CVAP-TR-78-019
July 1978

CODE VERIFICATION AND APPLICATIONS PROGRAM

STEAM GENERATOR COMPONENT STUDIES

WITH RELAP4/MOD6

By

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NRC Research and Technical Assistance Report

EG&G Idaho, Inc.

IDAHO NATIONAL ENGINEERING LABORATORY

DEPARTMENT OF ENERGY

IDAHO OPERATIONS OFFICE UNDER CONTRACT EY-76-C-07-1570

CVAP-TR-78-019
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ABSTRACT

This report presents the results of independent verification studies performed on the steam generator component with the RELAP4/MOD6, Update 3 computer code during the blowdown phase of the loss-of-coolant accident. RELAP4 steam generator component models were driven with measured boundary conditions from LOFT and Semiscale blowdown experiments, and the results were compared to test data. The sensitivity of the calculated results to steam generator model nodalization, code options, uncertainty in driving flow and changes in heat transfer coefficients was determined. Steam generator instrumentation requirements and the need for system effects studies are also discussed.

SUMMARY

This report describes the independent verification of the RELAP4/MOD6 Update 3 computer code for the analysis of simulated pressurized water reactor steam generators during the blowdown phase of a loss-of-coolant accident. As part of independent verification, RELAP4 component models, driven with measured boundary conditions, were used to calculate steam generator behavior during three 200% double-ended offset shear cold-leg break experiments: Semiscale Test S-06-5, a heated blowdown with an initial core power level of 1.44 MW and initial conditions of 15.58 MPa gauge and 553 K at the intact loop cold leg vessel inlet and 6.93 kg/s core inlet flow rate; Semiscale Test S-01-4A, an isothermal blowdown designed as the counterpart of L1-4 with initial conditions of 15.34 MPa gauge, 556 K, and 8.34 kg/s intact loop flow rate; and LOFT (loss-of-fluid test) L1-4, an isothermal blowdown with a core simulator assembly installed in place of the nuclear core and initial conditions of 15.65 MPa gauge, 552 K, and 268.4 kg/s intact loop flow rate.

Comparison of the S-06-5 base run with data showed more inflow on the pressurizer side in the first five seconds and less outflow after 15 seconds than the data. Calculated density on the pump side indicated saturation 1/3 second later and a much lower voiding rate than the data due to phase slip in the sump between 9 and 17 seconds. Calculated steam generator secondary temperature compared well to data until heat flux reversal occurred, then decreased less rapidly than the data for the rest of the blowdown. The heat transfer coefficient on the primary side is the controlling factor during this latter period.

The comparison of the S-01-4A base run with data showed the calculated mass flow on the pressurizer side in good agreement with data except between 5 and 20 seconds(the drag disc came in contact with a thermocouple during the test). The fluid on the pump side voided early in the calculation, in contrast to the data, which exhibits a rather high density until about 8 seconds and then rapidly drops off. Calculated steam generator secondary temperature compared well to data, which showed definite stratification after 10 seconds. Because of the differences in voiding on the pump side, the comparisons for S-01-4A were considered to be poor.

Comparison of the L1-4 base run with data showed very poor agreement. The calculated mass flow on the pump side was consistently higher than the measured flow and did not have the same characteristic behavior, although both generally exhibited null flow after 16 seconds. The calculated density on the core side after 6 seconds was much higher than the data and did not exhibit the same trends. Inaccuracy in modeling the mass and enthalpy of the pressurizer flow, which must be included in the LOFT model, could be largely responsible. No usable steam generator secondary measurements were recorded for this test.

Additional data comparisons were made with the Test S-06-5 model to assess the effects of nodalization and option choices and to recommend RELAP4 steam generator models for both component and system studies. The results clearly indicated that steam generator behavior during a Semiscale heated blowdown is a flow dominated problem. Accuracy in flow boundary conditions and the use of RELAP4/MOD6 phase separation options have significant effects on the comparisons of calculations and data.

Other topics covered in this report are the effects of changes in driving flow for all three tests, instrumentation requirements for steam generator component and scaling studies, and the need for further studies on the effects of inaccuracy in modeling steam generator phenomena on a PWR LOCA system calculation.

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I. INTRODUCTION

This study represents part of the initial effort to apply independent verification techniques to the RELAP4/MOD6[1], Update 3 computer code (Configuration Control File C0010005 for this version of the code and File H002011B for the associated steam tables[2]). Independent Code Verification 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 independent verification of codes[3]; and

(2) to apply these techniques, rules and guidelines to the RELAP/-MOD6, Update 3 code to understand the components of a successful (or unsuccessful) independent verification 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 pre-release verification. However, the analyses were treated in the structured manner of the independent verification 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 steam generator component studies performed for the PWR (pressurized water reactor) blowdown portion of the independent verification of RELAP4/MOD6 as shown in subtask 3 of Table I.

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 independent verification of codes[3], the limited guidelines for model and

TABLE I
MATRIX FOR INDEPENDENT VERIFICATION 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	TBD	X				X	X		X	
12. SEMISCALE MOD-3 REFLOOD	TBD		X			X	X		X	
13. SEMISCALE MOD-3 INTEGRAL	TBD	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)	TBD	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-03-8, FLECHT-SET 22139 PKL K7A		X		X	X			X	

option selection given in the RELAP4/MOD5[4] and RELAP4/MOD6[1] manuals, work done for U. S. Standard Problem 7, and consultations with code developers and with Semiscale, LOFT, developmental and independent verification 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. A list of the significant RELAP4 modeling and option features being verified is given in Table II.

The experiments selected for this study were Semiscale powered blowdown Test S-06-5, Semiscale isothermal blowdown Test S-01-4A, and LOFT (loss-of-fluid test) isothermal blowdown Test L1-4. Component models were constructed for each facility and were driven with test data for the boundary conditions. A time-dependent volume using measured values of pressure, temperature and density defines one boundary condition and a fill junction using measured flow defines the other boundary condition.

Initial comparisons between test data and RELAP4/MOD6 calculations were made with these base run models. After assessing the strengths and weaknesses of the comparisons and of the experimental data, appropriate sensitivity studies were conducted. The conclusions and recommendations drawn from this study are summarized in Section VI.

The input for the computer runs discussed in this report is on permanent file with the INEL Computer Science Center under reference number H00337IB. The file contains the base run decks and the replacement cards used in additional studies.

TABLE II

SIGNIFICANT MODELS AND OPTIONS USED
IN STEAM GENERATOR STUDY

1. Fluid Equations

RELAP4 Fluid Mass Equation

RELAP4 Fluid Energy Equation

RELAP4 Compressible Single-Stream Fluid Flow Equation with Momentum Flux (MVMIX = 0)

2. Phase Separation Models

Bubble Rise

Wilson's Bubble Rise

(Default) Vertical Slip

3. Heat Transfer Options

RELAP4/MOD6 Blowdown Heat Transfer Package (HTS2)

Modified Tong-Young Correlation for Transition Boiling

Condie-Bengston Correlation for Film Boiling

Natural Convection Model

Local Quality Calculation

II. EXPERIMENTAL FACILITIES

The Semiscale Program[5] and the LOFT Program[6] are conducted by EG&G Idaho, Inc. for the United 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 verification.

1. SEMISCALE

The objectives of the Semiscale program are to quantify the physical processes controlling system 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.

1.1 Facility Description

A description of the overall Semiscale program and test series with a detailed system description can be found in Reference 5. The major components of the system are shown in Figure 1. A diagram of the Semiscale steam generator and adjacent piping is shown in Figure 2. Flow and density measurements for RELAP4 boundary conditions are available near the steam generator at Spool Piece 5 in the hot leg near the inlet and at Spool Piece 10 in the cold leg near the outlet. Additional measurements are available at Spool Piece 1. upstream of the pressurizer near the vessel. However, driving the model from Spool Piece 1 requires the inclusion of a pressurizer boundary condition. Previous work for Standard Problem 7 using steam generator component models indicated that including the pressurizer in the model or simulating pressurizer effects using a fill junction adds enough uncertainty to the calculation to effectively mask the effects of steam generator model and option changes.

1.2 Test Selections

In order to exercise the full range of applicable code options, powered blowdown Test S-06-5[7] was selected from a number of appropriate tests on the basis of PWR typicality, similarity to the LOFT experiment, ability to exercise the code and operability of instrumentation. This test offered the additional advantage of being used in ongoing system verification studies. An initial screening of the data indicated no problems. Test S-06-5 was a 200% double-ended offset shear cold-leg break at an initial core power level of 1.44 MW. The test was conducted from initial conditions of 15.58 MPa gauge and 553 K at the intact loop cold leg vessel inlet and a core inlet flow rate of 6.93 kg/s. The break nozzle used was similar to that used in the LOFT tests. After initiation of blowdown, power to the heated core was reduced to simulate the predicted thermal response of nuclear fuel rods during a LOCA. Blowdown was accompanied by simulated emergency core coolant injected into the cold legs of the intact and broken loops.

The Semiscale Mod-1 tests in Series 1 were performed with hardware configuration and test parameters selected to yield a system response that simulates the LOFT system response during the LOFT nonnuclear blowdown experiments. Test S-01-4A[8], the counterpart of LOFT Test L1-4, was selected to provide data for scaling comparisons between the steam generators of the two facilities. Primary coolant system initial conditions for the isothermal test were 15.34 MPa gauge, 556 K, and 8.34 kg/s intact loop flow rate. The initial screening of the data indicated no problems except on the hot leg flow measurement between the pressurizer and the steam generator inlet. Although the data trace appeared little different from those on previous tests, the data record showed a thermocouple in contact with the drag disc, which may have invalidated the data.

1.3 Measurements and Accuracy

A description of the Semiscale measurement and data processing techniques with uncertainties can be found in References 5, 9, and 10. An instrumentation diagram showing measurement locations pertinent to a RELAP4/MOD6 Semiscale steam generator component model (i.e., from the vessel outlet to the pump inlet) is shown in Figure 2. Information on those transient parameters measured during Test S-06-5 relevant to this study are given in Reference 7; during Test S-01-4A in Reference 8. Some of the instrumentation shown in Figure 2 either was not used during the particular test or was not reliable during all or part of the transient.

2. LOFT

One of the primary objectives of the LOFT Program is to provide data required to evaluate the adequacy of and to improve the analytical methods currently used to predict the LOCA response of LPWRs.

2.1 Facility Description

A description of the overall LOFT program and test series with a detailed system description can be found in Reference 6. The major components of the system are shown in Figure 3. A diagram of the LOFT steam generator and adjacent piping is shown in Figure 4. The only flow and density measurements available near the steam generator for RELAP4 boundary conditions are at Instrument Station 2, on the vessel side in the hot leg, and at Instrument Station 3, upstream of the pump sump in the cold leg. LOFT component steam generator models will, therefore, be required to contain either the pressurizer or a pressurizer simulator, such as a fill junction.

2.2 Test Selection

Four LOFT tests had been run prior to this study, all part of the nonnuclear test series, designated series L1. The intact loop hot leg flow measurements, needed for a steam generator component comparison, are only available on Test L1-4[11]. The initial screening of the data from L1-4 indicated no apparent problems with primary side boundary condition measurements but showed a complete lack of usable transient data for the secondary side of the steam generator.

For Test L1-4, the LOFT Facility was configured to simulate a loss-of-coolant accident in a large pressurized water reactor resulting from a 200% double-ended offset shear break in a cold leg of the primary coolant system. The test is an isothermal blowdown, with a core simulator assembly installed in place of the nuclear core. Primary coolant system initial conditions were 15.65 MPa gauge, 552 K, and 268.4 kg/s intact loop flow rate. During system depressurization into a simulated containment, emergency core cooling water was injected into the primary coolant system intact cold leg to provide data on the effects of emergency core cooling on system thermal hydraulic response.

2.3 Measurements and Accuracy

A description of the LOFT measurement and data processing techniques can be found in Reference 6. An instrumentation diagram showing measurement locations pertinent to a RELAP4/MOD6 LOFT steam generator component model (i.e., from the vessel outlet to the pump inlet) is shown in Figure 4. Information on those transient parameters measured and computed during Test L1-4 relevant to this study are given in Reference 11. Some of the instrumentation shown in Figure 4 either was not used during the test or was not reliable during all or part of the transient. Measurement accuracies are presently under evaluation by the LOFT program.

3. STEAM GENERATOR DESCRIPTION AND TRANSIENT BEHAVIOR

The Semiscale Mod-1 steam generator, designated the Type I steam generator, and the LOFT steam generator are shown in Figures 5 and 6, respectively. The following discussion applies to both unless otherwise indicated.

The generators are vertical shell and U-tube recirculation-type heat exchangers with the primary coolant in the tube side and the secondary coolant in the shell side. The inlet plenum is on the vessel side and the outlet plenum on the pump side. An internal divider plate divides flow between the plena. As can be seen from Figures 5 and 6, the Semiscale generator has a substantially higher plenum length-to-diameter ratio than the LOFT generator.

The tube bundle assembly consists of a tube sheet and the U-tubes, 54 for Semiscale and 1845 for LOFT, on a 1.905 cm triangular pitch. The Inconel tubes have an inner diameter of 1.021 cm, a wall thickness of 0.1245 cm, and an average length of 5.136 m. Baffle plates extending approximately one half of the way across the bundle are spaced along the tube lengths.

Feedwater enters the secondary side through a spray ring and is injected into the downcomer annulus. The downcomer is separated from the tube bundle by a cylindrical flow shroud, which directs recirculated and makeup secondary water downward to the top of the tube sheet, producing a net subcooling. The fluid passes into the tube bundle region, and proceeds upwards, picking up heat from the primary, and exits as a two-phase mixture to the steam separator.

The steam separator is located at the upper end of the bundle region, and induces a swirling flow that separates the liquid from the vapor by centrifugal and gravity forces. The vapor phase passes upward through the steam dome to an exit nozzle where it leaves the secondary system, and the liquid phase is recirculated into the downcomer.

During steady state operating conditions, energy is transferred from the primary side to the secondary by subcooled forced convection heat transfer on the primary side and nucleate boiling on the secondary. After blowdown initiation, the inlet feedwater and steam outflow are stopped quickly, and the secondary temperature begins to rise, due to continued energy input from the primary coolant, until the primary temperature drops below that of the secondary. The energy flux then reverses, with forced convection evaporation (and, later, some superheating) on the primary side, and cooling of the secondary fluid by natural convection. The secondary liquid level remains near or above the top of the U-tubes if the steam valve closes within one or two seconds after blowdown initiation. In the isothermal tests, both the feedwater inlet valve and the steam outflow valve are closed throughout the test, and negligible energy is transferred to the secondary during steady-state conditions prior to the test.

III. BASE RUN MODELS

1. NODALIZATION AND CODE OPTIONS

Similar nodalization and options are used in base run data comparisons for both experimental facilities, except where measurement locations dictate otherwise. The choice of nodalization and options was based upon the best published (and unpublished) information available. Sources used were the NRC guidelines for independent verification of codes(3), the limited guidelines for model and option selection given in the RELAP4/MOD5(4) and RELAP4/MOD6(1) manuals, work done for U.S. Standard Problem 7, and consultations with code developers and with Semiscale, LOFT, and developmental and independent verification personnel.

Base run models for the Semiscale and LOFT steam generators are shown in Figures 7 and 8, respectively. Identical nodalization and options are used for the steam generator in both. In order to include the measurement locations, some cold leg piping and all of the hot leg piping, including a fill junction representing the pressurizer surge line connection, are modeled for LOFT, and some hot leg piping and all of the cold leg piping from the steam generator outlet to the pump inlet are modeled for Semiscale.

Features of the models are listed below. Volume and junction numbers refer to both Figures 7 and 8, unless otherwise stated.

1. The RELAP4/MOD6 blowdown heat transfer package (HTS2), including the natural convection model for the steam generator secondary, is used. The modified Tong-Young correlation is used for transition boiling and the Condie-Bengston correlation is used for film boiling. These models are expected to give a good approximation to the measured data.

2. Steam generator nodalizations (Volumes 1 to 9 and Junctions 1 to 11) are identical for both LOFT and Semiscale. The same code options, such as slip, are used in both facility models. There were no differences in design which would require different nodalizations or options.

3. Primary steam generator tubes are modeled in four volumes (Volumes 3 through 6) with a junction (Junction 5) at the highest elevation. No slip is used in the primary tubes.

4. The steam generator secondary (Volume 9) is modeled in one volume. Local quality is not calculated on the secondary side of the heat slabs. Downcomer liquid is included in the secondary side mass and volume inventory.

   For the heated blowdown, the bubble rise model was used in the secondary. The mixture level was chosen at the steam separator, the bubble density gradient was assumed to be one, and the bubble velocity was calculated to give the correct mass of steam exiting the steam dome at steady-state conditions.

   For the isothermal blowdowns, no bubble rise was used. Complete phase separation was assumed, and the mixture level was chosen to give the correct mass of liquid for the particular test.

5. The inlet and outlet plena (Volumes 1, 2, 7, and 8) are each divided vertically into two volumes, with phase slip (the default vertical slip model) between the volumes (at Junctions 2 and 8) to allow separation of liquid and vapor in the plena.

6. Steam generator inlet and outlet nozzles are lumped into the adjacent piping.

7. The Semiscale model (Figure 7) includes two hot leg spool pieces (Volumes 10 and 11) and the cold leg piping from the steam generator outlet to the pump inlet (Volumes 12 through 16) to reach the measurement locations.

The pump sump is modeled in 3 volumes (Volumes 13, 14, and 15) with default vertical slip at each junction.

The model is driven with a fill junction (Junction 17) on the pump side and a time-dependent volume (Volume 10) on the pressurizer side. The secondary side boundary conditions are determined by fill junctions (Junctions 10 and 11).

8. The LOFT model (Figure 8) includes all the hot leg piping (Volumes 10 through 13) and the two cold leg spool pieces adjacent to the steam generator outlet (Volume 14).

   A time-dependent volume (Volume 15) was used on the pump side, since all measurements at this station indicated unidirectional flow out. Junction 15, adjacent to Volume 15, was required to be homogeneous, a code constraint on the inlet to a time-dependent volume. A fill junction (Junction 16) was used on the core side to specify the primary coolant flow. The effect of pressurizer fluid addition to the system was also modeled by a fill junction (Junction 17).

2. BOUNDARY CONDITIONS

Measurements used as boundary conditions for the steam generator component models are shown on the Semiscale and LOFT instrument diagrams in Figures 2 and 4, respectively.

Boundary conditions for the S-06-5 model are shown in Figures 9 through 13. Flow (FTU-9 and GU-10VR) shown in Figure 9 drives the model on the pump side at Junction 17. Volume 10, the time-dependent volume, is described by transient fluid conditions (pressure, temperature and quality) in Spool Piece 5. The pressure measurement recorded nearest this location (PU-13 for this test) was adjusted by differential pressure readings to approximate pressure in the spool piece; the temperature during the subcooled part of the blowdown was approximated from the nearest temperature measurement (TFU-10 for this test); and the measured density (GU-5VR) was used with the pressure to calculate quality. The pressure and density boundary conditions for the time-dependent volume are compared with the data (PU-13 and GU-5VR) in Figures 10 and 11. Secondary flow (shown in Figures 12 and 13) was calculated to balance the system at steady-state and valve closure was based on test conditions.

S-01-4A boundary conditions are shown in Figures 14 through 16. Flow (FTU-9 and GU-10VR) as shown in Figure 14 is used for the fill junction at Junction 17. Volume 10, the time-dependent volume, is described by transient fluid conditions (pressure, temperature and quality) in Spool Piece 5. The pressure measurement recorded nearest this location (PV-UP+10 for this test) was adjusted by differential pressure readings to approximate pressure in the spool piece; the recorded temperature (TFU-5) was used during the subcooled part of the blowdown; and the recorded density (GU-5VR) was used with the pressure to calculate quality. The pressure and density boundary conditions for the time-dependent volume are compared with the data (PV-UP+10 and GU-5VR) in Figures 15 and 16. The secondary side was shut off during the test, so that flow in Junctions 10 and 11 is zero.

Boundary conditions for the LOFT L1-4 model are shown in Figures 17 through 20. Flow (FR-PC-212, calculated from DE-PC-2 and ME-PC-2) shown in Figure 17 drives the model on the core side at Junction 16. Volume 15, the time-dependent volume, is described by transient fluid conditions (pressure, temperature and quality) at Instrument Station 3. Measured pressure, and temperature (during subcooled flow) and average density calculated from measurements at this station were used to calculate the boundary conditions. The measured pressure (PE-PC-3A) and calculated average density (DE-PC-3) are compared to the input boundary conditions for the time-dependent volume in Figures 18 and 19, respectively. The pressurizer fill junction, Junction 17, was modeled with pressurizer mass flow calculated from measurements (FR-PC-010, calculated from LT-P139-6, PE-PC-4) shown in Figure 20 and saturated enthalpy calculated from the line pressure. The steam generator secondary side was closed off during the test, so that flow in Junctions 10 and 11 is zero.

IV. BASE RUN RESULTS

1. SEMISCALE TEST S-06-5

The results of comparing the S-06-5 base run with experimental data are given in Figures 21, 22, and 23. The mass flow at Junction 12 compared to the flow measured by the drag disc in Spool Piece 5 (FDU-5 and GU-5VR) shows good agreement (Figure 21), although the calculation gives more inflow in the first five seconds and less outflow after fifteen seconds compared to the data. The comparison of measured density (GU-10VR) to calculated density in Volume 16 (Figure 22) indicates saturation 0.5 seconds later and much higher density fluid between 9 and 17 seconds in the calculation. Steam generator secondary temperature in Volume 9 compares well to data (TFU-SG3, TFU-SG4) as shown in Figure 23 until heat flux reversal occurs, at about 8 seconds. The calculated secondary temperature decreases less rapidly than the data indicates for the rest of the blowdown. Differences between measured and calculated temperatures are well within the Semiscale secondary temperature measurement uncertainty[11], ± 4 K for three standard deviations. The heat transfer coefficient on the primary side is the controlling factor during this latter period.

2. SEMISCALE TEST S-01-4A

Figures 24, 25, 26 illustrate the comparison of the S-01-4A base run with data. The mass flow at Junction 12 compared to the flow measured by the drag disc in Spool Piece 5 (FDU-5 and GU-5VR) shows good agreement (Figure 24) except between 5 and 20 seconds (the drag disc came in contact with a thermocouple during the test). The lack of a reliable flow boundary condition creates substantial uncertainty in model results. The comparison of measured density (GU-10VR) to calculated density in Volume 16 (Figure 25) shows a marked decrease in calculated density for the first 9 seconds in contrast to the data, which exhibits a steady density of about 640 kg/m^3 until about 8 seconds and then rapidly drops off. No explanation for the discrepancy was apparent in the calculation or in a study of the test data. The fluid may have moved past the densitometer in a slug, rather than flashed, as in the calculation. This difference will also affect the flow comparison. Calculated steam generator secondary temperature in Volume 9 (Figure 26) compares well to data (TFU-SG1, TFU-SG2, TFU-SG3, TFU-SG4), which show definite stratification after 10 seconds.

3. LOFT TEST L1-4

The results of comparing the L1-4 base run with experimental data are given in Figures 27 and 28. The calculated mass flow at Junction 15 is consistently higher than the flow (FR-PC-311, calculated from FE-PC-3 and DE-PC-3) at Instrument Station 3 (Figure 27), and does not exhibit the same characteristic behavior, although both flows are essentially zero after 16 seconds. The effect of uncertainty in driving flow measurement on the calculation will be discussed later. The comparison of measured density (DE-PC-2 A, B, C) at Instrument Station 2 to calculated density in Volume 10 (Figure 28) shows poor agreement after 6 seconds with the calculated density above the data. Inadequacy in modeling the mass and enthalpy of the pressurizer flow (Junction 17., which must be included in the LOFT model, could be largely responsible. No usable measurements were recorded in the secondary on this test, and therefore no comparisons could be made.

V. ADDITIONAL STUDIES

A review of the base run data comparisons showed the need for additional studies on steam generator component modeling. Test S-06-5 was selected for an assessment of nodalization effects and model option choices, and to recommend an optimum RELAP4 steam generator model for both component and system studies. The substantial differences between RELAP4/MOD6 base run calculations and test data for Test S-01-4A and L1-4 comparisons indicate either high sensitivity to measurement accuracy which could mask modeling and option effects or unrealistic code simulation of thermal hydraulic effects. Also, a lack of reliable boundary condition data in these tests (evidenced by the flow derived from GU-5VR and FDU-5 for Test S-01-4A or the steam generator secondary measurements for Test L1-4) creates excessive uncertainty for component model data comparisons.

Evaluations of the sensitivity of the data comparisons to changes in driving flow data, the dominant boundary condition uncertainty, were made for all tests. The sensitivity of the S-06-5 data comparison to changes in heat transfer coefficients was also considered.

It should be noted that differences in Semiscale secondary temperatures in the cases discussed are negligible compared to the measurement accuracy of $\pm$ 4K for three standard deviations[10].

1. SEMISCALE TEST S-06-5

1.1 Nodalization and Model Options

Deleting the seven piping heat slabs, or deleting the seven piping heat slabs and the six plena heat slabs (leaving only those in the tubes), had almost no effect on calculated flow or secondary temperature. The energy added to the fluid from these slabs during a heated blowdown is very small compared to the total energy in this part of the system. Removing these heat slabs in the model decreases the voiding rate, as shown in the density comparisons (Figures 29 and 30) and further degrades the comparisons. The maximum difference in density with all slabs included and with slabs only in the tubes is about 64 kg/m^3 and occurs at 15 seconds after the break. Deleting piping heat slabs resulted in a 24 per cent decrease in running time; deleting piping heat slabs and plena heat slabs resulted in a 48 per cent decrease in running time. It is recommended that these heat slabs be included in Semiscale component steam generator models for heated blowdowns and excluded from Semiscale heated blowdown system models only when the number of heat slabs or running time is critical.

Modeling the steam generator tubes in three, five and six volumes rather than four volumes as in the base run had almost no effect on calculated flow and secondary temperature. The only effect on calculated density near the pump inlet was slightly earlier saturation with fewer tube volumes. All cases saturated 1/4 to 1/2 second later than the data. Differences are due to gravity effects on the fluid near the top of the tubes and to the propagation of the saturation front through the tubes. As will be discussed later, however, time of saturation near the pump inlet is primarily a function of separation in the plena, and only secondarily a function of the number of volumes in the tubes. The four-volume model for steam generator tubes is recommended for system and the six-volume model for component Semiscale heated blowdown models. The additional volumes do not improve the calculation appreciably. Addition or deletion of a volume in the tubes resulted in an increase or decrease in CPU time of about 6 percent compared to the base run.

The effects of using two volumes in the secondary, with the division between volumes at the top of the tubes, were investigated. Calculated flow and density were identical. Up to 16 seconds, secondary temperatures in both volumes match the base run (Figure 26). At this time, the collapse of the two-phase mixture following secondary system shutdown is complete and the lower volume is filled with water, which transfers heat to the primary. Heat transfer for the rest of the blowdown is dominated by the low heat transfer coefficient on the primary side. The temperature in the upper volume, which is effectively insulated from the rest of the system, stays constant. The lower volume calculated temperature is less than 0.5 K below the calculated temperature for the one-volume secondary (base run), and this difference has a negligible effect on heat transfer to the primary. Modeling the secondary in two volumes is not recommended for Semiscale heated blowdown system models and should only be used in Semiscale heated blowdown component models where stratification is of interest. Running time increased by 3 percent with a two-volume secondary.

The effects on the calculation of pump sump nodalization and slip were investigated. Density measurements upstream of the pump indicate that voiding proceeds at a fairly constant rate through the pump sump. Dividing the sump into several volumes and using slip at the junctions (as in the base run) causes liquid to pool in the sump inlet (Volume 13, Figure 7) and to be forced out in a slug, rather than entrained as indicated by the data. This liquid collection in the sump does not appear to affect the thermal hydraulic calculations in the rest of the model during a heated blowdown. The flow in the cold leg is always toward the pump, and tube heat transfer is affected only by the liquid inventory in the plena and the tubes. Flow reversal on the pressurizer side can pull lower quality fluid from the steam generator outlet into the tubes, but gravity effects in the essentially vertical volumes downstream of the outlet (Volumes 12 and 13, Figure 7) force sump liquid away from the plena.

Using no slip in the sump, and/or using no slip in the sump and combined piping (See Figure 31 for nodalization diagram) had no effect on calculated flows and secondary temperatures. The calculated voiding rate (Figure 32) is more similar to the data when slip is not used in the sump. If slip is not used, the change in nodalization has no effect. It is recommended that no slip be used in the sump, and that the sump be modeled in two volumes as shown in Figure 31, for both Semiscale component and system steam generator models during a heated blowdown. Running time decreased 12 percent from the base run with this modeling.

The degree of separation occurring in the plena can affect the heat transfer, since liquid collected in the plena is available for flow through the tubes. Using single plena with Wilson's bubble rise for plena phase separation instead of a two-volume plena with slip for plena phase separation, as in the base run, had no effect on calculated flows and secondary temperatures. Both cases have slip in the sump. Calculated densities near the pump inlet (Figure 33) are identical until the Wilson bubble rise model begins to give slower voiding between 14 and 20 seconds than calculated in the base run using the slip model. The maximum difference during this time is small, about 40 kg/m^3. Modeling the plena in one volume with bubble rise decreased the running time by 12 per cent.

Using one-volume plena with Wilson's bubble rise and also no slip in the sump produced calculated flow on the pressurizer side and calculated secondary temperature very similar to the base run (two-volume plena with slip in both the plena and in the pump sump). The change case showed slightly more inflow after 23 seconds and a slightly greater drop in secondary temperature (0.5K) by the end of the blowdown than did the base run. Calculated densities on the pump side (Figure 34) are similar until 9.5 seconds. The change case shows faster voiding than the base run from 9.5 to 14.5 seconds, and slower voiding after 14.5 seconds. Both cases void slower than the data.

The effect on the calculation of using one-volume plena with no bubble rise and no slip in the sump is compared to the base run (two-volume plena with slip in both the plena and the pump sump) in Figures 35 and 36. Calculated flows on the pressurizer side (Figure 35) are similar until 17 seconds, after which the change case shows more inflow than the base run or the data. Calculated density on the pump side in the change case shows saturation at the same time as the data (1/3 second earlier than the base run) and faster voiding than the base run through the remainder of the blowdown, although not as fast as the data (Figure 36). The slowdown in voiding at 9 seconds in the data, due to liquid collection in the plena, is not shown in the change case and is exaggerated in the base case. Calculated secondary temperatures are very similar.

Differences in running time with and without the Wilson bubble rise model are negligible. Modeling the plena as single volumes with no phase separation is recommended for component and system models in a Semiscale heated blowdown.

Using slip in the steam generator tubes is compared to using no slip in the tubes (base run) in Figures 37 and 38. Use of this model causes early dryout in the tubes after 12.5 seconds, as shown by the calculated secondary temperature curve in Figure 38, and results in a lower heat flux than is reflected by the data. The lack of heat transfer also slows down the voiding rate (Figure 37) and minimizes inflow after 12.5 seconds. Using slip in the tubes is not recommended for heated blowdowns.

Use of the local quality calculation on the secondary side is recommended for all models. The results using and not using this model were identical for Test S-06-5, but the additional computer time required to calculate the qualities was negligible. The effect of differences between local and average qualities prior to collapse of the two-phase mixture due to secondary system shutdown is not significant in the S-06-5 case, but may be important for other tests. The quality calculation is not used in the natural convection mode.

Downcomer liquid should be included in the secondary side mass inventory. In simplifying the complex secondary system (See Section II.3) for a RELAP4 model, an approximation is made in the calculation for the amount of steam above the mixture level, which then determines the input quality below the mixture level. Eliminating the mass and volume of water in the downcomer increases the calculated quality on the secondary side in the first 9 seconds, resulting in too high heat transfer coefficients in Mode 2 (saturated nucleate boiling).

Calculated quality on the secondary side is affected by the initial choices of bubble rise model and mixture level. Bubble formation occurs only in the tube region, and the percentage of bubbles increases from the bottom to the top of the tubes. No additional bubbles are produced between the top of the tubes and the steam separator, where complete separation of the liquid and vapor phases occurs. Since only one bubble rise model can be used in a volume, the selection is somewhat arbitrary. In these cases, bubble rise with constant bubble velocity was used, the mixture level was chosen at the steam separator, the bubble gradient was assumed to be one (ie., no bubbles at the tube sheet, maximum steam at the steam separator), and the bubble velocity was calculated to give the correct mass of steam exiting the steam dome at steady state conditions. This selection was considered the closest approximation to the physical situation which could be calculated within the constraints of RELAP4/MOD6 Update 3.

1.2 Sensitivity to Changes in Driving Flow

The effect on the Semiscale S-06-5 model calculations of a ±12% change in measured driving flow is shown in Figures 39, 40 and 41. This change is within the measurement uncertainty for the Test S-06 Series[9] for the first 8 seconds of blowdown and is substantially less than the measurement uncertainty after 8 seconds. An increase of 12% in driving outflow on the pump side results in a compensatingly larger calculated inflow on the pressurizer side, faster voiding in the pump sump, and higher secondary temperatures throughout most of the blowdown compared to the base run. A decrease of 12% in driving outflow results in a calculated inflow similar to measured data, later saturation and slightly faster voiding than the base run for the first 14.5 seconds of blowdown, slower voiding for the remainder of the blowdown, an overall secondary temperature history within the data for the first 8 seconds of blowdown, and as much as 3 K above the data by the end of blowdown. (Note that secondary temperature measurement accuracy for Semiscale is ± 4K for three standard deviations[9].) The effects of these uncertainties are large enough to mask the results of most model and option changes.

1.3 Sensitivity to Changes in Heat Transfer Coefficients

Heat transfer coefficient dials[1] were used to check sensitivity of the base run data comparison to changes in the heat transfer models. In general, the calculated heat transfer rate tended to be very slightly high compared to data during the first 8 seconds of the transient, and low during the remainder of the blowdown, as shown in Figure 26. Dial values were chosen to decrease heat transfer in the first 8 seconds and to increase heat transfer during the rest of the blowdown.

During the first 10 seconds of the transient, subcooled liquid forced convection (Mode 1) is occurring on the primary side and saturated nucleate boiling (Mode 2) on the secondary side. After heat flux reversal, the secondary side transfers heat by natural convection (Mode 11) and the primary side by saturated nucleate boiling (Mode 2), high flow film boiling (Condie-Bengston correlation, Mode 6), and low flow, high void fraction free convection and radiation (Mode 7). A dial value applied to a correlation modifies the heat transfer coefficient in that mode throughout the run.

Decreasing heat transfer during the first 10 seconds (by multiplying the Mode 1 heat transfer coefficient by 0.9) and increasing heat transfer after 10 seconds (by multiplying the Mode 11 heat transfer coefficient by 2.0) had a negligible effect on calculated flow and density. Secondary temperature (Figure 42) drops to about 0.5 K below the base case by the end of the transient, although still higher than data.

Heat transfer from the secondary to the primary after 10 seconds is dominated by the low heat transfer coefficient on the primary side. Much of the heat is transferred in Mode 6 on the primary side. Multiplying Mode 1 by 0.9 and Mode 6 by 2.0 had a negligible effect on calculated flow and density. Secondary temperature is very similar to the previous run (Figure 42) and drops to about 1.0 K below the base case by the end of the transient, although it is still higher than data.

From these cases and the cases discussed in the previous section, it can be concluded that uncertainty in steam generator heat transfer is governed by uncertainties in measured and calculated flows, rather than uncertainties in the heat transfer correlations. It is noted that although the steam generator natural convection model (Mode 11) is based on a length, L, between flow restrictions or baffle plates in the secondary which is assumed to be the same as the tube length in a volume, it is not necessary to model the primary tube volumes between baffle plates for a Semiscale heated blowdown. Differences in lengths between the baffle plate intersections and the lengths of RELAP4 volumes normally used in steam generator models have an insignificant effect on the heat transfer for this case because 1) the natural convection correlation is a function of $L^{0.2}$ for turbulent flow, and 2) the low heat transfer coefficient on the primary side dominates the calculation.

1.4 Results of Sensitivity Studies and Recommended Models

The sensitivity studies run with Test S-06-5 test data clearly indicate that realistically calculating steam generator phenomena during a Semiscale heated blowdown is a flow-dominated problem. Accuracy in flow boundary conditions and the use of RELAP4/MOD6 flow separation options have significant effects on the comparisons of data and steam generator component calculations.

The steam generator model recommended for a Semiscale Mod-1 heated blowdown component calculation is shown in Figure 43. Features of this model include six volumes in the steam generator tubes, one-volume plena, a one-volume secondary, and combined cold leg piping. Heat slabs are included throughout the model. No phase separation is used in the primary. The secondary system includes the water in the downcomer and is modeled with the mixture level at the steam separator, a bubble gradient of one, and the bubble velocity necessary to give measured steam outlet flow. Local quality is calculated on the secondary side of the slabs.

The steam generator model recommended for a Semiscale heated blowdown system calculation is similar to that for component calculations. The only differences are four tube volumes instead of six, and the deletion of all heat slabs except those in the tubes, since the size of the model and the number of heat slabs can be very critical in terms of computer time.

1.5 Comparison of Recommended Models with Data

Data comparisons using results of the recommended component model run and the base run are shown in Figures 44, 45 and 46. Calculated mass flows (Figure 44) are very similar, with the recommended component model run showing less outflow between 8 and 17 seconds than the base run. Calculated densities (Figure 45) indicate faster voiding between 9 and 16 seconds using the recommended component model than in the base run, in better agreement with the data. Calculated steam generator secondary temperatures (Figure 46) are identical until 14 seconds, when the temperature in the recommended component run drops slightly below that in the base run, a difference of 1.0 K by the end of blowdown.

Calculated flow and secondary temperature using the recommended system model are very similar to those using the recommended component model. Calculated density (Figure 47) with the recommended system model are higher between 15 and 25 seconds than both the base run and the recommended component model run. Generally, these differences in calculated density have little effect, since the pump performance has already substantially degraded when the local void fraction is greater than 0.2[10]. By 15 seconds into the transient, when heat added to the system from these slabs begins to affect the density, the void fraction is already greater than 0.6.

2. SEMISCALE TEST S-01-4A

2.1 Model Options

The effect of deleting slip in the pump sump had almost no effect on the Test S-01-4A calculation. Velocities were high enough during the transient to entrain the liquid in the vapor, so that the effect of phase slip was negligible.

The energy added to the fluid from plena and piping heat slabs during an isothermal blowdown will be a larger percentage of the energy in this part of the system than these slabs represented for a heated blowdown. It is recommended that slabs be included whenever possible in both system and component models for an isothermal blowdown.

2.2 Sensitivity to Changes in Driving Flow

The effect on the Semiscale S-01-4A model calculations of a ± 12% change in measured driving flow is shown in Figures 48, 49, and 50 for flow, density, and secondary temperature, respectively.

An increase of 12% in driving outflow on the pump side results in a compensatingly larger calculated inflow on the pressurizer side, faster voiding in the pump sump, and lower secondary temperatures throughout most of the blowdown compared to the base run. A decrease of 12% in driving outflow results in a calculated inflow similar to measured data, slower voiding more like the data, and up to 1.5K higher secondary temperature than the base run. These results indicate that flow uncertainty has a substantial effect on the comparison of steam generator model calculations and data for an isothermal test, as was shown earlier for a heated blowdown.

2.3 Results of Test S-01-4A Studies

The results of the S-06-5 sensitivity studies indicated that realistically calculating steam generator phenomena during a Semiscale heated blowdown is a flow-dominated problem. The S-01-4A base run and additional studies illustrate that this is also the case for an isothermal blowdown.

Assessing the ability of RELAP4/MOD6 to calculate thermal-hydraulic phenomena occurring in the Semiscale steam generator requires[12] reliable boundary conditions in the steam generator secondary and at the steam generator inlet and outlet. Base run comparisons with Test S-01-4A data (Section IV.2) showed the lack of a reliable flow boundary condition on the pressurizer side and also discrepancies between calculated and measured densities on the pump side. Previous (unpublished) work on steam generator data comparisons with a heated Semiscale blowdown for Standard Problem 7 illustrated the futility of extending the model past the pressurizer to pick up flow measurements at Spool Piece 1 (See Figure 2). Uncertainty in modeling the mass and enthalpy of the pressurizer flow masked modeling and option effects.

Steam generator models recommended for an isothermal blowdown are the same as those recommended for a heated blowdown, except that piping and plena heat slabs should be added to the system model whenever possible.

3. LOFT TEST L1-4

3.1 Sensitivity to Changes in Driving Flow

The effects on the LOFT calculation of driving flow changes of +4% for the first 5 seconds and +40% after 5 seconds, then -4% and -40% for the same time frames, were determined on flow, density, and secondary temperatures. Measurement accuracies are presently under evaluation by the LOFT program, and these changes are expected to be well within the Test L1-4 measurement uncertainty for the first 5 seconds of blowdown and less than the measurement uncertainty after 5 seconds. (Note that $\pm$ 12% flow changes were assumed in the corresponding runs for Semiscale.) Little change was seen in calculated values since the assumed change in driving flow is very small during the first 5 seconds, about equivalent to the pressurizer flow during this period, and driving flow is almost null after 5 seconds. (Refer to Figures 17 and 20 for Test L1-4 driving flow and pressurizer flow, respectively.) These measurement uncertainty approximations do not account for the lack of agreement between the base run calculations and the LOFT data.

3.2 Instrumentation Requirements for Component and Scaling Studies

Results of the LOFT steam generator model base run (Section IV.3), information contained in Reference 12, and the LOFT instrumentation diagram for the intact loop between the vessel and the pumps (Figure 4) illustrate several concerns of independent verification with LOFT steam generator data.

Boundary conditions are not available for single-component verification of the LOFT steam generator or of the LOFT pressurizer. No flow or density measurements valid for the transient are available between these two elements. Any partial system model must contain both components.

Steam generator secondary temperature was not recorded in any LOFT test to date. Since only one temperature measurement (TE-SG-3) is in the secondary, no information on stratification will be available for future tests. Additional thermocouples are also required to ascertain the secondary fluid energy, as discussed in Reference 12.

3.3 Results of Test L1-4 Studies

Additional flow measurement uncertainty information is needed to determine the importance of existing measurement accuracies on data comparisons.

Lack of instrumentation on the LOFT steam generator makes ascertaining the secondary fluid energy impossible and forces inclusion of the pressurizer in the steam generator model, resulting in undesirable uncertainties. Therefore, steam generator component analyses cannot be used to assess the capability of RELAP4/MOD6 to calculate thermal hydraulic phenomena in the LOFT steam generator or to predict the effects of scaling from Semiscale to LOFT on the phenomena and on the modeling techniques.

VI. CONCLUSIONS AND RECOMMENDATIONS

The results of the steam generator component studies lead to the following conclusions and recommendations relative to independent verification:

1) The steam generator model recommended for a Semiscale heated blowdown component run is shown in Figure 43. Features of this model include six volumes in the steam generator tubes, one-volume plena, a one volume secondary, and combined cold leg piping as shown. Heat slabs are included throughout the model. No phase separation is used in the primary. The secondary system includes the water in the downcomer and is modeled with bubble rise with constant bubble velocity, the mixture level at the steam separator, a bubble gradient of one, and the flow rate necessary to give measured steam outlet flow. Local quality is calculated on the secondary side of the slabs.

The only differences between the steam generator model recommended for a Semiscale heated blowdown system run and the component model are the deletions of two tube volumes and possibly of all heat slabs except those in the tubes, since the size of the model and the number of heat slabs can be very critical for system runs.

Steam generator models recommended for an isothermal blowdown are the same as those recommended for a heated blowdown, except that piping and plena heat slabs should be added to the system model whenever possible.

2) Realistically calculating steam generator phenomena during a Semiscale heated or isothermal blowdown is a flow-dominated problem. Accuracy in flow boundary conditions and the use of RELAP4/MOD6 flow separation options have significant effects on the comparisons of calculations and data using steam generator component models (Section V, 1.4 and 2.3). Including the pressurizer in a steam generator component model produces enough uncertainty in the calculation to mask modeling and option effects (Section IV, 3; Section V, 2.3 and 3.2).

Presently available information on flow measurement uncertainties indicates a requirement for higher measurement accuracy in component studies and for further work on determining measurement uncertainties. Lack of instrumentation on the LOFT steam generator makes ascertaining the secondary fluid energy impossible. This lack of measurements also forces the inclusion of the pressurizer in the steam generator model, producing considerable uncertainty (Section V, 3.2).

Therefore, steam generator component analyses cannot be used to assess the capability of RELAP4/MOD6 to calculate thermal-hydraulic phenomena in the LOFT steam generator or the effects of scaling from Semiscale to LOFT on the phenomena and on the modeling techniques.

3) One of the problems in assessing the adequacy of current steam generator modeling techniques is the lack of any statement of required steam generator model performance. Prior to any further component verification effort, an assessment of the effects of model uncertainties on system calculations (during both blowdown and reflood) should be made. From this uncertainty study, the accuracy requirements for steam generator calculated behavior can be determined.

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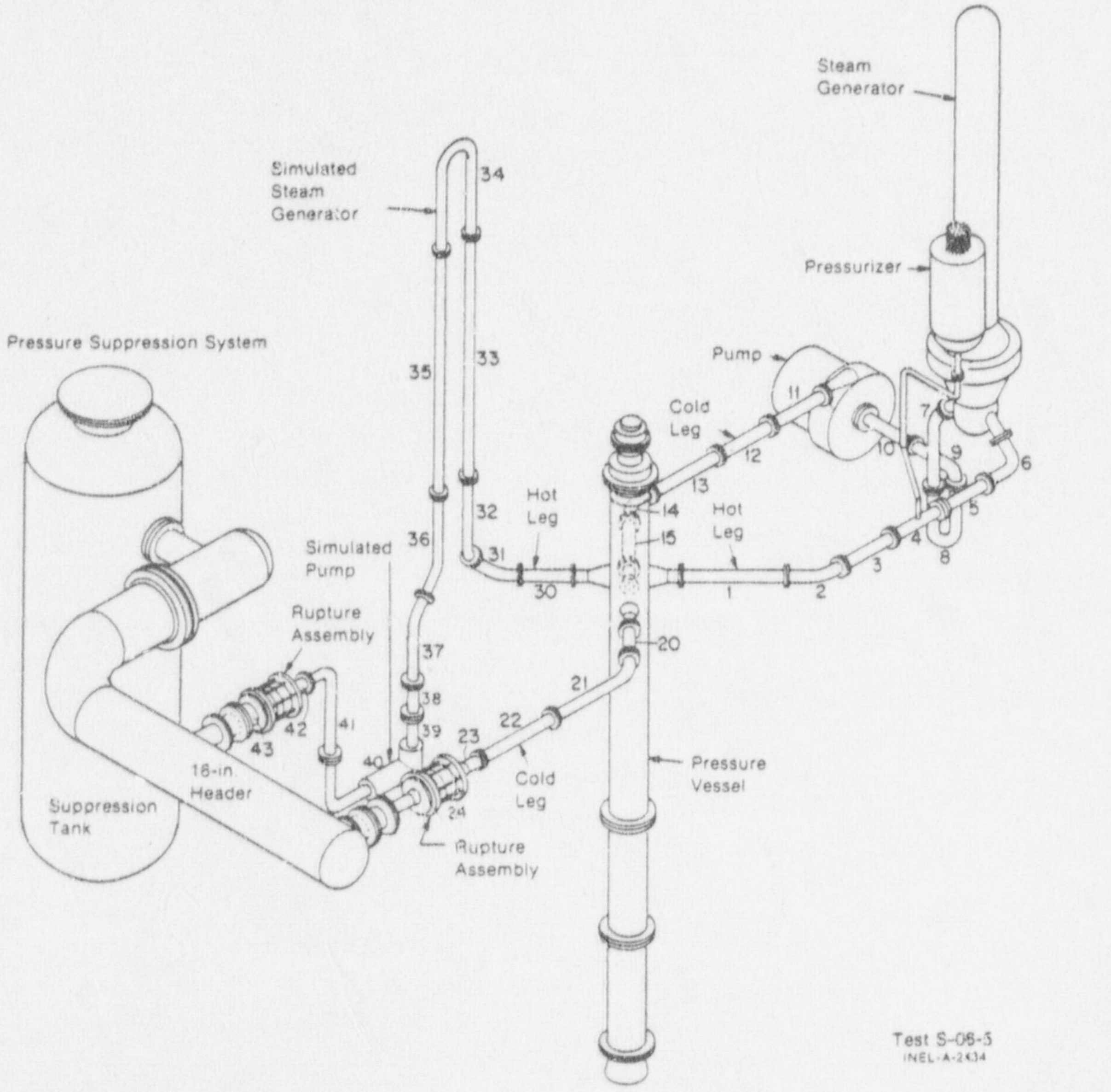


Fig. 1 Semiscale Mod-1 system for cold leg break configuration - isometric.

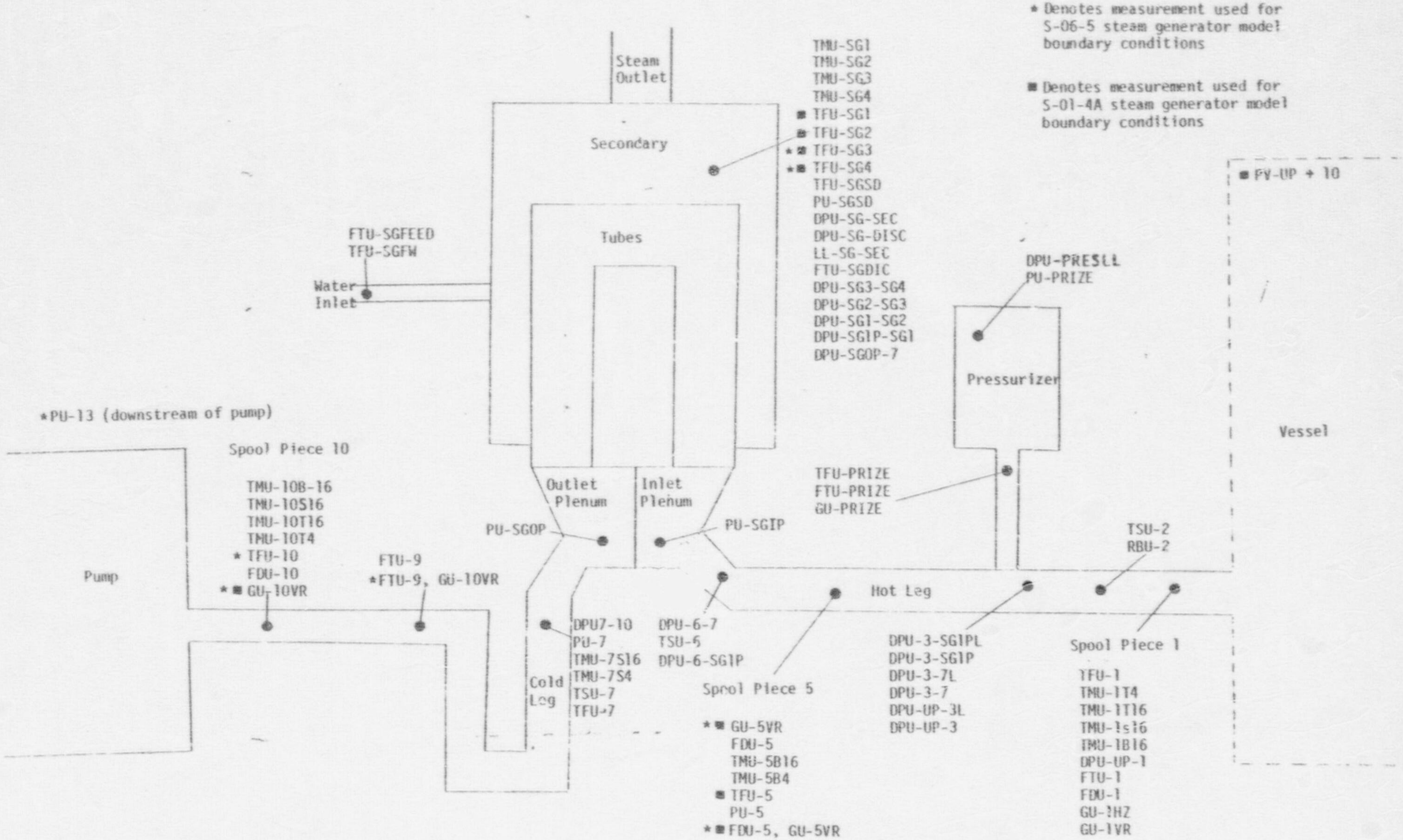


Fig. 2 Semiscale intact loop instrumentation between vessel and pump.

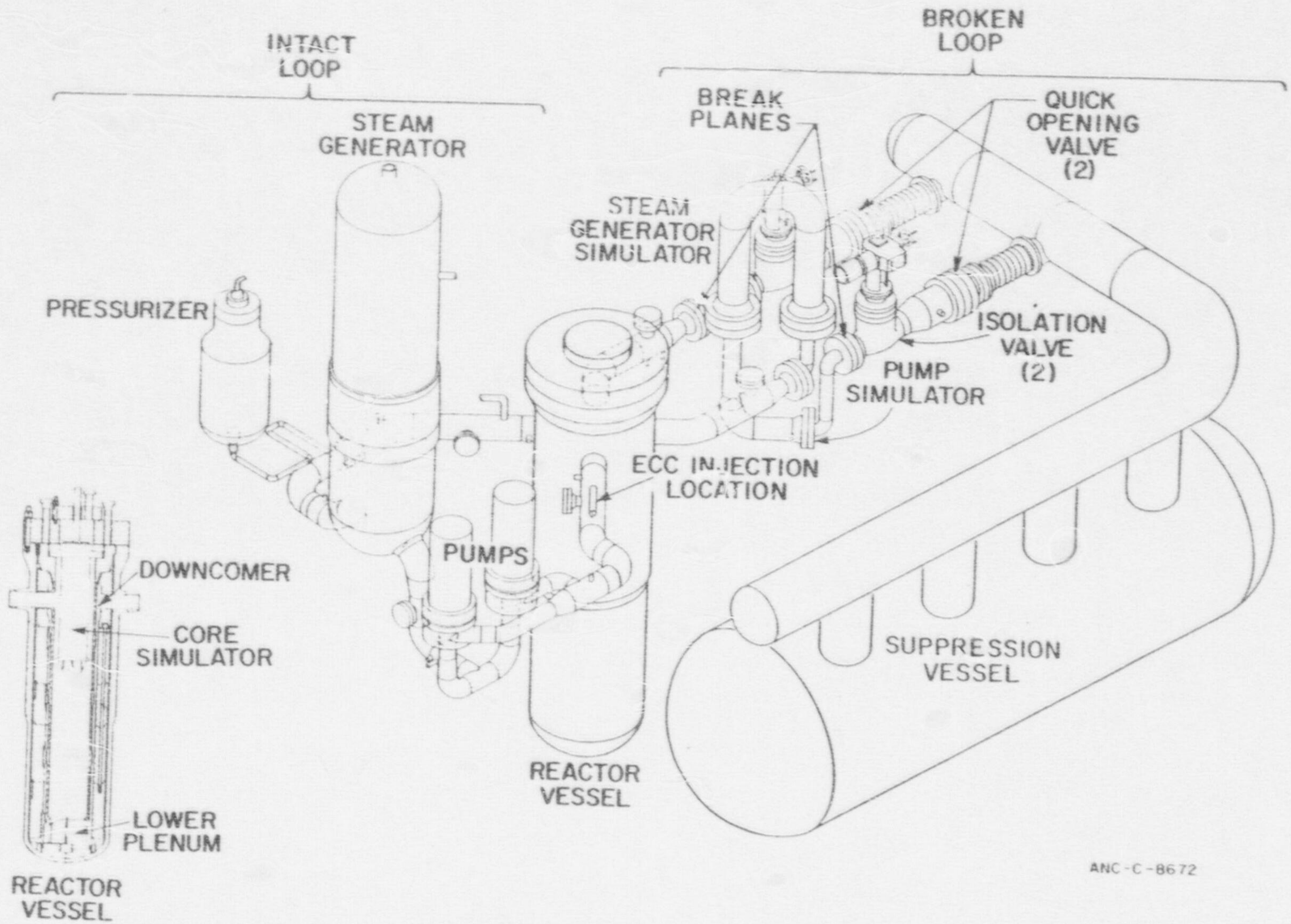


Fig. 3 LOFT system for cold leg break configuration - isometric.

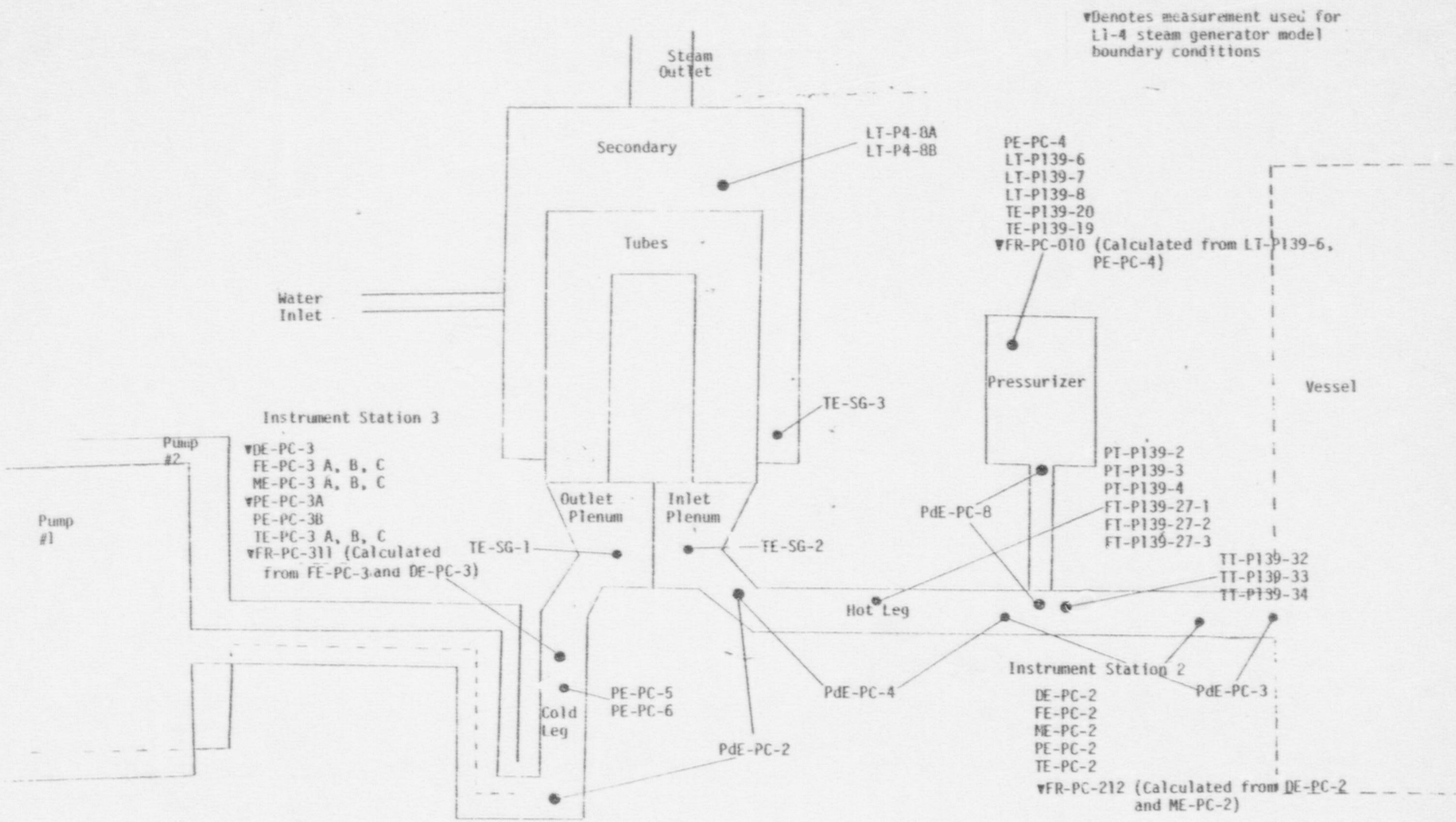
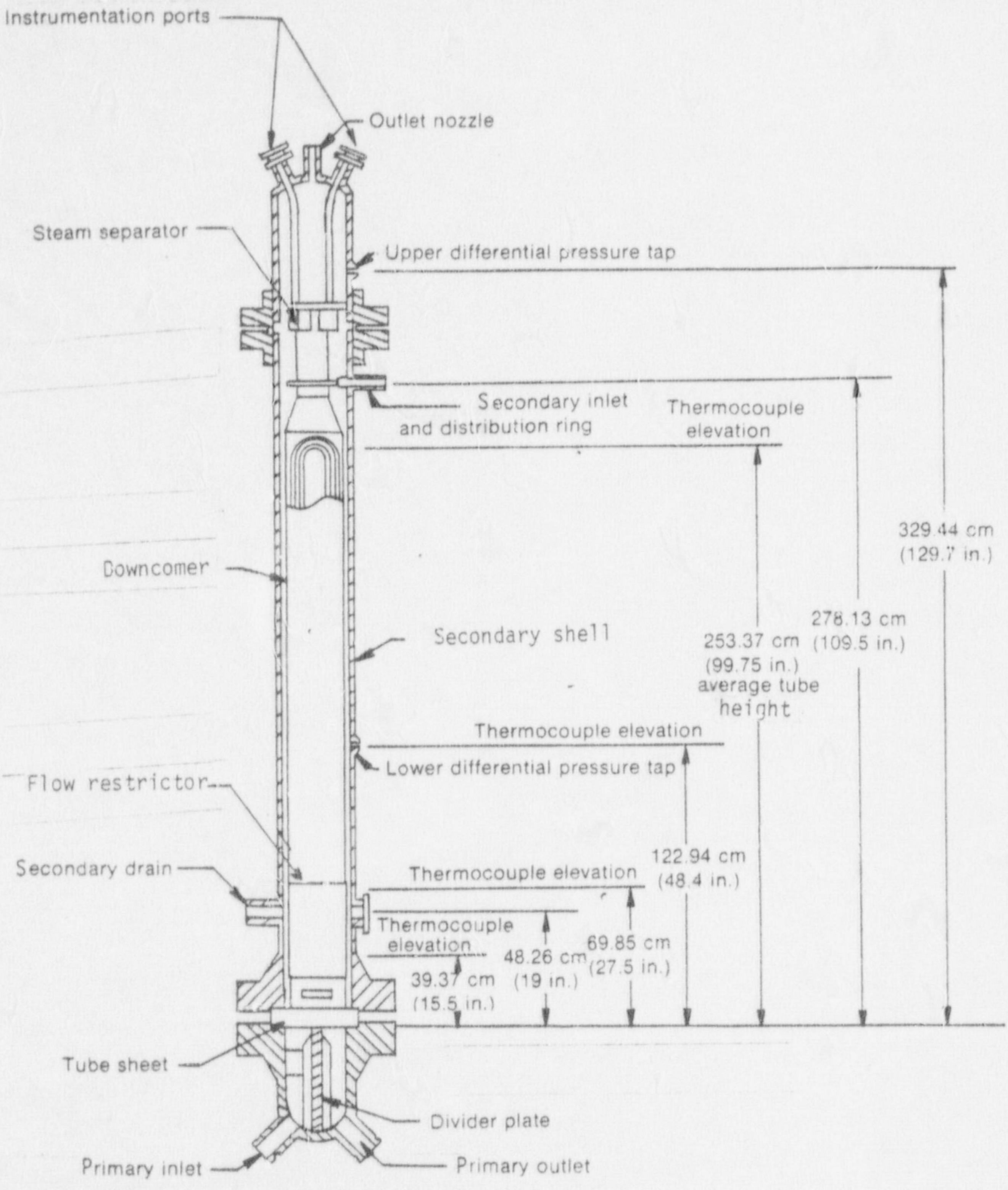
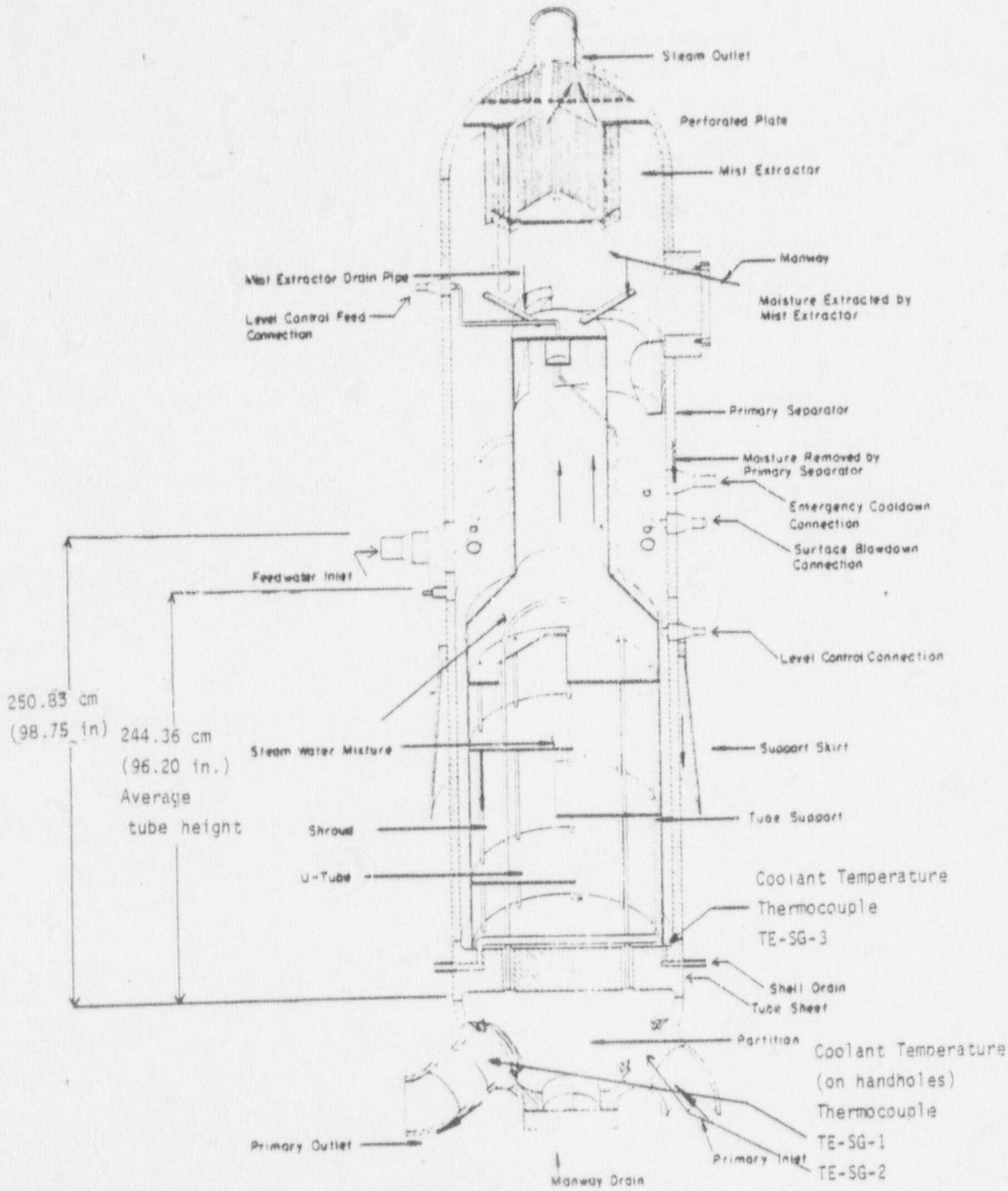


Fig. 4 LOFT intact loop instrumentation between vessel and pumps.



Note: Elevations measured from bottom of tube sheet

Fig. 5 Semiscale Type I intact loop steam generator configuration.



NOTE: Elevations measured from bottom of tube sheet.

Fig. 6 LOFT intact loop steam generator configuration.

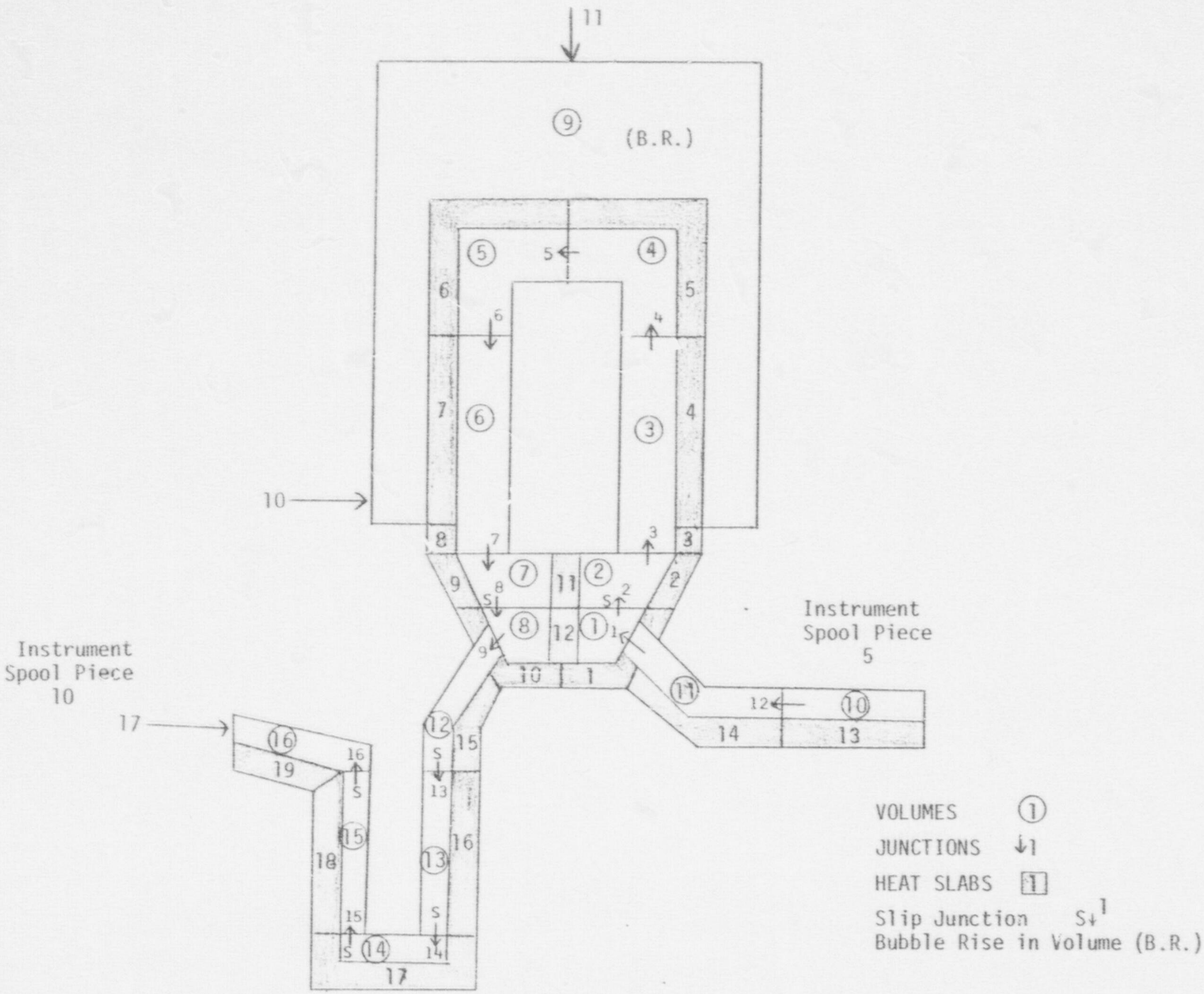


Fig. 7 Base run model of Semiscale steam generator.

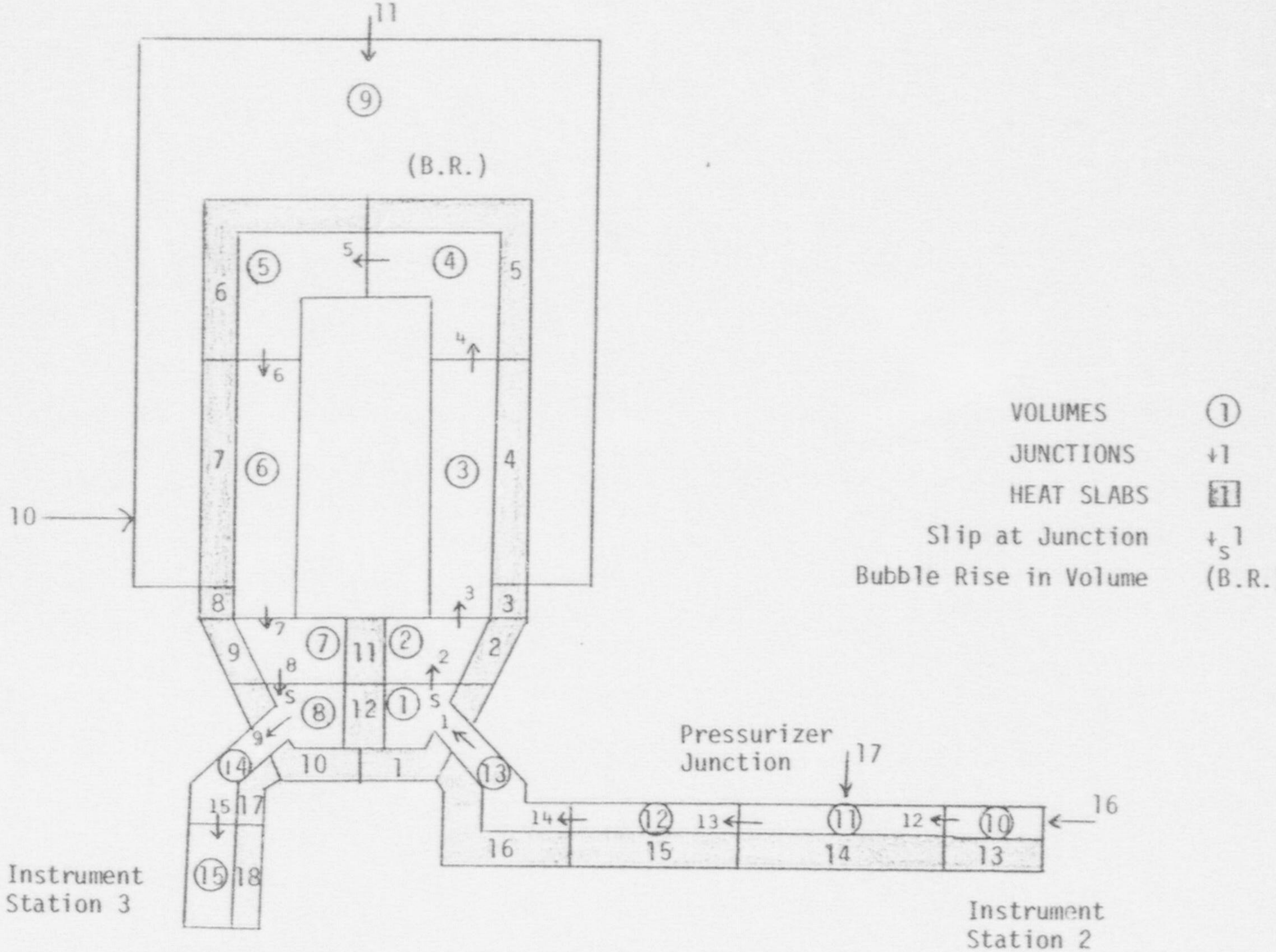


Fig. 8 Base run model of LOFT steam generator.

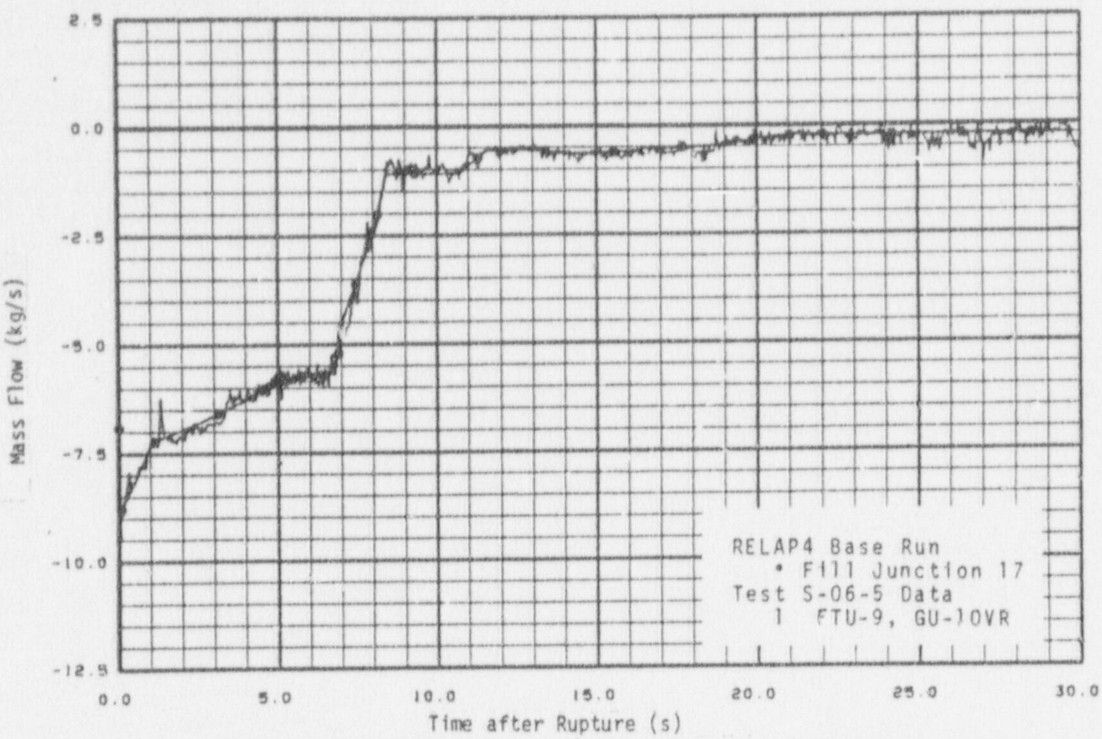


Fig. 9 Mass flow on pump side - Test S-06-5 boundary conditions.

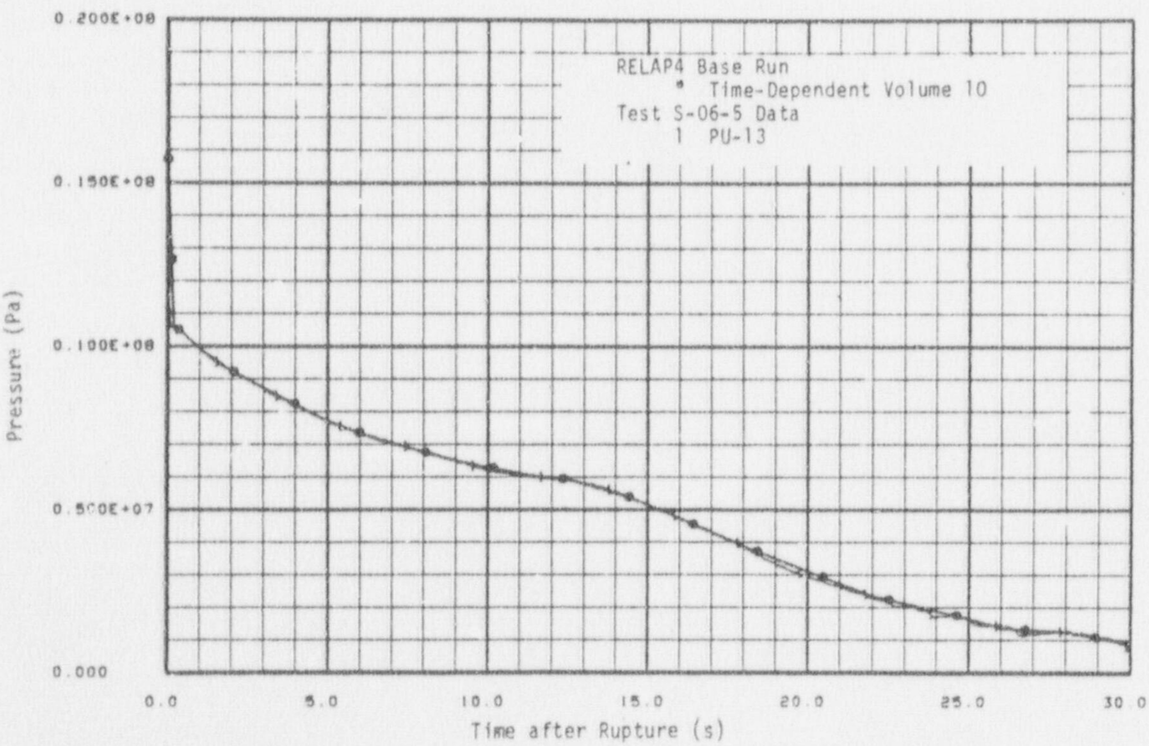


Fig. 10 Pressure on pressurizer side - Test S-06-5 boundary conditions.

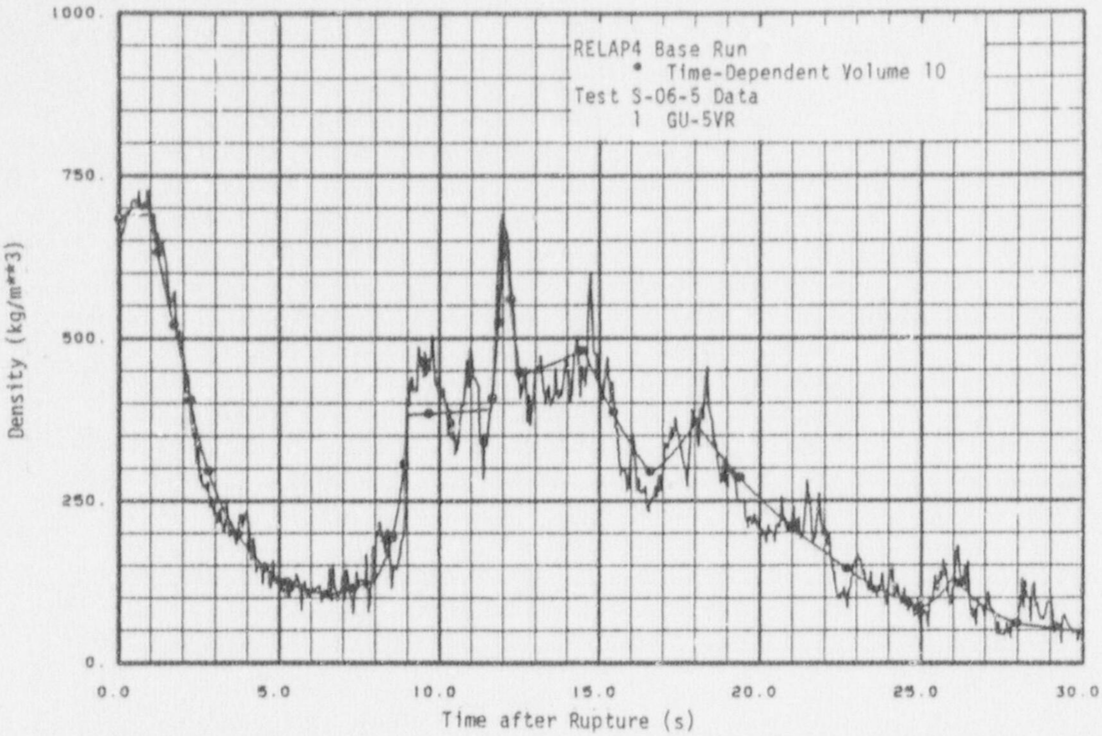


Fig. 11 Density on pressurizer side - Test S-06-5 boundary conditions.

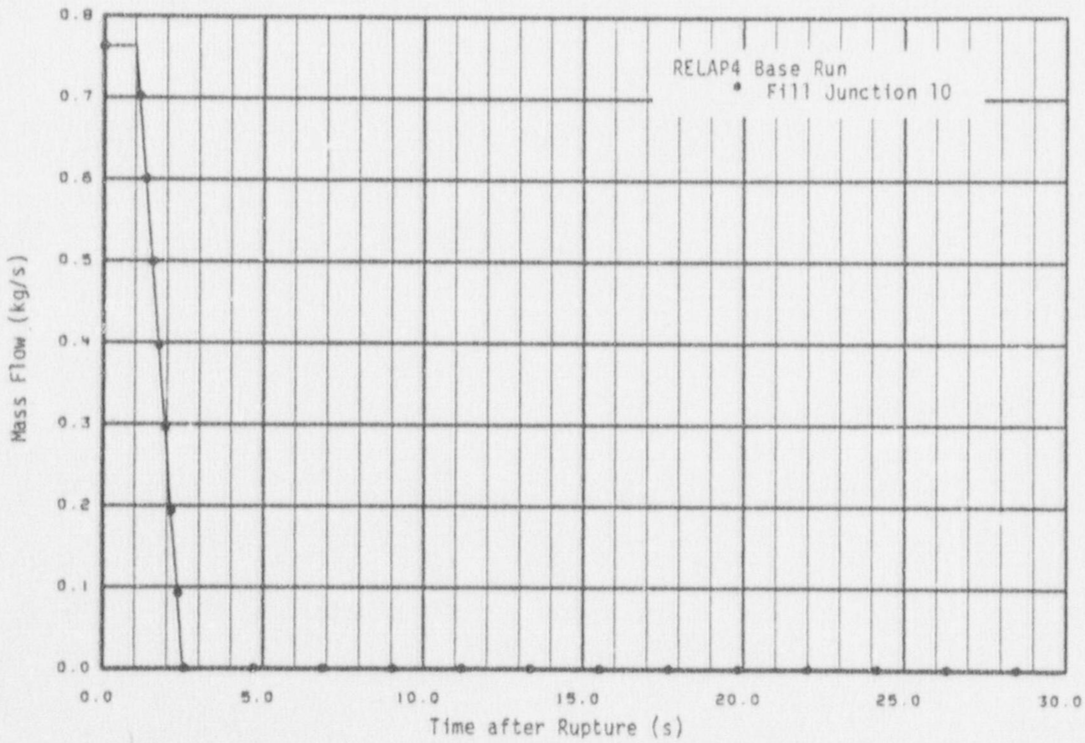


Fig. 12 Calculated mass flow at steam generator secondary inlet - Test S-06-5 boundary conditions.

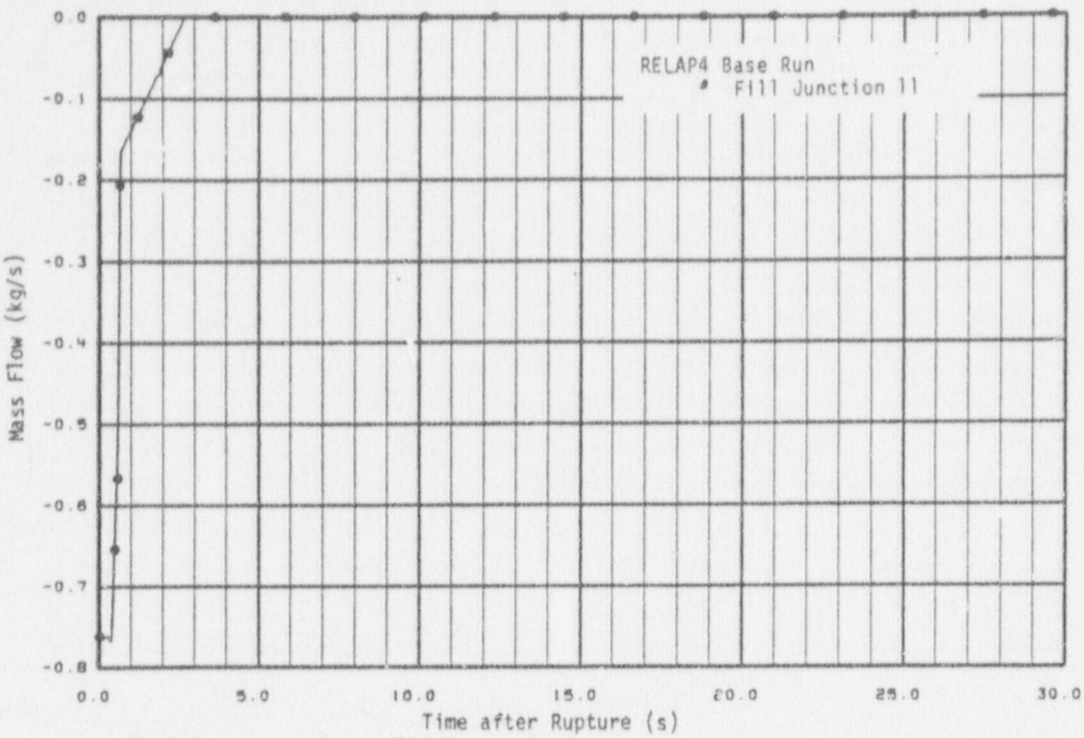


Fig. 13 Calculated mass flow at steam generator secondary outlet - Test S-06-5 boundary conditions.

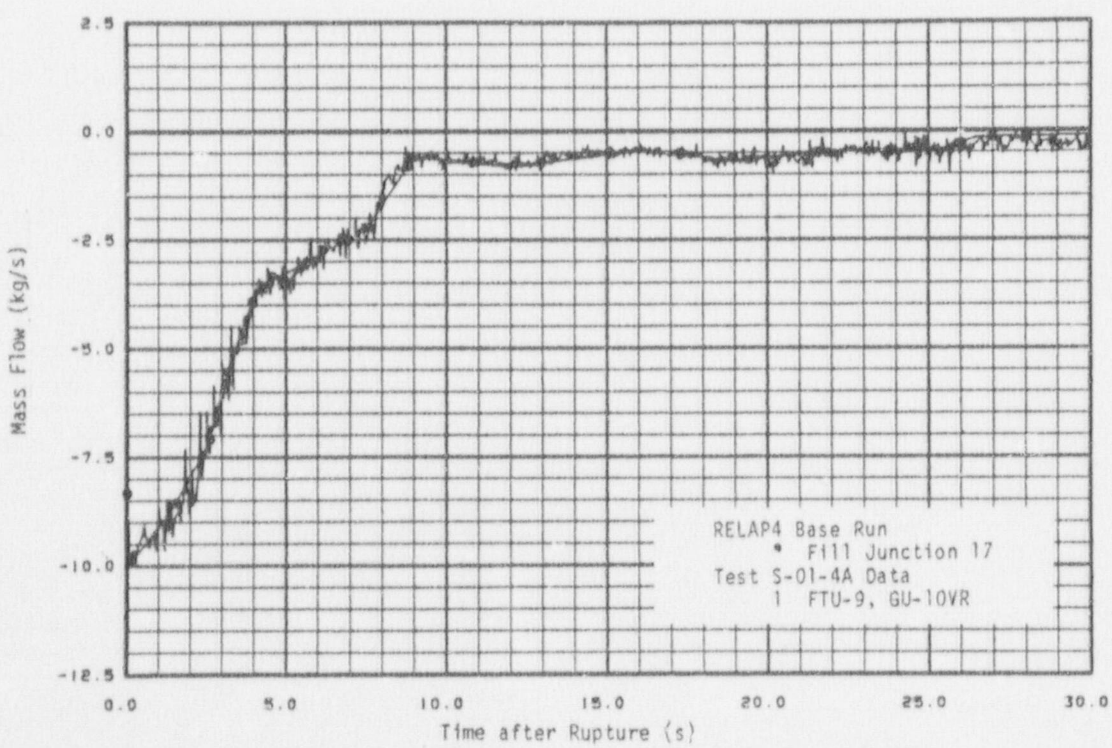


Fig. 14 Mass flow on pump side - Test S-01-4A boundary conditions.

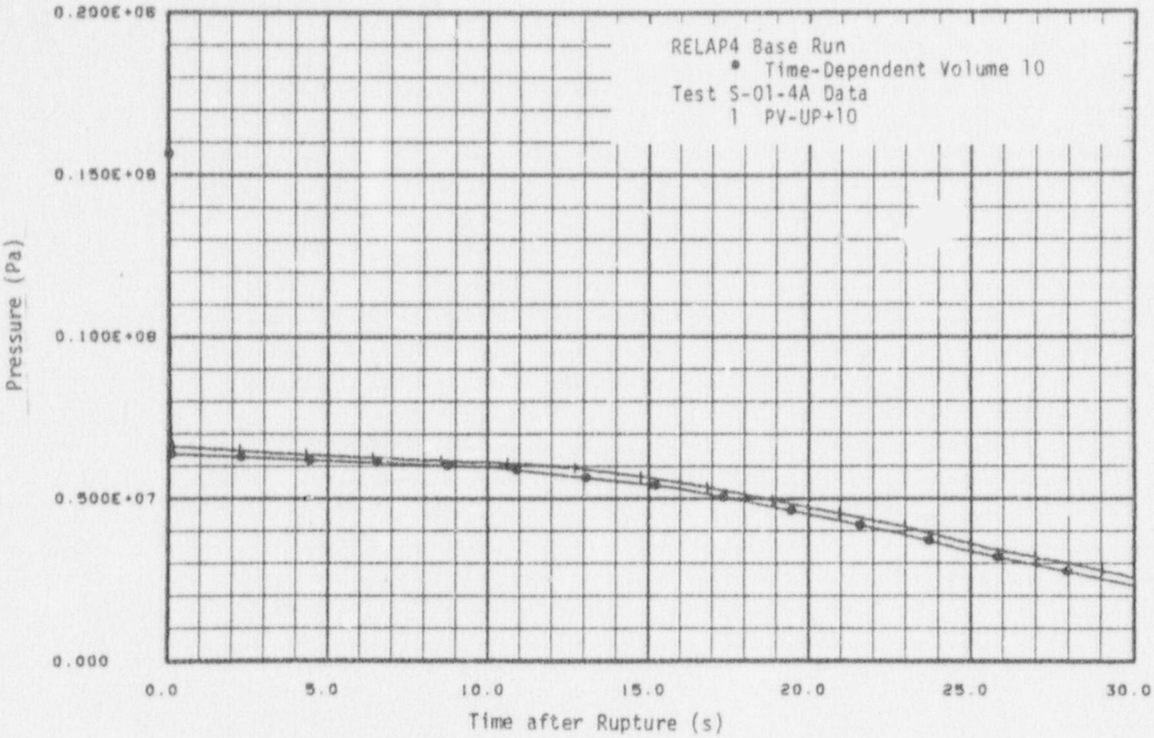


Fig. 15 Pressure on pressurizer side - Test S-01-4A boundary conditions.

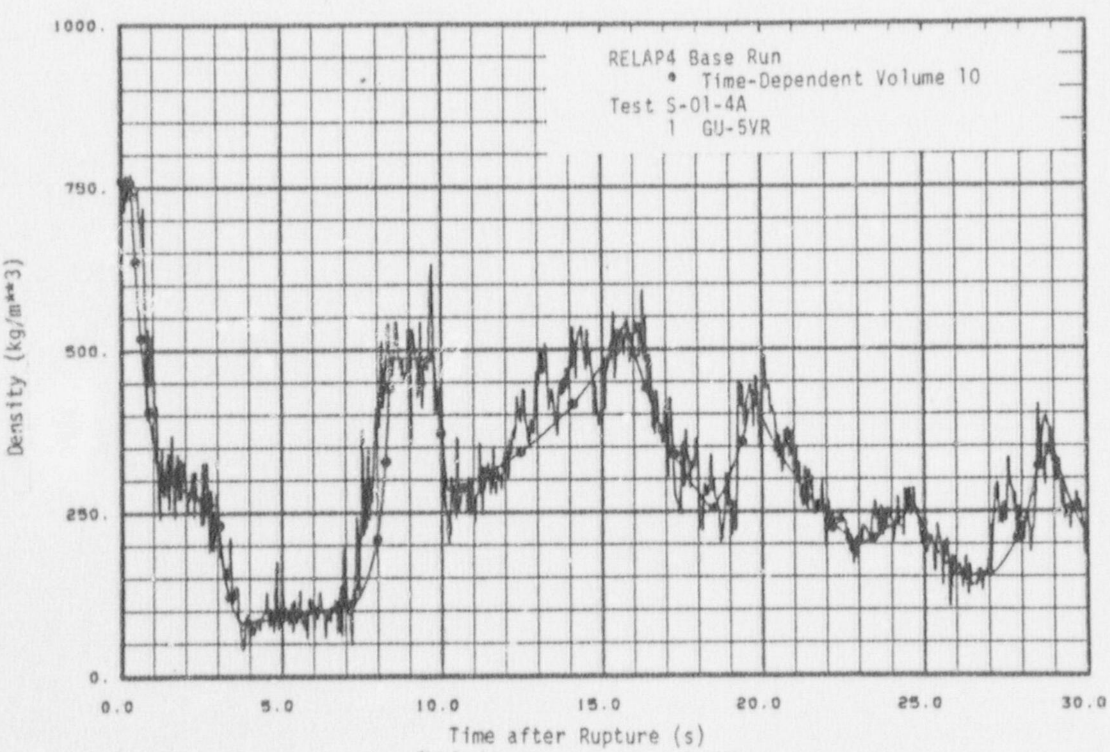


Fig. 16 Density on pressurizer side - Test S-01-4A boundary conditions.

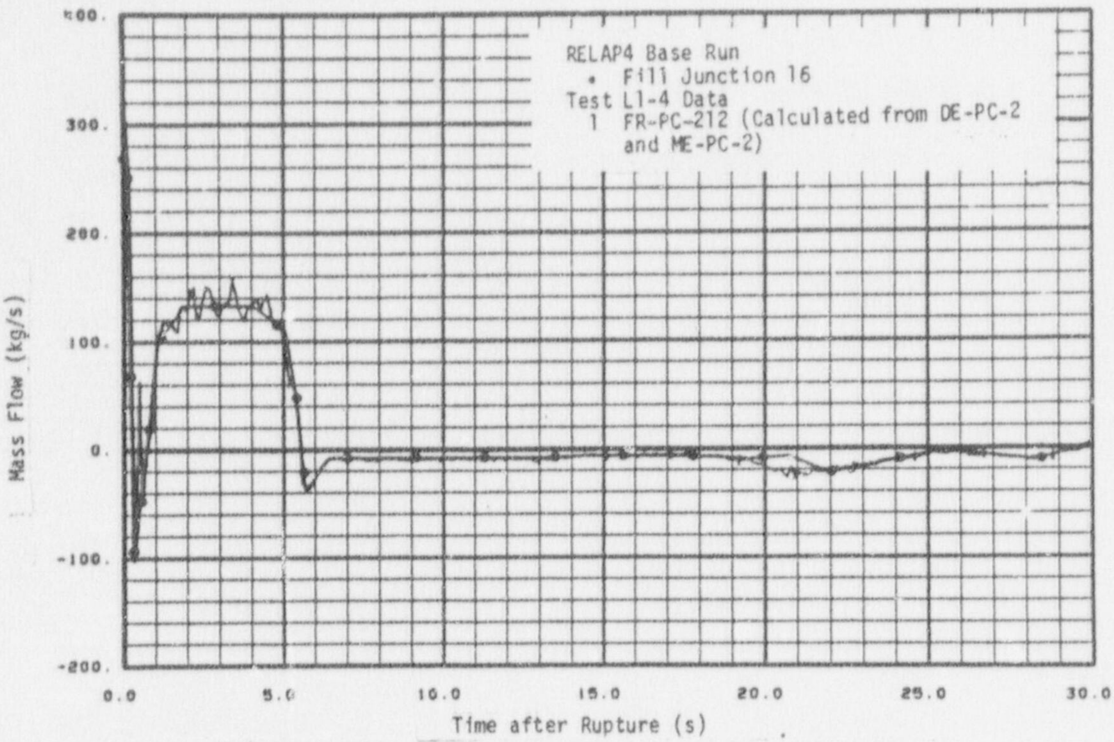


Fig. 17 Mass flow on core side - Test L1-4 boundary conditions.

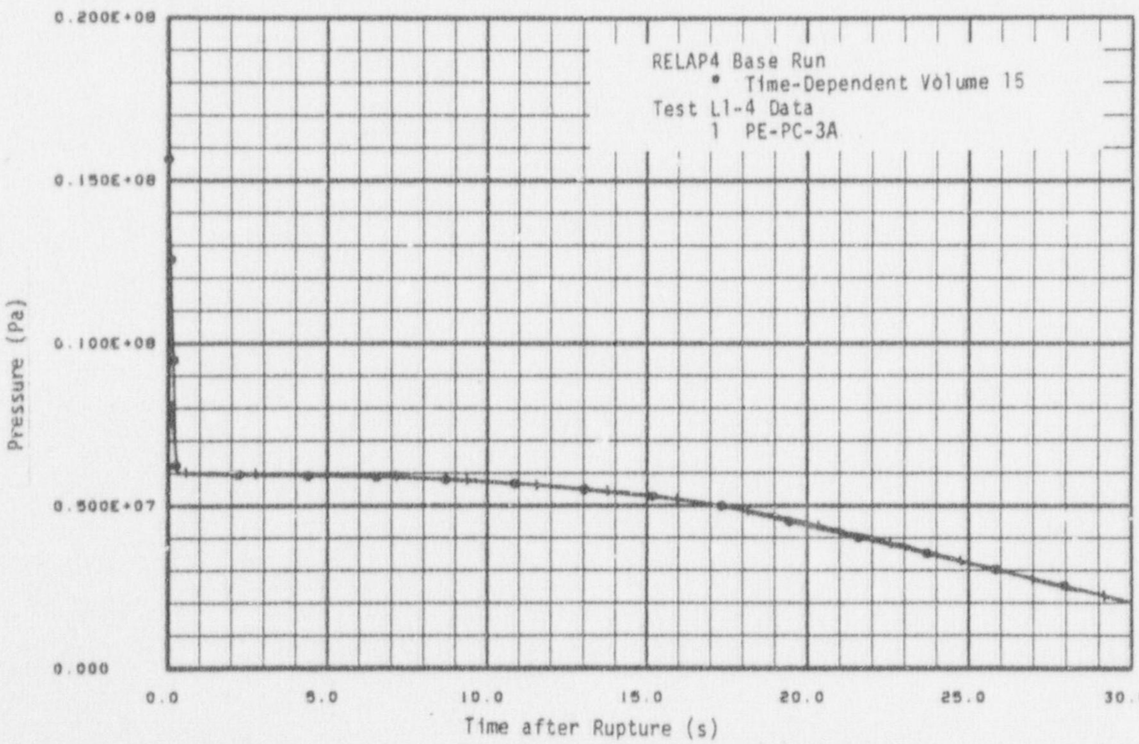


Fig. 18 Pressure on pump side - Test L1-4 boundary conditions.

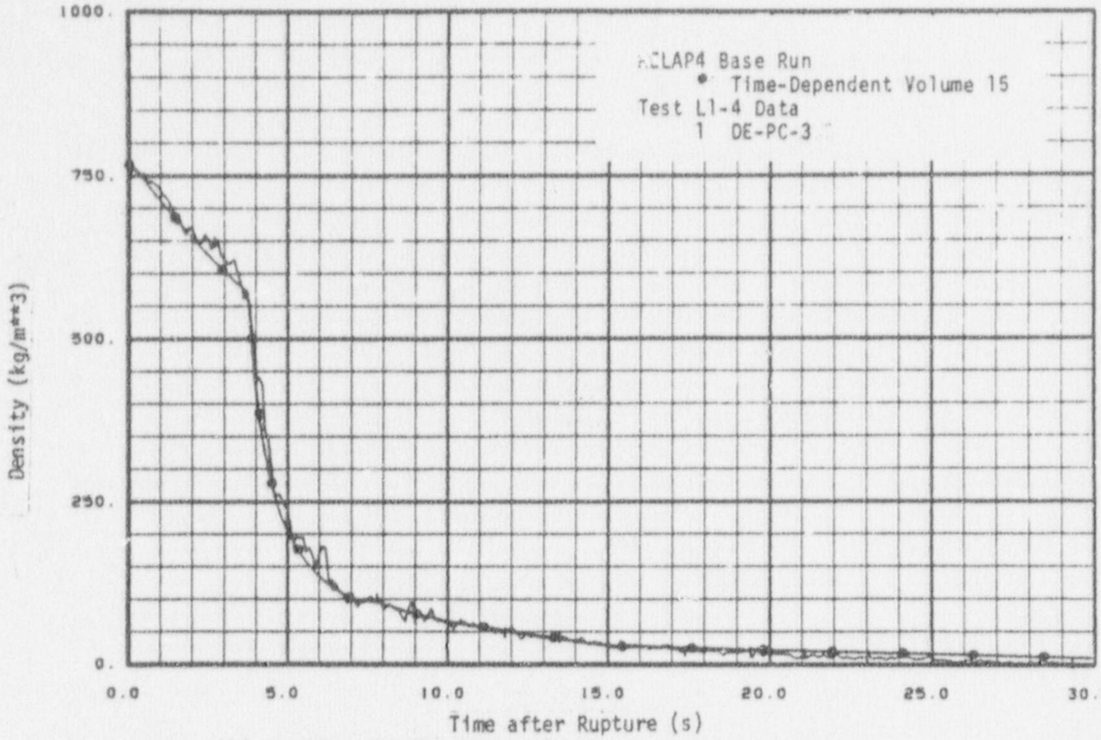


Fig. 19 Density on pump side - Test L1-4 boundary conditions.

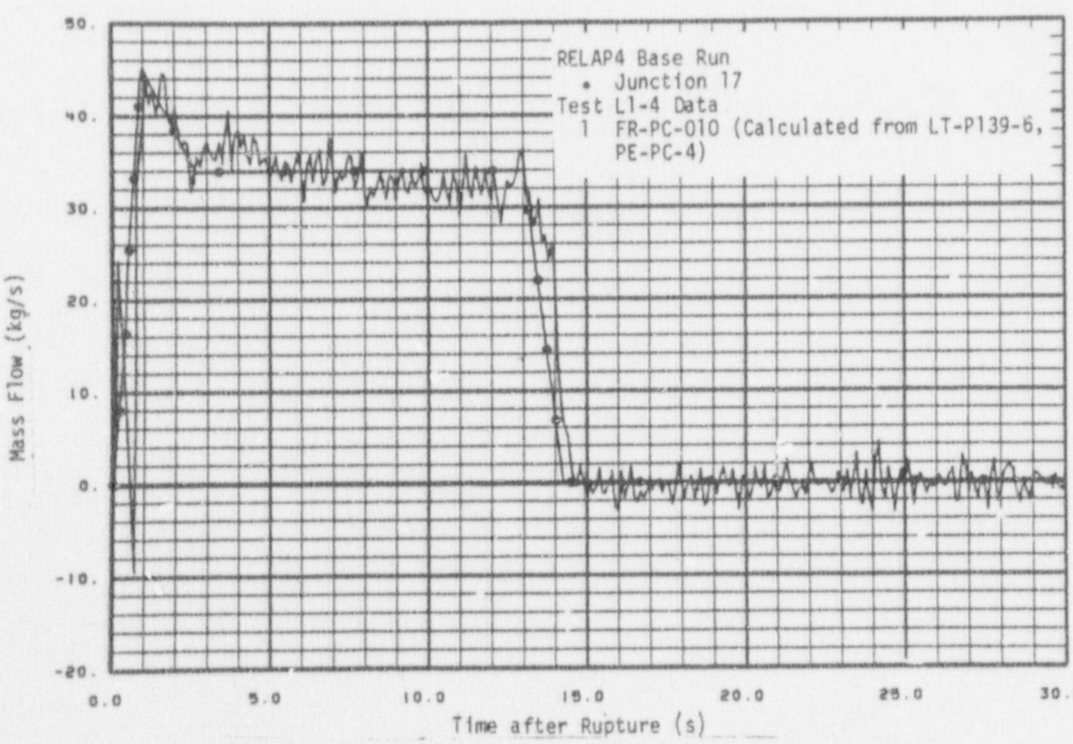


Fig. 20 Pressurizer mass flow - Test L1-4 boundary conditions.

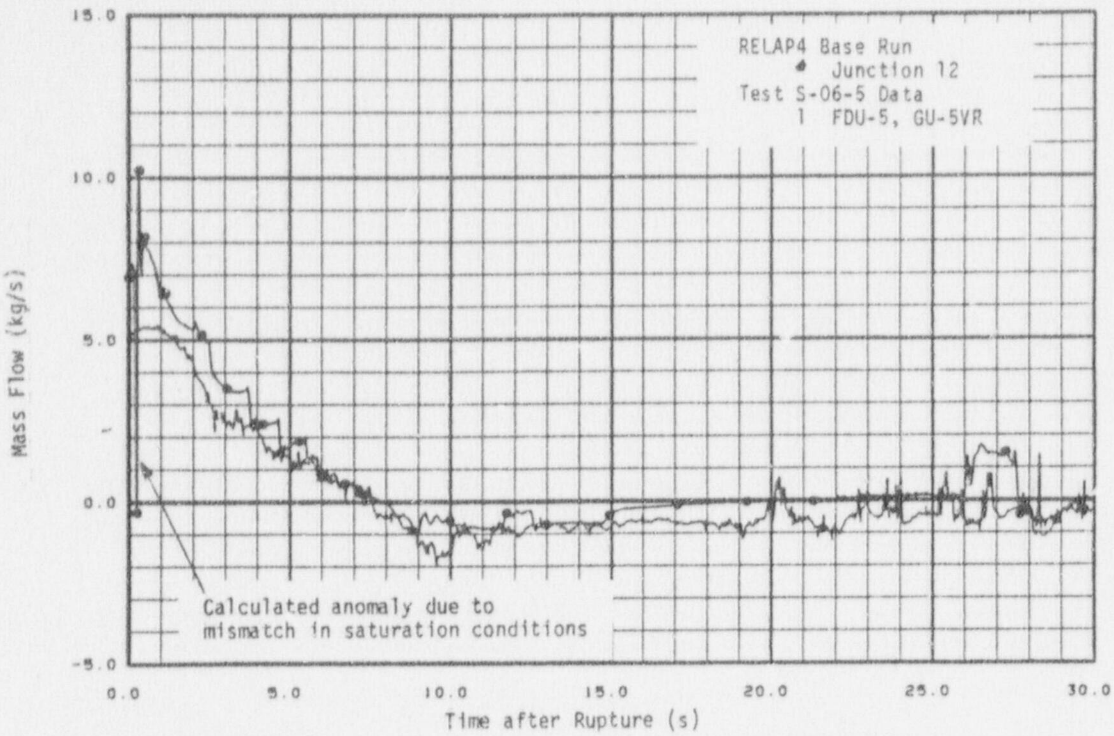


Fig. 21 Mass flow on pressurizer side - Test S-06-5 base run.

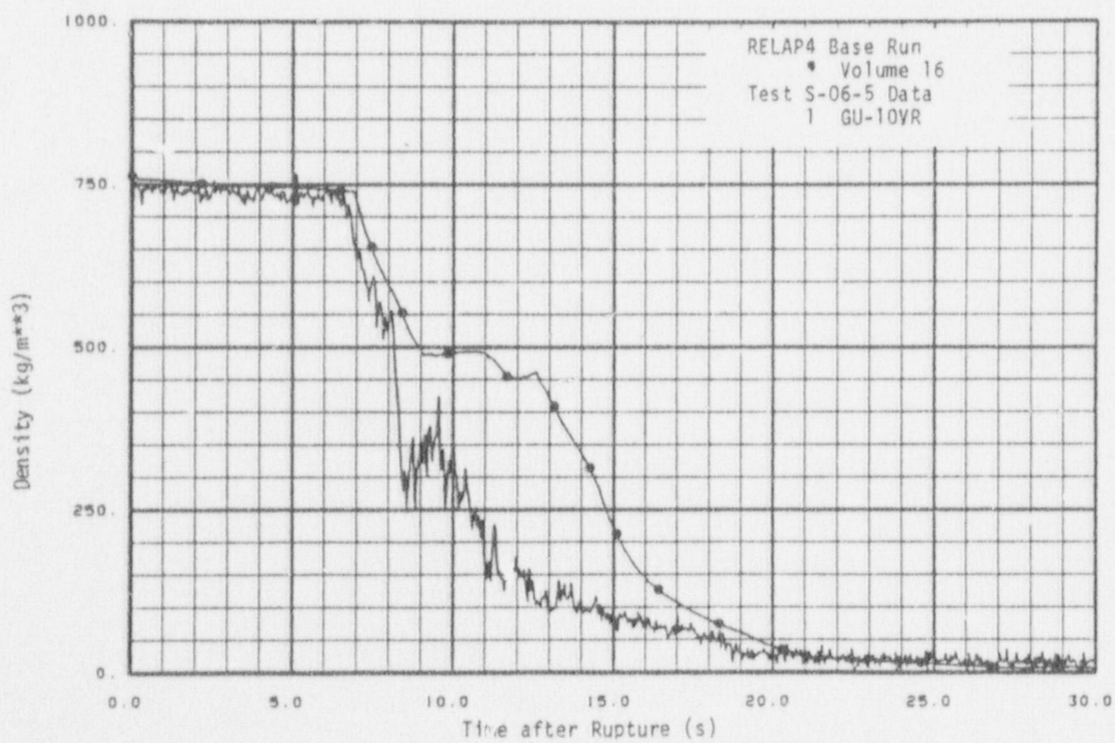


Fig. 22 Density on pump side - Test S-06-5 base run.

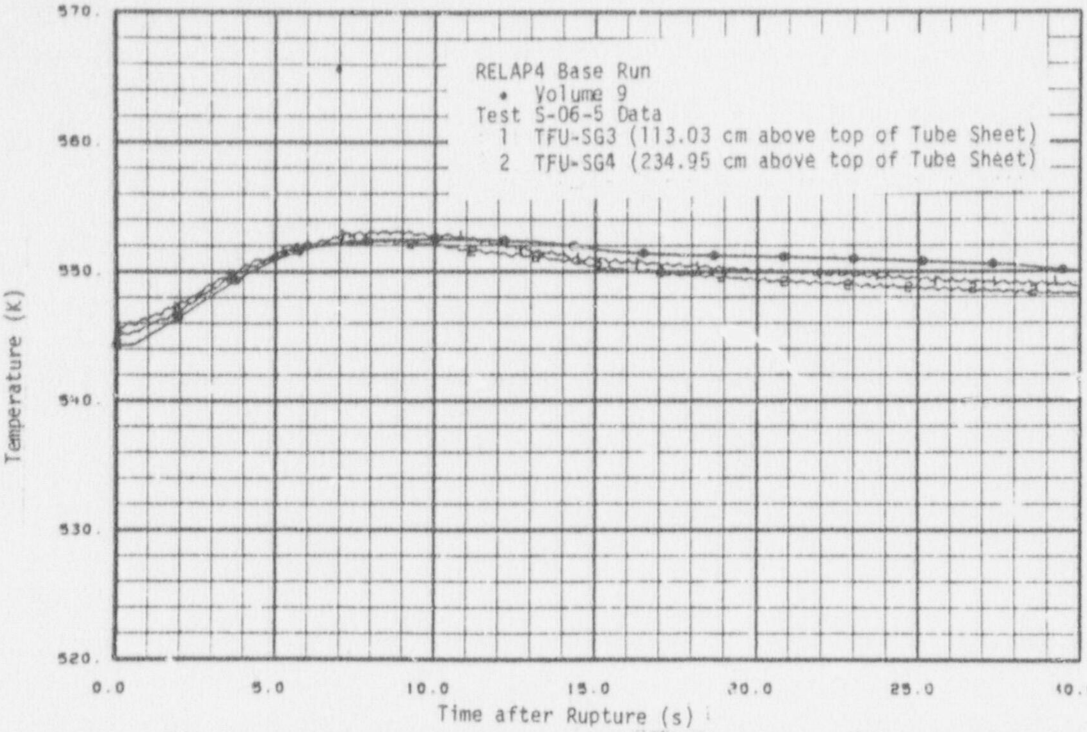


Fig. 23 Fluid temperature in steam generator secondary - Test S-06-5 base run.

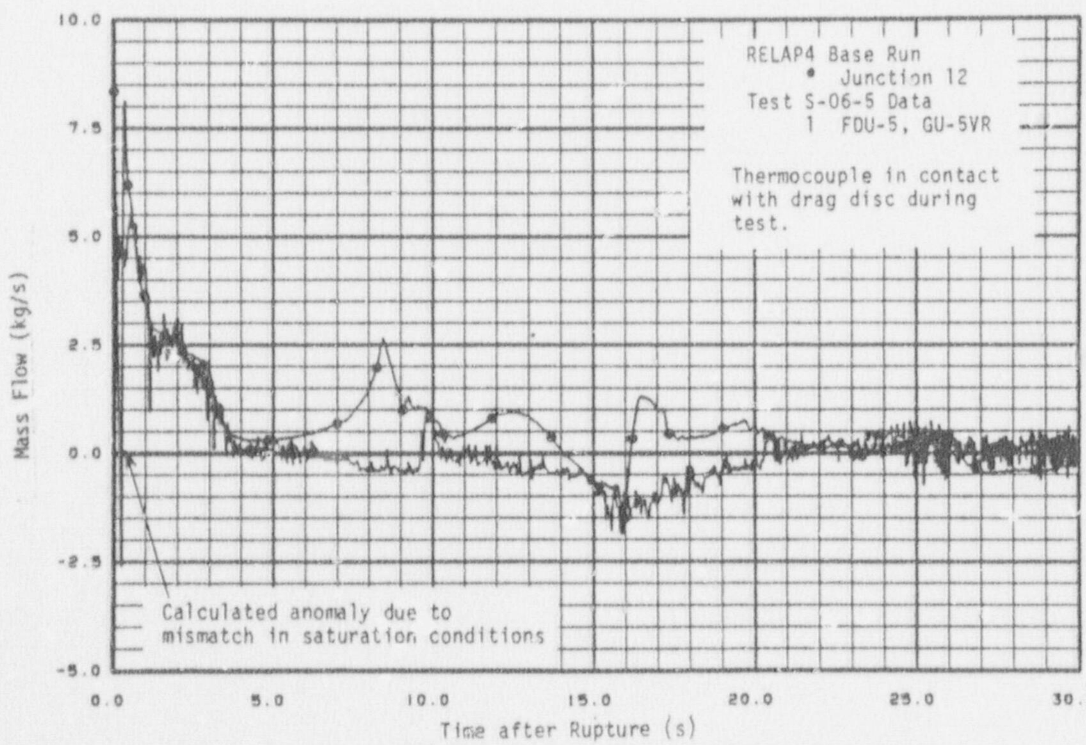


Fig. 24 Mass flow on pressurizer side - Test S-01-4A base run.

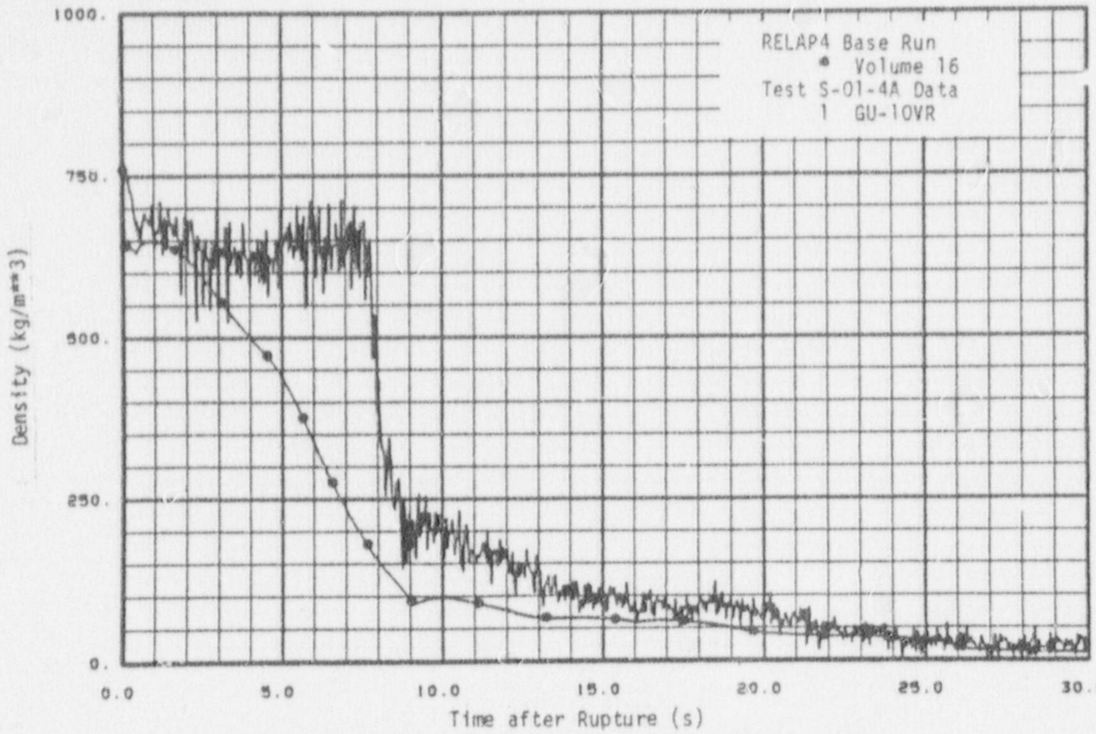


Fig. 25 Density on pump side - Test S-01-4A base run..

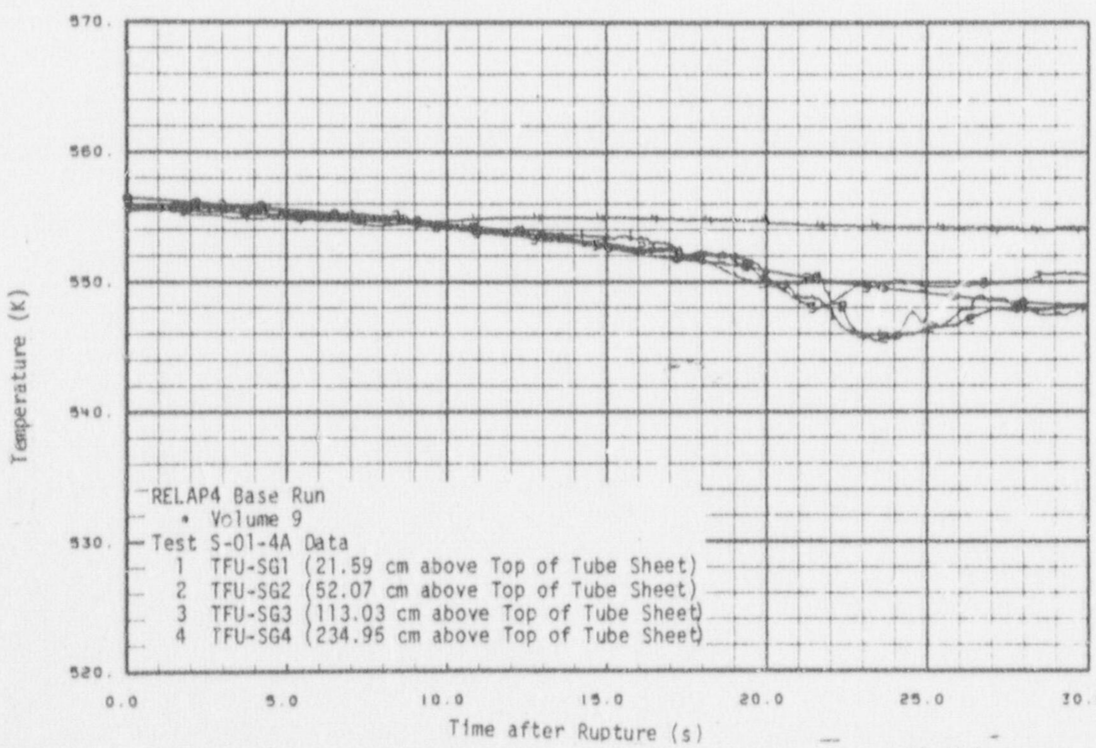


Fig. 26 Fluid temperature in steam generator secondary - Test S-01-4A base run.

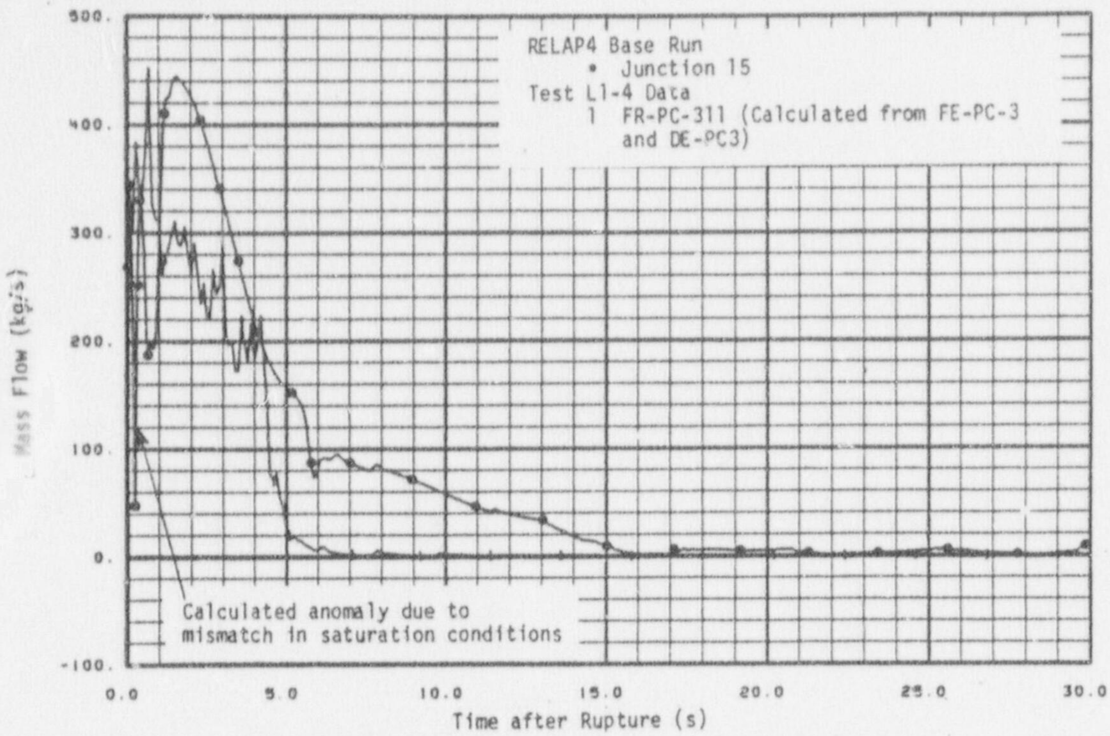


Fig. 27 Mass flow on pump side - Test L1-4 base run.

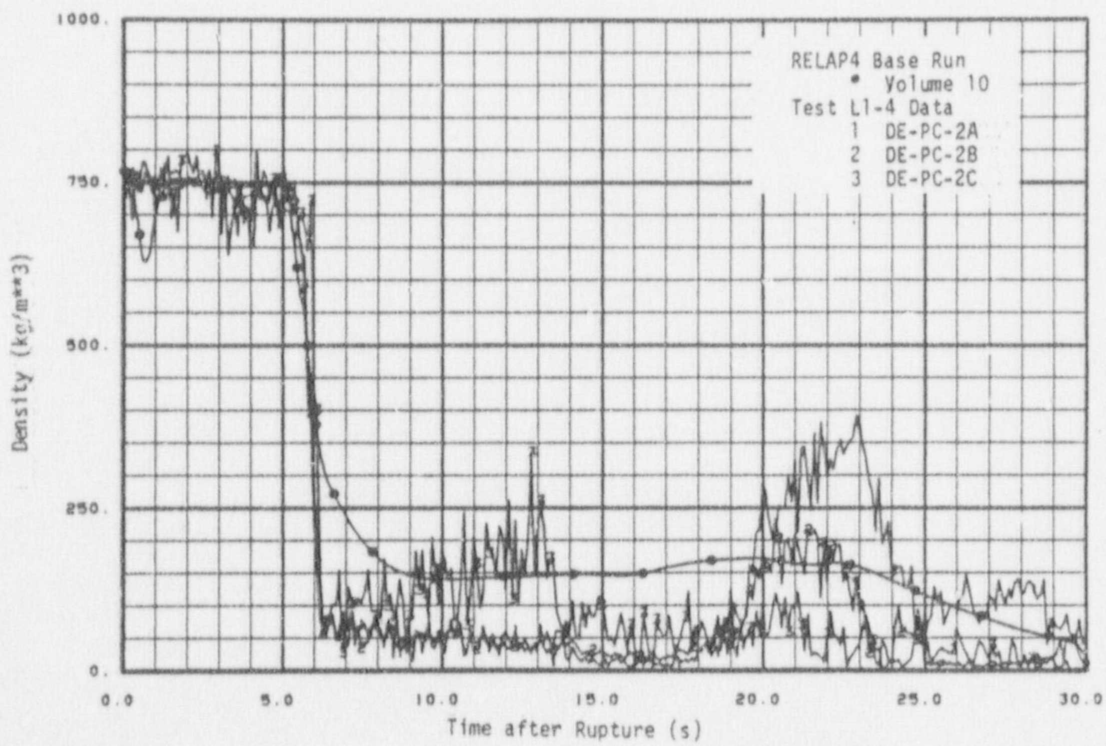


Fig. 28 Density on core side - Test L1-4 base run.

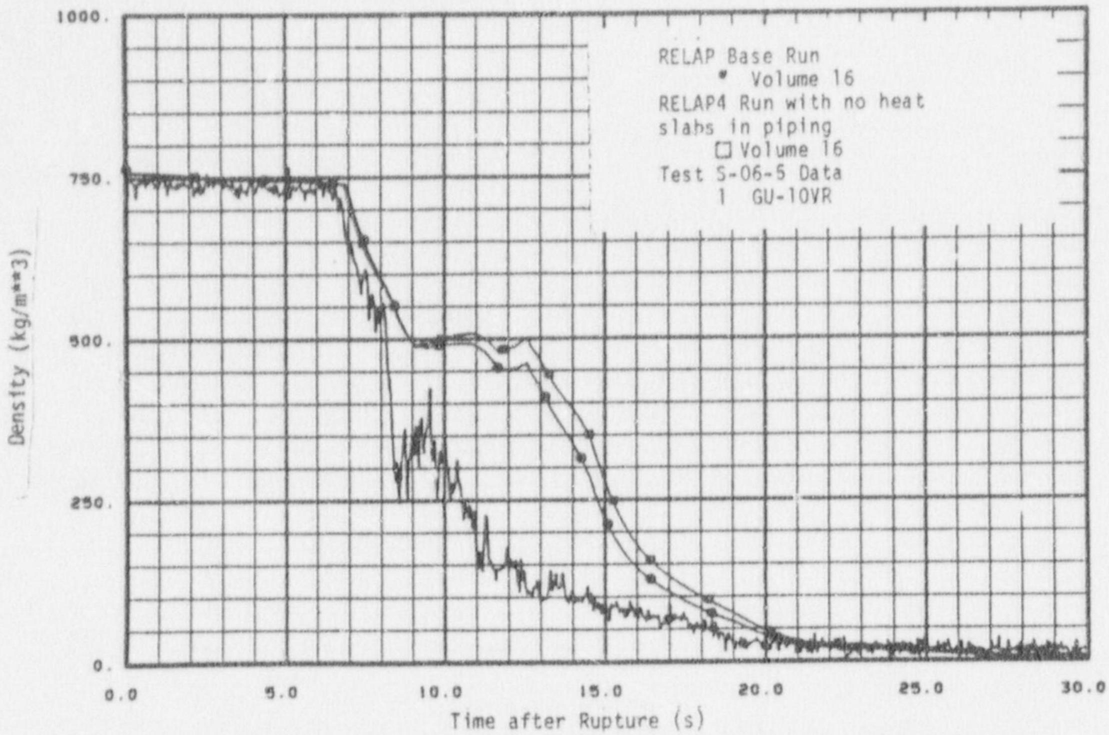


Fig. 29 Density on pump side - Test S-06-5 with no heat slabs in piping.

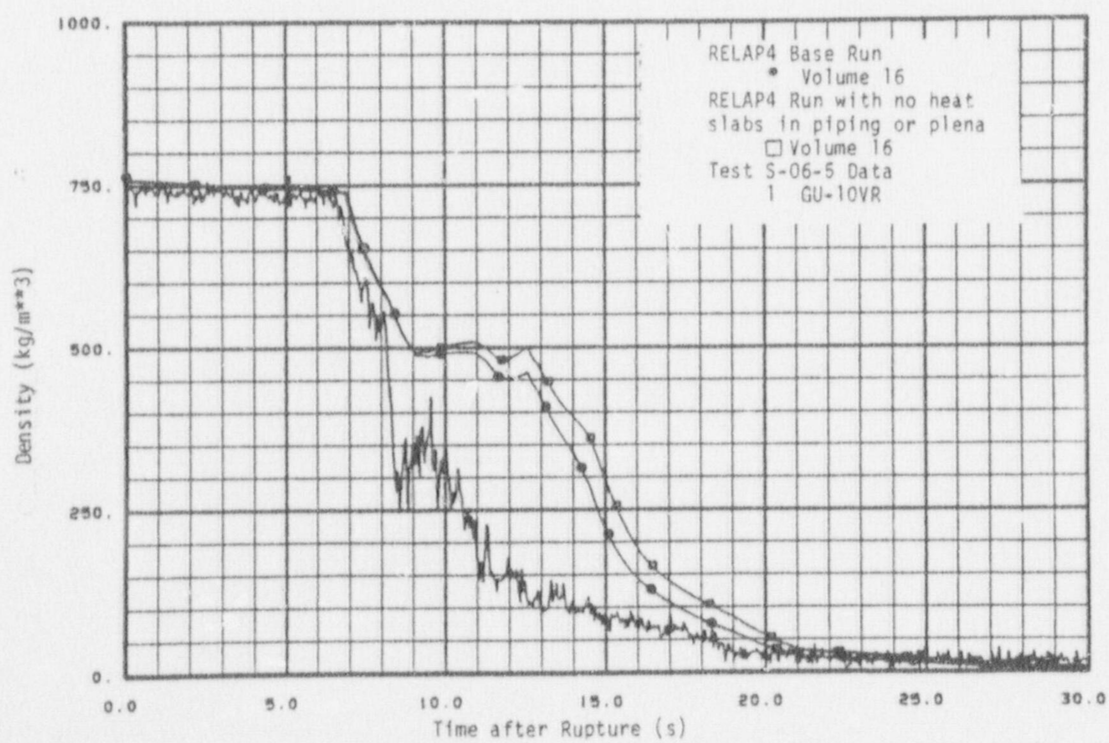


Fig. 30 Density on pump side - Test S-06-5 with no heat slabs in piping or plena.

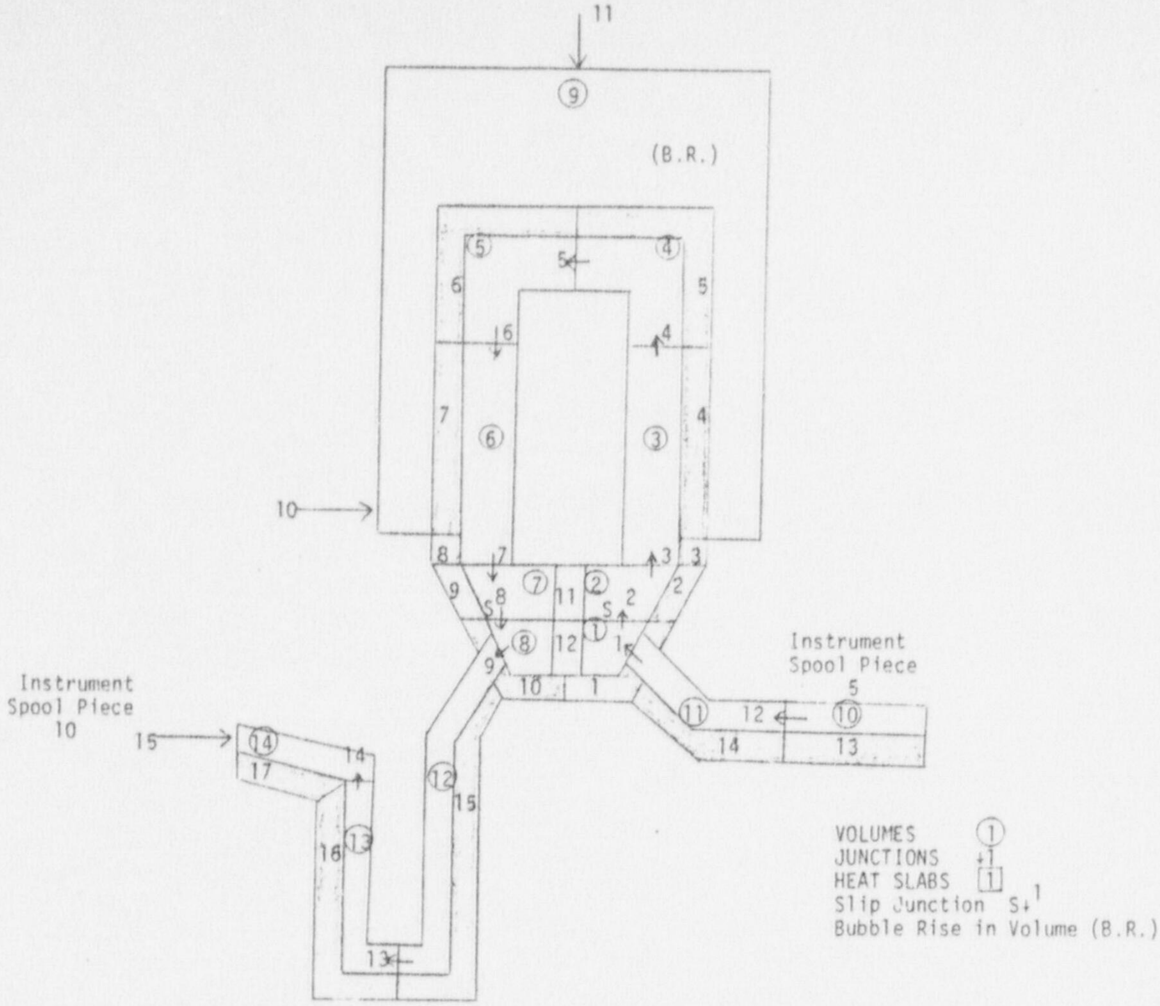


Fig. 31 Steam generator model with combined piping.

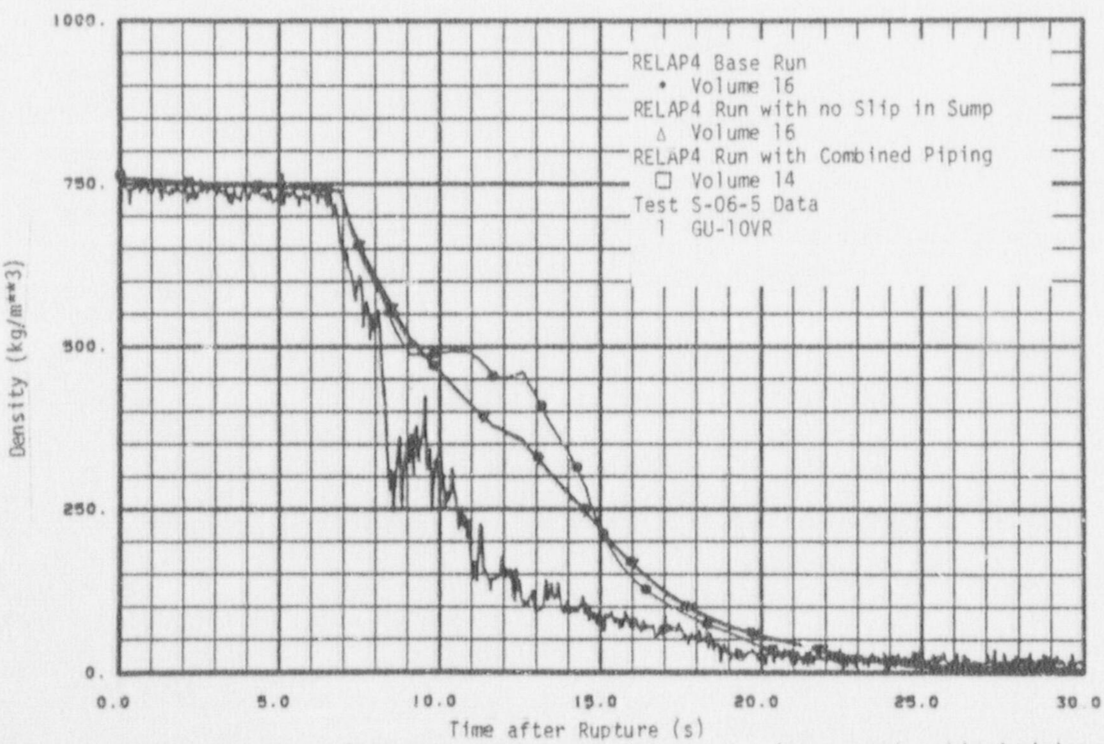


Fig. 32 Density on pump side - Test S-06-5 with no sl p in sump and combined piping.

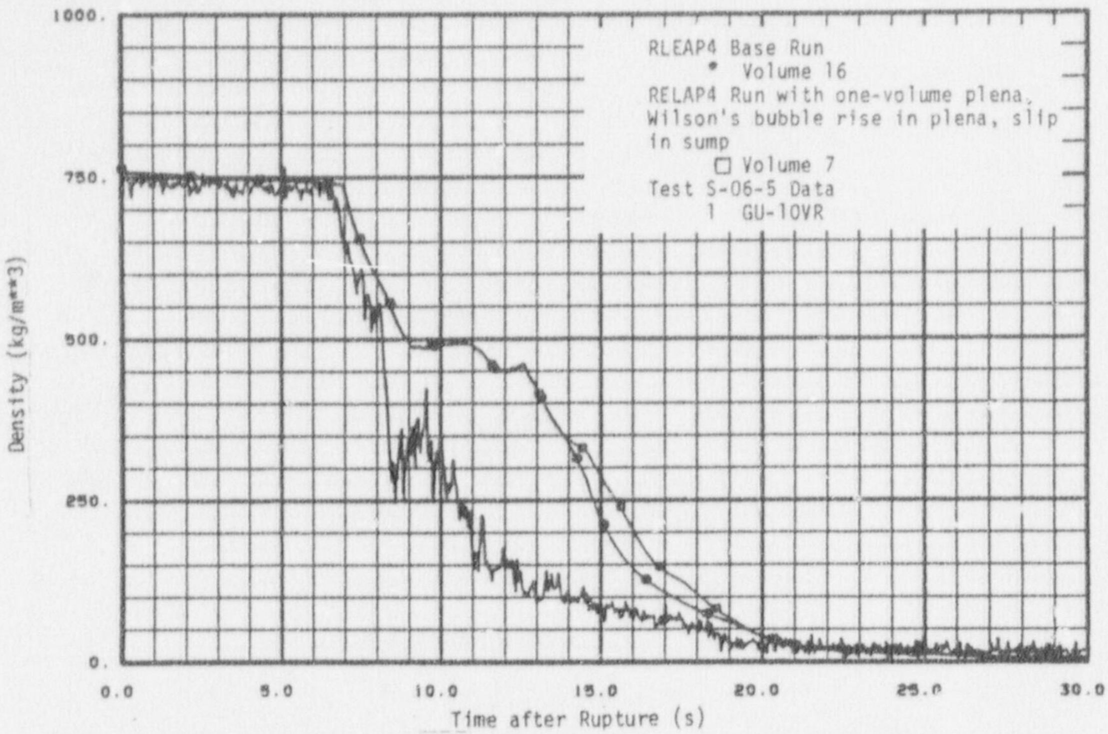


Fig. 33 Density on pump side - Test S-06-5 with one-volume plena, Wilson's bubble rise in plena, slip in sump.

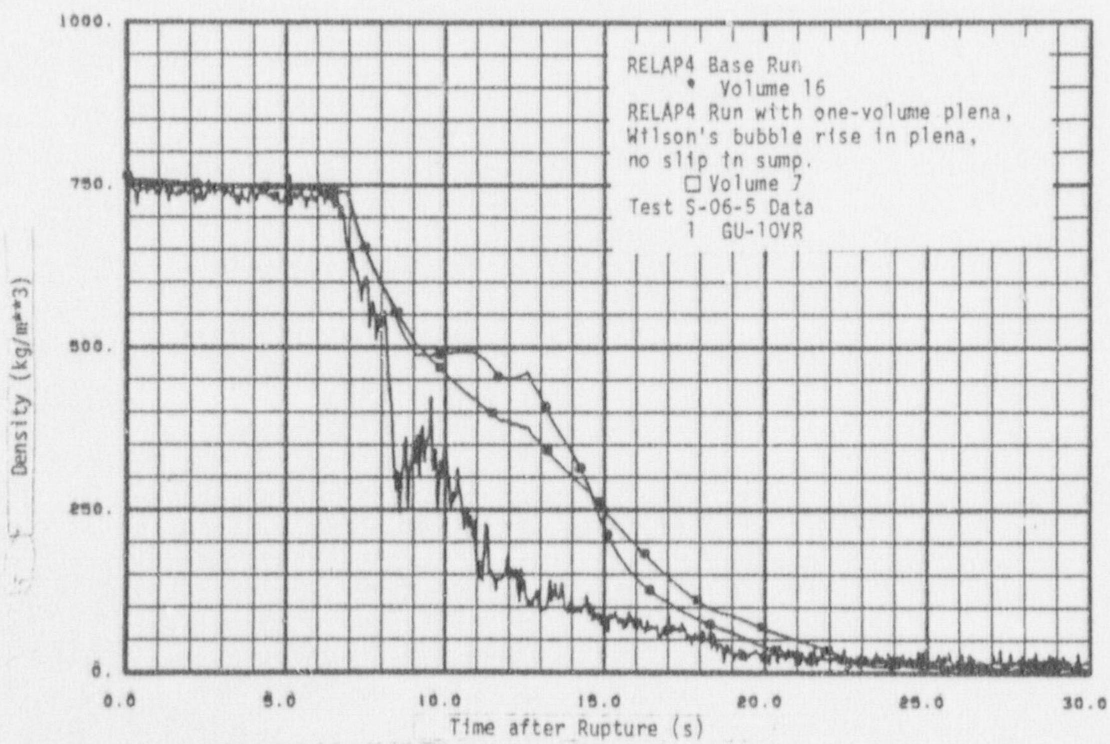


Fig. 34 Density on pump side - Test S-06-5 with one-volume plena, Wilson's bubble rise in plena, no slip in sump.

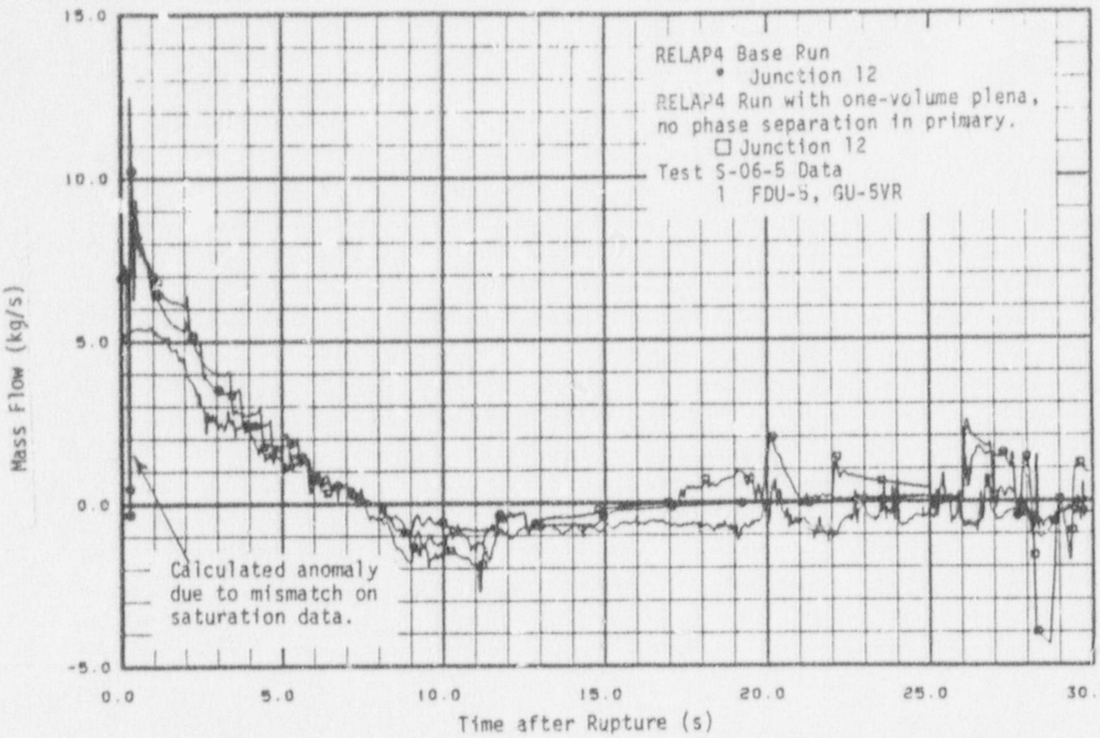


Fig. 35 Mass flow on pressurizer side - Test S-06-5 with one-volume plena, no phase separation in primary.

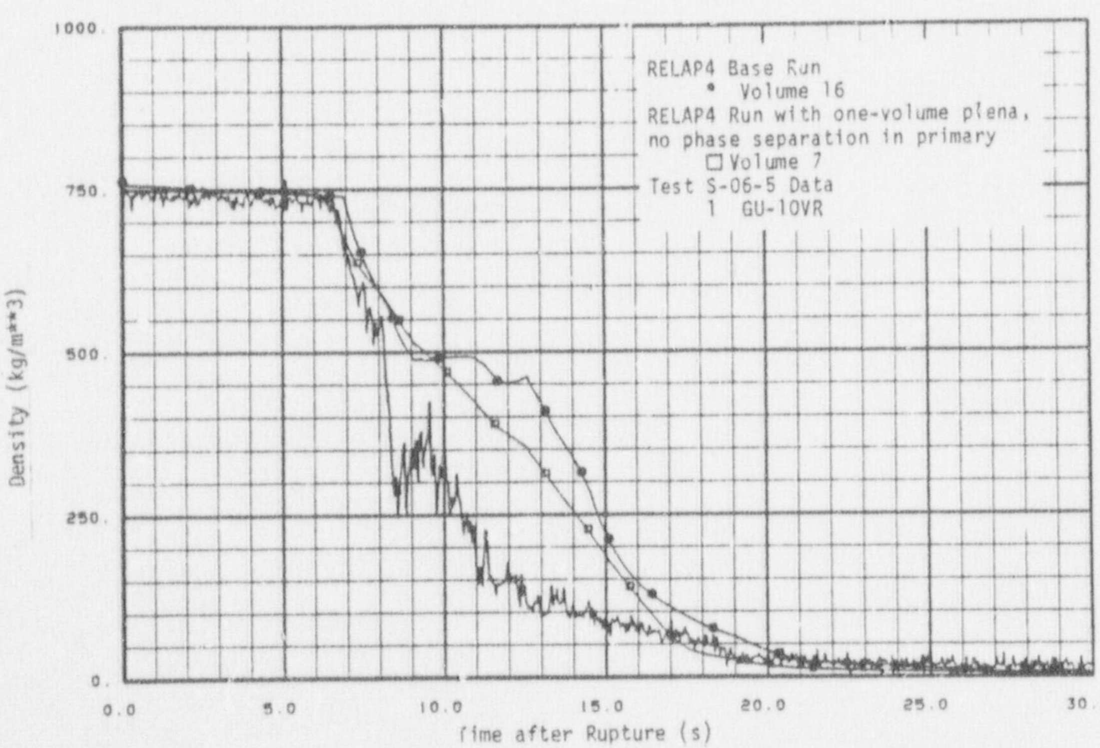


Fig. 36 Density on pump side - Test S-06-5 with one-volume plena, no phase separation in primary.

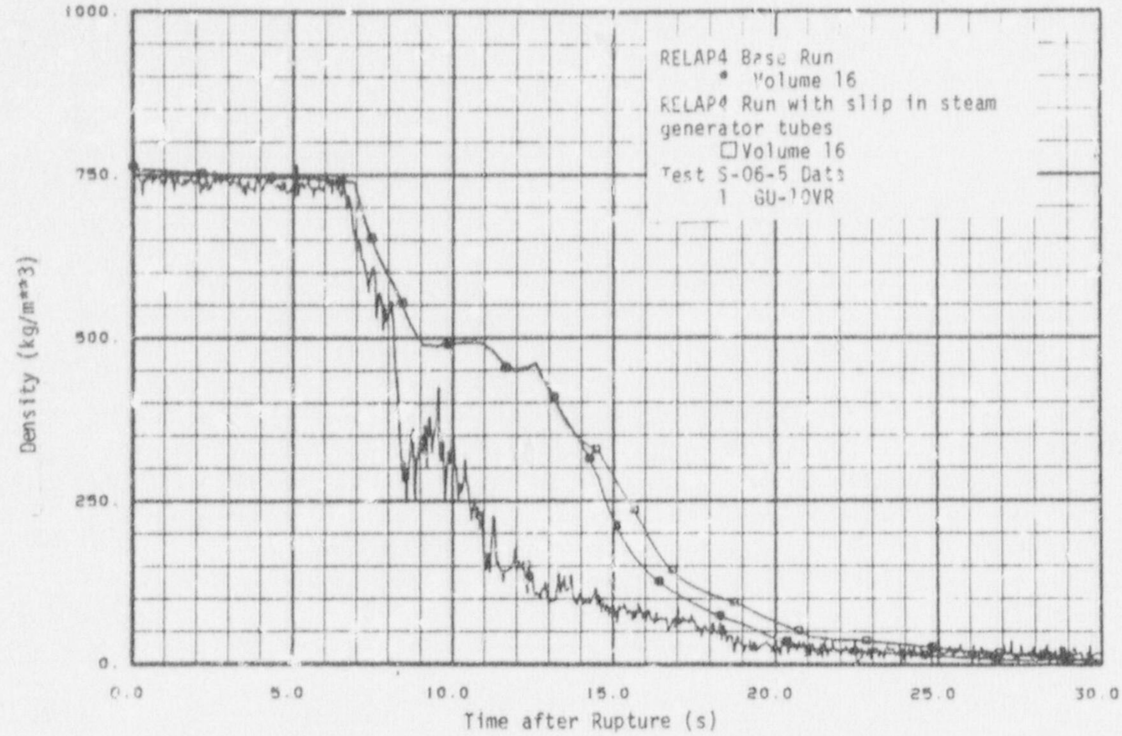


Fig. 37 Density on pump side - Test S-06-5 with slip in steam generator tubes.

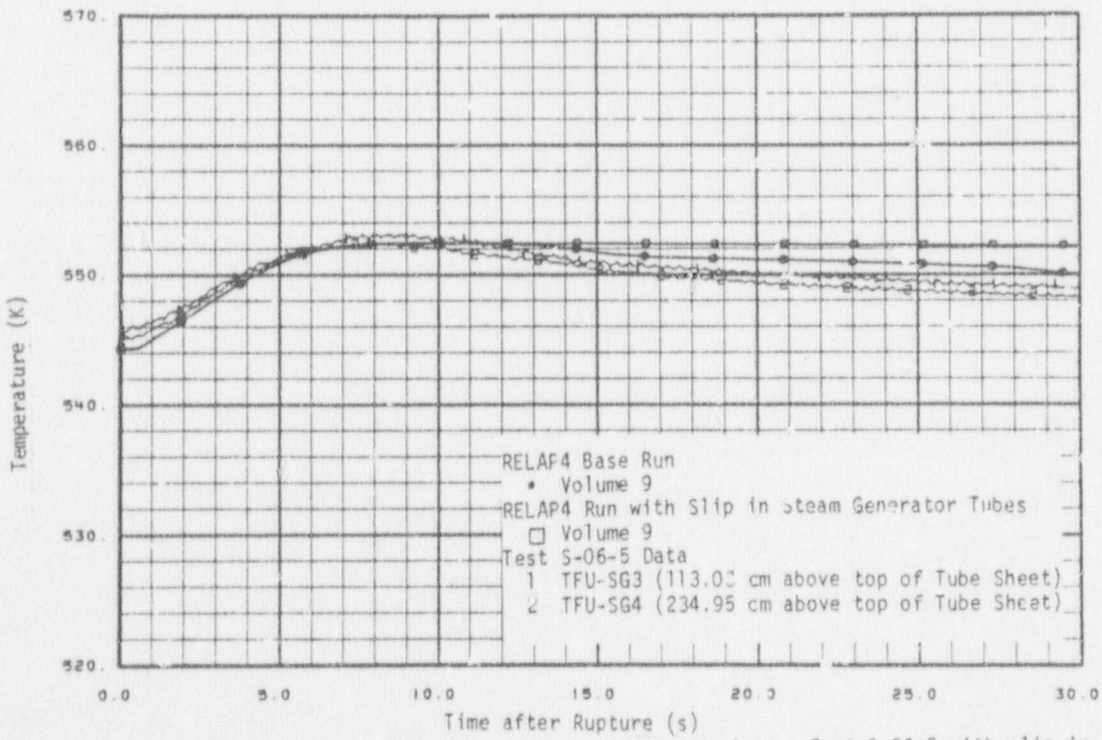


Fig. 38 Fluid temperature in steam generator secondary - Test S-06-5 with slip in steam generator tubes.

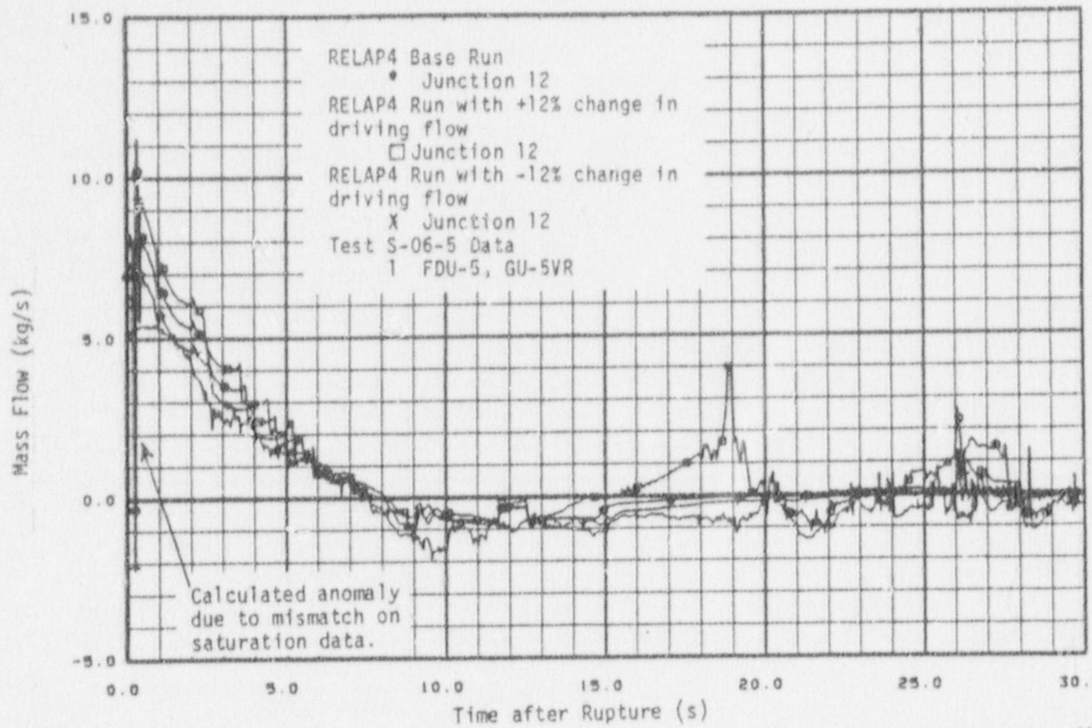


Fig. 39 Mass flow on pressurizer side - Test S-06-5 with ±12% change in driving flow.

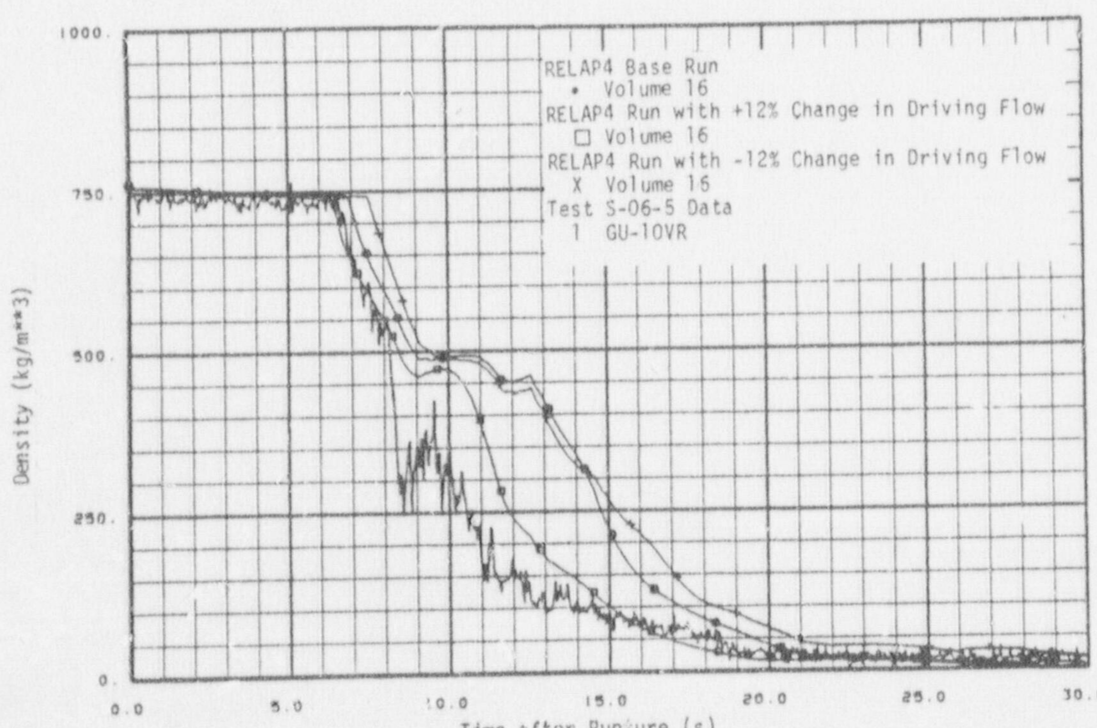


Fig. 40 Density on pump side - Test S-06-5 with ±12% change in driving flow.

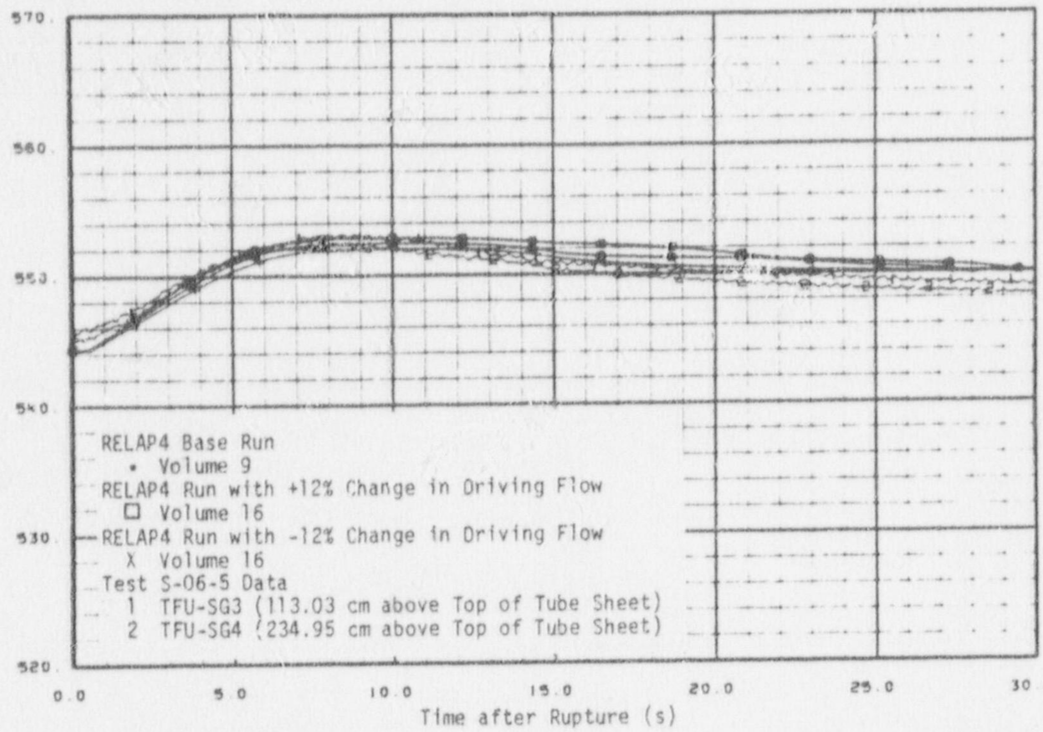


Fig. 41 Fluid temperature in steam generator secondary - Test S-06-5 with ±12% change in driving flow.

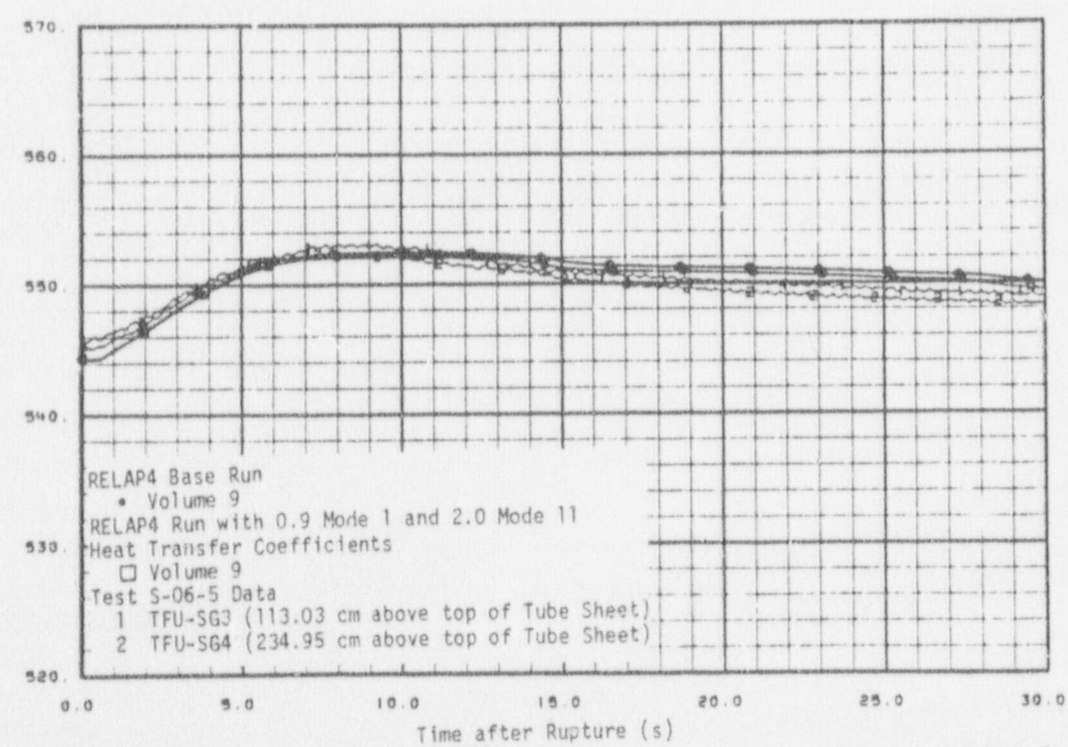


Fig. 42 Fluid temperature in steam generator secondary - Test S-06-5 with 0.9×Mode 1 and 2.0×Mode 11 heat transfer coefficients.

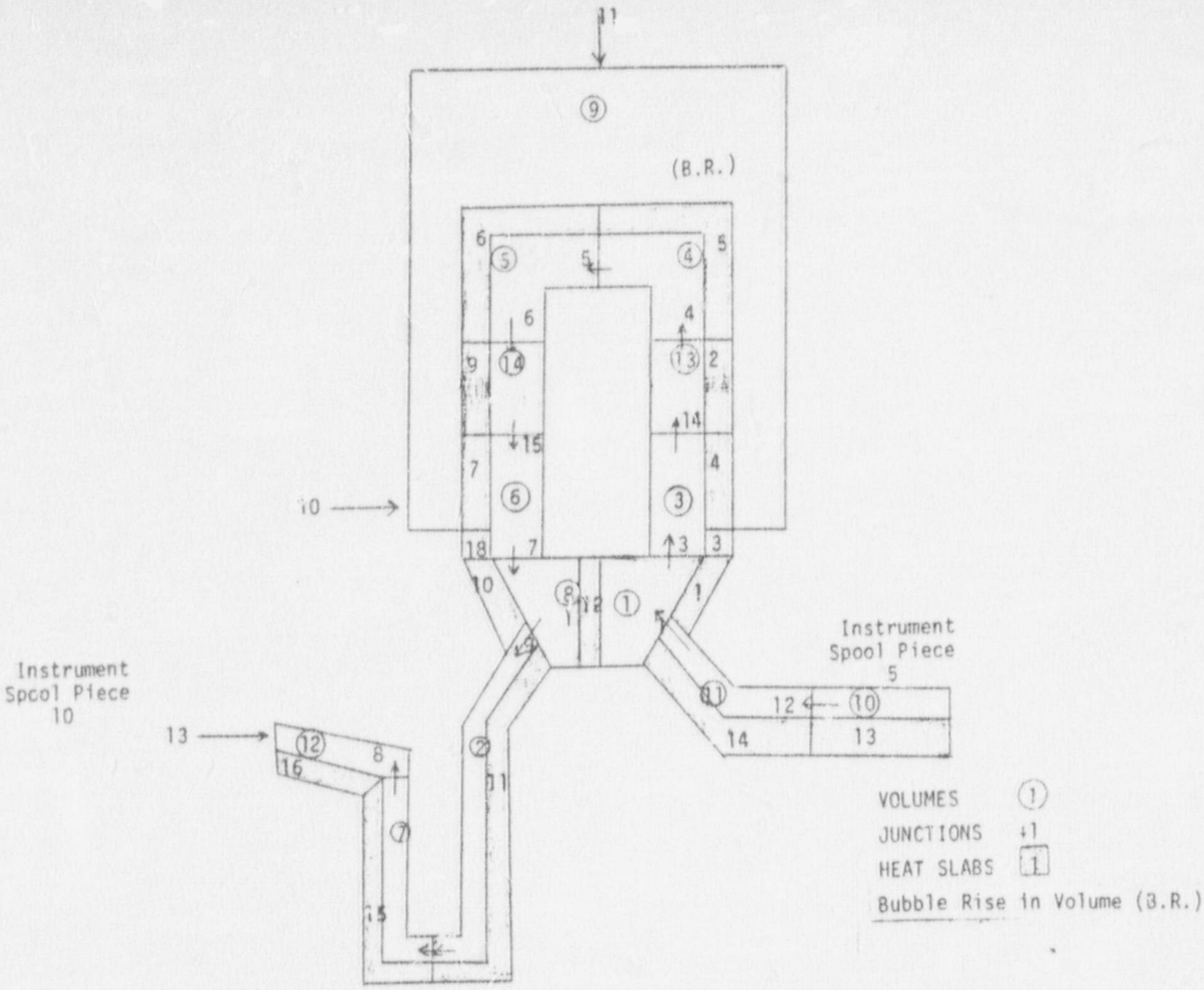


Fig. 43 Recommended component model of Semiscale steam generator for a heated blowdown.

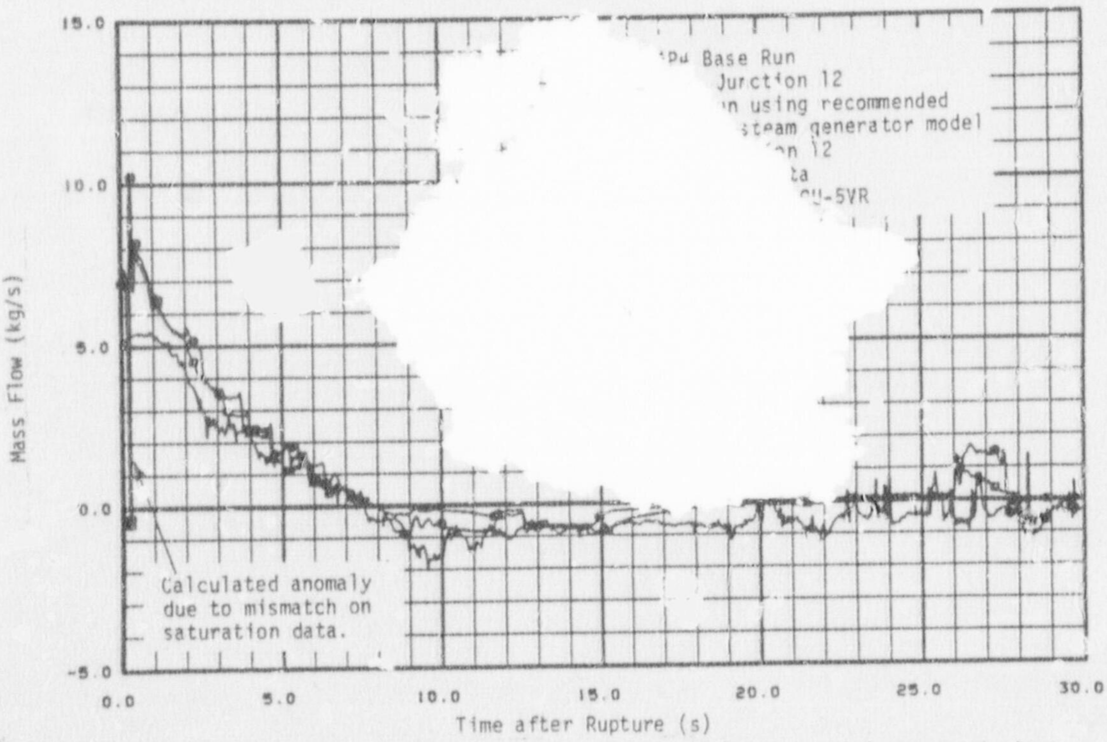


Fig. 44 Mass flow on pressurizer side - Test S-06-5 recommended component steam generator model.

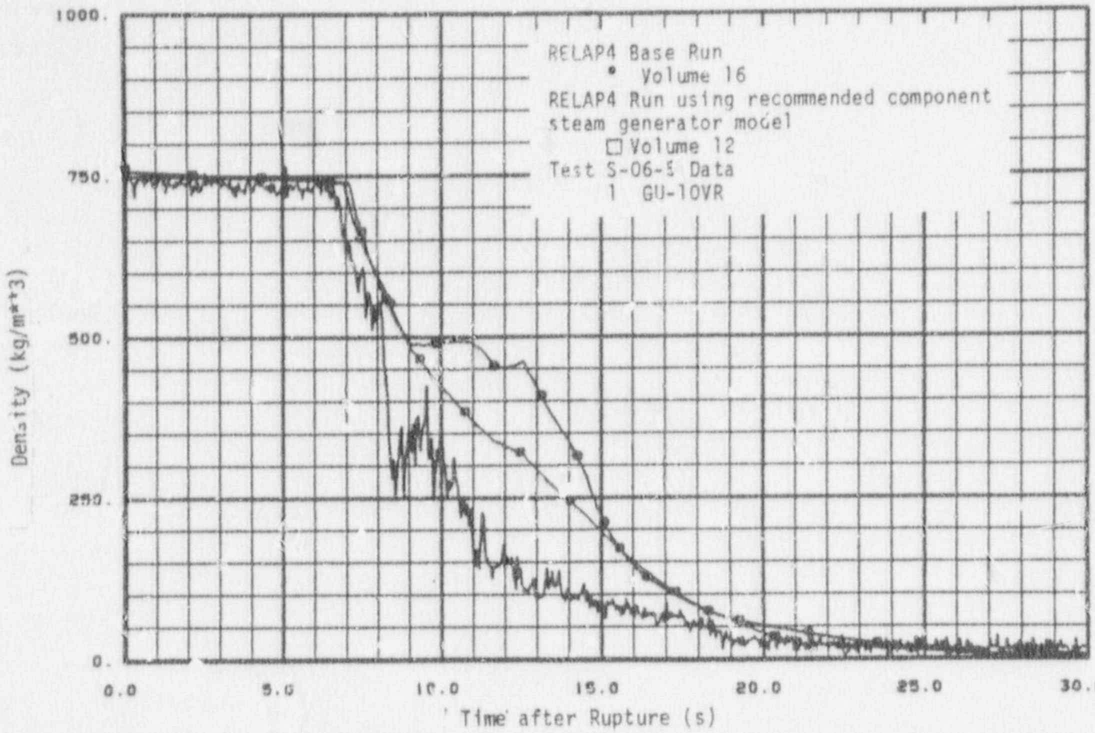


Fig. 45 Density on pump side - Test S-06-5 recommended component steam generator model.

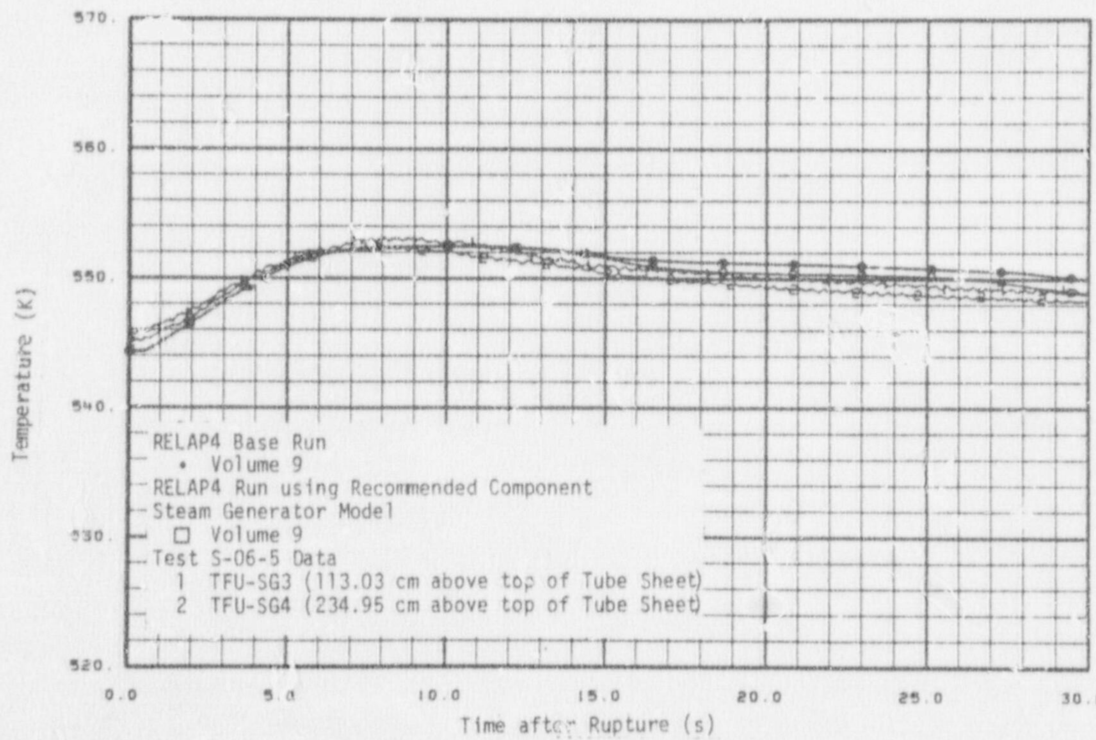


Fig. 46 Fluid temperature in steam generator secondary - Test S-06-5 recommended component steam generator model.

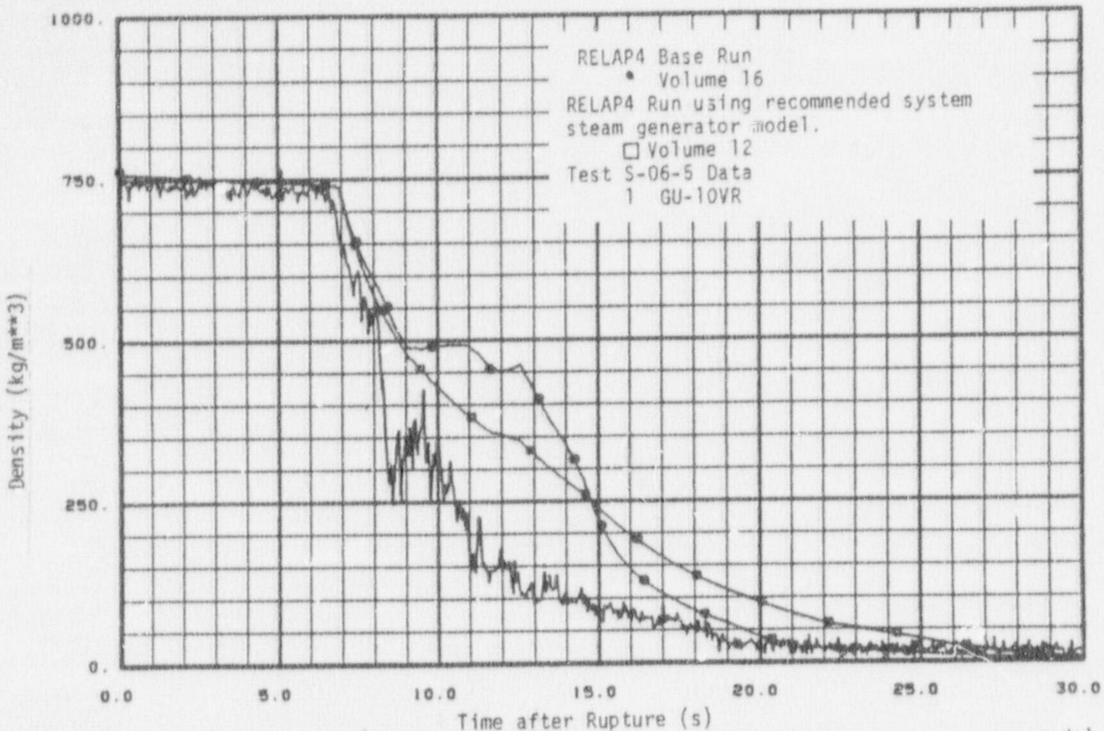


Fig. 47 Density on pump side - Test S-06-5 recommended system steam generator model.

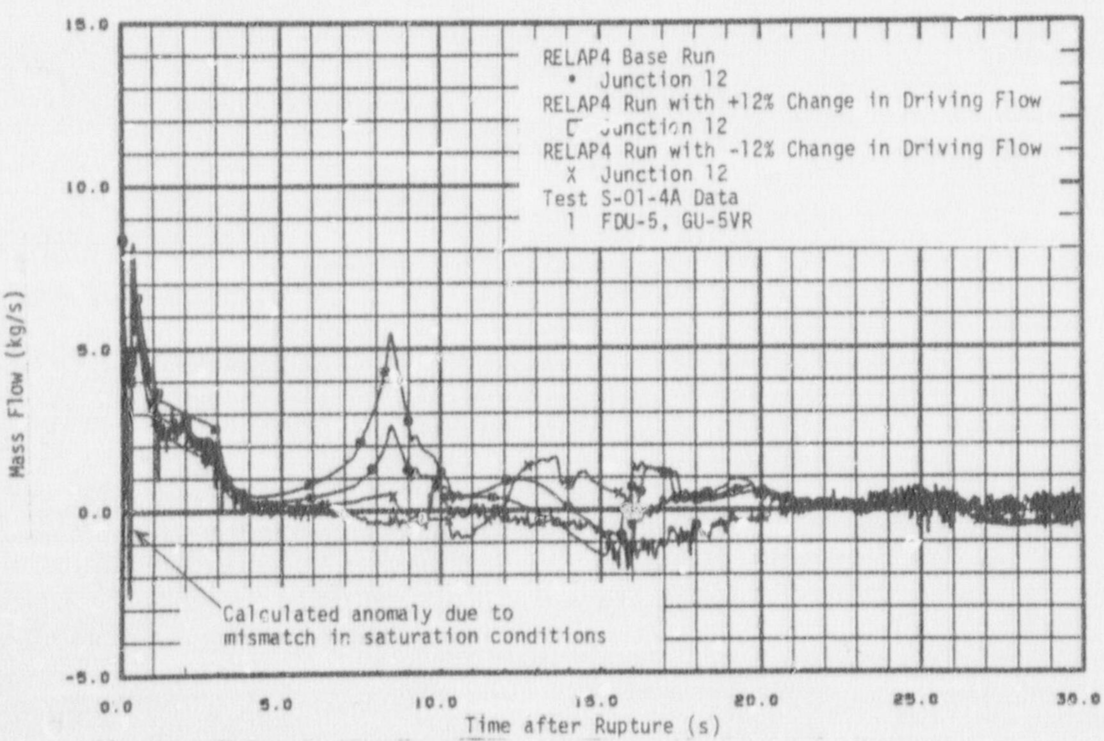


Fig. 48 Mass flow on pressurizer side - Test S-01-4A with ±12% change in driving flow.

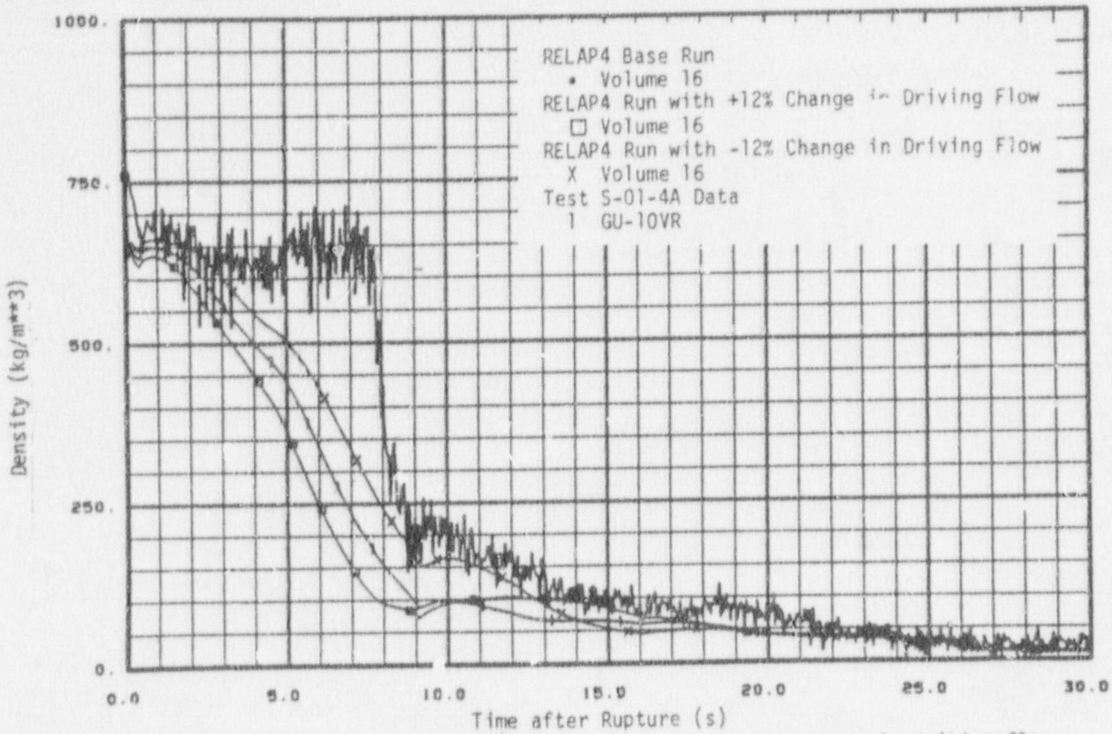


Fig. 49 Density on pump side - Test S-01-4A with ±12% change in driving flow.

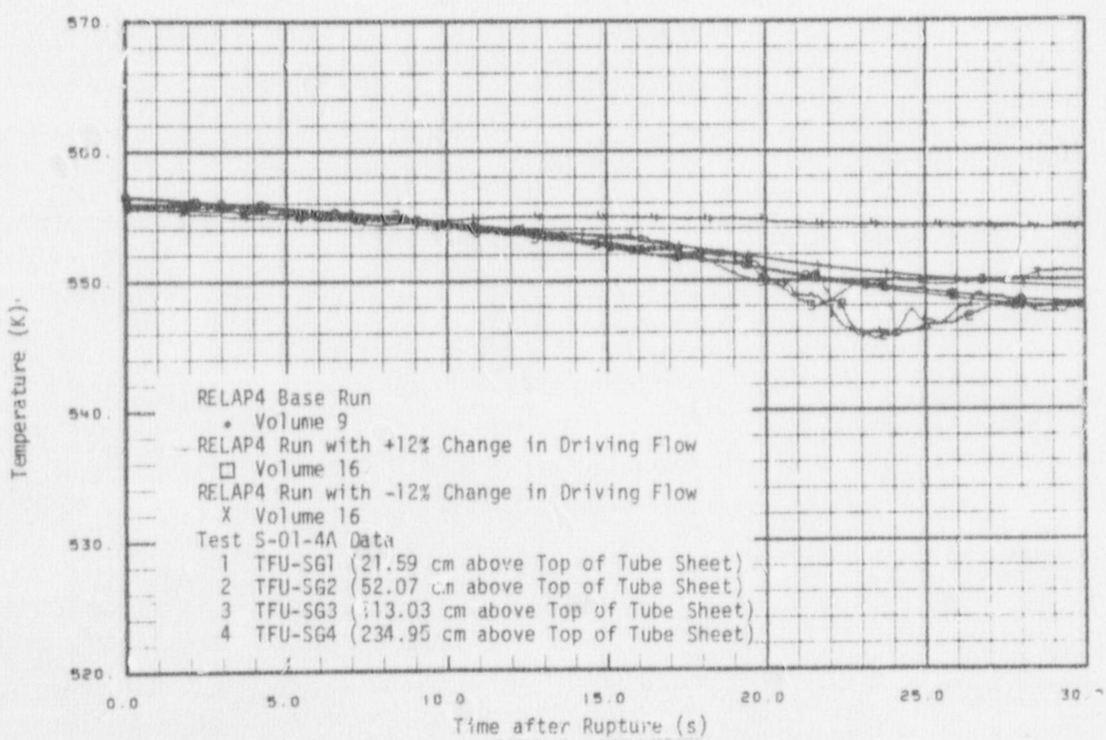


Fig. 50 Fluid temperature in steam generator secondary - Test S-01-4A with ±12% change driving flow.