APPENDIX C

SMALL BREAK LOCA SAMPLE CALCULATION

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C.1. INTRODUCTION

This appendix presents the application of the S-RELAP5 SBLOCA methodology (Reference C-1) to the U.S. EPR. The U.S. EPR has four loops with four hot-legs, four cold-legs, and four vertical U-tube steam generators. The reactor vessel contains a downcomer, upper and lower plena, and a reactor core with 241 fuel assemblies. The hot-legs connect the reactor vessel with the vertical U-tube steam generators. Feedwater is injected into the downcomer of each steam generator. The Main Steam Relief Trains (MSRTs) are used to depressurize the SG secondary side at a rate corresponding to 180 ^{o}F/hr following receipt of a Safety Injection (SI) signal and, thereby, help cool and depressurize the primary system in a LOCA event. There are four EFW pumps; all are motor driven. The SIS contains four MHSI pumps, four accumulators, and four LHSI pumps.

C.2. S-RELAP5 MODEL

The reactor coolant system of the plant is modeled in S-RELAP5 as a network of control volumes interconnected by flow paths. The model includes four accumulators, a pressurizer, and four steam generators in which both the primary and secondary sides are modeled. All the loops are modeled explicitly to provide an accurate representation of the plant. Figure C-1 and Figure C-2 are nodalization diagrams for the reactor vessel and secondary system. Figure C-3 presents the nodalization of the loops.

Decay heat is determined from reactor kinetics equations with actinide and decay heating as prescribed by Appendix K to 10 CFR Part 50.

The calculations assume a loss of off-site power concurrent with reactor scram. The single failure criterion required by Appendix K is satisfied by assuming the failure of one diesel generator. This causes the disabling of one MHSI pump, one LHSI pump and one motor-driven EFW pump. In addition, one SIS train is assumed to be off line for service, leaving active only two MHSI pumps, two LHSI pumps and two emergency feedwater pumps. All four accumulators are assumed to inject.

EFW is actuated on the combination of LOOP and SI signal or on SG low wide-range level. It was neglected, however, for this sample problem calculation. MHSI is initiated on a SI actuation signal. The delivery of water begins following a delay to account for the maximum time required to start up emergency diesel generators and actuate equipment. The two active trains of MHSI are assumed to inject into Loop 4 (the broken loop) and into Loop 3 (the intact loop adjacent to the broken loop). The adjacent loop was chosen because it provides the greatest opportunity for injected ECCS to flow directly to the break and bypass the core.

The MFW system and the RCPs are assumed to be tripped-off at reactor scram, coincident with an assumed LOOP.

The axial power shape used is a conservatively top-skewed, End of Cycle (EOC) shape. The power peak occurs at a normalized distance of 0.8089. The power in the hot rod is assumed at the technical specification peaking limits for the U.S. EPR. The sample problem assumes peaking limits of F_q = 2.6 and $F_{\Delta H}$ = 1.7.

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The RCPs are modeled to reflect how the fluid is distributed vertically in the pumps to incorporate the physical elevation of the impeller into the model and to allow the fluid in the pump volutes (the pump discharge regions) to overflow into the discharge cold-legs. The pump model consists of a PUMP component representing the region from the pump suction to the impeller outlet and a

BRANCH component representing the pump volute. The flow area of the PUMP component is set to that of the pump suction piping.

Following receipt of a SI signal, the SG MSRT system provides a controlled secondary system depressurization from 1406.9 psia to 892 psia (870 psia + 22 psi uncertainty) at a rate corresponding to 180 ^{o}F/h.

Steam generator tube plugging is set to 5% symmetrically.

The core is modeled with a two-dimensional component having 28 axial nodes and three radial nodes. The fuel pin model utilizes a radial nodalization having eight intervals in the pellet. This is for compatibility with the RODEX2 fuel code, which is used to generate the EOC burn-up conditions that are input to S-RELAP5. The Baker-Just metal water reaction correlation is used for all fuel rod heat structures. The rupture model was invoked for the hot rod.

The limiting case was identified via a break spectrum analysis.

C.3. INITIAL CONDITIONS AND OTHER INPUT PARAMETERS

Table C-1 provides a listing of the initial conditions for the S-RELAP5 analysis of the SBLOCA event.

Table C-2 presents the safety classified I&C signals considered for this SBLOCA analysis. Degraded conditions are used to establish an uncertainty offset for signals unless the action occurs before degraded conditions occur. Mitigating systems are assumed to be actuated in the analyses at setpoints with allowance for instrument inaccuracy in accordance with Regulatory Guide 1.105. The RPS scram trip credited in the SBLOCA analysis is generated on low pressurizer pressure. Conservative scram characteristics are assumed, i.e., maximum time delay with the most reactive rod held out of the core.

C.4. BREAK SPECTRUM

The sample problem analysis for the SBLOCA covers a range of breaks located in the pump discharge cold-leg. It includes 2.0, 2.5, 3.0, 3.5, 4.0 and 4.5-inch-diameter breaks. The 4.0-inch break produced the limiting PCT. (See Table C-3.)

The 2.0-inch and 2.5-inch breaks are small enough that MHSI flow is sufficient to prevent core uncovery. The 3.0-inch, 3.5-inch, 4.0-inch and 4.5-inch breaks depressurize to the accumulator injection setpoint. The analyses are terminated when the PCT turns around, the vessel downcomer is filled to the elevation of the cold-leg nozzles with a two-phase mixture, and the core collapsed level shows a steady or increasing trend.

The 4.0 -inch break is large enough to cause the system to depressurize to the accumulator injection pressure at 1056 seconds. The injected water causes a momentary increase in pressure so the accumulators stop discharging. The primary continues to depressurize causing a sustained accumulator injection between 1282 and 1372 seconds.

For the 4.0-inch break, the first core heatup occurs around 300 seconds due to loop seal plugging. This leads to a temporary depression in core level (Figure C-12). Following the loop seal clearing in Loop 1, the collapsed core level increases and leads to core quench. A core boil-off starts at about 700 seconds and leads to a deeper and prolonged core uncovery until about 1100 seconds when the core level sharply recovers. The recovery becomes more pronounced between 1282 and 1372 seconds due to accumulator injection (see Table C-4, Sequence of events). By the time the calculation is terminated, the accumulators have ceased to discharge and there is no additional heatup.

The 4.0-inch break is the limiting break. The 4.0-inch break causes a longer period of core uncovery than do the 3.5-inch and 4.5-inch breaks. The rate of depressurization to the accumulator discharge pressure for the 4.0-inch break is slower than that for the 4.5 inch break; and, therefore, the amount of time the hot rod remains uncovered is greater.

The 4.5-inch break behaves similarly to the 4.0-inch break in that it recovers as soon as accumulator discharge begins.

C.5. 4.0-INCH BREAK (LIMITING CASE)

Table C-4 presents the sequence of events for this break case. Cladding temperatures rise steadily from about 700 seconds to about 1350 seconds, when cladding quench occurs.

Break flow is plotted in Figure C-4. The break flow is driven by the combination of system pressure and the void fraction at the break (Figure C-5). Until the loop seal clears, break flow mirrors primary pressure (Figure C-6). Loop seal clearing causes the break to transition from liquid to steam and mass flow out the break drops precipitously (see Figure C-4).

Figure C-6 shows the pressure traces for the RCS and the secondary side of one of the four steam generators. The behavior is typical of limiting SBLOCA events. The primary pressure drops rapidly to saturation at about 50 seconds. From 50 seconds to about 550 seconds, when the first loop seal clears, primary pressure follows the secondary pressure controlled by the MSRT programmed depressurization. When the break flow transitions to a highly voided two-phase mixture at about 750 seconds, the energy removal by the break is sufficient to depressurize the primary system below the SG secondary side pressure. Primary pressure increases when the accumulators start to discharge because the volumetric flow through the break decreases with decreasing void fraction at the break due to the accumulator water and condensate.

Figure C-7 shows the pressure traces in all four SGs. After the programmed depressurization reaches the lower limit of 892 psia at about 1200 seconds, the secondary side becomes a heat source to the primary system.

Figure C-8 shows the inventories of the SGs. The inventory of SG1 decreases more than the others. This is attributed to the fact that the seal in loop 1 clears first and, therefore, SG1 removes more energy from the primary system.

Figure C-9 shows MSRT flow. Because break flow is not initially sufficient to offset decay heat, heat transfer to the SGs causes SG pressures to increase. For the sample problem, the MSRIV is assumed to open when the SI signal is reached and the SG pressure reaches the cooldown curve. When the MSRIV opens, SG pressure drops about 180 psia because the Main Steam Relief Control Valve (MSRCV) is assumed to be fully open at that time. From then on, the MSRCV modulates to depressurize the secondary side at a rate corresponding to 180 ^{o}F/hr. Figure C-10 shows the void fraction in the horizontal legs of the loop seals. As expected, because of the loop seal biasing methodology, only one loop (Loop 1) clears first at 546 seconds. This is defined as a void fraction in the horizontal leg that is greater than 0.97.

Loops 3 and 4 (broken loop) clear at 1342 seconds, followed by Loop 2 at 1352 seconds. After the initial clearing, the broken loop seal refills completely. Loops 2 and 3 experience some carryover of liquid from the vertical segments of the seal and from ECCS injection; however, there is always at least one loop seal that is open.

Figure C-11 shows the MHSI flow for loops 3 and 4. MHSI flow increases as the system depressurizes when the break flow transitions to a highly-voided two-phase mixture.

Collapsed liquid level for the hot fuel assembly is shown in Figure C-12. The core uncovers at about 300 seconds (see Figure C-15) because the loop seals in all loops are plugged. The two-phase level recovers to the top of the core after the loop seal clears in one loop. The core uncovers again at about 720 seconds. At about 1350 seconds, the core is recovered with a two-phase mixture due to accumulator injection.

Figure C-13 presents the total accumulator flow to all four loops. The accumulators start injecting at 1056 seconds and stop at 1080 seconds when primary system pressure increases slightly as break flow transitions from steam to liquid. The accumulators start injecting again at 1282 seconds, and the flow stops at 1372 seconds. As the core refloods, the rate of steam generation in the core increases and system pressure rises. The pressure rise reduces MHSI flow and the accumulator discharge ceases. This leads to a reduction in the collapsed core level. The core remains covered by a two-phase mixture, however, and there is no additional heatup for the duration of the calculation.

Figure C-14 presents the RCS and RPV inventory. At about 1350 seconds, the RPV inventory shows a sharp increase due to sustained accumulator injection. RCS and vessel inventories are stable when the calculation is terminated at 3000 seconds.

Figure C-15 shows the steam and cladding temperatures for the fuel segment experiencing the maximum PCT of 1581 ^{o}F at 1074.9 seconds. Cladding temperature starts to decline due to a drop in steam temperature when the accumulator injects initially. It quenches when there is sustained accumulator injection at 1350 seconds. Cladding temperature tracks saturation temperature after 1400 seconds.

The analysis is terminated at 3000 seconds, at which time RCS and RV inventories are stable and the decay heat is being removed by the combination of the MHSI and break flow.

C.6. RESULTS/SUMMARY/CONCLUSION

AREVA NP's, NRC-approved, SBLOCA evaluation methodology was used to perform a SBLOCA sample problem analysis for the U.S. EPR plant design. The analysis covered a spectrum of breaks in the pump discharge cold leg piping. The analyses assumed the worst-case failure of a diesel generator that takes out one entire train of SIS injection and EFW (no EFW injection was assumed). Additionally, it assumed another train of SIS injection was unavailable because of preventive maintenance. EOC fuel conditions were assumed as calculated by RODEX2-2A. Peak cladding temperature was calculated for the hot rod using S-RELAP5.

The analyses showed the following:

1. The highest PCT, 1581 ^{o}F, is calculated for a 4-inch break. This value is well below the 2200 ^{o}F PCT limit specified in 10CFR50.46(b)(1).
2. The total cladding oxidation at the peak location is 0.440%, well below the 17% limit specified in 10CFR50.46(b)(2).
3. The hydrogen generated in the core by cladding oxidation (0.021%) during these accidents is less than 1% limit specified in 10CFR50.46 (b)(3).
4. The calculation shows that the core retains a coolable geometry. There is no clad rupture for any of the four fuel rods in the three core region. Thus the coolable geometry criterion in 10CFR50.46 (b)(4) is satisfied.

Other observations are:

1. Sensitivity studies performed in Reference 1 for a three-loop Westinghouse plant indicate that the solution is converged with respect to time step size, restart application, loop seal biasing, pump application, core radial flow, and nodalization. Therefore, no additional sensitivity studies are required for the SBLOCA analysis of the U.S. EPR.
2. SBLOCA events in the U.S. EPR exhibit all the phenomena encountered in a U.S. PWR plant. The limiting break exhibits all five phases of a small break LOCA: blowdown, natural circulation, loop seal clearance, boil off and core recovery. As such, the U.S. EPR behaves in the same manner as other U.S. PWRs during a SBLOCA event.

The overall conclusion is that the current SBLOCA evaluation methodology is applicable to the U.S. EPR. The U.S. EPR is similar to other U.S. PWRs for which the methodology was used successfully to analyze SBLOCA events.

C.7. REFERENCES

C-1. “PWR Small-Break LOCA Evaluation Model, S-RELAP5 Based,” AREVA NP Report EMF-2328 (P)(A), Revision 0, March 2001.

Table C-1 Input Parameters

Parameter	EPR Value
Core power	4500.0 MWth + 2%= 4590 MWth
Axial power shape and power peaking	An EOC top skewed
Loop flow rate/per loop	119,670 gpm
Reactor vessel Average temperature	596.0 ^{o}F
Primary pressure (Pressurizer Pressure)	2250 psia
Initial Pressurizer Liquid Level	56%
Secondary pressure	1108 psia, consistent with the plugging level
Initial SG Level	49 % NR
SG Secondary Side Inventory	179,500 lbm/SG
Accumulator pressure	652.7 psia
Accumulator Volume	Accumulator Liquid Volume: 1324 ft^{3,} Accumulator Total Volume: 1942 ft^{3}
Accumulator temperature	90.5^{o}F
MHSI fluid temperature	140^{o}F
SG tube plugging[1]	5%
EFW Flow	Assumed not to inject

[1] Performing the SBLOCA analysis at higher tube plugging levels is conservative because the initial primary system mass inventory is reduced.

Table C-2. Safety Classified I&C Signals Considered for SBLOCA Analysis

Signal	Setpoint
Reactor Trip, on low PZR pressure	1958 psia – 43.51 = 1914.49 psia Degraded conditions 43.51 psi I&C Delay = 0.9 seconds
Turbine Trip, on RT signal	1958 psia – 43.51 psia Degraded conditions 43.51 psi Trip Delay = 1.2 seconds
Beginning of Rod Insertion	1.2 seconds after RT signal (0.9 I&C + 0.3 seconds for RT breaker opening and gripper release), 3.5 seconds for complete rod insertion (seismic conditions)
MFW Isolation	1.2 seconds after RT signal.
Safety Injection, on low-low PZR pressure	1667.96 - 43.51 = 1624.45 psia Degraded conditions 43.51 psi I&C Delay = 0.9 seconds 40 seconds delay for SIS pump start up (includes diesel delay + pump startup)
RCP trip	RCP trip on LOOP at the time of scram
MSRT opening and pressure control,(partial cooldown signal simultaneously with SI signal)	1385.13 + 21.76 psia before beginning of partial cooldown. 870.24 + 21.76 psia after the end of partial cooldown. Time delay: 2 seconds
EFWS	EFW assumed not to inject

Table C-3 Break Spectrum- Peak Cladding Temperature

Break Size	Break Area (ft^2)	PCT (°F)	Time of PCT (sec)
2 in	0.0218	No Heatup	N/A
2.5 in	0.0341	No Heatup	N/A
3.0 in	0.0491	1349	2412.8
3.5 in	0.0668	1480	1470.0
4.0 in	0.0873	1581	1074.9
4.5 in	0.1104	1569	806.7

Table C-4 Limiting Break Sequence of Events

Event	Time (sec)
Break initiation	0.0
Reactor and RCP trip (with 1.2 seconds delay)	18.7
SIS trip (with 40 seconds delay)	72.0
MHSI injection begins	476.8
Loop seal clearing – Loop 1 (Void >0.97)	546.4
Break uncovery (Void >0.97)	569
Accumulator injection	1056-1080 1282-1372
PCT occurs (1581 °F, Node 35)	1074.9
Emergency feedwater initiated	Neglected
Loop seal clearing – Loop 3 (Void >0.97)	1342
Loop seal clearing – Loop 4 (Void >0.97)	1342
Loop seal clearing – Loop 2 (Void >0.97)	1345
End of calculation	3000

Figure C-1 U.S. EPR Vessel Nodalization

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Figure C-2 U.S. EPR Steam Generator Nodalization

Figure C-3 U.S. EPR Loop Nodalization

Figure C-4 Break Flow Rate for 4.0 Inch Break

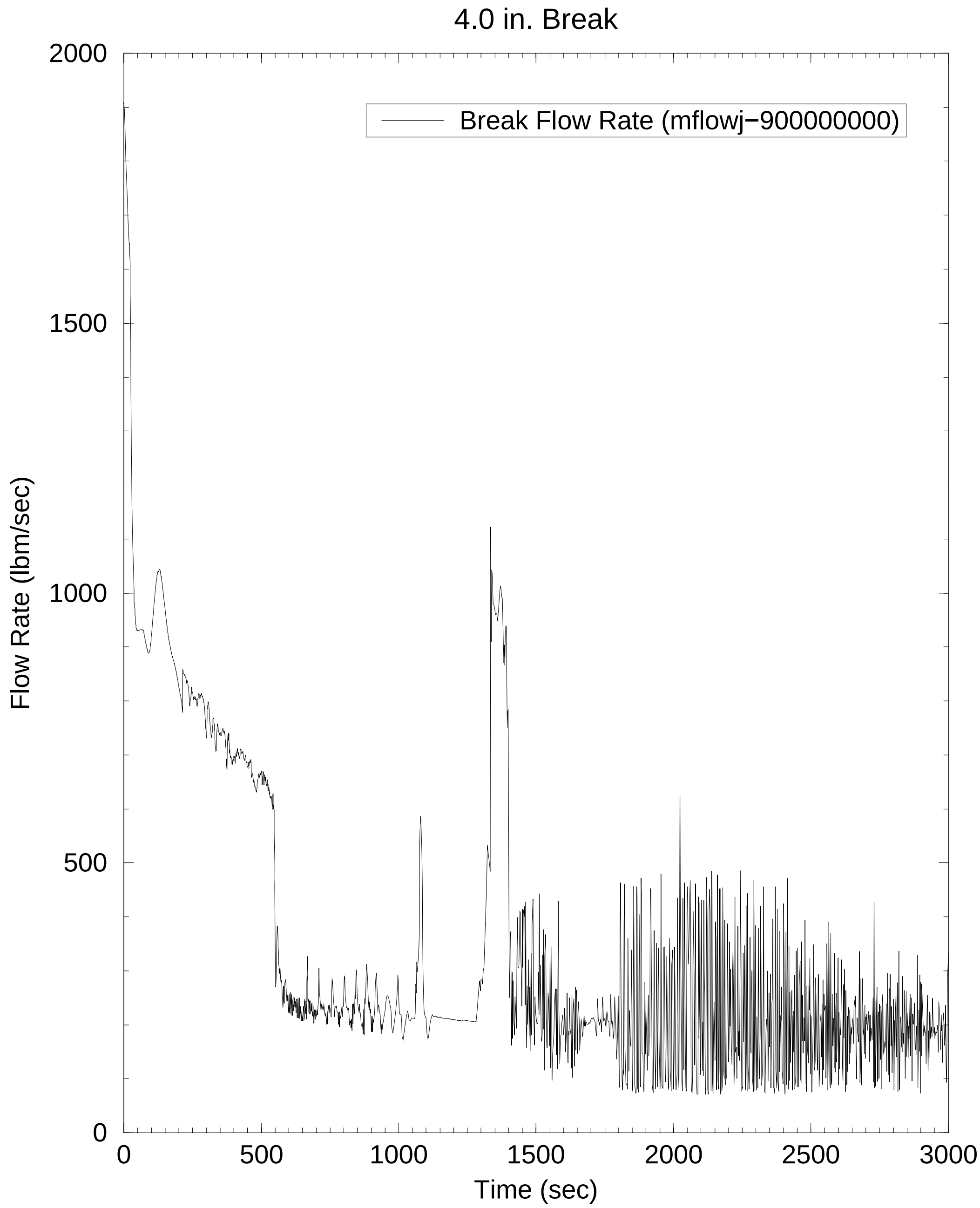

Figure C-5 Break Void Fraction for 4.0 Inch Break

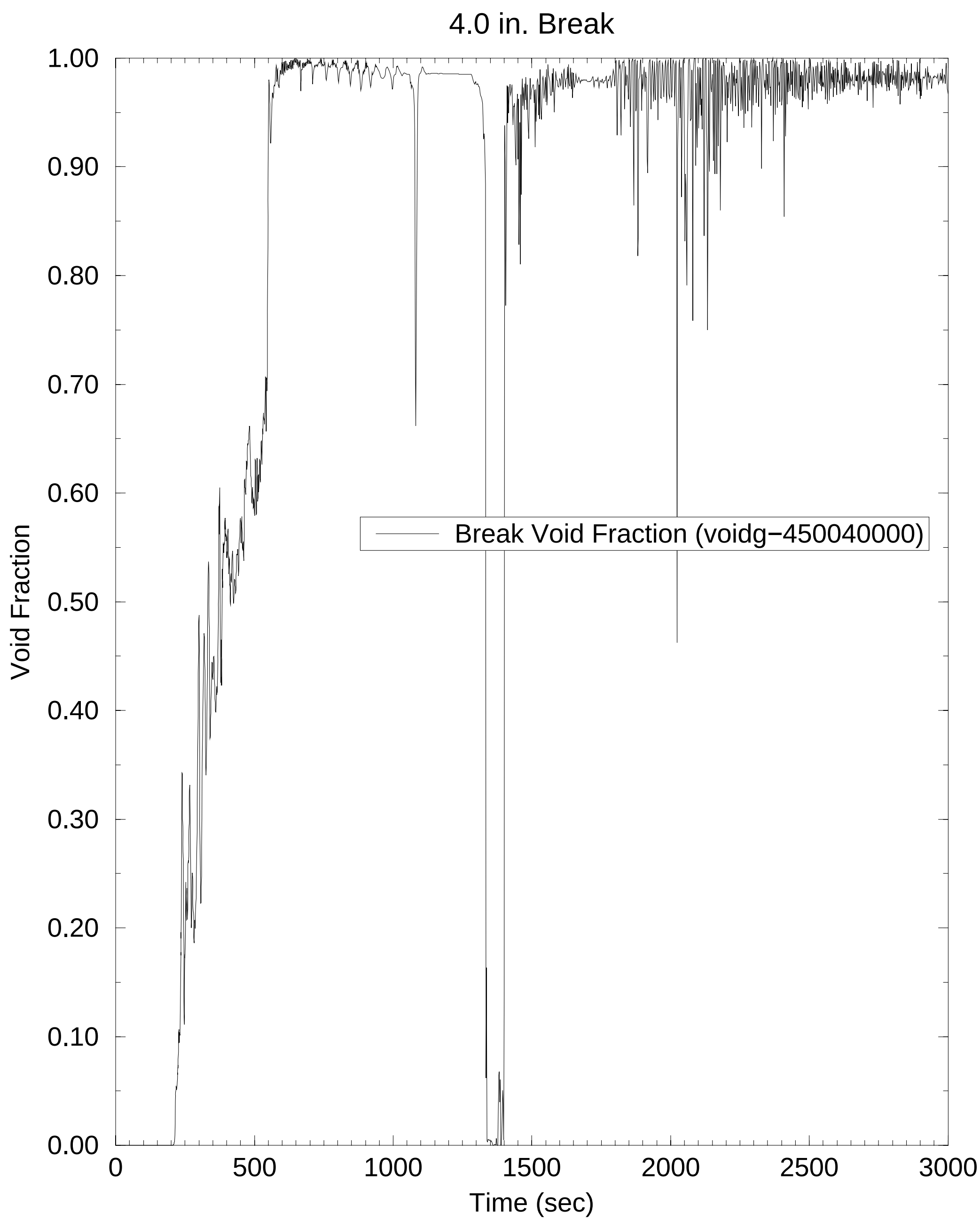

Figure C-6 Primary and Secondary System Pressures for 4.0 Inch Break

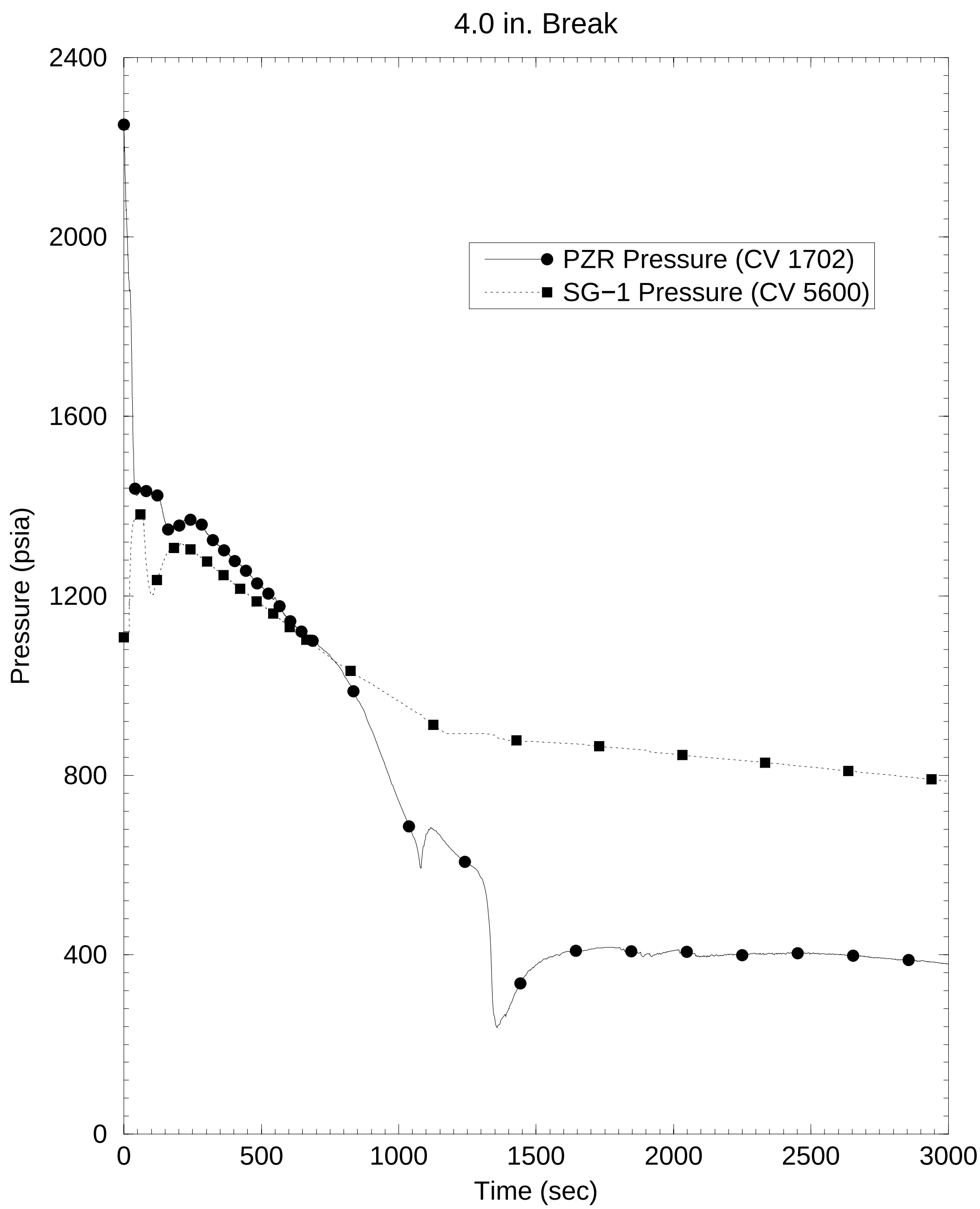

Figure C-7 Steam Generator Pressures for 4.0 Inch Break

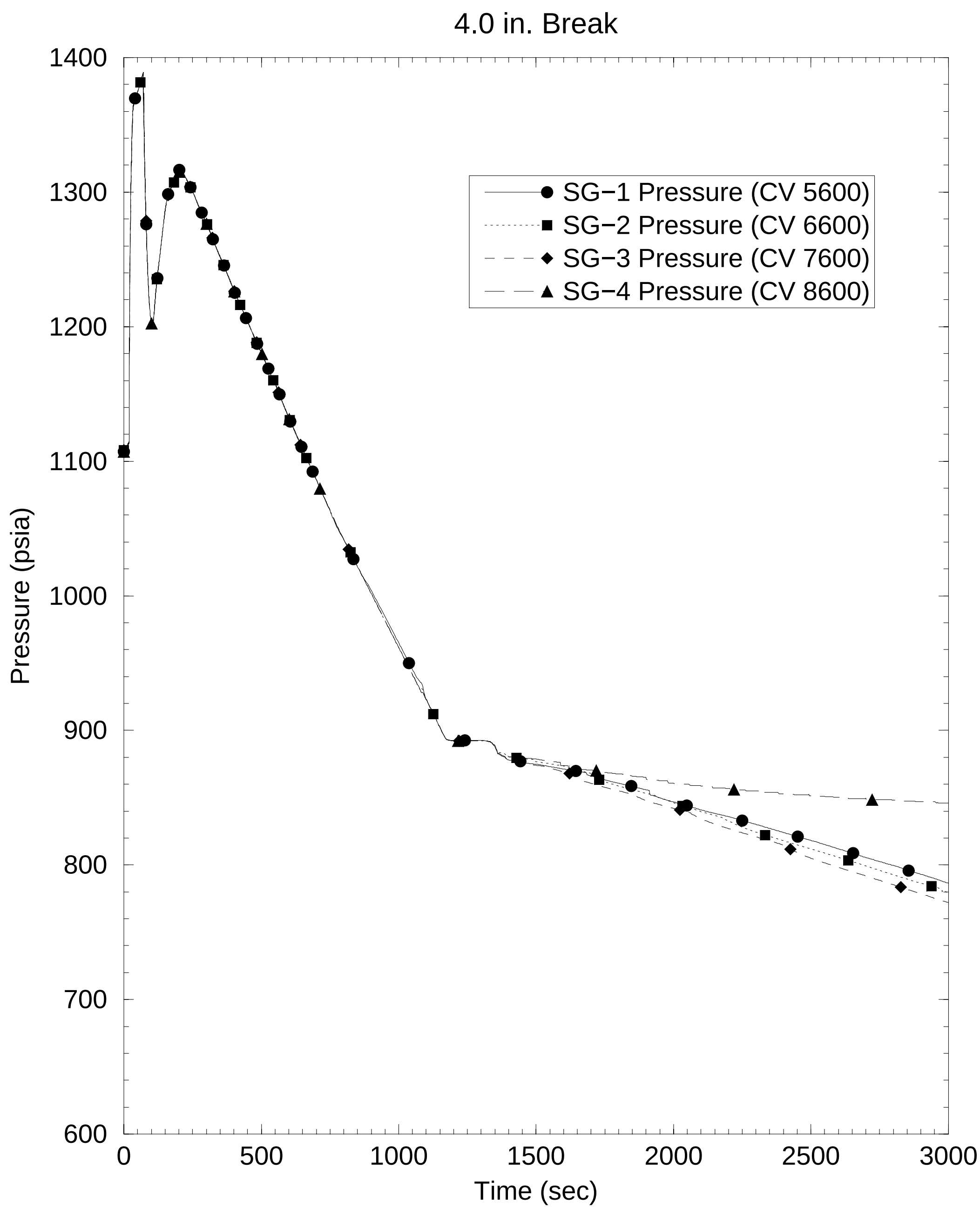

Figure C-8 Steam Generator Total Mass Inventories for 4.0 Inch Break

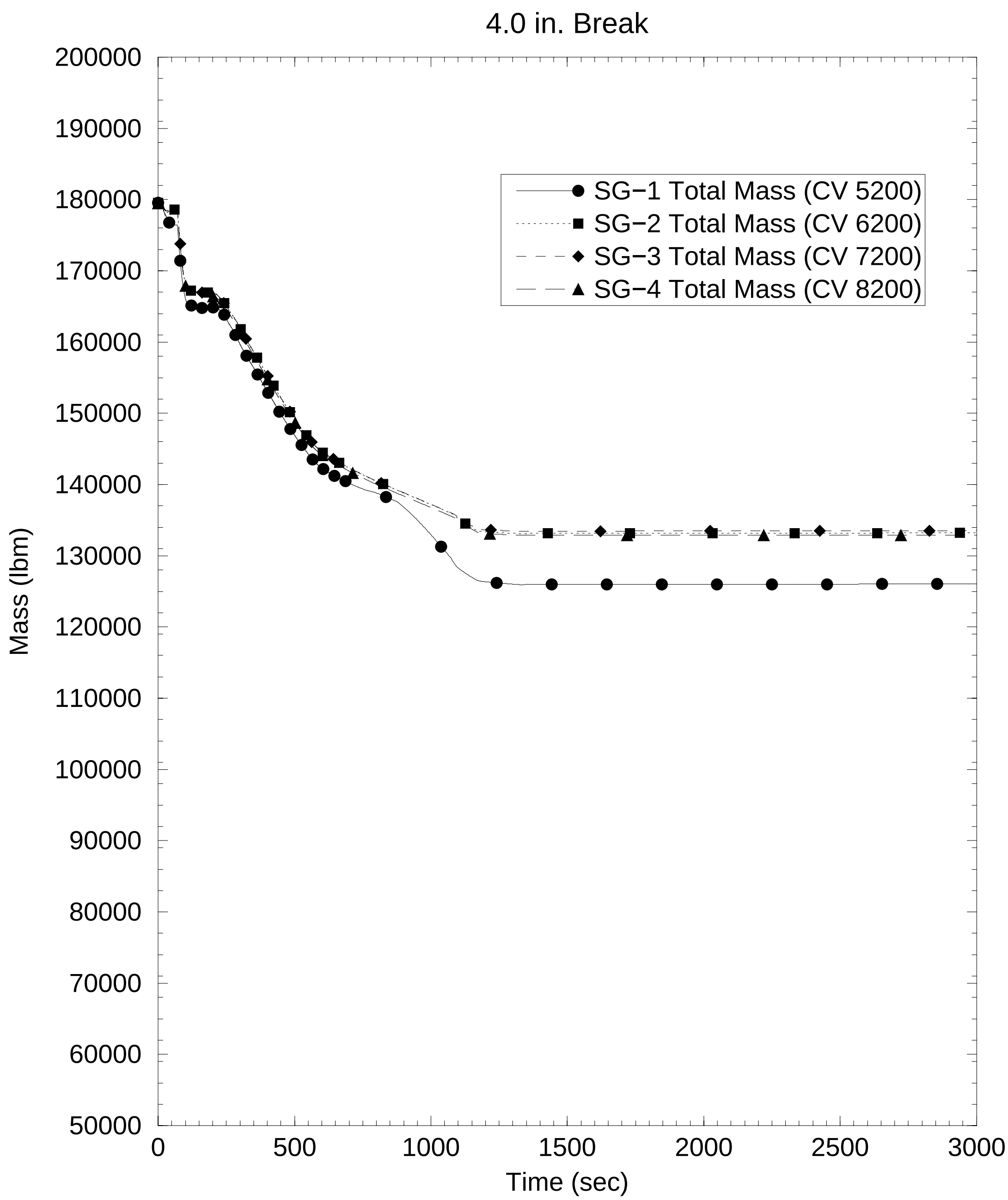

Figure C-9 MSRT Flow Rate for 4.0 Inch Break

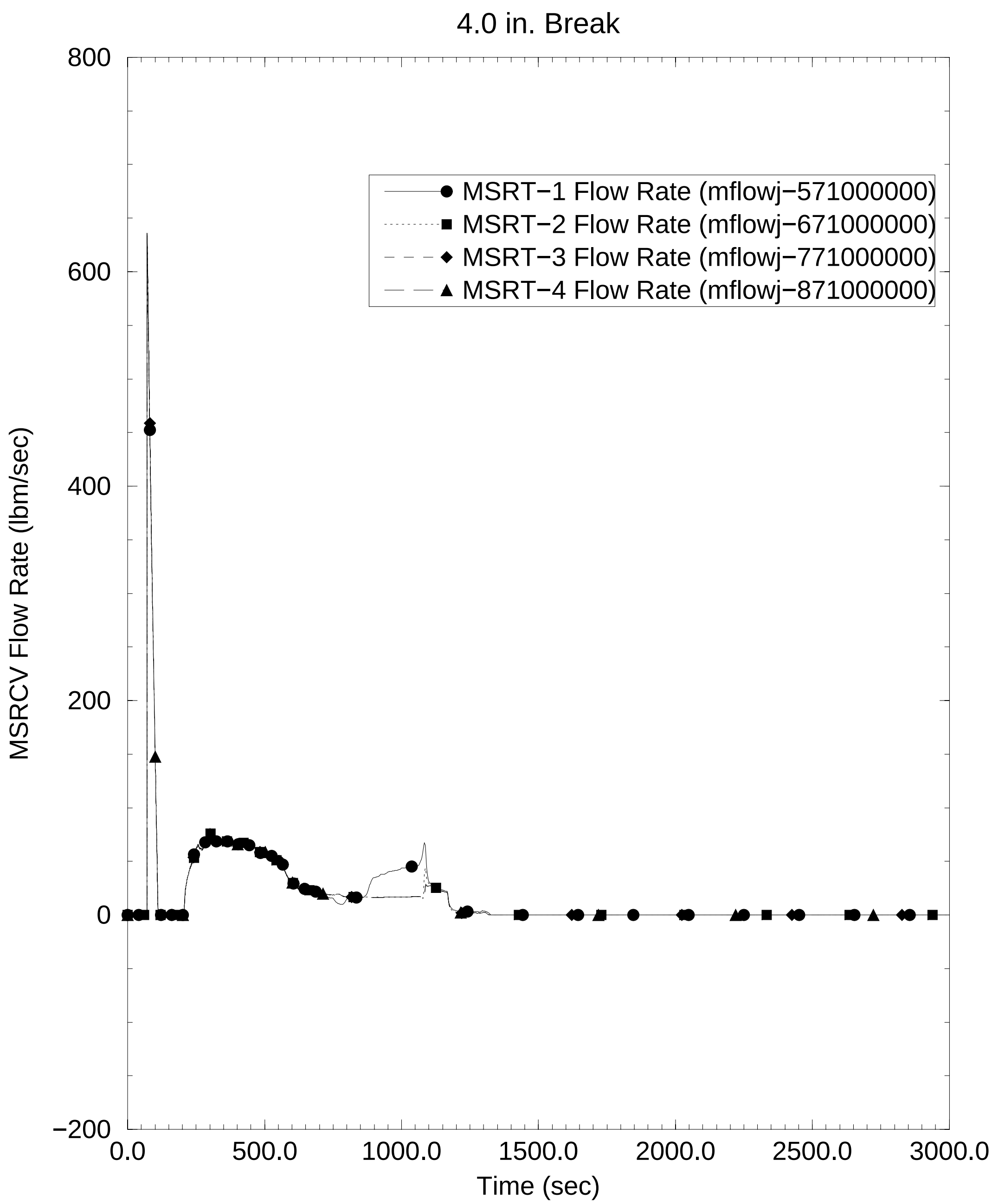

Figure C-10 Loop Seal Void Fraction for 4.0 Inch Break

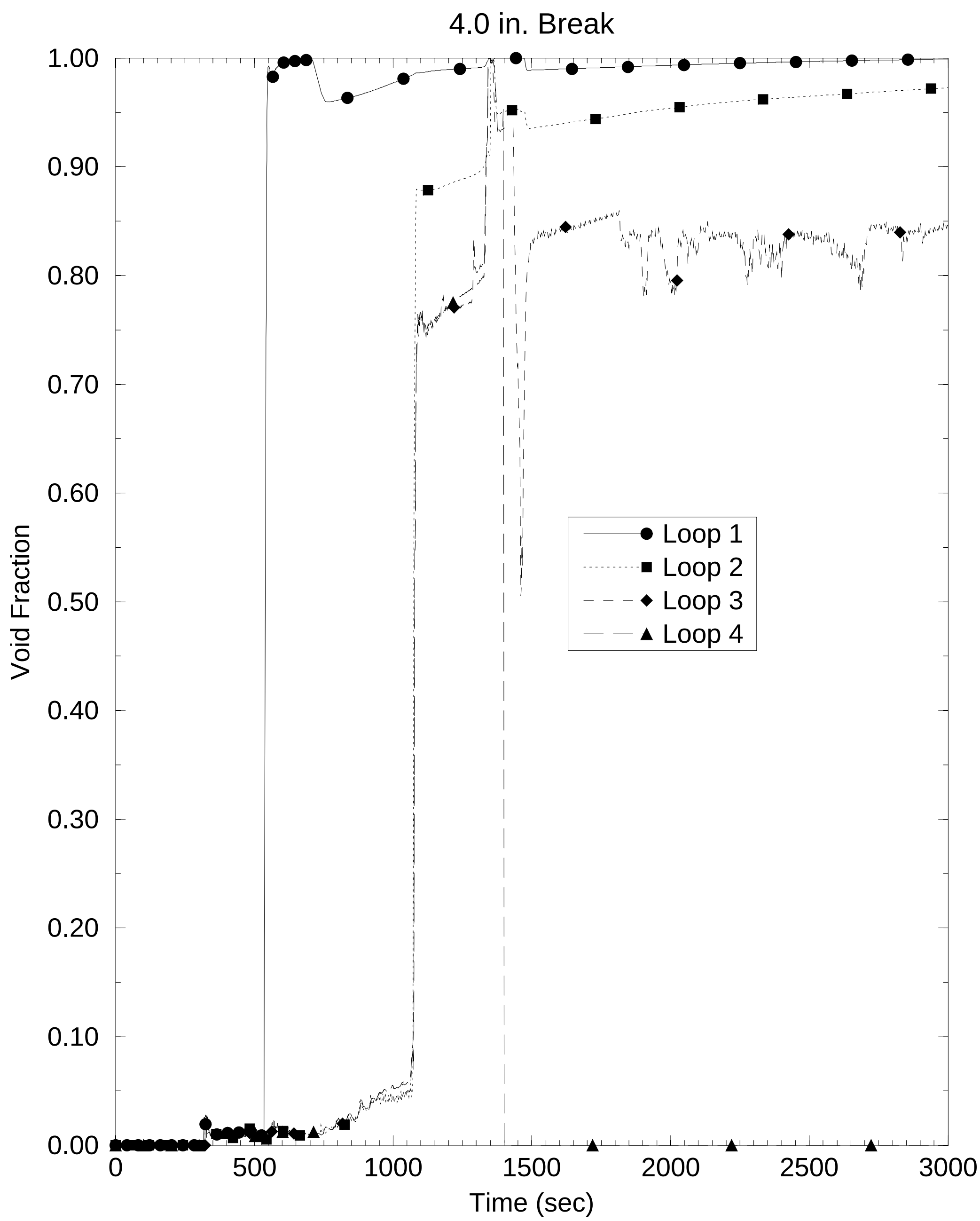

Figure C-11 MHSI Flow (Loops 3 and 4) for 4.0 Inch Break

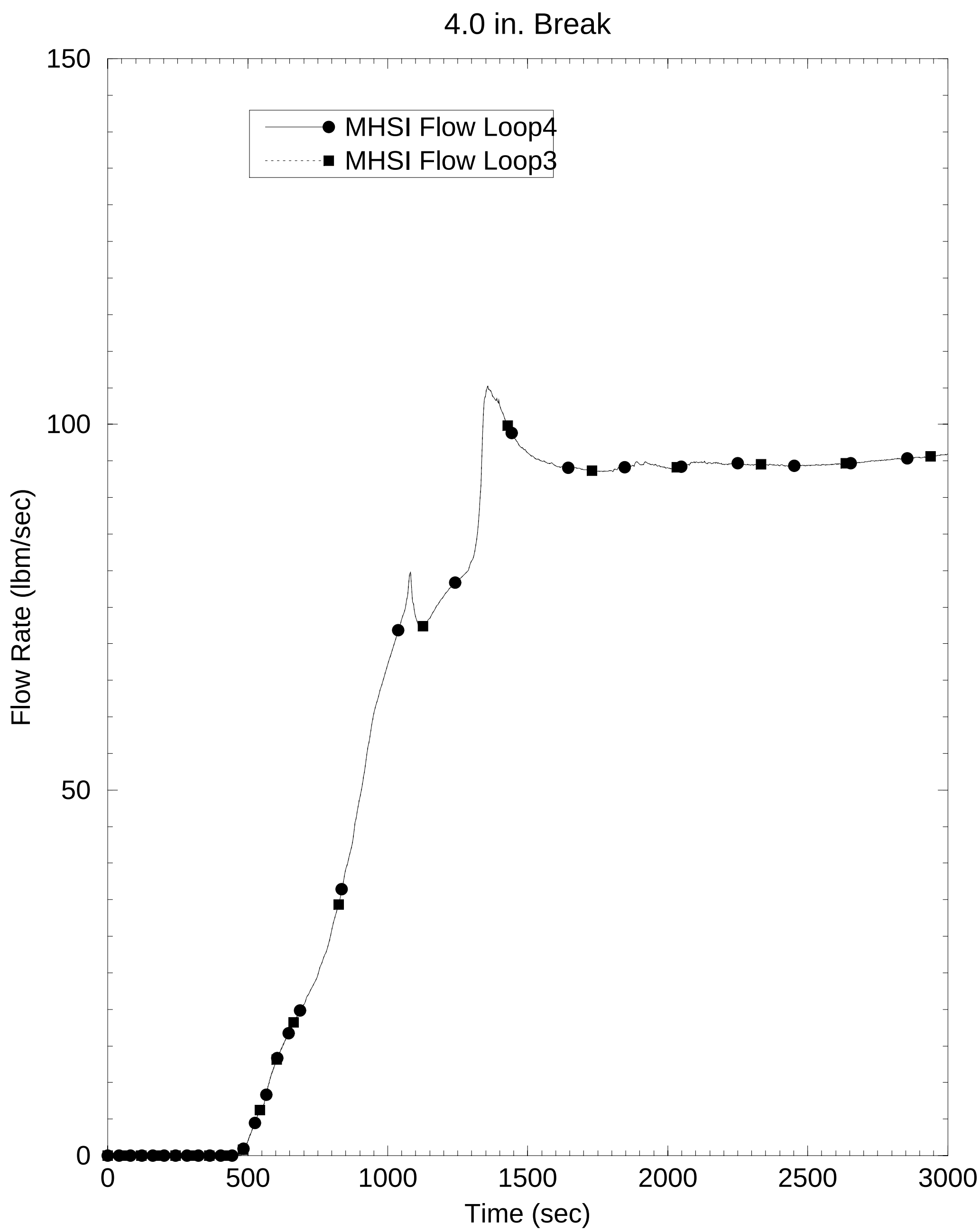

Figure C-12 Hot Assembly Collapsed Liquid Level for 4.0 Inch Break

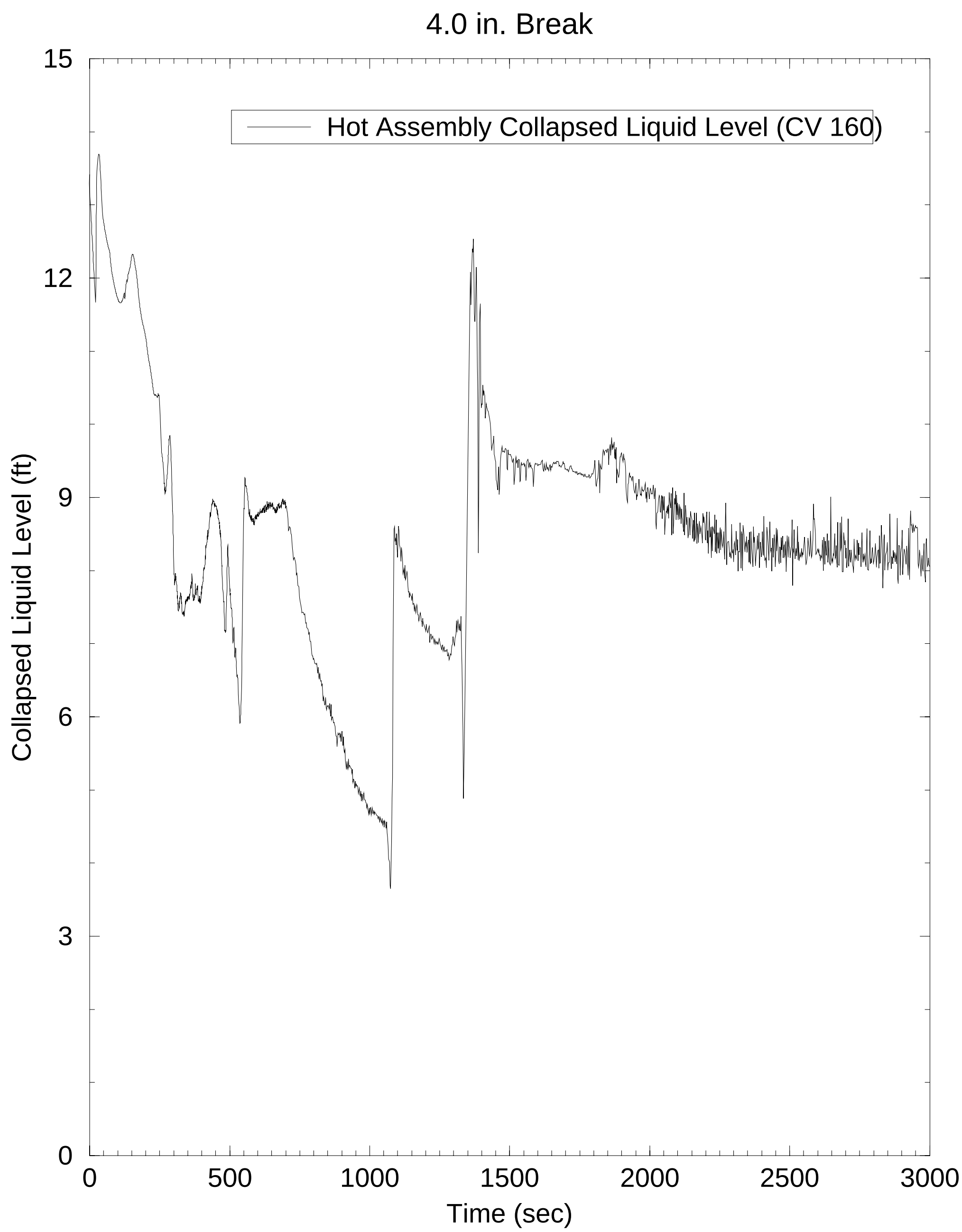

Figure C-13 Total Accumulator Flow for 4.0 Inch Break

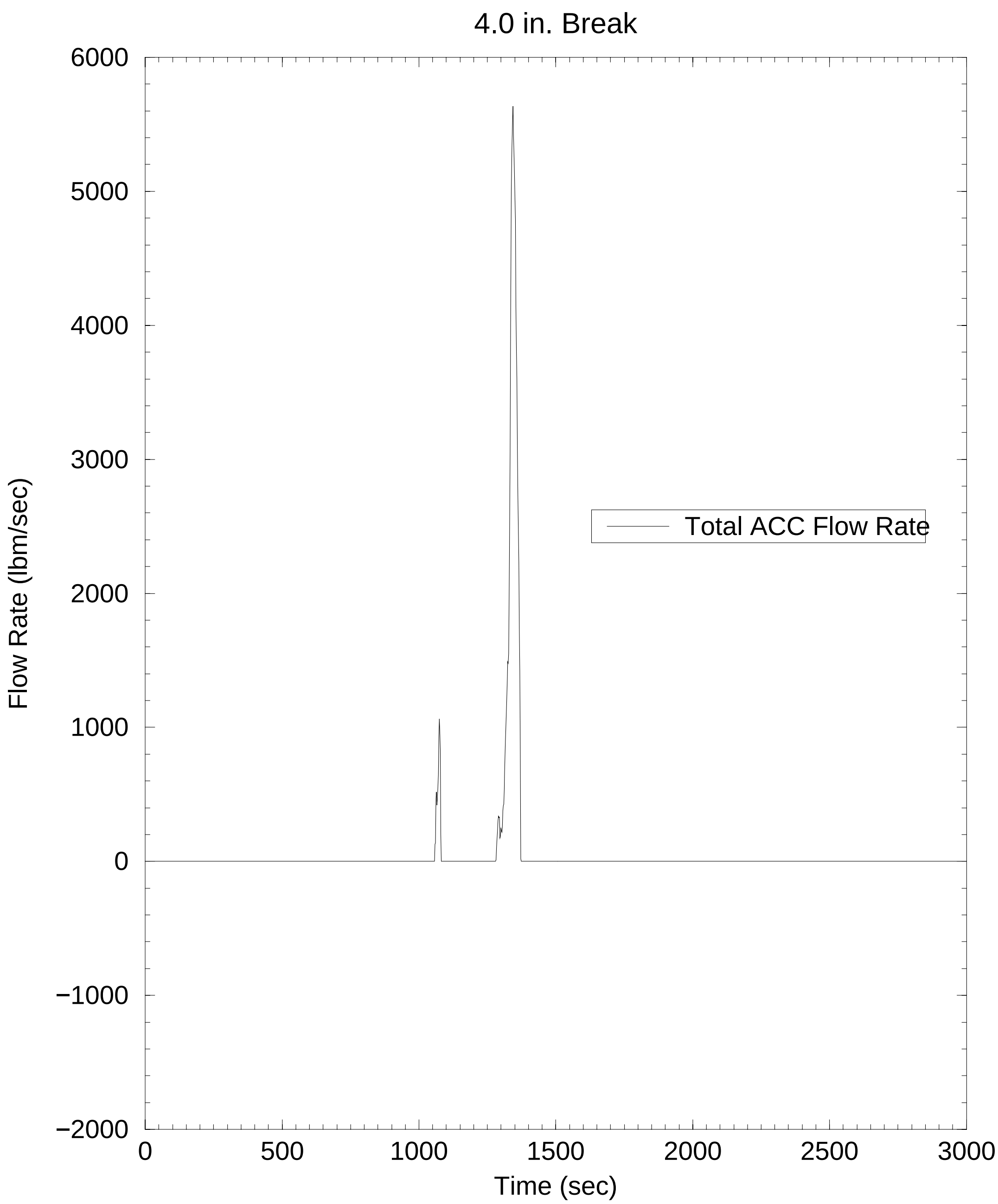

Figure C-14 Total RCS and RV Mass Inventories for a 4.0 Inch Break

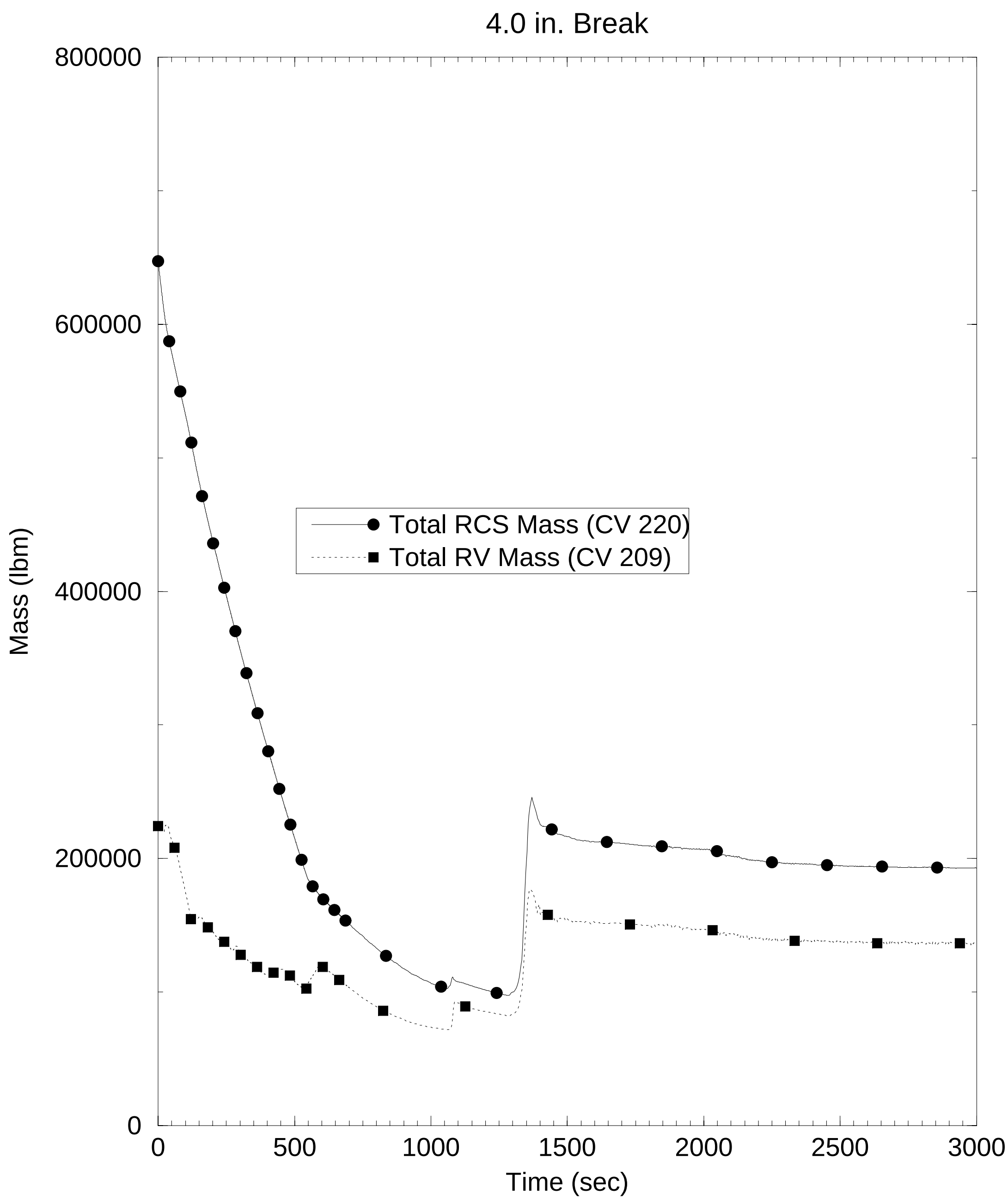

Figure C-15 Vapor and Clad Temperature for the Hot Node for a 4.0 Inch Break