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COMPARISONS OF RELAP4/MOD6 TO LOFT AND SEMISCALE ISOTHERMAL DATA

By

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INTERIM REPORT

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ABSTRACT

This report presents the results of the independent assessment studies of the RELAP4/MOD6 computer code utilizing LOFT and Semiscale system models to analyze isothermal blowdowns. RELAP4 calculations are compared to data from LOFT Test L1-4 and from Semiscale Test S-01-4A, the counterpart test to L1-4. The isothermal experiments provide a test of the RELAP4 hydraulic model in which the heat transfer effects are minimized. Deficiencies in the comparisons are noted, and improved modeling techniques recommended.

SUMMARY

This report describes the assessment of the RELAP4/MOD6 computer code for predicting the isothermal system behavior of LOFT and Semiscale Mod-1. The assessment process involved comparing calculations of system models with data from LOFT Test L1-4 and from Semiscale Test S-01-4A, the counterpart to the LOFT test. Both experiments were isothermal (no core power generation) blowdowns simulating 200% cold leg breaks with ECC injection from the following initial conditions: for LOFT - 15.65 MPa system pressure, 553 K fluid temperature, and 268.4 kg/s primary coolant mass flow; for Semiscale - 15.52 MPa system pressure, 558 K fluid temperature, and 8.31 kg/s primary coolant mass flow.

Base run models were developed for both LOFT and Semiscale and were based on the same modeling philosophy. RELAP4/MOD6 provides an adequate representation of the hydraulic behavior of the LOFT system, particularly prior to the beginning of accumulator injection. After accumulator injection begins, the calculated system pressure decays more rapidly than the data because of the equilibrium condensation effects of the subcooled emergency core coolant.

The Semiscale S-01-4A calculation overpredicts the system depressurization from the beginning of the transient. The problem is evident prior to the initiation of accumulator injection, and heat transfer effects are minimal during the early portion of an isothermal blowdown. Therefore, the overprediction of the system depressurization results from the multiplier on the critical flow model being too large. An improved data base is required for selecting multipliers for the critical flow models. Other than the depressurization problem, the calculated behavior and the resulting data comparisons for S-01-4A are similar to those for the LOFT L1-4 calculation.

The relation of the LOFT L1-4 model to the model used for the U. S. Standard Problem 7 analysis was investigated. The major

differences in the data comparisons were that the standard problem calculation overpredicted the broken hot leg mass flow and underpredicted the system pressure early. While there were some minor nodalization and option differences, it was concluded that the major cause of the differences was the fluid temperature initialization in the broken hot leg.

Cross flow paths were added to the downcomer in the LOFT base run model. The effect of the cross flow paths was in general to increase the flows at the downcomer junctions. While the data comparisons did not improve significantly, the cross connected downcomer is recommended for future LOFT analyses because the lower plenum filling does not result in the large, violent lower plenum density oscillations that were apparent in the base run analysis.

Because of the large length-to-diameter ratio of the Semiscale downcomer and the resulting one-dimensional hydraulic behavior, the split downcomer in the Semiscale S-01-4A base run model was combined into a single vertical stack of volumes. The effect of this nodalization change was to delay downcomer penetration until the vapor flow up the downcomer was lower. The delayed penetration prolonged bypass and thus increased the time to refill by 5 s. This change provided an improved comparison relative to time of lower plenum refill, and the single channel downcomer nodalization is recommended for future Semiscale Mod-1 analyses.

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I. INTRODUCTION

This study represents part of the initial effort to apply assessment techniques to the RELAP4/MOD6[1] computer code (INEL Computer Center Configuration Control Numbers C0010005 for this version of the code and H00201IB for the associated steam tables[2]). Code Assessment is a new field of study and is presently being developed into a structured process. The initial objectives of this effort were as follows:

(1) to explore and develop optimum techniques, rules and guidelines for performing the assessment of codes[3]; and

(2) to apply these techniques, rules and guidelines to the RELAP4/MOD6 code to understand the components of a successful code assessment and to gain further knowledge about the quality of the code.

At the time this study began, RELAP4/MOD6 had not been released to the Argonne Code Center; therefore, these comparisons must be considered as code checkout. However, the analyses were treated in the structured manner of the assessment process, one of the first steps of which is to develop a matrix (Table I) identifying the complete scope of effort. As shown in the table, that scope includes analyses of component, system and integral blowdown and reflood phenomena. This report presents the results of the LOFT and Semiscale isothermal system blowdown studies performed for the PWR (pressurized water reactor) blowdown portion of the code assessment of RELAP4/MOD6 as shown in subtask 5 of Table I. Also, the results of the RELAP4/MOD6 calculation of U.S. Standard Problem 7 (subtask 4) are presented.

Specific ground rules were formulated prior to all analyses. These ground rules covered modeling techniques, code option selection, and code user input values and were based on the best published (and unpublished) information available. Sources used were the NRC guidelines for assessment of codes[3], the limited guidelines for model

TABLE I

MATRIX FOR CODE ASSESSMENT

OF RELAP4/MOD6

	EXPERIMENTS SELECTED	FEATURES EVALUATED								
		BLOWDOWN HEAT TRANS. & HYDRAULICS	REFLOOD HEAT TRANS. AND HYDRAULICS	FUEL BEHAVIOR	SCALING EFFECTS	DIFFERENT SYSTEMS	TEST PREDIC-TION	COMPONENT EFFECTS	SYSTEMS EFFECTS	INTEGRAL EFFECTS
1. SEMISCALE, THTF CORE BLOWDOWN	SEMISCALE S-06-5, THTF 105	X				X		X		
2. SEMISCALE, LOFT PRESSURIZER BLOWDOWN	SEMISCALE S-04-4, S-06-5, LOFT L1-4				X	X		X		
3. SEMISCALE, LOFT STEAM GENERATOR BLOWDOWN	SEMISCALE S-01-4A, S-06-5, LOFT L1-4				X	X		X		
4. STANDARD PROB. 7 LOFT L1-4	LOFT L1-4						X		X	
5. SEMISCALE, LOFT ISOTHERMAL COMP.	SEMISCALE S-01-4A, LOFT L1-4				X	X			X	
6. SEMISCALE, FLECHT CORE REFLOOD	SEMISCALE S-03-0, FLECHT LFR 4019, 11003		X			X		X		
7. SEMISCALE, FLECHT-SET, PKL COMP.	SEMISCALE S-03-5 FLECHT-SET 27148 PKL K5A		X		X	X			X	
8. PKL PREDICTION	PKL K5A		X				X		X	
9. SEMISCALE INTEGRAL EXPERIMENTS (6)	SEMISCALE S-04-5, S-04-6, S-06-1, S-06-2, S-06-5, S-06-6	X	X						X	X
10. MARVIKEN CRITICAL FLOW TESTS	TBD				X			X		
11. SEMISCALE MOD-3 BLOWDOWN	SEMISCALE S-07-1	X				X	X		X	
12. SEMISCALE MOD-3 REFLOOD	SEMISCALE S-07-4		X			X	X		X	
13. SEMISCALE MOD-3 INTEGRAL	SEMISCALE S-07-6	X	X			X	X		X	X
14. PBF LOCA SERIES	LOC-11, LOC-3	X		X				X		
15. ADDITIONAL THTF TEST (Extension to Subtask 1	THTF 177	X					X	X		
16. LOFT L1-5 PREDIC-TION	LOFT L1-5						X		X	
17. ADDITIONAL SEMI-SCALE, FLECHT CORE REFLOOD (Extension to Subtask 6)	SEMISCALE S-03-A FLECHT LFR 2414, 13404, 13609		X			X		X		
18. ADDITIONAL SYSTEM REFLOOD TESTS (Ex-tension to Subtask 7)	SEMISCALE S-03-6, FLECHT-SET 22138 PKL K7A		X		X	X			X	

and option selection given in the RELAP4/MOD5[4] and RELAP4/MOD6[1] manuals, and consultations with code developers and with Semiscale, LOFT, code checkout and assessment personnel. The use of a fixed set of ground rules was necessary to avoid any appearance of code tuning during the base runs, and to provide consistency between the several models. The ability of the RELAP4 fluid equations to predict the system behavior during isothermal blowdowns was assessed.

Data used in the comparisons are from one LOFT isothermal blowdown experiment and from the Semiscale Mod-1 system counterpart to that LOFT test. Section II describes the experimental facilites and test selection. Section III describes the base case RELAP4 input models; the results of the comparisons of the base case models to data are described in Section IV. Section V gives the results of additional calculations with nodalization and initial condition changes. Section VI summarizes the conclusions and recommendations that resulted from the study.

II. EXPERIMENTAL FACILITES

The LOFT Program[5] and the Semiscale Program[6] are conducted by EG&G Idaho, Inc. for the Unites States Government. The programs are sponsored by the Nuclear Regulatory Commission through the Department of Energy and are part of the overall program designed to investigate the response of the pressurized water reactor system to a hypothesized LOCA (loss-of-coolant accident). Both programs are intended to provide integral system test data for thermal-hydraulic code assessment. The two facilities represent a large difference in physical scale.

1. LOFT

The objective of the LOFT Program is to provide data for the evaluation and improvement of analytical methods used to predict the response of a pressurized water reactor to a LOCA. Emphasis is placed on the performance of various engineered safety features, including the emergency core cooling system. Additionally, the tests are intended to identify and investigate any unexpected thermal-hydraulic behavior of the LOFT facility.

1.1 Facility Description

A description of the overall LOFT Program and test series with a detailed system description is contained in Reference 5. The facility has been designed to simulate the major component and system responses of a pressurized water reactor during a LOCA. The facility, shown in Figure 1, consists of a reactor vessel, an intact coolant loop, a broken coolant loop, the blowdown suppression system, and the emergency core cooling system.

The reactor vessel is constructed with an annular downcomer, a lower plenum, lower core support plates, a core region, and an upper plenum. For the L1 test series (except for the final test of the

series), a core simulator was installed in the core region to simulate the hydraulic resistances of a nuclear core. The downcomer connects with the cold legs of both the intact loop and the broken loop; the upper plenum connects with both hot legs.

The intact loop contains an active steam generator and two pumps for circulating the coolant. The pressurizer is connected to the hot leg of the intact loop.

The broken loop contains a steam generator simulator and a pump simulator. These simulators maintain elevations and represent the hydraulic resistances of active components with orifice plates. The broken loop also contains two quick-opening blowdown valves to initiate the LOCA transients and simulates a noncommunicating break. The blowdown valves connect the broken loop to the blowdown suppression system.

1.2 Test Selection

At the time this study was initiated, only isothermal blowdown experiments had been conducted in LOFT. An isothermal test is one in which the fluid temperature is constant throughout the primary system prior to the initiation of the experiment and there is no power generation in the core. LOFT test L1-4 was selected because it represented a test that had not been used in the development and checkout of the initial versions of RELAP4/MOD6 and because it was also U.S. Standard Problem 7. The test simulated a 200% cold leg break with ECC (emergency core coolant) injection into the intact loop cold leg; accumulator flow was initiated at a system pressure of 4.14 MPa.

Initial conditions for the test were as follows: 15.65 MPa system pressure, 553 K system fluid temperature, and 268.4 kg/s primary coolant mass flow. The test data are contained in Reference 7.

1.3 Measurements and Accuracies

The LOFT instrumentation and associated uncertainties pertinent to the data comparisons for this study are given in Table II. The uncertainties in the LOFT data are currently under evaluation by the LOFT Program. The uncertainties listed in Table II are estimates based on information contained in References 7 and 8.

2. SEMISCALE

The objectives of the Semiscale program are to quantify the physical processes controlling system integral behavior during a LOCA and to provide an experimental data base for assessing reactor safety analysis methods. The Semiscale Mod-1 program has the further objective of providing support to other experimental programs in the form of instrumentation assessment, optimization of test series, selection of test parameters, and the evaluation of test results.

2.1 Facility Description

A description of the overall Semiscale program and test series with a detailed system description can be found in Reference 6. As with the LOFT facility, the Semiscale Mod-1 facility has been designed to simulate the major component and system responses of a pressurized water reactor during a LOCA. Additionally, the Semiscale Mod-1 facility provides counterpart tests to the LOFT tests and is therefore scaled to the LOFT facility. The scaling philosophy is based on maintaining the ratio of primary system volume to the power generation rate (for powered tests). The facility is shown in Figure 2 and consists of a pressure vessel, an intact coolant loop, a broken coolant loop, the blowdown suppression system, and the emergency core cooling system.

The pressure vessel is similar to the LOFT reactor vessel. There is an annular downcomer, a lower plenum, a lower core support plate, a core region, and an upper plenum. The downcomer connects to the two

TABLE II

LOFT INSTRUMENTATION

Measurement	Instrument Designation*1	Estimated Uncertainty*2	Remarks
Core simulator pressure	PE-CS-1A	0.2 MPa	QEUD*3
Accumulator pressure	PE-P120-43	0.1 MPa	QEUD
Core simulator fluid temperature	TE-CS-1	5 K	QEUD
Broken loop cold leg density	DE-BL-1B	60 kg/m^3	QEUD, centerline measurement, inclined 45^{o} to vertical
Pressurizer liquid level	LT-P139-6	0.05 m	QEUD, 0 to 13 s
Intact loop pump 2 speed	RPE-PC-2	2 rad/s	Restrained data*4, unexplainable spikes
Broken loop cold leg mass flow	FR-BL-116	No Estimate	Based on differential pressure and density
Broken loop hot leg mass flow	FR-BL-216	No Estimate	Based on differential pressure and density
Intact loop hot leg mass flow	FR-PC-212	No Estimate	Based on momentum flux and density
Intact loop steam generator outlet mass flow	FR-PC-311	No Estimate	Based on turbine meter and density

*1 Instrument designations are consistent with the nomenclature of the LOFT data reports.

*2 Estimated two standard deviation value.

*3 LOFT designation, qualified engineering units data where measurements have been compared to other measurements and found to be within the accuracy of the instrument.

*4 LOFT designation, instrument did not fail, but data have some restrictions.

cold legs and the upper plenum connects with both hot legs. The core region for the S-01 (LOFT counterpart test) series contains a core simulator with orifice plates to represent the hydraulic losses associated with the electrical core in other test series.

Again, as in the LOFT facility, the intact coolant loop contains an active steam generator and an active pump (one as opposed to the two parallel pumps in LOFT). The pressurizer is connected to the intact loop hot leg.

The broken loop, in the cold leg break configuration, locates a simulated steam generator and a simulated pump in the hot leg. The steam generator and pump simulators represent hydraulic losses with orifice plates. A noncommunicating break is simulated; the LOCA transient is initiated by depressurizing and rupturing simultaneously the rupture disk assemblies in both the broken loop cold leg and the broken loop hot leg.

2.2 Test Selection

Semiscale Mod-1 test S-01-4A was selected for this study. The test represented a 200% cold leg break with ECC injection into the intact cold leg. The system hardware configuration and initial conditions were selected to yield a system response similar to that for LOFT Test L1-4 (S-01-4A was conducted prior to L1-4), and test S-01-4A is thus the counterpart to the LOFT test selected for this study.

Initial conditions for test S-01-4A were as follows: 15.52 MPa system pressure, 558 K system fluid temperature, and 8.31 kg/s primary coolant mass flow. Accumulator flow was initiated at a system pressure of 4.05 MPa during the blowdown. The test data are contained in Reference 9.

2.3 Measurments and Accuracies

The Semiscale instrumentation and associated uncertainties pertinent to the data comparisons for this study are giver in Table III. The uncertainties are based on the information contained in References 8 and 10; the uncertainties do not include the effects of nonhomogeneous, transient, two-phase flow and thus must be considered estimates.

TABLE III

SEMISCALE INSTRUMENTATION

Measurement	Instrument Designation *1	Estimated Uncertainty *2
Upper plenum pressure	PV-UP+10	0.1 MPa
Pressurizer pressure	PU-PRIZE	0.1 MPa
Core simulator fluid temperature	TFV-LOFT-COR	5 K
Broken loop cold leg density	GB-21VR	16 kg/m^3
Core flow mixer box fluid density	GV-COR-150 HZ	16 kg/m^3
Accumulator volumetric flow	FTU-ACC	0.1 l/s
Intact loop pump speed	PUMPU-RPM	2 rad/s
Broken loop hot leg mass flow	FDB-42 & GB-42VR	No Estimate
Broken loop cold leg mass flow	FDB-21 & GB-21VR	No Estimate
Intact loop hot leg mass flow	FDU-1 & GU-1VR	No Estimate
Core inlet mass flow	FTV-CORE-IN & GV-COR-150HZ	No Estimate

*1 Instrument designations are consistent with the nomenclature of the Semiscale data report.

*2 Estimated two standard deviation value.

III. BASE RUN MODELS

The base run models for both LOFT Test L1-4 and Semiscale Test S-01-4A were developed with the same modeling philosophy. The volumes were dictated by geometric details, with separate volumes or groups of volumes representing geometrically distinct regions. Code option selection and input parameters are generally consistent for the two models. The nodalizations and input option selections were reviewed with Code Development, LOFT, and Semiscale personnel. All input decks, including the base run models and the decks required for the calculations discussed in Section V, and necessary control cards are contained on file with the INEL Computer Center under Historical Configuration Control No. H003971B.

1. NODALIZATION

Similar nodalizations were developed for both experimental facilities, except where measurement locations dictated otherwise. The choice of nodalization was based on previous work for U.S. Standard Problem 7[11]. Some minor changes in nodalization were required to maintain consistency with other Semiscale Mod-1 models[12] developed for the assessment of RELAP4/MOD6. These modeling differences will be addressed in Section V.

The base run nodalization for LOFT Test L1-4 is shown in Figure 3; the model consists of 61 volumes, 65 junctions, and 48 heat slabs. The Semiscale Test S-01-4A model, consisting of 60 volumes, 63 junctions, and 49 heat slabs, is shown in Figure 4.

Both base run models utilize the two channel, or split, downcomer nodalization. Each downcomer channel consists of four vertically stacked volumes: one volume in the inlet annulus and three in the downcomer. The division of the downcomer into two vertical channels was determined based on rated accummulator flow. The ECC liquid was assumed to fill a sector of the annular gap in the downcomer and to

flow at the rated value at a constant velocity. The gravity head of the liquid column was balanced by frictional forces. The force balance permitted calculation of the liquid velocity, which together with the liquid density and the rated accumulator flow determined the flow area. This flow area is the flow area for the downcomer channel on the intact loop side. The remainder of the downcomer is modeled on the broken loop side. The downcomer split for the LOFT model is 7% on the intact loop side and 93% on the broken loop side. For the Semiscale model, the split is 11% on the intact loop side and 89% on the broken loop side.

The pressurizer nodalizations are consistent with recommendations in Reference 13. The steam generator nodalizations are consistent with base run nodalizations in Reference 14. The accumulator injection line volume is lumped with the accumulator volume for both models. The lower plenum in the Semiscale model is divided into two vertically stacked volumes because of the large length to diameter ratio (greater than 1.5).

The LPIS and HPIS (low pressure and high pressure injection systems) flows are modeled as fills because the flows are pumped. The blowdown suppression tanks in both facilities are modeled as time dependent volumes (specified fluid conditions, in particular pressure).

2. CODE OPTIONS

All volumes are homogeneous in both models except for the reflood assist bypass lines, the pressurizer, the accumulator, and the steam generator secondary. For these five volumes, complete phase separation is used. Complete phase separation is appropriate for the steam generator secondary during an isothermal test because there is no energy transfer from the primary to produce vaporization in the secondary. The vertical slip model is invoked at all vertically oriented junctions except for those in the steam generator tubes.

The compressible form of the momentum equation (MVMIX = 0) with the momentum flux terms is generally used. There are three exceptions for which the incompressible form of the momentum equation (MVMIX = 3) is specified:

(1) those junctions where the associated volume flow areas are defined for a flow direction different from the junction (in the case of multiply connected volumes);

(2) junctions internal to plenums where the flow areas are equal on both sides and the flows are small; and

(3) along dead end flow paths where MVMIX = 3 has been specified at another junction.

Critical flow is calculated with the HEM (homogeneous equilibrium model) (multiplier 1.0) in LOFT. In Semiscale the Modified Burnell model (multiplier 0.96), HEM (multiplier 0.845), and a transition quality of 2% are used to calculate critical flow. This discrepancy in selected critical flow models results from the original source of the RELAP4 input decks (Reference 11 for LOFT and Reference 12 for Semiscale) and from a preliminary evaluation of critical flow data applicable to the two facilities (Reference 15). The effect of the discrepancy is minimized in isothermal tests because the flows at the breaks saturate within a few milliseconds after the beginning of the transient and the quality rapidly increases through the 2% limit. The difference in the multipliers on HEM is a result of geometric differences in the break nozzles. The flow area of the volume upstream of the hot leg break plane in the LOFT model is artifically increased in the code input in order to calculate approximate stagnation conditions upstream of the break; for the LOFT cold leg break and both locations in the Semiscale model the piping flow area is already larger than the break area.

The rough wall friction option is selected for all piping volumes. The pumps are allowed to coast down only to specified limits (78.5 radians/s for L1-4 and 141.4 radians/s for S-01-4A). The blowdown heat transfer correlations (HTS2 with default correlation selections) are used.

IV. BASE RUN RESULTS

The results of the base run models described in Section III are compared to appropriate experimental data in this section. All calculations were performed on the INEL CDC 7600 computer. The running times of the models are comparable, requiring three cpu hours for the calculation of approximately 46 transient seconds. Each run terminated on a normal end cpu trip. It should be noted that the cpu time requirement is a function of the preload reduction option, the OPT10 option being required for both models. The OPT10 option requires an additional 20% or more cpu time (Reference 1).

1. LOFT TEST L1-4

The comparison of the LOFT L1-4 base run calculation to data is shown in Figures 5 through 14. Figure 5 shows the depressurization of the core simulator (volume 51); the agreement with data is very good until 21.5 s, after which the calculation depressurizes too rapidly. The 21.5 s point coincides with the initiation of accumulator injection, and the deviation of calculated and experimental pressures after that point is primarily related to equilibrium condensation resulting from subcooled ECC injection. The calculation reaches containment pressure between 38 and 40 s while experimentally the blowdown continues beyond 50 s. Figure 6 shows the fluid temperature in the core simulator; as expected the fluid temperature comparison reflects the system pressure comparison. The comparison is very good until 21.5 s, and then deviates below the data and follows saturation. The brief period of calculated superheating around 40 s is related to an initial period of lower plenum refill followed by appreciable voiding of the lower plenum and results from the volume drying out.

The broken loop hydraulic behavior is represented in Figures 7 through 9. The broken hot leg flow (junction 23) is shown in Figure 7; there are two periods during the first 21 s that the flow is overpredicted. Once the calculated system pressure falls below the experimental pressure, the hot leg flow is underpredicted. Figure 8 shows the comparison of broken cold leg flow (junction 44) to data; the comparison indicates an initial 6 s period during which the flow is overpredicted. Given the nature of the flow measurements (based on differential pressure and density, and calibrated after the test based on the blowdown suppression tank liquid inventory), the broken loop flow comparisons are considered acceptable. After 22 s in the calculation there is some evidence of ECC bypass in the broken cold leg flow. This observation is supported by the broken cold leg density comparison (Figure 9). From 22 to 33 s, the density is overpredicted; the overprediction is due to calculated ECC bypass around the vessel. The data indicates bypass, but in lesser quantity. The calculated density peaks at 36 and 46 s are also due to bypass.

The intact loop hydraulic performance is shown in Figures 10 and 11. Figure 10 is the intact hot leg mass flow comparison. The calculation does not predict the return to positive flow between 1 and 6 s. The discrepancy is due to not properly calculating the stagnation point in the intact loop, and is related to small deficiencies in the calculated pressurizer performance (Reference 16) and flow resistance in both the intact and broken hot legs. Figure 11 shows the mass flow rate at the steam generator outlet. The comparison is good, although the data exhibits a more rapid falloff at 5 s to zero flow than is seen in the calculation.

The remaining base run comparisons (Figures 12 through 14) show pump behavior, pressurizer behavior, and accumulator performance. Figure 12 shows the pump coastdown comparison. The calculated pump speed is significantly below the data until 26 s; this underprediction is primarily due to not modeling the effect of the pump variable

inertia. [LOFT pumps are controlled to simulate a typical LPWR coastdown. A variable pump inertia model was incorporated into RELAP4/MOD6, update 3; this model should be used in future LOFT analyses (References 16 and 17).] The overall effect on the system behavior is minimized as the pumps degrade at approximately 6s. The underprediction in speed is reflected by an underprediction in pump head prior to degradation.

The pressurizer liquid level comparison is shown in Figure 13. The liquid level is tracked within the uncertainty on the data. The depressurization of the pressurizer after emptying is reasonable.

The accumulator pressure comparison is shown in Figure 14; the code calculates the time (22 s) of accumulator injection very well. However, the calculated pressure does not subsequently decay as rapidly as the data. This overprediction is worse in light of the system pressure underprediction. The net result is to overpredict significantly the driving pressure differential for accumulator flow; consequently the accumulator flow is overpredicted (by approximately 20% maximum) and aggravates further the rapid system depressurization through increased subcooled ECC injection.

The trends in the calculated differential pressures (not shown) across the broken loop steam generator simulator, the intact loop steam generator, and the intact loop pump correspond to the trends exhibited in the data. The differences reflect discrepancies in the calculated flows or in the representation of hydraulic losses, or both. As indicated above, the pressure differential across the intact loop pumps is underpredicted early and is consistent with the underprediction of pump speed. These differences in calculated and measured differential pressures may also account for the inability to calculate positive flow in the intact hot leg between 1 and 6 s (Figure 10).

Finally, the code calculates the lower plenum to fill initially at 40 s followed by significant and sustained voiding until 45 s. Between 45 s and the end of the calculation, the code calculates a lower plenum density that varies between full liquid and a two-phase mixture. This behavior is similar to the lower plenum inventory indicated by the lower plenum liquid level detectors which indicate filling between 45 and 50 s, but with the continued presence of vapor. Downcomer flows (junctions 49 and 60) exhibit the same relative behavior to 23 s. Then the flow on the intact loop side indicates small positive flows into the lower plenum, but the broken loop side continues to be negative (out of the lower plenum). At 33 s, the broken loop side flow becomes oscillatory and the lower plenum liquid inventory begins to increase.

The RELAP4/MOD6 code provides an adequate representation of the hydraulic behavior of the LOFT system during an isothermal blowdown, particularly prior to the beginning of accumulator injection. After accumulator injection begins, the calculated system pressure deteriorates due to the equilibrium condensation effects of the subcooled ECC. Pump coastdown is not well calculated due to the lack of modeling the variable inertia of the pump. Accumulator pressure is overpredicted; future LOFT analyses should employ the polytropic expansion model (LOFT Program currently recommends an isentropic expansion of the accumulator nitrogen - Reference 17).

2. SEMISCALE TEST S-01-4A

The comparison of the Semiscale S-01-4A base run calculation to data is shown in Figures 15 through 25. Figure 15 is the upper plenum pressure comparison. After the system saturates, the code underpredicts the system pressure. This initial underprediction can be attributed to a difference in fluid temperature of approximately 4 K. This difference approximates the accuracy of the fluid temperature measurements; furthermore, there is sufficient variation in the reported initial fluid temperatures (Reference 9) to support this

conclusion. Accumulator injection is calculated to commence at about 20 s (versus 23 s in the data), hence the early calculated rapid depressurization is not attributable to equilibrium condensation problems. Containment pressure is reached at approximately 40 s in the calculation (versus in excess of 50 s in the data). The core simulator fluid temperature (Figure 16) reflects the system depressurization; some superheating in the calculation is evident after 30 s. The large temperature peaks at 41, 44, and 48 s are the result of volume dryout in the calculation and are not reflected in the data.

The broken loop hydraulic behavior is represented in Figures 17 through 19. Figure 17 is the broken loop hot leg mass flow comparison near the break; the comparison is generally good except for the period from 20 to 30 s. The broken loop cold leg mass flow comparison near the break is shown in Figure 18; again the comparison is good except for an initial period of overprediction. The flow spikes, both calculated and experimental, beyond 30s are due to ECC bypass. The broken cold leg density is shown in Figure 19. The broken cold leg voiding essentially parallels the data. The increase in calculated density beyond 21 s is due to ECC bypass; the data shows similar although lower density spikes.

Figures 20 and 21 show the density and mass flow at the core inlet mixer box. The density comparison indicates that in general the calculated core inlet region voiding is similar to the data; the differences between 5 and 20 s are due in part to comparing a calculated volume average quantity to a horizontal line measurement. The core inlet flow calculation is similar to the data, although the data does not show the initial flow reversal. The code calculates lower plenum (Volume 36) refill to occur between 48 and 50 s, with density fluctuations being apparent in the mixer box (Volume 2); the data shows refill to occur about 63 s or 15 s after the data. This difference is a direct result of the rapid depressurization in the calculation. The effect of the downcomer nodalization will be discussed in Section V.2.1. The downcomer flows (junctions 1 and 39) are similar throughout the transient and have the same direction.

Figure 22 shows the intact loop hot leg mass flow near the vessel. This comparison is similar to the intact hot leg mass flow comparison for LOFT L1-4. The code does not predict the sustained positive flow after initiation of the transient.

Figure 23 shows the depressurization of the pressurizer. The code calculates the pressurizer to empty approximately 3 s early. This early emptying adversely affects the intact loop hot leg flow comparison shown in Figure 22. The early emptying of the pressurizer is due in part to the too rapid system depressurization. It may also be affected by hydraulic losses in the surge line (see Reference 13).

Figure 24 shows the volumetric flow rate from the accumulator. The data spike between 3 and 4 s is due to the operation of valves and does not represent actual ECC injection. The code calculates the initiation of accumulator flow at approximately 20.5 s instead of 23 s in the data; this difference is due to the early system depressurization in the calculation. The overprediction of flow rate is similar to the overprediction of accumulator flow in LOFT.

The pump coastdown is shown in Figure 25. The offset in the calculated and experimental curves is partially due to the time of pump trip. The remainder of the difference is due to hydraulic differences in the intact loop. The calculation prevented coastdown below 141.4 rad/s and thus could not follow the data between 17 and 24 s (the pump was controlled experimentally to 141.4 rad/s)

The major problem with the S-01-4A base run calculation is the early system depressurization. This leads to a calculated early end of bypass and an early refill. Since the depressurization problem is evident prior to initiation of accumulator injection, the cause is not the equilibrium condensation phenomenon although it may contribute after 21 s. While the flows near the breaks (Figures 17 and 18) do

not indicate a clear deficiency in the critical flow calculation, the behavior (fast depressurization, reasonable mass flows near the breaks) is similar to that observed in other studies (Reference 12) and is probably due to a too high multiplier on the saturated critical flow model. Other than the depressurization problem, calculated behavior and the resulting comparisons are similar to those for the LOFT L1-4 calculation.

V. ADDITIONAL STUDIES

The base run models represent generally acceptable modeling techniques for both LOFT and Semiscale. However, there are differences with previous models. This section addresses the few major questions regarding the modeling techniques.

1. LOFT TEST L1-4

LOFT Test L1-4 was U. S. Standard Problem 7; the model used for the Standard Problem analysis[11] be addressed. Also, cross connections between downcomer volumes tend to generalize the nodalization to make it reflect more the possible flow paths and will be addressed.

1.1 Standard Problem Calculation

The standard problem nodalization differs from the base run nodalization as follows (refer to Figure 3):

1. The steam generator inlet and outlet plenums are single volumes instead of two vertical stacks of two volumes each.

2. The two pumps have a common pump suction volume instead of separate pump suction volumes.

3. The accumulator injection line is modeled as a separate volume instead of being combined with the accumulator. The LPIS and HPIS fills inject into the accumulator injection line.

4. The upper plenum region is represented by three vertically stacked volumes instead of by a single volume.

5. There are only two volumes in the broken cold leg between the vessel and the break plane instead of three.

These changes result in a model consisting of 59 volumes and 63 junctions. For the limited comparison to be discussed, the volume and junction numbers coincide with the base case model in Figure 3. The most significant option differences are in the application of rough wall friction (in general deleted) and in the use of the compressible form of the momentum equation (applied more universally). Also, there are some minor differences in form losses and inertias (these were reevaluated in developing the base run model). Also, the new MOD6 blowdown heat transfer package is used. The downcomer split is slightly different (10% intact and 90% broken).

The U. S. Standard Problem 7 calculation was performed on RELAP4/MOD5 originally. For this calculation, only the minimum changes required to convert the RELAP4/MOD5 deck to RELAP4/MOD6 were made (two errors in the original conversion to RELAP4/MOD6 were corrected). The input deck and necessary control cards are on file with the INEL Computer Center under Historical Configuration Control No. H00397IB.

The core simulator pressure is shown in Figure 26. The system depressurizes more rapidly than the data and more rapidly than the base run analysis; the calculated and experimental pressure begin to diverge almost immediately. This divergence is due to overpredicting the broken loop flows, primarily the broken loop hot leg flow (Figure 27). The broken loop cold leg hydraulics are similar to the base run analysis. As shown in Figure 28, the effect of bypass on the broken cold leg density is only slightly different when compared to the base run comparison (Figure 9).

The observed differences between this RELAP4/MOD6 standard problem calculation and the base run analysis can generally be explained in terms of the more rapid depressurization. No other significant discrepancies between the two calculations were observed. The depressurization problem is a direct result of overpredicting the broken hot leg mass flow. However, the critical flow model and the critical flow multiplier for the two analyses were the same. The

difference is in the manner in which the broken hot leg was initialized. There were two initial temperatures in the broken hot leg for the standard problem analysis: one near the vessel and a second near the quick opening blowdown valve. There was a difference between the two valves (approximately 6.6 K). The standard problem model was initialized by linearly interpolating the temperature by length down the broken hot leg so that there was a uniform temperature gradient. This resulted in subcooled flow at the hot leg break initially and resulted in the flow rate overprediction.

For the base run analysis, the location of the thermocouple near the break was considered to be removed from the flow circulation prior to the transient. Therefore, the broken hot leg was initialized with a constant temperature.

1.2 Cross Connected Downcomer Calculation

The model for the cross connected downcomer calculation was obtained from the base run L1-4 model by adding cross flow junctions in the downcomer between volumes 45 and 57, between volumes 46 and 58, and between volumes 47 and 59. This input deck and required control cards are on file with the INEL Computer Center under Historical Configuration Control No. H00397IB.

The cross connected downcomer calculation system behavior is characterized by the core simulator pressure history and the mass flows in the broken hot leg and in the broken cold leg, Figures 29, 30, and 31. These comparisons are essentially identical to the corresponding comparisons for the base run analysis (Figures 5, 7, and 8). The only differences are very slight and occur at about 35 s. Other comparisons to data indicate that while the calculational results changed slightly from the base run analysis, the comparisons were not significantly different.

The effect of cross connections on the downcomer flows was in general to increase the flows. Early, the cross flows themselves ranged upwards to 300 kg/s but were nearly zero by 10 s. During refill the flows are oscillatory. The lower plenum density changes from the base run analysis, and the lower plenum does not fill as violently as in the base run analysis. While the calculation did not run out that far, it appears that refill may be delayed by two or more seconds beyond the base run analysis. Based on the lower plenum calculated density, cross connections should be used in future LOFT calculations.

2. SEMISCALE TEST S-01-4A

The Semiscale test S-01-4A base run analysis utilized a two channel downcomer; most previous analyses of Semiscale were with a single channel downcomer. This section addresses the effect of the single channel downcomer on the S-01-4A analysis. Also, the effect of reducing the fluid temperature is addressed. Input decks for both calculations, together with necessary control cards, are on file with the INEL Computer Center under Historical Configuration Control No. H003971B.

2.1 Single Channel Downcomer Calculation

The Semiscale Mod-1 downcomer has a large length-to-diameter ratio that results in an overall one-dimensional hydraulic behavior. Therefore, the split downcomer nodalization was combined into a single channel. The single channel downcomer model was obtained from the base run nodalization (Figure 4) by combining the following pairs of volumes into single volumes: volumes 44 and 56, volumes 45 and 57, volumes 46 and 58, and volumes 47 and 59. For purposes of the comparisons to be shown, reference to Figure 4 for volume and junction identification is sufficient.

The system behavior is depicted in Figures 32 through 36. The system depressurization (Figure 32), hot leg break flow (Figure 33), and the cold leg break flow (Figure 34) are essentially identical to

the comparisons for the base run analysis (Figures 15, 17, and 18) throughout the transient. The core inlet flow (Figure 35) and the core inlet density (Figure 36) are also identical to the base run analysis (Figures 20 and 21), except that the oscillations related to lower plenum filling are delayed 5 s. Thus, the effect of the single channel downcomer is to delay downcomer penetration until the vapor flow up the downcomer is lower. The delayed penetration delays refill by extending the bypass period.

2.2 Single Channel Downcomer Calculation With Adjusted Fluid Temperature

The model used in Section V.2.1 was reinitialized with fluid temperatures 3.9 K lower than used in previous runs. A short calculation (22 s) was made to determine the effect of the change. The upper plenum pressure is shown in Figure 37. The system saturates at the correct pressure, but as expected, there is no effect on the too rapid depressurization rate. Thus, the rapid depressurization is due to the saturated critical flow multiplier being too high as suggested in Reference 12, since heat transfer is not of concern early in an isothermal blowdown.

VI. CONCLUSIONS AND RECOMMENDATIONS

The results of the various calculations described in previous sections have provided information relative to the capability of RELAP4/MOD6 to simulate thermal-hydraulic phenomena in an isothermal blowdown situation. This information is pertinent to heated blowdown experiments where problem areas may be otherwise masked by the heat transfer in the core. The conclusions and recommendations resulting from this study are summarized below.

1. *The homogeneous equilibrium assumption in RELAP4 causes severe underprediction of system pressure (Section IV.1).*

   This conclusion is a statement of a well known problem in RELAP4. The effect of the equilibrium assumption is to cause instantaneous condensation when subcooled ECC is injected. Not only does the system pressure degrade, but the code calculates an early end to blowdown, which affects the time of refill and the beginning of reflood.

2. *Accumulator pressure is overpredicted after the initiation of accumulator injection (Section IV.1).*

   After the accumulator injection begins, the system pressure is underpredicted and the accumulator pressure is overpredicted. The result is that the driving head for accumulator flow is too high, and the flow is overpredicted. Future analyses should employ the polytropic expansion model in the accumulator.

3. *The Semiscale S-01-4A calculated system pressure decays too rapidly from the beginning of the transient (Section IV.2).*

   The base run analysis of S-01-4A resulted in reasonable break flow comparisons, but the system pressure is decreasing too rapidly. In an isothermal test heat transfer

is not a major concern early in the transient. Therefore, the depressurization rate is only the result of the loss of mass and energy through the break. Very accurate separate effects data is needed for obtaining multipliers on the saturated critical flow model.

4. *The Standard Problem calculation of L1-4 overpredicts the broken hot leg mass flow due to the initialization of the fluid temperatures (Section V.1.1).*

The only significant difference between the Standard Problem model and the base run model is the initialization of the broken hot leg fluid temperatures. This change permits the base run analysis to predict both the early depressurization history and the hot leg mass flow.

5. *The cross connected downcomer, while not an obvious improvement based on the comparisons to LOFT L1-4 data, is recommended for future analyses (Section V.1.2).*

The cross connected downcomer model appears to provide a more realistic calculation of the lower plenum density history than the base run analysis. The lower plenum density during refill does not demonstrate the large, violent density oscillations that were apparent in the base run analysis.

6. *The single channel downcomer model is recommended for future Semiscale Mod-1 analyses (Section V.2.1).*

The Semiscale Mod-1 downcomer ha a large length-to-diameter ratio that results in an overall one-dimensional hydraulic behavior in the cowncomer. The single channel downcomer provides a better representation of this behavior. The

effect of the nodalization change is to delay downcomer penetration until vapor flow up the downcomer is lower. The delayed penetration prolongs bypass and thus increases the time to refill. The increased time to refill results in an improved data comparison.

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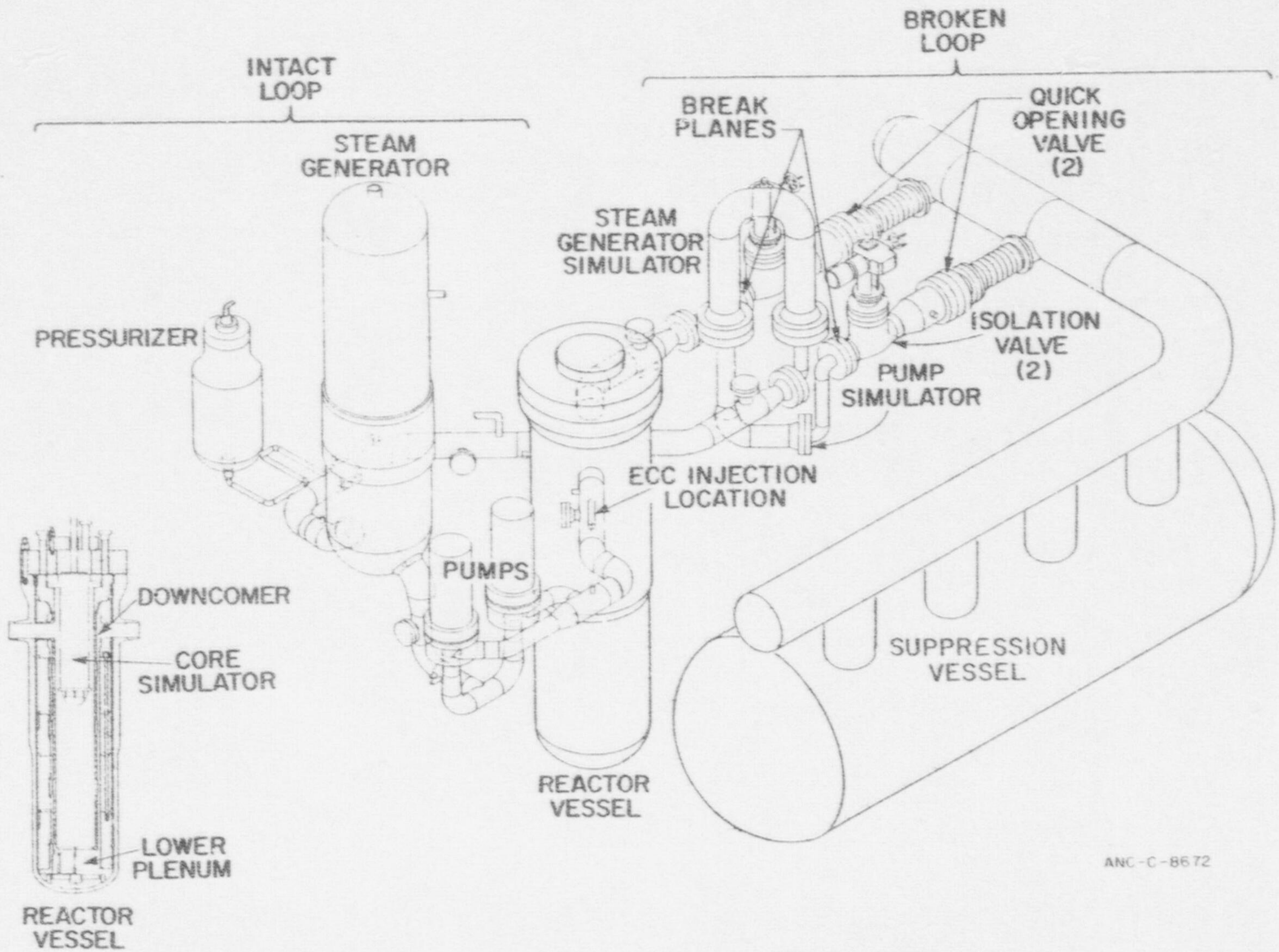

Fig. 1 LOFT system for cold leg break configuration.

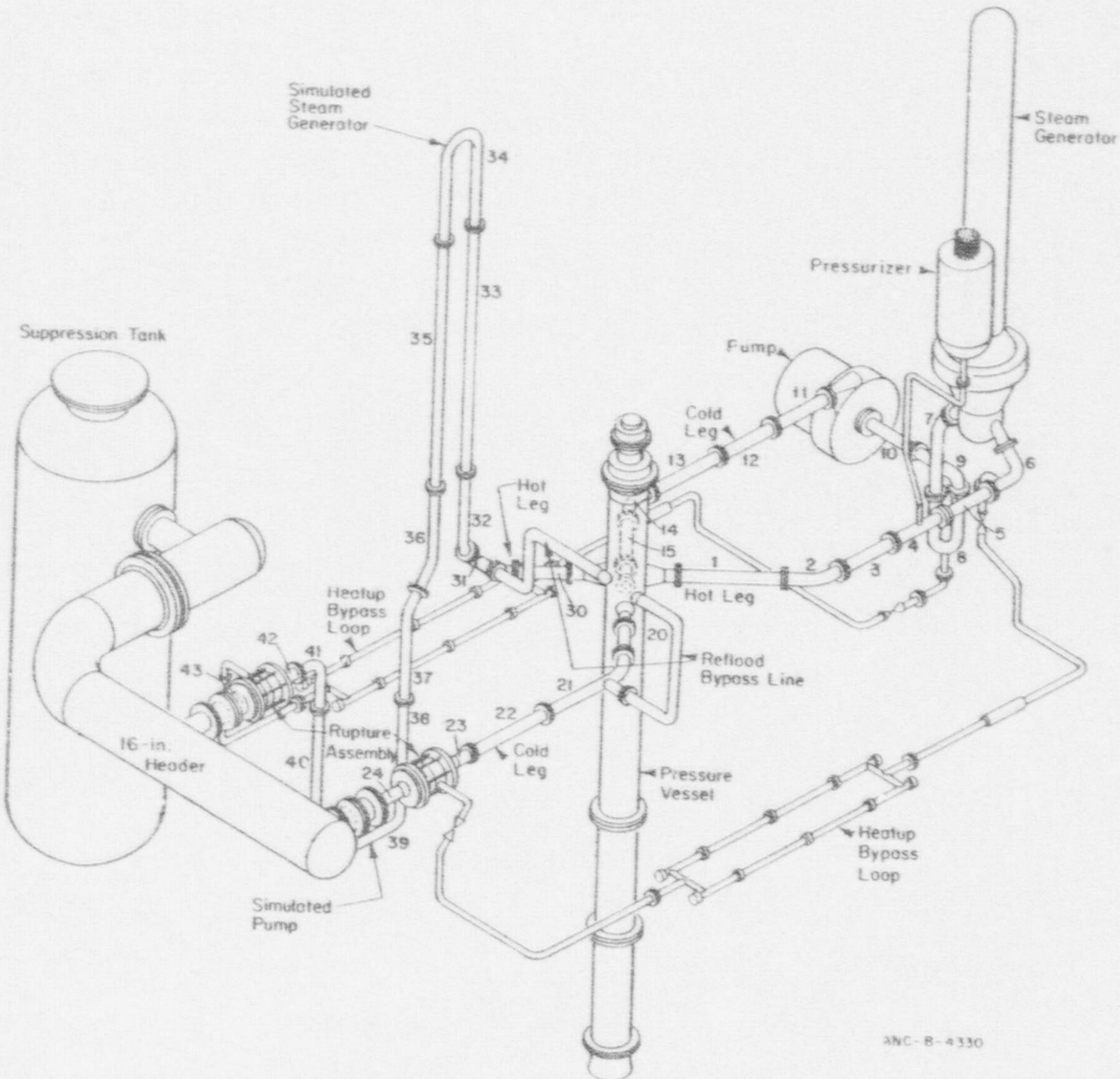

Fig. 2 Semiscale Mod-1 system for cold leg break configuration.

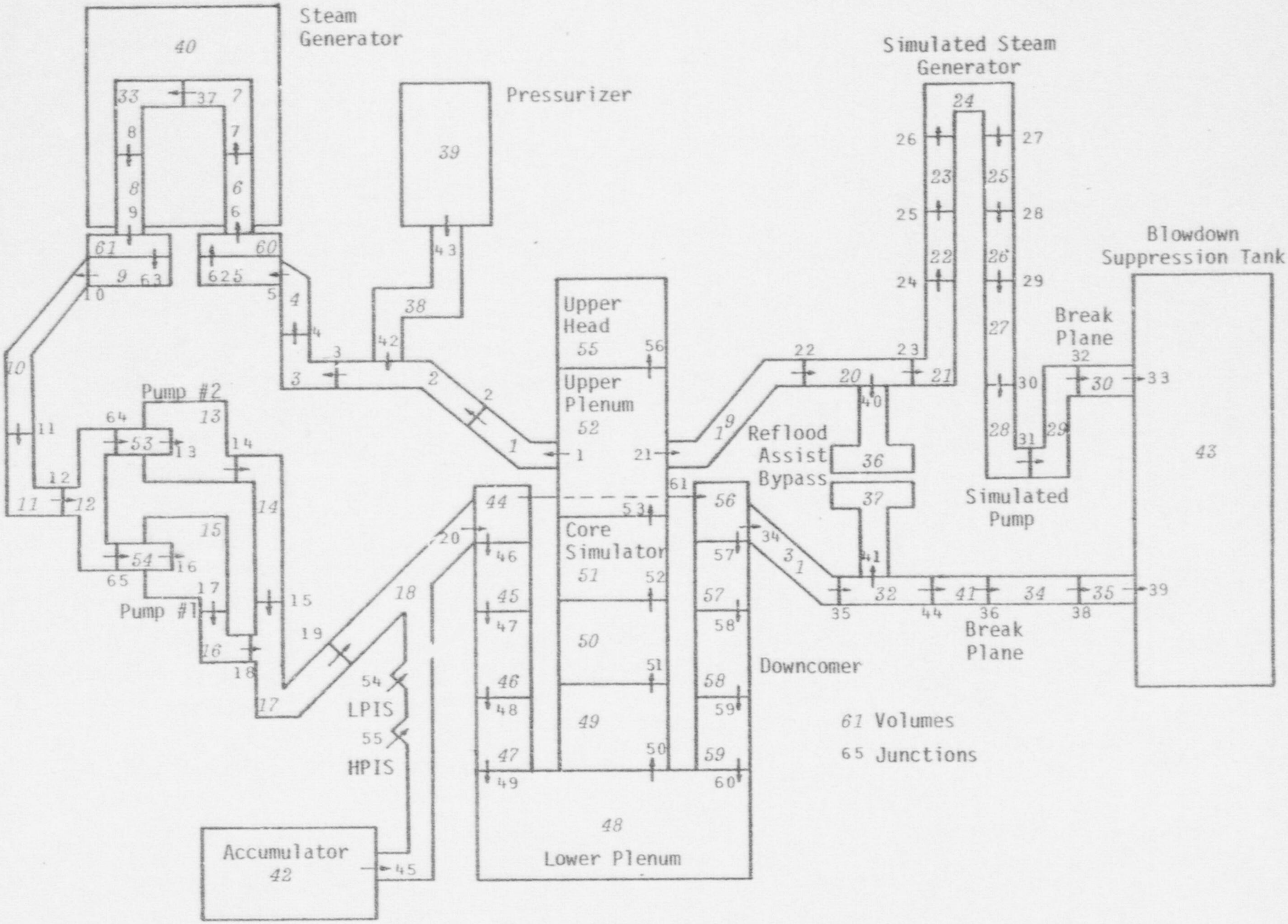

Fig. 3 LOFT Test L1-4 base run nodalization.

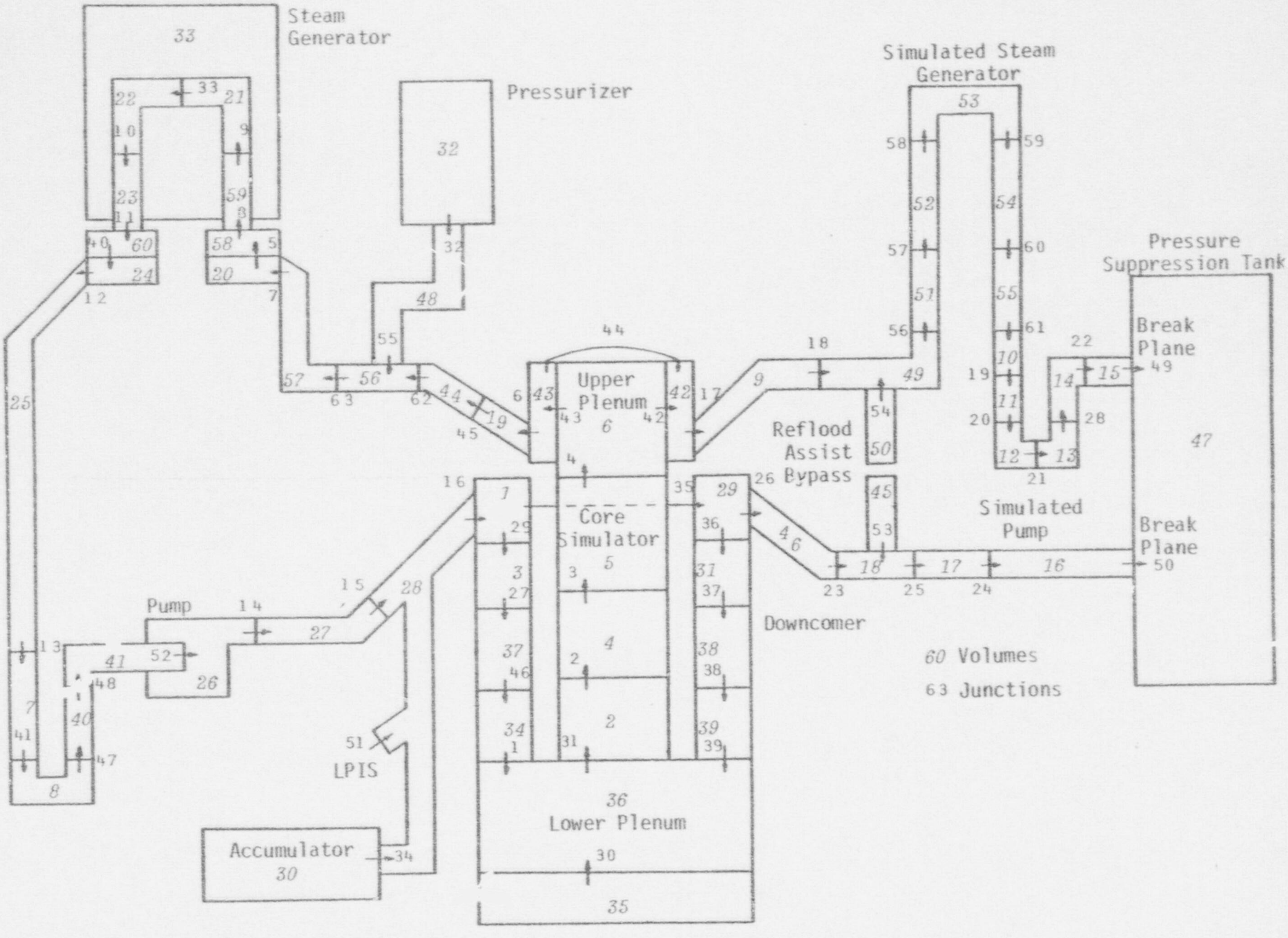

Fig. 4 Semiscale Test S-01-4A base run nodalization.

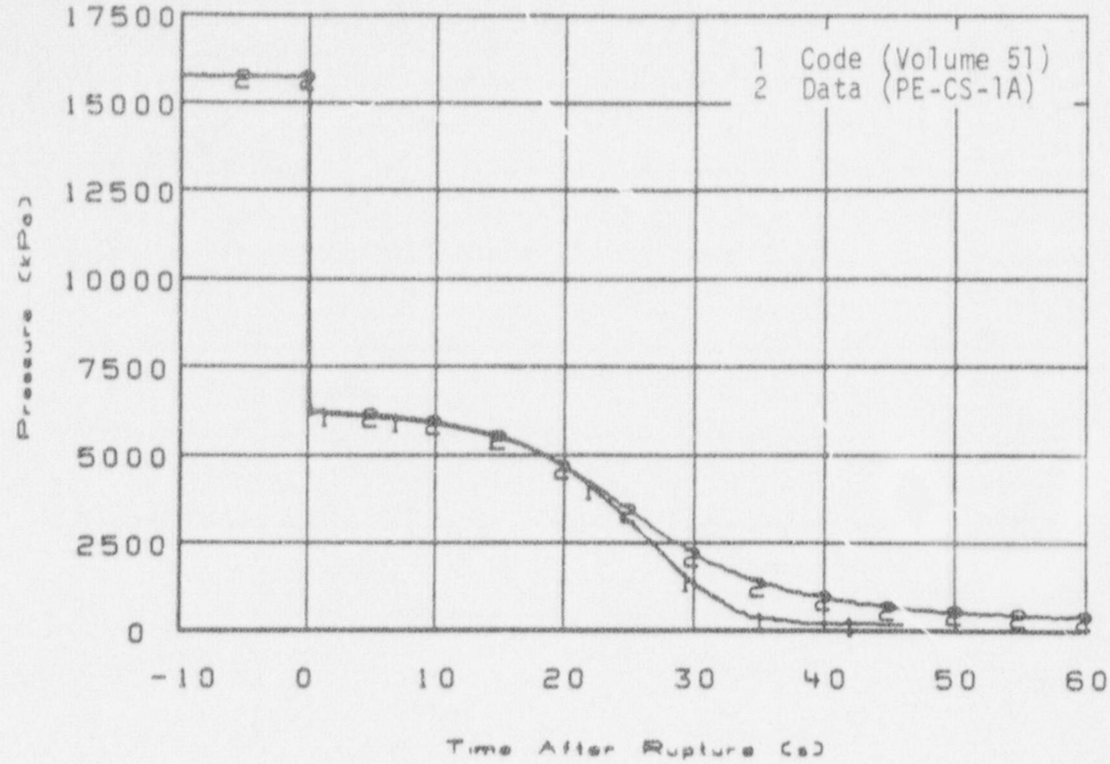

Fig. 5 LOFT L1-4 base run system pressure comparison.

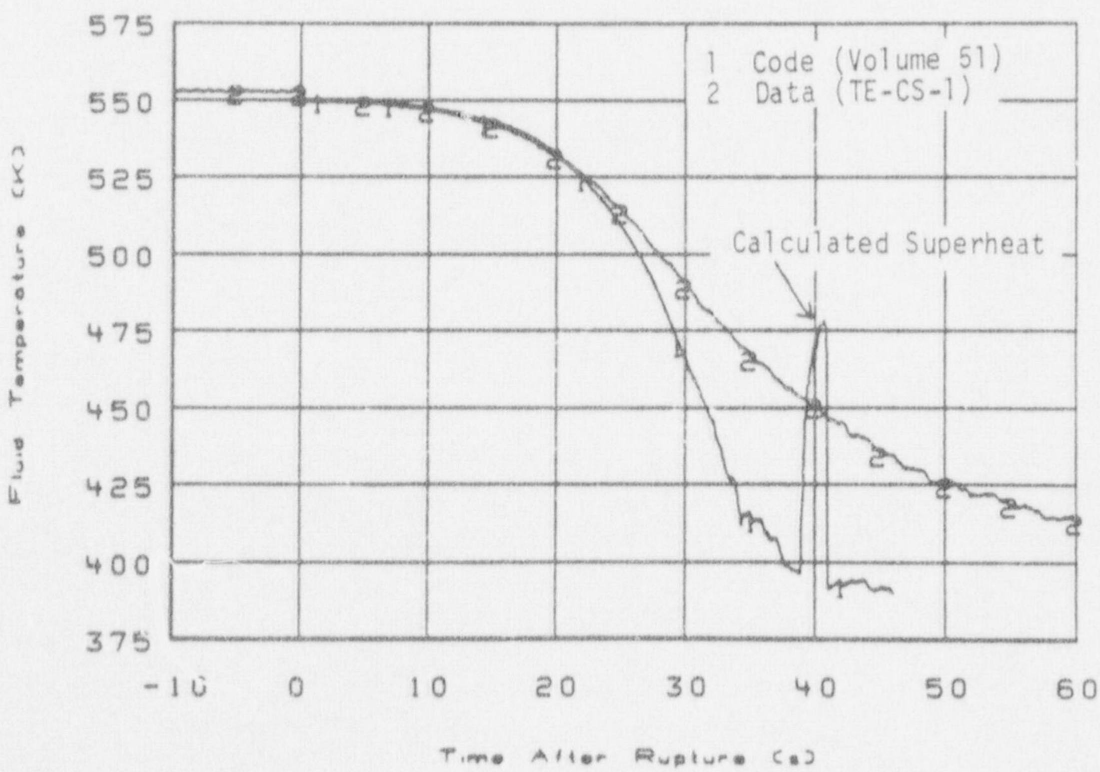

Fig. 6 LOFT L1-4 base run core simulator fluid temperature comparison.

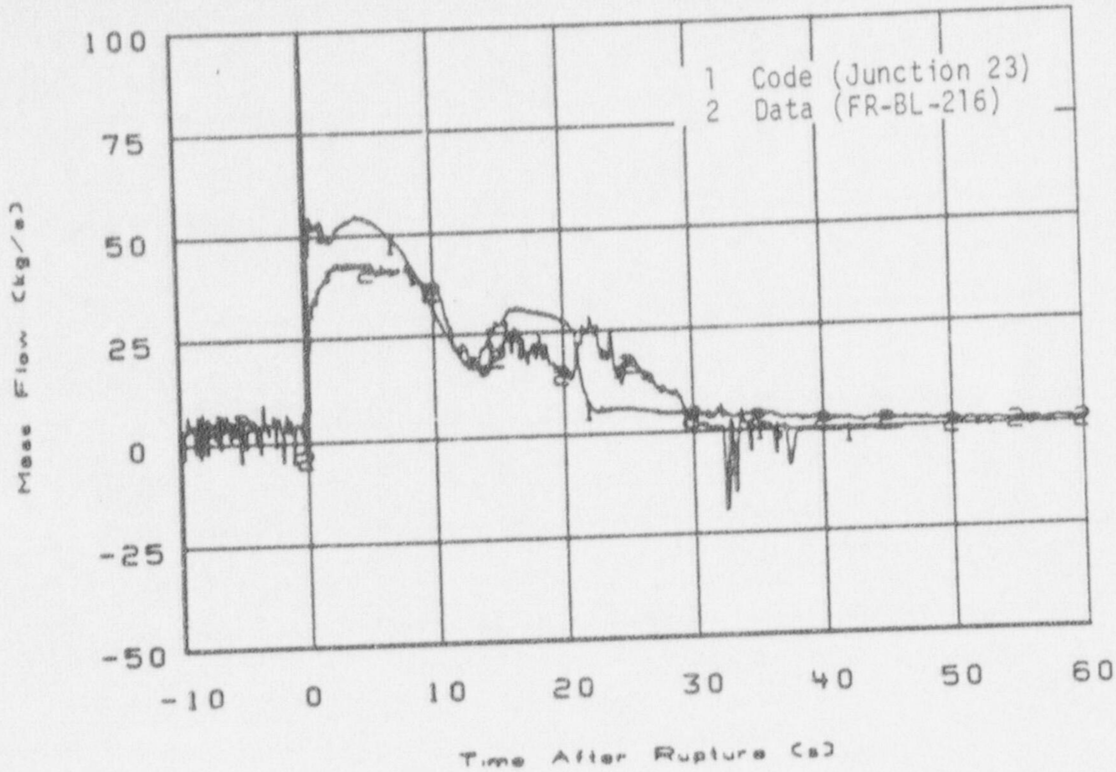

Fig. 7 LOFT L1-4 base run broken hot leg mass flow comparison.

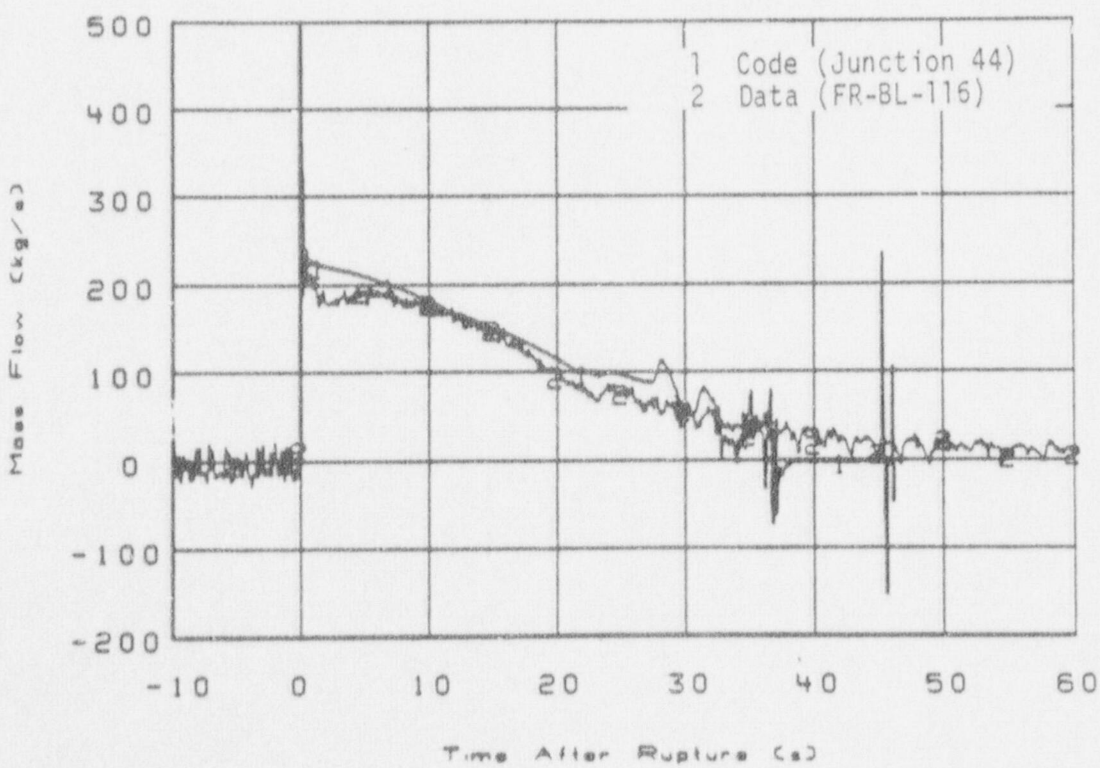

Fig. 8 LOFT L1-4 base run broken cold leg mass flow comparison.

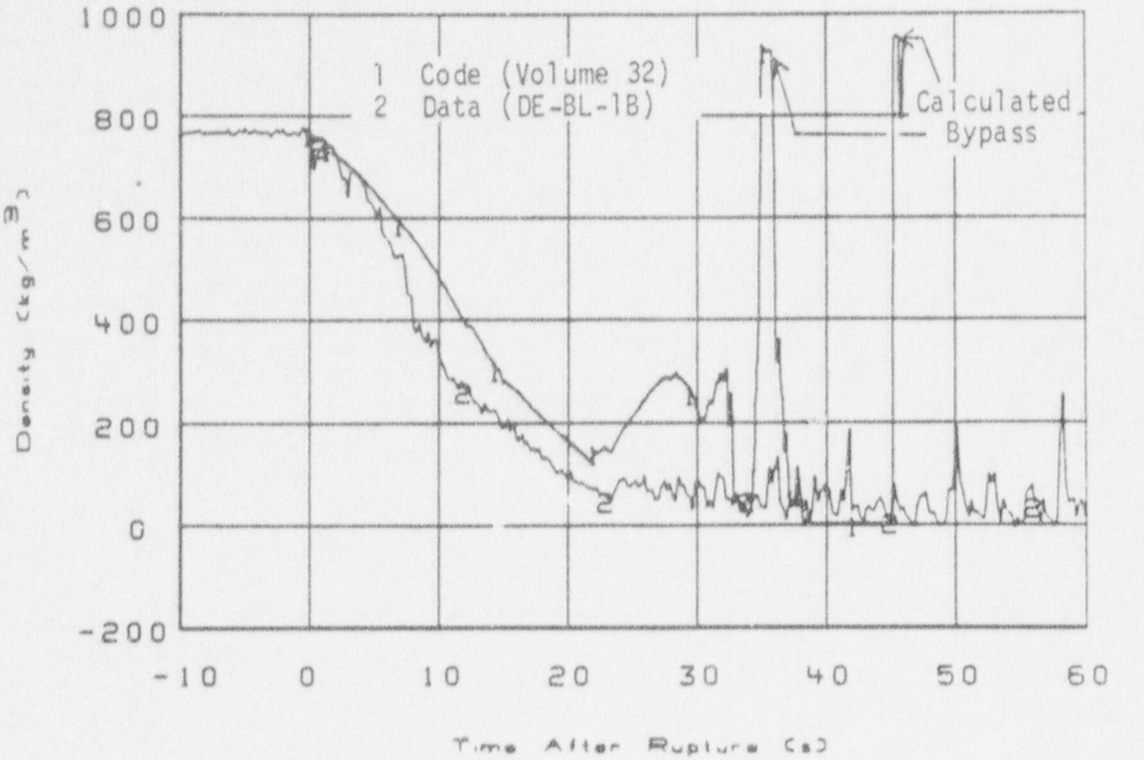

Fig. 9 LOFT L1-4 base run broken cold leg density comparison.

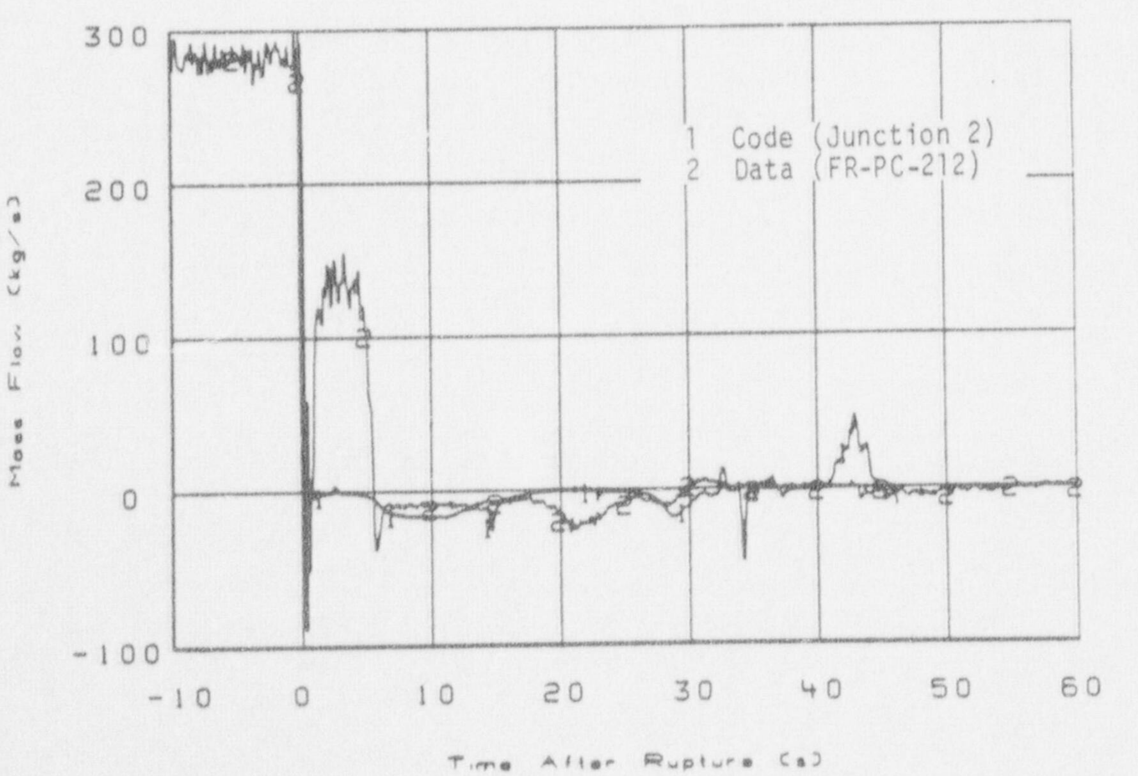

Fig. 10 LOFT L1-4 base run intact hot leg mass flow comparison.

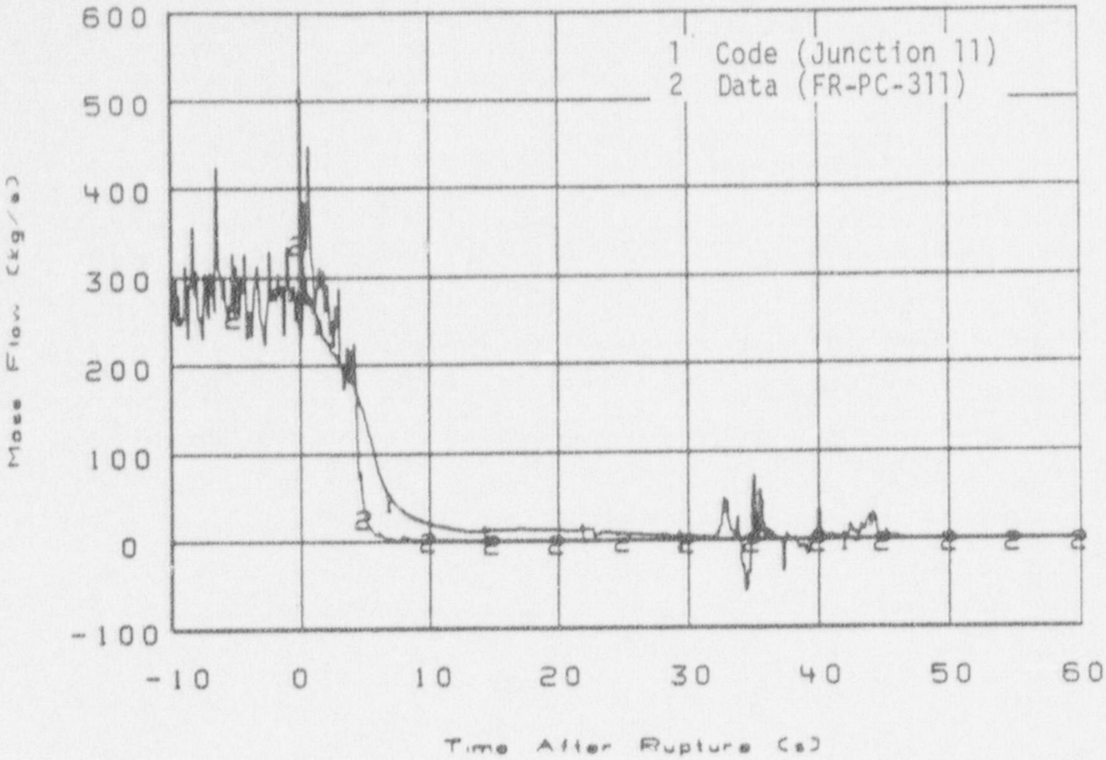

Fig. 11 LOFT L1-4 base run steam generator outlet mass flow comparison.

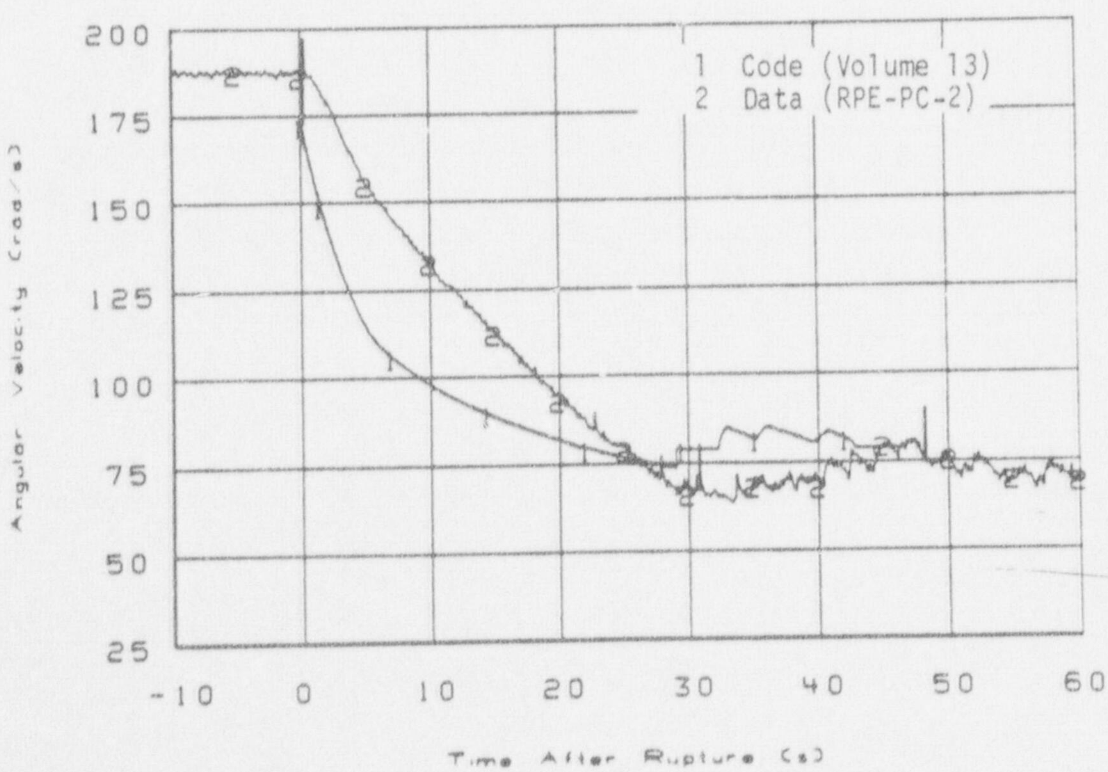

Fig. 12 LOFT L1-4 base run pump #2 speed comparison.

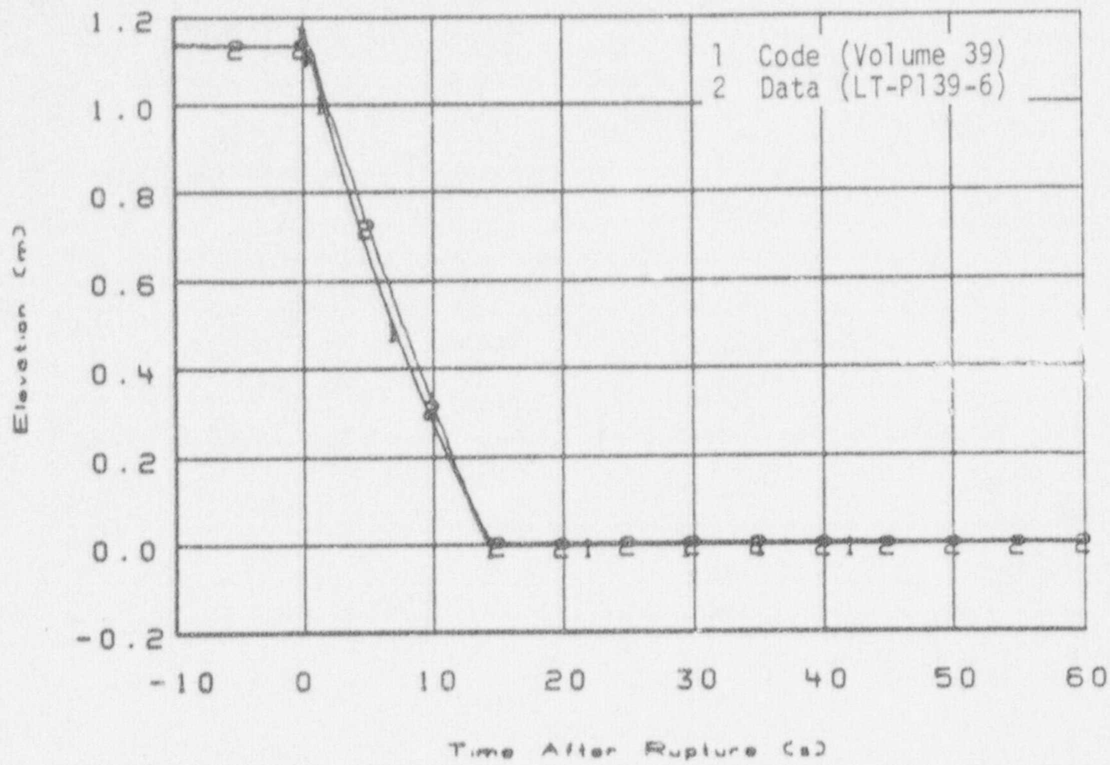

Fig. 13 LOFT L1-4 base run pressurizer liquid level comparison.

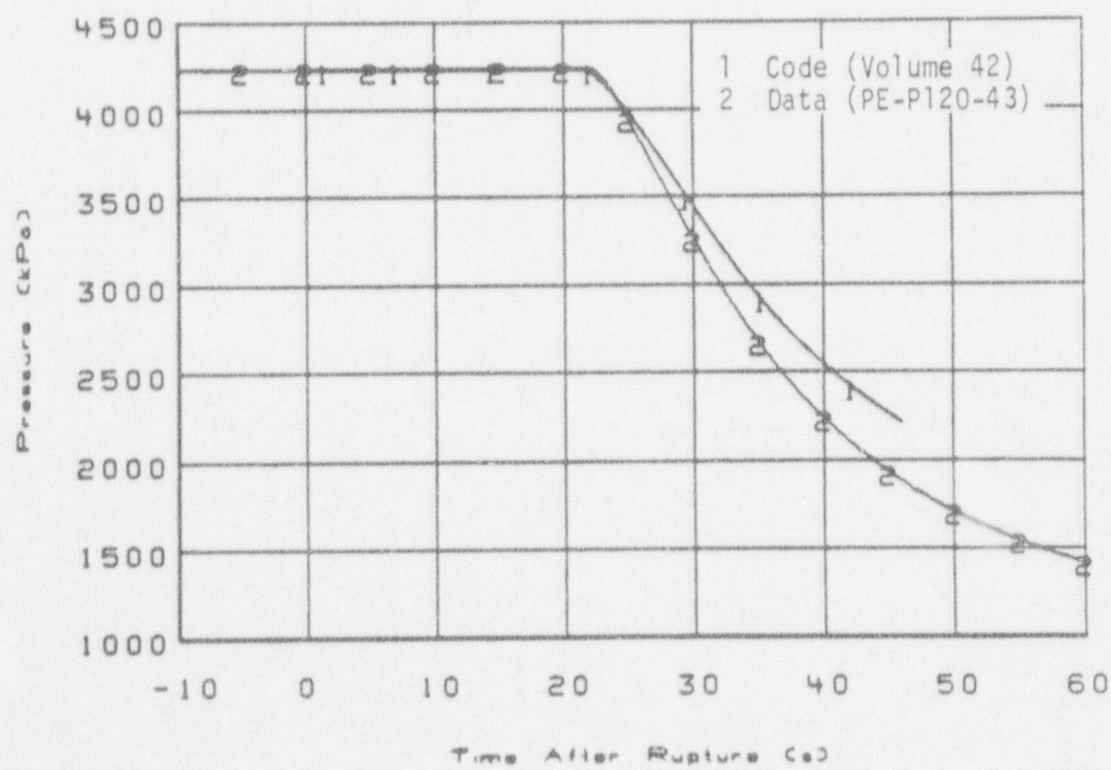

Fig. 14 LOFT L1-4 base run accumulator pressure comparison.

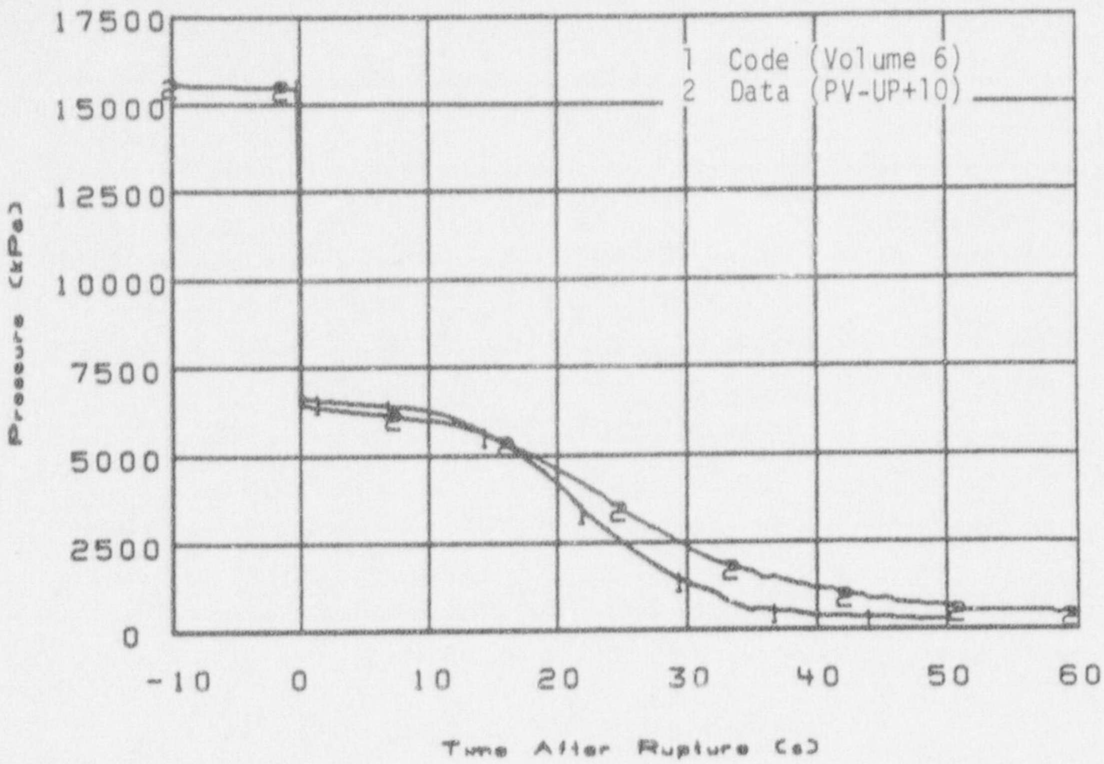

Fig. 15 Semiscale S-01-4A base run upper plenum pressure comparison.

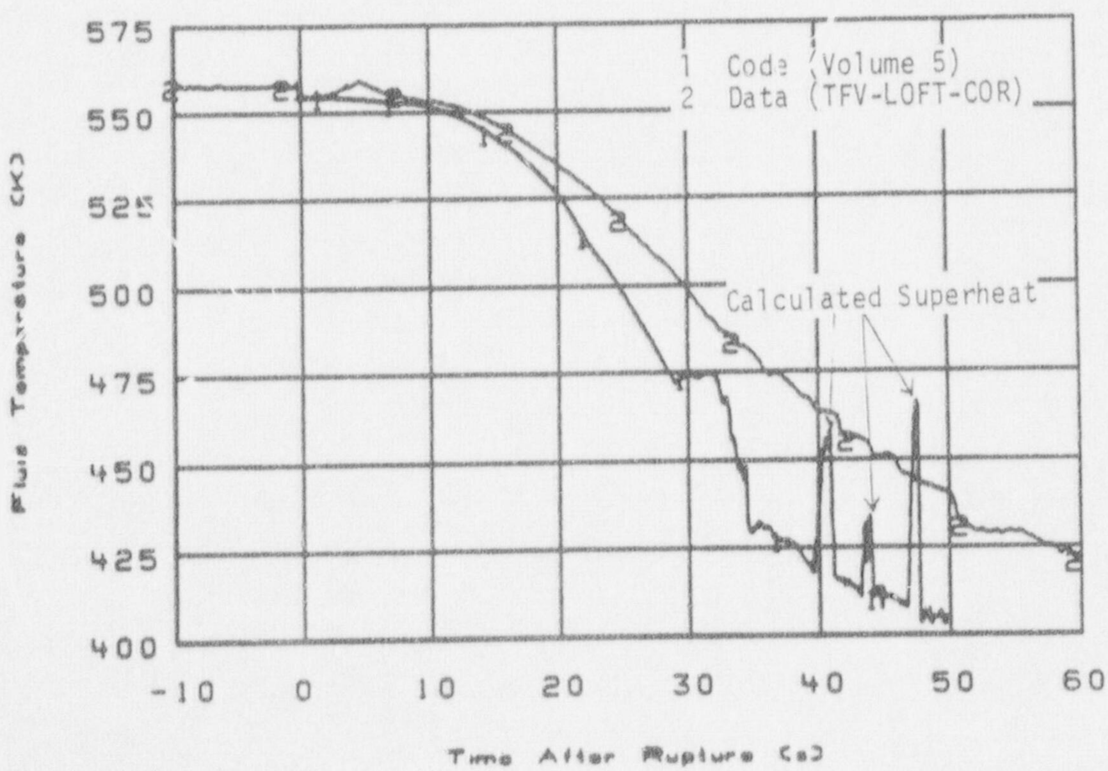

Fig. 16 Semiscale S-01-4A base run core simulator fluid temperature comparison.

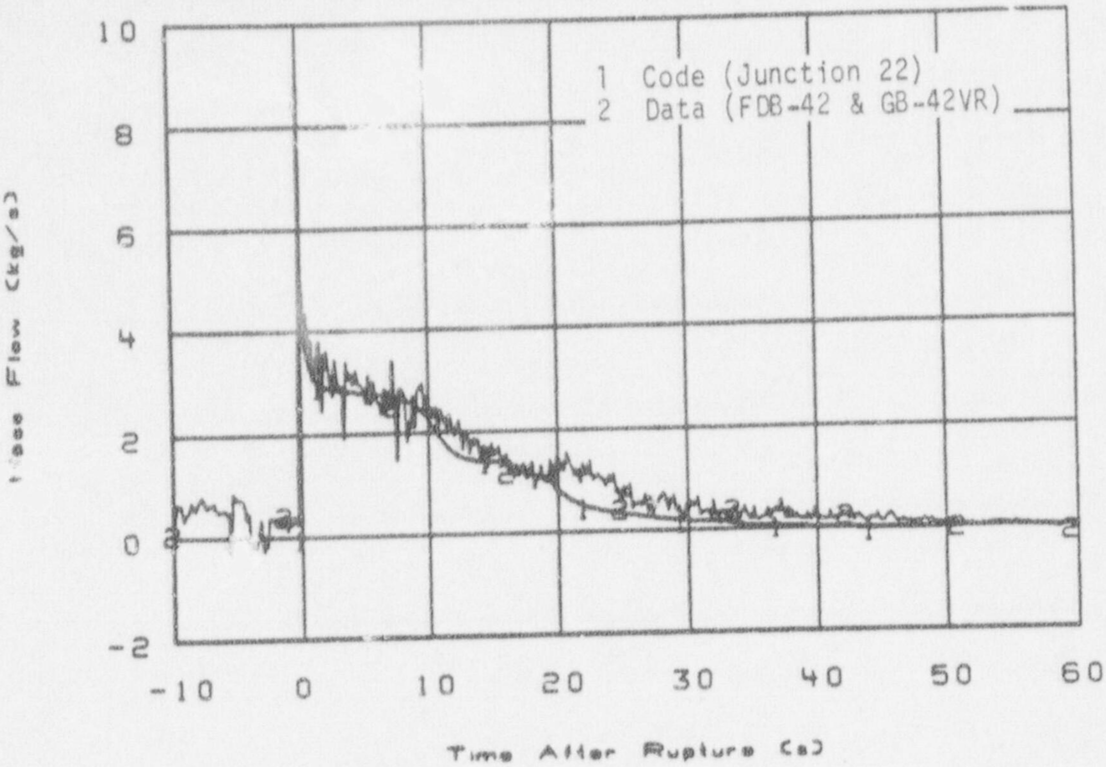

Fig. 17 Semiscale S-01-4A base run hot leg break flow comparison.

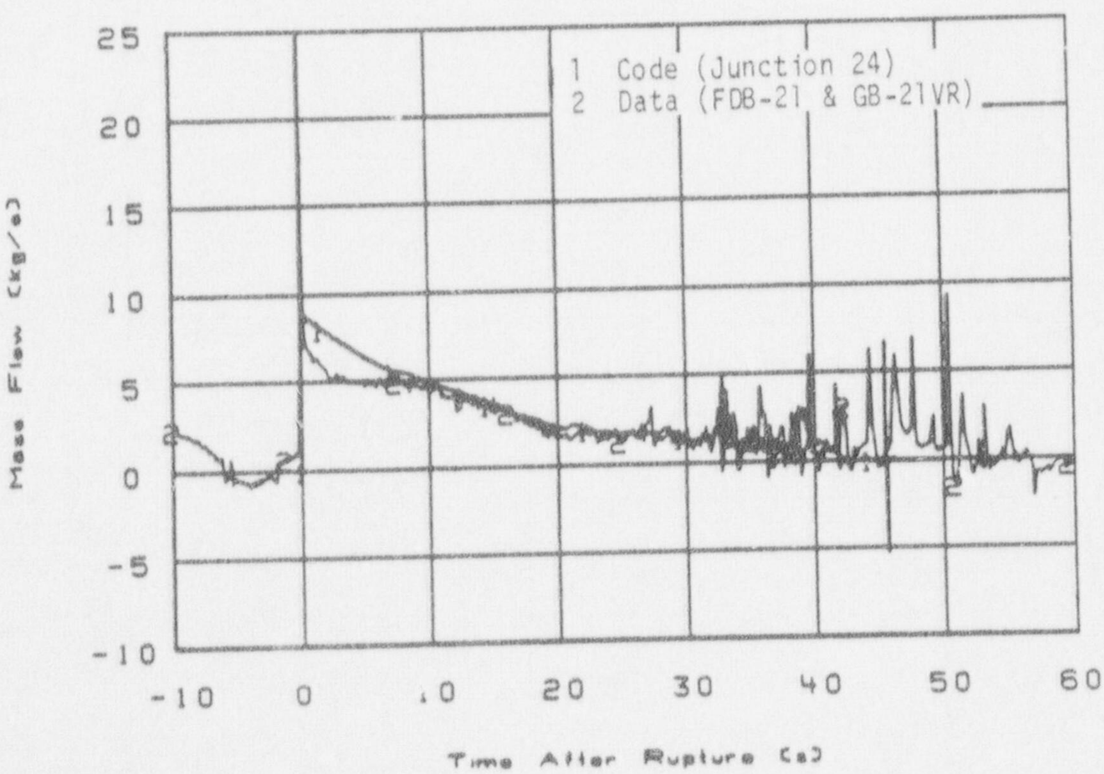

Fig. 18 Semiscale S-01-4A base run cold leg break flow comparison.

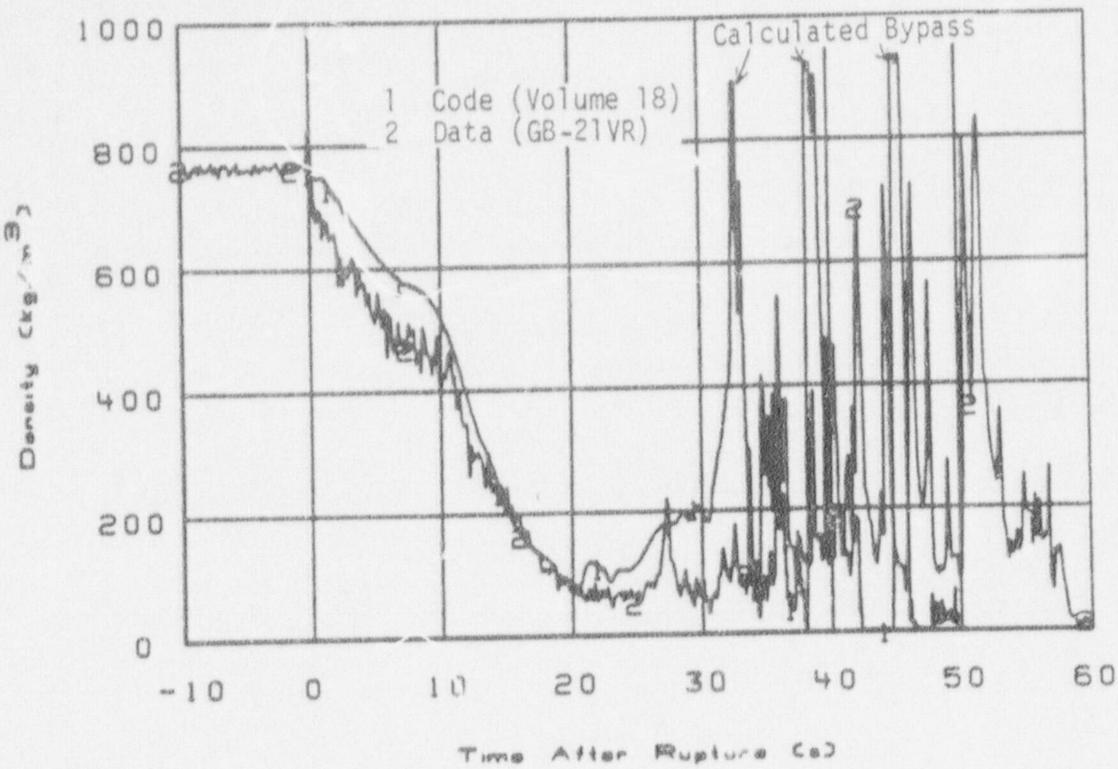

Fig. 19 Semiscale S-01-4A base run broken cold leg density comparison.

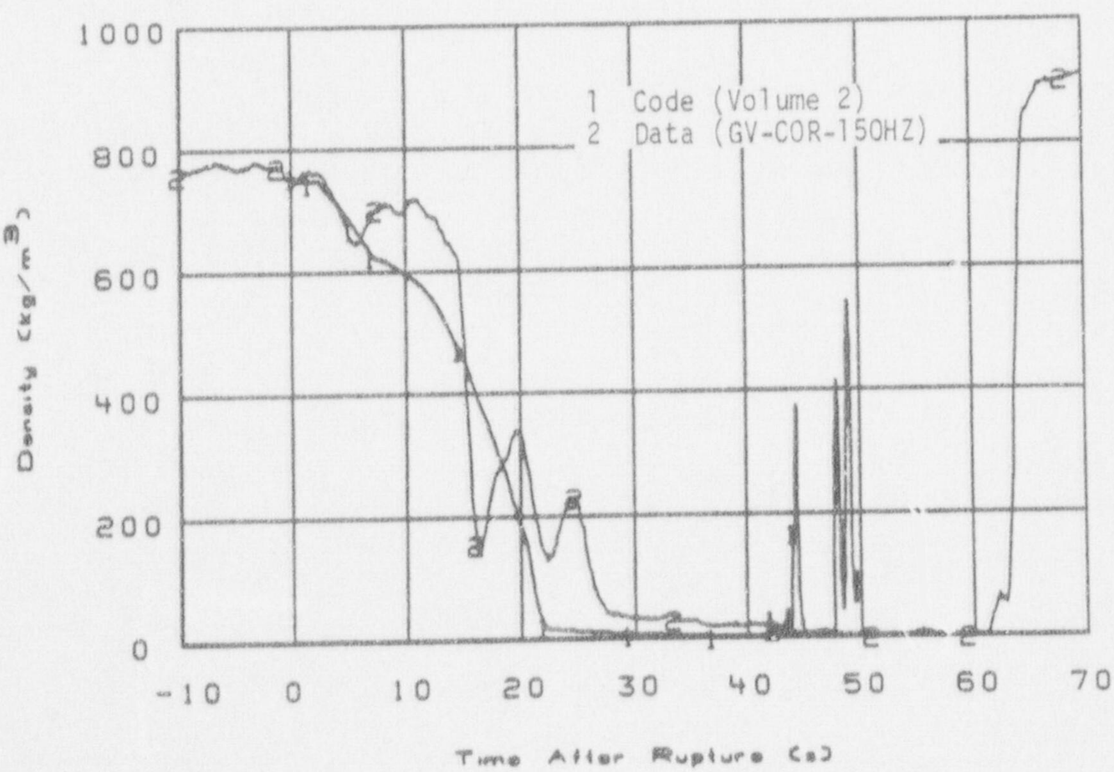

Fig. 20 Semiscale S-01-4A base run core inlet density comparison.

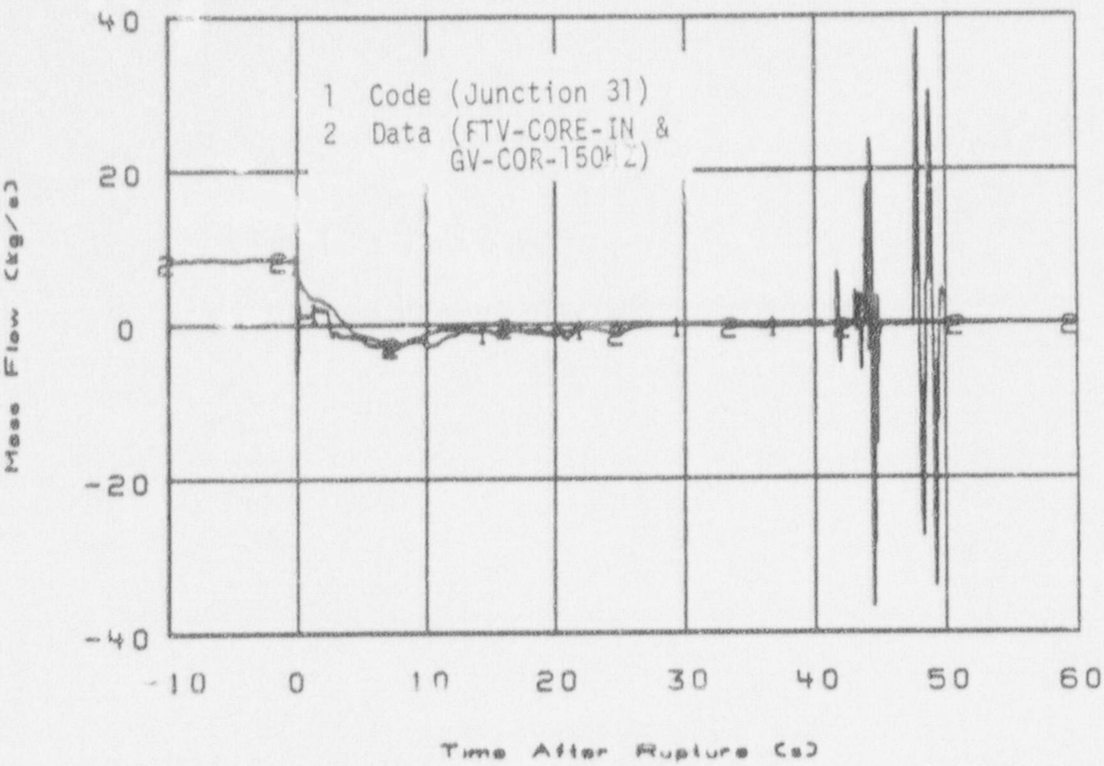

Fig. 21 Semiscale S-01-4A base run core inlet mass flow comparison.

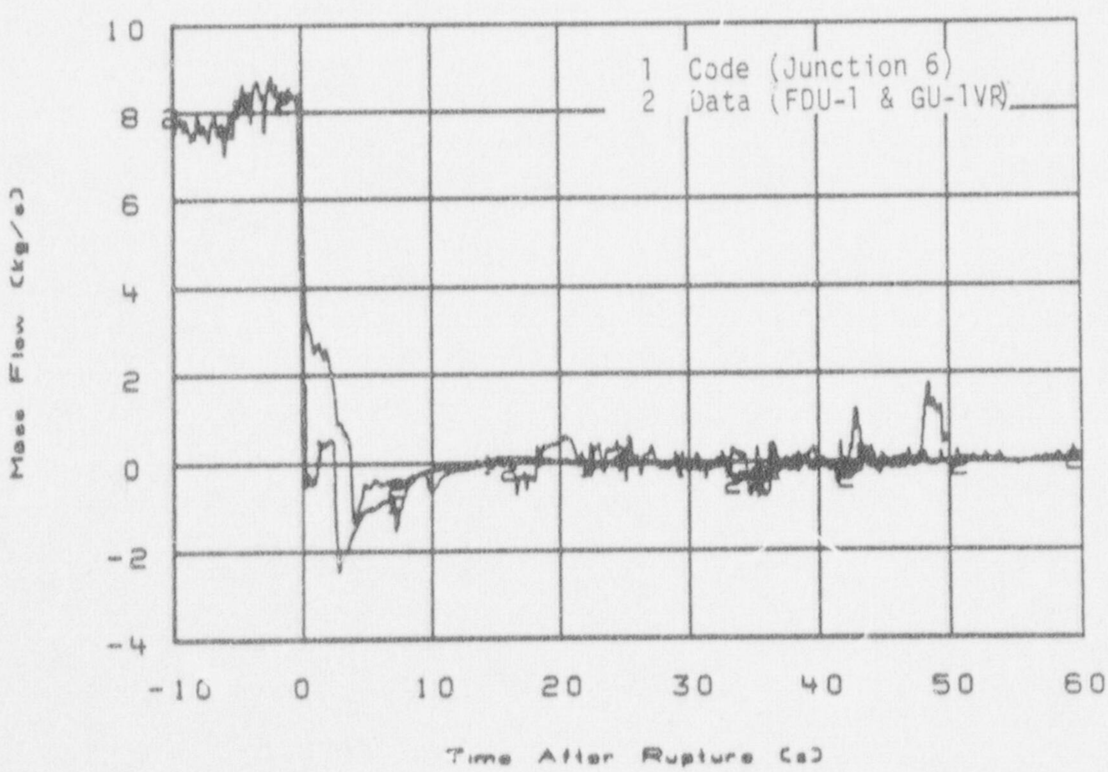

Fig. 22 Semiscale S-01-4A base run intact hot leg mass flow comparison.

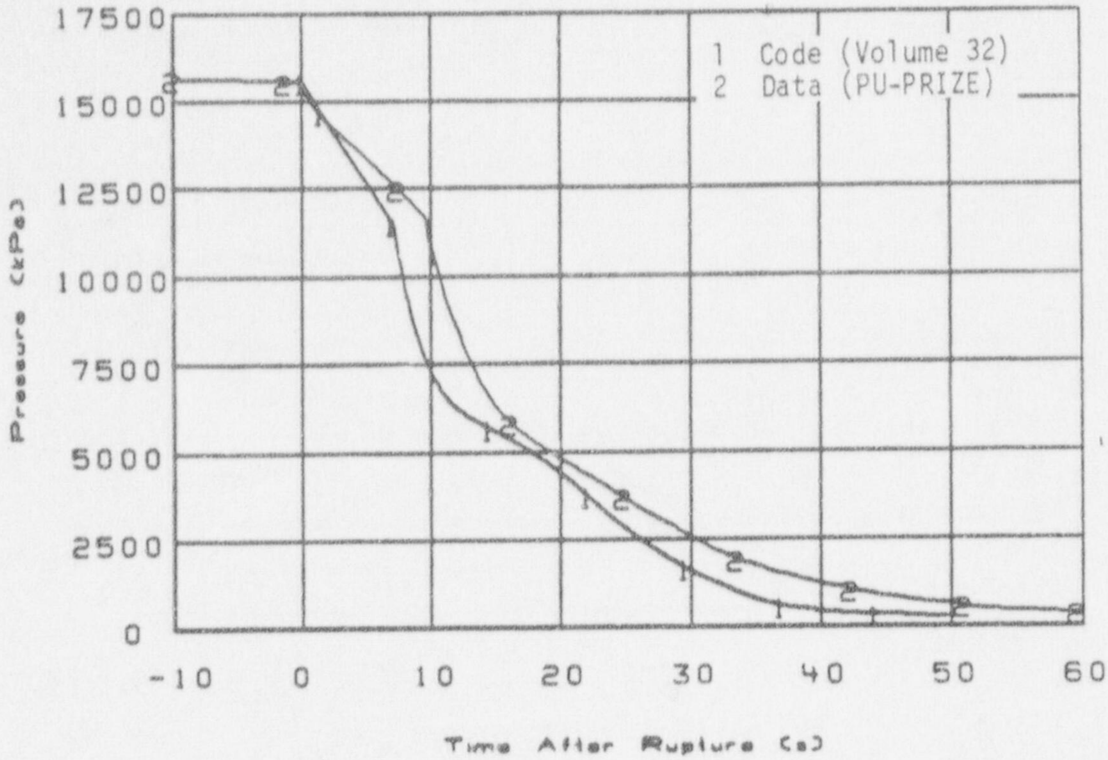

Fig. 23 Semiscale S-01-4A base run pressurizer pressure comparison.

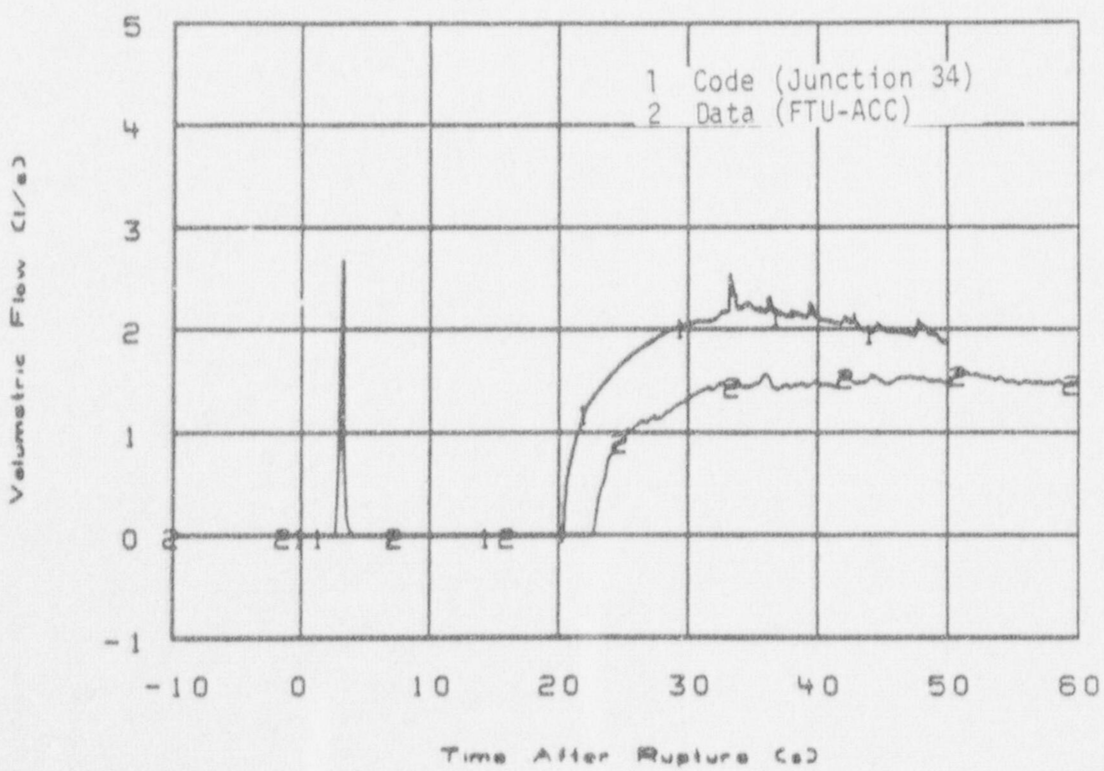

Fig. 24 Semiscale S-01-4A base run accumulator volumetric flow comparison.

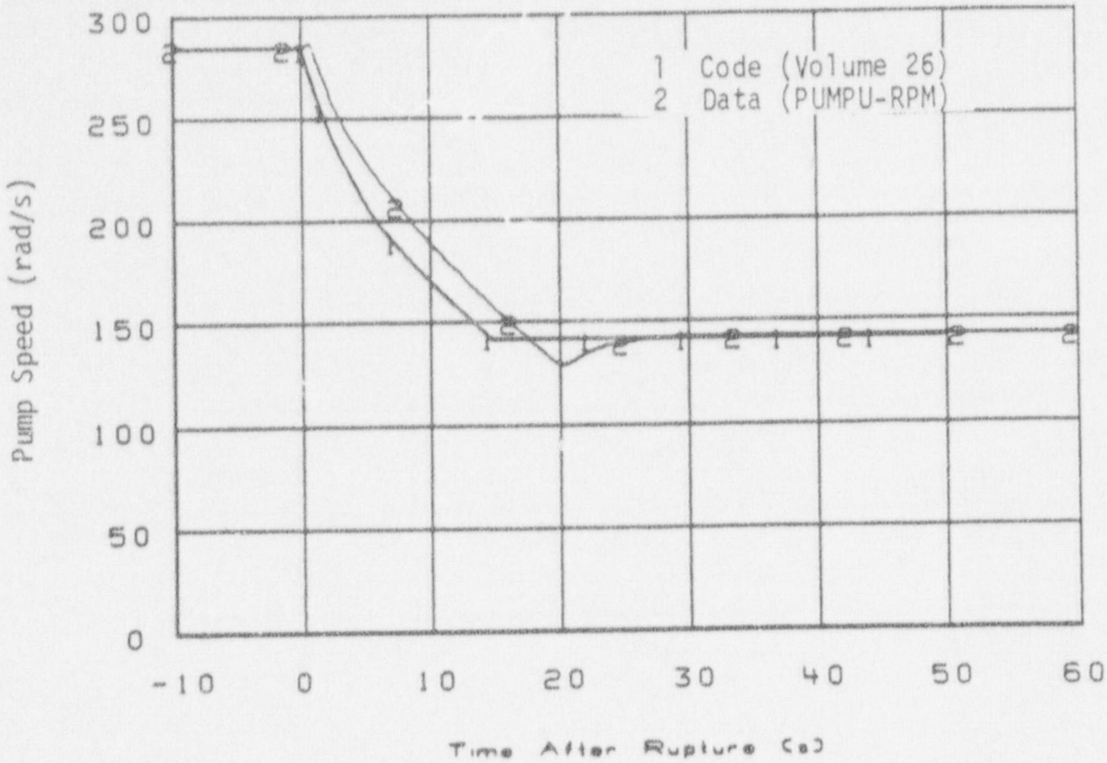

Fig. 25 Semiscale S-01-4A base run pump speed comparison.

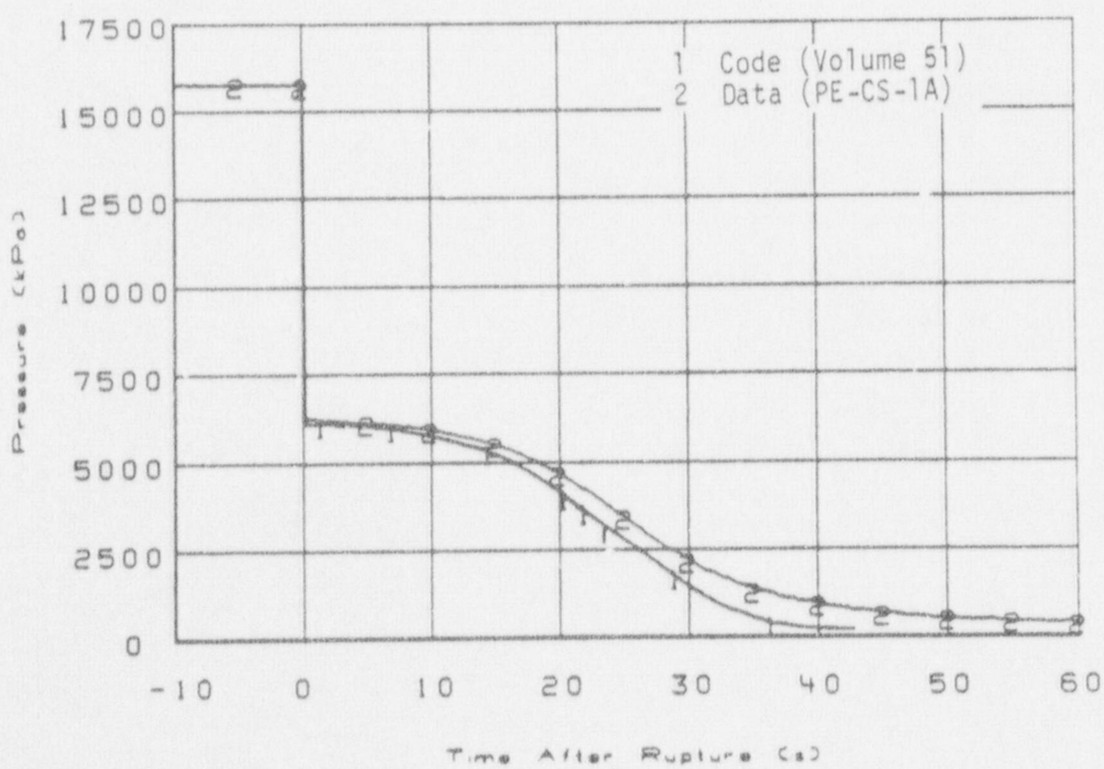

Fig. 26 LOFT L1-4 standard problem calculation system pressure comparison.

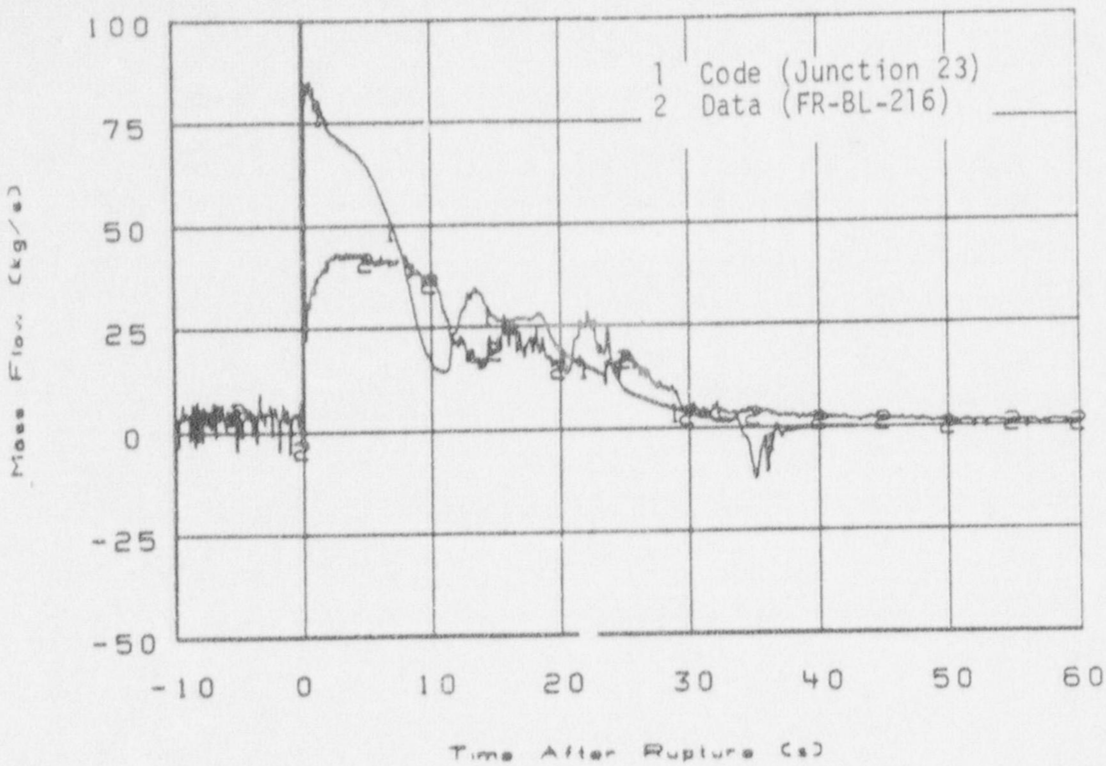

Fig. 27 LOFT L1-4 standard problem calculation broken hot leg mass flow comparison.

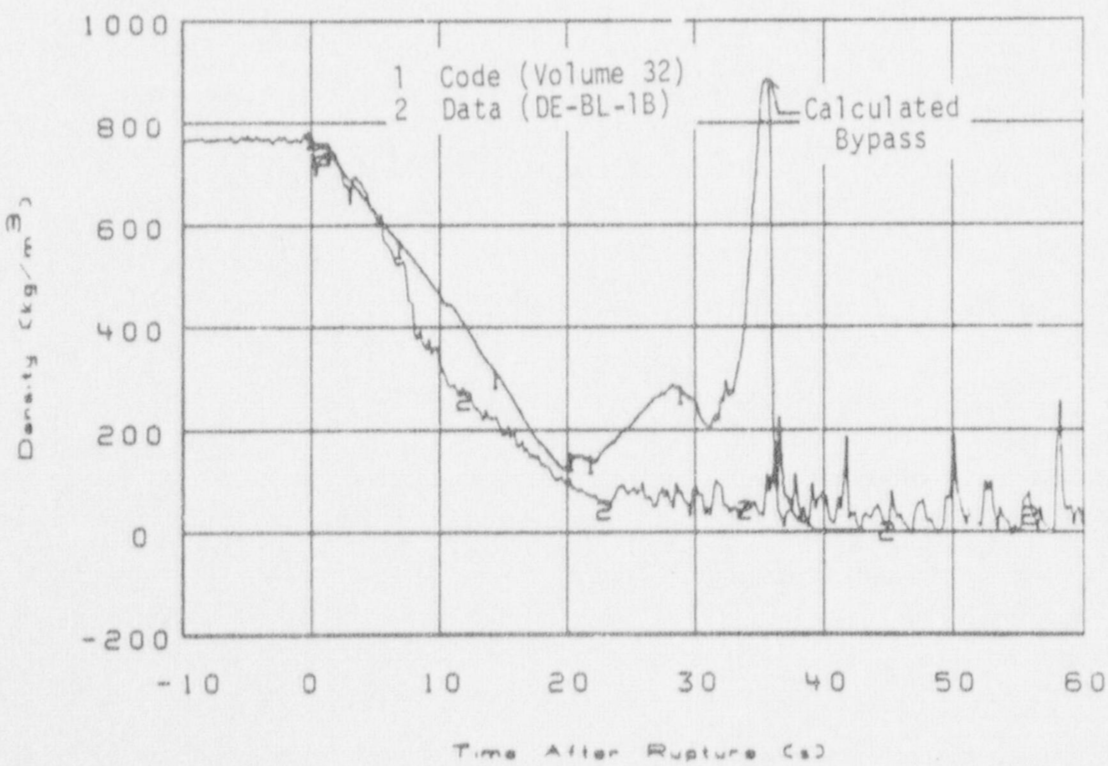

Fig. 28 LOFT L1-4 standard problem calculation broken cold leg density comparison.

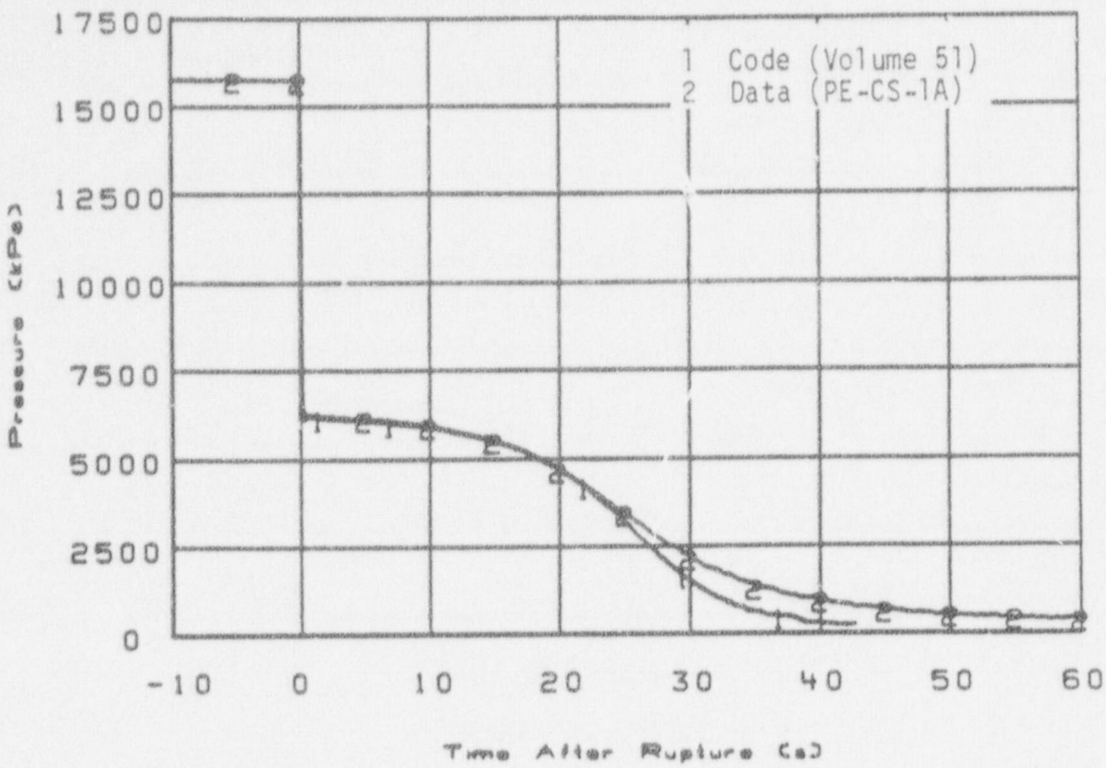

Fig. 29 LOFT L1-4 cross connected downcomer system pressure comparison.

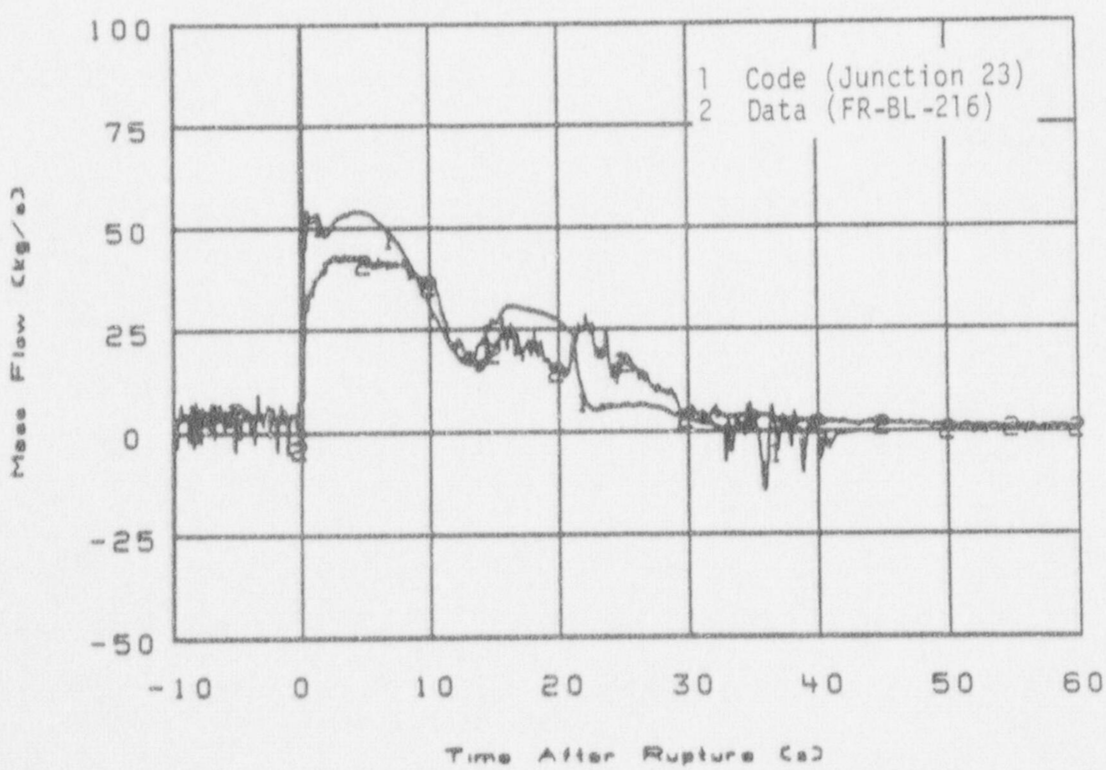

Fig. 30 LOFT L1-4 cross connected downcomer broken hot leg mass flow comparison.

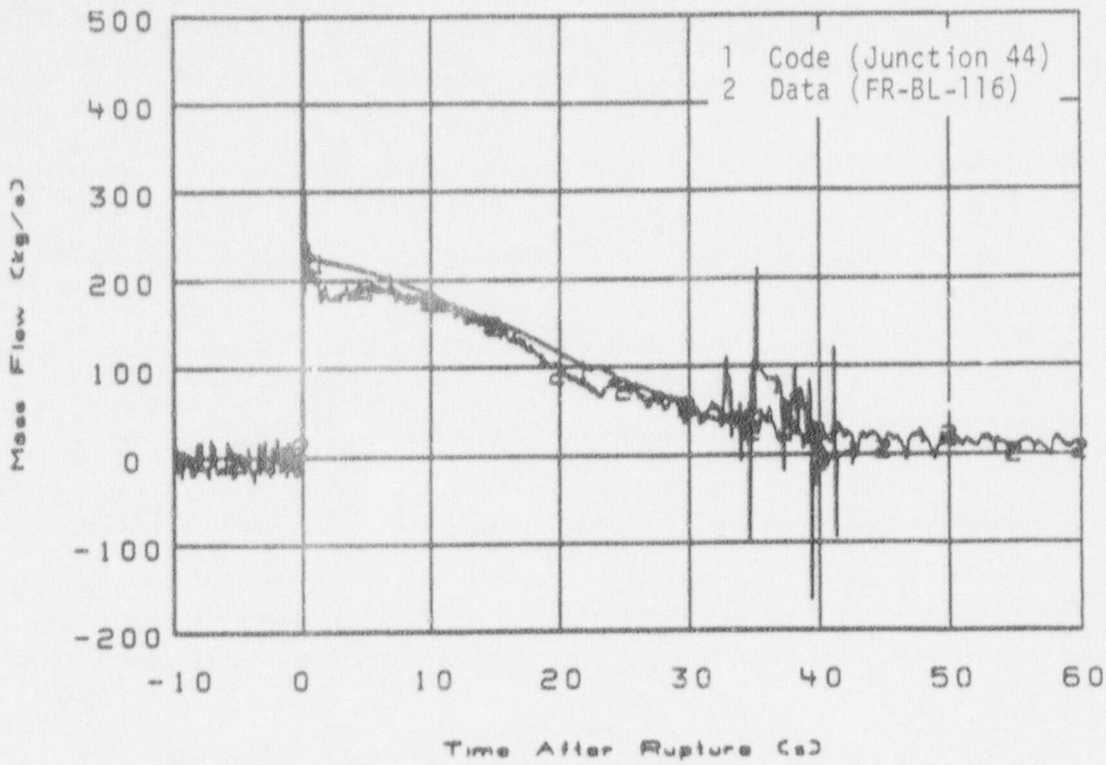

Fig. 31 LOFT L1-4 cross connected downcomer broken cold leg mass flow comparison.

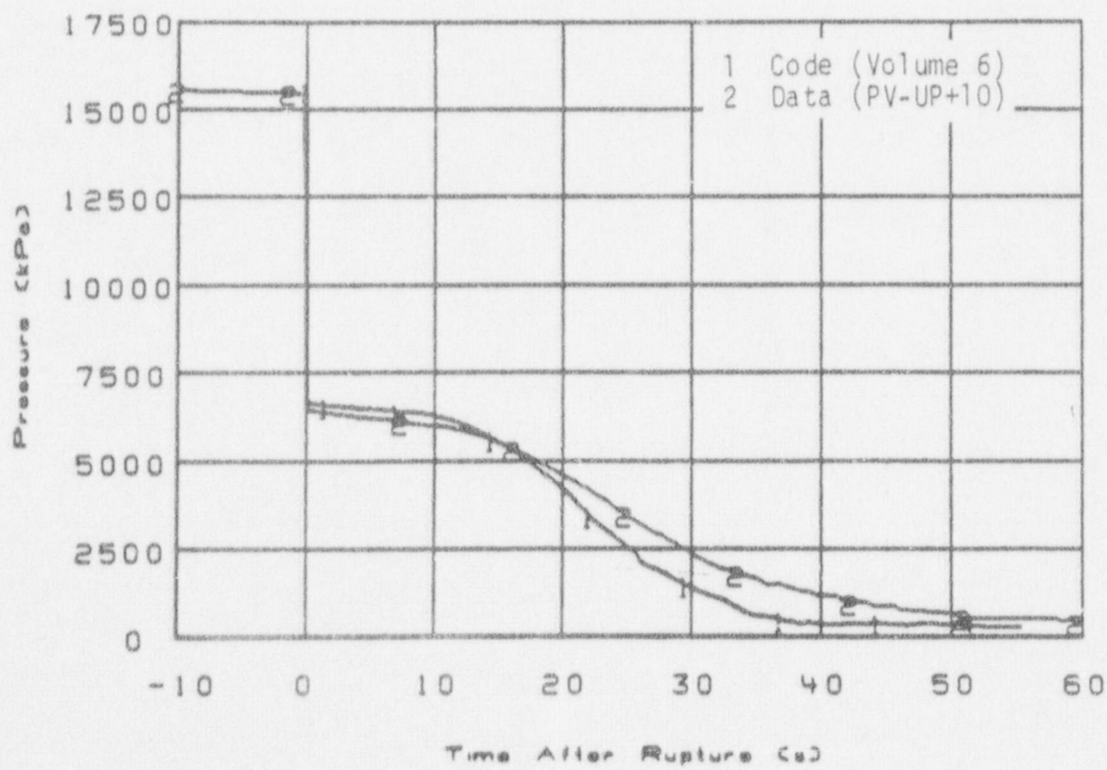

Fig. 32 Semiscale S-01-4A single channel downcomer upper plenum pressure comparison.

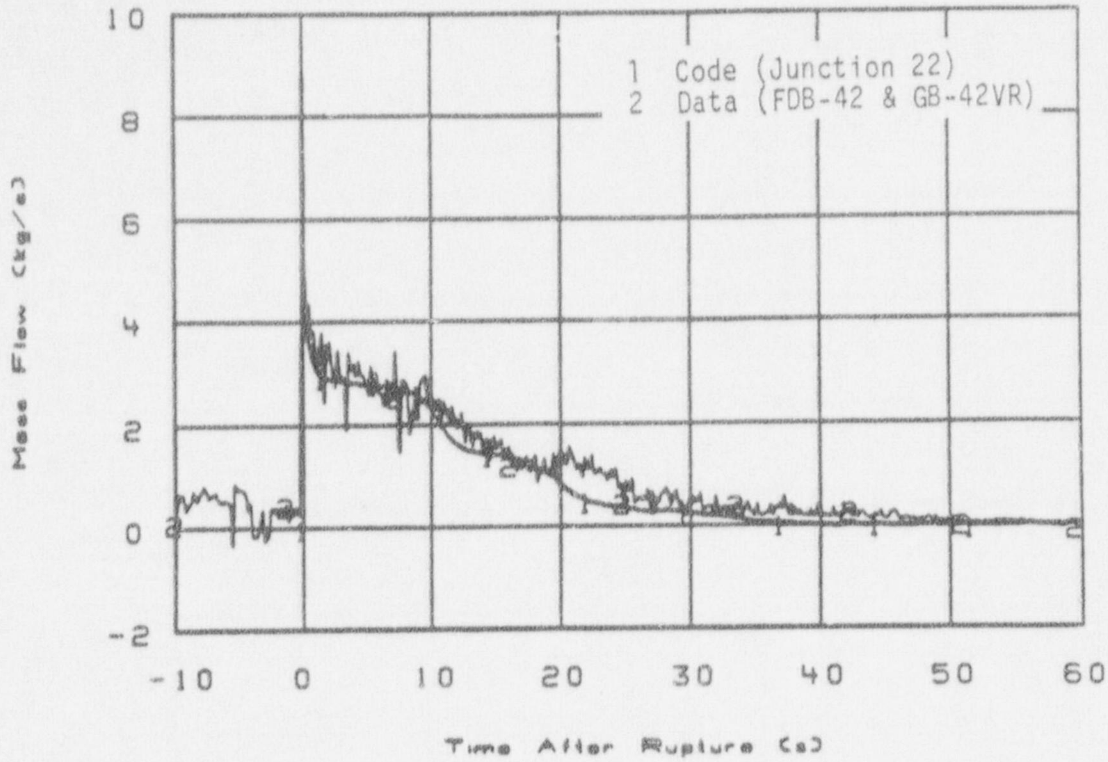

Fig. 33 Semiscale S-01-4A single channel downcomer hot leg break flow comparison.

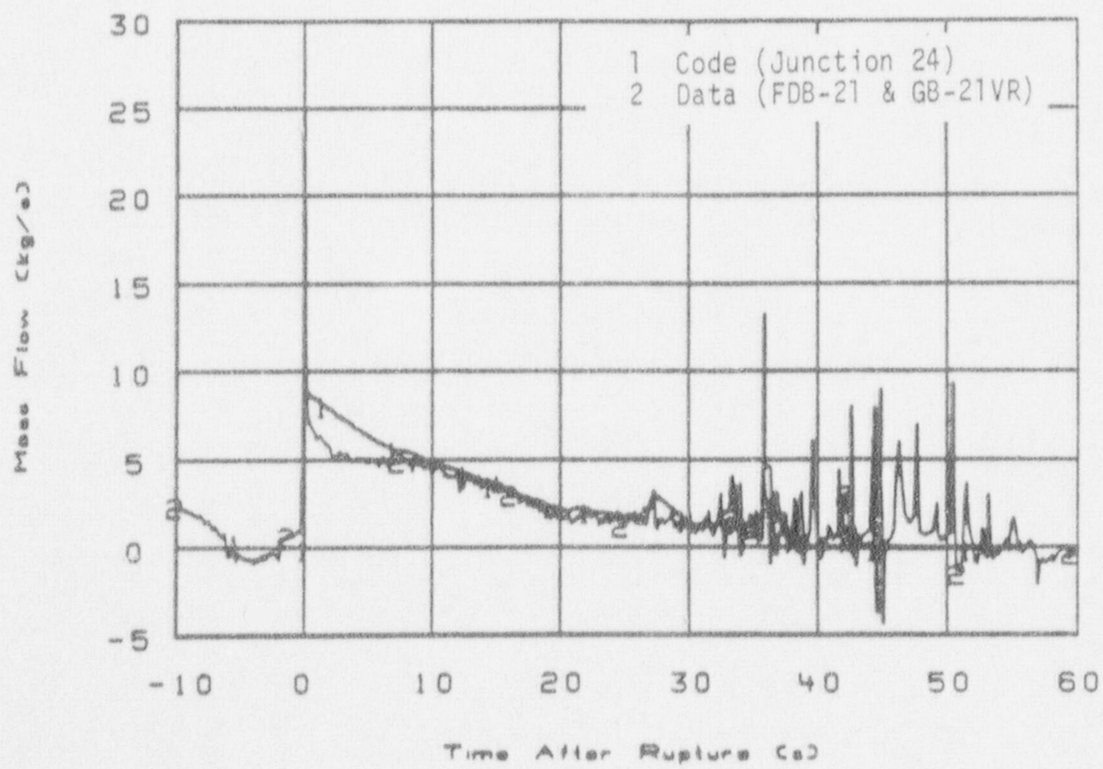

Fig. 34 Semiscale S-01-4A single channel downcomer cold leg break flow comparison.

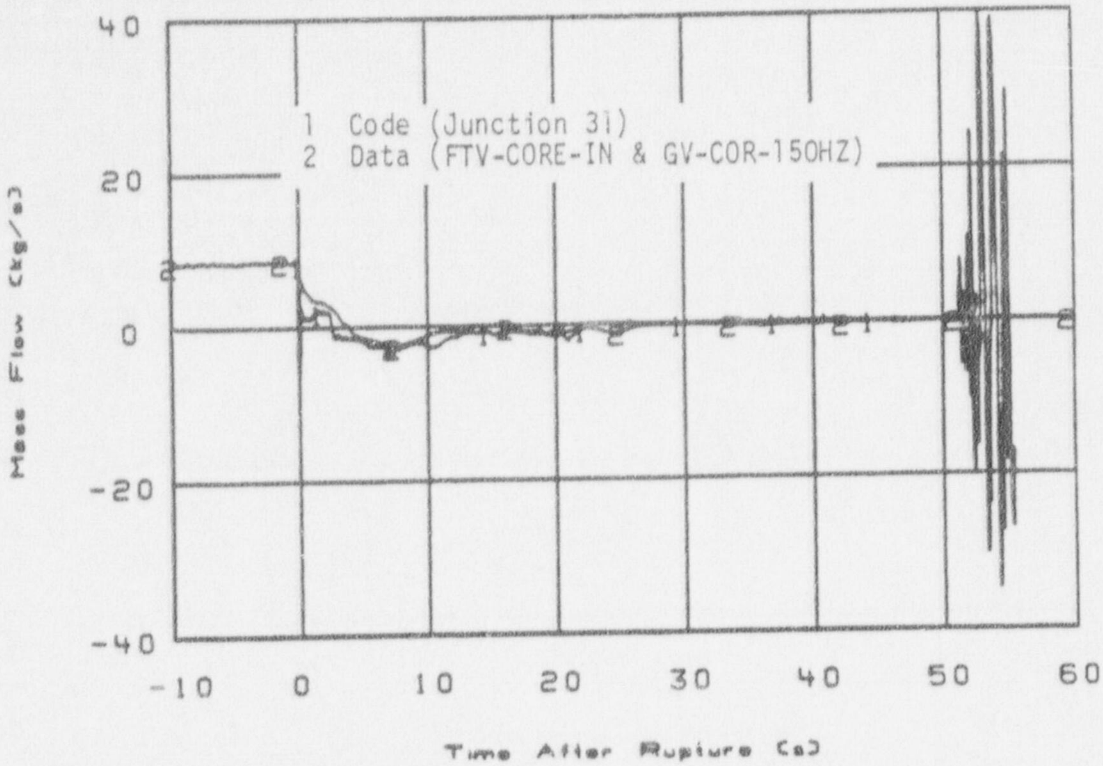

Fig. 35 Semiscale S-01-4A single channel downcomer core inlet flow comparison.

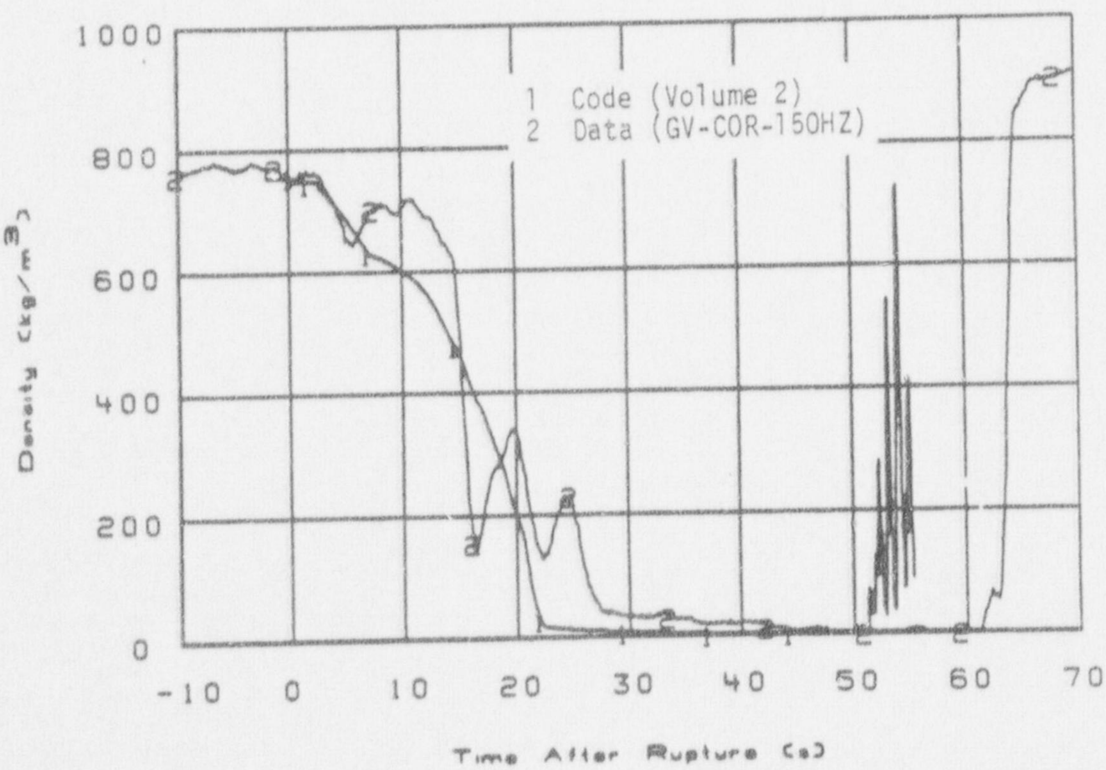

Fig. 36 Semiscale S-01-4A single channel downcomer core inlet fluid density comparison.

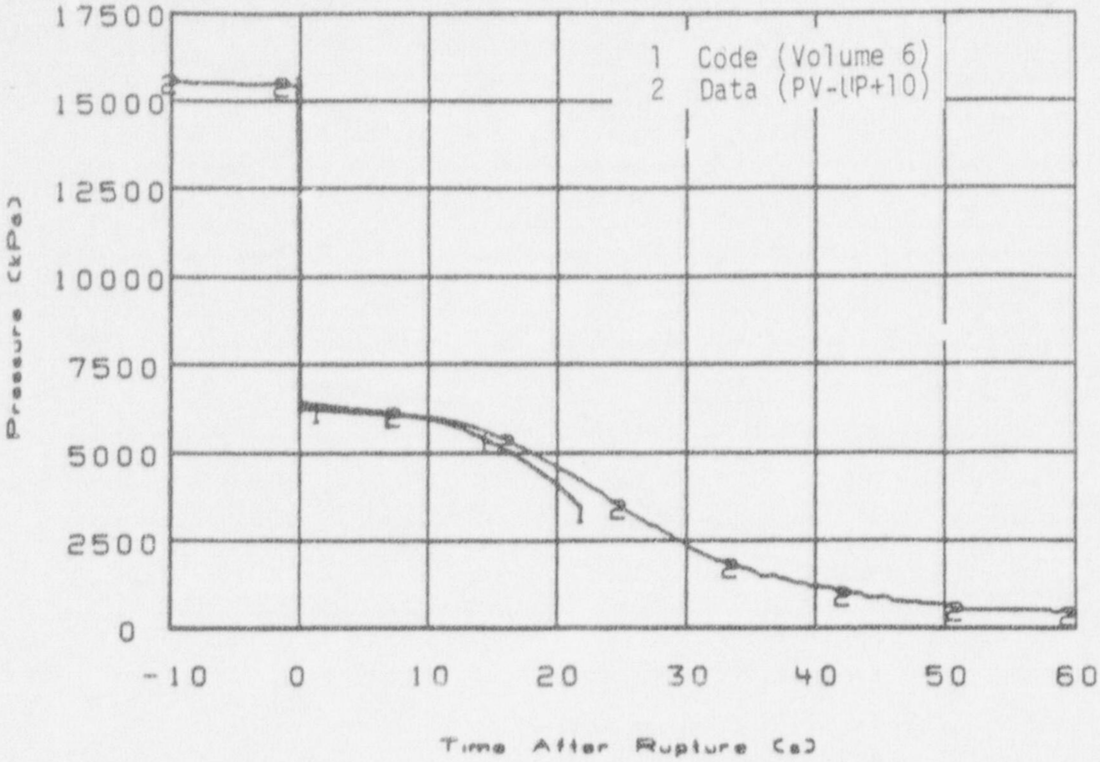

Fig. 37 Semiscale S-01-4A single channel downcomer with adjusted fluid temperatures, upper plenum pressure comparison.

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