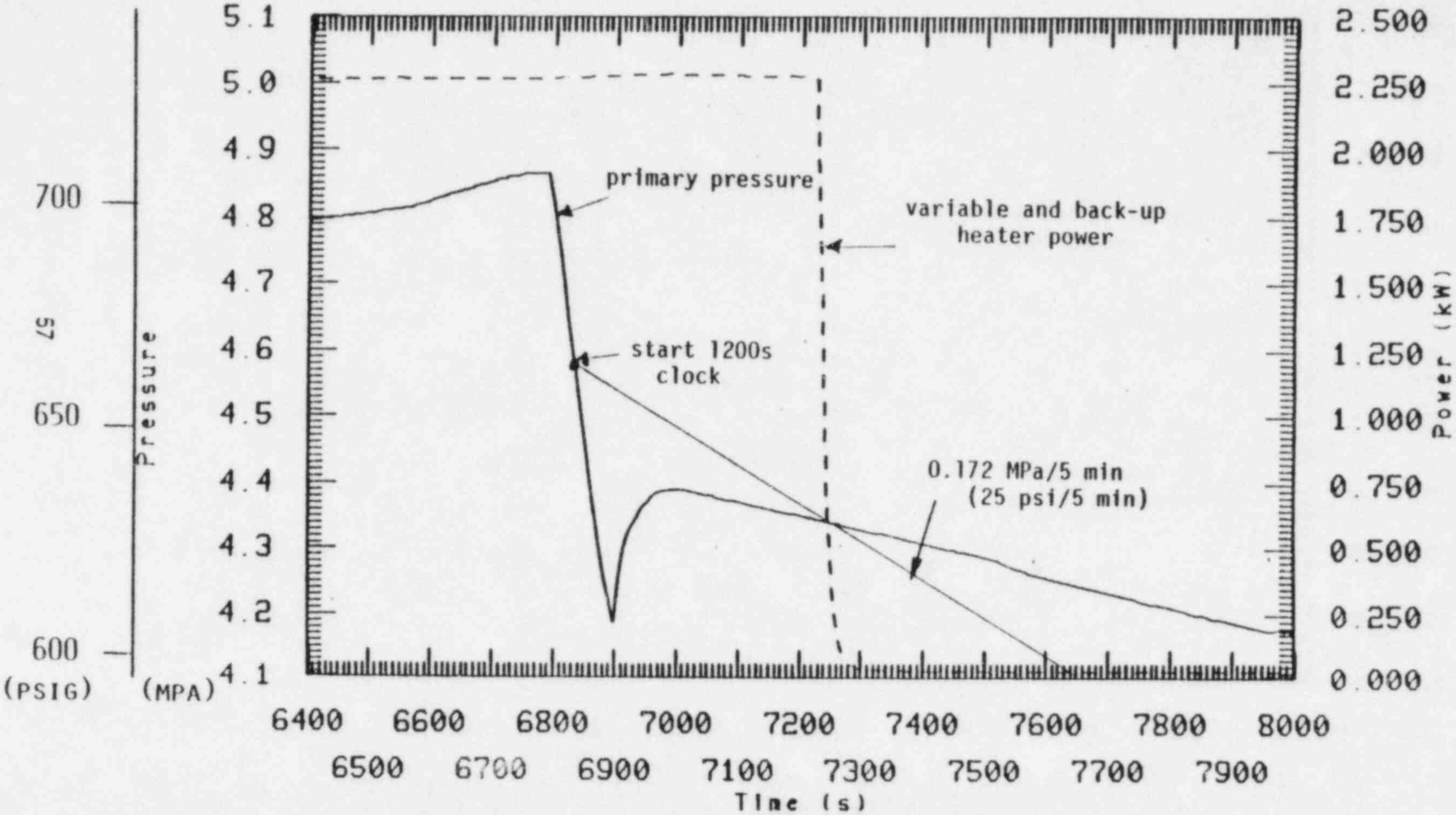

Figure 36. Comparison of pressurizer internal heater power and primary pressure during latched open intact loop ADV operation (phase 5)(S-SG-3).

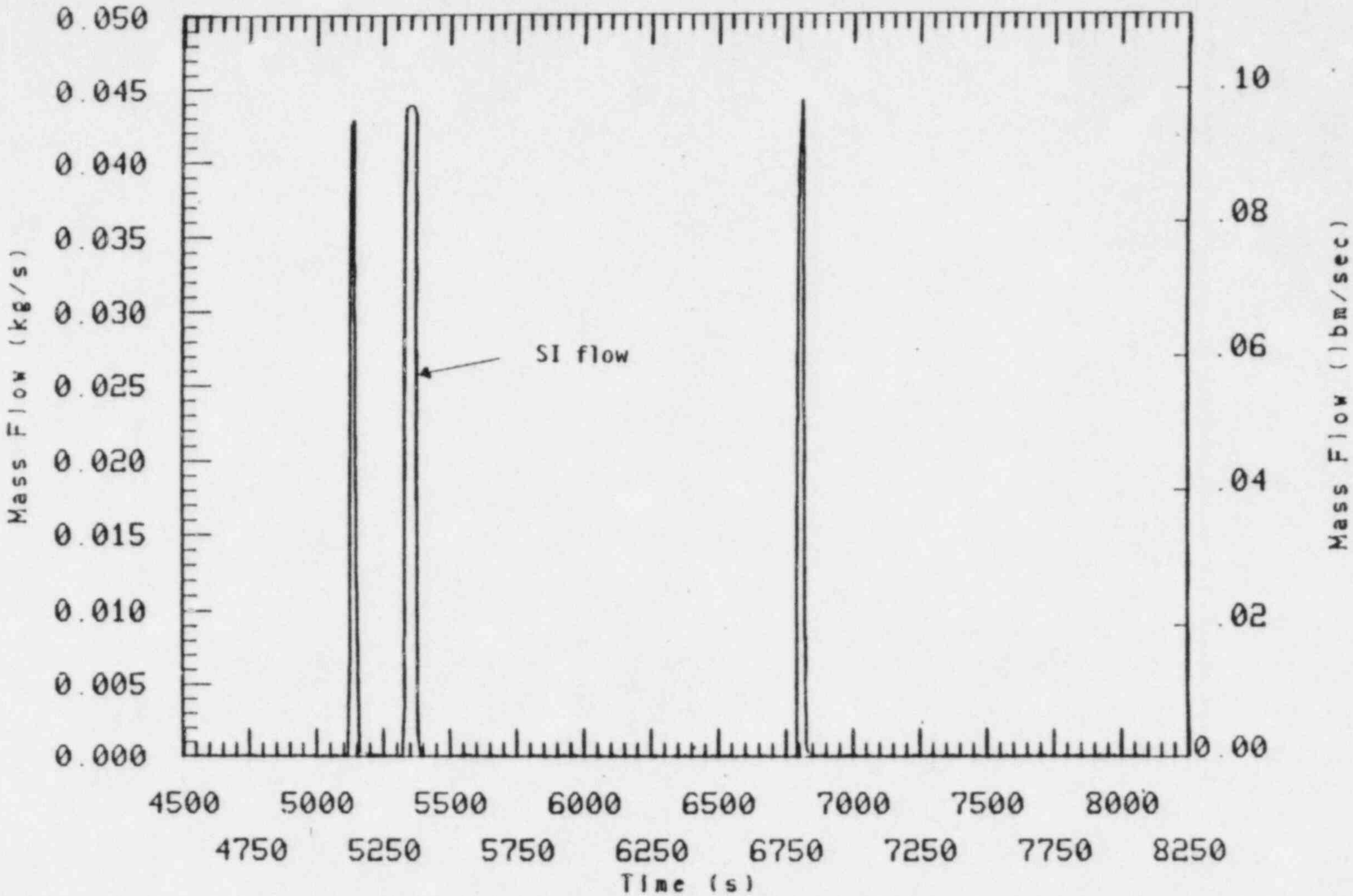

Figure 37. SI flow during latched open intact loop ADV operation (phase 5)(S-SG-3).

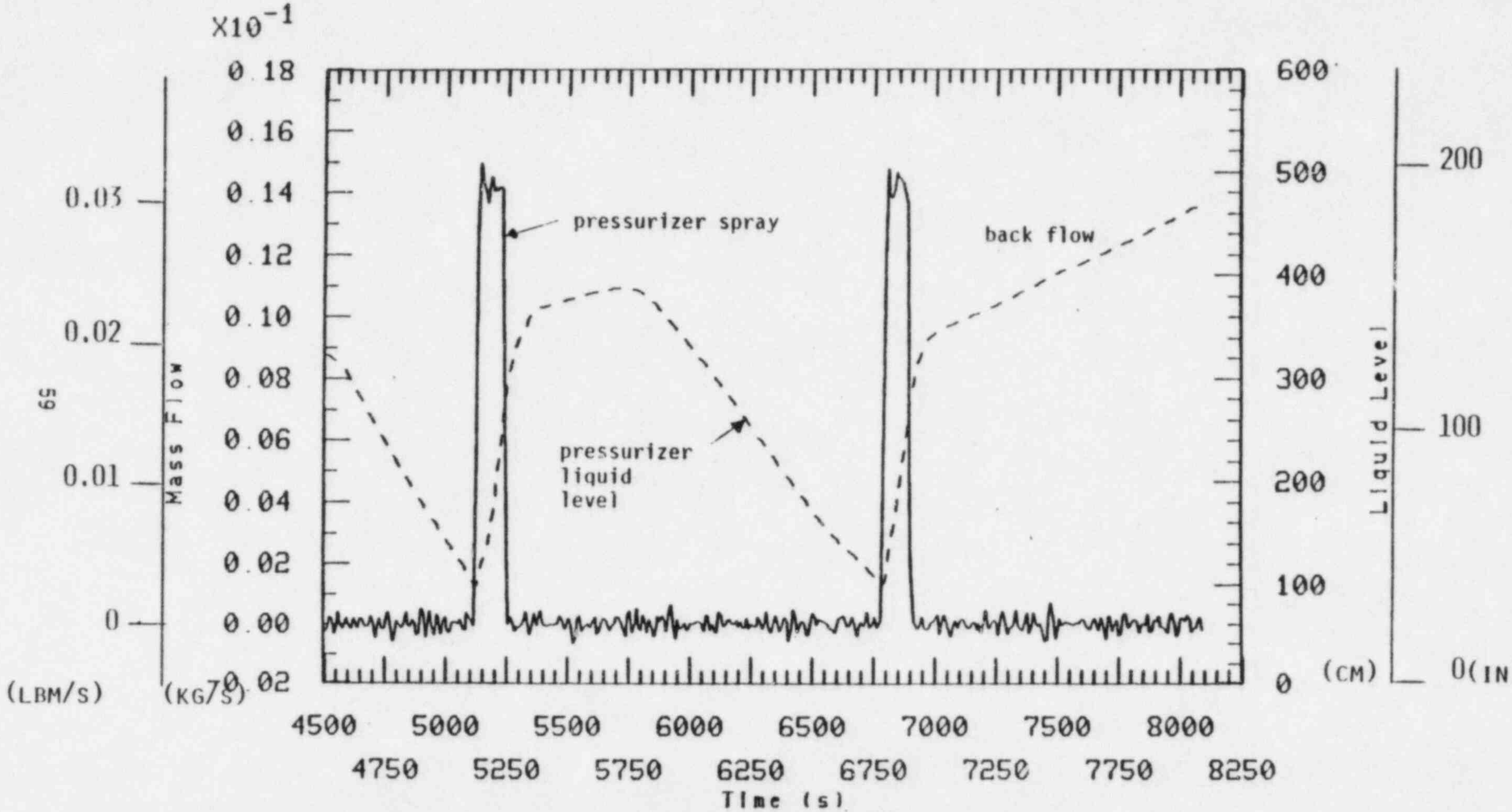

Figure 38. Comparison of pressurizer collapsed liquid level and auxiliary spray rate during latched open intact loop ADV operation (phase 5)(S-SG-3).

the broken loop generator. The combined recovery methods had reduced the primary pressure below the broken loop secondary pressure resulting in negative break flow as shown on Figure 39.

In summary, phase 5 combined intact loop pump operation, pressurizer auxiliary spray and internal heater operation, a latched open ADV, and SI flow to cause an increase in system fluid subcooling from 5 to 37 K (9 to 67°F). The reduction of loop temperature due to the increased heat sink provided by primary to secondary heat transfer is the main contributor to loop fluid sucooling. During a controlled 0.172 MPa/5 min (25 psi/5 min) depressurization period following attainment of 37 K (67°F) subcooling it was necessary to turn off the pressurizer heaters in an attempt to maintain the required depressurization rate.

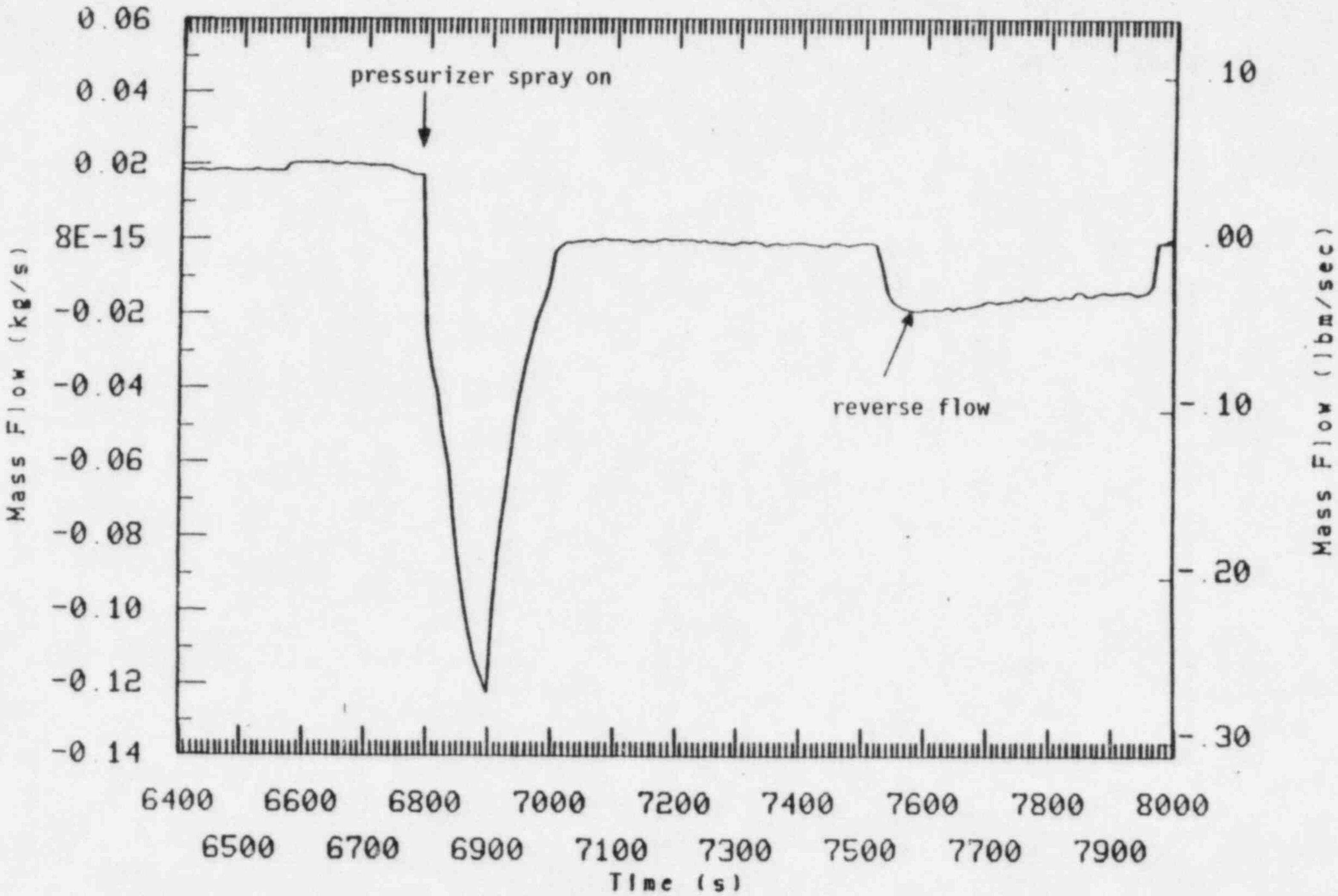

Figure 39. Break flow during intact loop ADV operation (phase 5)(S-SG-3).

4. COMPARISON TO THE PAD CALCULATION

This section compares the test results to the PAD calculation[8] for Test S-SG-3. The discussion is presented by test phase rather than chronologically to assist the reader in understanding. A comparison of calculated and measured initial conditions is presented in Table 3.

4.1 Test Phase 1: 0-600 s

During the first 600 s of the transient only automatic plant protection systems were assumed operable. The transient was initiated by opening the break which caused a rapid primary coolant system depressurization. As shown in Figure 40, the calculated and measured depressurization were in good agreement. The scram signal which was calculated to occur at 13.5 s actually was received at 16.4 s [based on a low pressurizer pressure trip at 13.1 MPa (1900 psia)]. SIS, predicted to occur at 15.9, was received at 17.1 s [based on pressurizer pressure of 12.51 MPa (1814 psia)].

At approximately 50 s, a slight primary repressurization had been predicted but did not occur. One reason for this was that less vapor was generated in the core than predicted (Figure 41).[a] In the calculation, natural circulation through the core quickly flushed part of that vapor out and the core liquid level was reasonably close to the actual by 120 s. Between 60 and 600 s very good primary pressure agreement between the calculation and test was obtained.

Break flow (Figure 42) was well predicted during the first 20 s of the transient. From that time through phase 1, the calculation underpredicted the break flowrate. The flow during the underpredicted portion was probably in error due to the lack of data against which the model could be

a. All liquid levels presented in this report are collapsed levels which were calculated by assuming that the entire pressure difference is due to saturated liquid.

TABLE 3. CALCULATED AND MEASURED INITIAL CONDITIONS

	Calculated	Measured
Pressurizer pressure	15.6 MPa (2263 psia)	15.45 (2240 psig)
Pressurizer liquid volume	0.0101 m^3 (0.36 ft^3)	0.0106 m^3 (0.37 ft^3)
Core power	2.0 ± 0.01 MW	1.99 MW
Loop to loop cold leg fluid temperature differential	1.0K (1.8°F)	0.1K (0.18F)
Core fluid temperature rise	37 K (67°F)	37.5K (67.5°F)
Steam generator pressure		
Broken loop	5.54 MPa (804 psia)	5.50 MPa (785 psig)
Intact loop	5.54 MPa (804 psia)	5.52 MPa (788 psig)
Steam generator secondary fluid mass		
Broken loop	100.4 kg (221.3 lbm)	93 kg[a,b] (204 lbm)
Intact loop	100.5 kg (221.3 lbm)	88 kg[c] (194 lbm)

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

b. Measured with differential pressure cell LBS+1117+51.

c. Measured with differential pressure cell LIS+1117+51.

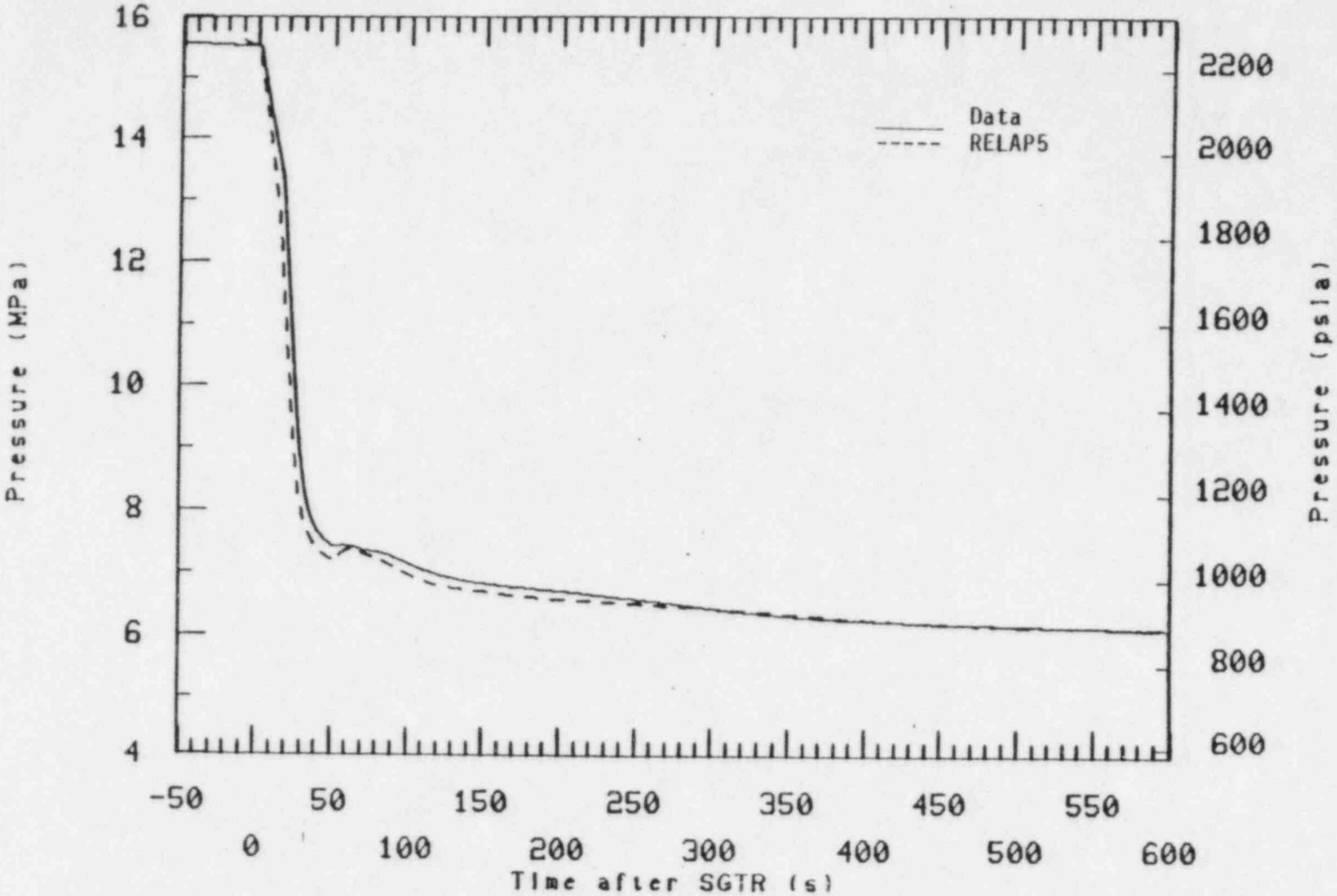

Figure 40. Phase 1 primary pressure comparison.

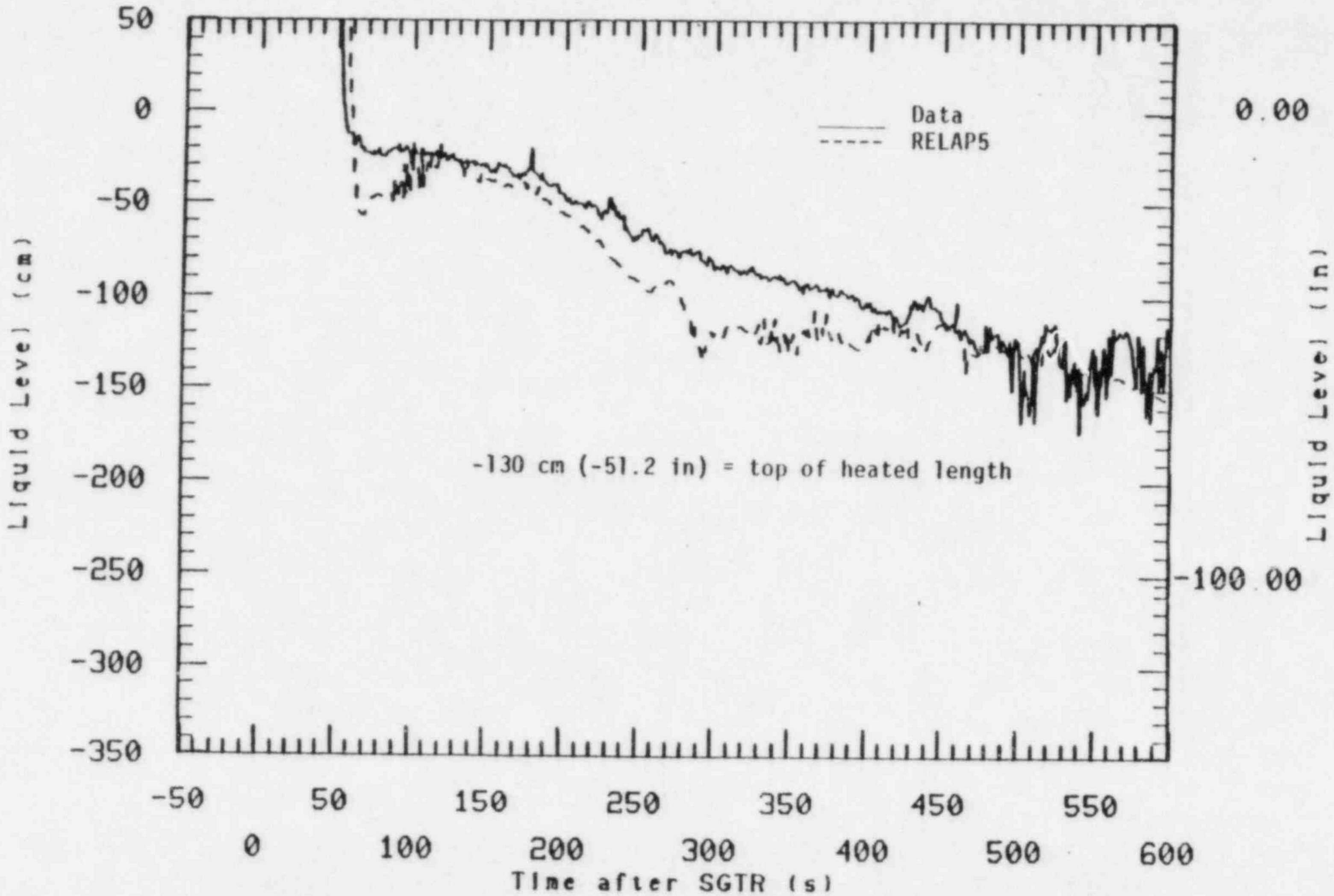

Figure 41. Phase 1 core liquid level comparison.

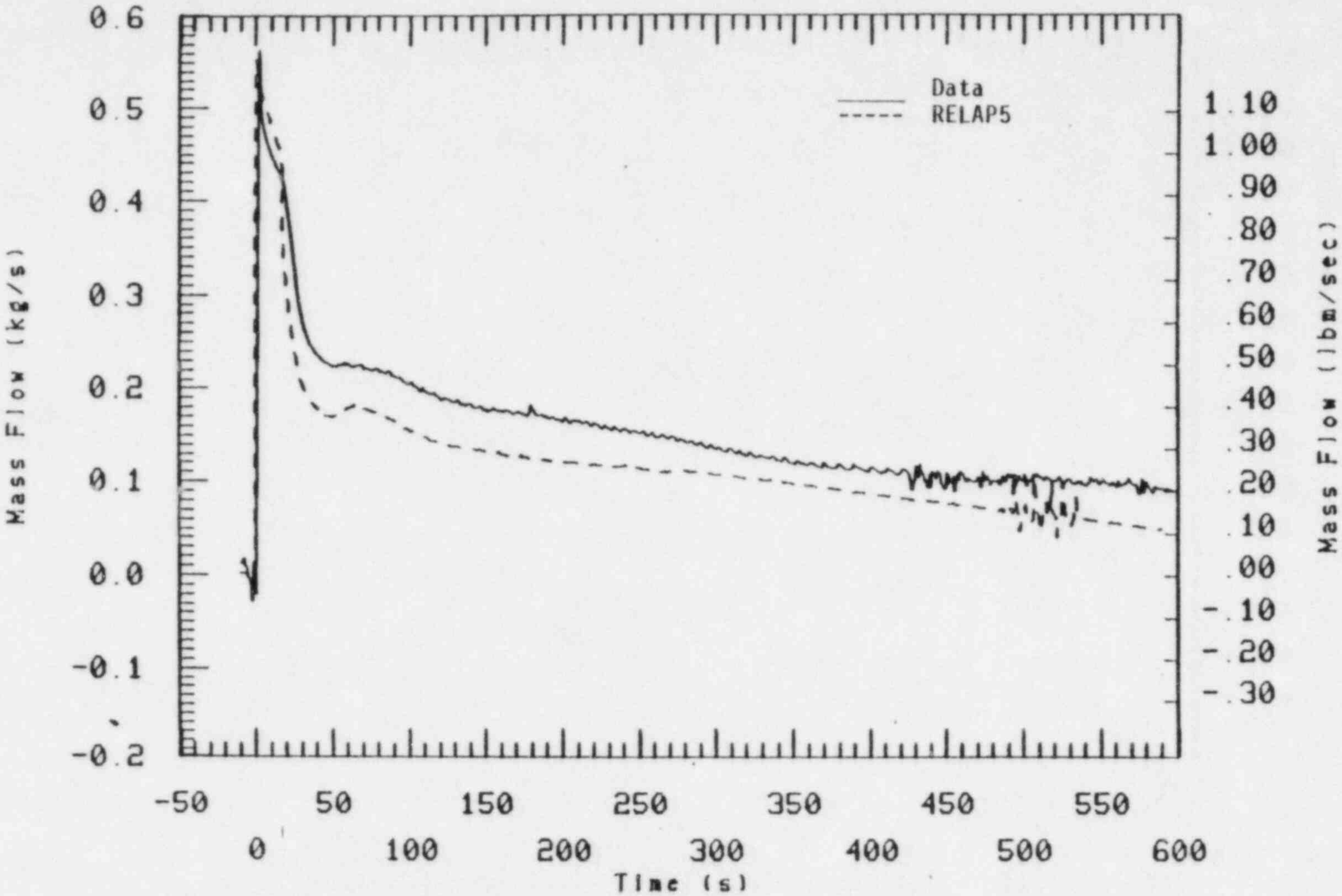

Figure 42. Phase 1 break flowrate comparison.

benchmarked. During unchoked flow, empirically determined form losses are used to calculate break flow. Since this was the first ten tube rupture test, no experimental data were available and the same form losses used for single and 5 tube ruptures were used.

The code also did a good job predicting the collapsed pressurizer liquid level (Figure 43) during phase 1. The 20 cm (8 in) difference between the calculated and measured level results from the lower pressure tap location in the pressurizer [30 cm (11.8 in)]. The remaining indicated level (after 50 s) was due to the steam pressure differential between the top and bottom.

The secondary pressure response is shown in Figure 44. The BLSG secondary pressure increased somewhat sooner and more rapidly in the calculation than actually occurred. The approximate 0.06 MPa (9 psid) offset between 50 and 600 s was apparently due to a slightly low setting on the relief valve at the facility. The ILSG secondary pressure was also well predicted during this phase of the test.

4.2 Test Phase 2--Pressurizer Auxiliary Spray Operation

Pressurizer auxiliary spray was initiated at 600 s and was cycled to maintain the pressurizer collapsed liquid level at 250 cm (98.4 in). Figure 45 shows that, after about a 150 s delay, the pressurizer fill rate was well calculated. The discontinuities in the calculated collapsed liquid level are a RELAP5 phenomenon which occur when the liquid/vapor interface enters a new volume in the pressurizer. RELAP5 calculates a rapid pressure increase when liquid first enters the volume and then no increase while the volume fills.

The objective during phase 2 was to lower the primary pressure to 5.6 MPa (812 psia). The measured depressurization rate (Figure 46) between 600 and 900 s was very comparable to the calculation. After 1000 s, the calculated pressurizer liquid level was above 250 cm (98.4 in) and spray did not operate again during this phase of the test as SI flow was sufficient to maintain that level. During the test, however, SI flow did

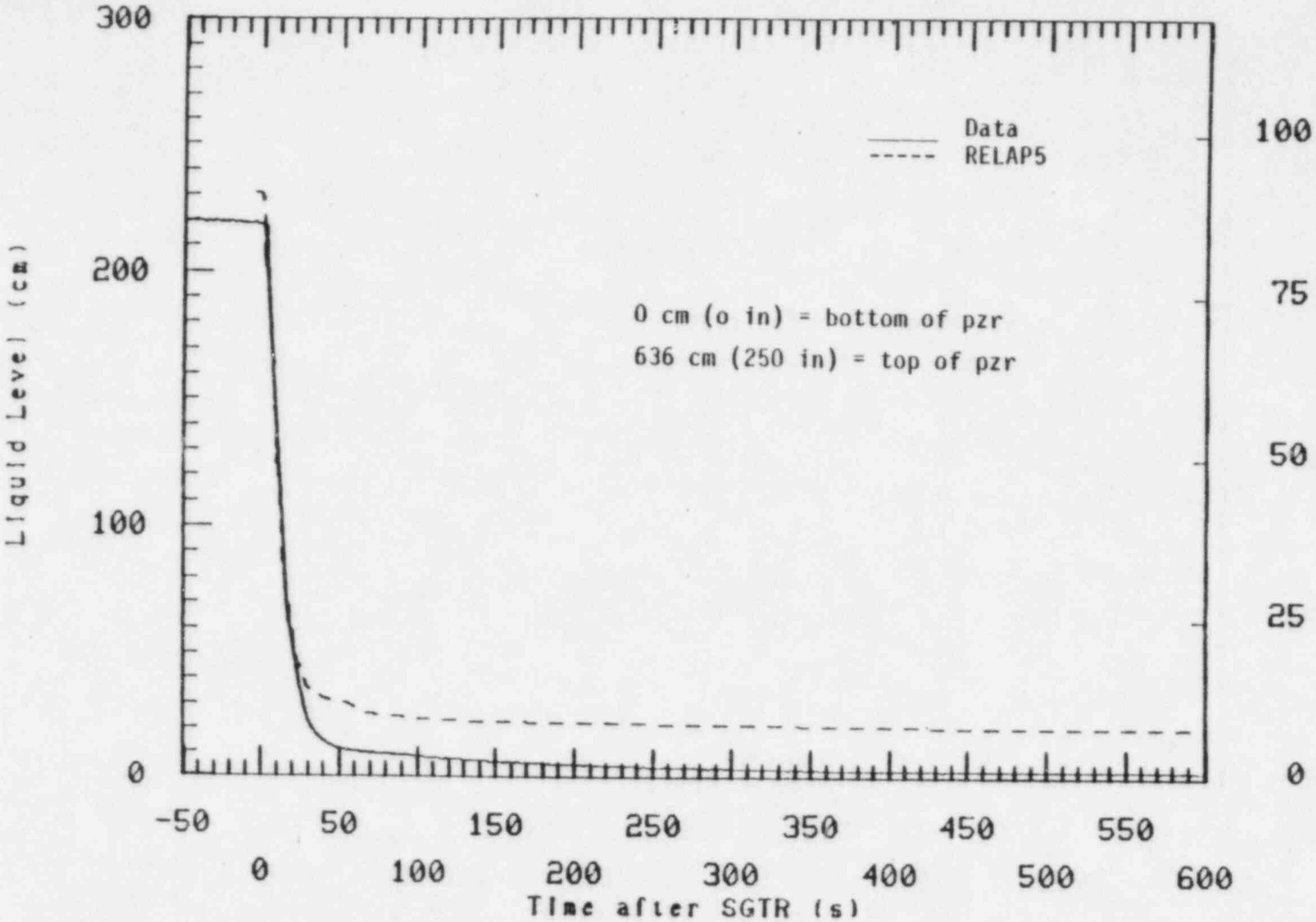

Figure 43. Phase 1 pressurizer liquid level comparison.

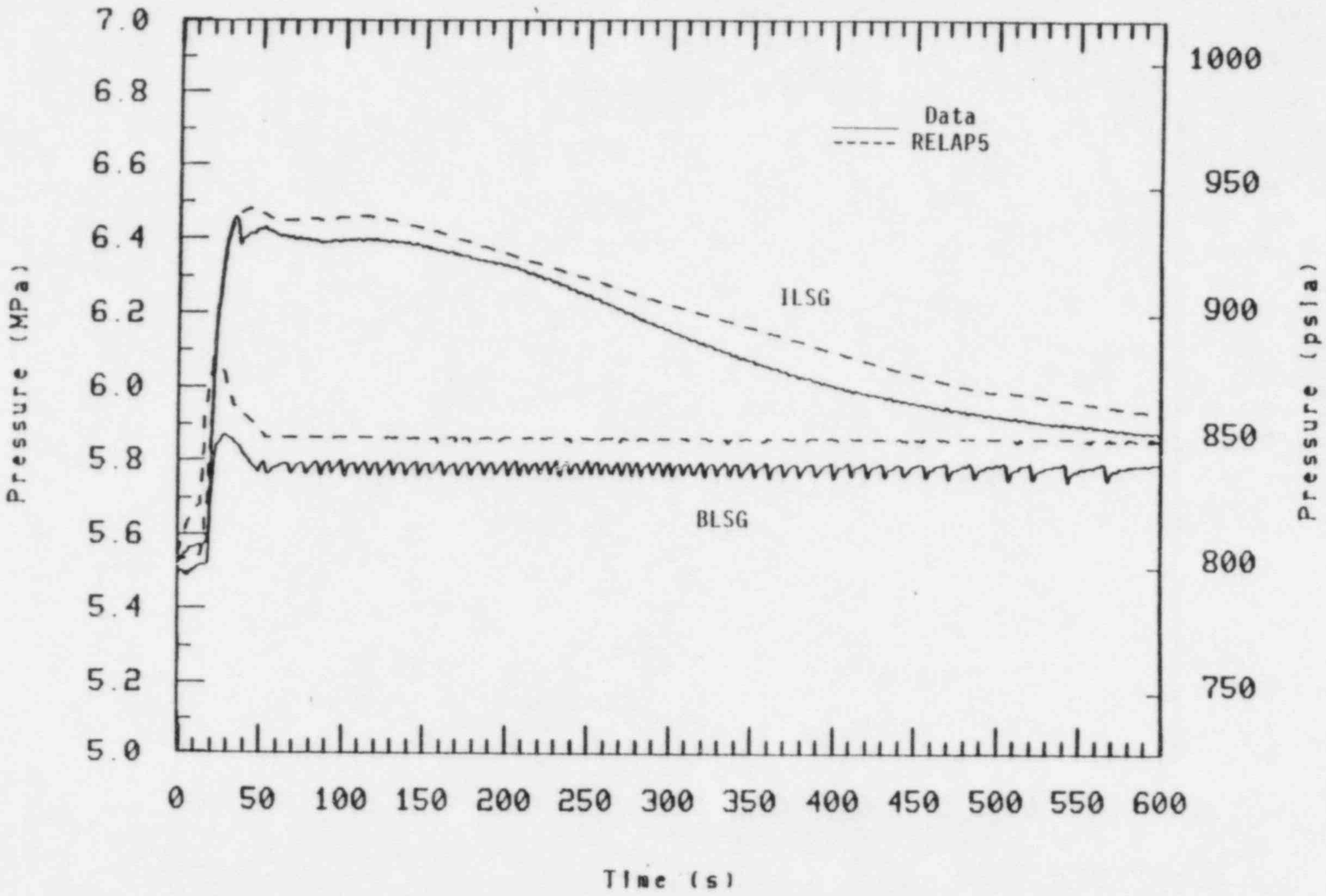

Figure 44. Phase 1 secondary pressure comparison.

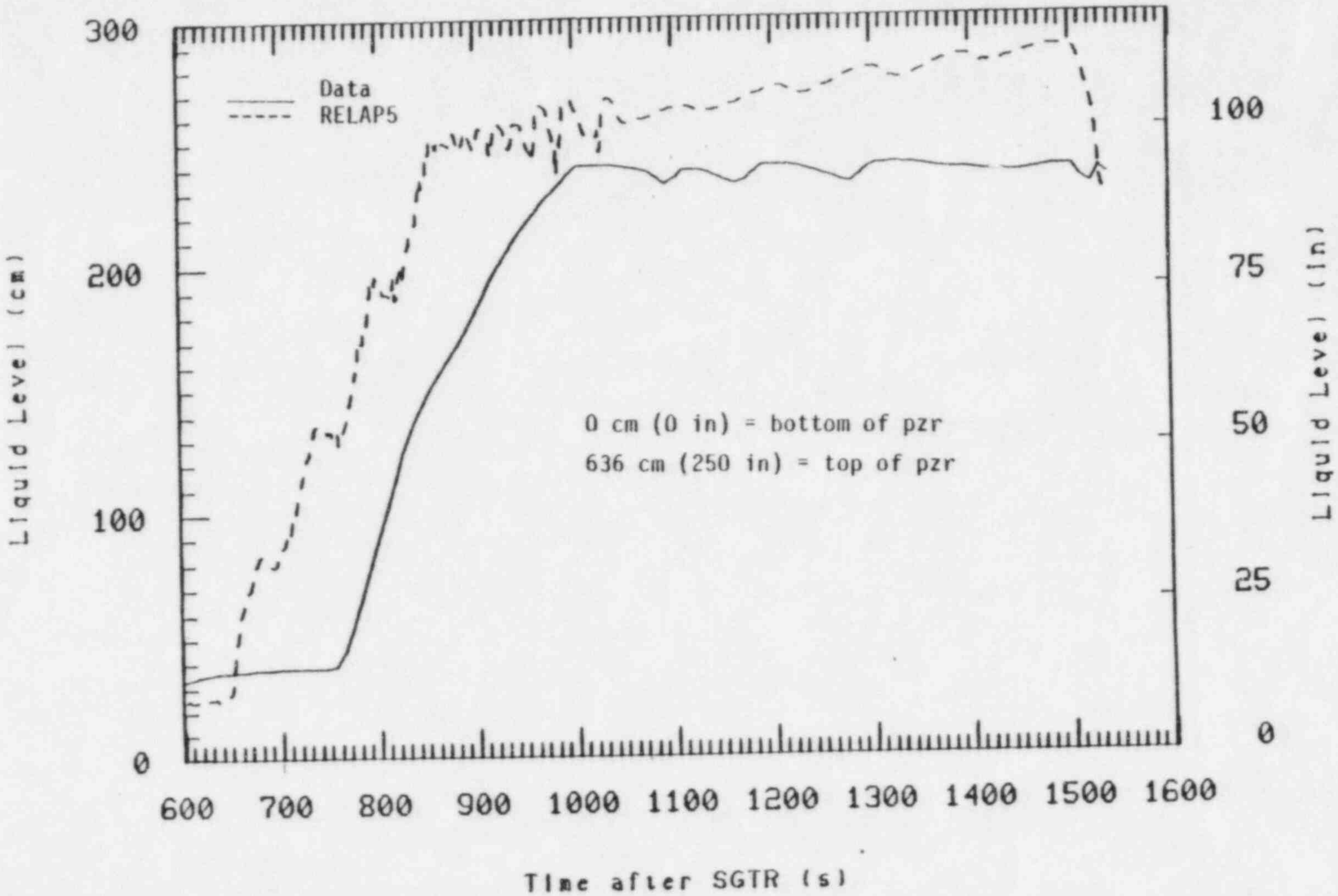

Figure 45. Phase 2 pressurizer liquid level comparison.

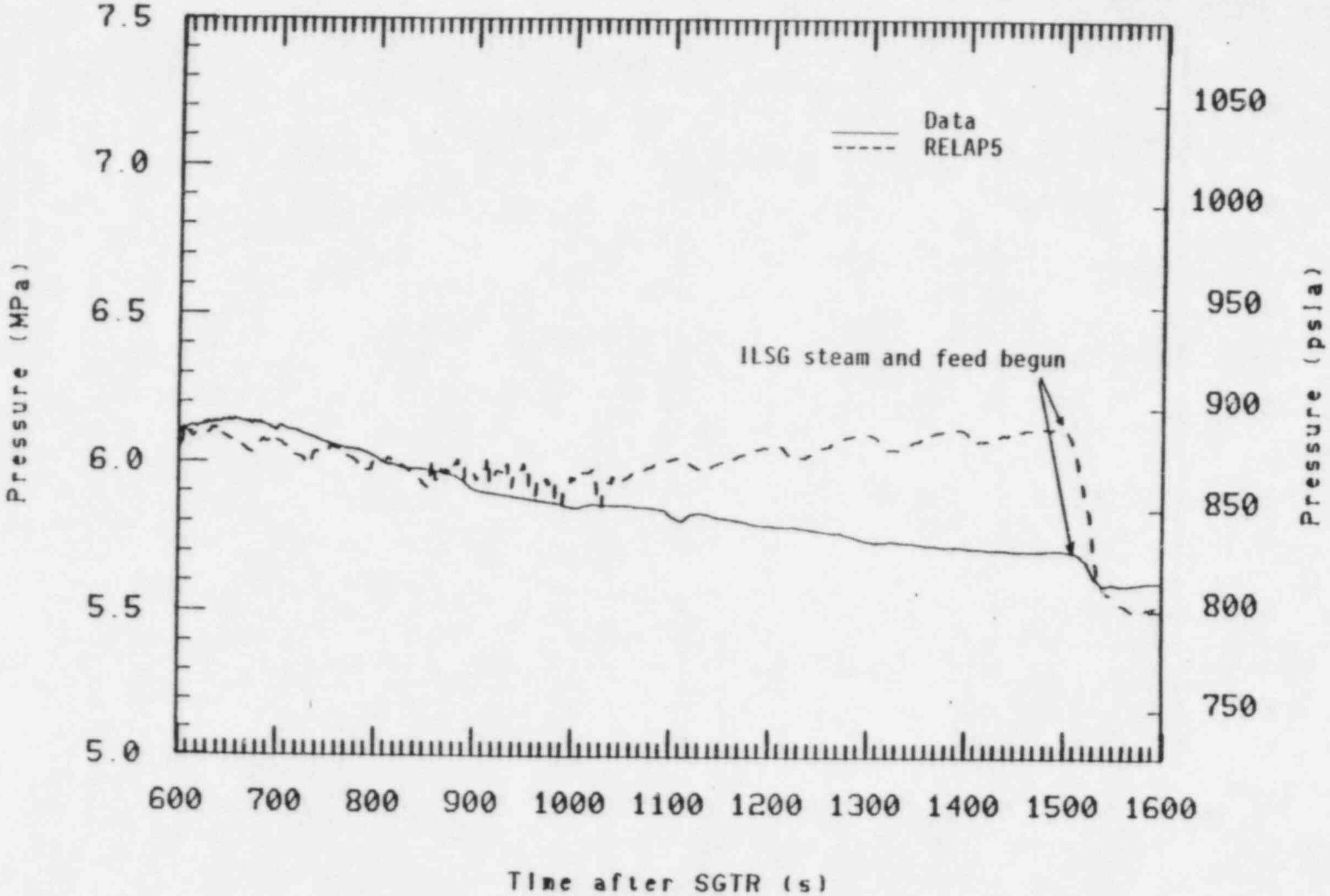

Figure 46. Phase 2 primary pressure comparison.

not maintain the 250 cm (98.4 in) level and spray cycled frequently between 1000 and 1500 s. This was due to the greater than calculated break flow. Those intermittant sprays caused the primary pressure to continue to decline whereas the calculation indicated a slight repressurization due to steam bubble compression.

At 1500 s, the primary pressure was greater than 5.6 MPa (812 psia) in both the calculation and test, thus, as per the experiment specification, ILSG feed and steam was started. Although the calculated primary pressure at 1500 s was higher than measured [6.1 MPa (884 psia) vs 5.7 MPa (826 psia)], the ILSG feed and steam operation reduced the primary pressure to the 5.6 MPa (812 psia) goal in approximately 40 s for both cases.

Another interesting phenomenon that occurred during the feed and steam operation was the calculated refilling of the core with liquid (primarily reverse break flow). During the test the core did not refill until the intact loop pump was restarted. It has been noticed in previous SG series tests that the code model is too responsive to the feed and steam operation, but, to date, a precise reason has not been determined. More intensive posttest investigation is planned.

4.3 Test Phase 3--Internal Pressurizer Heater Operation

During phase 3 of the test, the internal pressurizer heaters were to be operated such that the primary pressure would raise to 5.85 MPa (848 psia), thus subcooling the primary system. Beginning at approximately 1540 s for both the calculation and the test, the pressurizer heaters were activated to 2.4 kW (approximately 2.3 kW in the test).

The primary pressure response during this period is shown in Figure 47. The calculated primary pressure fell to approximately 5.5 MPa (798 psia) due to the residual effect of the ILSG feed and steam operation. By approximately 1560 s, the pressurizer heaters were successfully repressurizing the system and at 1734 s, the primary pressure had increased to 5.95 MPa (848 psia). During the test, however, the internal pressurizer heaters were able to maintain the pressure at the

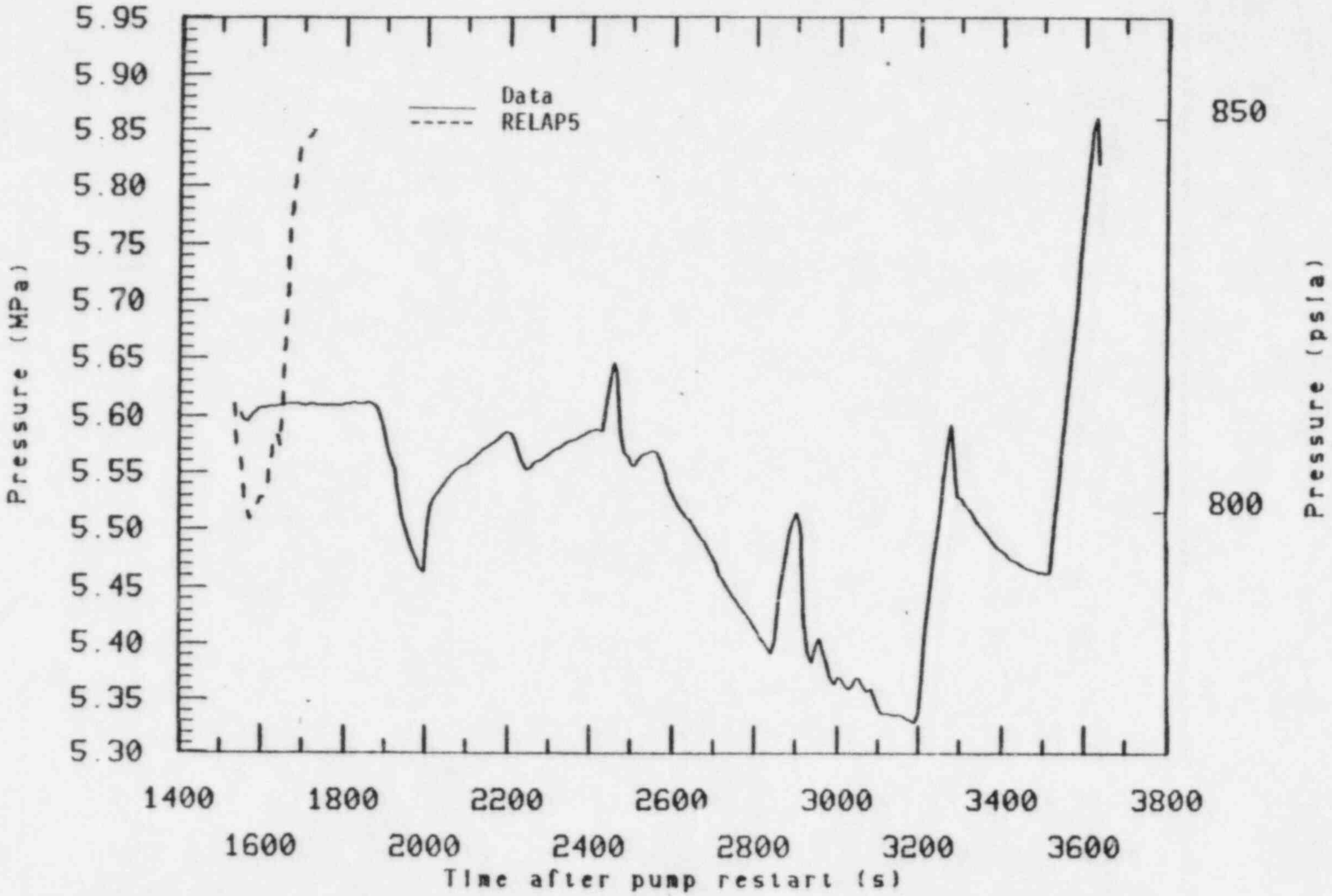

Figure 47. Phase 3 primary pressure comparison.

start of heater operation [approximately 5.61 MPa (814 psia)] but were unable to increase it significantly. At 1890 s the pressurizer auxiliary spray cycled on due to low pressurizer liquid level; that resulted in a primary pressure reduction. After numerous spray cycles and use of the warm-up pressurizer heaters (13.3 kW), the primary pressure was finally raised to 5.85 MPa (848 psia) at 3635 s. (See Section 3 for a detailed discussion of the measured primary pressure during that period of the test.)

The exact reason why the correct primary pressure response to the heater operation was not calculated is still unknown. The fluid temperature in the pressurizer was very close to the calculated value during this period, i.e., both were near the saturation temperature. One area to be investigated involves the effect of system heat loss. A hand calculation has indicated that the uncertainty associated with the system heat loss would be sufficient to cause a significant pressurizer level decrease due to system thermal shrinkage and thus negate the heaters effect. Comparison to other calculations also indicates that an interphase level dependence, i.e. the distance between the liquid/vapor interface and the heaters,[9] may exist within the model.

4.4 Test phase 4--Restart of the Intact Loop Pump

The intact loop pump was used to redistribute the primary fluid energy during this phase of the transient. In both calculation and test, the pump was operated at the steady state speed. The pressure response is shown in Figure 48. Initially following pump restart, the pressure responded closely as predicted. The more rapid calculated depressurization was due to the fact that the primary system had less volume voided (as mentioned above, the core did not refill until this time during the test). However, the minimum pressure reached was very well predicted. In addition, after reaching the minimum pressure, similar repressurization trends were established. Then, in the test, pressurizer auxiliary spray cycled on due to low pressurizer level and the primary pressure never recovered as it did in the prediction.

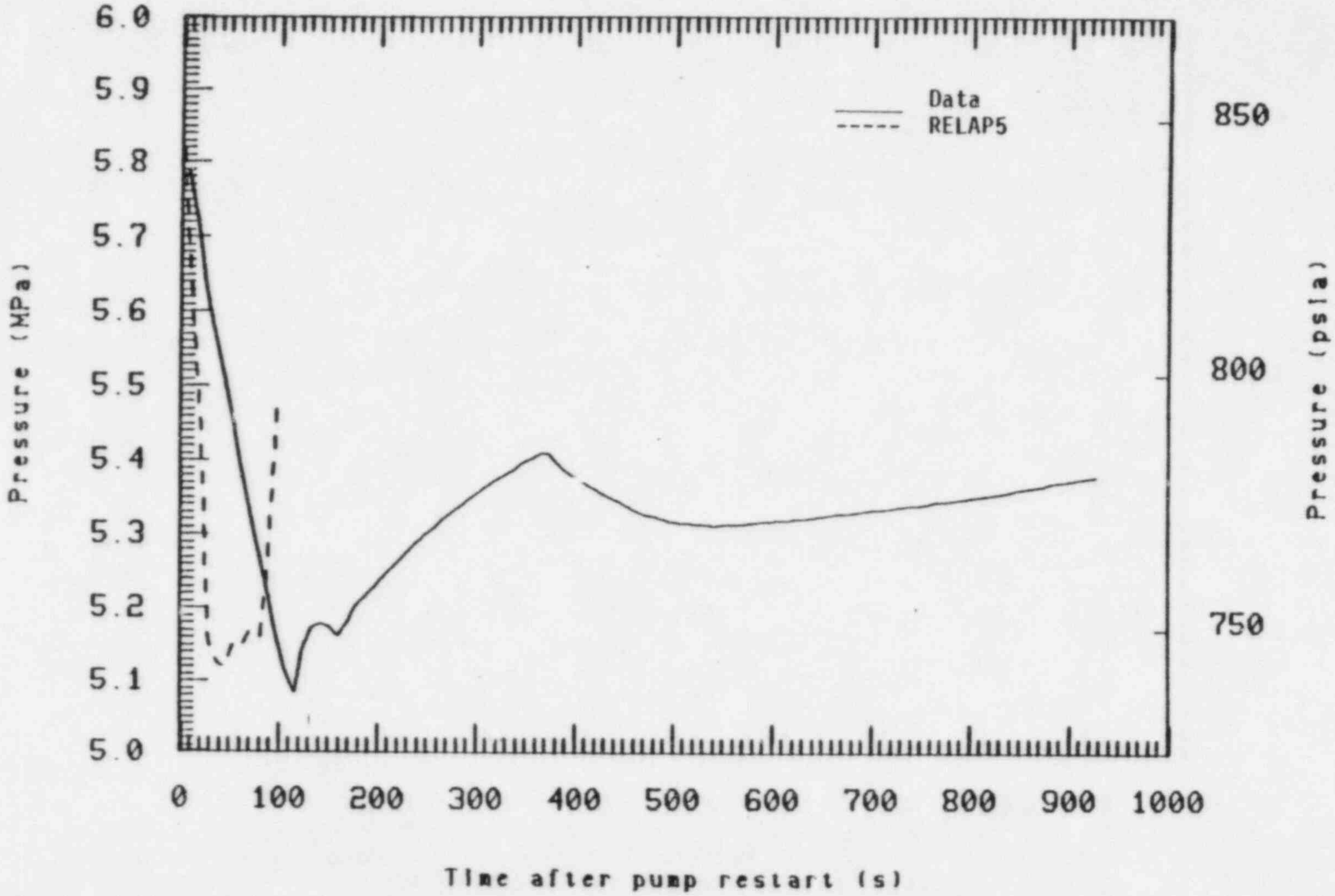

Figure 48. Phase 4 primary pressure comparison.

4.5 Test Phase 5--Subcooled Depressurization

Since different amounts time had elapsed to reach the beginning of phase 5, the parameters shown graphically have been shifted to show time after pump restart instead of time after break.

Phase 5 of this test was a subcooled depressurization using ILSG feed and steam. The ILSG ADV was latched open in an attempt to subcool the primary system by 39 K (70°F) after which time the internal pressurizer heaters, SI flow, and pressurize spray would all be cycled to depressurize the system at or below 575 Pa/s (25 psid/5 min).

The primary pressure comparison for this phase is shown in Figure 49. After the ILSG ADV was latched open, the calculation indicated a slight repressurization would occur, but, it did not as the primary pressure remained relatively constant. Note that even though the ILSG was under feed and steam operation, neither the calculation or test showed a primary depressurization. The reason for this is that the only steam in the primary system was in the pressurizer; thus any primary pressure reduction would result in reverse break flow, compress the vapor space in the pressurizer, and repressurize the primary fluid. Under these conditions, ILSG steam and feed will only subcool the primary, not depressurize it. The depressurization occurs only through environmental heat loss.

Another example of the over-effectiveness of ILSG feed and steam using the current Semiscale model can also be seen in Figure 49. Under comparable primary and secondary conditions, only 500 s was required (by calculation) to subcool the primary whereas, in actuality, over 2150 s was required. It should be noted that the intermittent cycling of the pressurizer auxiliary spray during the subcooling period had a noticeable effect on the ability to achieve the desired level. As the subcooling increased, spray would cycle on (based on pressurizer liquid level), cause a small depressurization, and thus a loss of subcooling.

From the time that the subcooling criterion was reached until the end of the test, comparable primary pressure response was obtained between the

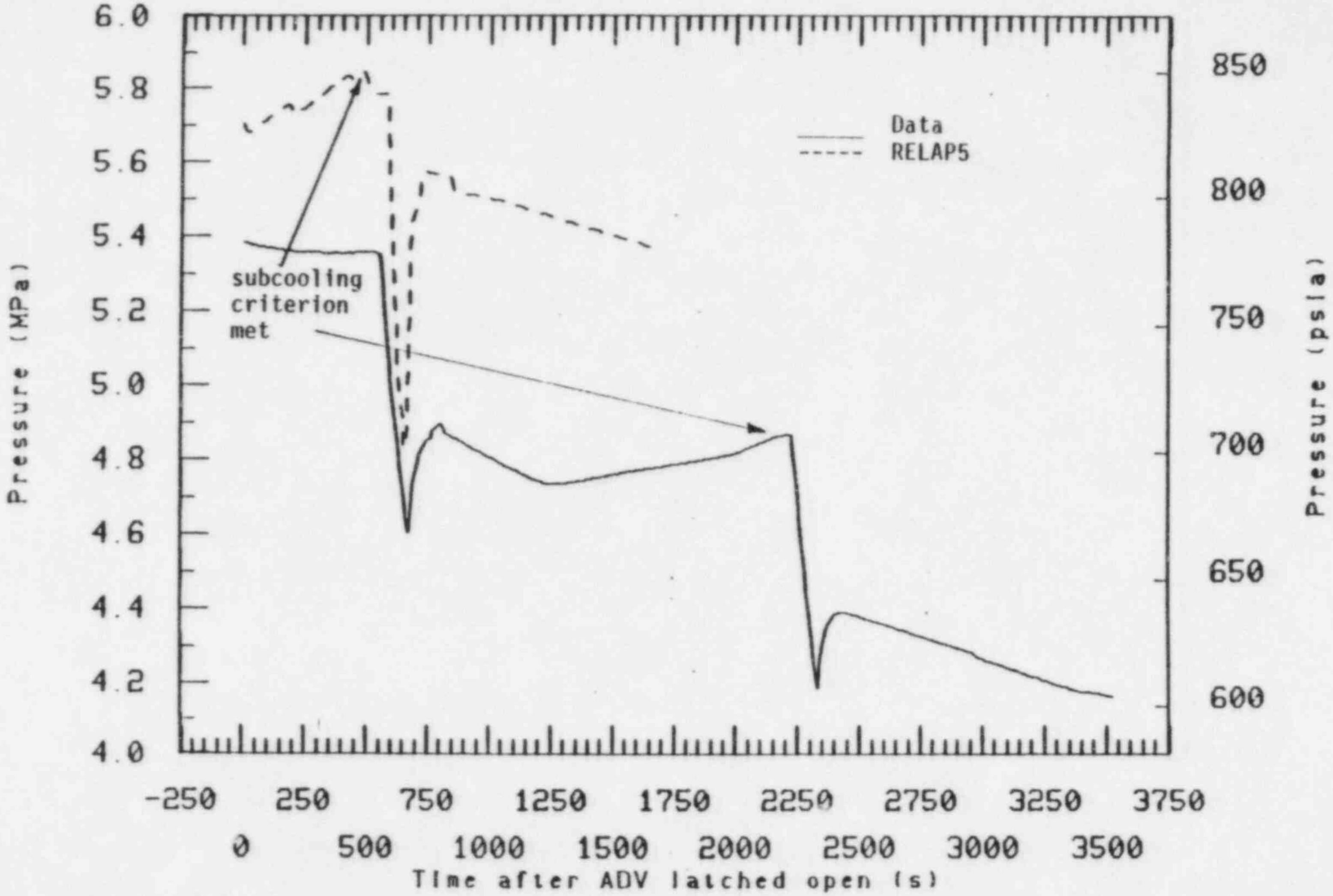

Figure 49. Phase 5 primary pressure comparison.

calculation and test. Upon reached 39 K (70°F) hot leg subcooling [37.2 K (67°F) in the test] the internal pressurizer heaters were turned off until the pressurizer pressure began decreasing too rapidly, which it did almost immediately in both the calculation and test. Once the heaters were repowered, the depressurization was slowed to a value less than the maximum in both the calculation and the test.

Following 1200 s under these conditions, the calculation and test were both terminated. The calculated and measured chronology of events are summarized in Table 4.

In summary, the accident signature was very well predicted by the code. The primary response during pressurizer auxiliary spray use was also well predicted; however, problems appear to exist with the Semiscale model used in these calculations that preclude calculating the correct response to internal pressurizer heater use. The failure to include accurate break form losses in the calculation also prevented some of the observed phenomena from being calculated, i.e., fewer calculated spray cycles were necessary due to the lower calculated break flow.

TABLE 4. CALCULATED AND MEASURED CHRONOLOGY OF EVENTS

Event	Time (s) Calculation	Test
Break initiated	0.0	0.0
SCRAM [P_p = 13.1 MPa (1900 psia)] Main steam valves began to close	13.5	16.4
SIS [P_p = 12.51 MPa (1814 psia)] Feedwater terminated Auxiliary feedwater began to ILSG SI initiated Primary pumps trip	15.9	17.1
Plant recovery began Pressurizer auxiliary spray on	600.0	600.0
ILSG feed and steam began to reduce P_p to 5.6 MPa	1500.0	1500.0
Primary pressure at 5.6 MPa (phase 2 ended) Pressurizer internal heaters on Vessel refilled	1536.4	1450.0
P_p = 5.85 MPa (phase 3 ended) Intact loop pump restarted at steady state speed	1734.0	1734.0
P_p = 5.6 MPa (phase 4 ended) ILSG ADV latched open to subcool primary	1837.0	4567.0
38.9 K (70°F) hot leg subcooling achieved SI, pressurizer spray and heaters all cycled off	2334.0	6730.0
Calculation terminated on 1200 s criteria	3534.0	7930.0

5. CONCLUSIONS

The following conclusions were derived based on a preliminary analysis of test S-SG-3 experimental results.

1. The signature response in the first 600 seconds of a 10-tube rupture in the Semiscale system is similar to both a 5 and 1 tube rupture with mainly the timing of events being different. The primary system depressurization rate for the early tube rupture (prior to core scram) is approximately proportional to the break size. The most signficiant difference between a 10 tube rupture and 5 and 1 tube rupture is the relationship of break flow and SI flow. Vessel voiding was increased as the number of tubes ruptured increased.

2. In the Semiscale system with a 10-tube rupture, pressurizer auxiliary spray alone can lower the primary pressure below the broken loop secondary ADV setpoint thus isolating the broken loop generator from atmospheric release. Pressurizer auxiliary spray when combined with intact loop ADV operation can further reduce the primary pressure margin below the broken loop ADV setpoint.

3. In the Semiscale system with a 10-tube rupture, the combined methods of pressurizer auxiliary spray and internal heater operation, intact loop pump flow, safety injection, and intact loop secondary feed and steam was successful in first subcooling the primary fluid and then causing a slow primary depressurization at a predetermined rate. The subcooling was accomplished primarily by intact loop primary to secondary heat transfer as the latched open ADV caused a secondary depressurization. The slow depressurization was accomplished primarily by using pressurizer internal heater operation and continued intact loop feed and steam.

4. The accident signature and the response to pressurizer auxiliary spray was well predicted by RELAP5. The calculated response to the internal pressurizer heaters and intact loop pump restart were not well predicted in part due to the low calculated break flow which resulted in fewer pressurizer spray cycles during the calculation.

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16. ABSTRACT (200 words or less)

Results of a preliminary analysis of the sixth test performed in the Semiscale Mod-2B Steam Generator Tube Rupture Series are presented. Test S-SG-3 simulated a pressurized water reactor accident initiated by a double-ended offset shear of ten cold side steam generator tubes. The transient was characterized by five distinct phases of operation. Phase 1 involved an initial 600 s period during which only automatic plant protection system response to the initiating event occurred. Phase 2 included an operator induced recovery involving pressurizer auxiliary spray to reduce system pressure below broken loop ADV setpoints. This pressure reduction was aided by intact loop generator feed and steam. Phase 3 involved using pressurizer heaters to subcool the system by increasing primary pressure. Phase 4 used the intact loop pump to redistribute the system fluid energy and promote core cooling. Finally, phase 5 involved a combination of pressurizer spray, intact loop pump flow, SI, pressurizer heaters, and intact loop generator feed and steam to establish a subcooling margin and to slowly depressurize the primary system. These procedures were all accomplished without sufficient core uncovery to cause a core rod heatup.

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