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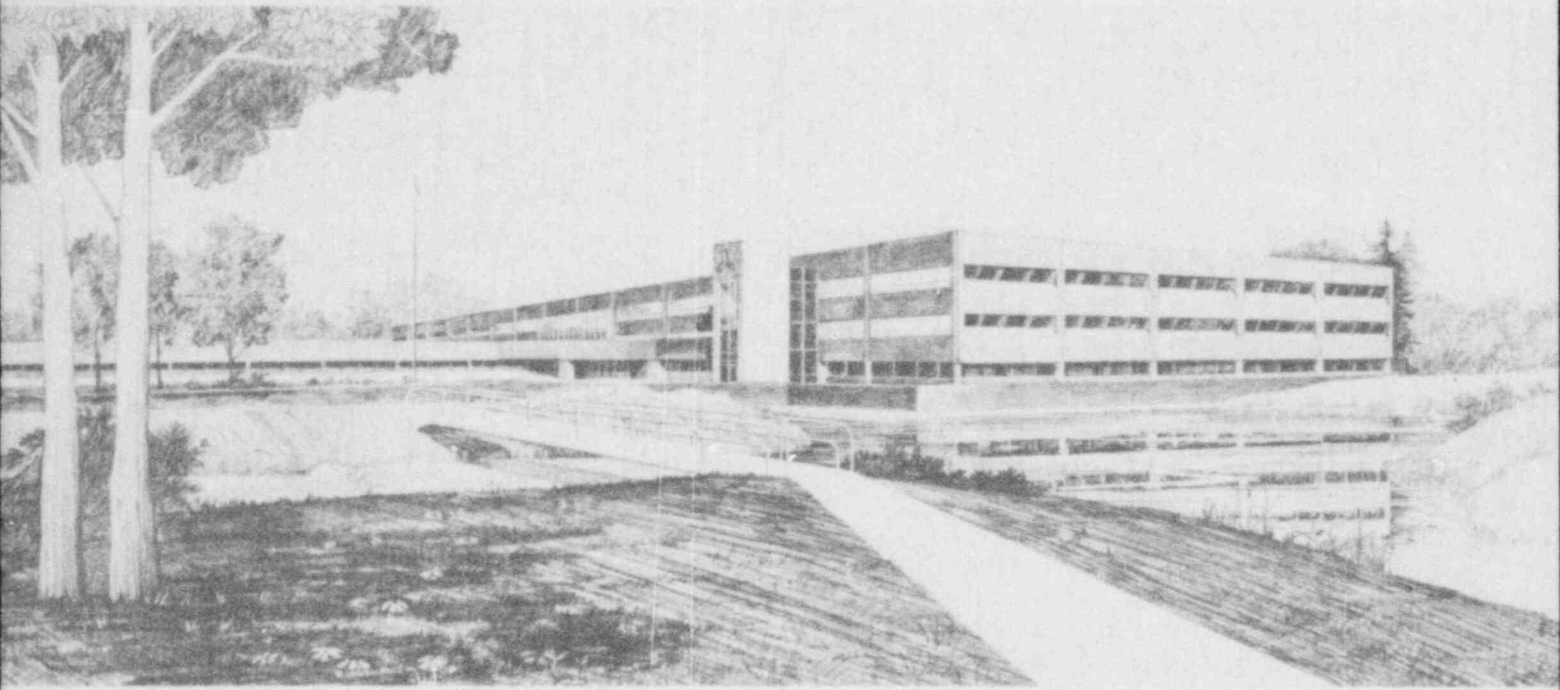

Idaho National Engineering Laboratory
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Determining Critical Flow Valve Characteristics Using Extrapolation Techniques

Donald B. Jarrell

January 1985

Prepared for the
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DETERMINING CRITICAL FLOW VALVE CHARACTERISTICS USING EXTRAPOLATION TECHNIQUES

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Idaho Falls, Idaho 83415

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FIN No. A6048

ABSTRACT

This report presents the methodology and documentation of the calibration of the Loss-of-Fluid Test (LOFT) power-operated relief and safety relief valve (PORV + SRV) for the L9-3 anticipated transient without scram (ATWS) experiment. A multiposition globe valve was calibrated to produce scaled high-pressure flow rates using a low-pressure calibration facility and a simple RELAP5 critical flow model to extrapolate the calibration data to expected operating pressures. It was demonstrated that an accurate high-pressure, multiphase flow calibration can be performed without the necessity of actual high-pressure testing. This technique, when applied to large pressurized water reactor (LPWR) safety and relief valves, represents a potentially large savings in the capacity qualification procedure of full-scale pressure reduction valves.

FIN No. A6048--LOFT Experimental Instrumentation

SUMMARY

The L9-3 anticipated transient without scram (ATWS) experiment simulated a complete loss of all feedwater in a commercial pressurized water reactor (PWR). The experiment was conducted in the Loss-of-Fluid Test (LOFT) experimental facility at the Idaho National Engineering Laboratory (INEL).

A major objective of this experiment was to achieve a maximum primary system pressure that was several measurement standard errors above the code safety relief valve (SRV) opening pressure setpoint, but below 110% of the setpoint pressure. A second objective was to determine the actual high-pressure, multiphase flow characteristics of the experimental pressurizer power-operated relief valve (PORV) and SRV.

In order to meet the first of these objectives, the experimental PORV had to be adjusted to provide LOFT a scaled flow modeling both the PORV and the combined capacity of the PORV and SRV of a generic Westinghouse large pressurized water reactor (LPWR).

A two-position globe valve was calibrated at the LOFT Test Support Facility (LTSF) under critical flow conditions for both saturated steam and subcooled liquid upstream conditions with inlet pressures ranging from 4 to 11 MPa (580 to 1600 psia). The effluent from the valve was condensed in a tank suspended on load cells to measure the resultant mass increase, which was subsequently processed to produce a mass flow rate. Since the LTSF is not capable of producing the pressure and temperature conditions expected to occur during the LOFT L9-3 ATWS, "target" mass flow as a function of upstream pressure was generated using the RELAP5 code to model the predicted critical flow requirements of the LOFT experiment in the attainable LTSF pressure range. The valve position was then adjusted such that the measured flow was within ±4% of the extrapolated target value at the mean calibration pressure.

Measurements of mass flow through the valve during the performance of the L9-3 ATWS indicated that the flow rate was 4.7% greater than predicted using the LTSF-corrected calibration data for the PORV position with steam inlet conditions. In the combined PORV + SRV position, the subcooled liquid flow was 2.2% below the projected calibration value.

The calibration and subsequent test demonstrated that (a) the RELAP5 code can be a useful tool in extrapolating a low pressure and temperature calibration to near critical point testing, and (b) the catch tank-load cell system, when suitably calibrated, can produce accurate (±5%) steady-state and low-frequency (<0.1 Hz) transient reference mass flow data.

ACKNOWLEDGMENTS

I would like to thank the crew of the LOFT Test Support Facility for their patience and diligence in the face of a very demanding test schedule; also, J. S. Martinell and W. A. Owca for test supervision and their assistance in the engineering analysis presented in this report.

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DETERMINING CRITICAL FLOW VALVE CHARACTERISTICS USING EXTRAPOLATION TECHNIQUES

INTRODUCTION

The United States Nuclear Regulatory Commission (USNRC) considered the risk associated with anticipated transient without scram (ATWS) events sufficient to justify their evaluation and sponsored the L9-3 (and L9-4) experiments in the Loss-of-Fluid Test (LOFT) facility for this purpose. LOFT is a volumetrically scaled pressurized-water reactor (PWR) designed to simulate the major components and system responses of large commercial PWRs during both loss-of-coolant accidents and anticipated transients.

A major objective of the L9-3 experiment was to attain a maximum primary system pressure that was several measurement standard errors above the computer code safety relief valve (SRV) opening pressure setpoint, but below 110% of the setpoint pressure, thereby challenging the SRV. The power-operated relief valve (PORV) and SRV flow characteristics could then be checked against the code-predicted behavior. To achieve these pressure and flow measurement goals in LOFT, it was necessary to produce an accurately scaled relief line flow. A critical flow valve characteristic determination was performed on the LOFT experiment PORV to allow positioning of the valve to the desired flow rate.

The PORV (shown in Figure 1) is a two-position, pneumatically actuated globe valve with a linear trim package to facilitate flow rate adjustment. The stem position relative to the valve body can be adjusted for either of the open positions with a resulting change in effective flow area. The intent of the calibration documented herein was to adjust the effective flow areas of the two valve positions such that: (a) the smaller of the two areas gave a scaled flow representative of a large PWR PORV; and (b) the larger of the two areas gave a scaled flow representative of the combined effective flow areas of a large PWR PORV and SRV.

The scaled flow rate required to simulate each of these positions was derived from predictive calculations using the RELAP5 computer code. The valve calibration specifications[1] were given as follows:

1. PORV position—the valve was to pass 0.66 kg/s (5250 lbm/h) of saturated steam at 16.2 MPa (2350 psia),

2. PORV and SRV position (PORV + SRV)—the specification was given in terms of an effective RELAP5 flow area of 4.718×10^{-5} m^2 (5.08×10^{-4} ft^2); this was evaluated to be 1.53 kg/s (12,118 lbm/h) of saturated steam at 17.2 MPa (2500 psia).

An additional test requirement was to determine the subcooled liquid flow rate through the valve in its PORV + SRV position with 5 to 40 K (9 to 72°F) of subcooling.

The calibration approach described in the next section details the method used to obtain a calibration "target" and the measurement techniques used to obtain the data. The section on valve calibration performance describes the valve calibration in the test facility. The performance of the test valve during the L9-3 Loss-of-Coolant Experiment is described in the fourth section. An analysis of the differential between the desired and the actual behavior is given in the section on calibration error investigation, followed by a section giving the conclusions which may be drawn from the calibration and subsequent experiment. Appendix A gives details of the calibration facility and techniques.

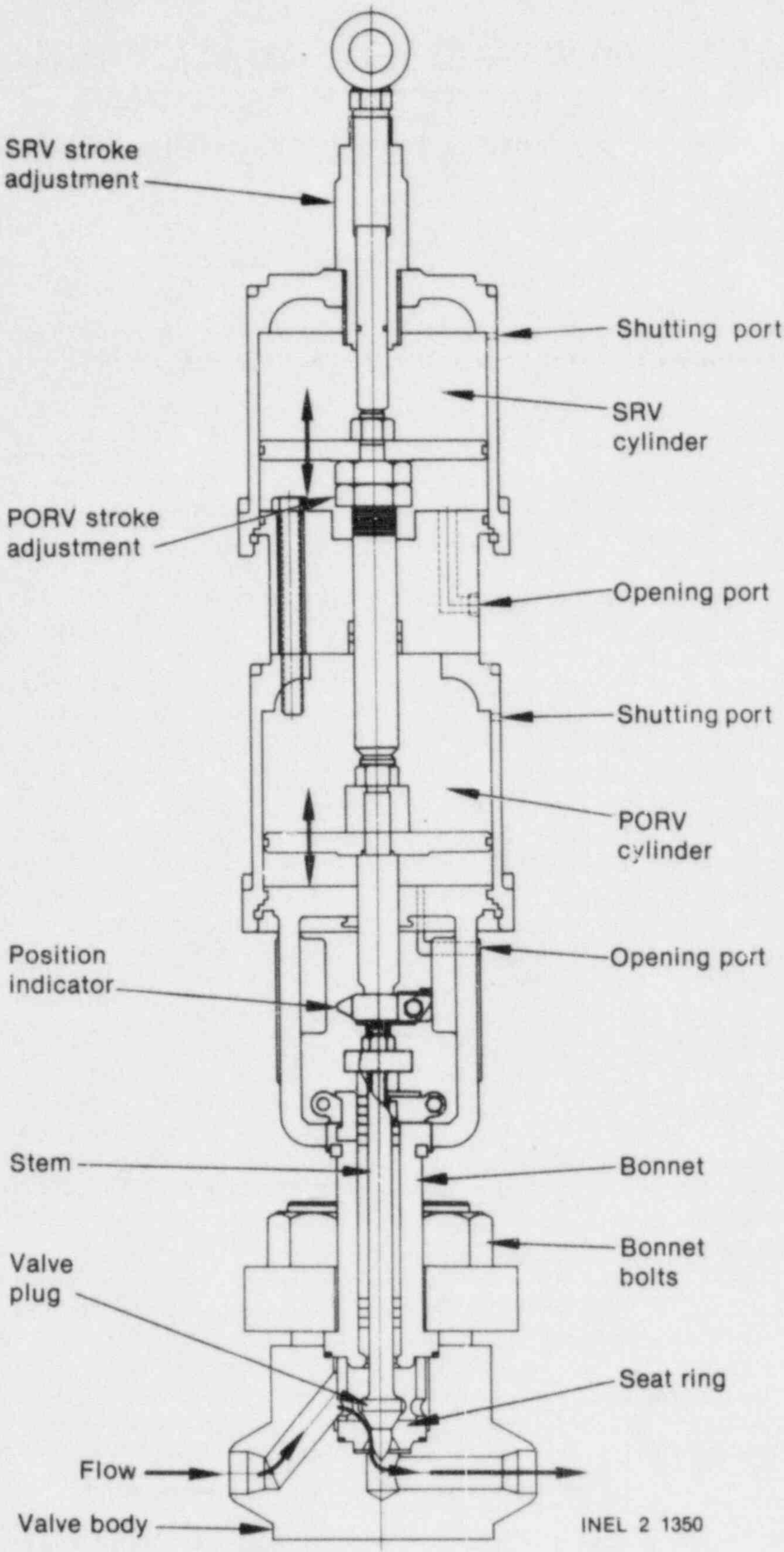

Figure 1. LOFT experimental power-operated relief valve (PORV).

CALIBRATION APPROACH

This section describes the measurement techniques and extrapolation method used to project the LOFT Test Support Facility (LTSF) critical flow test results from the obtainable calibration conditions to LOFT experimental conditions.

The LTSF is not capable of producing saturated steam at LOFT test conditions. An extrapolation technique was, therefore, required to relate the 4- to 11-MPa (580 to 1595 psia) calibration data to the 16- to 18-MPa (2320 to 2610 psia) LOFT test conditions. A simple RELAP5 model of the test valve and associated L9-3 LOFT geometry, Figure 2, was constructed to allow the necessary extrapolation. A listing of the RELAP5 input data used is given in Table 1.

Separate approaches were used to model the equivalent valve flow area for each position. For the PORV position, the specified pressure and flow rates were known well in advance, so the equivalent flow area required to produce the desired flow in RELAP5 was determined by iteration. The upstream time-dependent volume was then ramped slowly down in pressure while maintaining saturated steam conditions. This produced a "target" mass flow through the valve (shown in Figure 3) which could be correlated to the test pressure in the PORV position. For the larger PORV + SRV opening, the procedure was similar except that, due to time restrictions, the equivalent valve effective area rather than the desired mass flow specification was used to produce the calibration curve of Figure 4.

Test data were then evaluated to produce the valve mass flow for a fixed stem position. Typical results are shown in Figure 5 for a stem position 20% open. The mass flow for the valve is below the desired values given by the RELAP5 extrapolation. Subsequent tests run with the valve 24% open yield the results shown in Figure 6. This figure shows that, while the slope of the mass-flow-versus-pressure function is somewhat less for the test data, the mean value is only 4% below the target value. Similar test data for nozzles taken over a wide range of pressures and flow rates have shown this same slope disparity for individual tests, but a composite of nozzle test data indicates that the overall shape of the predicted curve is maintained.[2] We were therefore justified, in theory at least, in extrapolating the test data along the RELAP5-generated pressure curve to the high-pressure LOFT test conditions. The same pressure-versus-mass-flow evaluation was repeated to fix the PORV + SRV position.

The final calibration step was to determine the expected mass flow characteristics of the valve in its PORV + SRV position under subcooled liquid flow conditions. Again, the RELAP5 extrapolation technique was used. The prediction calculations showed subcooling as high as 20 K (36°F) and, since critical flow rate increases with increasing subcooling, this was chosen as a maximum condition. In the model, liquid with 20 K (36°F) of subcooling was provided to the valve with pressures ranging from 19 to 4 MPa (2755 to 580 psia); the result is shown in Figure 7. After an initial stabilization period, the mass flow increased from 3.6 kg/s (28,512 lbm/h) at 19 MPa (2755 psia) to a maximum of ∿4.9 kg/s (38,808 lbm/h) at 12 MPa (1740 psia). This apparently contradictory behavior can be explained by the increase in liquid density due to the temperature decrease required to maintain the 20 K (36°F) of subcooling during the pressure drop. Below 12 MPa (1740 psia), pressure becomes the dominant factor; and the flow rate decreases as one might expect. No attempt was made to adjust the PORV + SRV position for the subcooled flow rate. Predictive calculations[3] did, however, indicate that the peak pressure during L9-3 would be reached during subcooled liquid flow through the PORV.

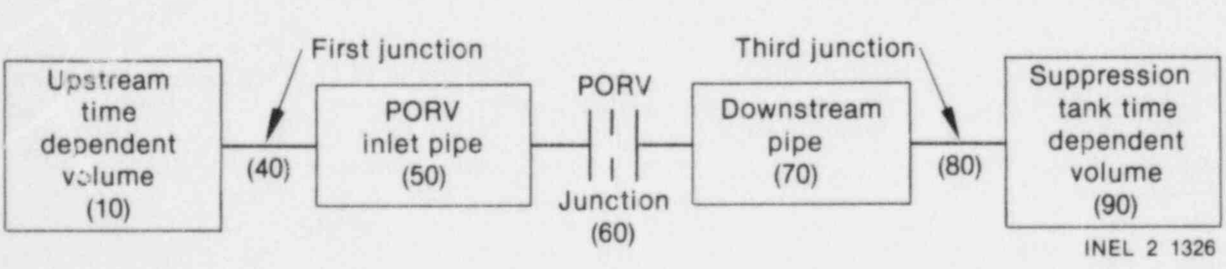

Figure 2. RELAP5 extrapolation model.

Table 1. RELAP5 critical input data

```
- L9-3 PORV MASFLO
0000100 NEW , TRANSNT
0000105 20.0,30.0
* TIME STEP CONTROL
0000201 40.0,1.0E-8,0.1,00001,10,100,1000
* MINOR EDIT REQUESTS
0000310 P,050020000
0000311 RHO,050020000
0000312 VELFJ,060000000
0000313 VELGJ,060000000
0000314 MFLOWJ 060000000
*o*o* HYDRODYNAMIC MODEL   *o*o*
* UPSTREAM BOUNDARY (FLUID PROPERTIES FOLLOW PRESS TRAN)
0100000 "UPSTREAM", TMDPVOL
0100101 6.340E-1,10.0,0.0,0.0,0.0,0.0,0.0,0.0,11
0100200  3
0100201  0.00     19.000E6    614.
0100202  1.0      19.090E6    614.
0100203  40.       1.000E6     433.
0400000 "FIRST" SNGLJUN
0400101 010000000,050000000,9.07E-4,0.0,0.0,1001
0400201 1,3.0,1.0,0.0
* PIPING, 1.5 INCH SECTION
0500000 "PORV-INL" PIPE
0500001 2
0500101 9.07E-4,2
0500301 0.250,2
0500601 0.0,2
0500801 4.7E-5,0.0,2
0501001 10,2
0501101 1001,1
0501201 3,19.E6,614.,0.0,0.0,2
0501301 1.0,1.0,0.0,1
* L9-3 PORV   COMBINED  FLOW AREA (4.7E-5 M2)
0600000  "L9-3 PORV" SNGLJUN
0600101 050010000,070000000,4.718E-5,0.0,0.0,0100
0600201 1,3.0,0.0,0.0
0700000 "DWNSTRM" PIPE
0700001 4
0700101 3.97E-3,4
0700301 0.857E-1,4
0700601 0.0,4
0700801 4.57E-5,0.0,4
0701001 00,4
0701101 1000,3
0701201 2,0.1E6,1.0,0.0,0.0,4
0701301 0.0,0.0,0.0,3
* FINAL JUNCTION
0800000 "THIRD" SNGLJUN
0800101 070010000,090000000,3.96E-3,0.0,0.0,0100
0800201 1,50.0,50.0,0.0
0900000 "SUP TANK" TMDPVOL
0900101 1.0E-1,10.0,0.0,0.0,0.0,0.0,4.5E-5,0.0,11
0900200 2
0900201 0.0,9.7E+5,1.0
. END OF MODEL
```

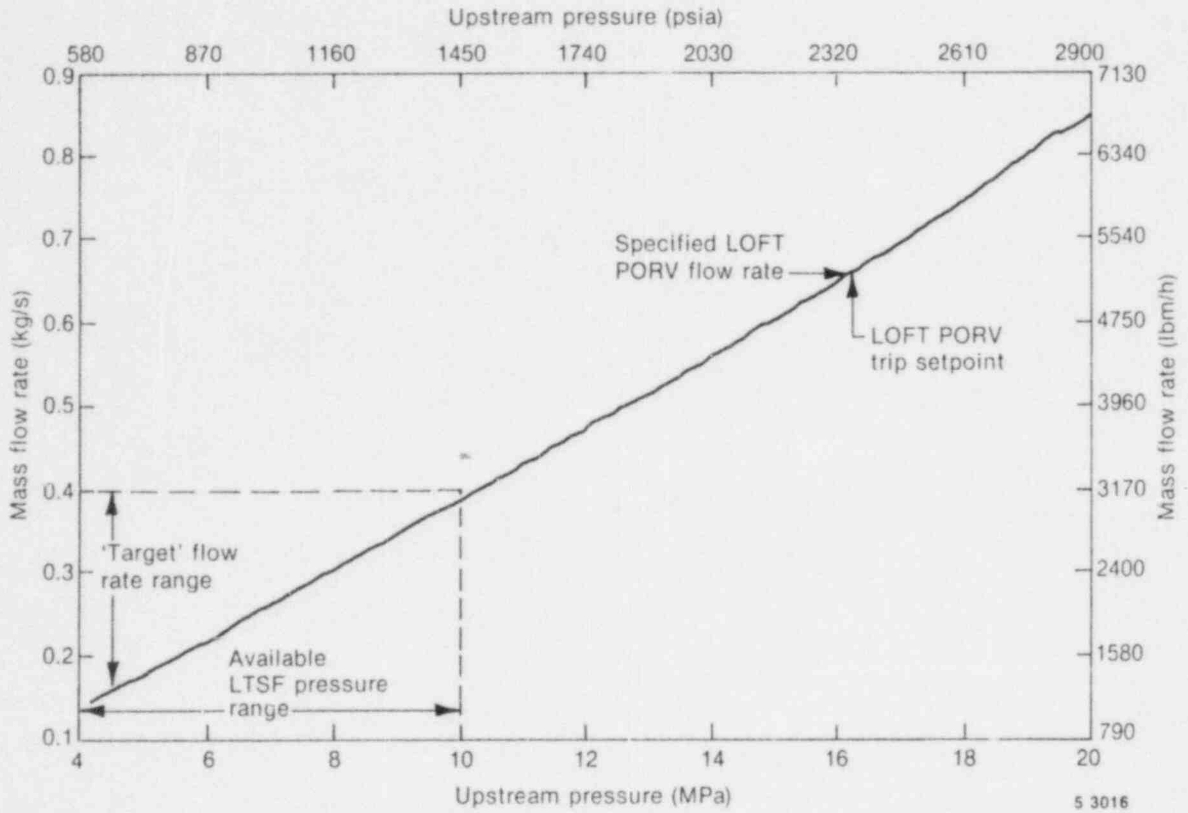

Figure 3. RELAP5 predicted mass flow for L9-3 PORV calibration.

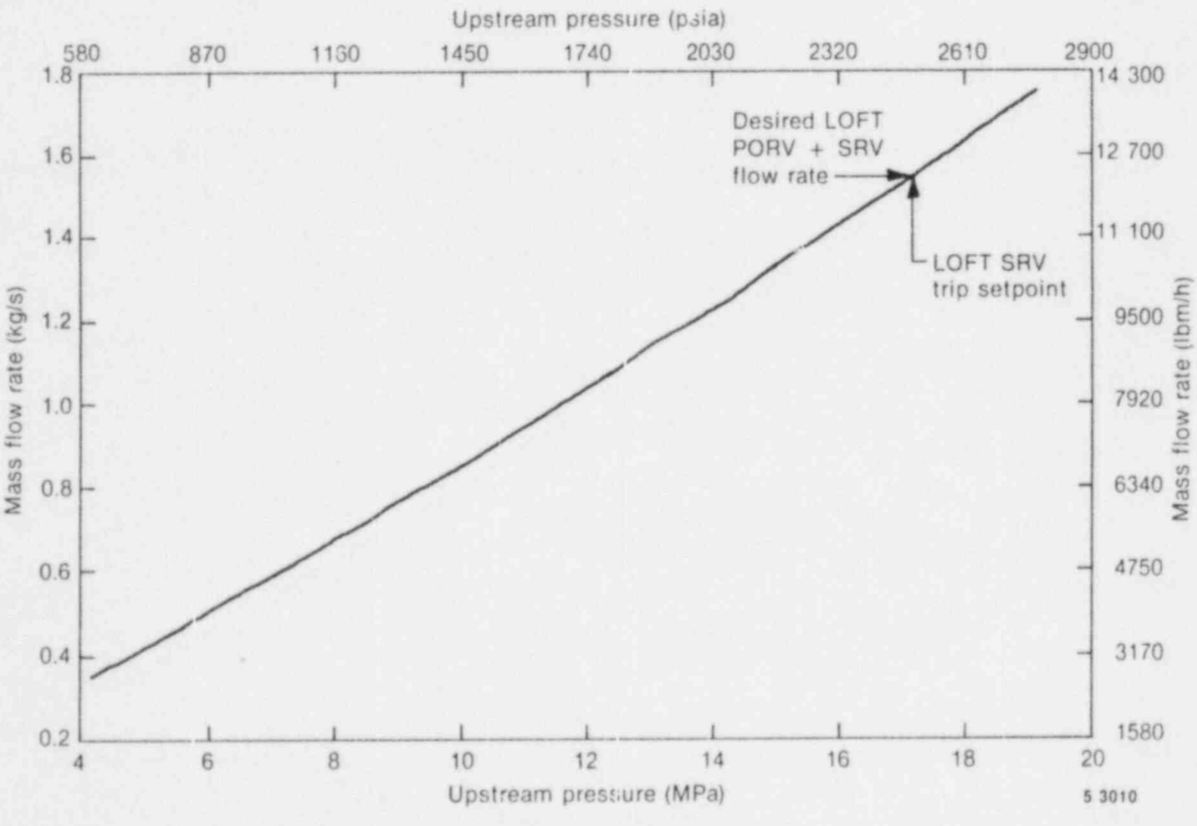

Figure 4. RELAP5 predicted mass flow for L9-3 combined PORV + SRV calibration.

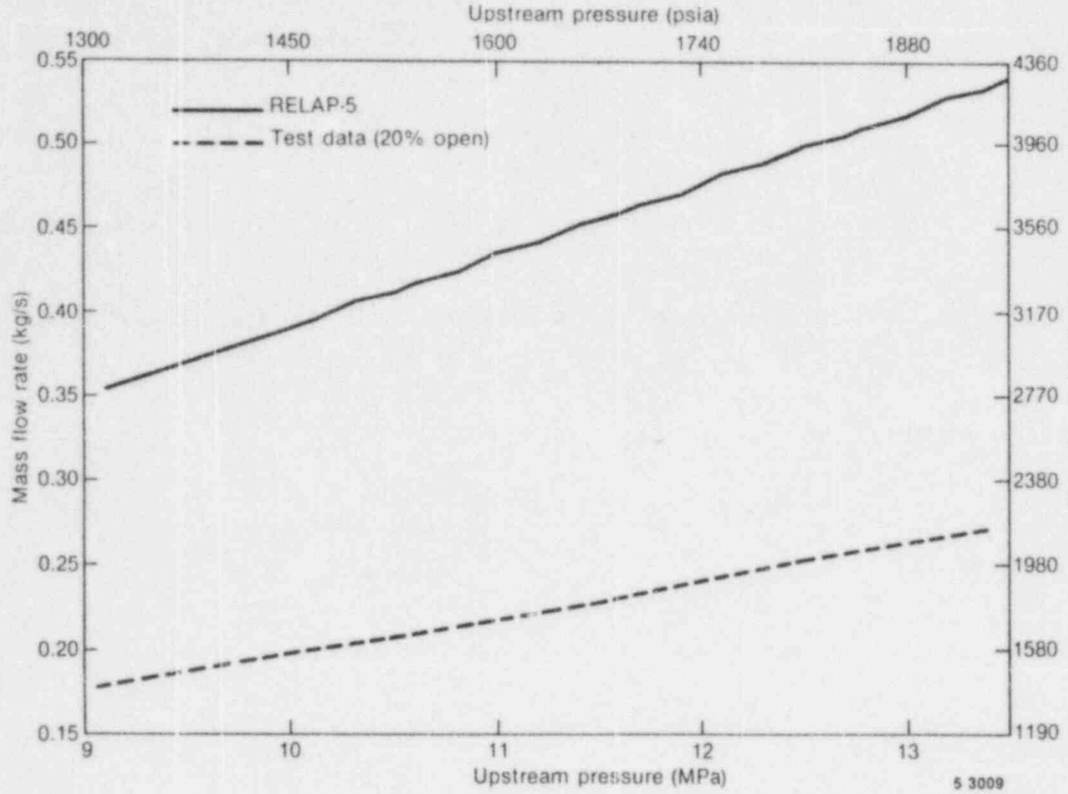

Figure 5. A comparison of RELAP5 mass flow and 20% open test data.

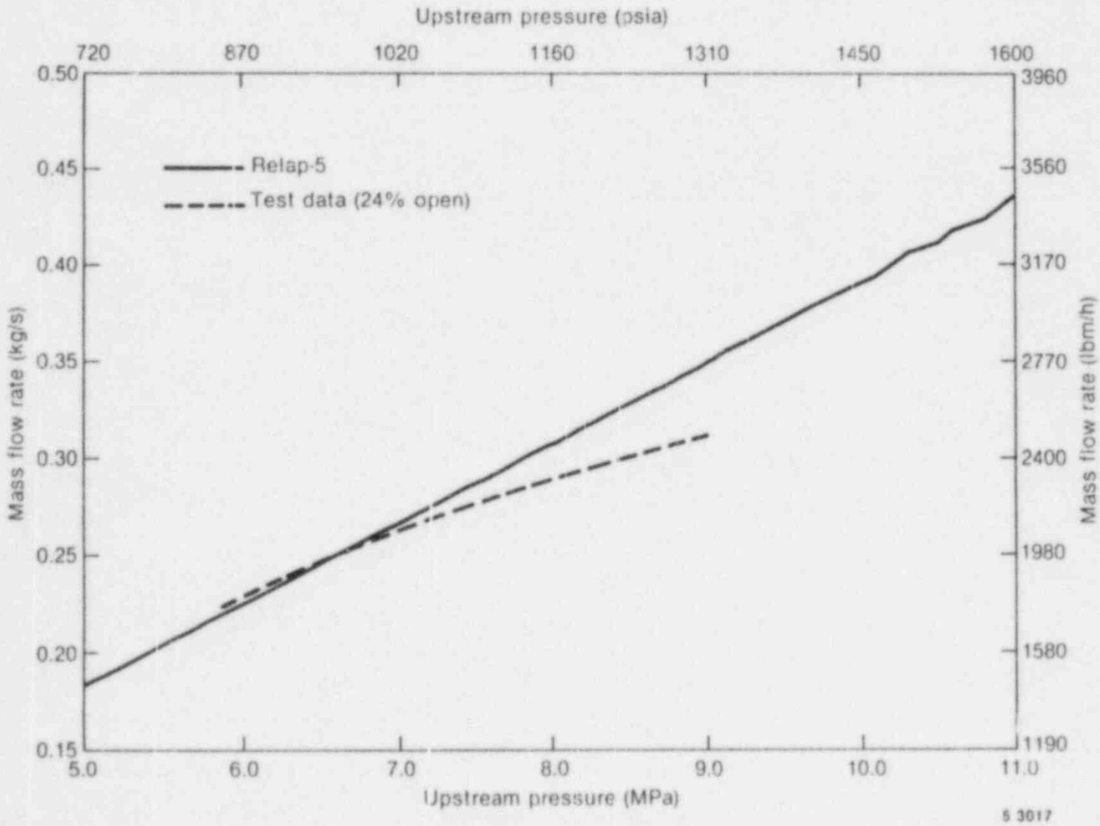

Figure 6. A comparison of RELAP5 mass flow and 24% open test data.

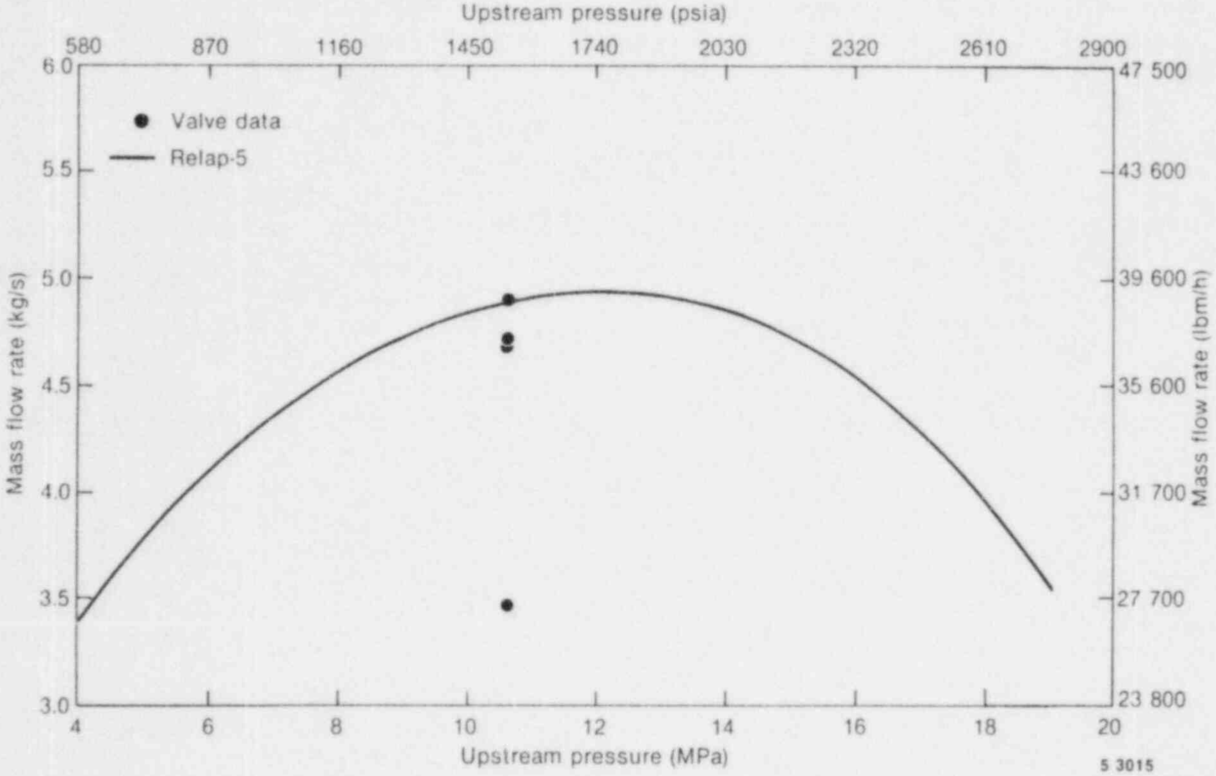

Figure 7. L9-3 PORV subcooled calibration for combined PORV + SRV position.

VALVE CALIBRATION PERFORMANCE

This section describes the PORV and PORV + SRV calibration and the subcooled mass flow determination. Additional details of the calibration apparatus and a complete documentation of the recorded data are given in Reference 4.

PORV Position Calibration

The specified conditions for the PORV mass flow were 0.66 kg/s (5250 lbm/h) of steam at 16.2 MPa (2350 psia). The RELAP5 equivalent area was varied until the required flow was produced by the given upstream conditions. The RELAP equivalent area was fixed at 2.13E-5 m^2 (2.3E-4 ft^2), saturated steam conditions were maintained, and the pressure was ramped from 19 to 4 MPa (2755 to 580 psia) to produce the "target" mass flow as a function of pressure (Figure 3).

A 20% valve position test was performed, and the data were examined for consistency. Since this was a saturated steam blowdown, the orifice ΔP measurement could not be performed, leaving the catch tank load cell data as the only method of deriving a reference mass flow. Using the curve-fit-differentiation technique discussed in Appendix A, the pressure-versus-mass flow function for the 20% test was produced and is shown overlayed with the target curve in Figure 5. Obviously this valve position allowed less mass flow for a given pressure than was required by the RELAP5 projection. Four additional iterations produced a final valve position of 24% of full open with a calculated mean mass flow value 3.5% below the RELAP5 target (see Figure 6). This value was within the $\pm 7\%$ tolerance specified. A confirmatory run was performed at the same valve position, with a resulting mean flow value 4% below the RELAP5 curve, which adequately demonstrated repeatability. The mass flow projected to 16.2 MPa (2350 psia) using the RELAP5 curve was 0.637 kg/s (5040 lbm/h).

PORV+SRV Position Calibration

As a result of time restrictions, the specification for the PORV+SRV position was initially formulated in terms of a RELAP5 equivalent area which would produce the desired result peak system pressure of 18.6 MPa (2700 psia) using the LOFT best-estimate pressurizer model.[3] When this equivalent area [4.718E-5 m^2 (5.08E-4 ft^2)] was used to control the critical flow model (Figure 2), a mass flow of 1.52 kg/s (12,050 lbm/h) of steam resulted at 17.2 MPa (2500 psia). This area was subsequently used to produce the mass flow as a function of pressure curve shown in Figure 3.

Using the curve-fit-differentiation method described in Appendix A, saturated steam blowdowns were performed to arrive at a valve stem position of 52.2% of full stem travel. A mean load cell mass flow of ~2% less than the RELAP5 target resulted in a projected mass flow of 1.49 kg/s (11,800 lbm/h) of steam at the specified pressure of 17.2 MPa (2500 psia).

Subcooled Flow Determination

The final calibration task was to determine the critical flow through the valve in its PORV+SRV position under varying degrees of inlet subcooling. Again the RELAP5 critical flow model was used, but in this instance it provided a comparison rather than an actual calibration of the valve position. Four tests were run with 2, 10, 17, and 30 K (3.6, 18, 30.6 and 54°F) of subcooling.[4] A reference ΔP orifice meter was installed to provide a redundant measurement of mass flow rate. These subcooled tests, all run at 10.6 MPa (1550 psia), illustrate the effect that subcooling has on short nozzle lengths with radical outlet geometry. Figure 7 shows the four data points on a pressure-versus-mass-flow-rate plot overlayed with a constant 20 K (36°F) subcooled RELAP5 computed mass flow using the derived 4.718E-5 m^2 (5.08E-4 ft^2) equivalent flow area. The data points show that a 40% change in mass flow rate through the valve is produced by simply varying the upstream temperature by 28 K (50.4°F). Experiments involving subcooled upstream conditions for critical flow through short nozzles[2] also indicate that nonequilibrium effects require an empirical correction factor for subcooling of less than 30 K (54°F). Since less than a 5% correction was necessary to align the 20 K (36°F) subcooled ΔP cell data with the computed load cell values, agreement was considered to be good. The maximum mass flow for subcooled liquid (T_{sat} - 20 K) projected to 17.2 MPa (2500 psia) was 4.02 kg/s (31,800 lbm/h).

Pretest Calibration Summary

The initial calibration values for the two PORV positions are as follows:

1. PORV position—0.637 kg/s (5040 lbm/h) of steam at 16.2 MPa (2350 psia),
2. PORV+SRV position—1.49 kg/s (11,800 lbm/h) of steam at 17.2 MPa (2500 psia),
3. PORV+SRV position, subcooled liquid—4.02 kg/s (31,840 lbm/h) at 17.2 MPa (2500 psia) with 20 K (36°F) subcooling.

Prior to PORV calibration testing, eight tests were run in LTSF to characterize the accuracy and response of the catch tank system and the mass flow data reduction techniques. Unfortunately, a valve malfunction during the first valve calibration test caused a flex hose rupture which significantly altered the response characteristics of the system. Several subcooled tests were run following this incident using orifice ΔP mass flow instrumentation which did allow a partial *in situ* recalibration of the catch tank measurements.

The steam flow values given in this report were derived from data based on the load cell calibration prior to the flex hose rupture incident.

VALVE PERFORMANCE DURING THE L9-3 EXPERIMENT

The actual mass flow rate during L9-3 was assessed using installed drag disc, flow turbine, and densitometer instrumentation. The pressurizer relief line instrument configuration is given on page 29 of Reference 5, and the calculation method is explained on page 30 of that reference. Basically, the momentum flux (ϱV^2) from the drag disc is multiplied by the density (ϱ) to give the $\varrho^2 V^2$ product. Subsequently, the square root is taken; and the continuity equation $m = \varrho VA$ (mass flow = density x velocity x area) is used to compute mass flow. Alternately, the flow turbine can be used to give the fluid velocity; and, through similar manipulations, mass flow is found through the continuity equation. A comparison plot of both approaches is shown in Figure 8.

Referring to Figure 8 between 75 and 85 s, the valve was open to its PORV position and passed an average steam flow of 0.873 kg/s (6,900 lbm/h) at 15.86 MPa (2300 psi). The steam fluid state was verified by examination of the upstream densitometer data. Correcting for the differences in pressure, this compares to a calibration projected flow from Figure 3 of 0.64 kg/s (5070 lbm/h), 26.8% below the measured value.

Between 97 and 107 s, the valve operated in the PORV + SRV position with a subcooled liquid (verified from densitometer data) flow of 4.45 kg/s (35,200 lbm/h) at an average pressure of 16.0 MPa (2320 psia). The target calibration flow projection (Figure 7) corrected to the same pressure conditions yields 4.55 kg/s (34,200 lbm/h), some 2.2% above the measured mass flow.

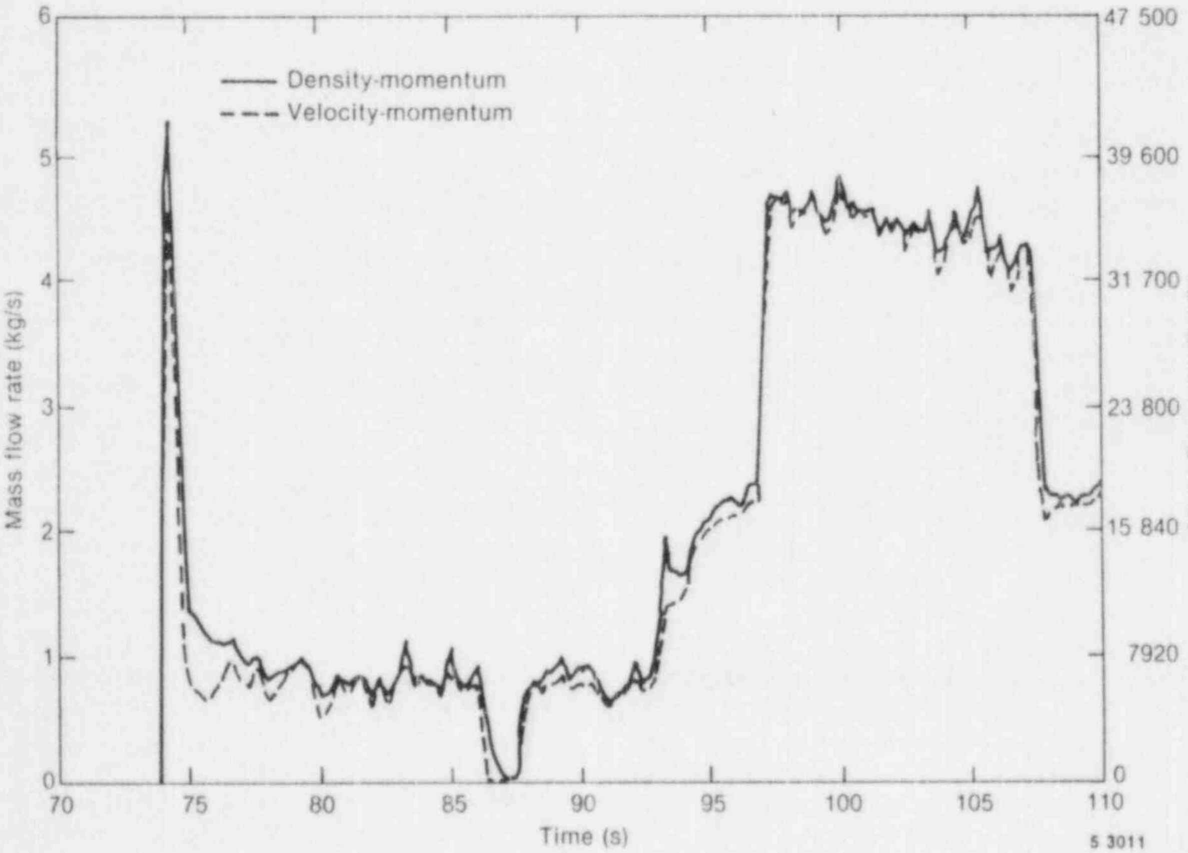

Figure 8. L9-3 mass flow comparison.

CALIBRATION ERROR INVESTIGATION

Considerable differences (see Reference 6, Section 3.2) existed between the valve performance necessary to reach the desired peak test pressure of 18.6 MPa (2700 psia) and the actual flow rates realized during L9-3. The purpose of this section is to discuss and quantify these differences.

Two basic sources of error were identified: computer modeling, which resulted in incorrect flow specifications, and calibration, which resulted in underpredicting the measured mass flow.

Computer Modeling

The specification of the desired flow rate for the L9-3 PORV came directly from power scaling the minimum PORV capacity of Westinghouse large PWRs. The valve flow necessary to produce the PORV + SRV flow required integrated plant computations using the RELAP5 code. As discussed in Reference 3, there were uncertainties associated with reactor power, test valve flow rate, pressurizer level, moderator feedback effects, and steam generator level. A sensitivity analysis of the code prediction to each of these parameters is given in Reference 3, pp 19-26.

Two additional computational difficulties were potential contributors to the differences between desired and actual performance:

1. *The entrainment of pressurizer spray liquid in the relief line flow.* The top volume of the pressurizer (Figure 1, Reference 3) receives the pressurizer spray and warmup lines from the cold leg. The code uses volume average properties and, since this volume is in the pressurizer steam space, it homogenizes the influx of liquid in this top volume rather than allowing the liquid to evaporate or reach saturation conditions in the entire pressurizer steam volume. Since the period of interest is at higher-than-normal primary system pressure, pressurizer spray is operating. Liquid entering this volume is homogenized by the code and, with the PORV open, immediately exits through the pressurizer relief line. The result is an artificially high mass flow through the PORV. Since this problem has not yet been remedied, the magnitude of its effect on the target PORV flow is not known.

2. *The geometric differences that exist between the model used to determine the RELAP5 equivalent flow area and the model used to derive the mass flow-pressure "target curve."* A more detailed nodalization was used in the target model (Figure 2), which resulted in lower form losses internal to the code with subsequent differences in mass flow rates. For the same upstream subcooled liquid conditions [18.6 MPa (2700 psia) and 20 K (36°F) subcooled], the predictive model passes 3.05 kg/s (24,150 lbm/h); whereas the target model indicates a flow of 4.30 kg/s (34,400 lbm/h), a 40% increase.

Load Cell Calibration

Prior to performing the L9-3 PORV calibration, the LTSF System (refer to Appendix A) was calibrated to accurately determine the rate of mass flow through the valve. During the performance of the first PORV test, a valve malfunctioned, causing a flex hose leading to the catch tank to burst. The resulting explosion was violent enough to damage the system to the extent that the measurement system calibration was invalidated. This fact was not realized at the time, and the PORV test series was continued after installation of a new flex hose. The final series of subcooled liquid tests, done with a backup ΔP flowmeter installed, did not indicate a departure from prerupture characteristics. A posttest calibration of the mass flow measurement system revealed that only the low-flow characteristics had been significantly altered. Figure 9 illustrates the changes due to the flex hose rupture.

The result of this incident is that the PORV position calibration flow is ~30% higher than the original target value and ~14% higher at the PORV + SRV for steam. The subcooled tests which had ~4.3 kg/s (34,056 lbm/h) flow were essentially unaffected.

Table 2 summarizes the known deviations from nominal that potentially affected the flow rate in the L9-3 experiment PORV.

The magnitude and direction of the effects of plant vs RELAP5 differences and the extent that homogenization changed the relief line flow rate will be addressed in the L9-3 posttest analysis.

Table 2. Off-nominal conditions

Source	Effect
Off-prediction plant response	Integral effect will require additional analysis—see Ref. 2, Section 4, and Ref. 5, Sections 2 and 3.
Pressurizer spray entrainment	Will be investigated in posttest RELAP5 analysis.
Model nodalization differences	Resulted in combined PORV + SRV target flow being ∿40% high.
Mass flow system characteristic	Resulted in ∿30% high PORV flow and 14% high PORV + SRV flow rate relative to target flow rate.

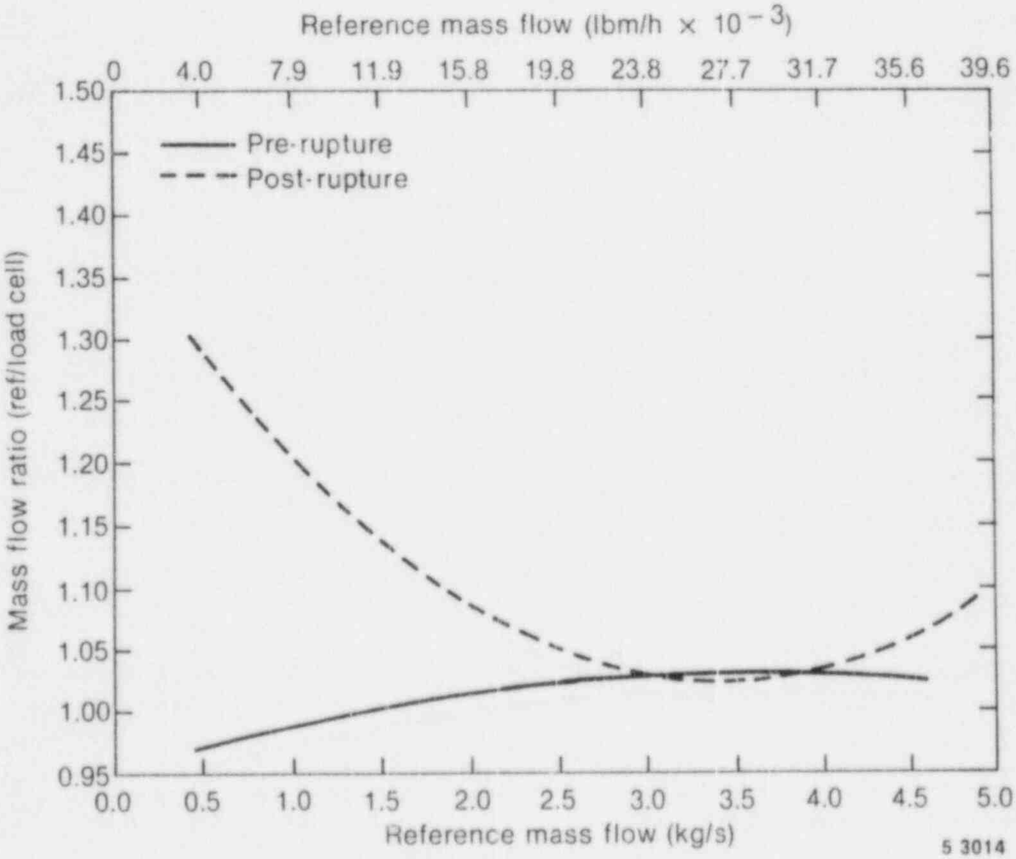

Figure 9. Catch tank characteristics before and after the flex hose rupture.

CONCLUSIONS

The previous section discussed the valve performance relative to the L9-3 prediction objective of reaching 18.6 MPa (2700 psia). Reaching the peak pressure depended not only on the accuracy of the actual calibration, but on a myriad of other factors as well. This section assesses the merits of the calibration relative to the calibration goal, or "target" flow values.

The change in load cell response following the flex hose rupture was evaluated, using subcooled flow tests with alternate reference mass flow metering systems installed. This change in load cell characteristic was then factored into the calibration.

At the mean mass flow value [Figure 6, 0.27 kg/s (2,138 lbm/h)] measured in LTSF at the 24% stem position, Figure 9 shows that a correction factor of +34% should be applied. The net result, accounting for the flow being 4% below the RELAP5 "target," is a projected flow of 0.86 kg/s (6800 lbm/h) at the 16.2 MPa (2350 psia) specified pressure. Adjusting to the L9-3 test pressure (Figure 4) of 15.86 MPa (2300 psia) and applying the +30% calibration correction factor, a flow of 0.832 kg/s (6590 lbm/h) is projected. This projected figure is 4.7% below the actual flow realized during the L9-3 experiment.

In the PORV+SRV position, the flow did not stabilize sufficiently with saturated steam flow to make an accurate assessment (see Figure 8 at ~95 s). Subcooled liquid flow was well established from 97.5 to 107 s, followed by two-phase flow thereafter. The average conditions during the stated interval of liquid flow were 16.0 MPa (2320 psia) and 4.45 kg/s (35,244 lbm/h). The calibration curve shown in Figure 7 for liquid flow projects 4.55 kg/s (36,036 lbm/h) at the same pressure with 20 K (36°F) of subcooling, 2.2% above the actual flow recorded.

This calibration and subsequent test demonstrated that (a) the RELAP5 code can be a useful tool in extrapolating a low pressure and temperature calibration to near critical point testing, and (b) the catch tank-load cell system, when suitably calibrated, can produce accurate (±5%) steady-state and low-frequency transient (<0.1 Hz) reference mass flow data.

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APPENDIX A

REFERENCE MASS FLOW MEASUREMENT CALIBRATION

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The key parameter in determining the critical flow characteristics of any component is an accurate knowledge of the actual flow passing through the device as a function of the upstream conditions. To accomplish this, the LOFT Test Support Facility (LTSF) was designed and built at the INEL. This system, shown in Figure A-1, consists of a pressure vessel to contain the liquid, pumps, heaters and associated piping required to heat and pressurize to the desired conditions; a regulated nitrogen supply system to provide isobaric flow; and a catch tank suspended on precision strain gauge load cells to condense and measure the effluent. As shown in Figure A-2, a header runs the full length of the catch tank, with 100 submerged sparger nozzles mounted on opposite sides to condense steam without producing a net reaction force. The mass increase as a function of time, as indicated by the load cells, provides the raw data for determining the mass flow rate into the tank.

Load Cell Analysis

Several methods for translating the mass increase in the catch tank into a mass flow rate through the test device were evaluated. Typically, the combined load cell response to steady-state mass flow during a test appears as in Figure A-3. Load cell data are collected at 50 samples per second, which allows frequency resolution down to approximately 10 Hz.

The rate of mass flow is mathematically the slope of the mass increase of both load cells as a function of time.[A-1] Any attempt to take a point-by-point derivative to obtain the slope is impossible, due to the high amplitude spikes caused by noise that are superimposed on the load cell signal. Three different approaches were used to smooth the raw data in an attempt to produce a continuous differential which accurately represents the mass flow through the test device. These approaches are described below.

The first approach involved the use of a digital filter[a] to identify and remove the various frequency components in the raw data signal. The first and most obvious wave form can be seen without filtering by examining either load cell individually (Figure A-4). This oscillation is started by the header clearing pulse at experiment initiation, which produces a ~0.5 Hz end-to-end surface wave. The catch tank is not baffled, and this wave continued through the duration of all calibration runs. The second wave form was found to have a frequency of ~3 Hz (see Figure A-5) and is thought to be caused by condensation fluctuations in the sparger header. Figure A-5 was made by using a 1- to 5-Hz band pass filter, then adding a constant value to the result [20 kg (44 lb) in this case] so that it could be clearly seen in the overlay plot. The final noise component was stochastic and had a ~10-Hz lower threshold. This signal had a considerably smaller amplitude and was produced by the condensation collapse of the steam injected into the highly subcooled water. Much of this high-frequency noise is undoubtedly transmitted to the load cells via the header supports which are fixed to the bottom of the catch tank (see Figure A-2).

A second approach to evaluating the slope of the mass inventory time history was the use of regression curve fit techniques to formulate an equation for the curve from which a derivative expression can be obtained. The INEL CYBER graphics package MAGNUM[a] was used extensively to produce first- through seventh-order regression fits to the data with subsequent differentiation to obtain the mass flow rate as a function of time. Satisfactory results for steady-state or slowly varying test segments can be rapidly obtained using lower-order (first through third) curve fits. Care must be taken, however, that pressure, temperature, or phase changes with a frequency >0.5 Hz are not present.

A third method of data preparation was to smooth the fluctuations using a moving average technique. This approach finds the average value for a specified number of data points (for example, 100 points), outputs this average, then advances one data time frame and repeats the process. The degree of smoothing using this "moving average" is dependent on the data acquisition rate and the specified averaging interval. Taking the differential of the curve thus produced again yields the mass flow as a function of time. This method did not compare as favorably with the ΔP cell as the first

a. EG&G Idaho, Inc., Configuration Control Number F00290.

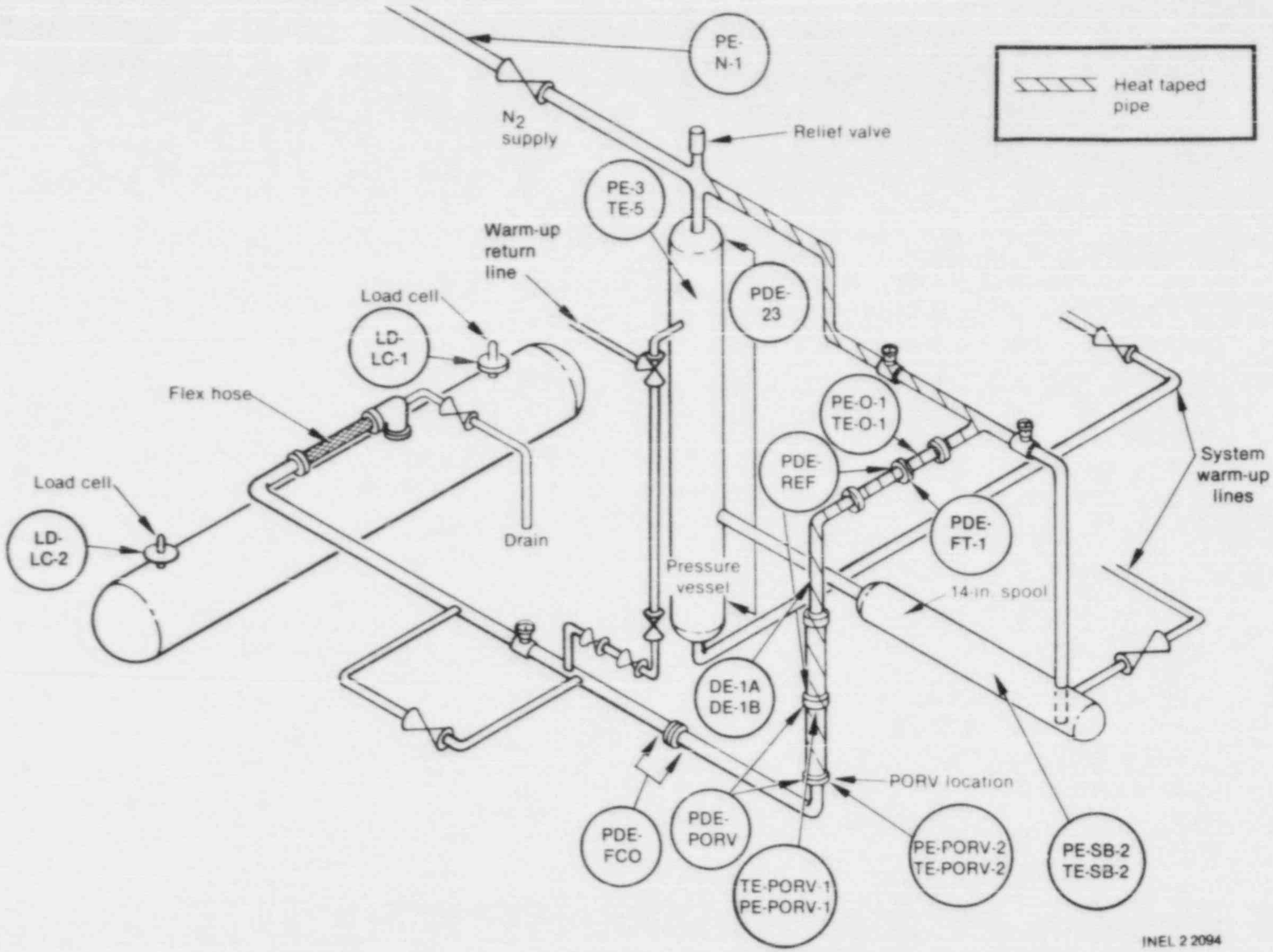

Figure A-1. LTSF blowdown calibration facility.

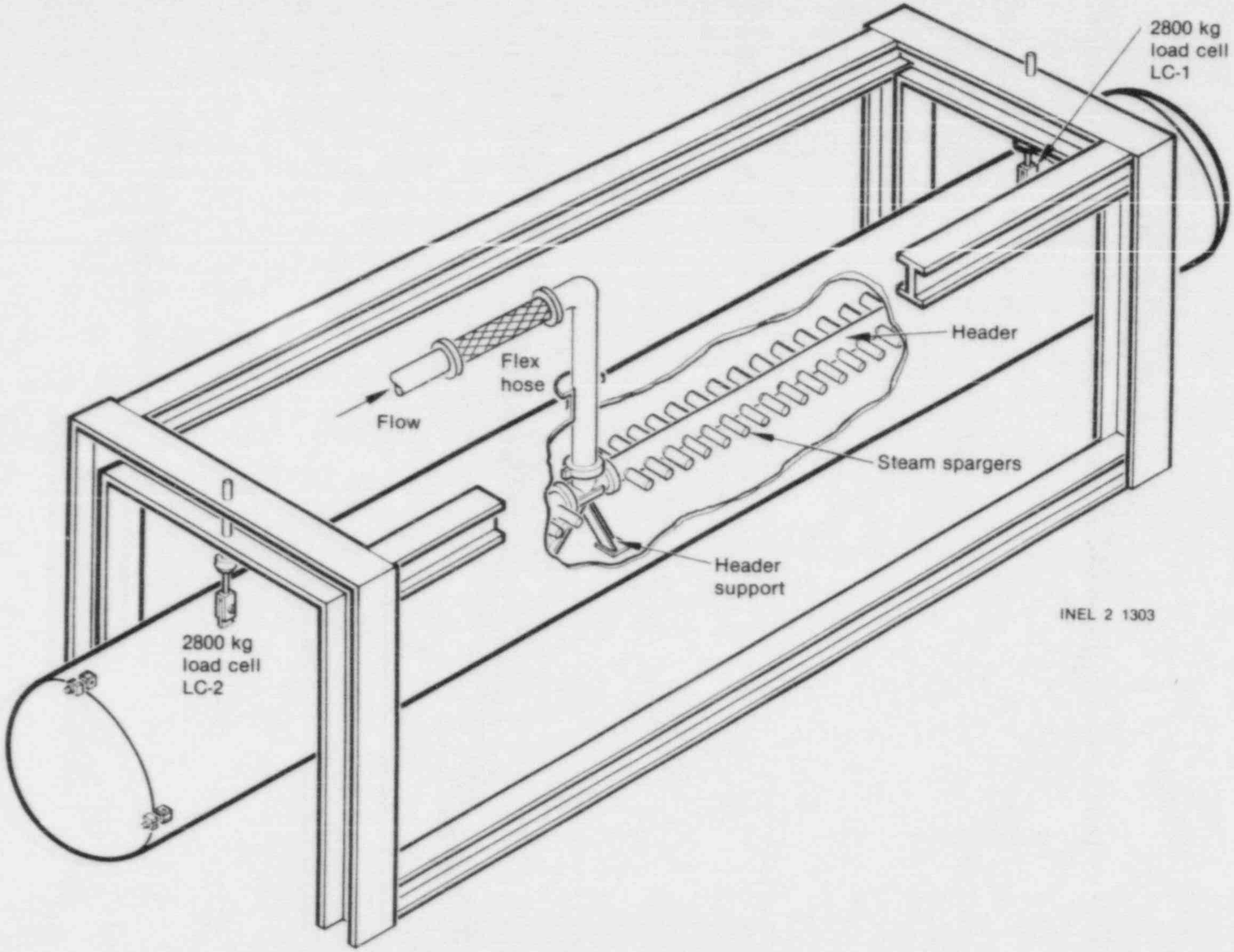

Figure A-2. LTSF catch tank.

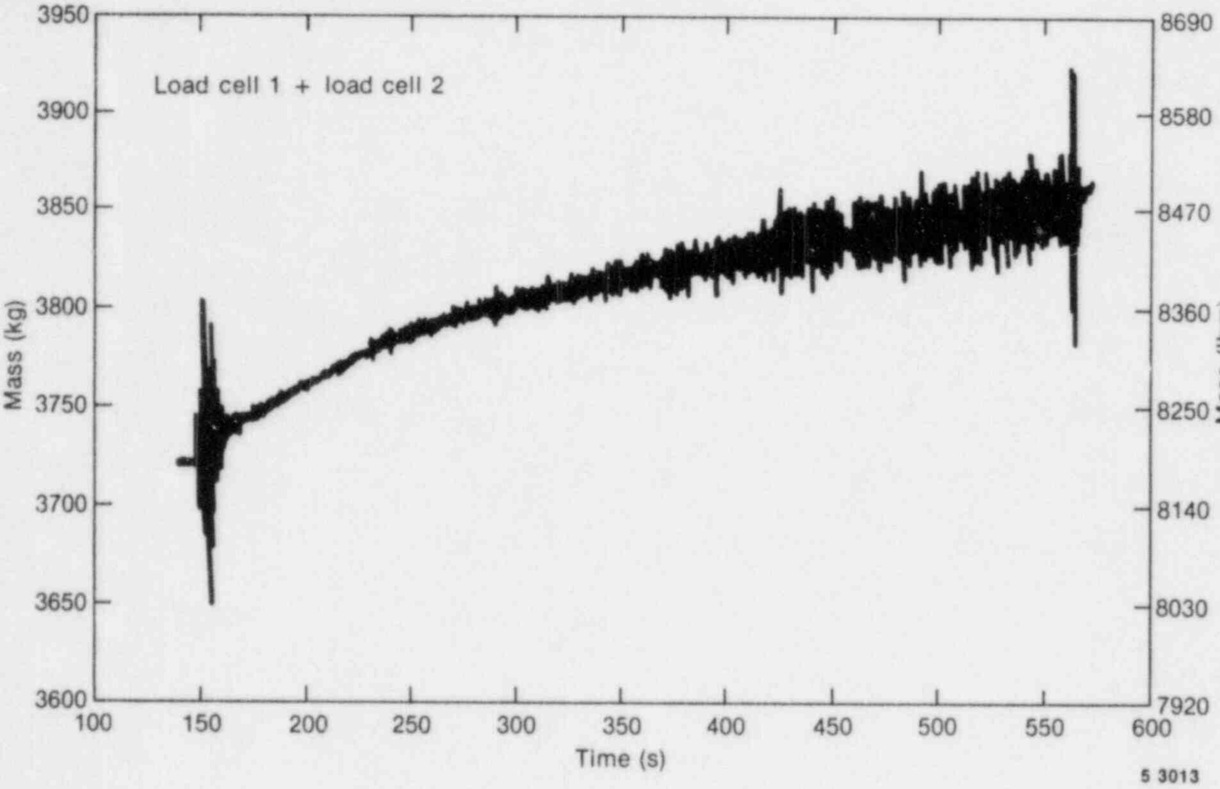

Figure A-3. Load cell mass as a function of time.

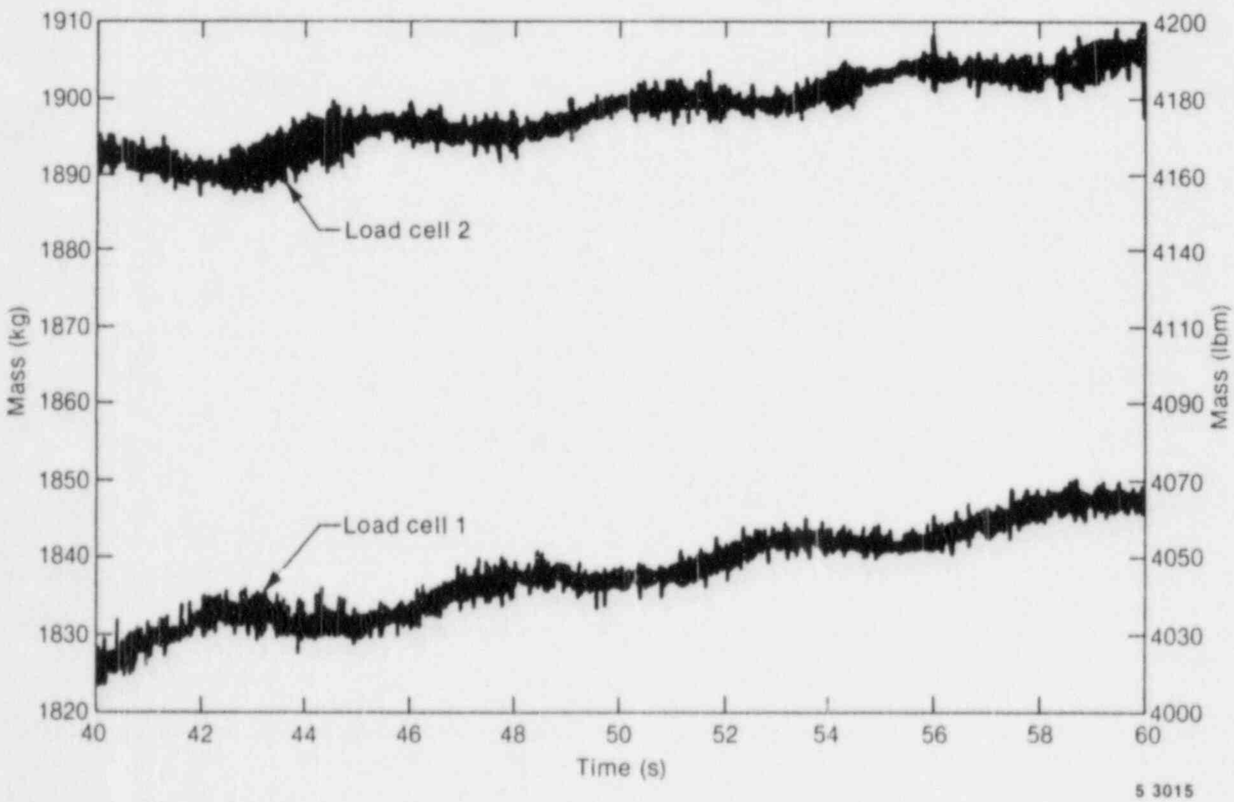

Figure A-4. Header clearing oscillation, reference flow calibration.

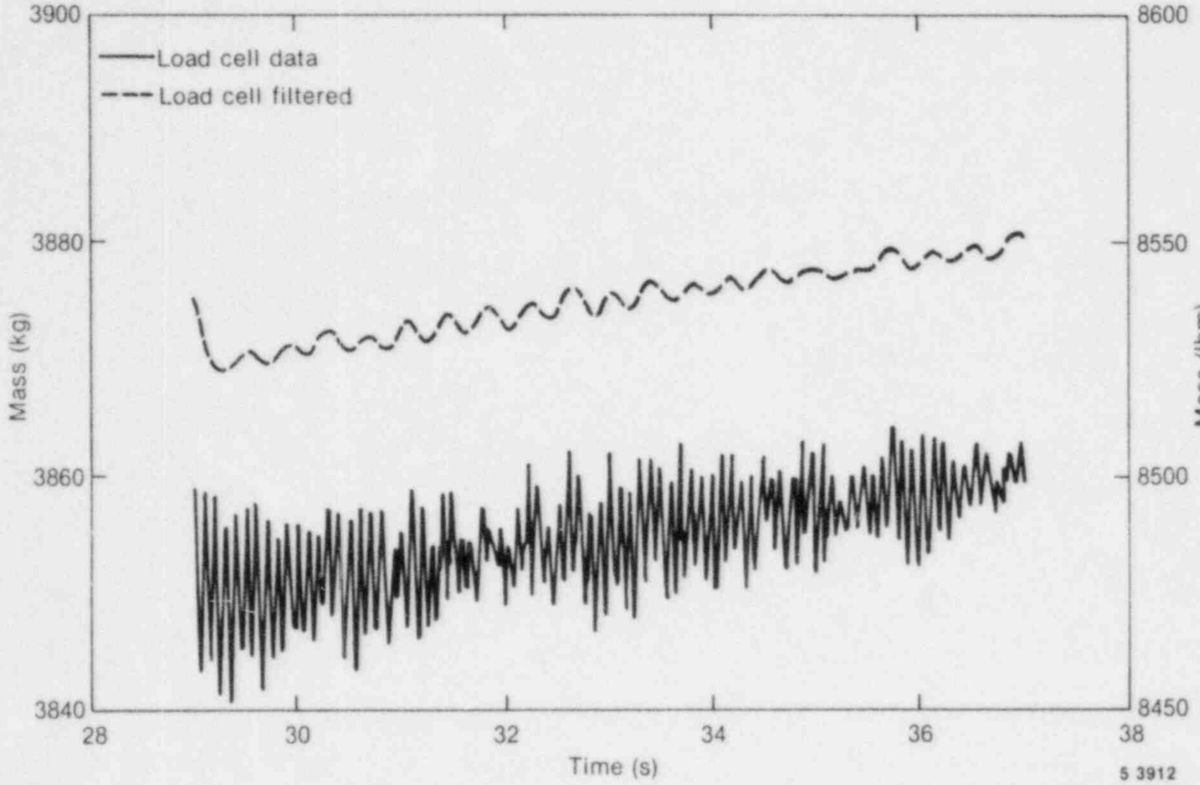

Figure A-5. Header condensation wave, reference flow calibration.

two methods, possibly because the test duration (typically 20 to 40 s) did not allow a sufficiently large averaging interval.

The best methodology in terms of matching ΔP cell performance to catch-tank mass increase for a transient mass flow evaluation was the use of a combination of filtering and curve-fit techniques. The raw load cell data was summed to get the total mass inventory, filtered to remove frequencies above 2 Hz, and then curve-fit and differentiated to produce a final mass flow record. The slowly varying (<0.8 Hz) load cell and ΔP orifice meter data agree within steady-state data tolerances (±4%) when treated in this manner.

The catch tank calibration (Table A-1) quantified the load cell mass flow measurement accuracy and analysis methodology prior to the L9-3 PORV calibration.

1. Under steady-state isobaric testing, the load cell system accuracy using second order fit/differentiation techniques is: (a) 0.4-0.5 kg/s (3,168-3,960 lbm/h), ±4.1%; (b) 1.7-1.8 kg/s (13,464-14,256 lbm/h), ±3.7%; and (c) 4.6-4.8 kg/s (36,432-38,016 lbm/h), ±2.7%.

2. Limited transient testing using filter-fit-differentiation techniques indicated an accuracy of ±4.1% for a mass flow of 1.2-1.5 kg/s (9,504-11,800 lbm/h), with a trend frequency of <0.1 Hz (period >10 s).

Load Cell System Response to L9-3 PORV Testing

Due to the failure of the flex hose leading into the catch tank during the first test to be run on the PORV, the accuracy figures derived in the previous paragraphs were invalidated. Some measure of the magnitude of the changes in system response can be obtained from an examination of seven subcooled steady-state tests run during and immediately after the PORV test series. As in the previous series, a calibrated ΔP reference orifice meter was installed upstream of the choke plane to assess the accuracy of the catch tank system. The results of these tests are given in Reference A-2. Tests SC1, SC2, SC3, and SC4R were performed with the PORV as the controlling element; Test GR was a repeat of BF-CTC-6 in the pre-L9-3 calibration series; and the L5 tests were cold-fill tests at 0.5 and 1.5 L/s (476 and 1427 gph).

Table A-1. Pre-L9-3 catch tank calibration tests

Test Designation	Nozzle Throat Diameter (mm)	(in.)	Test Pressure (MPa)	(psia)	Test Temperature (K)	(°F)	Subcooling Margin (K)	(°F)	Load Cell Differential From Reference (%)
BF-CTC-1	5.4	0.021	6.9	1000	550-547	530-525	11.0-8.5	19.8-15.3	+1.8
BF-CTC-2	5.4	0.021	6.9	1000	547-543	525-518	16.5-11.5	29.7-20.7	+2.3
BF-CTC-3	5.4	0.021	6.9	1000	540-537	512-507	21.0-18.5	37.8-33.3	+1.1
BF-CTC-4	5.4	0.021	4.9-3.8	710-551	532-517	498-471	3.5-17	6.3-30.6	+3.1
BF-CTC-5	5.4	0.021	12.0	1740	589-584	600-591	10.0-14.7	18-26.5	-3.1
BF-CTC-6	2.8	0.011	12.0	1740	585-583	593-590	13.5-15	24.3-27.0	-0.9
BF-CTC-7R	2.8	0.011	11.9	1726	562-570	552-566	26.5-35	47.7-63.0	+2.2

The difference in catch tank performance before and after the flex hose rupture is displayed in Figure A-6. The ordinate is the ratio of the measured reference meter flow to the computed load cell flow. The abcissa gives the reference meter flow in kg/s. Curve Number 1 shows that before rupturing the flex hose the performance of the system is within ±3% of the ideal ratio (1.0) over the measured range. Curve Number 2, following the rupture, shows a dramatic drop in load cell computed flow (hence the increase in mass flow ratio) for measured flow below 3 kg/s (23,760 lbm/h). It is hypothesized that this is caused by a sway brace interfering with tank movement relative to its support. Although no physical evidence of binding was found, the load cell raw data curve obtained during the calibration runs displayed a somewhat discontinuous nature which had not been seen in previous testing. Disassembly of the system and separate calibration testing of the individual load cells showed the load cells to be within the manufacturer's tolerance limits (0.5% of full scale).

As a result of the flex hose incident, Figure A-6 shows that the L9-3 experiment PORV flow is ∿30% higher at the PORV position [calibration flow rate 0.3 kg/s (2,376 lbm/h)] and ∿14% higher at the PORV + SRV position [calibration flow rate 1.5 kg/s (11,880 lbm/h)] than was indicated by the calibration specification.

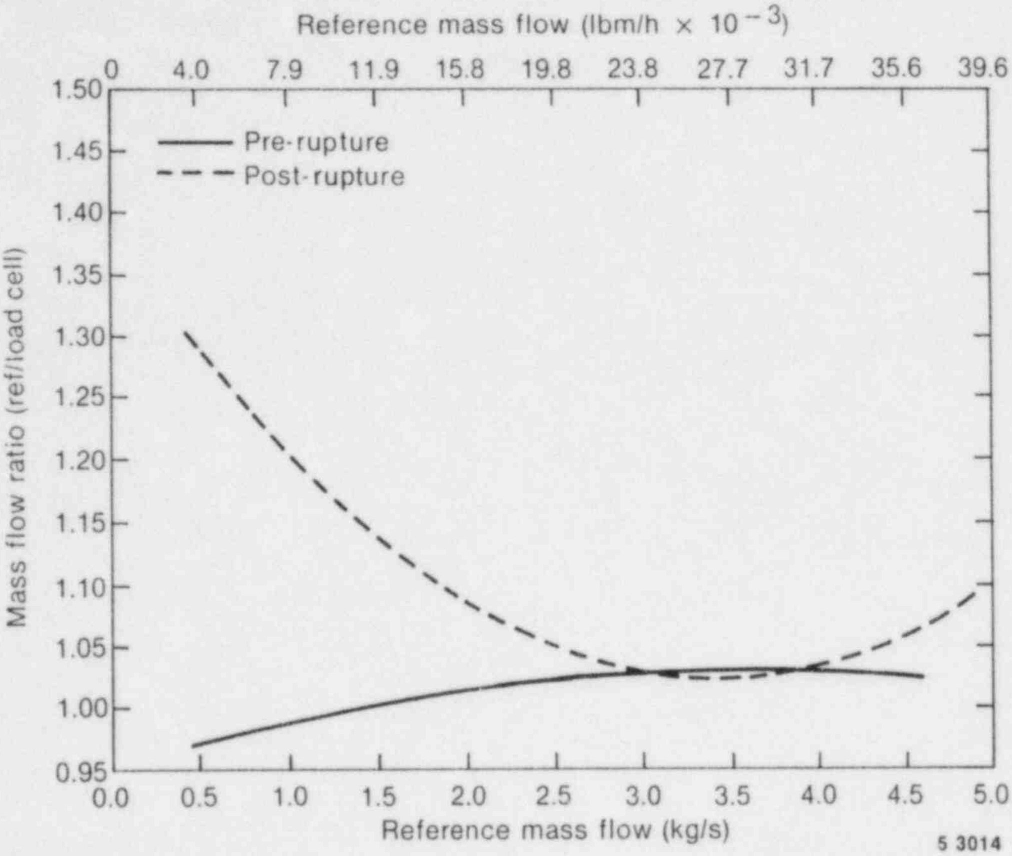

Figure A-6. Catch tank characteristics before and after the flex hose rupture.

References

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A-2. W. A. Owca, *Experimental Data Report for the L9-3 Experimental PORV Calibration Tests*, EGG-SEMI-5919, June 1982.

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