CONF-790655--7

BLOWDOWN MASS FLOW MEASUREMENTS DURING THE POWER BURST FACILITY LOC-11C TEST

J. M. Broughton and P. E. MacDonald
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83401

ABSTRACT

An interpretation and evaluation of the two-phase coolant mass flow measurements obtained during Test LOC-11C performed in the Power Burst Facility (PBF) at the Idaho National Engineering Laboratory (INEL) are presented. Although a density gradient existed within the pipe between 1 and about 6 s, the homogeneous flow model used to calculate the coolant mass flow from the measured mixture density, momentum flux, and volumetric flow was found to be generally satisfactory. A cross-sectional average density was determined by fitting a linear density gradient through the upper and lower chordal densities obtained from a three-beam gamma densitometer and then combining the result with the middle beam density. The integrated measured coolant mass flow was subsequently found to be within 5% of the initial mass inventory of the PBF loss-of-coolant accident (LOCA) system. The posttest calculations using the RELAP4/MOD6 computer code to determine coolant mass flow for Test LOC-11C also agreed well with the measured data.

1. INTRODUCTION

The most serious accident generally considered in the safeguards analysis and licensing of a pressurized water reactor (PWR) is the hypothesized LOCA occasioned by the instantaneous double-ended rupture of an inlet (cold leg) coolant pipe[1]. If such an accident were to occur, the system would depressurize within about 50 ms to the coolant vapor pressure. Steam voids would then be formed within the system and the coolant flow would choke at the break. The fluid enthalpy within the core would then increase and a boiling crisis would be reached leading to a marked rise in cladding temperatures. With the blowdown proceeding, the coolant inventory in the primary system would decrease to the point at which the core would be steam blanketed. Relatively poor core cooling by convection and radiation to steam would be expected at this point. The transient would eventually be terminated by injection of emergency core coolant (ECC).

The damage that would occur to a PWR core during such an accident is highly dependent on the behavior of the two-phase coolant during the approximately 35 s of saturated blowdown. However, the evaluation of PWR system depressurization and two-phase mass flow presents special problems, which have not been entirely resolved. The measurement and calculation of two-phase mass flow within special LOCA simulation tests also presents special problems. In single-phase experiments, mass flow can be determined readily through use of traditional fluid velocity measurements. However, in two-phase situations, density is a function of void fraction as well as the temperature, pressure, or both of the individual phases and the individual phases generally have different velocities (slip). The two-phase flow problem is further complicated by the fact that the velocity and void fraction profiles change dramatically with flow regime[2,3,4].

A series of LOCA simulation experiments are being conducted in the PBF by EG&G Idaho, Inc., at the INEL to investigate a range of expected fuel rod behavior[1]. The basic objective of the LOCA experiment series is to balloon and rupture the zircaloy cladding of the PBF test fuel rods at given cladding temperatures. To satisfactorily obtain the desired test rod thermal and mechanical response, the PBF-LOCA system depressurization and mass flows must be known. The two-phase flow measurements are obtained from instruments installed in three pipe sections, or "spool pieces". The spool pieces employ flow instruments of differing measurement principles including a velocity sensor, a momentum sensor, and a mixture density sensor. Data from these instruments are combined with measurements of the thermodynamic state to determine two-phase mass flow rates.

The purpose of this paper is to address the interpretation and evaluation of the measured inlet, hot leg, and cold leg mass flows during the PBF-LOCA Test LOC-11C. To better understand these results and to evaluate the current capability to accurately calculate two-phase mass flow rates, posttest computer calculations using the RELAP4/MOD6 code, which is an updated version of RELAP4/MOD5[5], are compared with appropriate data. References 6 and 7 present details of the LOC-11 experimental results.

A brief description of the experiment design and conduct of Test LOC-11C is presented in Section 2. The posttest RELAP4/MOD6 computer model is presented in Section 3. The interpretation and evaluation of the PBF two-phase coolant flow measurements is presented in Section 4, and Section 5 presents conclusions.

2. EXPERIMENT DESIGN AND CONDUCT

The PBF LOC-11 tests were performed with the PBF-LOCA blowdown system. The system depressurization was controlled with converging-diverging nozzles and the tests were terminated with quench of the test fuel rods. The system hydraulic response was monitored with instruments mounted in measurement spool pieces located in the hot and cold legs of the blowdown piping. The conditions of Test LOC-11C were similar to those anticipated for a hypothetical double-ended cold-leg-break LOCA. Additional details regarding the experiment design and conduct are presented in the following discussion.

2.1 PBF-LOCA Blowdown System

The PBF-LOCA blowdown system and primary coolant loop are illustrated in Figure 1. During steady state operation, cooling for the test rods within the in-pile tube (IPT) was provided by the primary coolant loop. The blowdown was initiated by isolating the IPT from the primary coolant loop by opening LOCA bypass Valve HSV-7 and closing isolation Valves HSV-5 and -6. After a brief period of flow stagnation ($\sim$ 1.0 s), the IPT was depressurized into the blowdown tank

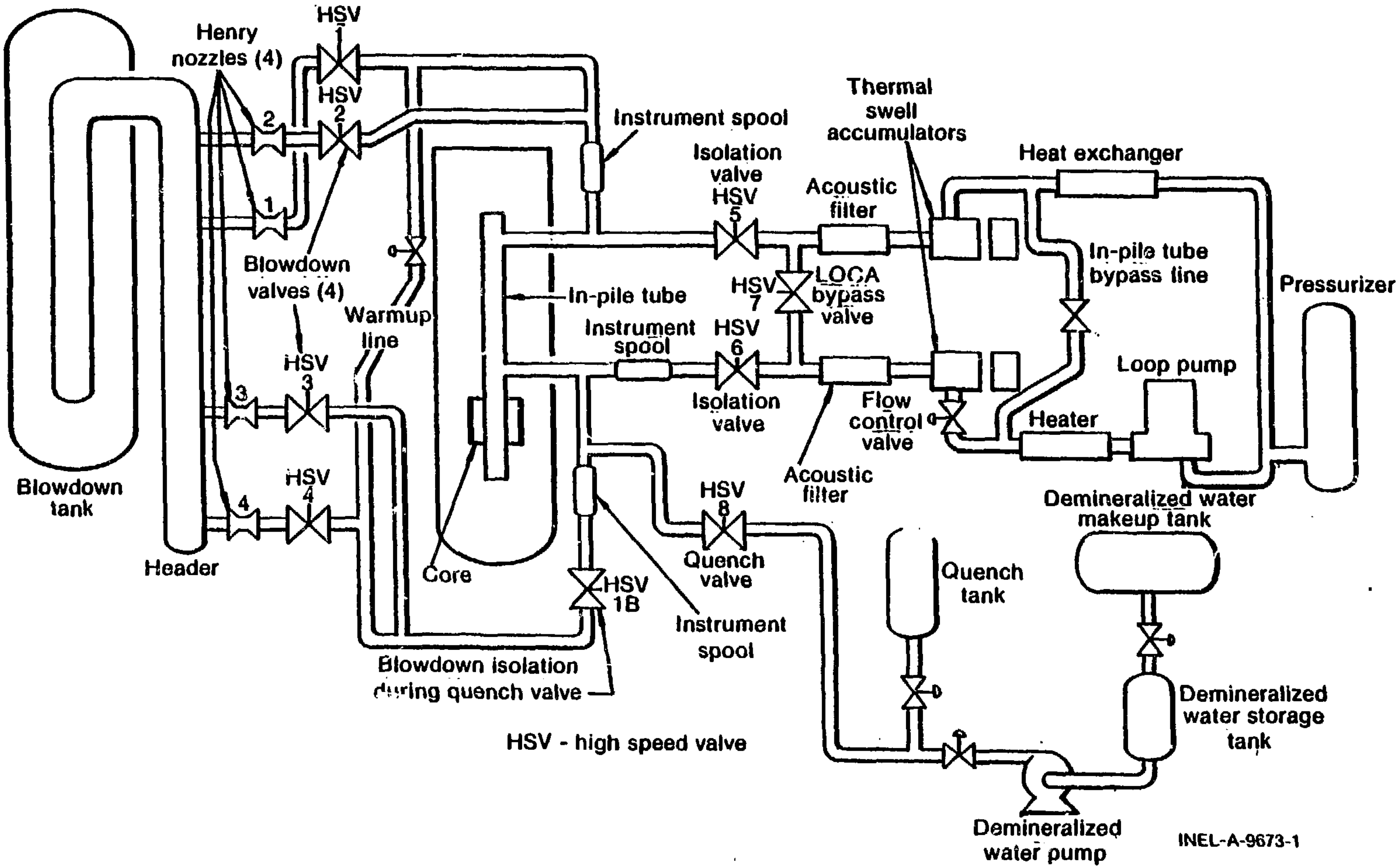


Fig. 1 PBF-LOCA blowdown system illustration.

through converging-diverging nozzles designed with a cylindrical throat section having equal length and diameter. The nozzles are located downstream of blowdown Valves HSV-1, -2, -3, and -4. The characteristics of the system depressurization were controlled by opening and closing the blowdown valves. The converging-diverging nozzles provided the break plane and controlled the break flow rate and depressurization rate. The test was terminated by quenching the test fuel rods. Quench was activated by opening quench Valve HSV-8 and closing the cold leg blowdown valves to permit coolant from the quench tank (pressurized by a nitrogen gas system) to enter the IPT.

2.2 Measurement Spool Piece Instrumentation

In the PBF-LOCA system, measurement of coolant conditions prior to blowdown is provided by the initial conditions instrument spool piece, and measurement of transient coolant conditions during and following blowdown is provided by the instrument spool pieces located in the hot and cold legs of the blowdown piping. A blowdown leg instrument spool piece is illustrated in Figure 2. The spool piece instrumentation includes a resistance temperature detector (RTD) (Rosemount) to measure the preblowdown temperature of the coolant; an exposed Type-K ribbon thermocouple (Rosemount) to measure the coolant temperature during the transient; a flush-mounted pressure transducer (Precise Sensors) to measure the preblowdown and subcooled decompression; a water cooled, stand-off mounted pressure transducer (Precise Sensors) to measure the preblowdown and saturated decompression; a full-flow turbine flowmeter with graphite bearings (Flow Technology) to measure both preblowdown coolant velocity in the inlet condition spool and transient velocity in the blowdown piping; a drag disc (EG&G Idaho, Inc.) in the blowdown leg spools to measure the coolant momentum flux during the transient; a three-beam gamma densitometer on the blowdown leg spools to measure the coolant density; and a hot-leg-to-cold-leg pressure difference transducer.

Each of the multibeam gamma densitometers located in the cold and hot legs was used to measure coolant density along three chords

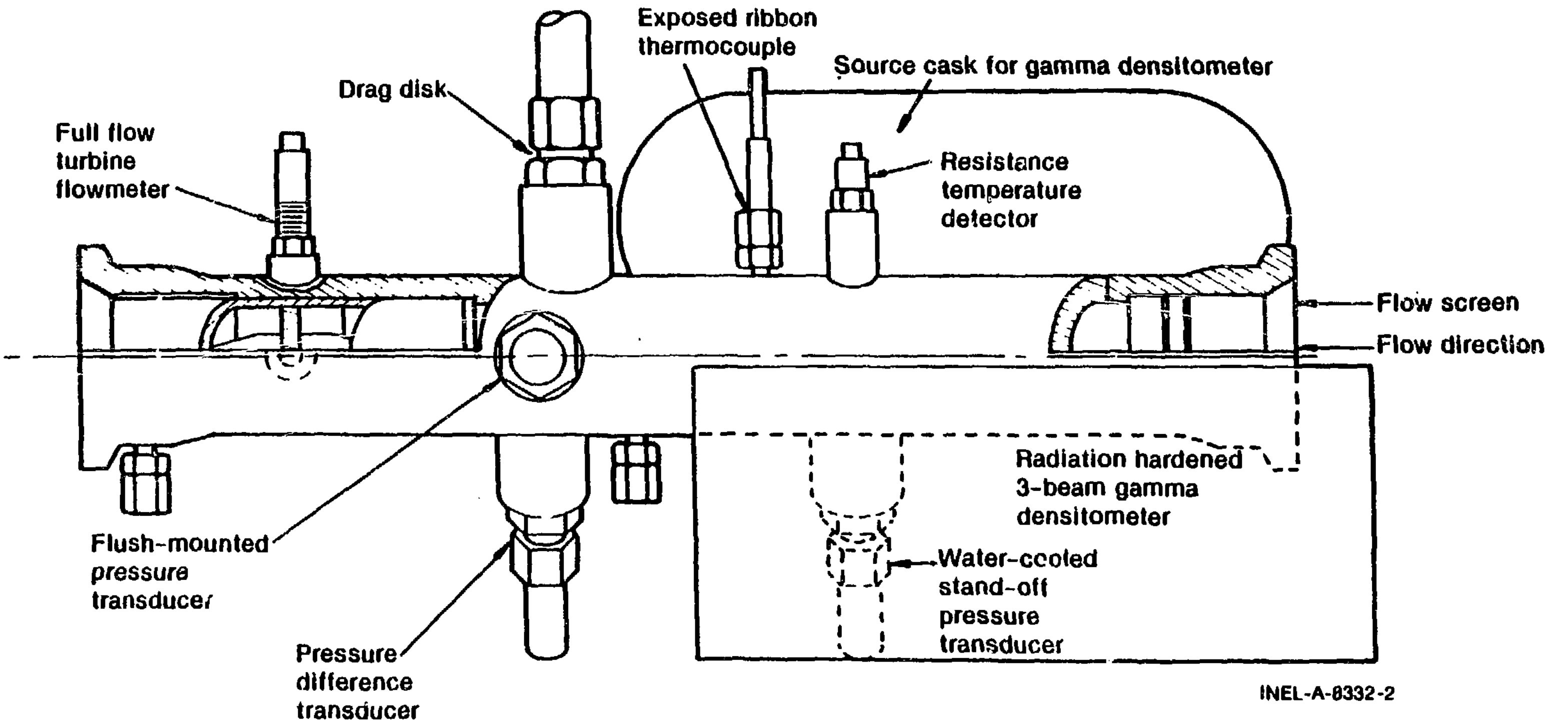


Fig. 2 Blowdown leg instrument spool piece with instrumentation.

through the piping and to determine the flow regime within the piping. These devices used the attenuation of gamma rays from a Cesium-137 source to sense the density of the mixture within the spool piece. Screens were placed at the inlet end of the measurement spools to minimize swirl and to disperse the liquid and vapor phases during the two-phase portion of blowdown. This should have permitted more representative and accurate measurements by both the turbine flowmeters, which measure the average coolant volumetric flow rate, and the drag discs, which measure coolant momentum flux. The drag disc was located in the center of the flow area and intercepted approximately 12% of the flow area.

Additional details of the IPT and fuel train instrumentation are discussed in Reference 6. Additional details of the instrumentation designation, location, range, response time, and signal conditioning are given in Reference 7.

2.3 Test LOC-11C Conduct and System Depressurization

The LOC-11 tests consisted of three separate blowdowns initiated from nuclear power operation. Data from the third blowdown, Test LOC-11C, are discussed in this paper. Test LOC-11C was conducted with an axial peak power of 69.9 kW/m, inlet coolant pressure of 15.3 MPa, inlet coolant temperature of 596 K, and a flow rate per rod of 0.99 l/s.

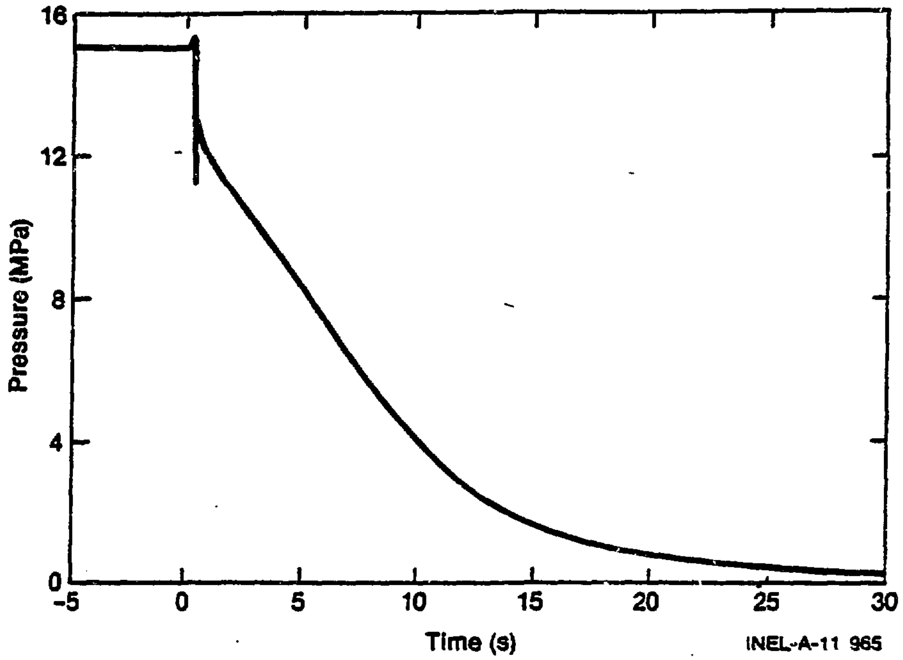
Prior to Test LOC-11C, Test LOC-11B was run with blowdown system isolation and reactor scram occurring at time zero. One blowdown valve opened in the hot and cold legs piping at about 0.9 s, as planned. This sequence allowed for a 0.9-s stagnation period prior to blowdown. Critical heat flux (CHF) occurred 3.2 s after isolation during Test LOC-11B and the peak measured cladding temperature reached 880 K. The initial peak rod power of Test LOC-11C was increased from the Test LOC-11B value in an attempt to obtain CHF at approximately 0.5 s and to obtain higher peak cladding temperatures. Also, for Test LOC-11C, blowdown was programmed to begin about 0.2 s after isolation and reactor scram, rather than at the 0.9 s programmed for Test LOC-11B. During Test LOC-11C, CHF occurred 1.6 s after isolation and the peak measured cladding temperature was 1030 K.

The measured system depressurization in the hot leg for Test LOC-11C is shown in Figure 3. The coolant pressure throughout the system was essentially uniform, with the primary pressure drop to the blowdown tank occurring across the converging-diverging nozzles in the cold and hot leg break lines (shown in Figure 1). From an initial steady state value of 15.3 MPa, the pressure dropped sharply to about 11.2 MPa immediately after the blowdown valves were opened at about 0.24 s. The system pressure remained relatively constant for approximately 0.1 s and then recovered to about 13.3 MPa at about 0.4 s. The small pressure fluctuations that were measured immediately following the subcooled depressurization at 0.24 s may only be ringing of the pressure transducer. The pressure recovery at about 0.38 s was approximately coincident with the establishment of choked flow at the nozzles which caused a pressure wave (water hammer) to propagate through the system. The saturated depressurization of the system followed, and system depressurization was completed within about 30 s.

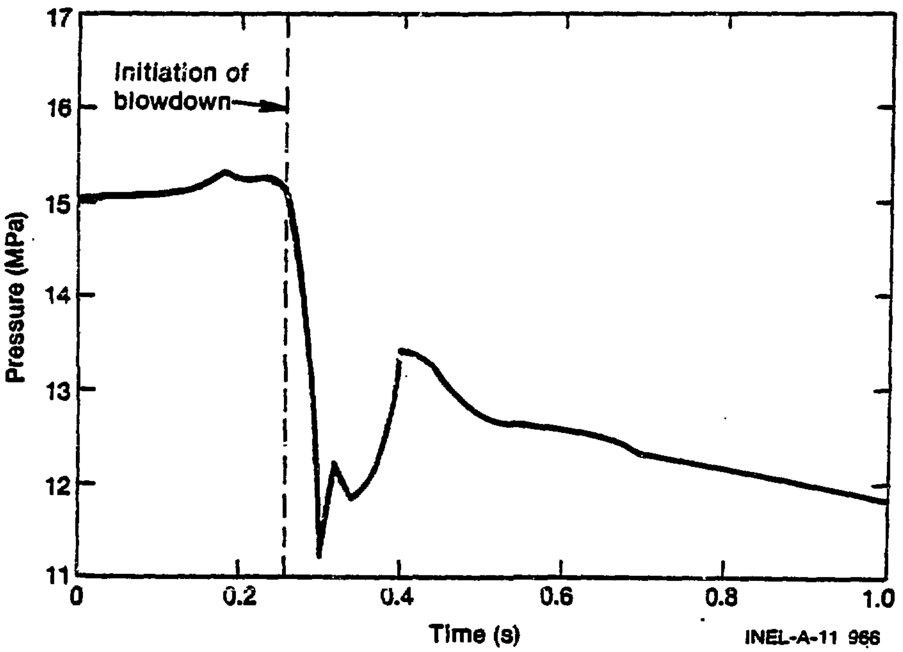
3. RELAP4/MOD6 MODEL

The mass flow leaving a simulated break in a piping system has been a difficult variable to calculate. The RELAP4/MOD6[a] computer code, which is an updated version of RELAP4/MOD5[5], was used for posttest calculations of the system thermal-hydraulics to better understand the test results and to evaluate the capability of the code to accurately calculate the fuel rod thermal-hydraulic boundary conditions. The nodalization of the posttest RELAP4/MOD6 model is shown in Figure 4. The most significant modeling options used in the posttest RELAP4/MOD6 calculations are summarized as follows:

(a) RELAP4/MOD6, Update 4, Idaho National Engineering Laboratory Configuration Control Number H003321B. This code is available from the National Energy Software Center, 9700 South Cass Ave., Bldg. 203, Room C230, Argonne, Ill. 60439.



(a) Long-term plot.



(b) Short-term plot.

Fig. 3 Comparison of measured and RELAP4/MOD6 calculated pressures in hot leg for Test LOC-11C.

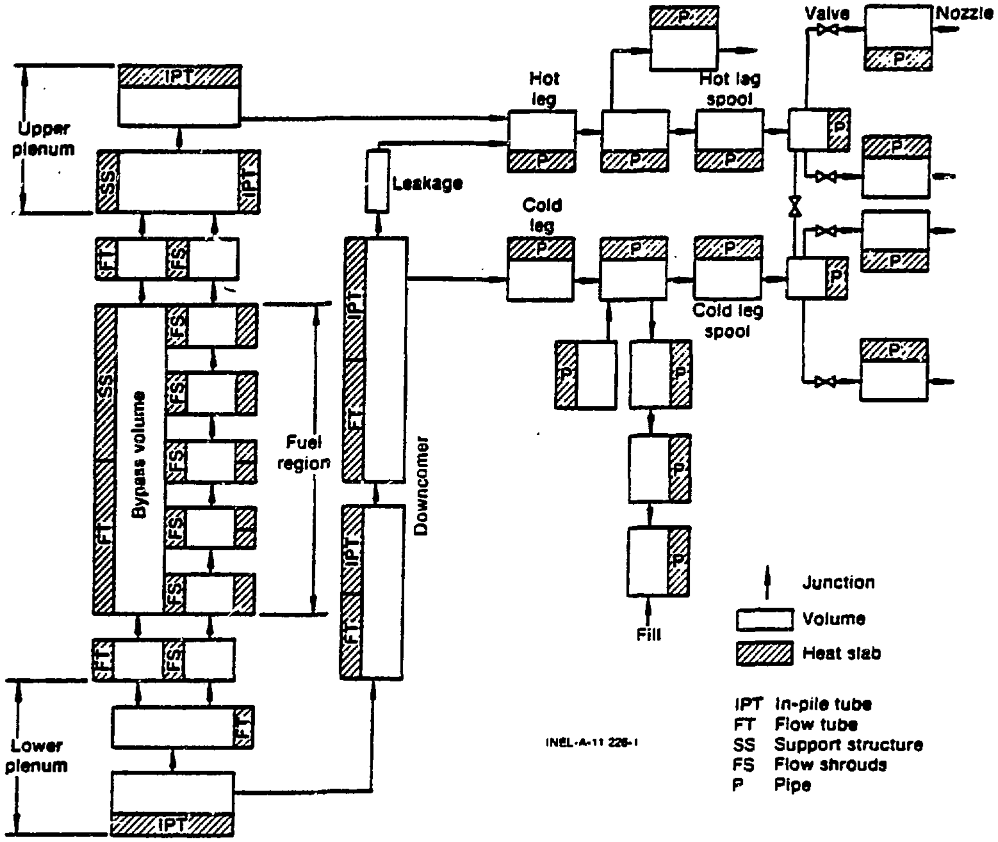


Fig. 4 RELAP4/MOD6 posttest model of PBF-LOCA blowdown system for LOC-11 tests.

(1) The Henry-Fauske[8] and the homogeneous equilibrium model (HEM)[2] critical flow models were used. The Henry-Fauske model, which is used to calculate break flow rates with subcooled upstream coolant conditions, includes thermodynamic nonequilibrium effects at the break plane which have been demonstrated to be important during subcooled blowdowns[8]. The HEM, used when the upstream coolant conditions are two-phase with a quality greater than 0.02, assumes the flow at the break plane to be homogeneous and in thermal equilibrium. Recommended values for the multiplier function resulted in an overestimate of the system depressurization. Posttest

calculations using a multiplier of unity gave the best agreement between posttest calculations and coolant flow rate as measured at the measurement spool pieces.

(2) The RELAP4/MOD6 best estimate blowdown heat transfer package, which includes: Tong's W-3[9] correlation for subcooled CHF; the Hsu-Beckner[10] modified W-3 correlation for saturated high flow CHF; the modified Zuber[11] correlation for saturated low flow CHF; the modified Condie-Bengston[5] film boiling correlation; and natural convection and radiation heat transfer to superheated steam. The heat transfer subroutine was modified to include radiation heat transfer from the fuel rod to the flow shroud.

(3) The RELAP4/MOD6 default model for slip at all vertical junctions.

(4) The Ross-Stoute[12] pellet-to-cladding gap conductance, and Cathcart[13] zircaloy metal-water reaction models.

(5) A radial rod power profile (not available in the standard RELAP4/MOD6 version).

The posttest RELAP4/MOD6 calculations of coolant volumetric flow, density, and mass flow are discussed later in the next section.

4. TEST LOC-11C TWO-PHASE MASS FLOW MEASUREMENTS

The hot and cold legs coolant mass flows during Test LOC-11C were determined from independent measurements of coolant volumetric flow (Q), density (ρ), and momentum flux(ϕ). These variables were measured with the full-flow turbine flowmeters, gamma densitometers, and drag disc discussed previously. The measurements of hot leg coolant volumetric flow and density are evaluated and compared with RELAP4/MOD6 calculations. The measured coolant momentum flux is not evaluated separately because the instrument range was severely restricted to obtain a relatively high resolution during the transient after the initial flow spike. The measurement was relatively constant throughout much of the transient. The three independent determinations of the hot leg coolant mass flow for Test LOC-11C are compared in Section 4.3, and an average coolant mass flux is discussed in Section 4.4. The average mass flow is also compared with posttest RELAP4/MOD6 calculations. Finally, the total measured mass of coolant ejected from the system during Test LOC-11C is compared with the initial mass inventory in Section 4.5.

4.1 Volumetric Flow

The measured and calculated hot leg coolant volumetric flow for Test LOC-11C are shown in Figure 5. During the subcooled depressurization, a large flow spike of about 62 l/s was observed. The flow decreased to less than 10 l/s when the flow choked at the nozzle at about 0.5 s. After the establishment of choked flow, the flow rate again increased, almost linearly, for about 12 s until it reached approximately 38 l/s at around 13 s. The hot leg coolant velocity then remained essentially constant throughout the remainder of blowdown. The changes observed in the hot leg volumetric flow during the saturated blowdown basically reflect the variations in the coolant density which are discussed in Section 4.2.

The calculated volumetric flow, shown in Figure 5, is in good agreement with the measured data. The magnitude and duration of the initial flow spike was calculated very well. During the first 15 s of the saturated depressurization, the mass flow was only slightly undercalculated. After 15 s, the coolant volumetric flow was overcalculated, and RELAP4/MOD6 calculated that the flow became unchoked between 23 and 25 s. The overestimation of the volumetric flow after 15 s is probably related to the choice in break flow model and multiplier. However, as will be shown in Section 4.3, the net effect of this error on the determination of coolant mass flow is very small because of the low coolant density after about 10 s.

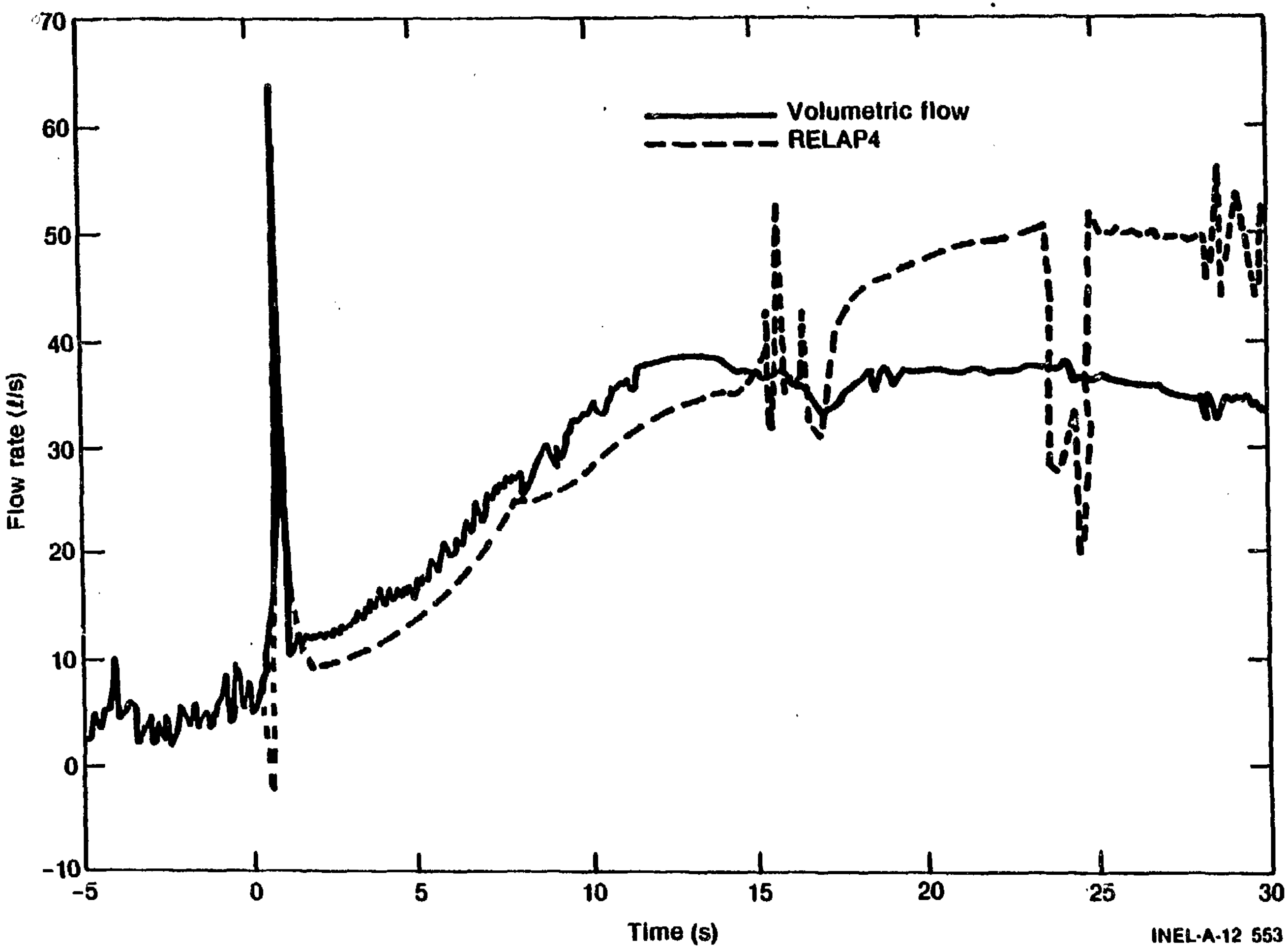


Fig. 5 Comparison of measured and RELAP4/MOD6 calculated volumetric flows in hot leg for Test LOC-11C.

4.2 Coolant Density and Phase Separation

The model used to determine the coolant mass flow rate from the measured coolant velocity, density, and momentum flux is based on the assumption of homogeneous flow. Chordal density data were obtained from the gamma densitometers at different elevations within the horizontally oriented measurement spool pieces. These data provided a direct measurement of coolant density and also an indication of flow regime and possible phase separation. The chordal density data from the three hot leg gamma beams are shown in Figure 6. Over the interval from 1 to 6 s, a density gradient existed as a function of elevation within the hot leg spool, indicating that phase separation had occurred. After 9 s the chordal average densities became nearly equal, with the quality approaching unity. A more uniform density was reasonable after 9 s because the high coolant velocity promoted increased mixing and phase dispersion at this high quality.

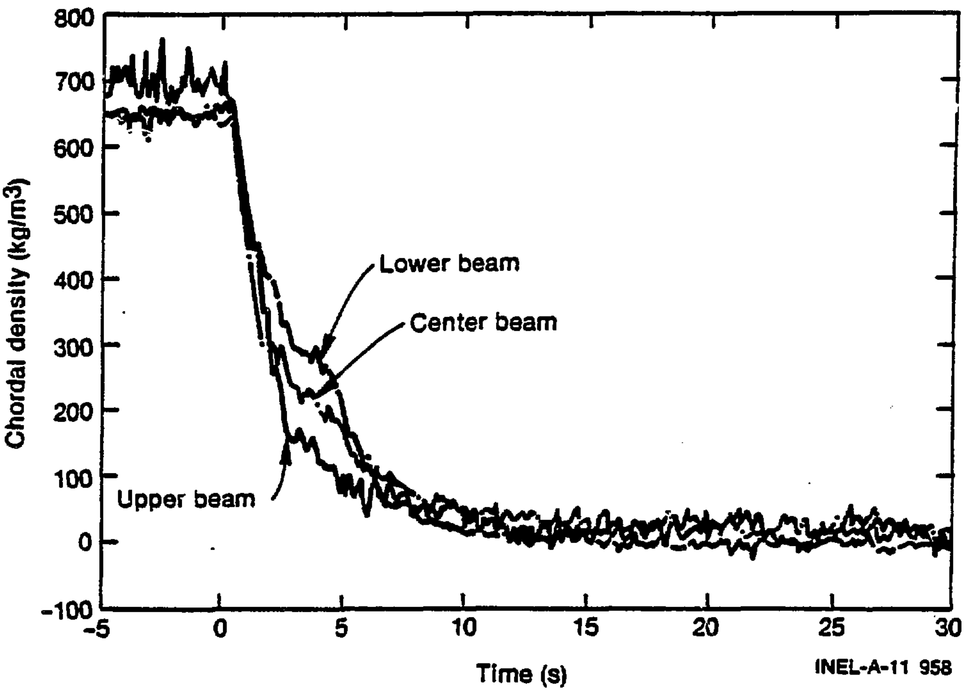


Fig. 6 Hot leg spool chordal average density as determined from three beams of gamma densitometer for Test LOC-11C.

A cross-sectional average density for the hot leg spool piece was determined by fitting a linear density gradient through the upper and lower chordal densities, integrating the gradient over the cross-sectional area, and then combining the result with the center beam density. The density obtained from integrating the gradient was weighted by two-thirds, and the center beam density was weighted by one-third. Since the density does not appear to be uniform across the pipe from 1 to 6 s, as illustrated by Figure 6, the excellent agreement in Figure 7 between the RELAP4/MOD6 calculations and the measured LOC-11C data suggests that the assumption of a linear density gradient was probably correct, except possibly between 2 and 3 s.

4.3 Mass Flow as Determined by the Three Independent Measurements

Coolant mass flow rates in the PBF Test LOC-11C measurement spools were determined from the three independent hydraulic measurements: average density ($\bar{\rho}$), momentum flux (ϕ), and volumetric flow rate (Q) or velocity. The mass flows (W) were determined using the following equations for the three combinations of the measurements:

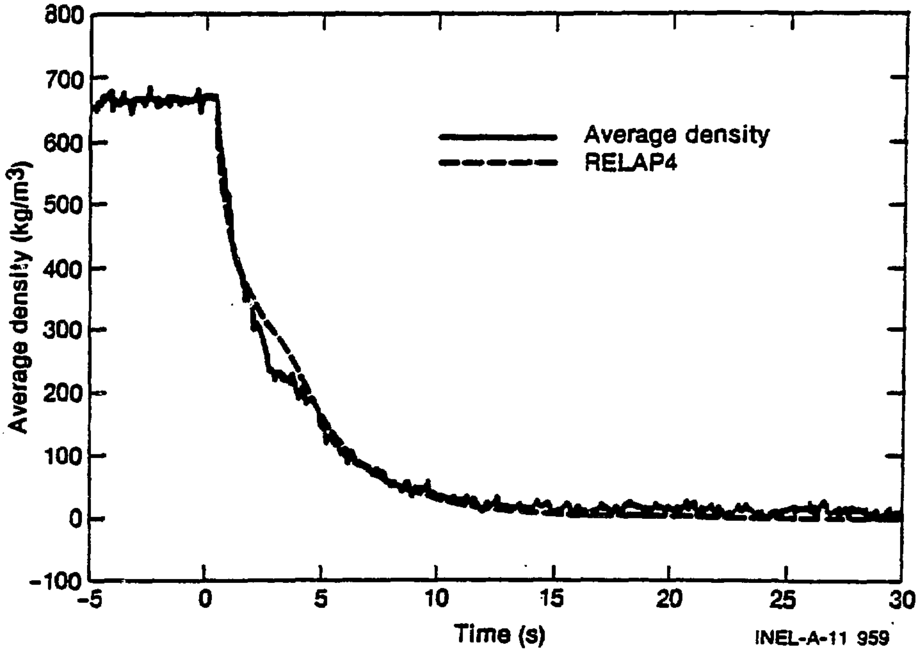


Fig. 7 Hot leg spool average density as determined from three-beam gamma densitometer for Test LOC-11C.

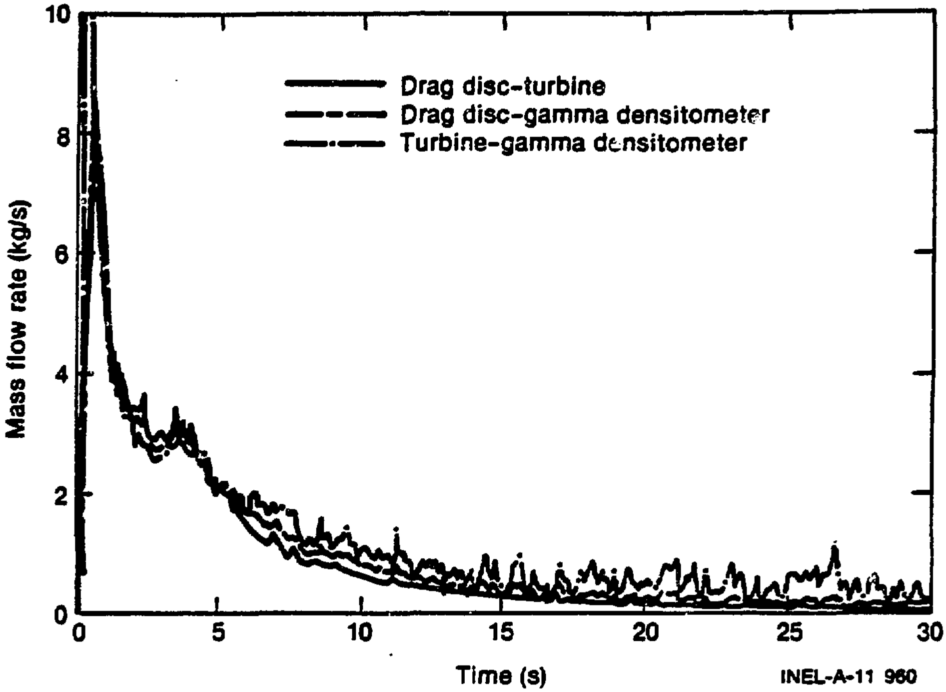
$$\text{Momentum flux/volumetric flow} - W_1 = A^2 \phi/Q \quad (1)$$

$$\text{Volumetric flow/density} - W_2 = \bar{\rho}Q \quad (2)$$

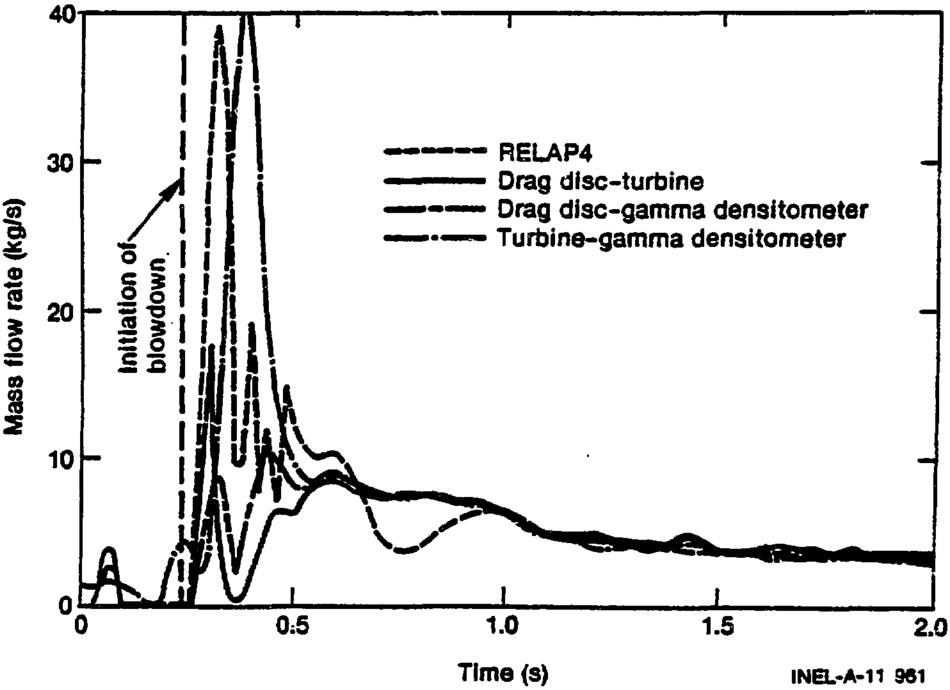
$$\text{Momentum flux/density} - W_2 = A(\bar{\rho}\phi)^{1/2}. \quad (3)$$

The hot leg coolant mass flows determined from the three independent measurements are shown in Figure 8. The measurements indicate that when the hot leg blowdown valve was opened a large flow spike with a duration of about 0.15 s occurred. Only the volumetric flow and density measurement combination indicates the large flow spike because the momentum flux measurement was range-limited at high flow so that the instrument would have a high resolution at lower mass flow rates. The measured mass flow rapidly decreased after the large flow spike, and the three independent calculations of mass flow are in excellent agreement after 0.6 s.

During the initial flow spike at about 0.4 s, a rather complex three-component, two-phase flow process may have been occuring at the high-speed blowdown valves and the converging-diverging nozzles. Initially, the sections of pipe between the blowdown valves and nozzles were air-filled at a pressure of approximately 0.1 MPa and a temperature of about 318 K, compared with about 600 K for the upstream piping. Also, an axial temperature gradient existed along these pipes, since heat was being transferred to the pipes by axial conduction from the blowdown valves. When the blowdown was initiated by opening the blowdown valves, the coolant flowing into the downstream piping between the valves and nozzles flashed due to the 15.2 MPa initial pressure difference across the valves, and choked flow was established at the minimum area section of the valves. The relatively cold pipe condensed the steam and cooled the liquid as it entered the sections of pipe between the blowdown valves and the nozzels. The flashing process continued until the pressure increased to the saturation pressure (11 to 12 MPa).



(a) Long-term plot.



(b) Short-term plot.

Fig. 8 Comparison of measured and RELAP4/MOD6 calculated mass flow rates in hot leg for Test LOC-11C.

If no mixing of the air with the steam-water mixture is assumed, the air would be cleared from the piping upstream of the nozzle throat within 10 ms. Since the time to clear the air was short compared with the time required to open the blowdown valves ($\sim$100 ms), the presence of air in the piping upstream of the nozzles should not significantly affect the system blowdown. Posttest calculations indicate that approximately 80 ms are required to raise the pressure in the piping between the blowdown valves and nozzles to the saturation pressure and to condense the steam formed by flashing across the blowdown valves. After all the steam had been condensed upstream of the nozzles, a water hammer occurred because the flow choked at the nozzles which reduced the flow rate through the valve (a reduction in coolant momentum results in a pressure shock wave). The pressure wave propagated upstream and was rapidly dissipated, since coolant flashing occurred simultaneously in the blowdown piping legs.

4.4 Comparison of Average Mass Flow with the RELAP4/MOD6 Calculation

An average mass flow rate was determined by arithmetically averaging the three mass flow rates calculated with Equations (1), (2), and (3), as

$$\overline{W} = \frac{1}{3}\left[(\overline{\rho}\phi) + \frac{A^2\phi}{Q} + A\ (\overline{\rho}\phi)^{1/2}\right]. \qquad (4)$$

More exact models have been postulated which include slip between phases[6].

The hot leg average mass flow rate determined from using Equation (4) and the RELAP4/MOD6 calculated mass flow are shown in Figure 9. The different phases of the transient (that is, blowdown, heatup, and quench) are denoted to illustrate the specific flow behavior associated with each phase. The calculated mass flow, shown in Figure 9, is in excellent agreement with the data except during the initial flow spike at about 0.4 s, when the average measured mass flow is about 13 l/s compared with a RELAP4/MOD6 calculated value of

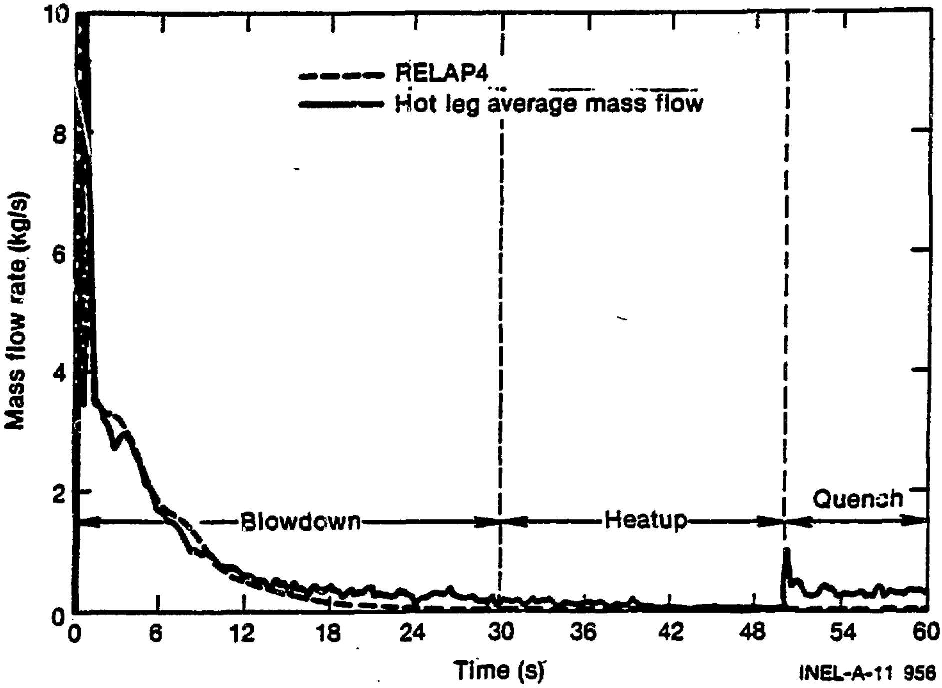


Fig. 9 Comparison of averaged and RELAP4/MOD6 calculated mass flow rates in the hot leg for Test LOC-11C.

approximately 38 l/s. The RELAP4/MOD6 calculated mass flow is compared with the three independent measurements of mass flow in the short-term plot in Figure 8. Of the three methods of determining mass flow, only the turbine-gamma densitometer combination indicates a large flow spike (~40 l/s), which is in good agreement with the RELAP4/MOD6 calculations. As mentioned previously, the range of the drag disc was limited; therefore, the spike was not evident in the measurement from that system. After the initial spike, the mass flow rate decreased as the coolant density and pressure in the system decreased during blowdown and finally equilibrated with the blowdown tank pressure. When coolant was injected at 50 s to quench the fuel rods, the observed flow rate increased almost immediately, reaching a value equal to the coolant injection flow rate after the system had filled and the injected coolant had reached the hot leg measurement spool.

4.5 Total Mass Flow Ejected from the System

The total coolant mass ejected from the system during Test LOC-11C was obtained by time integrating the hot and cold legs mass flow measurements with respect to time. Results of the integration show that 33.88 and 37.40 kg of coolant mass was ejected from the hot leg and cold leg, respectively. The sum total of coolant mass ejected is 71.28 kg compared with the initial inventory of 68.44 kg. The small difference (2.84 kg) between the integrated mass flows and mass inventory suggest the spool mass flow measurements are correct to within approximately 5%. The time-integrated mass flows were calculated using the average values from 0.6 s until completion of the test and the values obtained from the volumetric flow-density measurements during the initial flow spike.

5. CONCLUSIONS

The coolant mass flows calculated from the measured Test LOC-11C mixture densities, momentum fluxes, and volumetric flows by the homogeneous relationships was found to be generally satisfactory. Cross-sectional average densities were determined by fitting a linear density gradient through the upper and lower chordal densities obtained from a three-beam gamma densitometer and then combining the result with the middle beam density. This technique was determined to be satisfactory even when a density gradient as a function of elevation within the horizontal blowdown pipes existed between 1 and 6 s. An average coolant mass flow in the hot and cold legs was determined by arithmetically averaging the mass flows calculated using separate combinations of the coolant mixture density, momentum flux, and velocity. These average values were apparently correct except during periods of very high volumetric flow, when the drag disc was range-limited (between 0.3 and 0.5 s). The integrated measured coolant mass flow was found to be within 5% of the initial coolant mass inventory of the PBF-LOCA blowdown system. The RELAP4/MOD6 posttest calculations of coolant mass flow also agreed well with the measured data

6. REFERENCES

1. United States Nuclear Regulatory Commission, Reactor Safety Research Program, A Description of Current and Planned Reactor Safety Research Sponsored by the Nuclear Regulatory Commission's Division of Reactor Safety Research, NUREG-75/058 (June 1975).

2. H. Estrada, Jr., and J. D. Sheppard, Some Aspects of Interpreting Two-Phase Flow Measurements in Instrumented Piping Spool Pieces, NUREG-0280 (June 1977).

3. Y. Y. Hsu, Two-Phase Flow Instrumentation Review Group Meeting, NUREG-0375 (March 1978).

4. M. N. Hutcherson, Contribution to the Theory of the Two-Phase Blowdown Phenomenon, ANL-75-82 (1975).

5. K. R. Katsma et al, RELAP4/MOD5, A Computer Program for Transient Thermal-Hydraulic Analysis of Nuclear Reactors and Related Systems, User's Manual, ANCR-NUREG-1335 (September 1976).

6. J. R. Larson et al, PBF-LOCA Test Series Test LOC-11 Test Results Report, NUREG/CR-0618, TREE-1329 (April 1979).

7. R. J. Buckland, C. E. Coppin, C. E. White, Thermal Fuels Behavior Program Experiment Data Report for Tests LOC-11B and LOC-11C, NUREG/CR-0303, TREE-1232 (October 1978).

8. R. E. Henry and H. K Fauske, "The Two-Phase Critical Flow of One Component Mixtures in Nozzles, Orifices and Short Tubes," Journal of Heat Transfer, Transactions of the American Society for Mechanical Engineers, 93 (May 1971) pp 179-187.

9. L. S. Tong, Boiling Crisis and Critical Heat Flux, TID-25887 (August 1972)

10. Y. Y. Hsu and W. D. Beckner, "A Correlation for the Onset of Transient CHF," cited in L. S. Tong and G. L. Bennet, "NRC Water Reactor Safety Research.Program," Nuclear Safety, 18 (1) (January/February 1977)

11. R. A. Smith and P. Griffith, "A Simple Method for Estimating Time to CHF in a PWR LOCA," Transactions of the American Society of Mechanical Engineers, Paper No. 76-HT-9 (1976).

12. A. M. Ross and R. L. Stoute, Heat Transfer Coefficient Between UO_2 and Zircaloy-2, AECL-1552 (June 1972).

13. J. V. Cathcart, Quarterly Progress Report on the Zirconium Metal-Water Oxidation Kinetics Program Sponsored by the NRC Division of Reactor Safety Research for October-December 1976, ORNL/NUREG/TM-87 (February 1977).