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QUICK LOOK REPORT FOR SEMISCALE MOD-2B TEST S-SG-6

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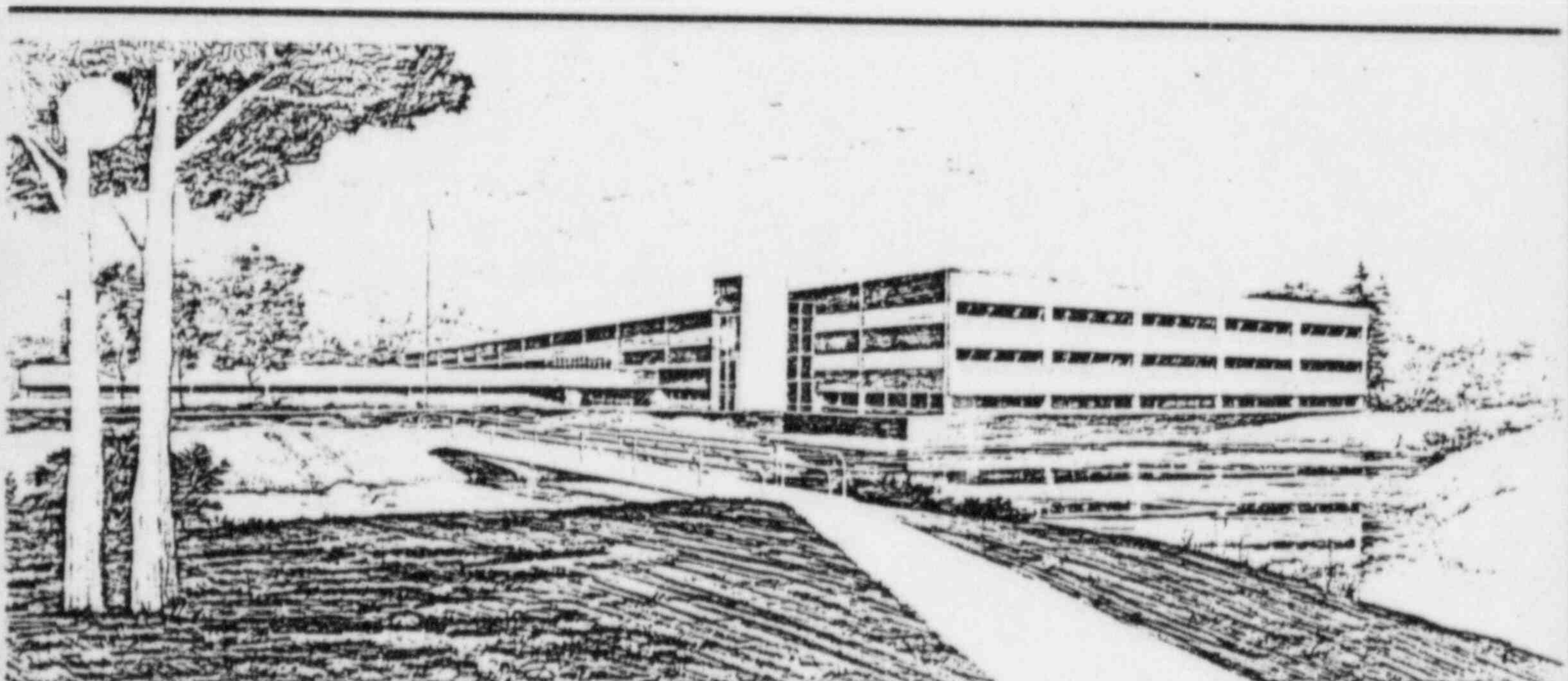

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QUICK LOOK REPORT FOR SEMISCALE MOD-2B
TEST S-SG-6

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ABSTRACT

Results of a preliminary analysis of the eighth test performed in the Semiscale Mod-2B Steam Generator Tube Rupture Series are presented. Test S-SG-6 simulated a pressurized water reactor accident initiated by a double-ended offset shear of five hot side steam generator tubes. Early operator identification of the tube rupture transient was assumed to occur 60 s after core scram. At t = scram + 60 s operator action included latching open both steam generator atmospheric dump valves (ADV's) in an attempt to depressurize the primary system pressure below the steam generator ADV setpoints. An additional operator action was to initiate pressurizer spray at t = scram + 120 s. At t = 600 s it was assumed that the operators identified which steam generator had the tube rupture (in Semiscale, the broken loop) and an attempt was made to terminate broken loop auxiliary feed and close the broken loop atmospheric dump valve (ADV). The unique problem posed by S-SG-6 was that the broken loop ADV once latched opened was assumed to stick open for the remainder of the transient. However the auxiliary feed water to the broken loop was terminated at t = 600 s. The intact loop ADV and pressurizer auxiliary spray were operated to stimulate a slow primary cooldown and depressurization to the low pressure injection system pressure setpoint 1.38 MPa (188 psig). These procedures were all accomplished while maintaining the vessel liquid level at least 40 cm (16 in) above the top of the core.

SUMMARY

This report presents a preliminary analysis of the Semiscale Mod-2B Steam Generator Tube Rupture Series (SG) test S-SG-6. S-SG-6 was 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. The test 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, recovery procedures, and provide data to assess computer code capability.

Test S-SG-6 was designed primarily to investigate the effectiveness of operator response to reduce the primary pressure to the low pressure injection pressure setpoint with a stuck open broken loop atmospheric dump valve (ADV) during a five-tube rupture transient. At 60 s after scram, operator identification of a tube rupture transient was assumed. However, at first, no knowledge of which steam generator suffered the tube rupture was assumed. To reduce primary system pressure below the steam generator ADV pressure setpoint (thus isolating the affected generator from atmospheric release) both the intact and broken loop ADV's were latched open at t = scram + 60 s. At t = scram + 120 s auxiliary pressurizer spray was activated to further aid the primary pressure reduction. At t = 600 s it was assumed that the operators identified which generator had the tube rupture (broken loop generator in Semiscale). At this time, the auxiliary feedwater was terminated and the broken loop generator ADV which would normally have been closed was assumed to remain latched open for the remainder of the transient. Using only safety injection (SI), intact loop generator feed and steam (latched open ADV), and pressurizer auxiliary spray, an attempt was made to reduce the primary pressure to the low pressure injection setpoint thus reducing release of broken loop secondary fluid to atmosphere through the stuck open ADV.

The five-tube rupture signature early in time (prior to operator identification 0 to 94 s) 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 the early period were core scram and main steam isolation valve (MSIV) closure. Secondary pressure during this early period increased rapidly in both loops due to primary-to-secondary heat transfer 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. Only minor voiding of the vessel occurred during the first 94 s [30 cm (12 in) below the top of the vessel].

The overall effect on primary pressure of early operator action in opening the intact and broken loop ADV's and use of auxiliary pressurizer spray was small. The main effect early in time (94 to 600 s) was to remove superheat from the pressurizer fluid and walls due to pressurizer auxiliary spray and to cool the loop due to primary to secondary heat transfer from the secondary steam and feed operations. Voiding in the loop and vessel caused by a higher break flow than SI flow eventually lead to a transition from single phase natural circulation to two-phase natural circulation with a resulting increase in primary to secondary heat transfer which stimulated primary depressurization.

At t = 600 s it was assumed the operator identified which generator had the tube rupture (the broken loop in Semiscale) and an attempt was made to close the broken loop ADV but failed. The broken loop ADV remained latched open for the remainder of the transient but auxiliary feedwater was terminated. For the remainder of the transient, pressurizer auxiliary spray and intact loop steam and feed were used to stimulate a primary depressurization.

The operator response of using intact loop ADV feed and steam and pressurizer auxiliary spray operations with a stuck open broken loop ADV (600-8181 s) was sufficient to reduce the primary pressure to the LPIS setpoint pressure [1.38 MPa (188 psig)]. Intact loop ADV operation was

useful for cooling the loop fluid and causing a general slow primary depressurization due to fluid shrinkage. Also during this period, pressurizer auxiliary spray was effective in stimulating the primary depressurization due to pressurizer fluid void collapse from the condensation process. For any given spray cycle, once spray was stopped on a high pressurizer level trip, (spray was cycled on and off on pressurizer level) the relatively rapid primary depressurization provided by the condensation process was stopped. If the combination of pressurizer auxiliary spray and intact loop ADV operation were correctly aligned (both off at the same time), the primary pressure actually increased. This increase in primary pressure was caused by a sequence of events starting with closing the intact loop ADV on a low secondary level trip. Eventually, the loss of heat sink caused a cessation of the existing two-phase natural circulation flow in the intact loop (complete stagnation of flow) which lead to a primary pressure increase and an increase in pressurizer level due to expansion of system fluid from core decay heat. Eventually, natural circulation flow restarted in the broken loop due to bridging of fluid in a blocked generator tube. This restart of broken loop flow started removing core decay heat via primary to broken loop secondary heat transfer and the primary pressure decreased. The entire recovery procedure of reducing the primary pressure to LPIS setpoints was accomplished while maintaining the collapsed vessel level no lower than 40 cm (16 in) above the top of the core.

Comparison of hot side and cold side five tube rupture transient experiments early in time show almost identical results. Test S-SG-6 (hot side-five tube rupture transient) and test S-SG-7 (cold side-five tube rupture transient) showed close agreement for such parameters as primary pressure, pressurizer level, loop flow, and break flow.

The system response during the operator diagnostic period was well predicted by RELAP5. The break flow and the system depressurization rates during the recovery period were not well calculated resulting in poor agreement of event timing.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

This reports documents preliminary results from Semiscale Mod-2B test S-SG-6, the eighth experiment performed in the Semiscale Steam Generator Tube Rupture (SG) Test Series.[1] Test S-SG-6 was performed March 7, 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-6 simulated a pressurized water reactor transient initiated by a double-ended offset shear of five hot side steam generator tubes. The test simulated a five tube rupture transient with a recovery scenario assuming a stuck open broken loop ADV. The scenario consisted of both automatically occurring events and operator actions. Automatically occurring events included core scram, main steam isolation valve closure, termination of main feedwater, auxiliary feedwater initiation, coastdown of the main coolant pumps and start of safety injection. Early operator identification (t = scram + 60 s) was assumed, and at this time, both steam generator ADVs were latched open to maximize the primary depressurization rate to below the ADV setpoint pressure thus isolating the affected generator from atmospheric release. At t = scram + 120 s, pressurizer auxiliary spray was initiated to aid in decreasing the primary pressure. At t = 600 s it was assumed that the operators had identified which generator had the tube rupture and the operator action was to attempt to isolate that generator from atmospheric release (close the broken loop generator ADV and terminate auxiliary feedwater). In the experiment, auxiliary feedwater was secured but the broken loop ADV was assumed to fail

open and was left open for the remainder of the transient. A combination of intact loop feed and steam (latched open ADV with auxiliary feedwater), SI, and pressurizer auxiliary spray were used to slowly reduce the primary pressure to the low pressure injection system setpoint pressure. This action was designed to lower the differential pressure between the primary and broken loop secondary and thus reduce the potential for atmospheric release via the stuck open ADV. It was assumed that the operator bypassed accumulator flow, therefore no accumulator injection was used for S-SG-6.

A preliminary analysis of test S-SG-6 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

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a. For test S-SG-6, only 21 rods were powered.

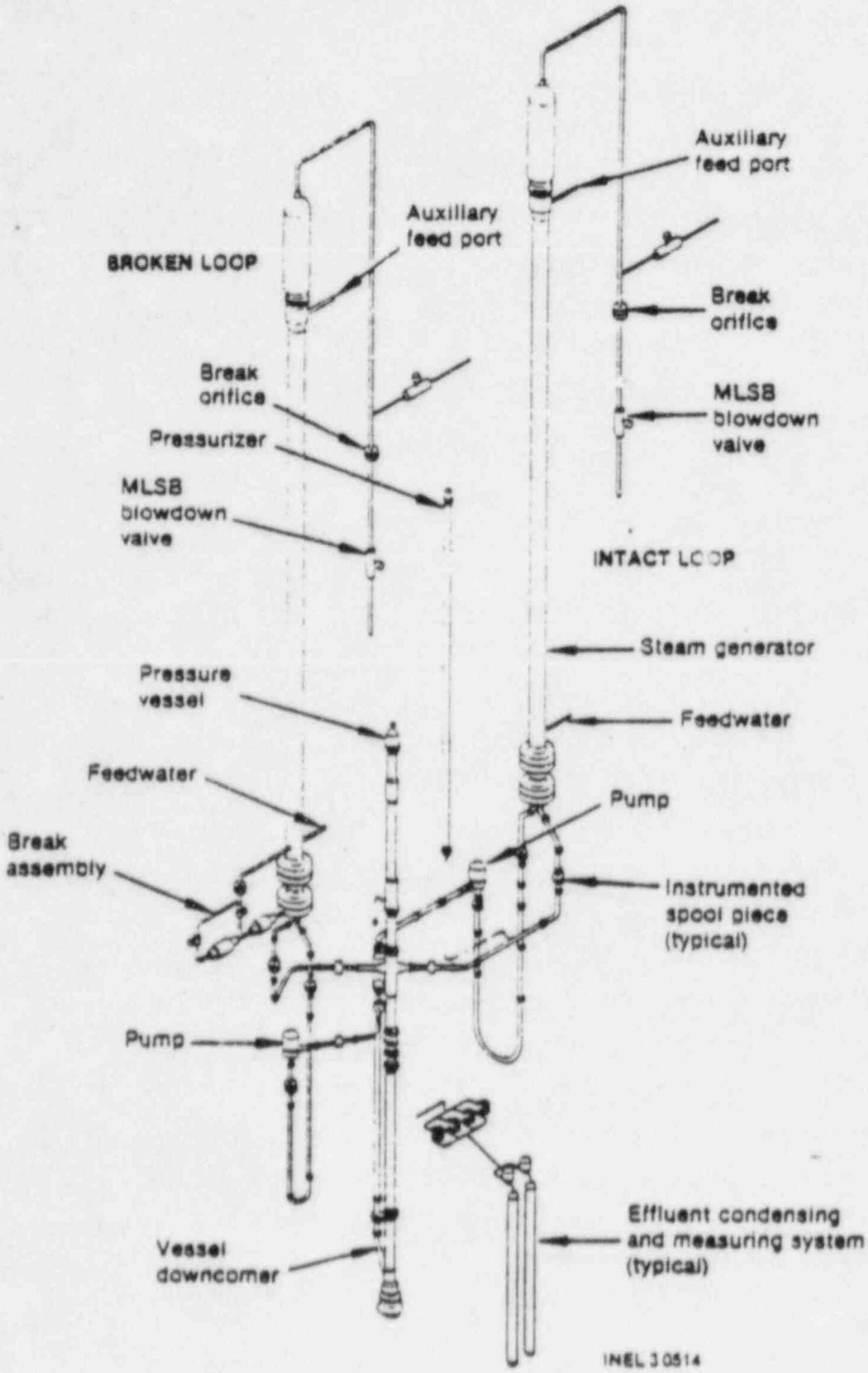

Figure 1. Semiscale Mod-2B system as configured for the SG test series.

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 (848 psia) in the broken loop and 6.55 MPa (950 psia) in the intact loop. The first stage SRV relief setpoint is 5.94 MPa (861 psia) in the broken loop and 6.74 MPa (978 psia) in the intact loop.[a] Figures 3 and 4 show mass flow rate versus pressure for ADV and SRV operation for the broken and intact loops, respectively. The ADV can also be manually latched open during the recovery procedure with the SRV block valve shut.

The pressurizer PORV[b] provides a means of manually relieving primary system pressure from the top of the pressurizer. Semiscale uses a single valve with a flow control orifice to simulate the two PORVs of a full scale PWR. A 0.141 cm (0.055 in.) sharp edged orifice was sized to pass 0.03 kg/s (0.069 lb/s) at 16.2 MPa (2350 psia). The scaling criteria are presented in Appendix A of Reference 1. The pressurizer surge line hydraulic resistance was 1.8×10^{9} m^{-4} for test S-SG-6. Pressurizer internal heaters can be operated in the variable mode, backup mode or warmup mode. The variable and backup mode total power is 2.35 kW and the

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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-6.

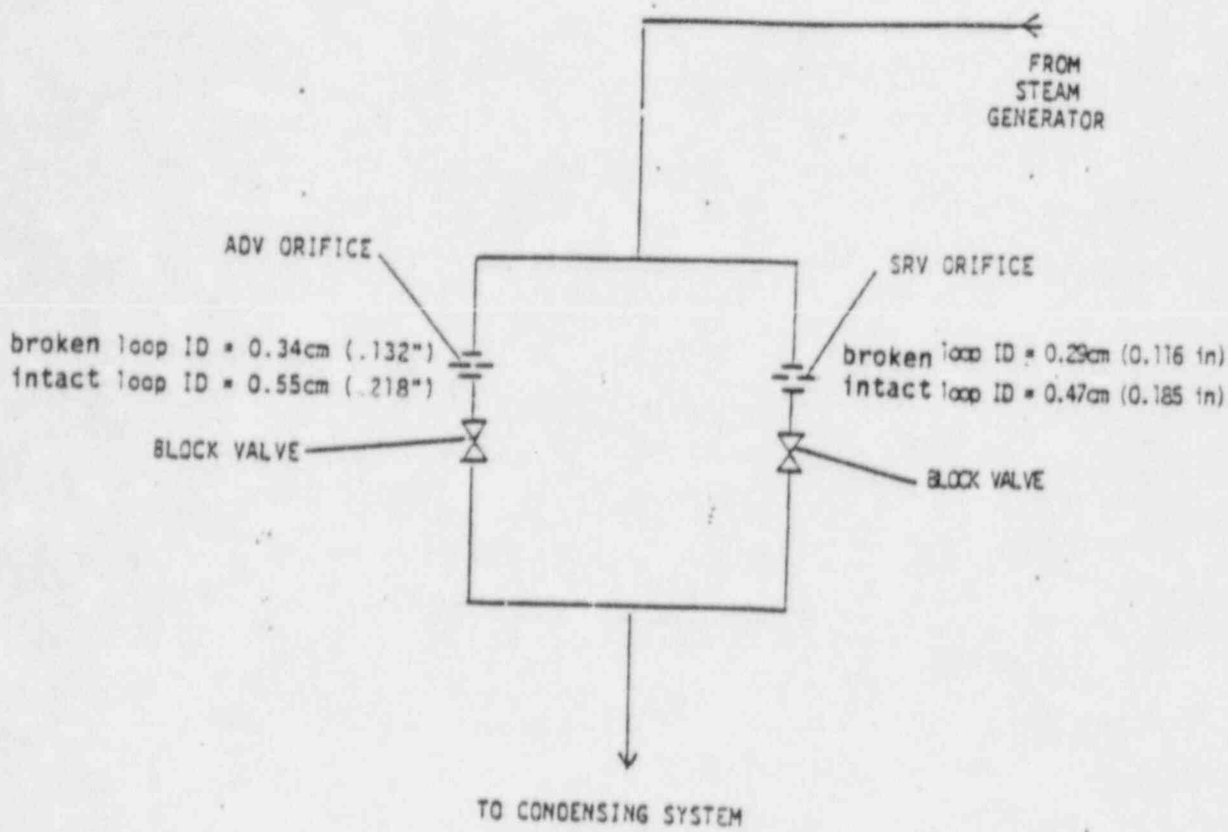


Figure 2. ADV and safety relief valve system.

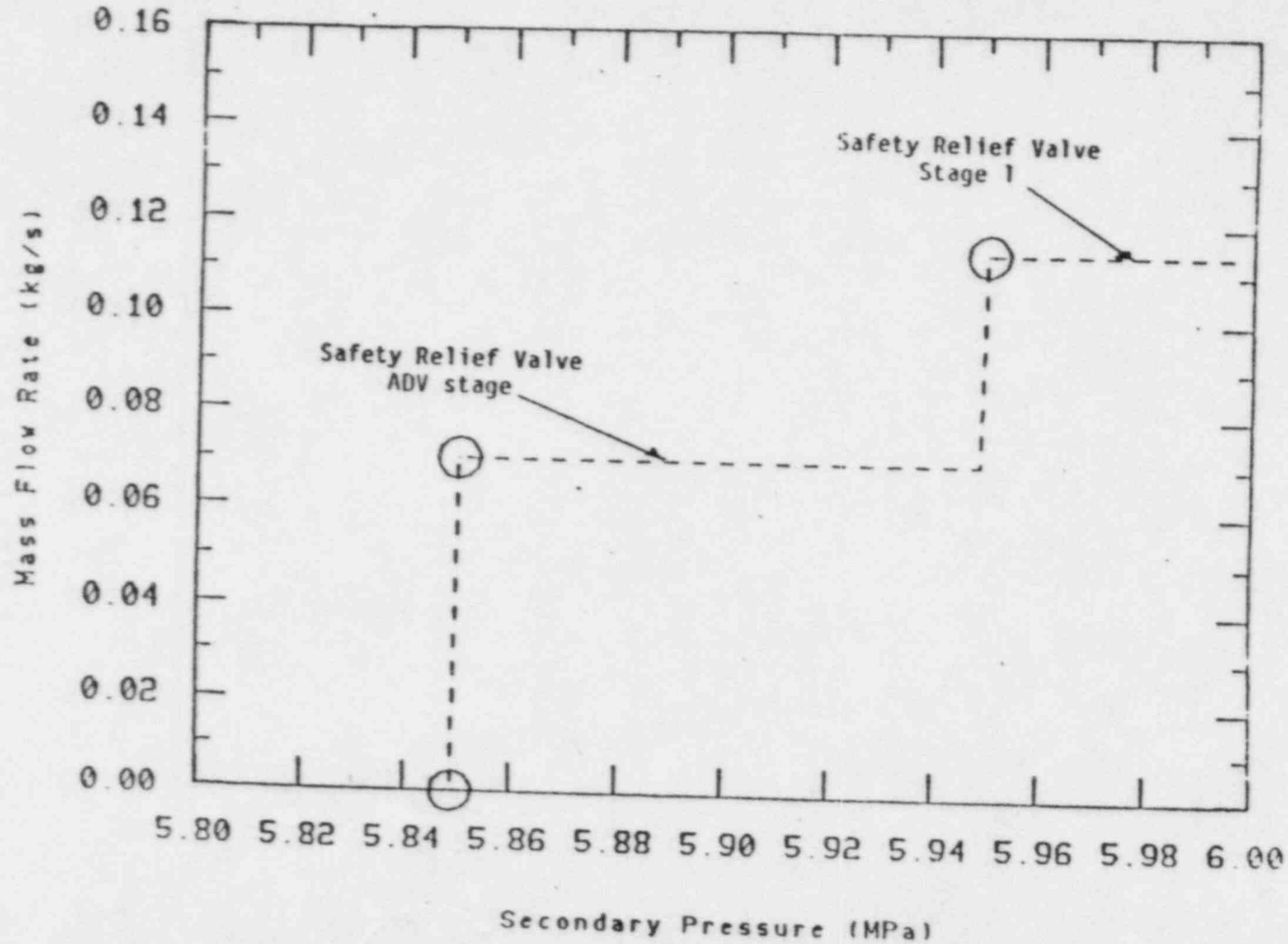


Figure 3. Broken loop steam generator safety relief valve operation.

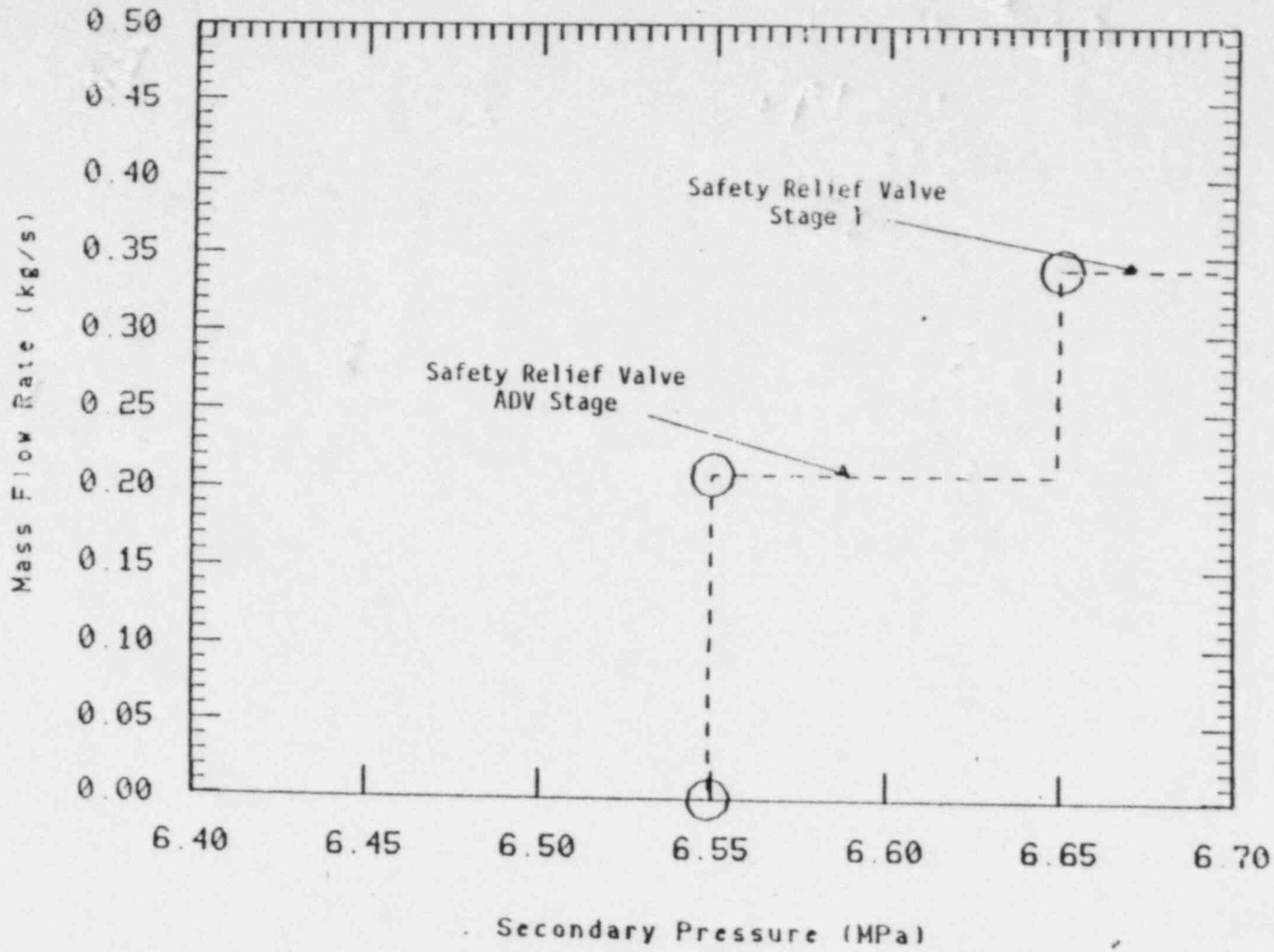


Figure 4. Intact loop steam generator safety relief valve operation.

warmup mode is 13.3 kW. Pressurizer internal heaters were not used during S-SG-6. 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. For test S-SG-6 the break assembly was on the hot leg side of the primary. 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. 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-6 used the 5 tube break orifice with a 0.175 cm (0.069) in.) ID. The flow tube was calibrated in single phase water and can be used to monitor break mass flow rate in both directions because of the symmetry of the flow tube.

Heat loss makeup in the Semiscale system is accomplished by using external heaters distributed fairly uniformly throughout the Semiscale system. These heaters are controlled by six separate power supplies including: vessel, hot legs, cold legs, intact loop pump suction, broken loop pump suction, and pressurizer. The total power provided by these heaters is 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-6. Power to the vessel upper head and upper vessel heater banks were controlled as follows: when the hot collapsed liquid level as measured by LV+421-13M reached 20% of the

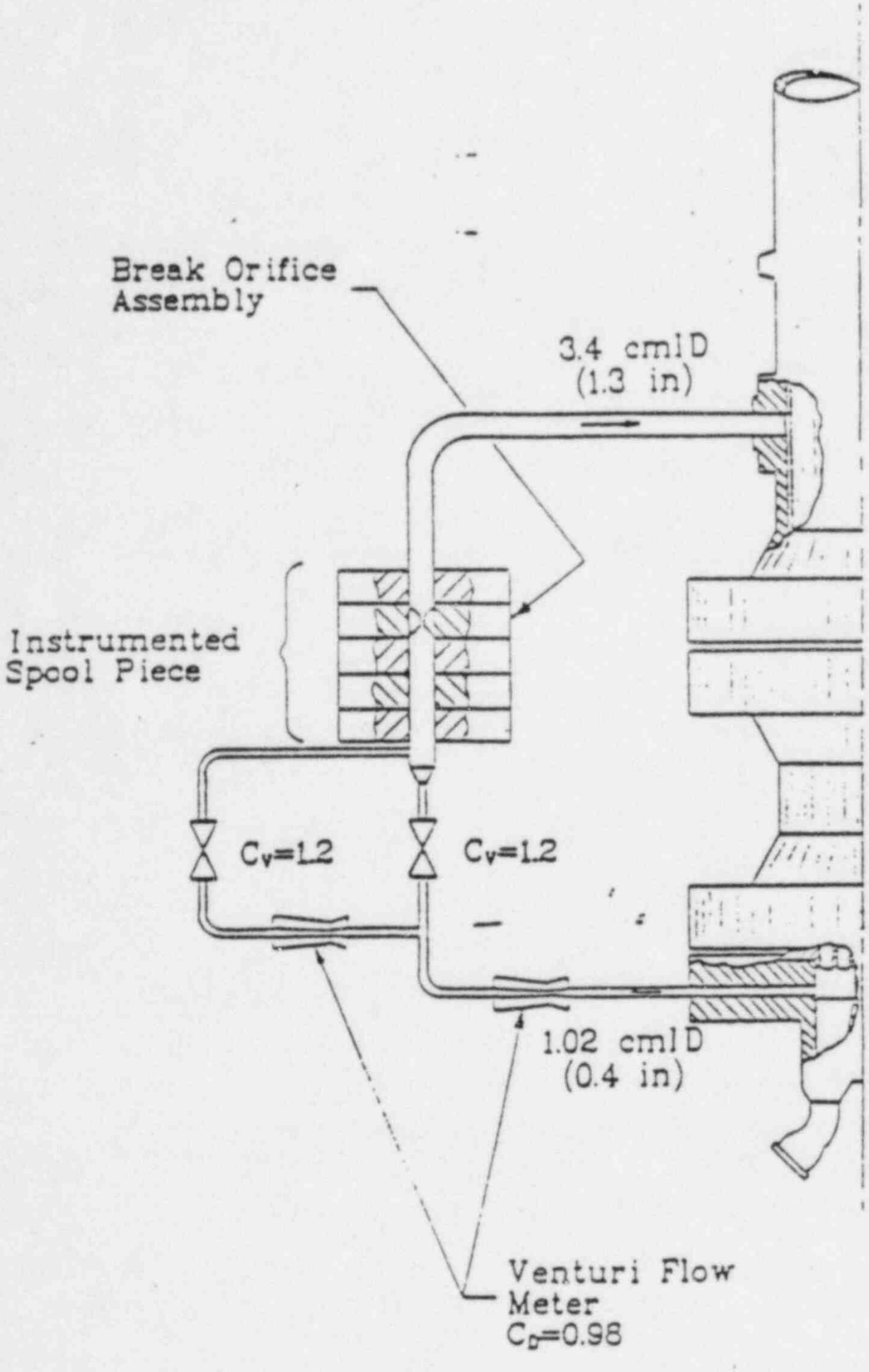
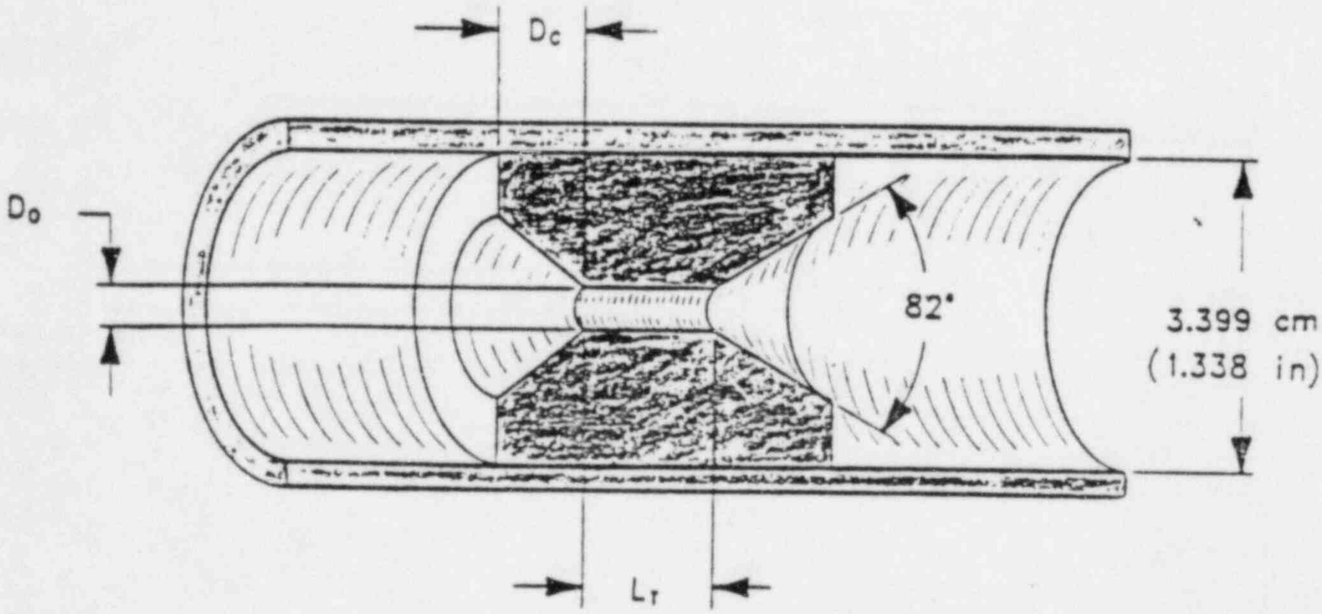


Figure 5. Semiscale tube-rupture break assembly.



TUBE RUPTURE	Do		LT		Dc	
	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.

span of either the vessel upper head or upper vessel external heaters, power was terminated. Once the power to a vessel heater bank was terminated it was not reinitiated.

2.2 Test Conduct

The system was filled with demineralized water and vented to ensure liquid full conditions. 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-6 consisted of both 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-6. Automatically occurring events included 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 (1900 psia)] and SI signal [12.51 MPa (1813 psia)]. Power to the pressurizer internal and external heaters were terminated at t = 0.

Test S-SG-6 involved early operator identification of the tube rupture transient (t = scram + 60 s). At t = scram + 60 s both the intact and broken loop ADVs were latched open and for the first 600 s the auxiliary feedwater was operated to control the hot collapsed liquid level between 800 and 1050 cm (315 and 414 in.) from the top of the tube sheet. At t = scram + 120 s pressurizer auxiliary spray was initiated [at 13.75 g/s (0.029 lbm/s)]. The pressurizer spray was operated to maintain the hot collapsed pressurizer liquid level between 75 and 250 cm (30 and 98 in.). If the level reached 250 cm (98 in.) the spray was terminated until the level dropped to 75 cm (30 in.). These two actions were designed to bring the primary pressure below the broken loop secondary ADV setpoint [5.85 MPa (848 psia)] as quickly as possible. For the first 600 s it was assumed that the operator knew a tube rupture had occurred but did not know which

TABLE 1. INITIAL CONDITIONS FOR TEST S-SG-6

	Specified	Measured
Pressurizer pressure	15.6 ± 0.14 MPa (2264 ± 20 psia)	15.68 MPa (2274 psia)
Pressurizer liquid volume	0.0102 ± 0.0008 m^3 (0.36 ± 0.028 ft^3)	0.0097 m^3 (0.34 ft^3)
Core power	2.00 ± 0.01 MW	1.99 MW
Loop to loop cold leg fluid temperature differential	2.0K (3.6°F)	0.3K (0.54°F)
Core fluid temperature rise	37.0 ± 1.5K (66.6 ± 3°F)	37.9K (68.2°F)
Steam generator pressure		
Broken loop	5.55 ± 0.07 MPa (805 ± 10 psia)	5.62 MPa (815 psia)
Intact loop	5.55 ± 0.07 MPa (805 ± 10 psia)	5.56 MPa (806 psia)
Steam generator secondary fluid mass[a]		
Broken loop[b]	100 + 40 - 20 kg (220 + 88 - 44 lbm)	96.6 kg (213 lbm)
Intact loop[c]	100 + 40 - 20 kg (220 + 88 - 44 lbm)	88 kg (194 lbm)
Steam generator feedwater temperature		
Broken loop	505 ± 3 K (450 ± 6°F)	505 K (450°F)
Intact loop	505 ± 3 (450 ± 6°F)	508 K (456°F)
Primary leakage	<0.0060 kg/s (<0.0132 lbm/s)	0.0033 kg/s (0.0073 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-6

Specified Criteria	Actual Time(s)	Event
	Phase 1	
0 s	0	Break flow initiated
P_{PRZ} = 13.1 MPa (1888 psig)	33.9	SCRAM
SCRAM	34.6	Core power on ANS decay curve
SCRAM	34.4	MSIV closure
P_{PRZ} = 12.5 MPa (1803 psig)	36.5	SIS
SIS	36.7	Main feedwater secured
SIS	37.4	Auxiliary feedwater initiated
SIS	38.5	Pumps off
SIS	37.4	Safety injection on
t = scram + 60 s	94	Intact and broken loop ADV's latched open
t = scram + 120 s	154	Pressurizer auxiliary spray (13.83 g/s) started. Spray cycled to maintain pressurizer level between 75 cm (30 in) and 250 cm (98 in)
t = 600 s	600	Broken loop secondary auxiliary feedwater terminated
Test terminated	8181	Primary pressure reaches low pressure injection system set point pressure [1.38 MPa (188 psig)]

generator had been affected. At t = 600 s it was assumed the operator identified which generator suffered the tube rupture but could not close the ADV in that generator. In this Semiscale simulation, at t = 600 s auxiliary feedwater to the broken loop secondary was terminated and both intact and broken loop ADVs remained latched open. For the intact loop secondary the ADV was closed if the hot collapsed level dropped to 250 cm (98 in.) until the level recovered to 400 cm (157 in.) at which time the ADV was again latched open.

SI was operated during the transient to maintain the hot collapsed pressurizer level between 75 and 381 cm (30 and 150 in.). If the level reached 381 cm (150 in.) SI was terminated only if the vessel upper head (as measured by LV+421-13M) was greater than 291 cm above the -13M tap [13 cm (5 in.) below the cold leg]. Following any termination of SI, SI was restarted when the pressurizer level dropped to 75 cm (30 in.). For test S-SG-6, SI, once on, remained on for the entire transient. Using the combination of SI, intact loop ADV operation, a stuck open broken loop ADV, and pressurizer spray, the system primary pressure was gradually reduced to the low pressure injection setpoint pressure of 1.38 MPa (188 psig) which was the required termination criteria. Since it was assumed that the operator bypassed accumulator injection, no accumulator injection was used for S-SG-6. Table 3 contains a summary of intact loop ADV operation and Table 4 contains a summary of pressurizer auxiliary spray operation.

TABLE 3. INTACT LOOP ADV OPERATION DURING S-SG-6

Operation	Time
Open at nominal, t = scram + 60 s	94 s
250 cm (98 in) low limit reached, ADV closed	881 s
400 cm (157 in) high level reached, ADV opened	1621 s
250 cm (98 in) low limit reached, ADV closed	2312 s
400 cm (157 in) high level reached, ADV opened (remained open rest of experiment)	3288 s

TABLE 4. PRESSURIZER SPRAY OPERATION DURING S-SG-6

Operation	Time
Spray on at nominal, t = scram + 120 s	154 s
Spray off at 250 cm (98 in) level trip	719 s
Spray on at 75 cm (30 in) level trip	928 s
Spray off at 250 cm (98 in) level trip	1068 s
Spray on at 75 cm (30 in) level trip	1973 s
Spray off at 250 cm (98 in) level trip	2170 s
Spray on at 75 cm (30 in) level trip	2754 s
Spray off at 250 cm (98 in) level trip	2857 s
Spray on at 75 cm (30 in) level trip	4020 s
Spray off at 250 cm (98 in) level trip (remained off for rest of experiment)	4148 s

3. RESULTS

This section discusses the overall thermal-hydraulic response of the Semiscale system during Test S-SG-6. Test S-SG-6 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 three areas: the initial response to automatically occurring events (0 to 94 s), the recovery period involving operator actions, and a comparison of the response for a 5 tube cold side (Test S-SG-7)[4] and 5 tube hot side (Test S-SG-6) break experiment.

3.1 <u>System Behavior--Tube Rupture Signature Early in Time (0 to 94 s)</u>

The occurrence of a 5 tube rupture event during normal operation of 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 t = 0 s. Primary fluid originally at 15.68 MPa (2274 psia), flowed through the conical flow tube break orifice into the broken loop steam generator originally at 5.6 MPa (812 psia). The loss of mass from the primary loop caused a fairly steady primary depressurization until about 34 s, at which time a marked increase in the depressurization rate occurred. At 34 s the low pressurizer pressure setpoint of 13.1 MPa (1900 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 (MSIV) were closed on the steam generators. The large decrease in system pressure following core scram at 34 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 secondary pressure in both generators briefly reached the ADV setpoints [6.55 MPa (950 psia) in the intact loop and 5.85 MPa (848 psia) in the broken loop)].

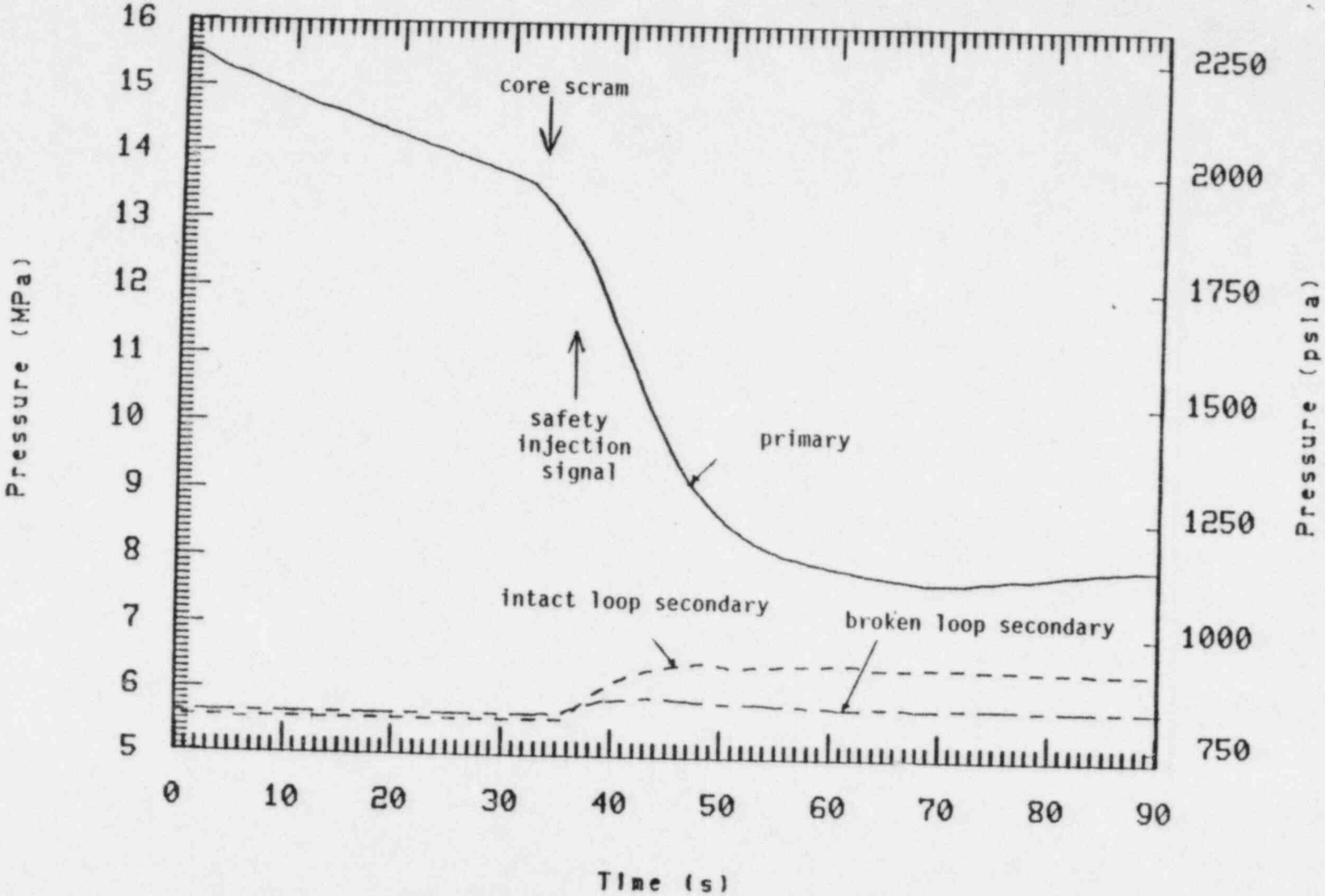


Figure 7. Comparison of primary and secondary pressures during a hot-side five-tube rupture transient (S-SG-6).

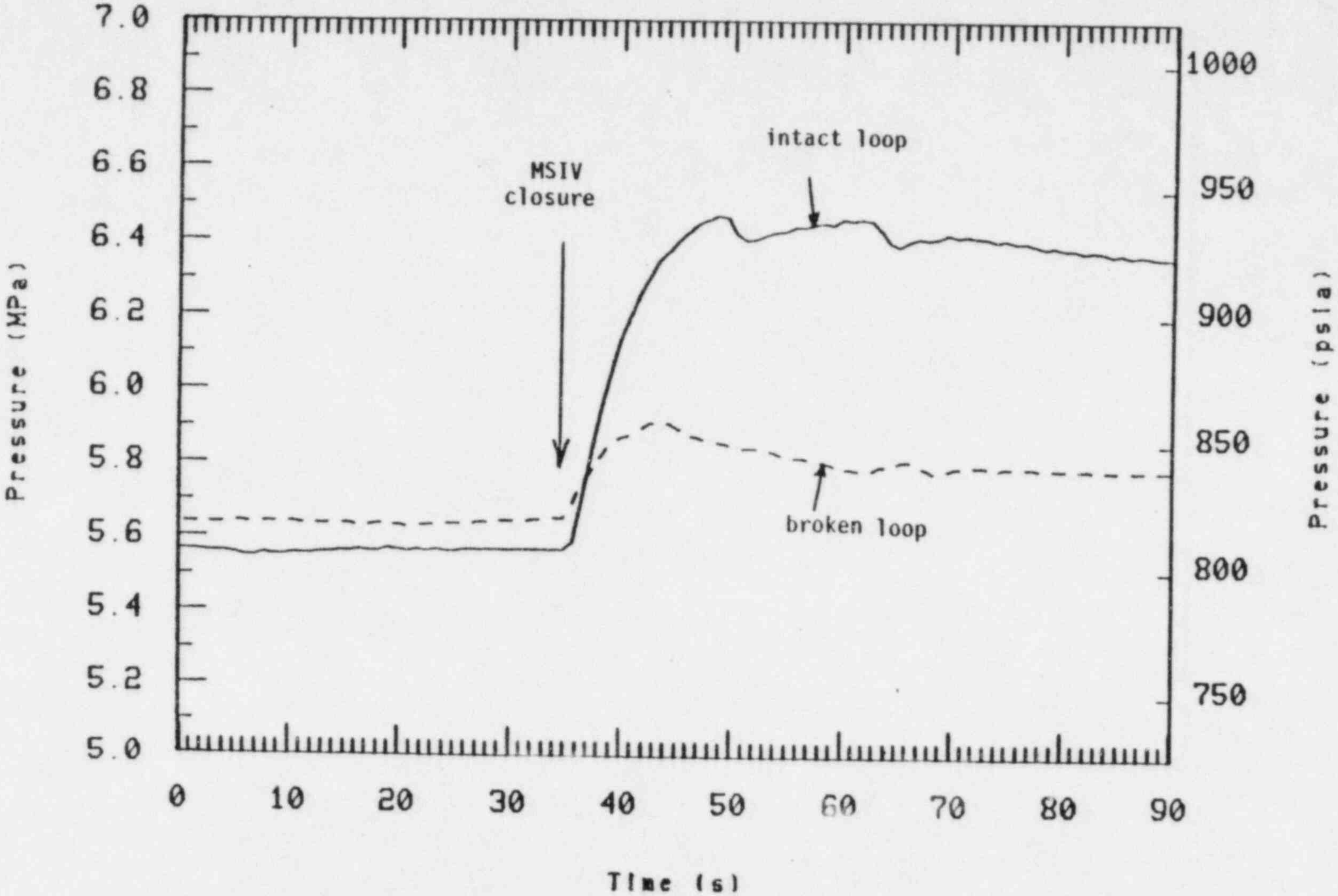


Figure 8. Comparison of intact and broken loop steam generator secondary pressures during a hot-side five-tube rupture transient (S-SG-6).

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 broken loop secondary from break flow had a negligible effect on secondary pressure during this period because it was overpowered by the over all primary to secondary heat transfer.

The safety injection signal was achieved at 12.5 MPa (1813 psia) and initiated: (a) terminating power to the primary coolant pumps, (b) terminating main feedwater and starting auxiliary feedwater to the secondaries, and (c) initiating safety injection. 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 in Figure 9. The pronounced drop in flow occurring at about 68 s corresponds to the loop pump achieving 0 rad/s (0 rpm). 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 55 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 starting at 70 s. This repressurization was mainly caused by superheated steam in the pressurizer (Figure 10), reduced heat transfer to the intact loop secondary caused by the change to natural circulation, and flashing in the reactor vessel.

Primary pressure remained above broken loop secondary pressure (Figure 7) and caused a primary-to-broken loop secondary mass flow which was higher than SI flow thus resulting in a net loss of system fluid (Figure 11). Figure 12 shows the pressurizer collapsed liquid level essentially depleted after 50 s. Figure 13 shows the vessel upper head

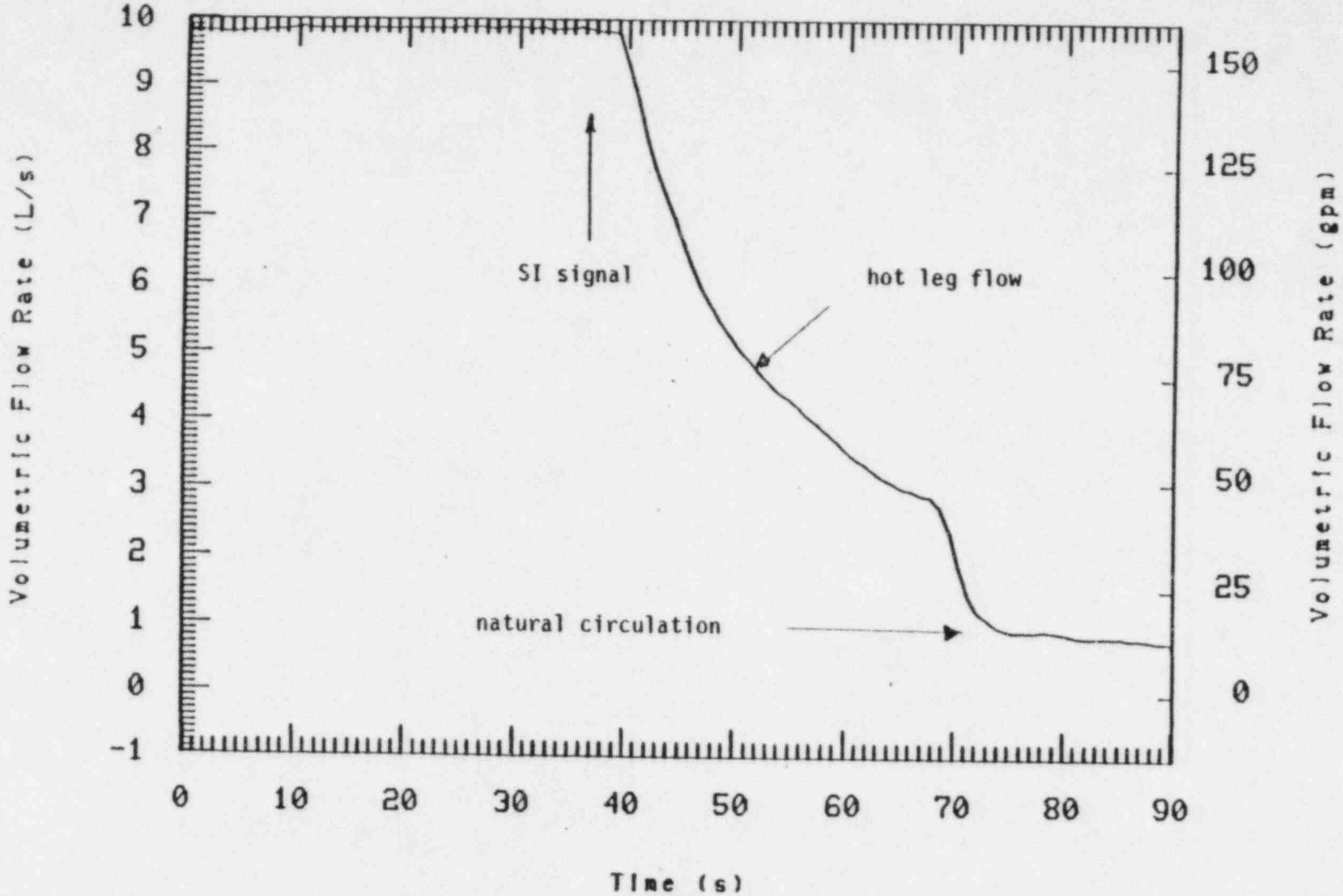


Figure 9. Intact loop hot leg flow during a hot-side five-tube rupture transient (S-SG-6).

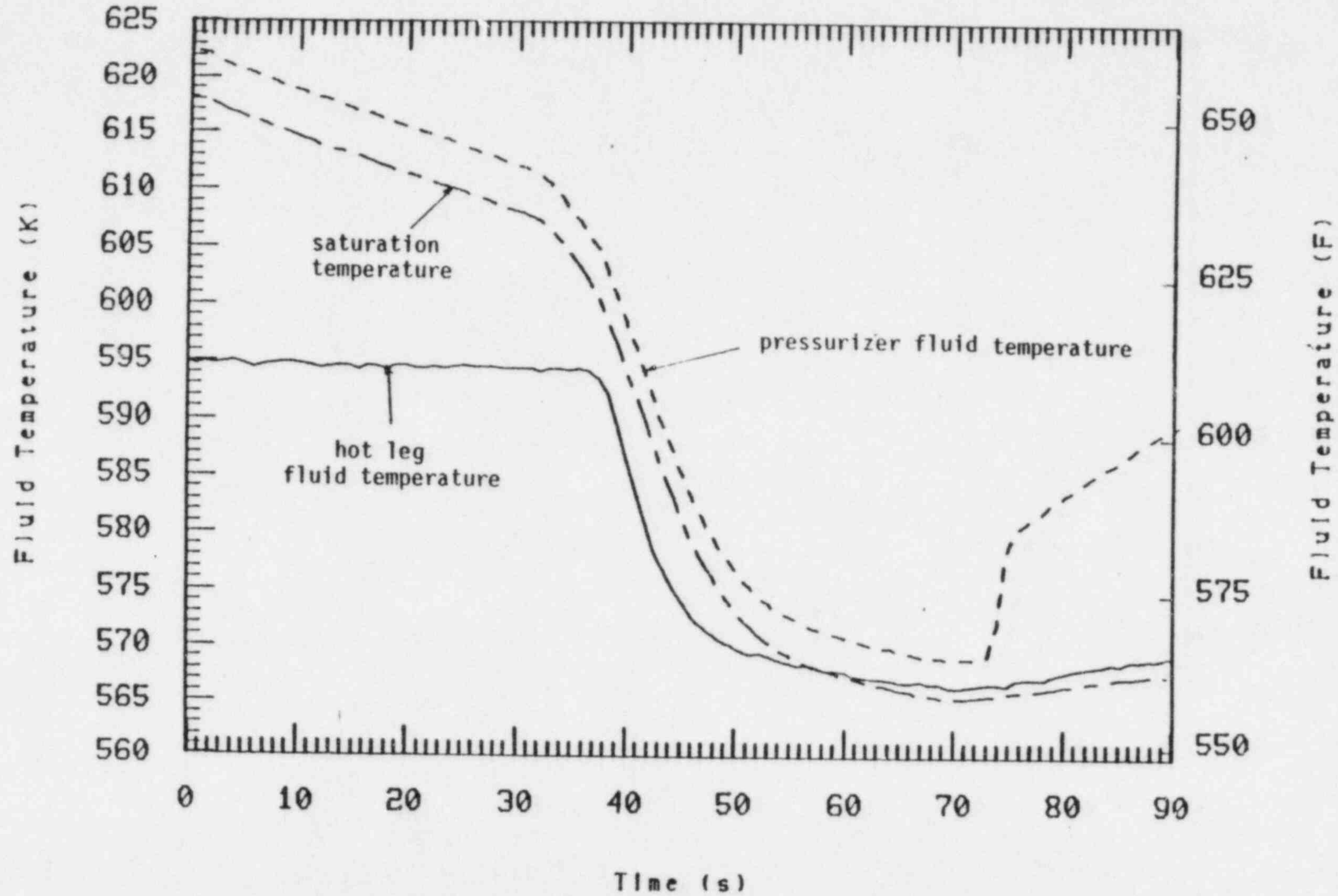


Figure 10. Comparison of saturation temperature to the intact loop hot leg and pressurizer fluid temperature during a hot-side five-tube rupture transient (S-SG-6).

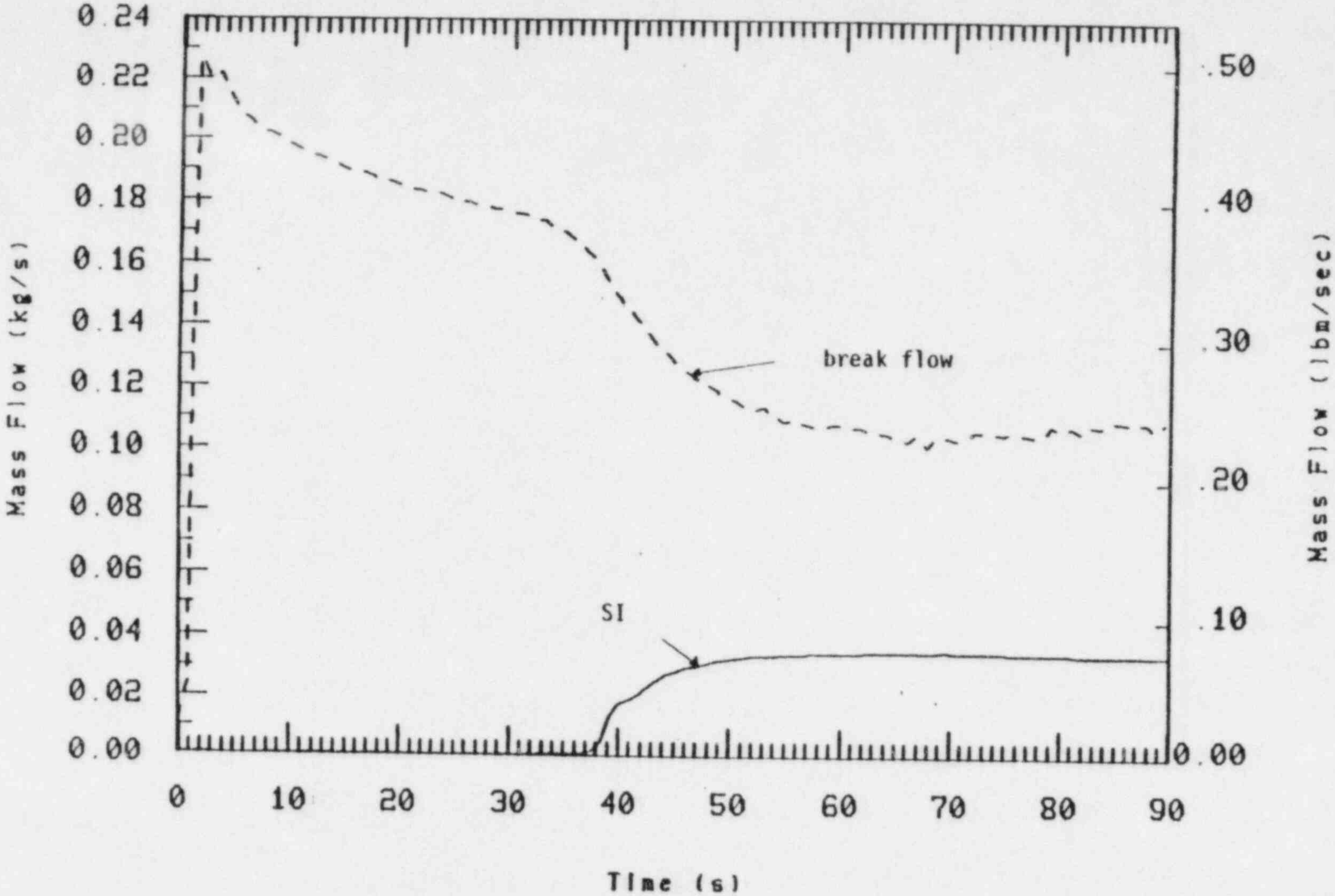


Figure 11. Comparison of break flow and SI flow during a hot-side five-tube rupture transient (S-SG-6).

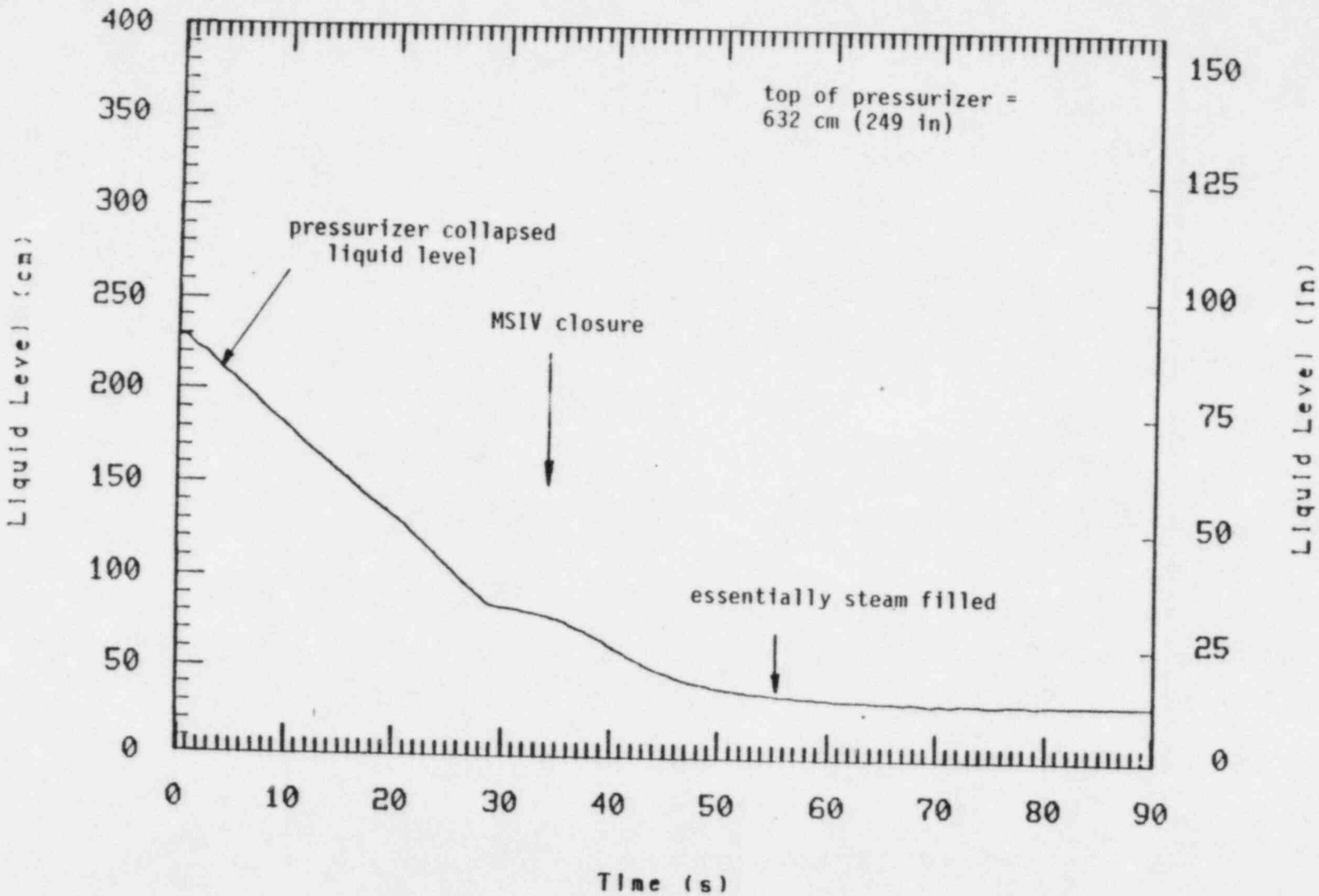


Figure 12. Pressurizer collapsed liquid level during a hot-side five-tube rupture transient (S-SG-6).

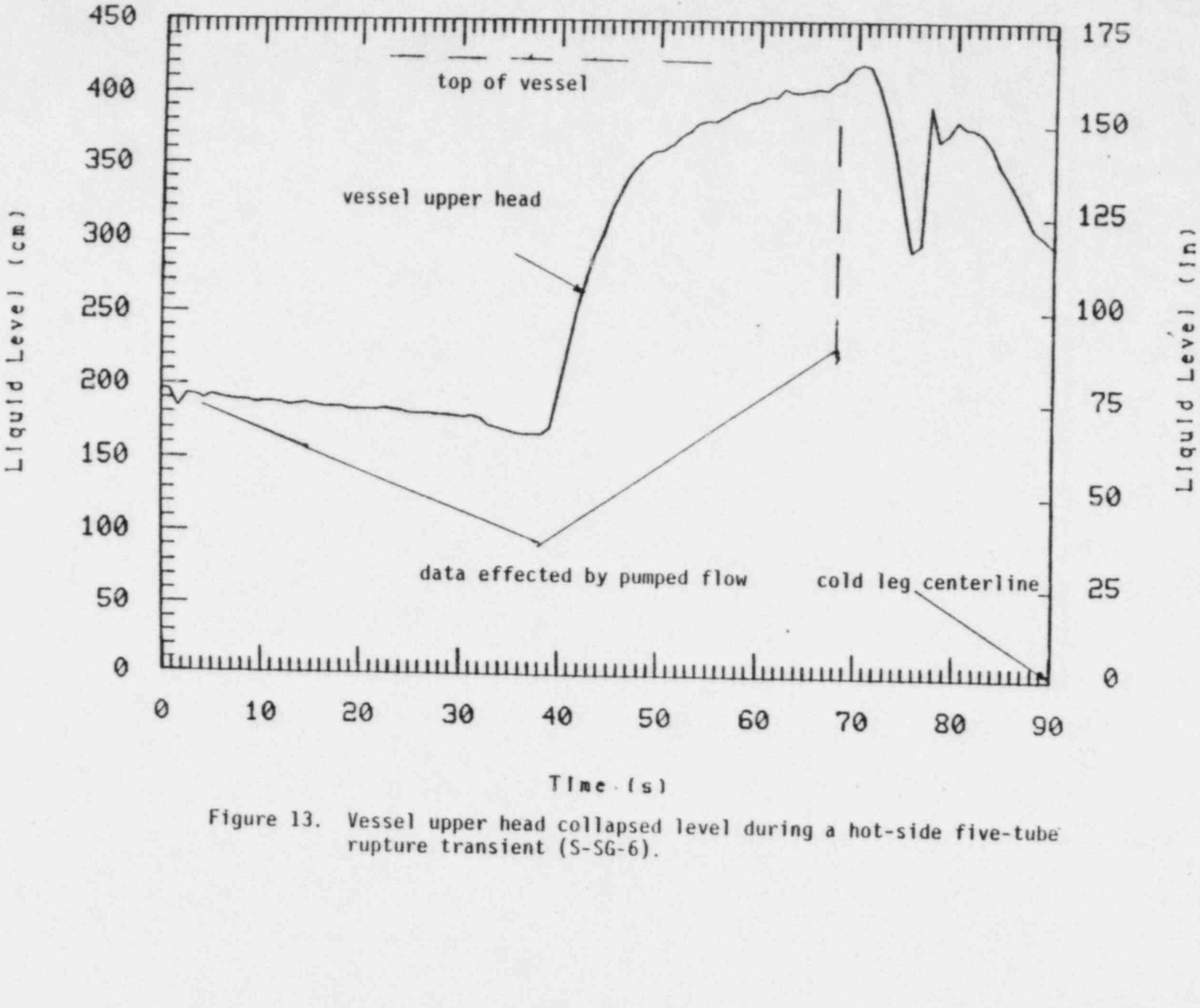


Figure 13. Vessel upper head collapsed level during a hot-side five-tube rupture transient (S-SG-6).

level[a] had only minor depletion [30 cm (12 in.)] during the first 94 s. At t = scram + 60 s (94 s) an operator induced recovery began involving latching open both intact and broken loop ADVs and pressurizer auxiliary spray. This recovery operation is discussed in the following sections.

3.2 Recovery Phase

Recovery during S-SG-6 involved using a combination of SI, intact and broken loop ADV operation, and pressurizer auxiliary spray. Early operator identification of a tube rupture event was assumed.

3.2.1 Early Operator Response (94-600 s)

At t = scram + 60 s (94 s) the experiment scenario assumed early operator identification of a tube rupture but no knowledge of which generator suffered a tube rupture. In the Semiscale experiment, the operator response was to latch open both intact and broken loop ADVs in an attempt to first reduce the system pressure below the ADV setpoints [broken loop setpoint is 5.85 MPa (848 psia)]. Latching open the intact loop and broken loop ADVs caused a rapid depressurization of both steam generator secondaries which stimulated a decrease in primary pressure (Figure 14). At 94 s (t = scram + 60 s) the primary pressure was still increasing due to pressurizer superheat and the transition to natural circulation as discussed in Section 3.1. Latching open the ADVs at 94 s increased the secondary heat sink and stimulated primary to secondary heat transfer. The increase in heat transfer caused the primary pressure to stop increasing and eventually slightly decrease as shown in Figure 14. Increased primary to secondary heat transfer after 94 s reduced the primary fluid temperature (Figure 15) and caused primary fluid shrinkage which aided in the primary depressurization.

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a. This level measurement was affected by pump operation and is only valid after the pumps coasted down about 70 s.

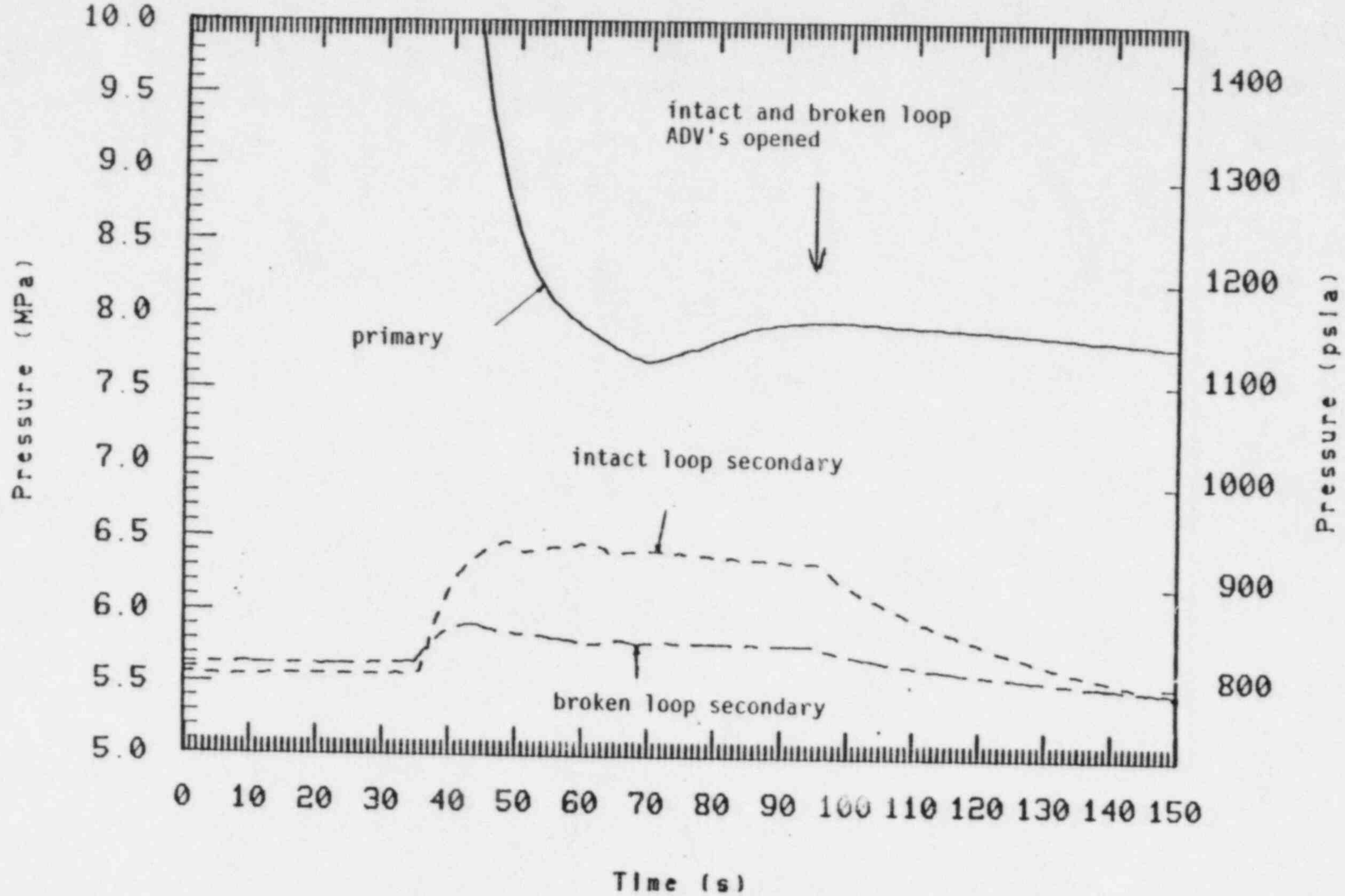

Figure 14. Comparison of primary and secondary pressure following intact and broken loop ADV opening during a hot-side five-tube rupture transient (S-SG-6).

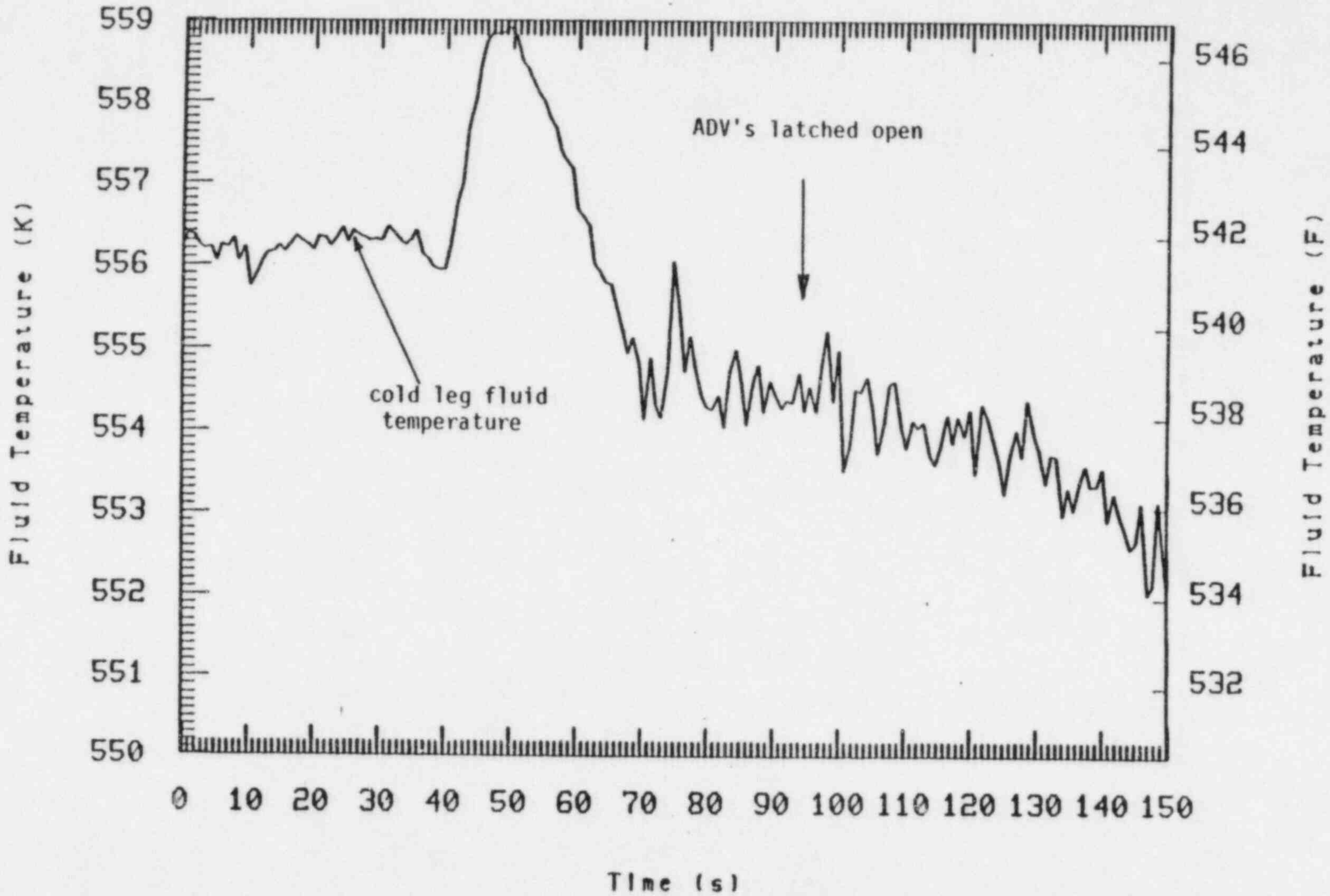

Figure 15. Intact loop cold leg fluid temperature during a hot-side five-tube rupture transient (S-SG-6).

At t = scram + 120 s (154 s) pressurizer auxiliary spray was initiated to further stimulate the primary pressure decrease to the ADV setpoints. With the introduction of pressurizer auxiliary spray there was no immediate increase in primary depressurization as shown in Figure 16. The spray was introduced into an essentially empty pressurizer (Figure 17) full of superheated steam (see Figure 18). The spray first removed the superheat in the steam and the hot pressurizer walls (see Figure 19). The net effect on primary depressurization was minimal.

During the time period of early operator action (94-600 s) the break flow was higher than SI flow as shown in Figure 20 causing a decrease in system mass inventory as evidenced by decreasing vessel collapsed level (Figure 21). When the vessel collapsed liquid level reached the hot leg elevation at about 250 s several prominent events occurred. There was a transition from single-phase to two-phase natural circulation in the intact loop, increasing the flow rate as shown in Figure 22 which caused an increase in primary to secondary energy removal and a corresponding increase in primary system depressurization rate (see Figure 16 at 250 s). This transition from a single-phase to two-phase natural circulation was caused by an increase in the overall loop density gradient between hot and cold sides of the system as discussed in Reference 5.

Following the transition to two-phase natural circulation and the corresponding change in the system depressurization rate, the primary system depressurization rate was fairly constant and eventually at about 400 s the primary pressure was below the broken loop ADV setpoint pressure of 5.85 MPa (848 psia) (Figure 16). Throughout the 94-600 s time period break flow into the broken loop secondary with a latched open ADV resulted in a slower secondary depressurization than the intact loop with a latched open ADV as shown in Figure 16. At about 450 s, break flow and SI flow were about equal (Figure 20) which had a retarding effect on the primary depressurization rate (see Figure 16). From 450 s until 600 s the system depressurization rate was fairly constant, SI flow was greater than or equal to break flow and the vessel collapsed liquid level depleted to within 40 cm (16 in.) above the top of the core (Figure 21).

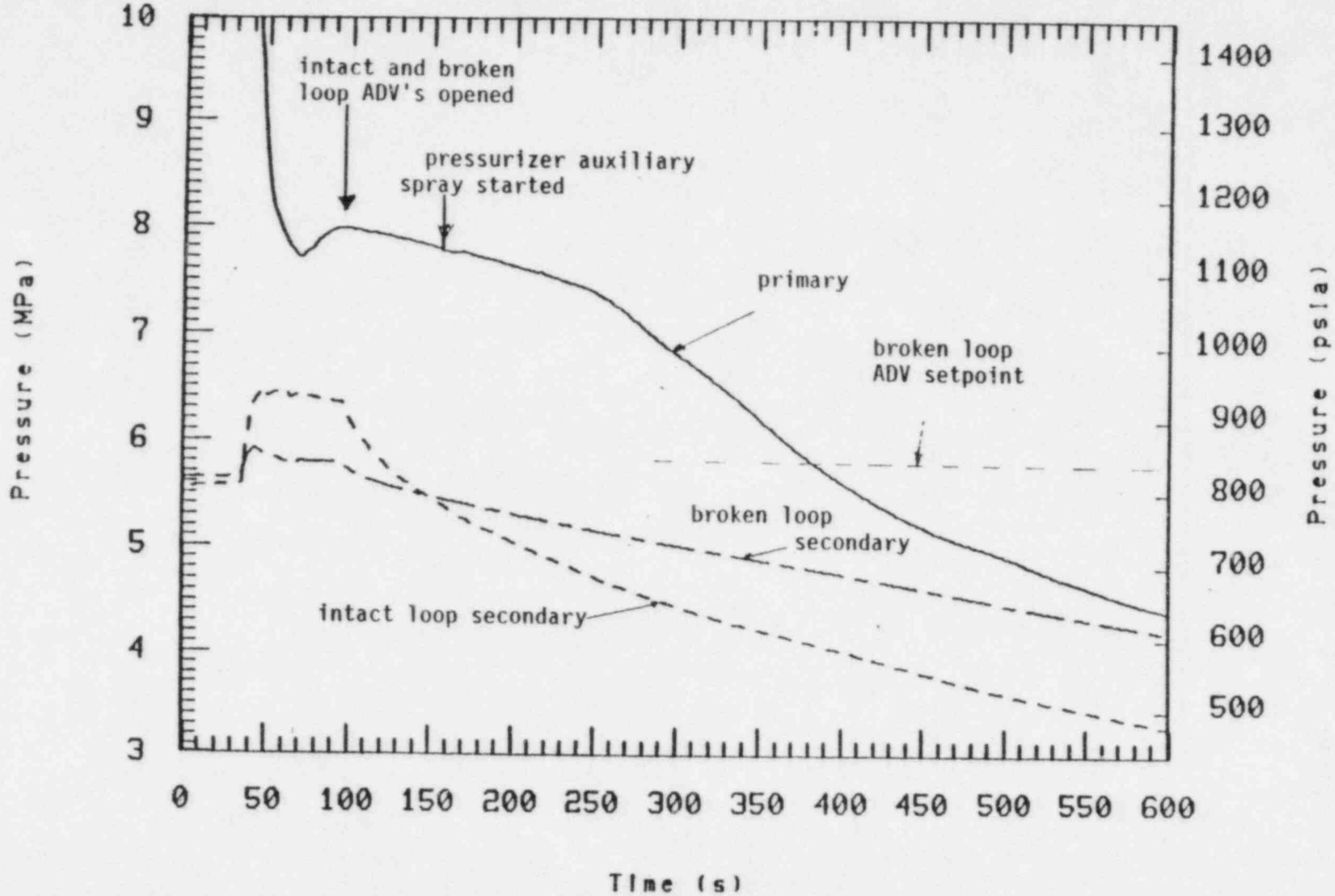

Figure 16. Comparison of primary and secondary pressure during initial ADV and pressurizer spray operation during a hot-side five-tube rupture transient (S-SG-6).

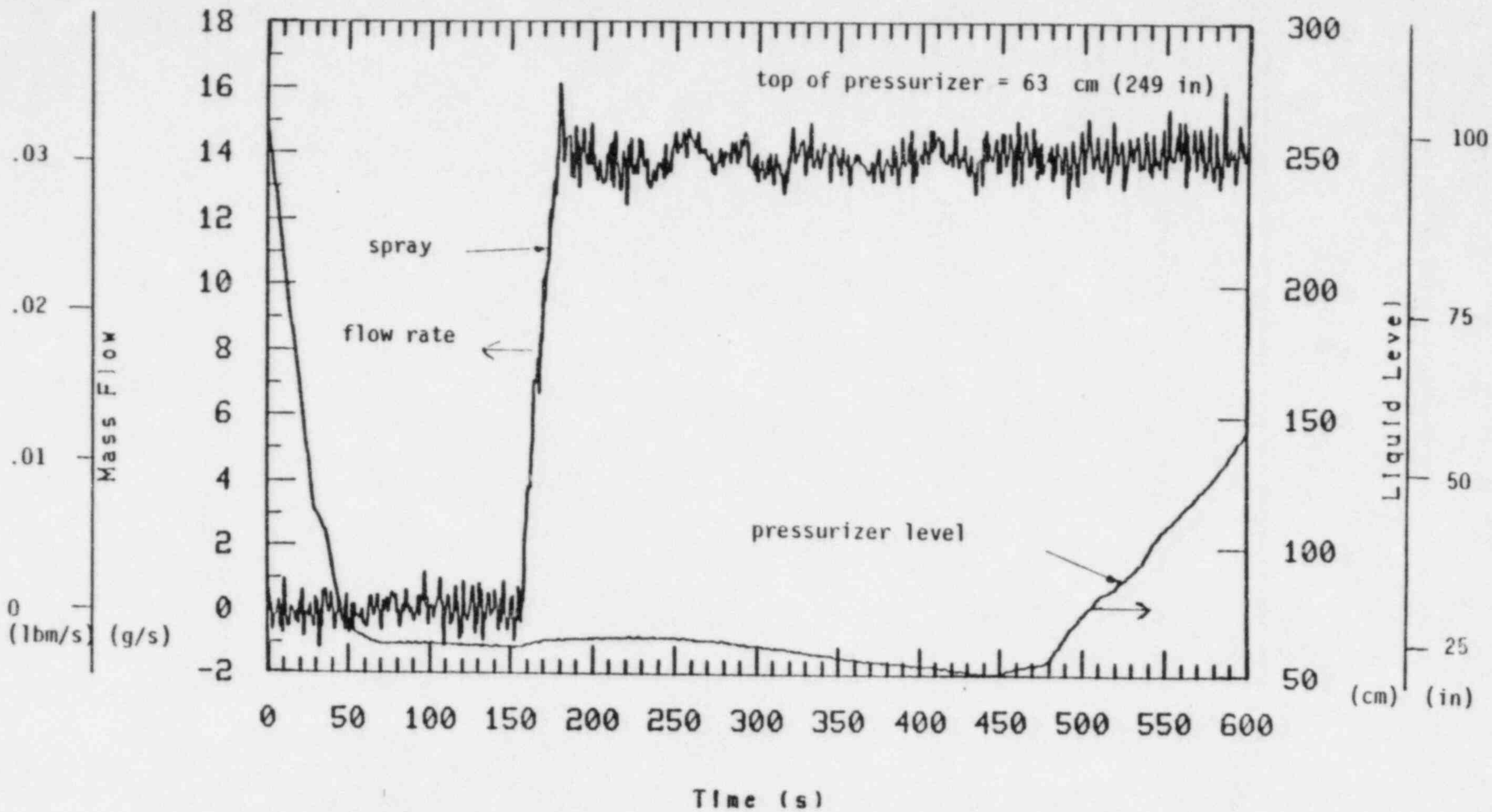

Figure 17. Comparison of pressurizer auxiliary spray and collapsed level during a hot-side five-tube rupture transient (S-SG-6).

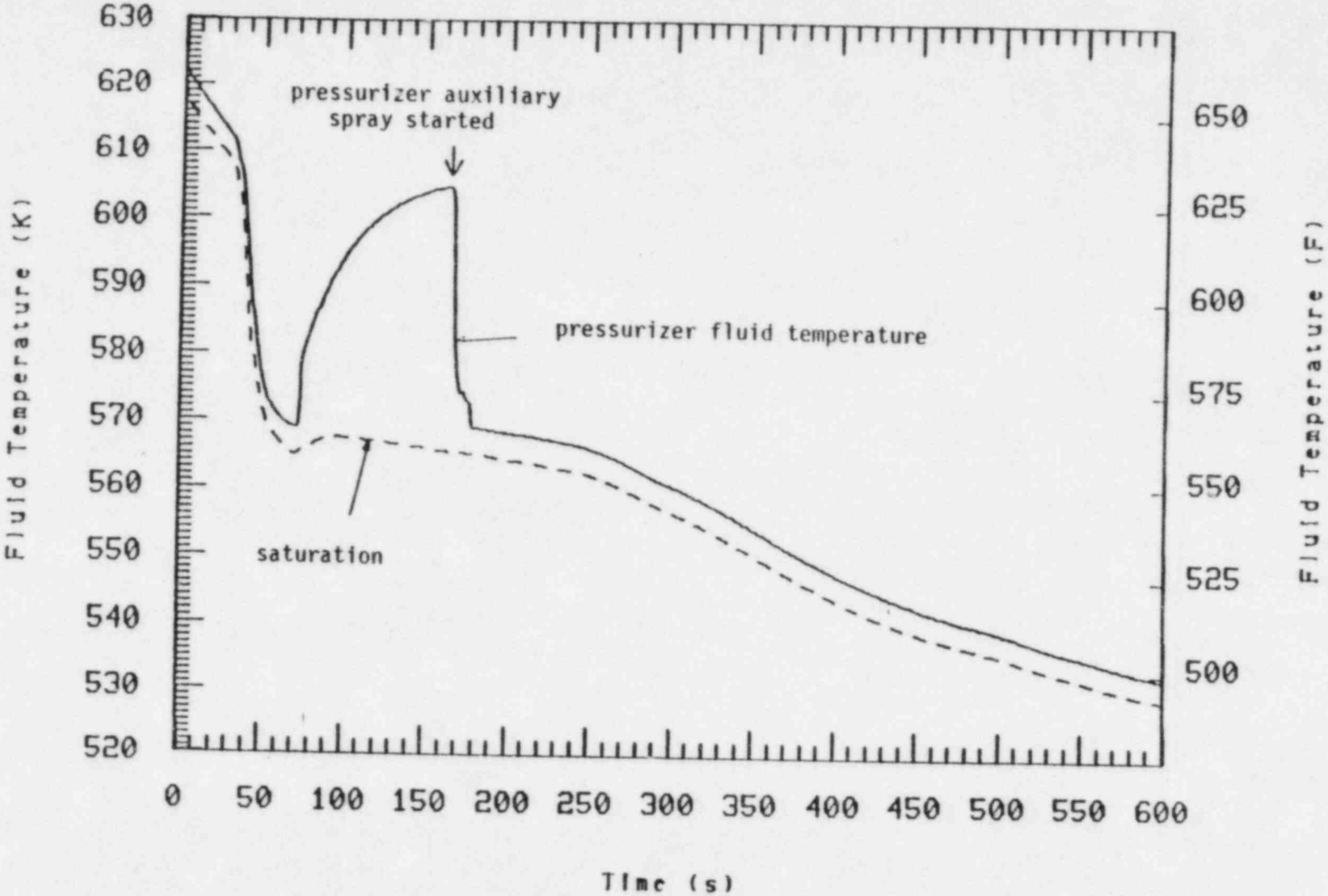

Figure 18. Comparison of saturation temperature and pressurizer fluid temperature during spray operation for a hot-side five-tube rupture transient (S-SG-6).

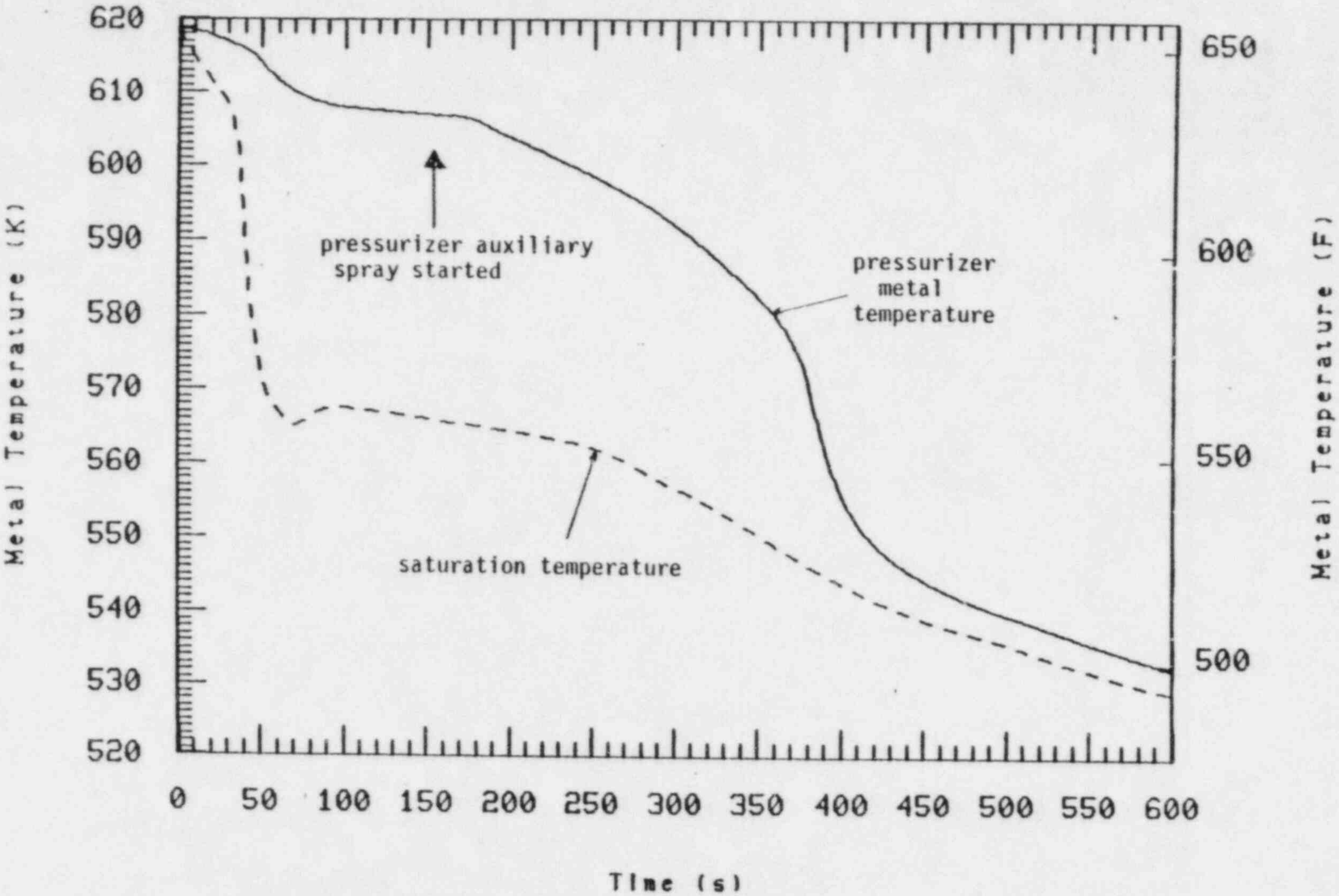

Figure 19. Comparison of saturation temperature and pressurizer metal temperature during initial spray for a hot-side five-tube rupture transient (S-SG-6).

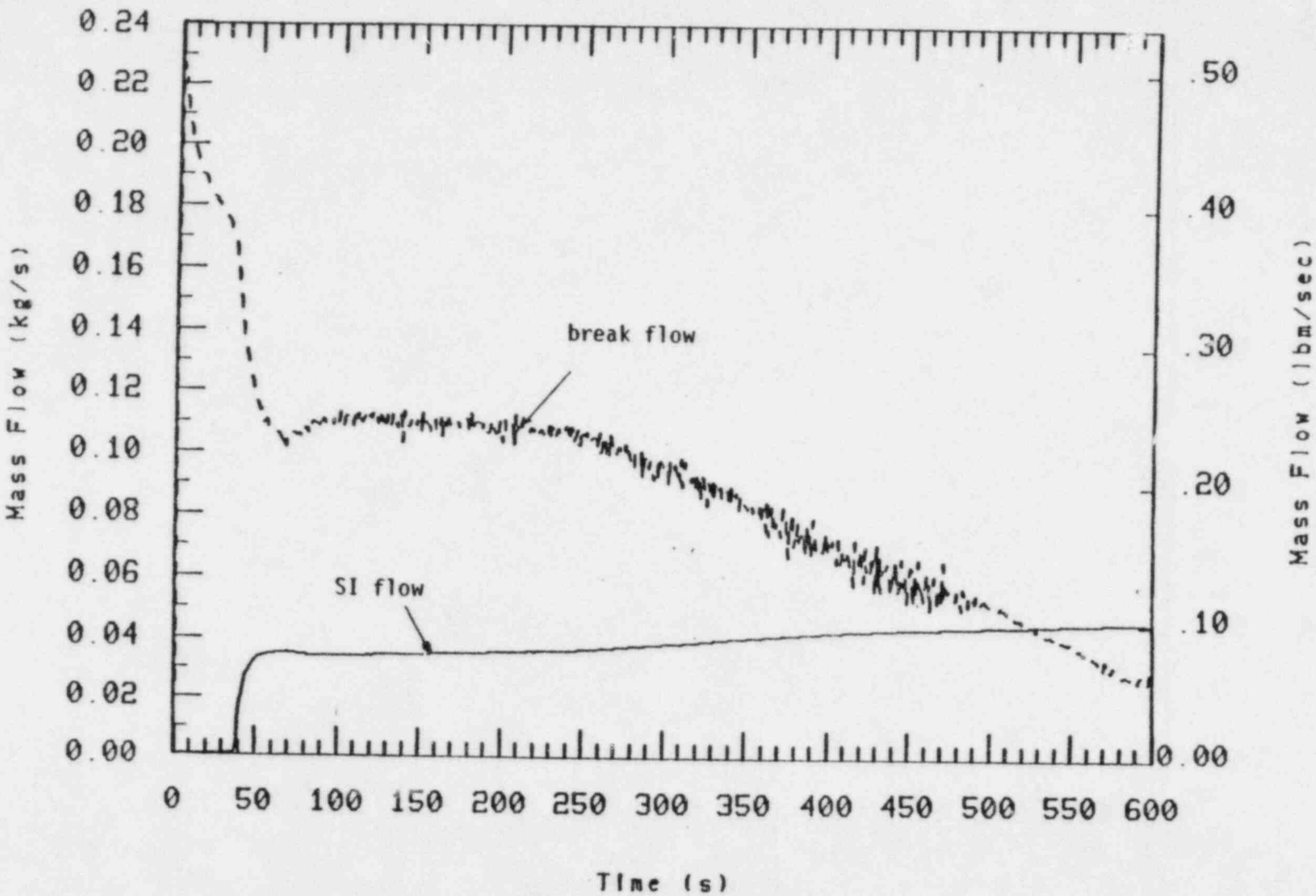

Figure 20. Comparison of break flow and SI flow during a hot-side five-tube rupture transient (S-SG-6).

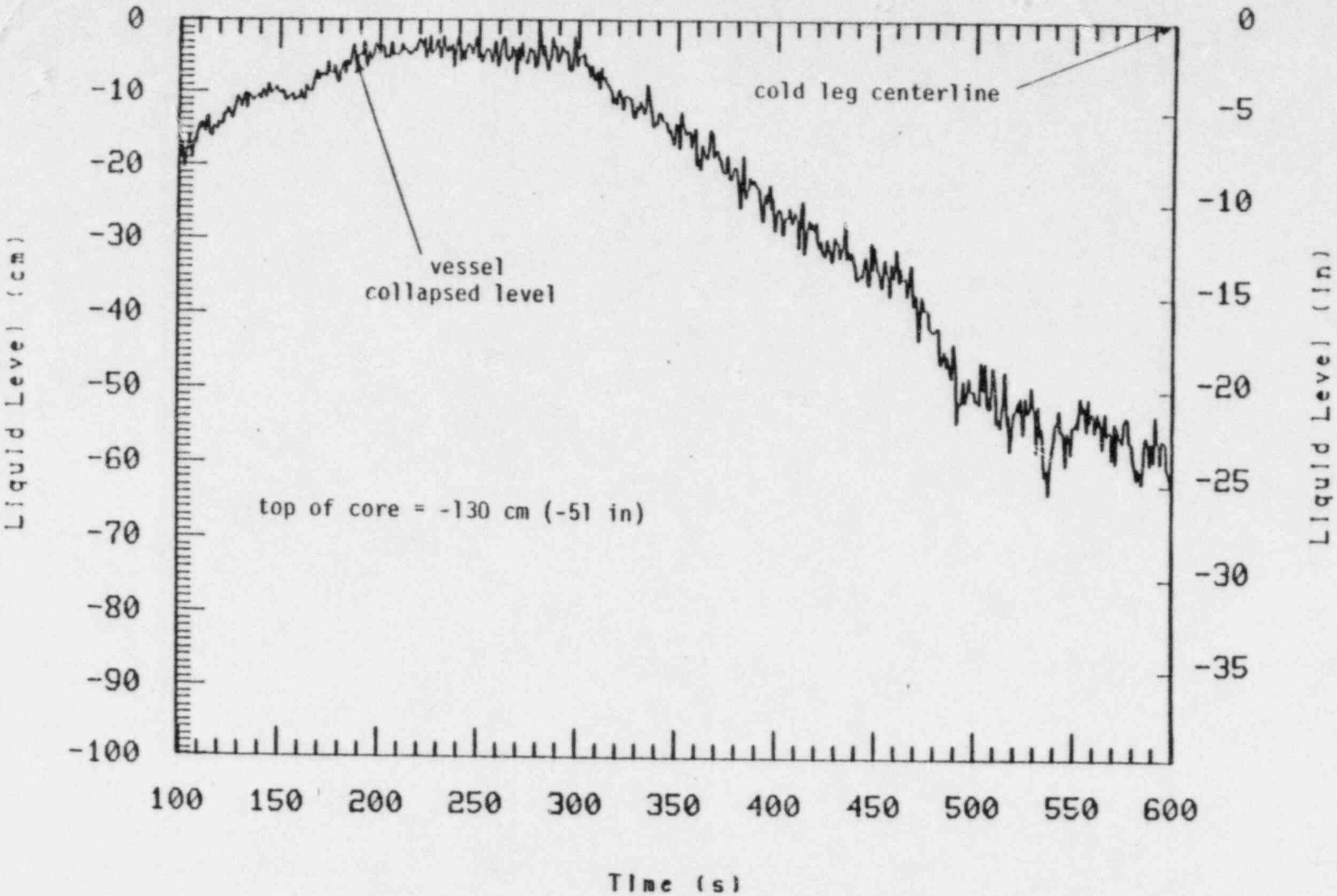

Figure 21. Vessel upper head collapsed level during a hot-side five-tube rupture transient (S-SG-6).

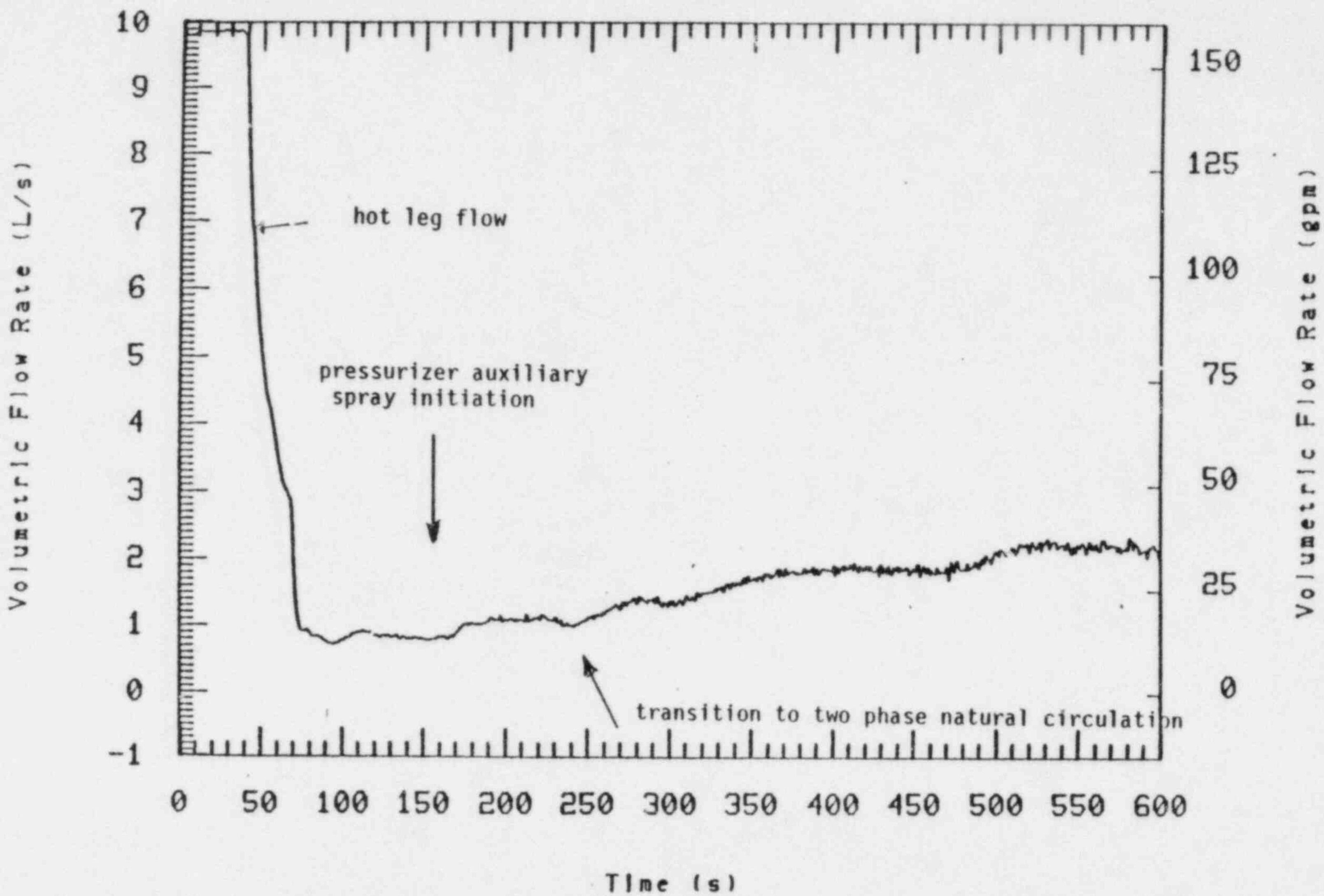

Figure 22. Intact loop hot leg volumetric flow during initial spray for a hot-side five-tube rupture transient (S-SG-6).

In summary, the early operator action (94-600 s) of opening the intact and broken loop ADVs and use of auxiliary pressurizer spray on primary pressure was small. The main effect early in time (94-600 s) was to remove superheat from the pressurizer fluid and metal walls due to pressurizer auxiliary spray and to cool the primary loop due to primary to secondary heat transfer from the secondary steam and feed operations. Voiding in the loop and vessel caused by a higher break flow than SI flow eventually lead to a transition from single phase natural circulation to two phase natural circulation with a resulting increase in primary to secondary heat transfer which stimulated the primary depressurization.

3.2.2 Recovery With a Stuck Open Broken Loop ADV (600-8181 s)

At t = 600 s it was assumed that the operators identified which steam generator had the tube rupture (in Semiscale the broken loop) and it was further assumed that the operator attempted to close the broken loop ADV but was unable to accomplish this task. Therefore, in the Semiscale simulation the broken loop ADV remained open for the remainder of the transient. However, the auxiliary feedwater to the broken loop was shut off to minimize the amount of water in the broken loop secondary. The intact loop ADV was open and shut on a 250 to 400 cm (98 to 157 in.) secondary level band and pressurizer auxiliary spray was cycled to maintain the pressurizer collapsed level between 75 and 250 cm (30 and 98 in.). SI remained on for the entire transient. These operator actions were used to reduce the primary pressure to the LPIS setpoint pressure of 1.38 MPa (200 psia). The purpose of this recovery scenario was to reduce the primary pressure as quickly as possible so as to minimize the primary to broken loop secondary to atmosphere flow rate via the break and the stuck open broken loop ADV.

Using intact loop feed and steam, SI, and pressurizer auxiliary spray was a sufficient operator response to reduce the primary pressure to the LPIS setpoint pressure without core uncovery even with a stuck open broken loop ADV. Figure 23 shows the primary pressure response with pressurizer auxiliary spray cycles and intact loop ADV cycles indicated. The overall primary pressure response was a gradual reduction in primary pressure with

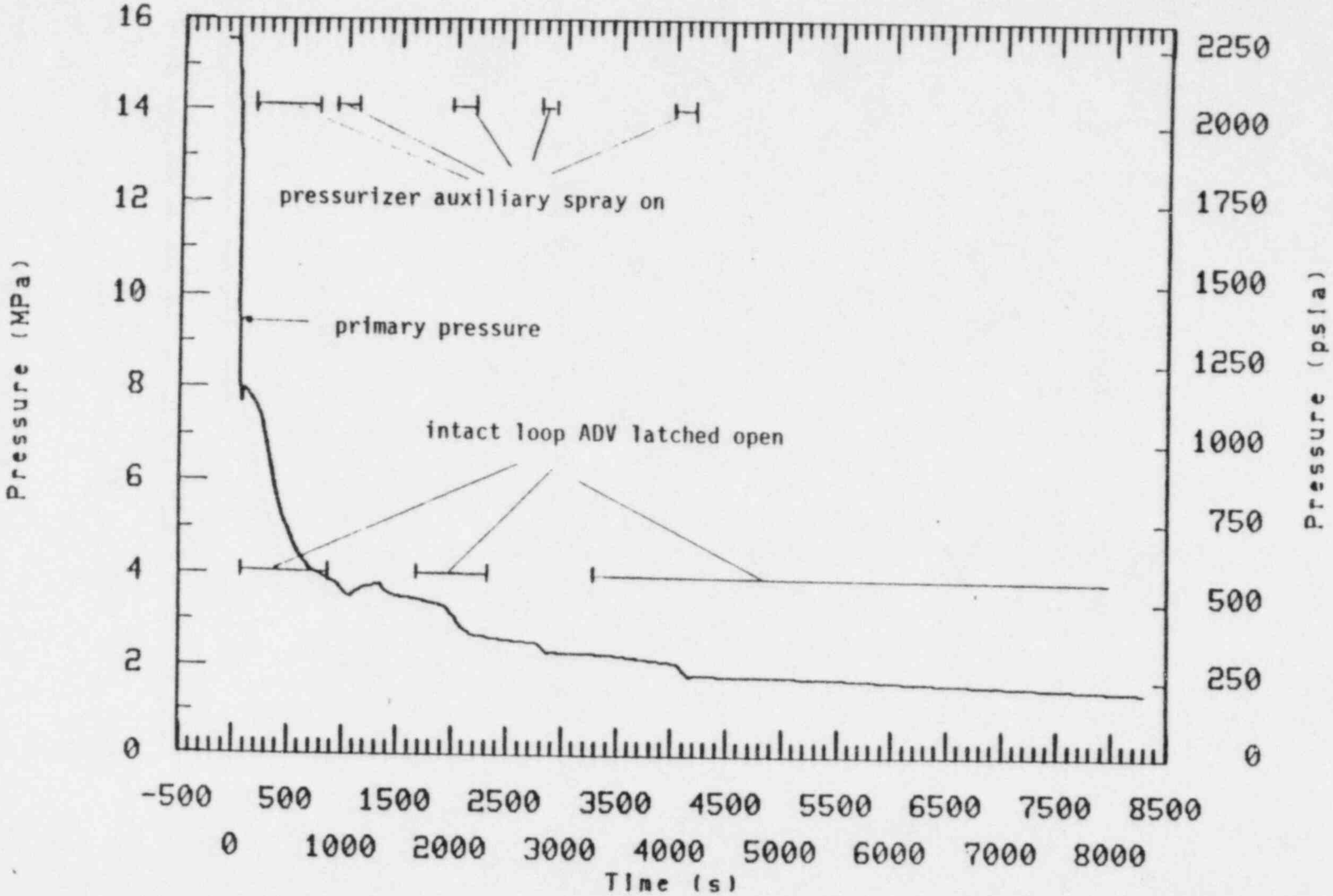

Figure 23. Primary pressure during recovery from a hot-side five-tube rupture transient (S-SG-6).

several major inflections in pressure caused by the various operator actions. Figure 24 shows the vessel collapsed liquid level with a minimum level of 40 cm above top of core and a general filling trend throughout the recovery phase.

Pressurizer auxiliary spray had a pronounced effect on primary depressurization. Figure 25 shows the auxiliary spray operation as a function of pressurizer level. Except for two spray cycles (928-1973 s and 4148-8181 s), the instant spray was terminated, the pressurizer level dropped as pressurizer water drained to the vessel and out the break. Figure 26 compares primary pressure with spray flow rate showing a marked increase in depressurization rate during a period of spray and a decrease in depressurization rate when spray was terminated. Auxiliary spray condensed steam in the pressurizer causing a slight decrease in vessel collapsed level as shown on Figure 27 which compares spray flow rate and vessel level. The pressure reduction due to void collapse associated with the condensation process caused flashing in the vessel and a temporary decrease in vessel inventory as discussed in Reference 4. Once the condensation process stopped (due to termination of spray) the vessel level recovered due to draining of the pressurizer.

The main effect of intact loop ADV operation (alternatingly latched open and closed based on secondary level, Figure 28) was to cause a decrease in temperature of the primary fluid which caused a very slow long term depressurization of the primary system due to fluid shrinkage. The effect of the intact loop ADV being latched open on primary system, depressurization can be isolated by examining a time period with no pressurizer spray (1068-1937 s). Figure 23 shows that during this time period no significant change in the loop depressurization rate occurred following the ADV latched open operation. However in contrast, when the spray was turned on a large depressurization occurred.

During the recovery procedure, when the combination of pressurizer auxiliary spray and intact loop ADV operation were aligned such that both were off, the system primary pressure actually increased as shown on Figure 29 which shows the auxiliary spray and intact loop ADV operation

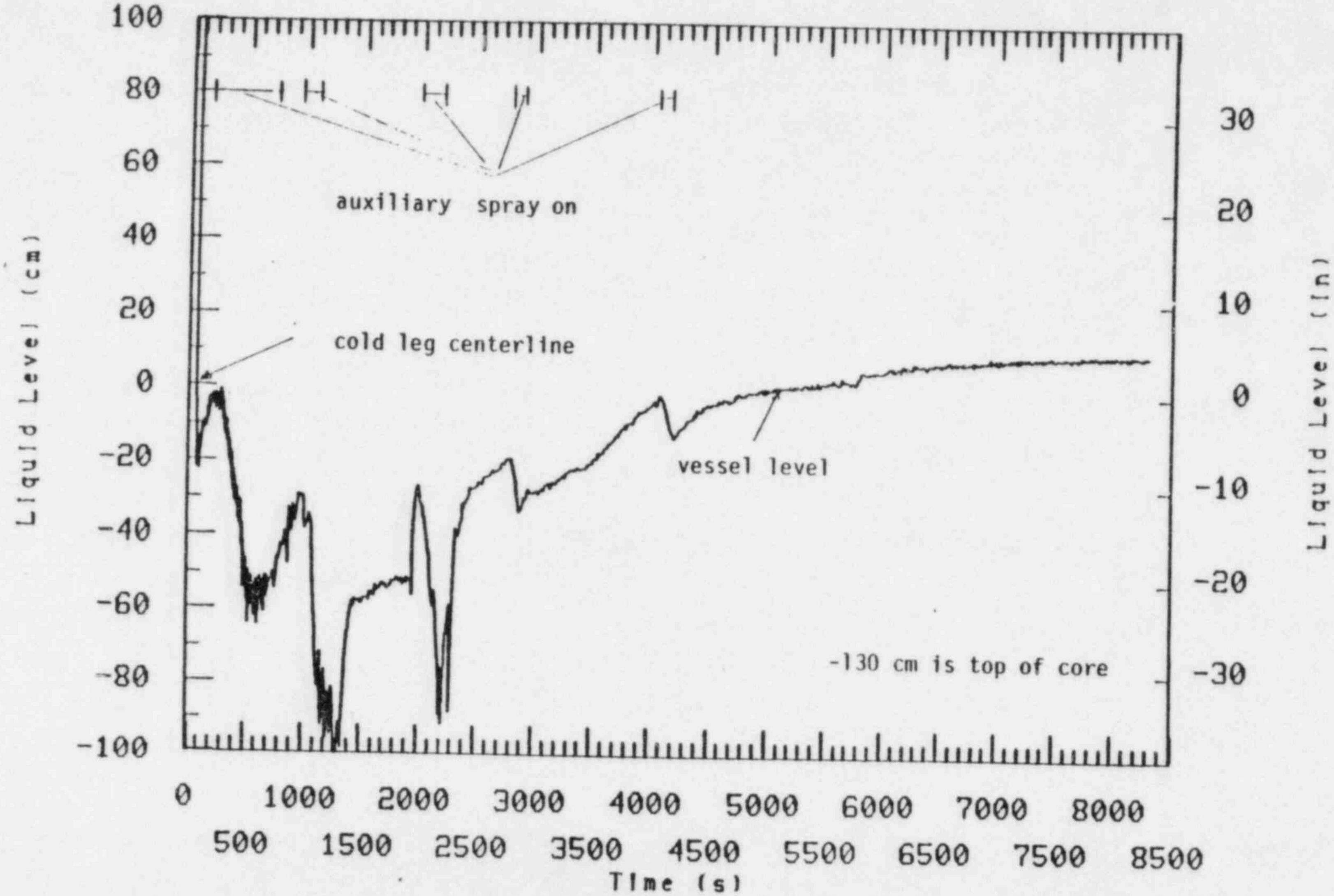

Figure 24. Vessel collapsed level during recovery from a hot-side five-tube rupture transient (S-SG-6).

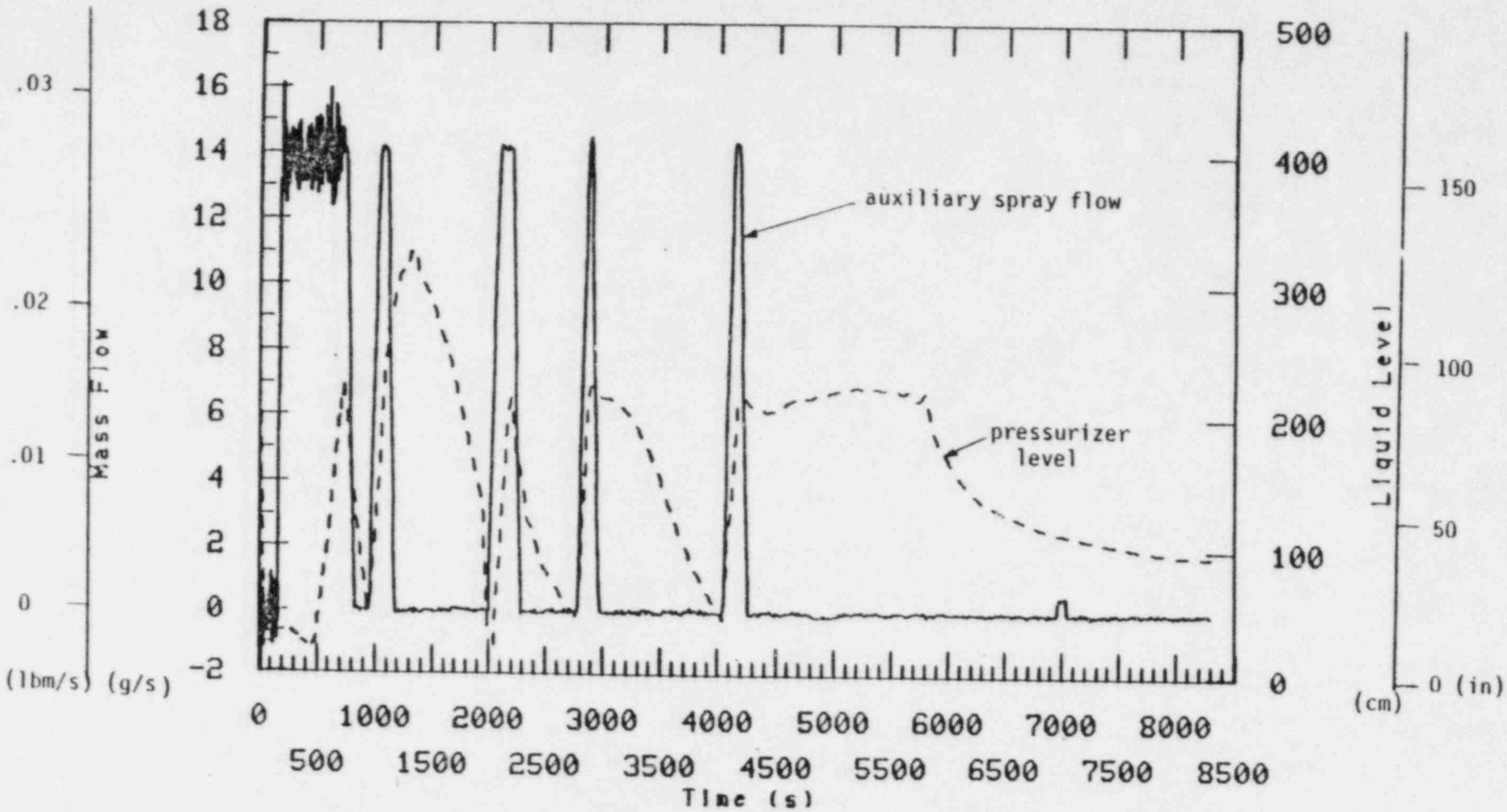

Figure 25. Comparison of pressurizer auxiliary spray and pressurizer collapsed liquid level during recovery from a hot-side five-tube rupture transient (S-SG-6).

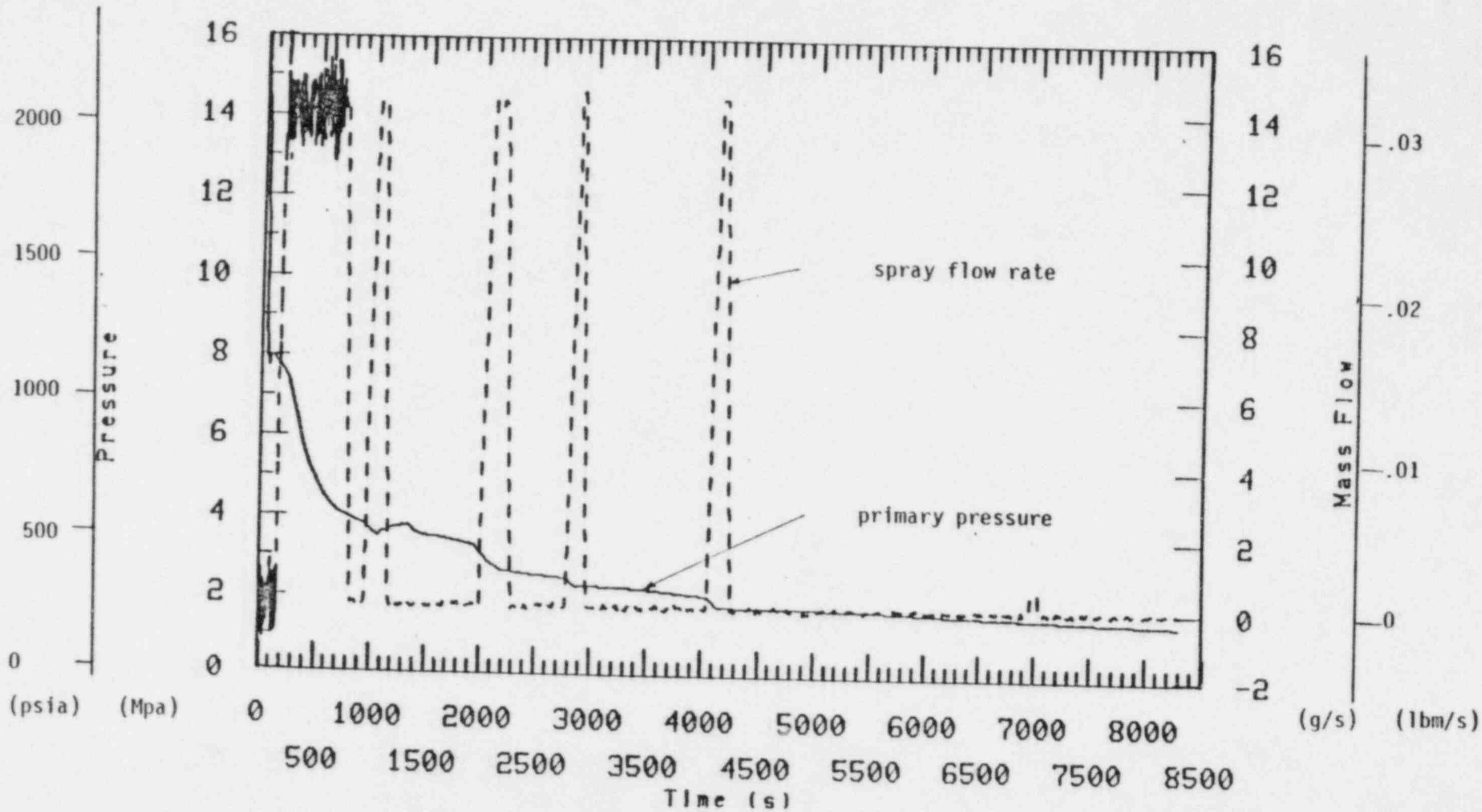

Figure 26. Comparison of primary pressure and spray flowrate during recovery from a hot-side five-tube rupture transient (S-SG-6).

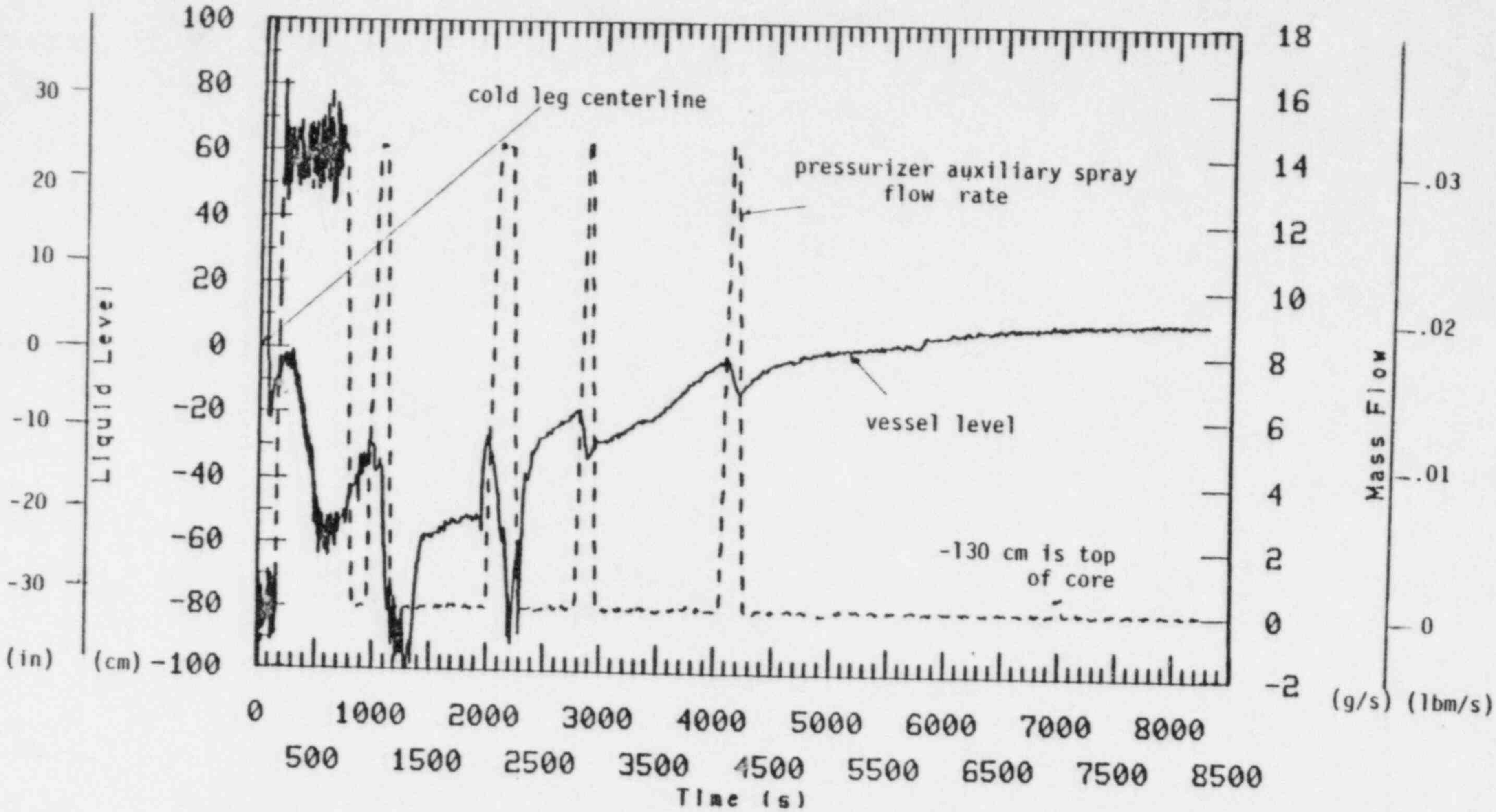

Figure 27. Comparison of vessel level and spray cycles during recovery from a hot-side five-tube rupture transient (S-SG-6).

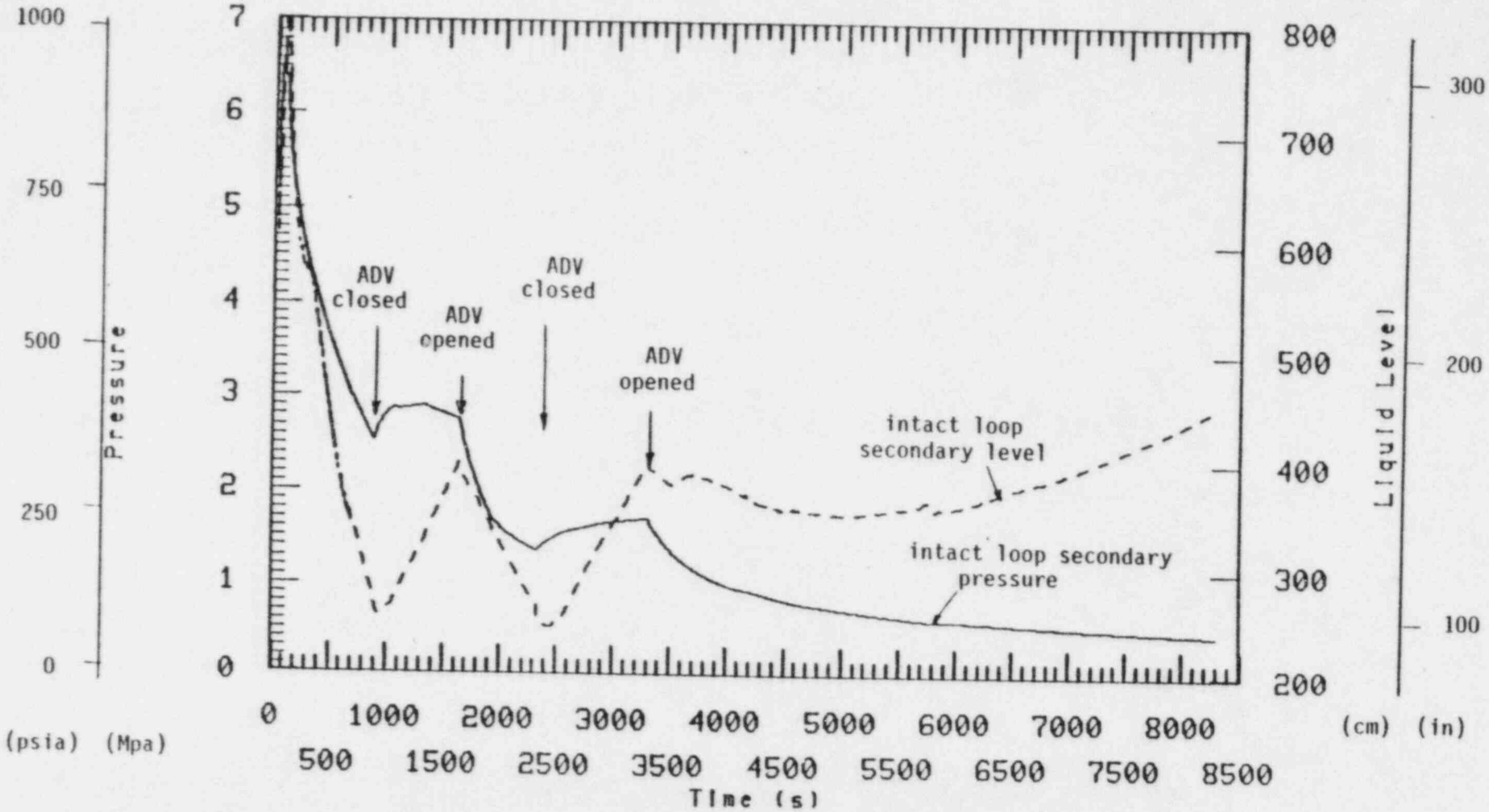

Figure 28. Comparison of intact loop secondary collapsed level and pressure during ADV operation for a hot-side five-tube rupture transient (S-SG-6).

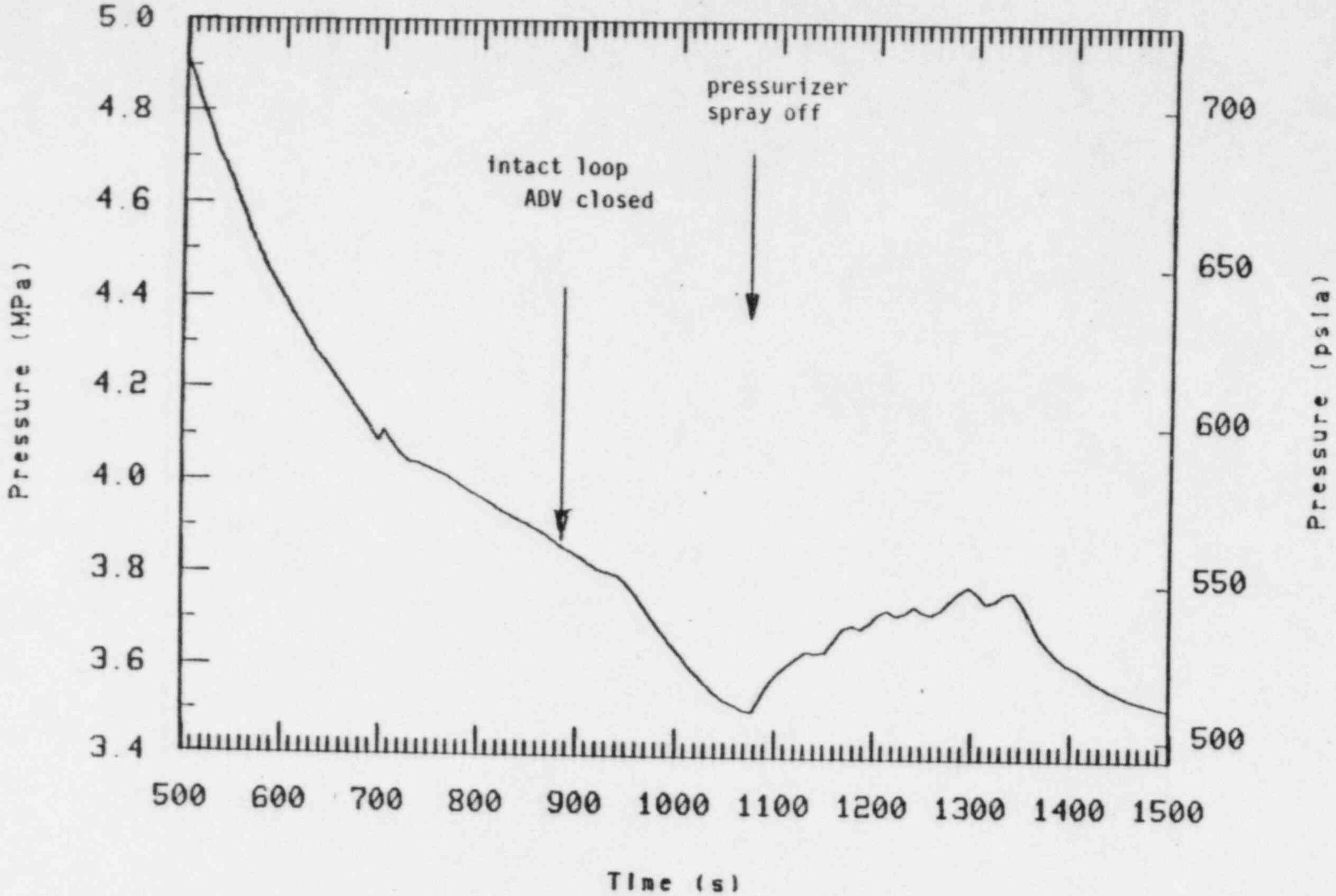

Figure 29. Primary pressure during recovery from a hot-side five-tube rupture transient (S-SG-6).

superimposed on the primary pressure plot. The ADV was shut at 881 s on a low secondary level. Auxiliary feedwater was allowed to refill the secondary from about 250 cm to 400 cm throughout this period. The auxiliary pressurizer spray was turned off at about 1068 s at which time the system primary pressure started increasing. The primary pressure increase starting at 1068 s was not only attributed to the cessation of condensation induced by the spray but was primarily due to a complete shutdown of natural circulation in the intact loop. Figure 30 shows the intact loop flow dropping to zero coinciding with the primary pressure increase. The two-phase natural circulation flow had been supported by the heat sink created by a latched open intact loop ADV. Core power had been removed via primary to secondary heat transfer supported by this intact loop two-phase natural circulation and secondary feed and steam. However, once this heat removal mechanism stopped two-phase natural circulation ceased and without core heat removal, fluid was pushed up into the pressurizer [to about 360 cm (142 in.)collapsed level] due to expanding fluid in the primary system as shown on Figure 31.

The phenomena that eventually turned around the pressure increase was a restart of two-phase natural circulation in the broken loop as shown on Figure 30. The natural circulation flow had been blocked in the broken loop as evidenced by a partially voided broken loop steam generator tube as shown on Figure 32. During the pressurization period the collapsed level in the tube increased until it bridged over the top restarting natural circulation flow in the broken loop but not in the intact loop. With an increase in heat removal due to primary to broken loop secondary heat transfer, the primary system pressure dropped and pressurizer level decreased as the primary fluid shrunk (see Figure 31). This starting and stopping of intact and broken loop natural circulation flow is discussed fully in Reference 5.

Eventually the mass balance between break flow into the broken loop secondary and broken loop ADV flow (see Figure 33) caused a filling of the broken loop secondary such that there was chugging of liquid out the top of the broken loop generator. Figure 34 compares broken loop ADV flow and secondary level showing an increase in ADV flow when the secondary level

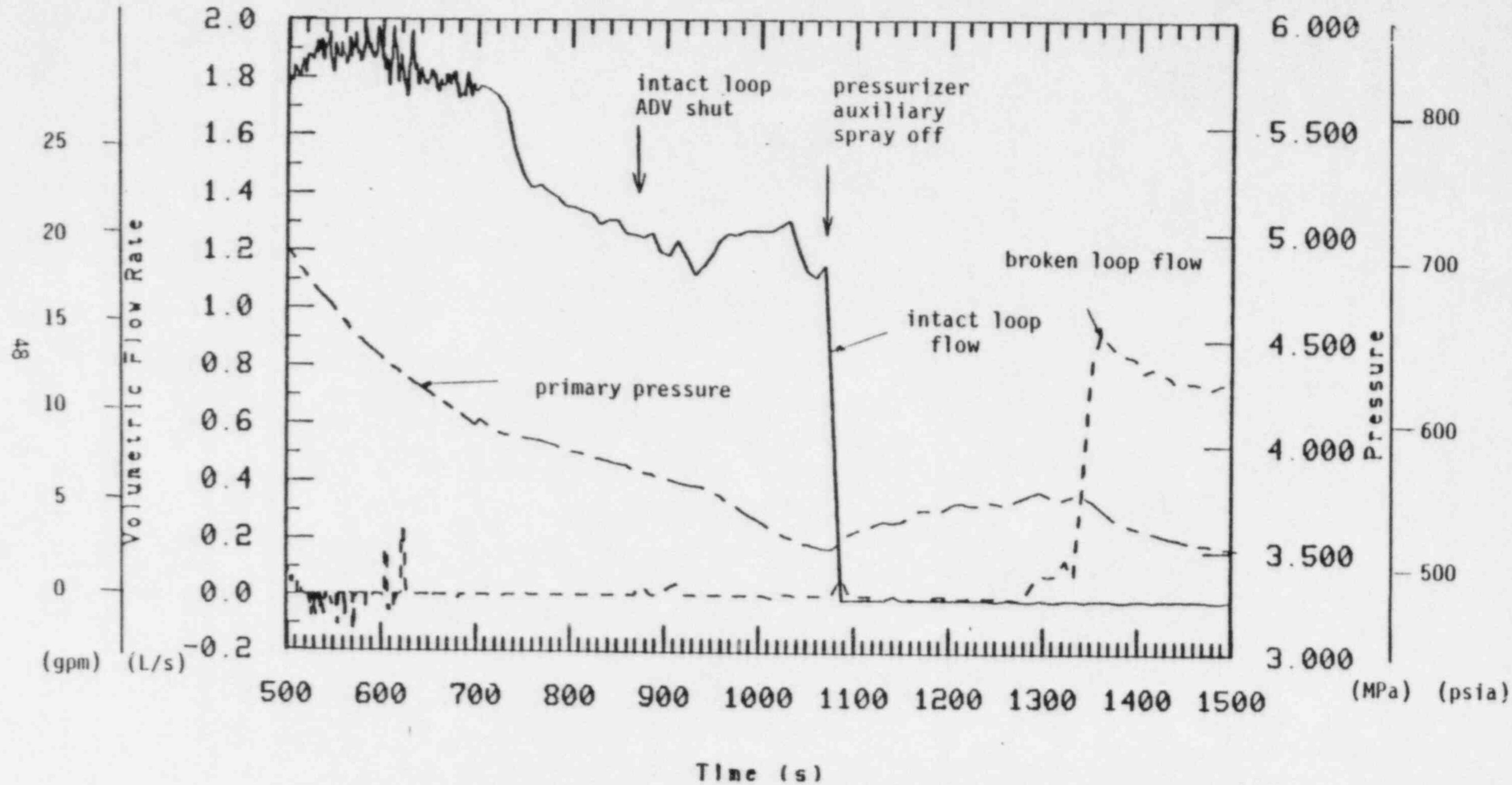

Figure 30. Comparison of intact and broken loop hot leg flow and primary pressure during recovery for a hot-side five-tube rupture transient (S-SG-6).

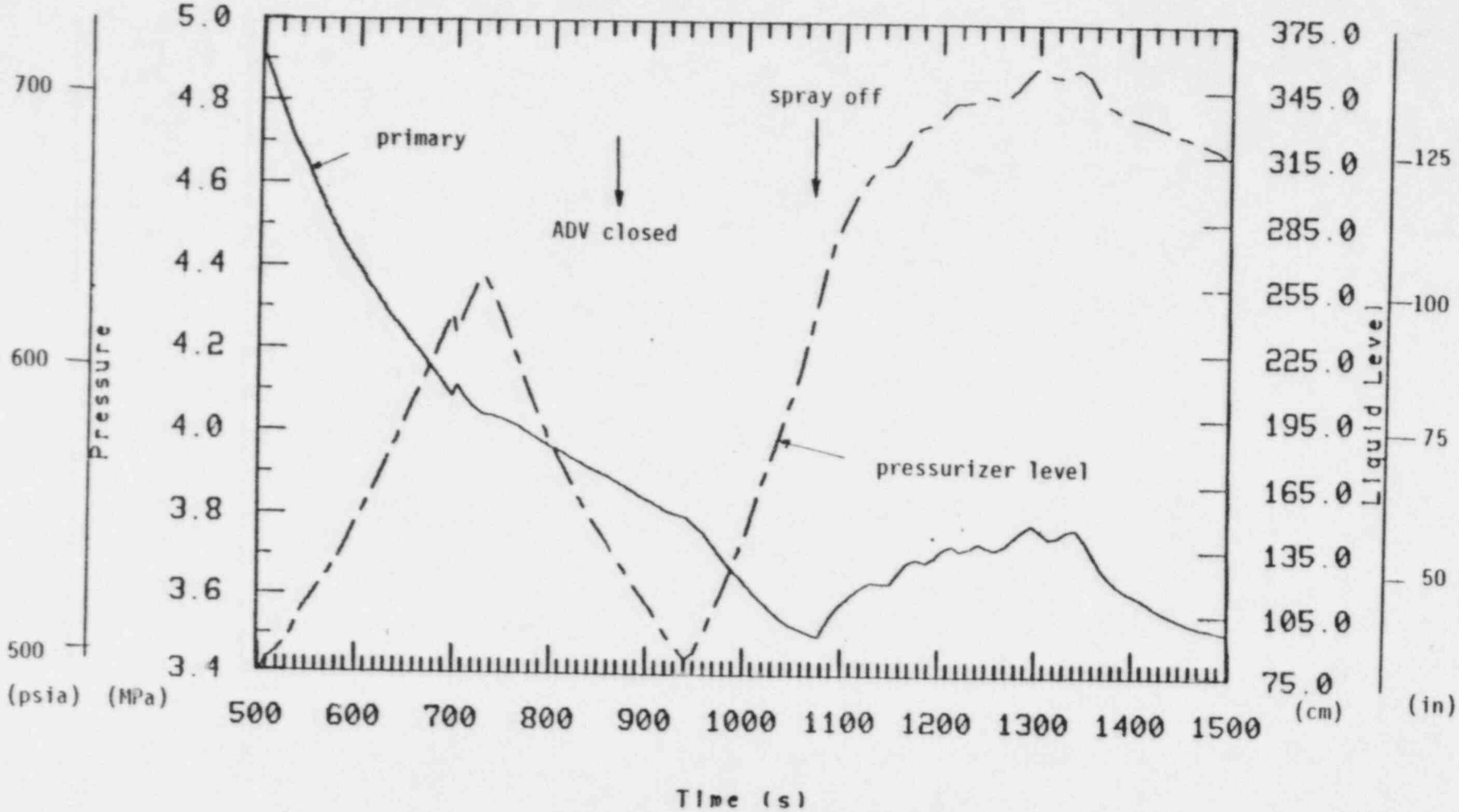

Figure 31. Comparison of pressurizer level and primary pressure during recovery of a hot-side five-tube rupture transient (S-SG-6).

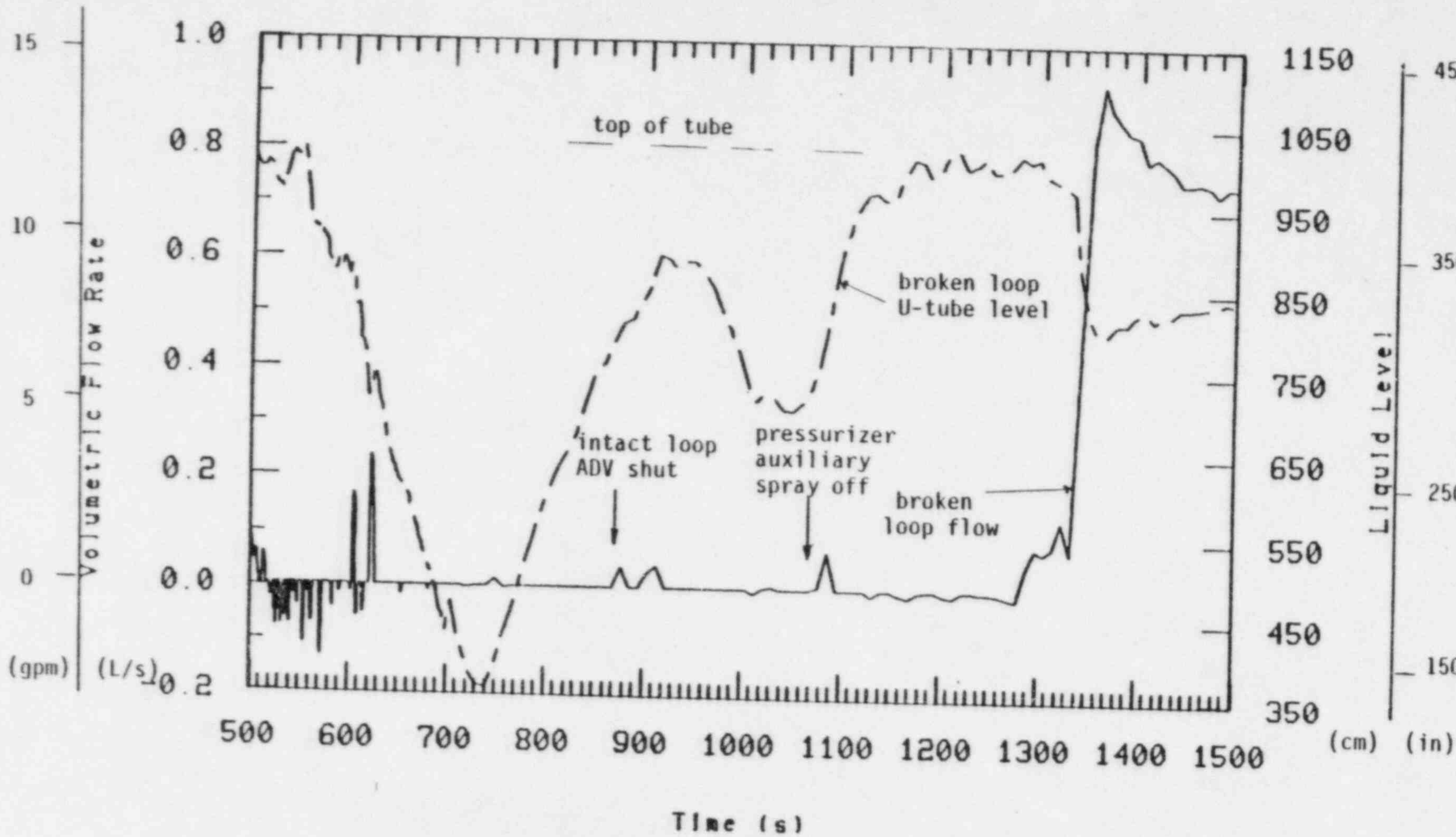

Figure 32. Comparison of broken loop hot leg flow and U-tube level during recovery from a five-tube rupture transient (S-SG-6).

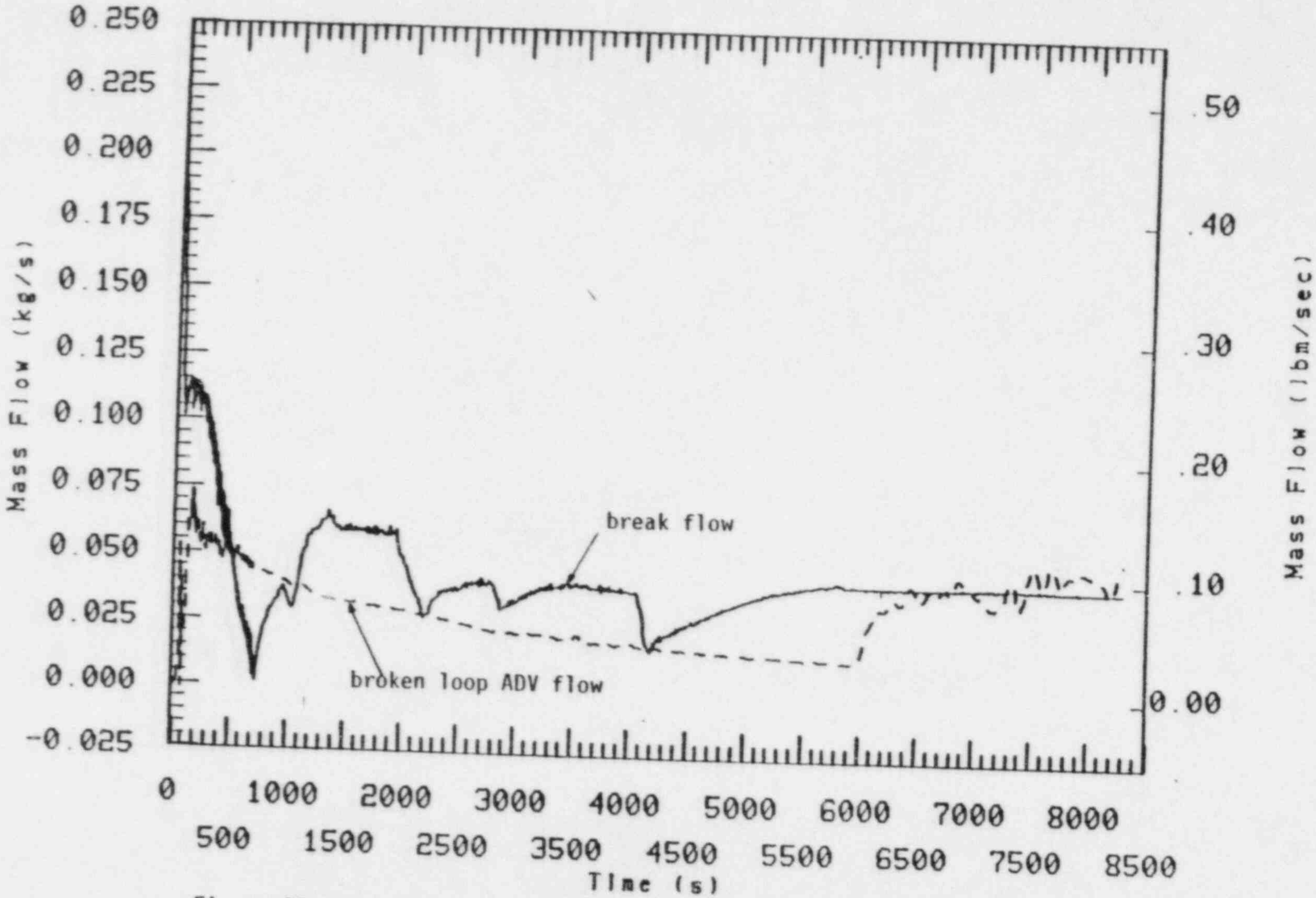

Figure 33. Comparison of break flow and broken loop ADV flow during recovery for a hot-side five-tube transient (S-SG-6).

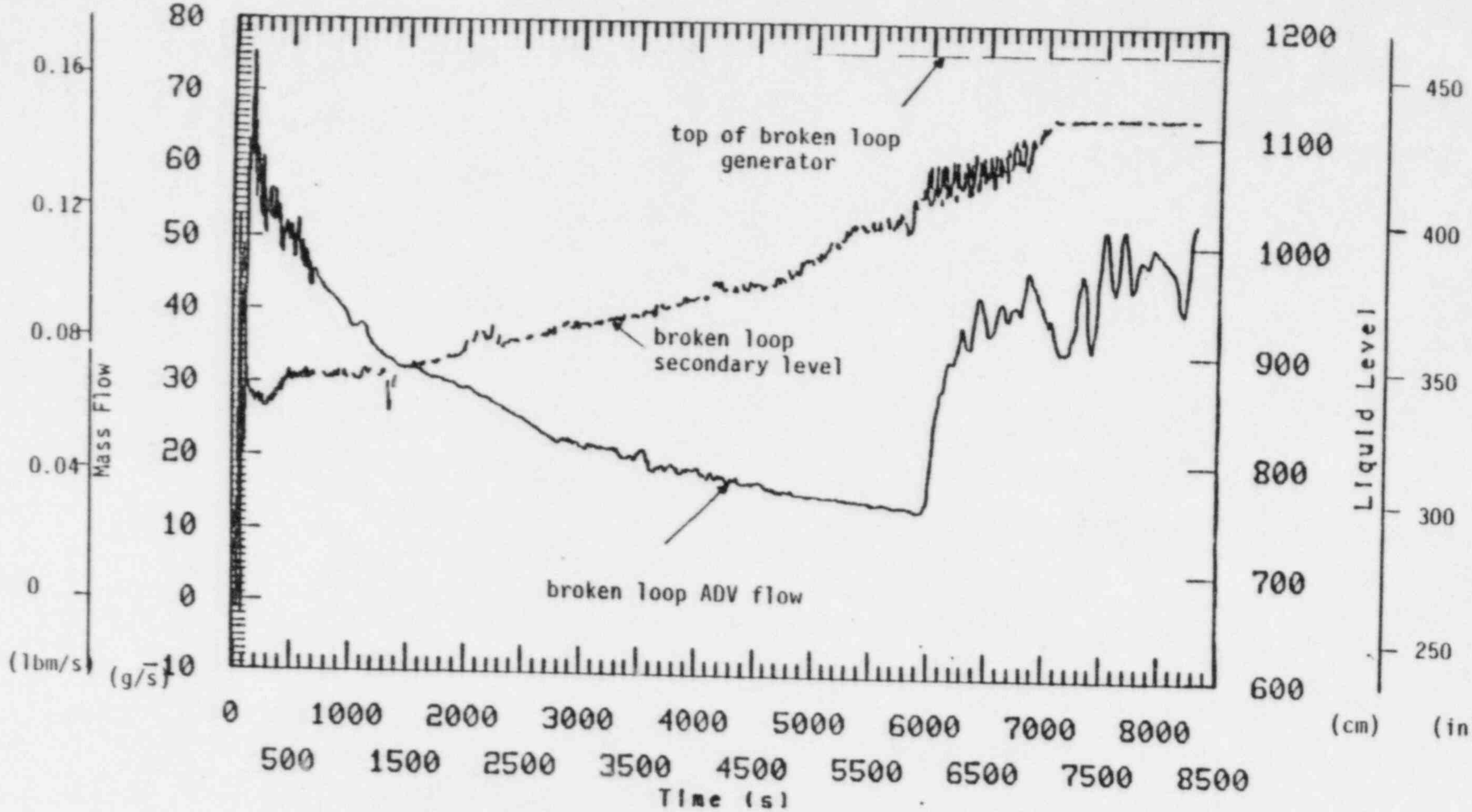

Figure 34. Comparison of broken loop ADV flow and broken loop secondary level during recovery from a hot-side five-tube rupture transient (S-SG-6).

increased to near the top. The primary system and broken loop secondary were somewhat hydraulically coupled through the break and surges of liquid out the ADV caused a general increase in the primary depressurization rate (Figure 35). Eventually the primary pressure reached the termination criteria of the LPIS setpoint pressure [1.38 MPa (200 psia)].

In summary, the operator response of using intact loop ADV operation, SI, and pressurizer auxiliary spray operation with a stuck open broken loop ADV (600-8181 s) was sufficient to reduce the primary pressure to the LPIS setpoint pressure 1.38 MPa (200 psia). During this operator response, intact loop ADV operation (feed and steam in the latched open mode) was useful for cooling the loop fluid and causing a general slow primary depressurization due to fluid shrinkage. Also during this period, pressurizer auxiliary spray was effective in stimulating the primary depressurization due to pressurizer void collapse from the condensation process. For any given spray cycle, once spray was stopped on a high pressurizer level trip, the relatively rapid primary depressurization provided by the condensation process was stopped. If the combination of pressurizer auxiliary spray and intact loop ADV operation were aligned off at the same time, the primary pressure actually increased. The increase in primary pressure was caused by a sequence of events starting with closing the intact loop ADV on a low secondary level trip. Eventually the loss of heat sink caused a cessation of the existing two-phase natural circulation flow in the intact loop (complete stagnation of flow) which lead to a primary pressure increase and an increase in pressurizer level due to expansion of system fluid (due to core decay heat). Eventually natural circulation flow restarted in the broken loop due to bridging of fluid in a blocked tube. This restart of broken loop flow started removing core decay heat via primary to broken loop secondary heat transfer and the primary pressure decreased. The entire recovery procedure of reducing the primary pressure to the LPIS setpoints was accomplished while maintaining the collapsed vessel level 40 cm (16 in) above the top of the core.

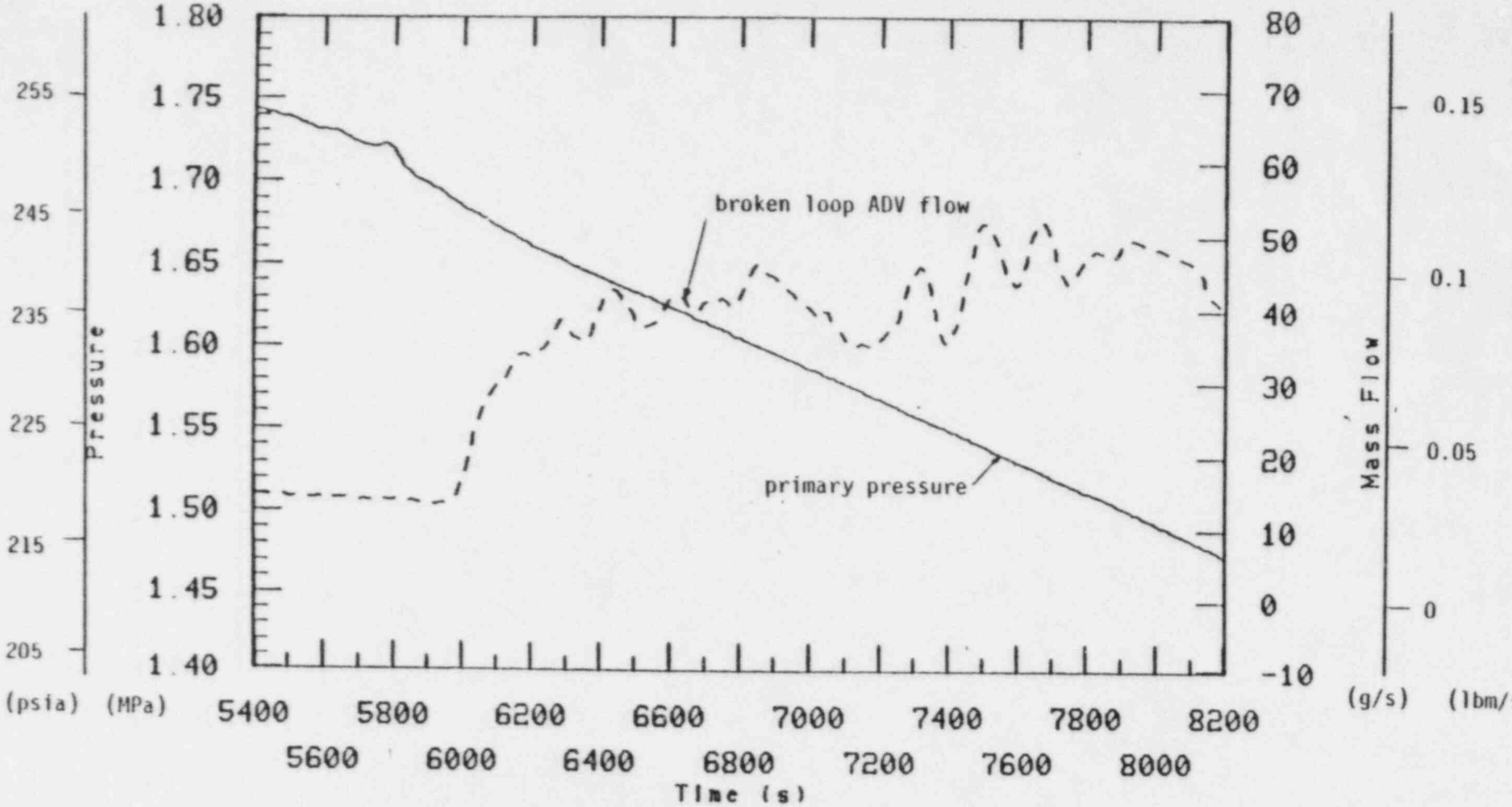

Figure 35. Comparison of broken loop ADV flow and primary pressure during recovery from a hot-side five-tube rupture transient (S-SG-6).

3.3 Effect of Tube Rupture Location During the Semiscale Tube Rupture Test Series

Prior to early operator response at 94 s Test S-SG-6 procedure was identical to Test S-SG-7 (Reference 4) except for the location of the break. For Test S-SG-6 the break was located on the hot side of the broken loop steam generator and for Test S-SG-7 the break was located on the cold side. Test procedures and initial conditions were essentially identical for the two experiments.

During the first 90 s of the tube rupture (involving automatically occurring events) there was essentially no difference in hot side 5 tube rupture transients and cold side 5 tube rupture transients. Similarity in response for the two experiments is shown on Figure 36 which compares the primary pressure response, Figure 37 which compares the pressurizer level response, Figure 38 which compares the break flow, and Figure 39 which compares the intact loop flow.

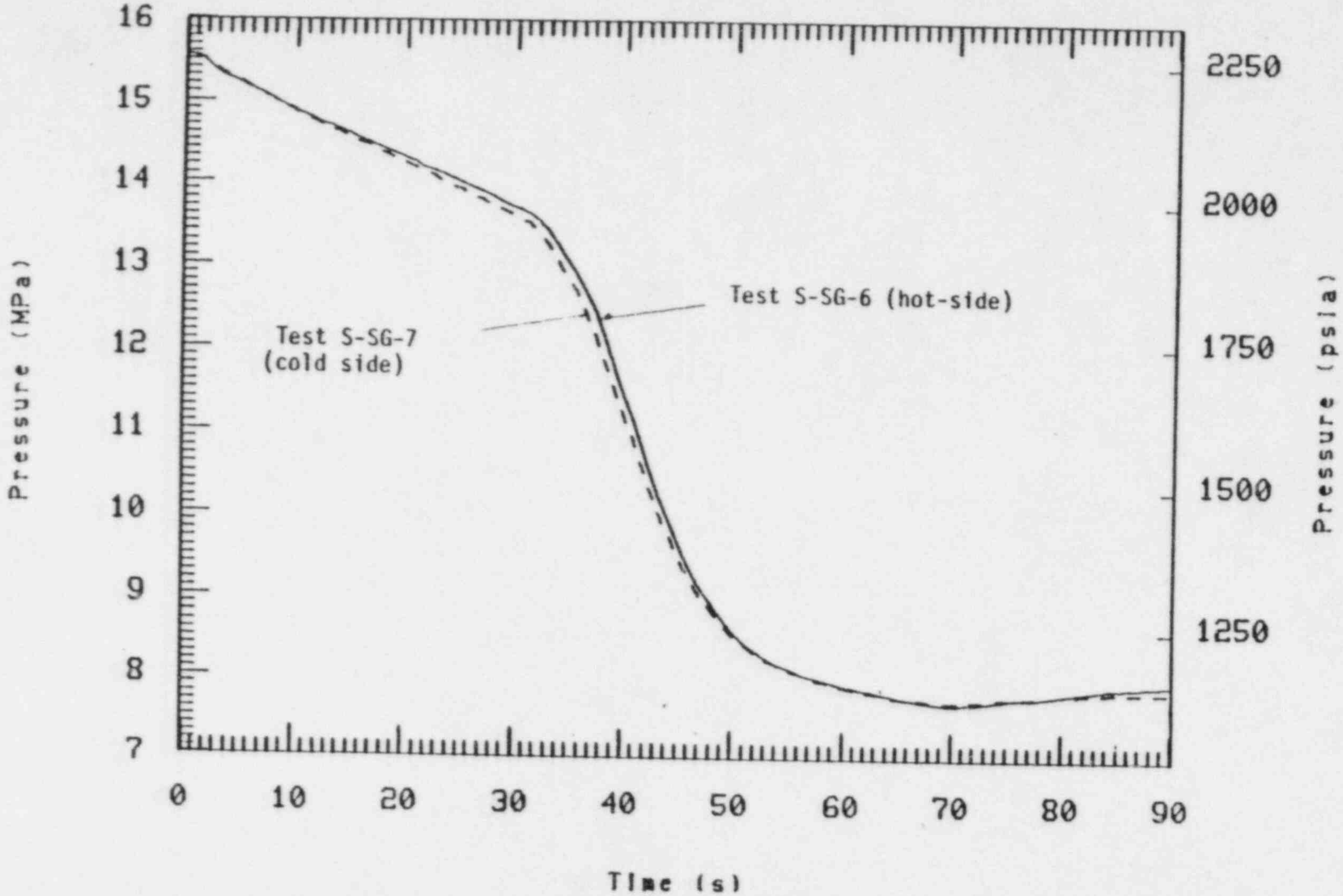

Figure 36. Comparison of primary pressure for hot-side (S-SG-6) and cold-side (S-SG-7) five-tube rupture transients.

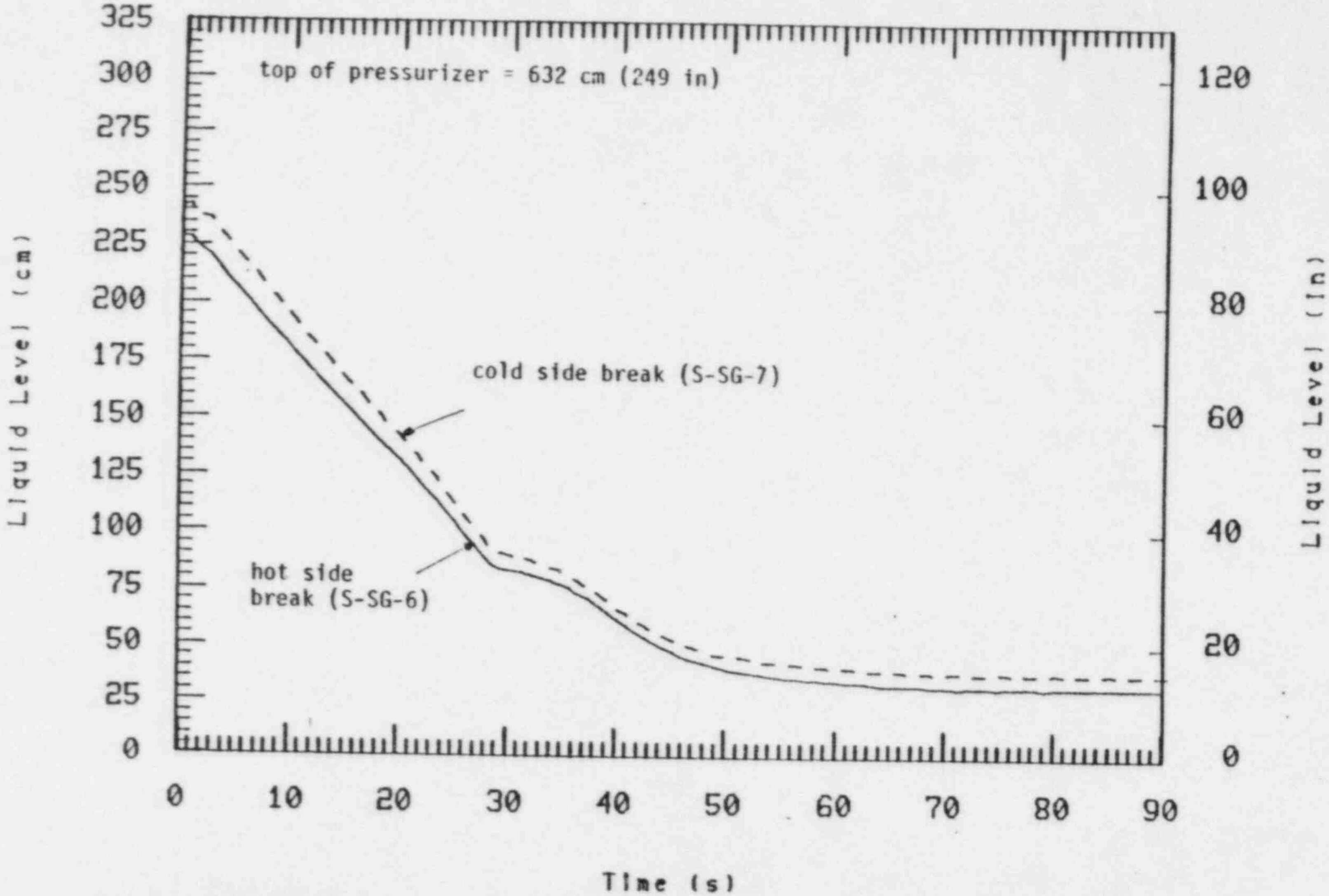

Figure 37. Comparison of pressurizer collapsed liquid level for a hot-side (S-SG-6) and cold side (S-SG-7) five-tube rupture transient.

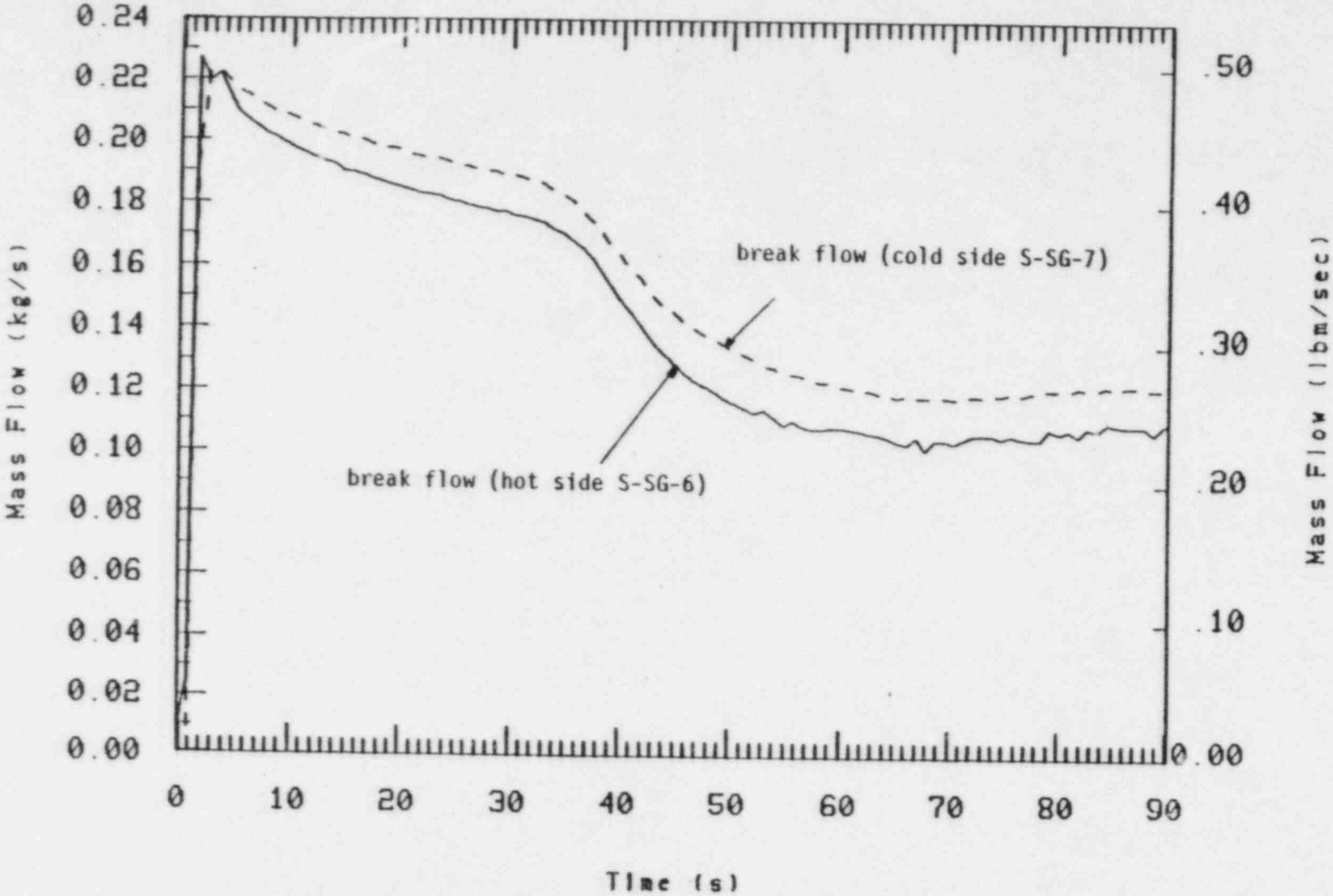

Figure 38. Comparison of break flow for hot-side (S-SG-6) and cold side (S-SG-7) five-tube rupture transients.

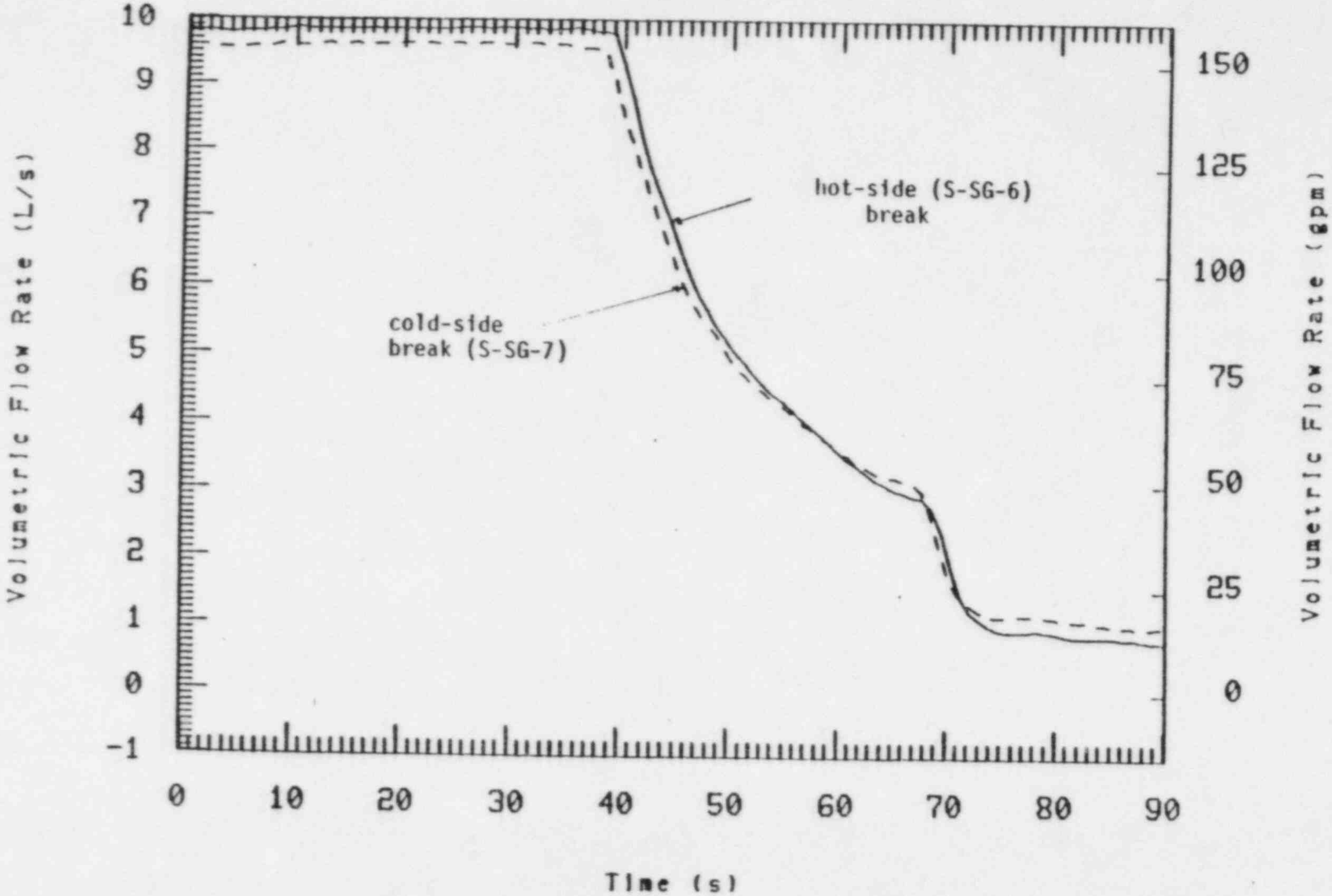

Figure 39. Comparison of hot leg flow for a hot-side (S-SG-6) and cold-side (S-SG-7) five-tube rupture transient.

4. COMPARISON OF PRETEST CALCULATION TO TEST DATA

This section compares the S-SG-6 test results to the best-estimate calculation documented in the S-SG-6 Pretest Analysis Document.[6] Discussion of the calculated and test results comparisons are presented in the following three subsections: Operator Diagnostic Period (4.1), Plant Recovery (4.2), and Summary and Recommendations (4.3). Table 5 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 from time zero through 94 s. Table 6 presents the actual and calculated initial conditions. All of the calculated and actual initial conditions, with one exception, agreed well enough that the subsequent transient responses were not significantly influenced by any differences. The one exception was the initial water mass in the ILSG, which was 9.3 kg less in the test than in the calculation. Its effect is discussed in Section 4.2. Figures 40, 41, and 42 compare the pressurizer pressures ILSG and BLSG secondary pressures, respectively, showing good agreement through and beyond the 94 s diagnostic period.

Two methods are used to compute liquid levels in this report, collapsed and interfacial. The collapsed level method assumes that the entire differential pressure between two points is due to saturated liquid and is calculated by

$$LL_c = \frac{\Delta P}{\rho_{fsat} g} ,$$

TABLE 5. COMPARISON OF PREDICTED AND MEASURED EVENT TIMING

Event	Calculated Time (s)	Actual Time (s)
Transient initiation	0	0
Scram	33.5	33.9
Pressurizer initially empty	36.0	35.5[a]
SIS	37.0	36.5
AUX FW ON	37.0	37.4
BLSG relief valves last cycles	51.1	50
PCS pump coastdown complete	75.5	68
Operator opens ILSG and BLSG ADVs	93.5	94
ILSG collapsed secondary liquid level drops to 250 cm (98.4 in.) and closes ADV	1433	881 2312
ILSG liquid level climbs to 400 cm (157.5 in.) and opens ADV	2438	1621 3288
BLSG liquid full	4500	5950
HPIS terminated	5534.3	8181
Calculation/test terminated	5677	8181

a. Actual pressurizer emptying time is estimated based on level measurement LPRZ+30-28.

TABLE 6. COMPARISON OF PREDICTED AND MEASURED INITIAL CONDITIONS

Parameter	Actual	Calculated
Pressurizer pressure	15.68 MPa (2274 psia)	15.56 MPa (2257 psia)
Core temperature differential	37.9 K (68.2°F)	37.3 K (67.1°F)
Cold leg fluid temperature loop to loop difference--max	0.3 K (0.54°F)	0.33 K (0.6°F)
Initial core power	1.99 MW	2.0 MW
Pressurizer liquid volume	0.0097 m^3 (0.34 ft^3)	0.0102 m^3 (0.36 ft^3)
Nominal primary flowrates[a]		
Intact loop	8.1 ℓ/s (128 gpm)	9.6 ℓ/s (151.7 gpm)
Broken loop	2.7 ℓ/s (43 gpm)	3.4 ℓ/s (54.1 gpm)
SG secondary pressure		
Intact loop	5.56 MPa (806 psia)	5.56 MPa (806 psia)
Broken loop	5.62 MPa (815 psia)	5.52 MPa (801 psia)
SG secondary water mass		
Intact loop	88 kg (194 lbm)	97.3 kg (221.1 lbm)
Broken loop	96.kg (213 lbm)	101.6 kg (220.5 lbm)
Primary leakage at t = 0	0.0033 kg/s (0.0073 lbm/s)	0.006 kg/s (0.013 lbm/s)

a. Varied to achieve 37 K core temperature differential.

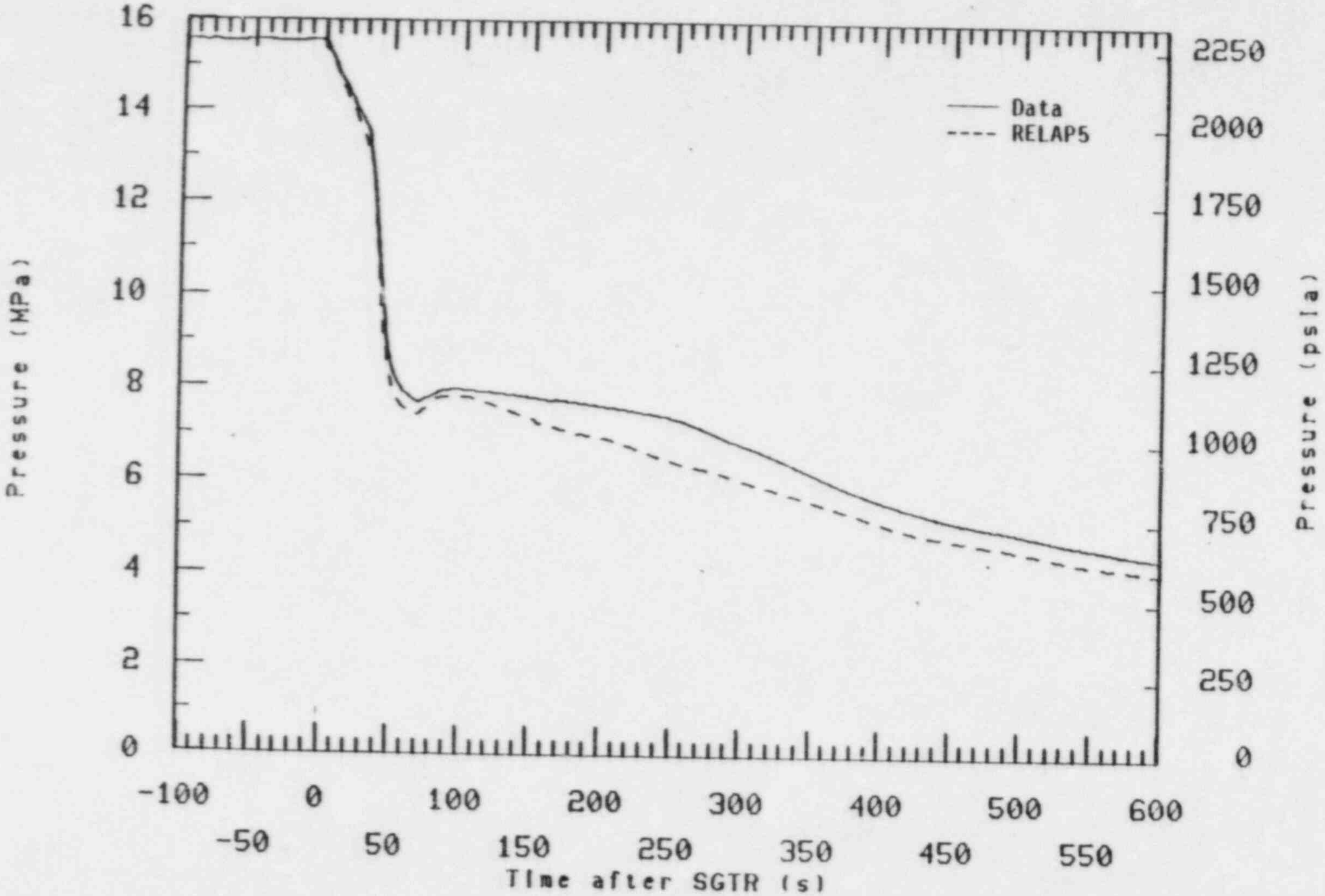

Figure 40. Primary pressure comparison - diagnostic period.

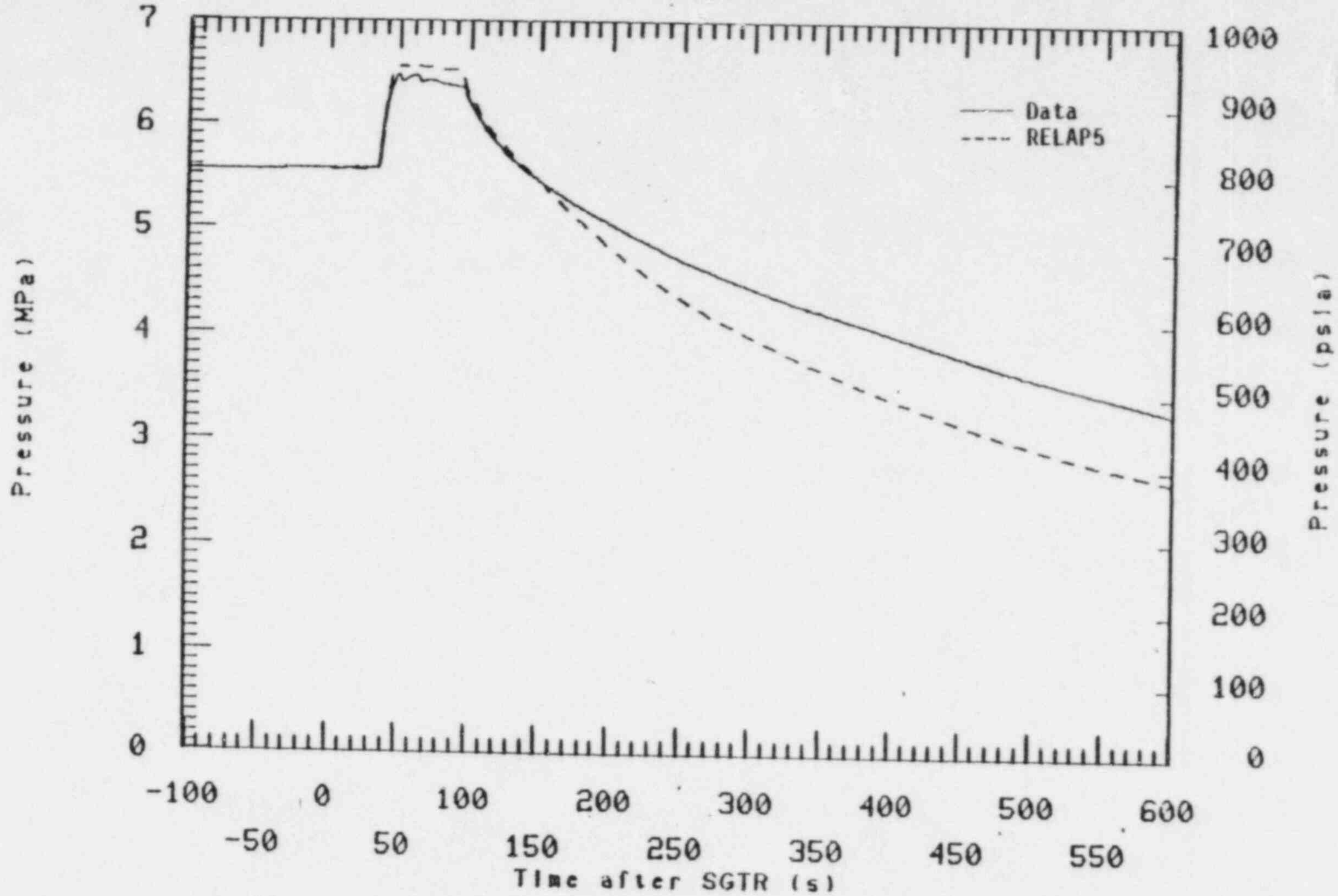

Figure 41. ILSG pressure comparison - diagnostic period.

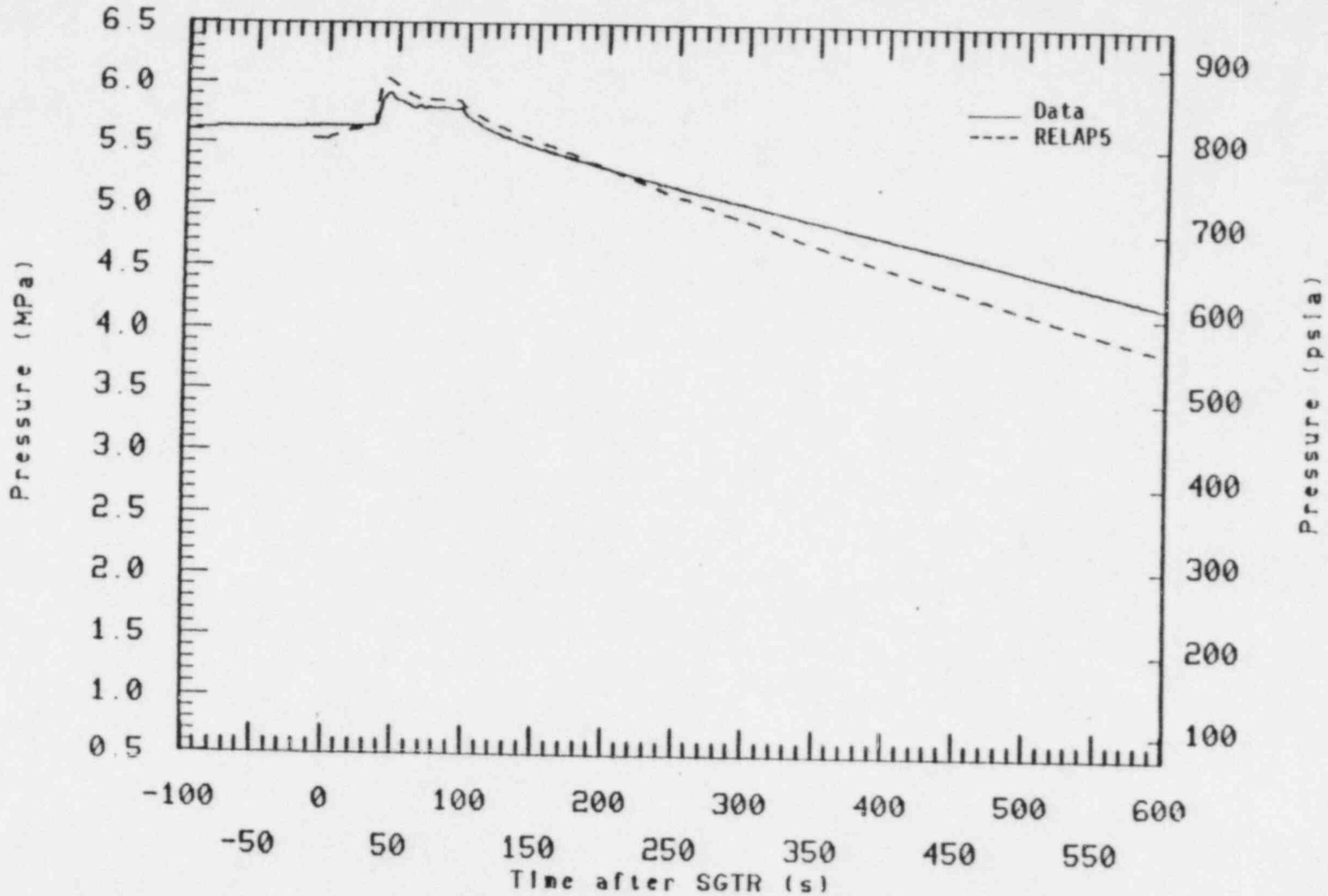

Figure 42. BLSG pressure comparison - diagnostic period.

where

ΔP = pressure at lower tap minus pressure at upper tap,

ρ_{fsat} = the density of saturated liquid, and

g = the acceleration of gravity.

The interfacial level represents the position of the liquid-vapor interface assuming the two phases are completely separated in the region of interest. The interfacial level is the sum of the product of the liquid fraction and volume length and is calculated by

$$LL_I = \sum_{i=1}^{n} (1 - \alpha_i) L_i \quad ,$$

where n is the number of individual volumes in the region of interest, and L and α are their length and void fraction, respectively. The physical interpretation of collapsed and interfacial liquid level are the same for the data and the code calculations, although the equations used to reduce the measured DP readings are not the same as those described above for the RELAP5 analysis.

Figure 43 compares the pressurizer interfacial liquid levels. The lower ΔP tap (elevation 29.7 cm, 11.7 inches) is the lower limit for the test level measurement but the pressurizer actually emptied at the same time as the calculation (based on ΔP measurement LPRZ+30-28).

The timing of all events during the operator diagnostic period was closely predicted as shown in Table 5.

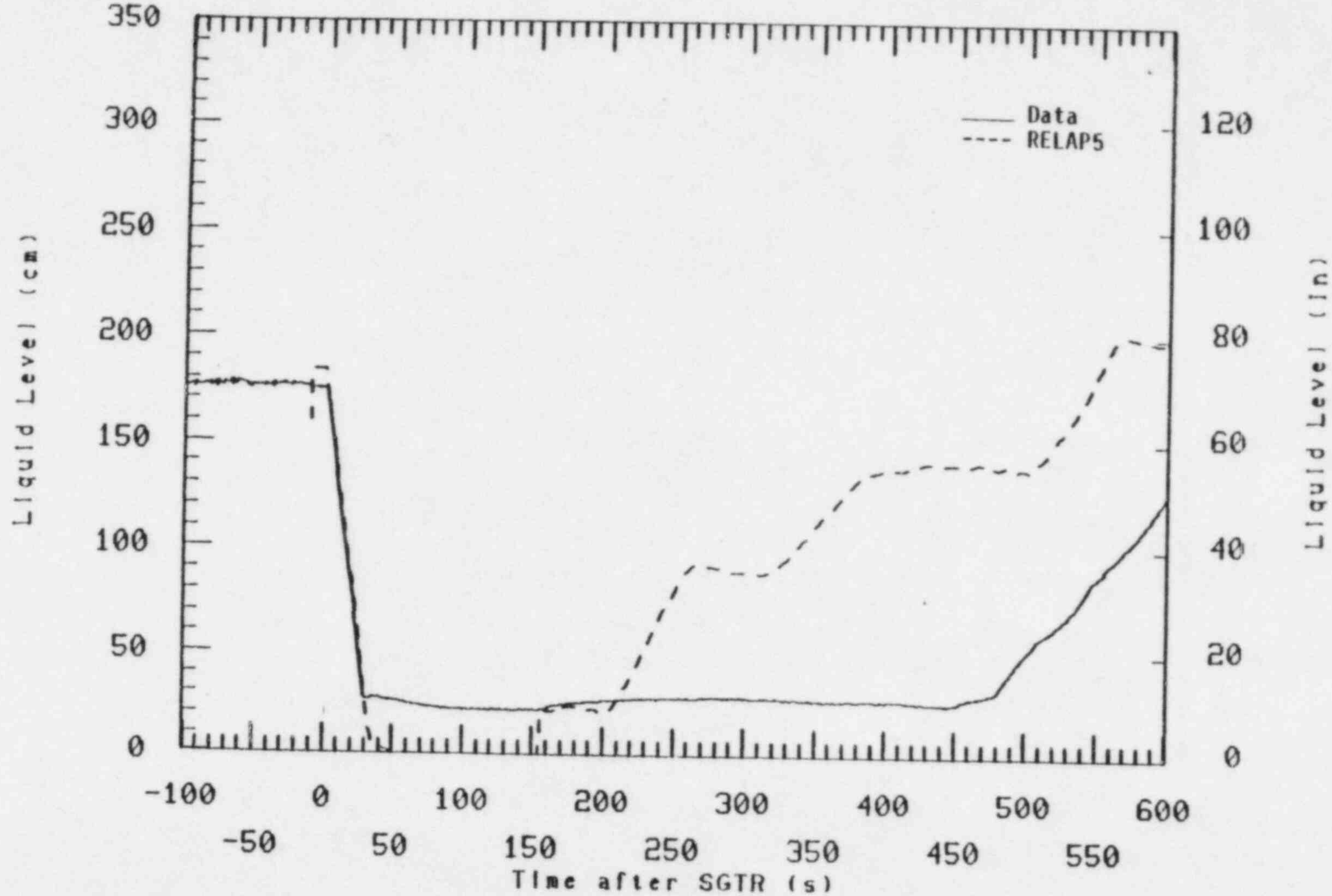

Figure 43. Pressurizer interfacial liquid level - diagnostic period.

4.2 Plant Recovery Period

This section discusses comparisons of calculated and test results for the recovery phase of the transient. The test ran to 8181 s but the calculation terminated at 5677 s, so the comparisons will cover the period from 94 to 5677 s.

Figure 44 compares pressurizer pressures. Starting at approximately 120 s, the calculation overpredicts the depressurization rate until approximately 2000 s. From 2000 s until the end of the calculation, although depressurization rates were similar, the calculation pressure was less than the test pressure. The abrupt rise in test pressure at 1068 s was caused by the combined actions of the ILSG ADV and the pressurizer spray as discussed in Section 3.2.

In the calculation the ILSG ADV did not close until 1433 s, 552 s later than in the test (Figure 45). Table 7 lists several parameters useful for illustrating some reasons for differences in ILSG ADV closure timing. The small increase in secondary mass inventories between test initiation and 37 s is due to a mismatch between main steam and feedwater flow rates in the test and to closure of the main steam valves before closing the main feedwater valves in both the test and the calculation. The measured mass at the time the auxiliary feedwater started (37 s) was 8 kg (17.6 lbm) less than the calculated mass. Based upon the test net outflow rate (ADV flow minus auxiliary feedwater flow) at ADV closing time, an additional 8 kg in the steam generator would have required another 167 s of ADV open time to reach the closure criteria.

Since the ADV's in both cases are closed when the collapsed downcomer level falls to 250 cm (98.4 in), the remaining 385 s of the difference in closure timing is due to the higher estimated ADV flow rate in the test (Figure 46). It is important to note that one of the two catch tanks on the ILSG was apparently in error, resulting in a reading too high for this test. Based on comparisons with previous experience (especially Test S-SG-5) and with the BLSG results in this test, the high readings were

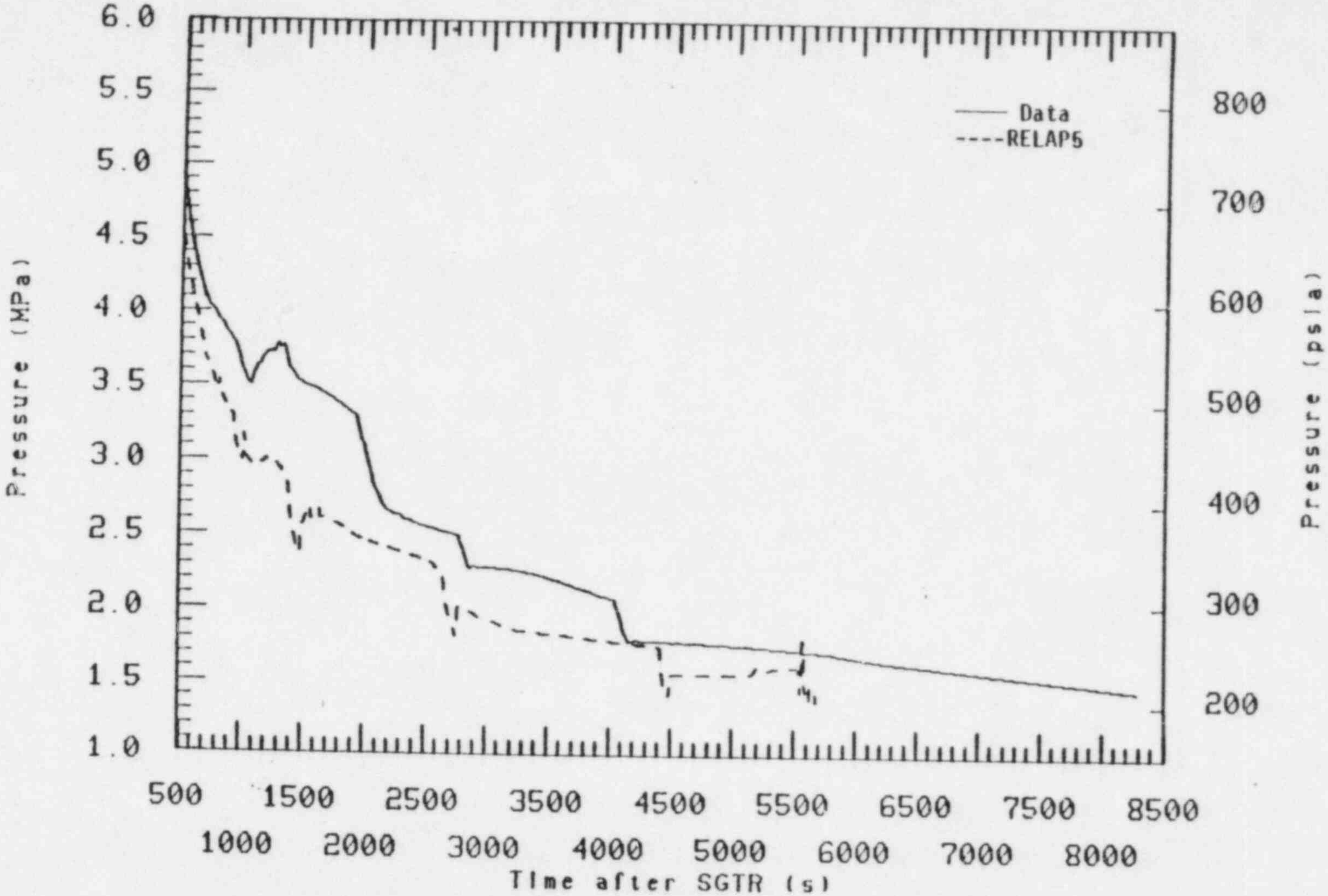

Figure 44. Pressurizer pressure comparison - recovery period.

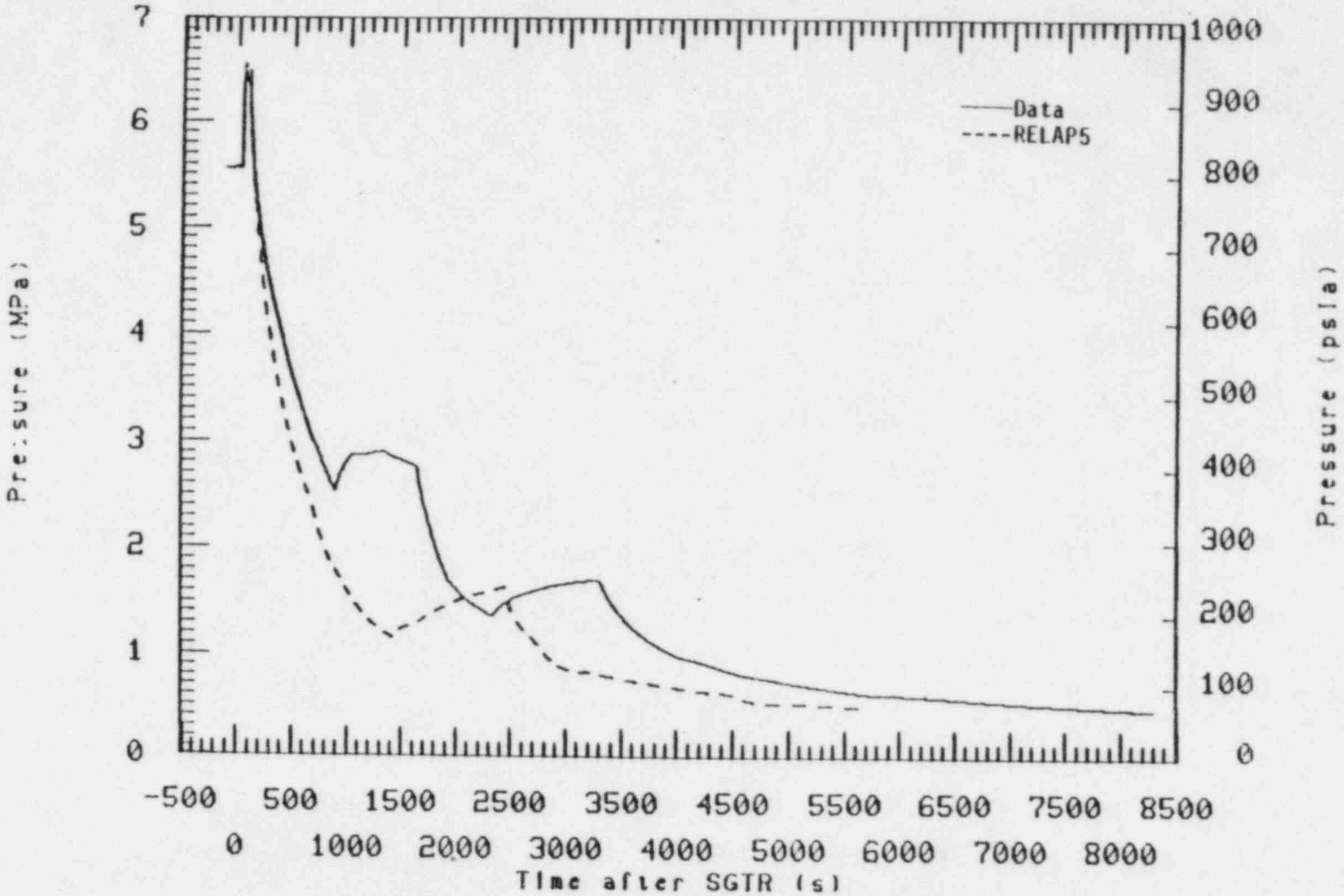

Figure 45. ILSG pressure comparison - recovery period.

TABLE 7. ILSG SECONDARY MASS

ILSG	Test	Calculation
Initial mass	88 kg (194 lbm)	97 kg (214 lbm)
Mass at 37 s when auxiliary feedwater starts	92 kg (203 lbm)	100 kg (220 lbm)
ADV opening time	93.5 s	94 s
ADV closing time	881 s	1433 s

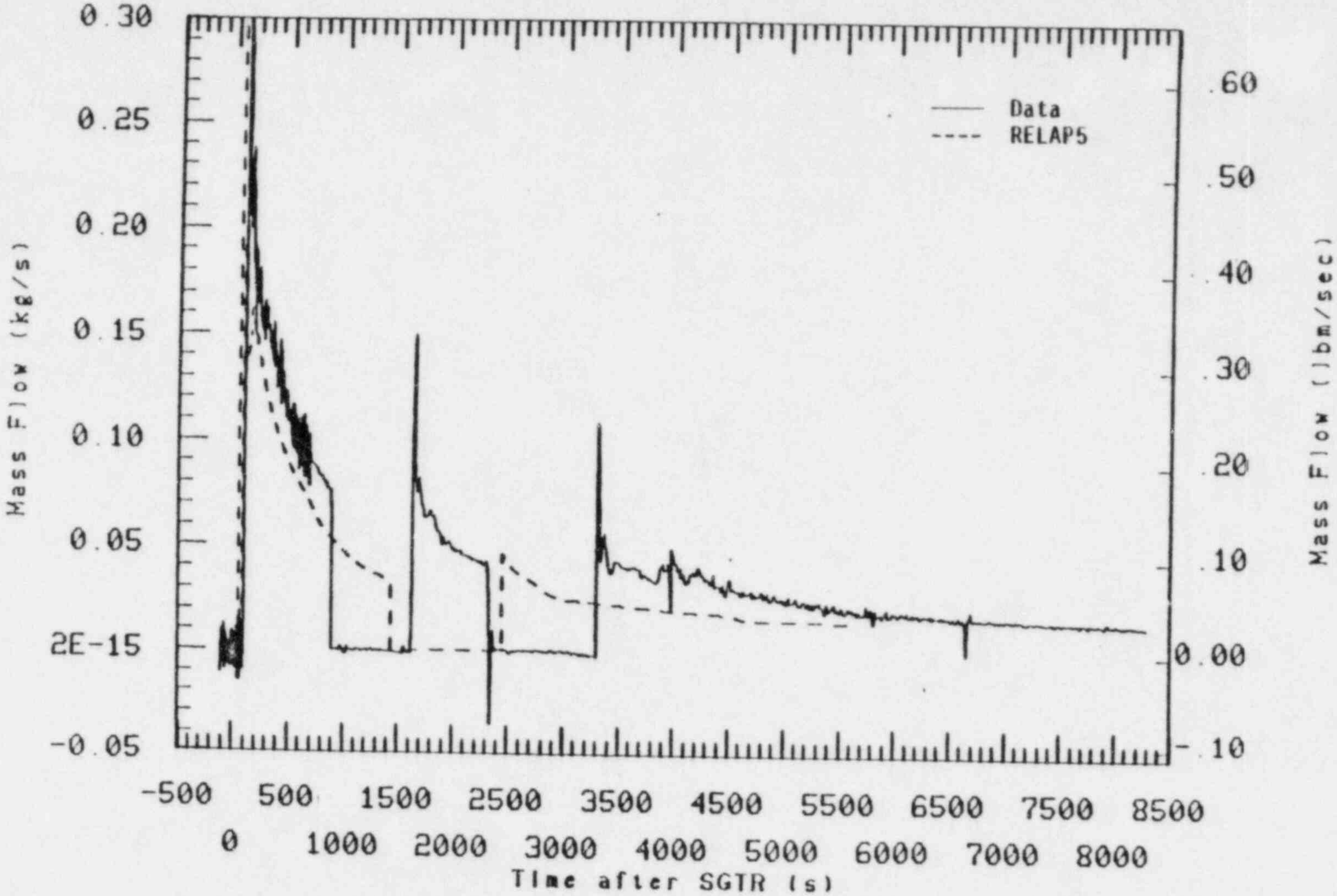

Figure 46. ILSG ADV flow comparison.

adjusted downward to be compatible with the other ILSG catch tank data. This proviso should be kept in mind when considering the ILSG test ADV flow rate. Choked flow comparisons for both the test and the RELAP5 calculations, based upon upstream pressure and density, show good agreement with the data in Figure 46. These comparisons indicate that the difference in ADV flow rates was caused by the difference in measured and calculated secondary system pressure. Higher pressure during the test resulted in higher ADV flow then predicted. It is observed (Figure 45) that when the test ADV reopened at approximately 1600 s the secondary pressure was 2.76 MPa (400 psia) and when the calculated ADV reopened at approximately 3300 s the secondary pressure was 1.64 MPa (238 psia). Again, this resulted in a higher measured ADV flow than calculated when the valves reopened, with the downcomer level falling to the ADV closure level for the second time. Because of the lower calculated ADV flow, no second opening of the ADV occurred.

A comparison of break flows is presented in Figure 47. The test break flow was saturated at the flow measuring venturi after the first 60 s so the venturi flow measurement was considered questionable. A two phase break flow calculation was made using the break orifice data, but the calculation should be viewed as qualitative only. The calculation apparently underpredicted the break flow, resulting in less voiding in the upper-plenum/upper-head area (Figure 48). The calculation predicted nearly compete voiding of the upper head by 500 s and nearly complete refilling by 1000 s, whereas the test showed nearly complete voiding and no refilling until 5900 s, and only slight refilling after 5900 s. The vessel liquid level comparison is shown in Figure 49 indicating more voiding than the calculation predicted, but no voiding in the core area. Although the break flow measurement was only approximate, the vessel voiding comparisons are consistent with a low break flow calculation.

Figures 45 and 50 compare the ILSG and BLSG depressurization rates respectively. It is seen that the calculation overpredicts the depressurization rates in both steam generators. A less noticeable effect is a slightly higher repressurization rate after the main steam valves are closed at 37 s. These effects have been noted in Test S-SG-5 and other

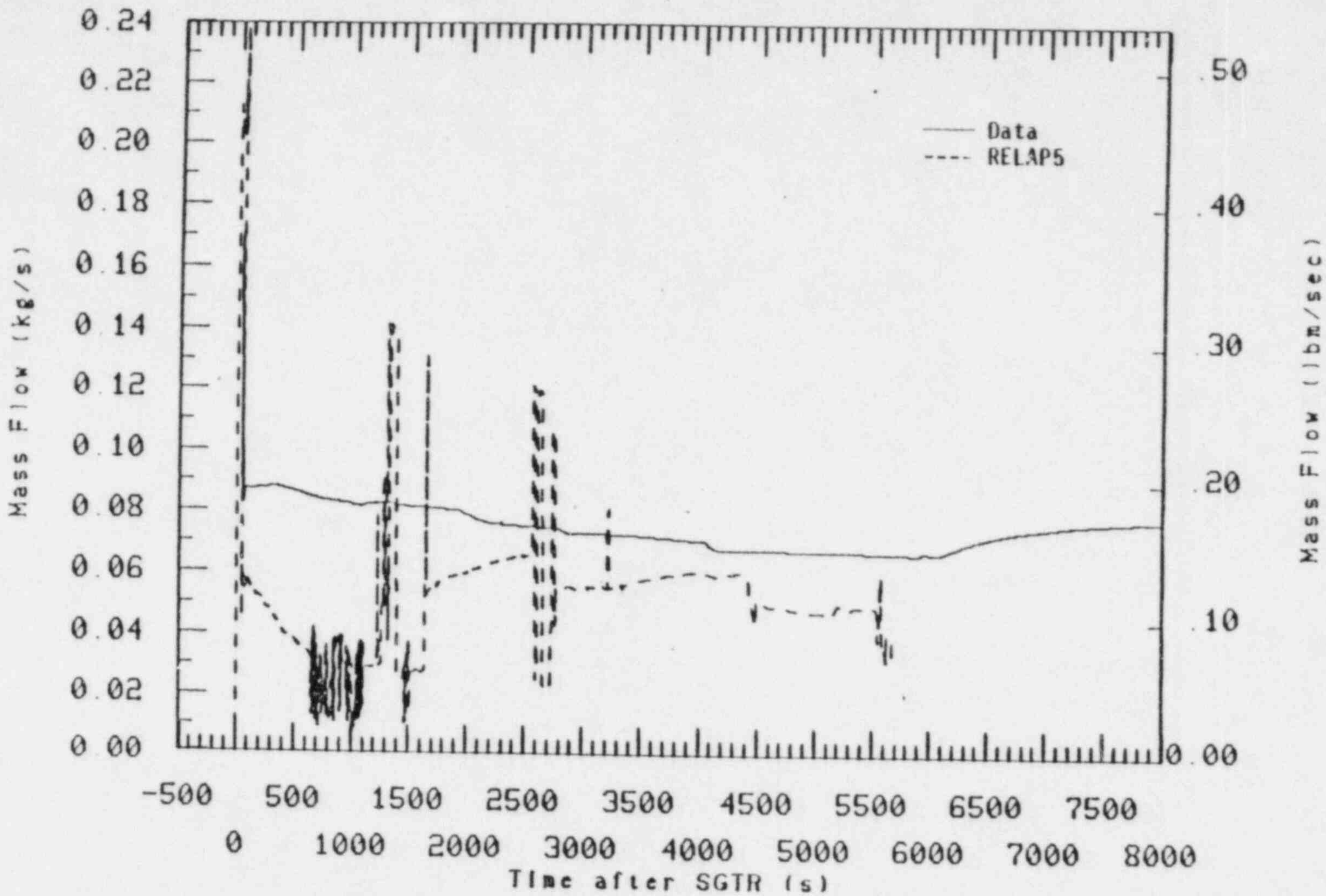

Figure 47. Break flow comparison - recovery period.

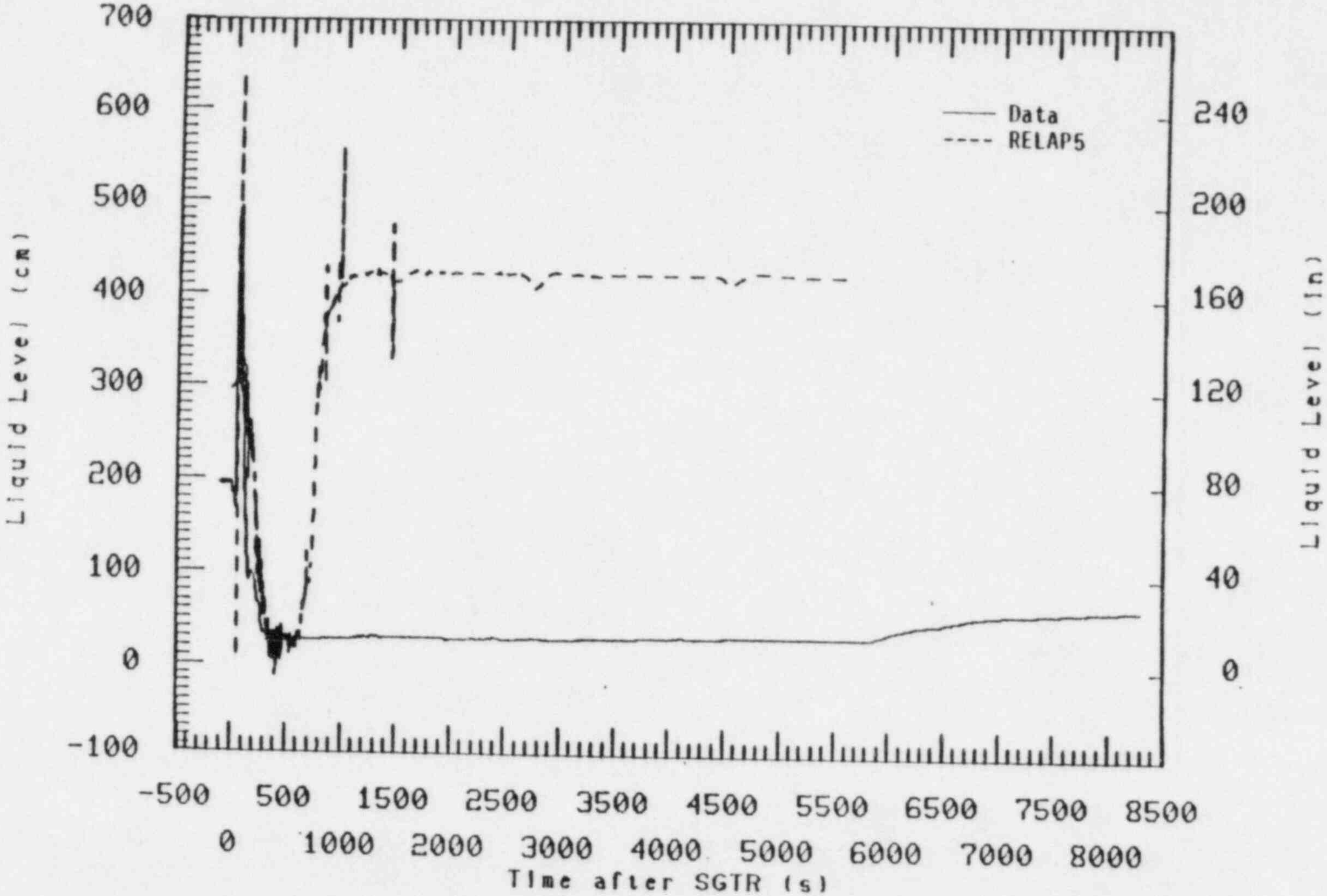

Figure 48. Upper-head/upper-plenum liquid level comparison referenced to cold leg centerline.

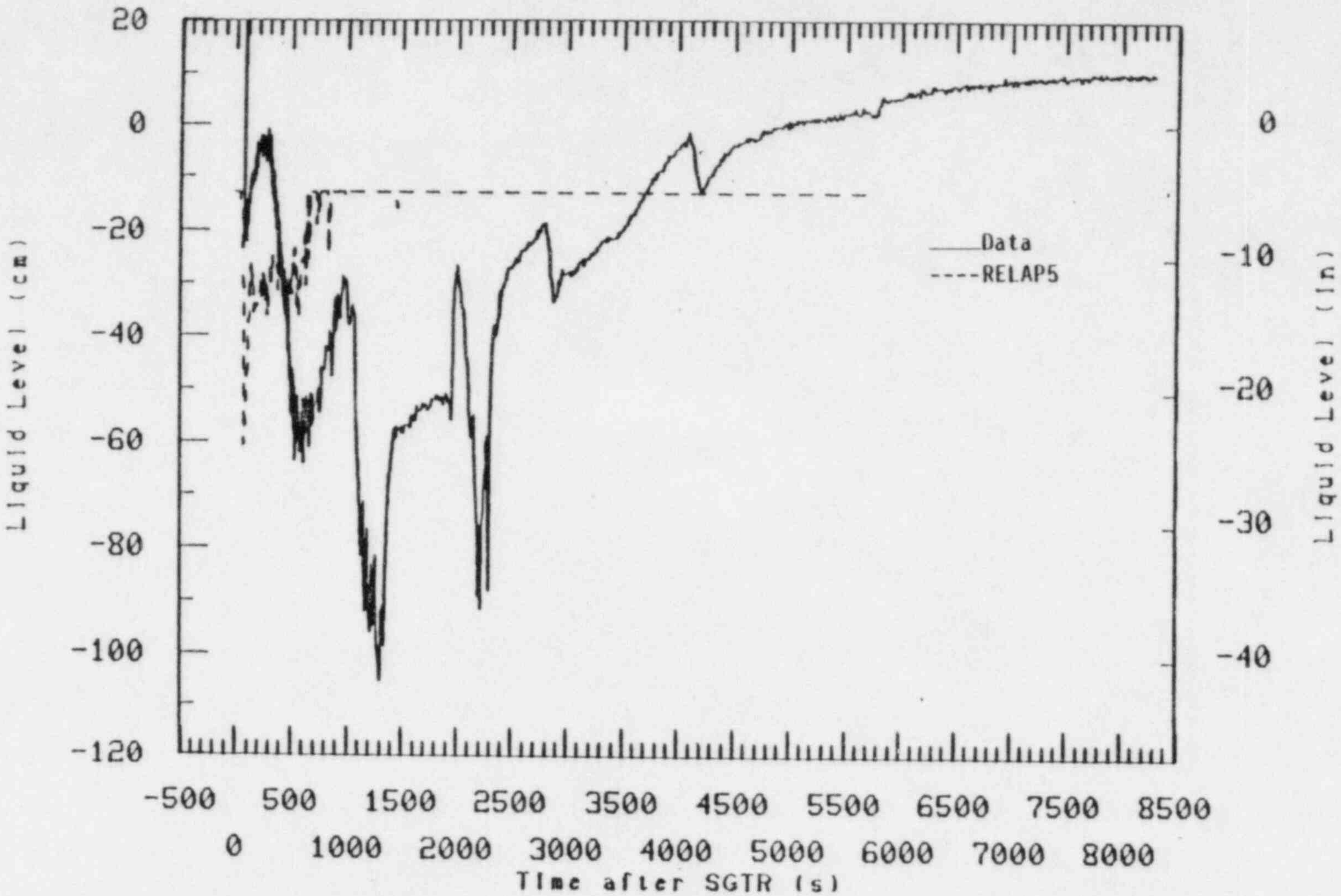

Figure 49. Vessel liquid level comparison -13 cm to -578 cm referenced to cold leg centerline.

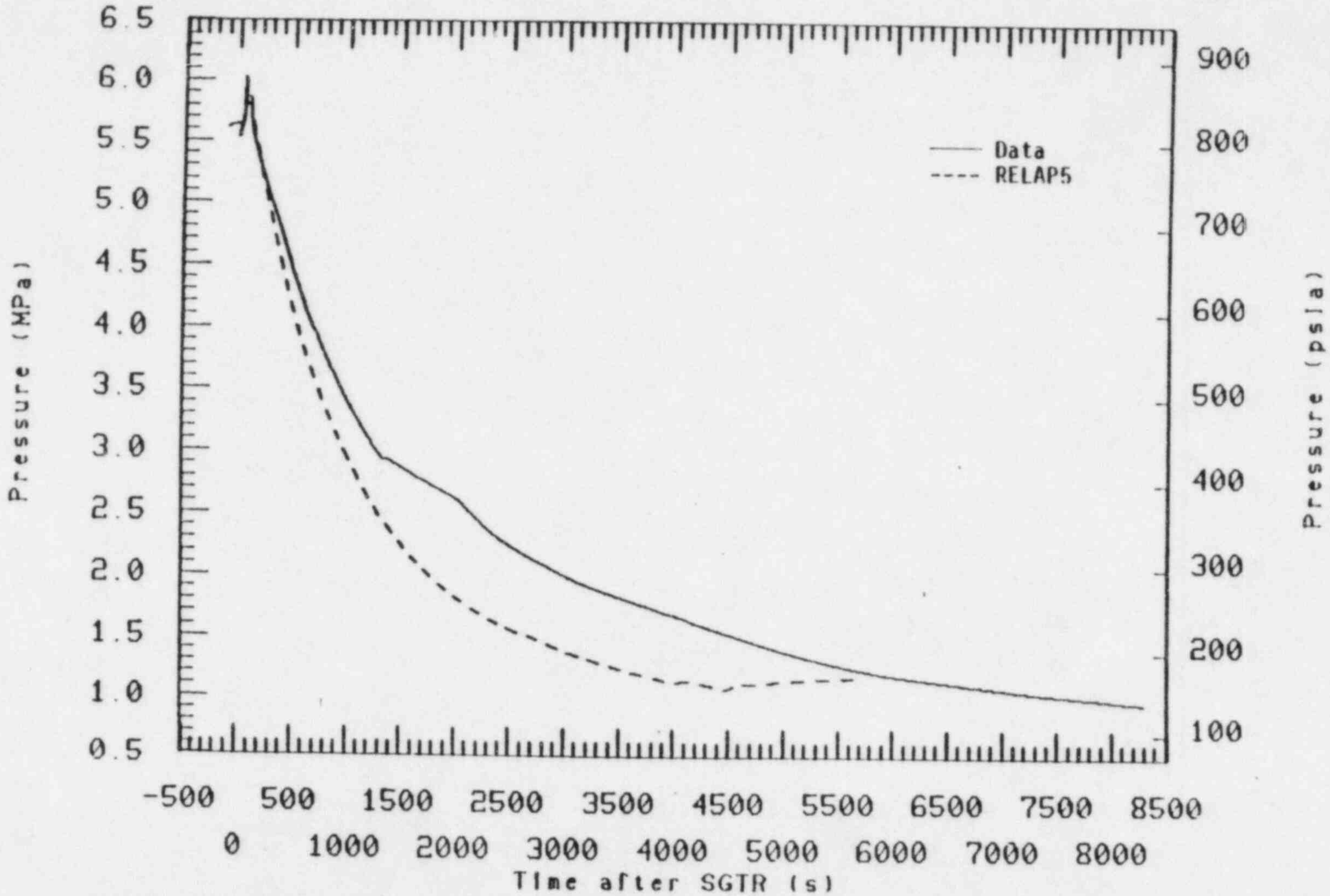

Figure 50. BLSG pressure comparison - recovery period.

tests in the S-SG tube rupture series. The faster steam generator depressurization rates resulted in overprediction of the PCS depressurization mentioned earlier and had a significant effect on the calculated ADV flow rates. The steam generator models have been benchmarked for environmental heat loss,[7] and the calculations accurately reflected the measured losses. The calculated secondary energy removal was less than measured due to the lower ADV flow rates. The foregoing evidence would suggest that the total heat capacity in the steam generators might be higher than in the RELAP5 model. This question will be addressed to determine whether it can be resolved when the BLSG is removed for system modifications.

Figures 51 and 52 are overlays of pressurizer steam temperature, saturation temperature and auxiliary spray flow rate for the test and calculation respectively. The most obvious difference between the two plots is the much larger superheat of the steam, when the pressurizer spray is off, for the calculation compared to the test. When the spray is on, the steam temperature drops quickly to saturation temperature in both cases. It would be expected that the higher superheat in the calculation would tend to retard the PCS depressurization rate relative to that of the test, but the faster depressurization rates of the steam generators overwhelm this effect. The pressurizer model has been benchmarked for environmental heat loss[8], but the high pressurizer superheat is a code problem. The RELAP5/MOD1.5 code does not compute wall heat transfer directly to subcooled spray droplets. Instead it assumes the liquid spray has been raised to saturation temperature before computing the wall heat transfer. Thus the heat transfer is under-calculated and the wall cools too slowly, causing the high superheat observed when the spray is off. This problem has been corrected in RELAP5/MOD2.[9]

The high pressurizer superheat probably had a small effect on the timing of spray actuation, since the steam volume would expand somewhat due to the superheat and reach the 75 cm (29.5 in) level spray initiation point sooner than without the superheat. A comparison of the pressurizer levels is made in Figure 53 showing poor agreement on timing of the spray

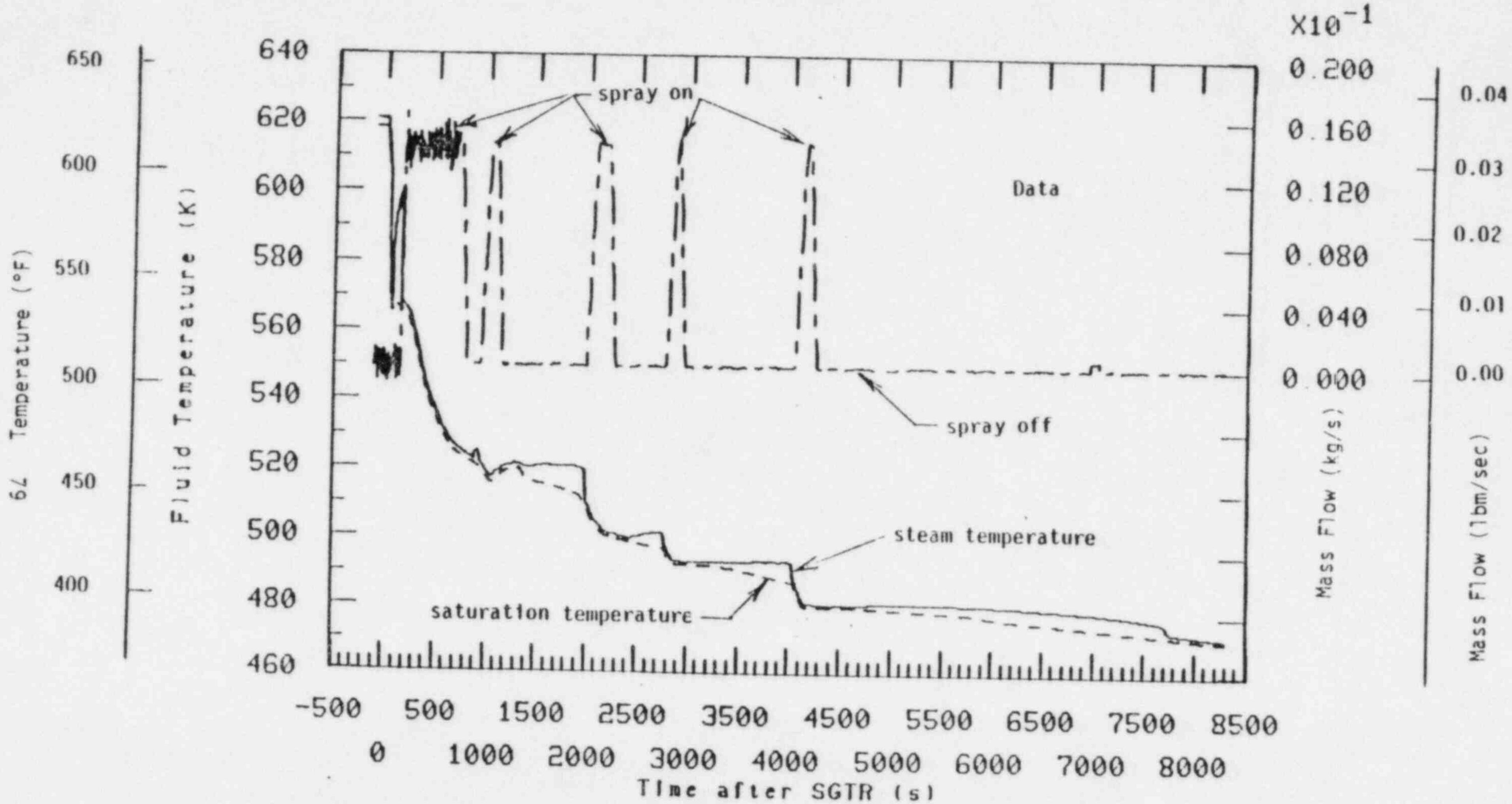

Figure 51. Pressurizer steam temperature, saturation temperature and spray flow - test.

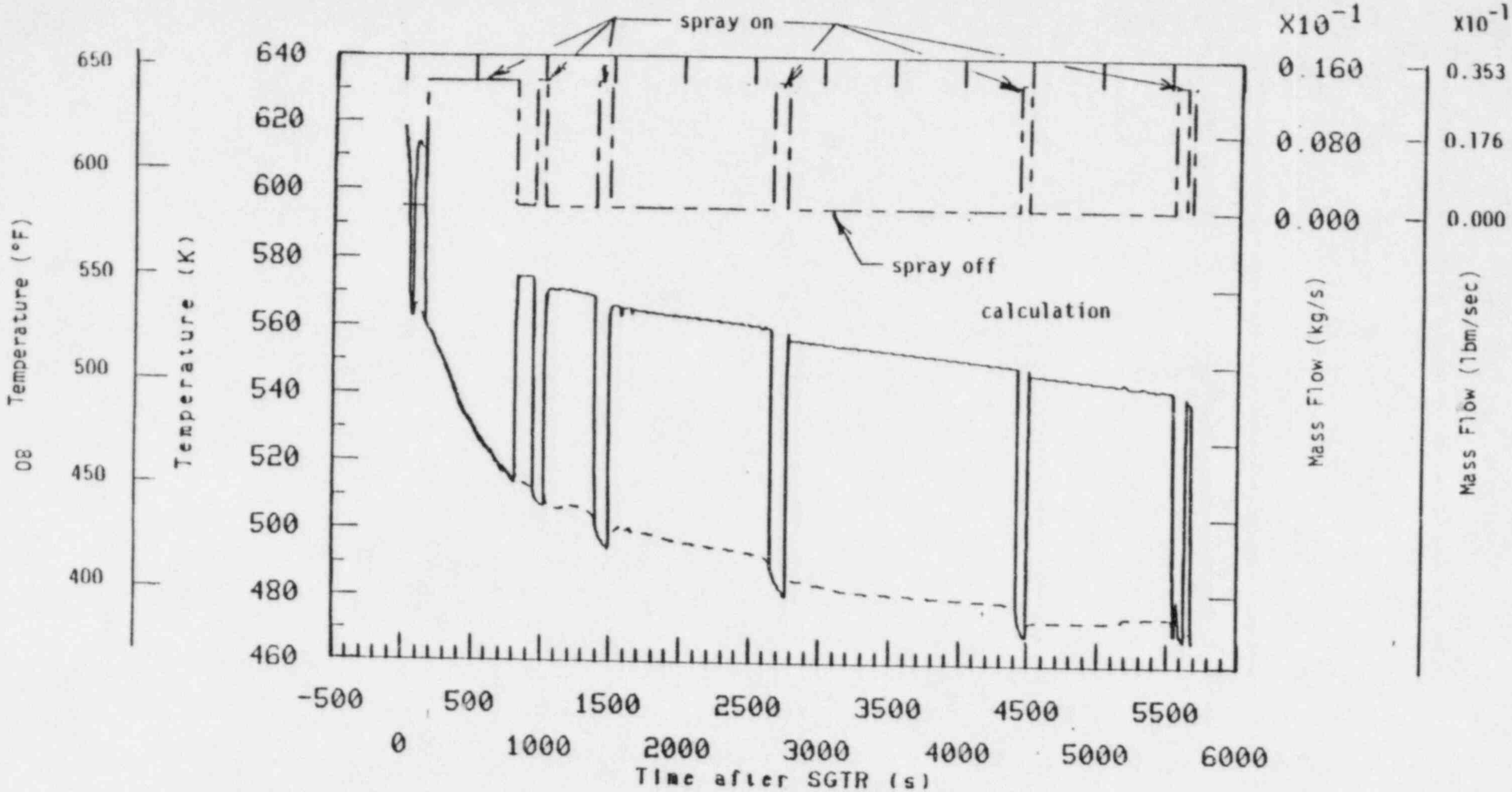

Figure 52. Pressurizer steam temperature, saturation temperature and spray flow - calculation.

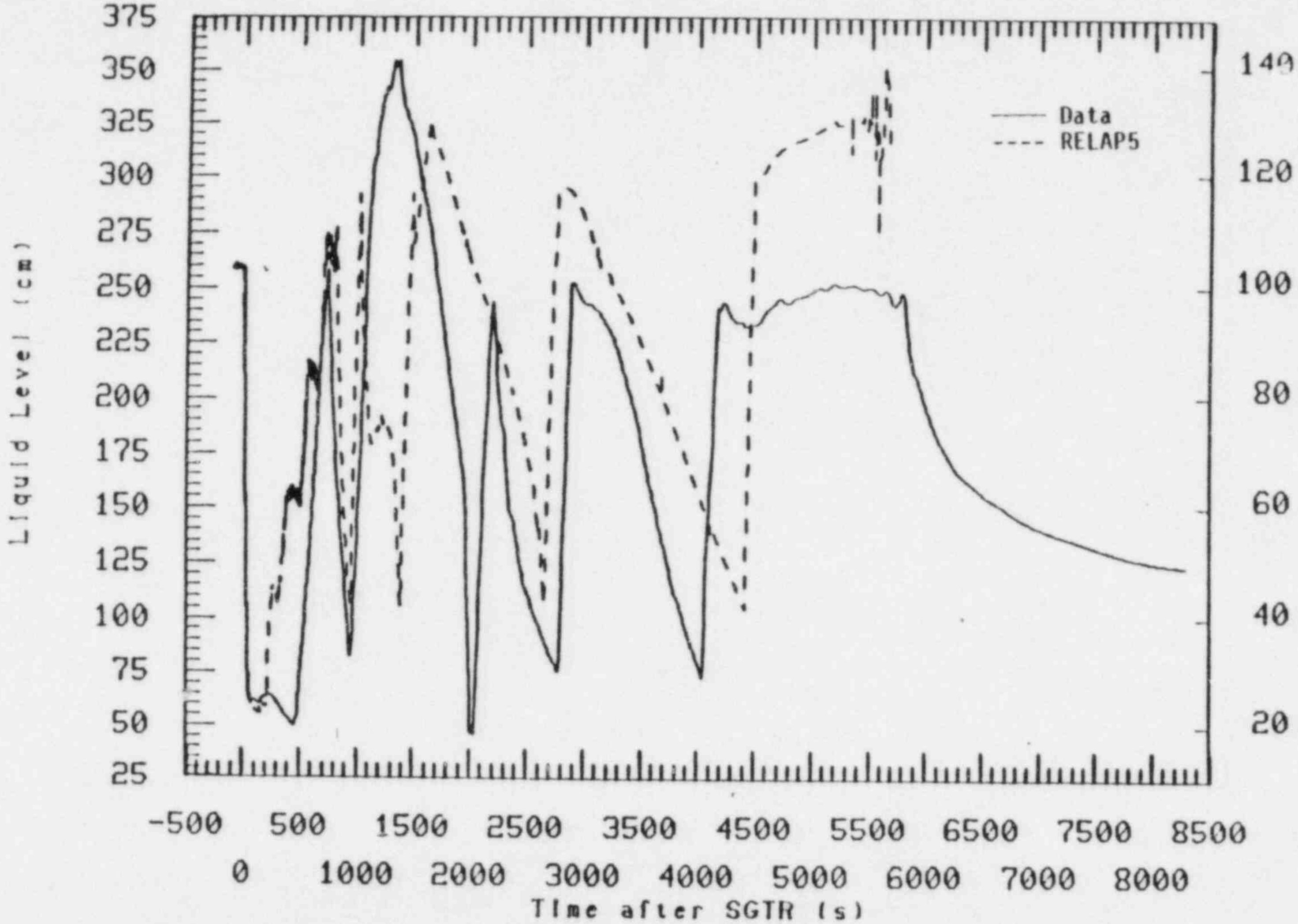

Figure 53. Pressurizer collapsed liquid levels.

actuations. However, this is probably due more to the larger break flow in the test. The effect of the high superheat is not believed to have had a very significant impact on the calculation results.

4.3 Summary and Recommendations

The transient signature was well calculated during the short diagnostic period. The major differences were noted in the recovery period as follows:

1. Break flow was underpredicted.

2. Depressurization rates of the primary and secondary systems were overpredicted.

These factors affected the timing of events such as ILSG ADV actuation, pressurizer spray actuation, time to reach liquid full condition in the BLSG and the extent of voiding in the PCS.

It is recommended that the break flow model be given further study to improve benchmarking. Also examination of the facility steam generators may reveal problems affecting their thermal capacity, which would result in modifying their thermal response characteristics.

5. CONCLUSIONS

The following conclusions are based on a preliminary analysis of Semiscale test S-SG-6 results.

1. Natural circulation phenomena occurring in the Semiscale system greatly effected the primary system pressure response during a hot side five tube rupture transient.

   Parameters that effect the natural circulation in the system include the intact loop ADV operation, break flow, and SI flow. Interruption of natural circulation can cause a pressurization of the primary and a restart of natural circulation can cause an increase in primary depressurization. The change from single-phase to two-phase natural circulation accompanied by an increase in flow (two-phase peaking) can cause an increase in the primary depressurization rate.

2. In the Semiscale system during a hot-side five tube rupture transient with a stuck open broken loop ADV, the combination of intact loop ADV operation, SI, and pressurizer auxiliary spray was sufficient operation to reduce the primary pressure to LPIS setpoints.

   This primary pressure reduction was accomplished while maintaining the vessel collapsed level at least 40 cm (16 in.) above the top of the core. Pressurizer auxiliary spray, when on, causes a relatively rapid primary depressurization due to condensation and intact loop ADV operation provides for a slow primary depressurization due to primary fluid shrinkage caused by primary to secondary heat transfer.

3. Early in time during automatically occurring events there is essentially no difference in phenomena between hot side five tube rupture transients and cold side five tube rupture transients. Parameters such as system pressure, flow, pressurizer level, and break flow show almost identical results.

4. Although the RELAP5 pretest calculation agreed qualitatively with the test data in predicting the important events in the transient, several deficiencies are apparent.

   The calculation underpredicted the break flow indicating the need for further study of the break flow model. The calculation also overpredicted the depressurization rates of both steam generators resulting in overprediction of the PCS depressurization rates indicating the need to examine the thermal capacitance of the steam generators in the test facility for comparison with the RELAP5 model.

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16. ABSTRACT (200 words or less)

Results of a preliminary analysis of the eighth test performed in the Semiscale Mod-2B Steam Generator Tube Rupture Series are presented. Test S-SG-6 simulated a pressurized water reactor accident initiated by a double-ended offset shear of five hot side steam generator tubes. Early operator identification of the tube rupture transient was assumed to occur 60 s after core scram. At t = scram + 60 s operator action included latching open both steam generator atmospheric dump valves (ADV's) in an attempt to depressurize the primary system pressure below the steam generator ADV setpoints. An additional operator action was to initiate pressurizer spray at t = scram + 120 s. At t = 600 s it was assumed that the operators identified which steam generator had the tube rupture (in Semiscale, the broken loop) and an attempt was made to terminate broken loop auxiliary feed and close the broken loop atmospheric dump valve (ADV). The unique problem posed by S-SG-6 was that the broken loop ADV once latched opened was assumed to stick open for the remainder of the transient. However the auxiliary feed water to the broken loop was terminated at t = 600 s. The intact loop ADV and pressurizer auxiliary spray were operated to stimulate a slow primary cooldown and depressurization to the low pressure injection system pressure setpoint 1.38 MPa (188 psig). These procedures were all accomplished while maintaining the vessel liquid level at least 40 cm (16 in) above the top of the core.

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