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DEVELOPMENT REPORT

**FLASH6 SIMULATION OF SEMISCALE
BLOWDOWN DATA, NRC STANDARD
PROBLEMS 2 AND 3**

EB (LWBR Development Program)

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BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA
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FOREWORD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the DOE-owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and is expected to be operated for about 3 to 4 years. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expanded Core Facility for a detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration established the Advanced Water Breeder Applications (AWBA) program to develop and disseminate technical information which would assist U. S. industry in evaluating the LWBR concept for commercial-scale applications. The program will explore some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information to be developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores while producing electric power, improvements for breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) have been administered by the Division of Naval Reactors with the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

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FLASH6 computer program calculations are compared with experimental data from two simulated loss-of-coolant accident blowdown tests which are designated as numbers 2 and 3 in the Standard Problem Series sponsored by the Nuclear Regulatory Commission for reactor safety assessment. Both tests are isothermal blowdowns simulating a double-ended, cold-leg break and were conducted in the electrically-heated, 1-1/2 Loop Semiscale System at Idaho National Engineering Laboratory. The blowdown tests were initiated at nominal conditions of 575°F, 2250 psia and 17.3 lbm/sec loop flow rate. Comparisons were made of a wide variety of variables over the entire time period of each experiment including emergency cooling injection for Standard Problem No. 3. Good agreement is demonstrated between the FLASH6 best estimate analysis results and the data, particularly during the blowdown phase of the transient.

FLASH6 SIMULATION OF SEMISCALE BLOWDOWN DATA,
NRC STANDARD PROBLEMS 2 AND 3
(LWBR Development Program)

I. INTRODUCTION

The Nuclear Regulatory Commission's Comparative Analysis of Standard Problems program consists of a series of pretest predictions of experimental data related to reactor safety assessment. The objective of conducting these analyses is to assess the degree of conservatism inherent in licensing calculations and to partially qualify FLASH6 for analysis of the LWBR postulated loss-of-coolant accident. Best estimate simulations have been conducted with the FLASH6 computer program (Reference 1) for Standard Problems No. 2 and No. 3, which are isothermal blowdowns of the 1-1/2 Loop Semiscale System.

There have been several separate series of tests conducted at the Idaho National Engineering Laboratory (INEL) which have used the name

Semiscale. The first Semiscale test apparatus had a single loop with a pump, steam generator and rupture discs. The simulated core had 120 rods with a nine inch electrically heated length. FLASH simulations of tests from this series are discussed in Reference 2. A second series of tests called the 1 1/2 Loop Semiscale tests have an operating loop with a steam generator and pump and an inactive loop with hydraulic resistances simulating the pump and steam generator. Although a nine rod bundle was inserted in the vessel, the rods were used only to heat the system up to operating conditions. No heat was generated in the rods during a blowdown. Standard Problems 2 and 3 are a part of this test series. Standard Problem 2 is a double ended cold leg break at 80% of full nozzle flow area without ECCS injection. Standard Problem 3 is a double ended cold leg break at 100% of full nozzle flow area with ECCS injection into the operating and broken loop cold legs.

Semiscale isothermal test 1011 (Standard Problem 2) and Semiscale isothermal test 1009 (Standard Problem 3) have been simulated using the FLASH6 program as discussed in the following sections. These computer simulations were performed with the intent of providing best estimate calculations. Extensive comparisons between FLASH6 calculations and the experimental data are provided to demonstrate the ability of FLASH6 to predict LOCA phenomena. The time period over which FLASH6 comparisons are made is the entire time period for which data are reported; 0-45 seconds for Standard Problem No. 2 and 0-90 seconds for Standard Problem No. 3. Other Standard Problem participants provided calculations for the blowdown portions of the transients only (approximately 0-30 seconds).

II. SYSTEM AND COMPONENT DESCRIPTION

The 1-1/2 Loop Semiscale apparatus models a four-loop PWR during a simulated loss-of-coolant accident. A detailed description of this test program and the apparatus is given in Reference 3. Figure 1 shows an isometric view of the 1-1/2 Loop Semiscale system including instrument locations. The system components include a pressure vessel with a core barrel and electrically heated rod bundle; a blowdown loop which includes a simulated steam generator, simulated pump and two rupture disc assemblies; an operating loop which includes a pressurizer, steam generator, and a pump; and a pressure suppression system which includes a header and a tank.

A. Vessel and Core Assembly

The Semiscale vessel components consist of a pressure vessel which is 11 feet high, a vessel filler and filler insulator, a core barrel and barrel insulator and nine electrical heating rods. The vessel and core assembly consists of an inlet annulus, downcomer annulus, a lower plenum, flow mixer box, a rodded core region, and an upper plenum. Flow enters the vessel by way of the inlet annulus and flows down the downcomer into the lower plenum during normal operation. After arrival in the lower plenum, the coolant travels inside the core barrel through the turbine flow meter into the rodded region of the core.

B. Blowdown Loop

The blowdown loop models one broken loop of a PWR during a LOCA and is composed of a simulated steam generator, simulated pump, two rupture disc assemblies and the primary coolant piping which is 2 inch schedule 160. The simulated steam generator consists of a U-shaped housing with restricting orifices. Four orifices are used to obtain the specified hydraulic resistance. Two orifices in a U-trap simulate the blowdown coolant pump. Each of the two rupture assemblies consists of a blowdown nozzle and two banana-peel-type rupture discs. The chamber between the rupture discs is filled with helium at about one-half the primary system pressure. When the operating pressure is reached within the primary system, the discs are ruptured by the helium being vented from the chamber to increase the differential pressure between the cavity and the primary system and this differential pressure causes the primary pressure to rupture the inner (blowdown

loop side) disc first and then the outer (suppression system side) disc.

C. Operating Loop

The operating loop consists of the primary coolant piping, steam generator, pressurizer and circulating pump. The primary coolant piping is mostly 3-inch Schedule 160. The piping consists of replaceable spool pieces which are connected by Grayloc fittings. The steam generator is a tube-and-shell heat exchanger. The primary coolant flows into the inlet plenum, downward through 43 coolant tubes into the outlet plenum, and out the exit nozzle. The pressurizer is an electrically heated vessel connected to the primary piping between the pressure vessel and the steam generator inlet. Pressurizer operation is similar to that of its counterpart in a PWR in that the water in the partially filled pressurizer is maintained at the saturation temperature corresponding to the desired system pressure. The circulating pump is a volute type, heavy duty horizontal centrifugal pump rated for a nominal flow of 182 gpm at a total head of 192 ft of water at 3560 rpm. The pump is belt-driven through an integral torque motor by a variable speed, DC electric motor.

D. Pressure Suppression System

Blowdown effluent is discharged from the blowdown loop into a 16-inch header that simulates, in general, the drywell in a PWR pressure suppression system. The effluent flows from the header into the vessel water pool through an 8-inch downcomer. The pressure suppression system accepts 100% of the blowdown water in the 1-1/2 loop primary system.

E. ECC Injection System

The ECC injection system consists of two accumulator subsystems and two pump subsystems. The system can supply simulated emergency core coolant to the pressure vessel lower plenum or to the operating loop and the blowdown loop. The ECC Injection System was designed to provide simulated core cooling to the operating loop and to the blowdown loop in identical ratios of ECC flow to loop volume; that is, the operating loop ECC system (scaled to represent three injection systems of a typical PWR) provides about three times the flow of the blowdown loop ECC system (simulating the injection system of the broken loop of a typical PWR).

No ECCS was used in Standard Problem 2, and only accumulator injection into the cold legs was used for Standard Problem 3.

III. DESCRIPTION OF EXPERIMENTS

Both tests 1011 (Standard Problem 2) and 1009 (Standard Problem 3) are isothermal blowdowns from nominal conditions of 575°F, 2250 psia and 17.3 lbm/sec loop flow rate. Test 1011 is a double ended cold leg break at 80% of full nozzle flow area, while test 1009 is a double ended cold leg break at 100% of full nozzle flow area with ECCS injection into the operating loop and blowdown loop cold legs. The actual initial conditions differed slightly from the nominal conditions and are given in Table I.

TABLE I
Conditions at Blowdown Initiation

	<u>Test 1011</u>	<u>Test 1009</u>
Core Outlet Temperature (°F)	577.	577.
System flow rate (gpm)	172.	173.
System pressure at vessel outlet (psig)	2258.	2245.
Pump differential pressure (psid)	37.	41.
Pump speed (rpm)	2983.	3050.
Suppression tank pressure (psia)	Atmospheric	Atmospheric
Pressurizer water volume (ft ³)	.48	.52
Operating loop accumulator pressure (psig)	--	1120.
Blowdown loop accumulator pressure (psig)	--	600.

With the exception of pump speed, the initial conditions of Test 1011 were used in the FLASHG simulations for both tests.

Experimental data recorded for Isothermal Test 1011 and 1009 included the following test variables: fluid temperature, metal temperature, momentum flux, mass flow rate, volumetric flow rate, pressure, differential pressure, density, pump speed, pump torque and pump power. Data for Standard Problems 2 and 3 are reported in References 4 and 5, respectively.

IV. FLASH6 MODEL DESCRIPTION

FLASH6 represents a thermal-hydraulic system such as the Semiscale facility using a combination of control volumes (nodes) and connecting flow paths. Mass and energy balances are performed on the control volumes, and the conservation of momentum equation is applied to the flow paths to determine the mass transport rate between the control volumes. A complete description of the FLASH6 computer program is given in Reference 1.

A schematic of the FLASH6 model used to represent the Semiscale system in the analysis of Standard Problem 2 is shown in Figure 2. The fourteen node, sixteen flowpath model was selected to preserve important liquid levels and pressure drops. Scaling of the Semiscale apparatus is such that orifices are placed in the operating and blowdown loops to obtain pressure drops typical of a PWR. Steady-state tests were run to determine the pressure drops. Measurements were made at a limited number of points around the loops at locations between orifices. The availability of the measured pressure drops between these points plus the presence of the orifices, across which most of the pressure drop occurred, made it convenient to select node boundaries at or near orifices. Also, vertical stacking of nodes was minimized.

The FLASH6 model for Standard Problem 3 is identical to that for Standard Problem 2 except: 1) four additional flowpaths are added to represent accumulator injection and reverse flow through the rupture assemblies, 2) the break flow area is modified and 3) pump speed is set to match test conditions.

A. Control Volumes

The operating loop is represented by nodes 1 through 7. The pressure vessel region is represented by nodes 8, 9 and 13. The broken loop is represented by nodes 10, 11 and 12. The cold leg stub and attached rupture disc assembly are included in node 13.

The pressure suppression system is modeled in node 14. Node 14 contains both the header and pressure suppression tank. Since the header pressure versus time plots were provided to Standard Problem participants, pressure in Node 14 was specified as a function of time.

Both the simple and the detailed FLASH6 plant metal heat capacity models are used to represent heat transfer from the hot metal. Also the bubble rise velocity is set to zero in all nodes except nodes 1, 8, 9 and 14 which represent the pressurizer, outlet plenum, inlet plenum and pressure suppression system, respectively. This results in a homogeneous representation of the remaining nodes during the blowdown.

B. Flow Paths

Flow paths 1 and 2 represent the simulated core path (i.e. rodged region) and the leakage path (i.e. annulus between the inner and outer core barrels) with no heat generation.

The operating loop flow is represented by flow paths 3 through 10. Quadratic representations were used for both the pump head and efficiency curves. The flow around the blowdown loop is represented by flow paths 11 through 13. Flow path 14 represents the downcomer. The detailed momentum equation option without momentum convection was used in all 14 momentum type paths.

Flow paths 15 and 16 model the flow into the pressure suppression system. For Standard Problem 3 it was necessary to add two additional leak paths to connect the containment to the system. The injected cold ECCS liquid depressurizes the system and causes reverse flow through the break nozzles. FLASH6 leak paths do not permit reverse flow, so it was necessary to add leak paths to model the flow back into the system. In Standard Problem 2 there is no reverse flow to be represented. Also, accumulator paths were added for Standard Problem 3 to represent the ECCS system. The large and small accumulator tanks are modeled by flow paths 19 and 20, respectively. The ECC of the large accumulator is injected into node 2 while the ECC of the small accumulator is injected into node 12.

The simulations were first run for 20.0 seconds in the steady-state and then the blowdown transient was initiated on restart.

V. NODING AND SENSITIVITY STUDIES

As discussed in Section IV, the FLASH6 noding for the Semiscale test system was selected to preserve important liquid levels and pressure drops. The limited availability of measured pressure drops together with the fact that most of the pressure drop occurred across orifices combined to fairly well determine the selection of nodes. A limited noding sensitivity study was conducted for Standard Problem 2 in the downcomer region in which nodes 9 and 13 were combined into a single node. However, this model failed to give a reasonable representation of the liquid level in the lower plenum.

Time step sensitivity studies for Standard Problem 2 revealed that time steps of size 0.003 sec and 0.0015 seconds yielded virtually identical solutions. Hence a time step size of 0.0015 seconds was used. Total CDC-7600 run time was approximately nine minutes for the 45.0 second transient.

The same 14 nodes were used for Standard Problem 3. As discussed in Section IV, two additional leakage paths connecting the pressure suppression system back to the blowdown loop and two accumulator injection paths were added. A number of sensitivity studies were conducted to study the behavior of the FLASH calculations in the region of ECCS injection in the operating loop. These sensitivity studies were prompted by observed differences between the experimental data and the calculated system response. The data show no significant reversed flow in the piping represented by flow path 4. However, the calculations show a period of significant reverse flow (from node 2 to node 3) during which node 3 becomes completely filled with liquid.

A noding sensitivity study was made in which nodes 2 and 3 were represented by a total of five nodes. No significant differences in calculated system response were detected with this 17 node model. Another sensitivity study consisted of specifying a very large reverse flow loss factor for the pump path (flow path 5). It was observed that just prior to reverse liquid flow in path 4, there was reverse flow of steam through the pump even though the pump was rotating in the forward direction at a fairly high speed (~ 3000 rpm). The high loss factor prevented significant reverse flow through the pump, but delayed reverse flow in path 4 by only about one second.

To keep the calculated flow of operating loop ECCS liquid towards the vessel and lower plenum, a run was made using the drift flux model in FLASH6 for the downcomer (path 14) and the two "core region" flow paths (paths 1 and 2). Although some countercurrent flow (liquid down, vapor up) was predicted in the downcomer, reverse flow in flow path 4 was nevertheless predicted to occur.

To diminish the condensation effect of the injected liquid, a run was made with the accumulator fill water injected at 280°F rather than the actual 80°F. As expected, the system pressure remained higher when the hotter fill water was injected. Reverse flow in flow path 4 still occurred at about the same time. However, the rates of pressure decrease and node filling were less. Node 3 did not fill with subcooled liquid but rather with a two-phase mixture. Since the fill water was still about 100°F subcooled, reverse flow still occurred, though to a lesser degree. This indicates that an improved representation of the steam-water interaction in the ECCS region with non-equilibrium effects could improve the comparison between FLASH6 predictions and experimental data. The fill water temperature sensitivity was run to provide information on the steam water interaction. All other runs were made with 80°F fill water.

When the rapid pressure dropoff accompanying reverse flow in path 4 was first observed, it was speculated that the lack of inertia in the accumulator fill path could be responsible for the anomaly. That is, as the pressure dropped in node 3, and hence also in node 2, the accumulator flow rate increased because of the larger pressure difference and more subcooled liquid was added. To insure that the accumulator model was not responsible for the phenomena, a run was made with the fill flow specified as a function of time to match the experimental data. The rapid pressure dropoff and reverse flow in path 4 occurred also for this run thus assuring that the anomaly is not due to the lack of inertia in the accumulator fill path.

Standard Problem 3 was run with a time step of 0.003 seconds for the first 20 seconds and 0.0003 seconds between 20 and 90 seconds. The smaller time step was required after 20 seconds since nodes begin to fill solid with liquid during this period. Total CDC-7600 run time for the 90 second transient was approximately 73 minutes.

VI. COMPARISON OF FLASH6 CALCULATIONS WITH DATA

The accuracy of experimental data for the 1-1/2 Loop Semiscale tests is discussed in Reference 6 and in the Appendix. Table 1.1 of Reference 1 gives total maximum and total probable errors for each of the measured variables, based upon the assumption of homogeneous flow. As discussed in the Appendix, another perspective on the accuracy of the experimental data can be obtained by examining the several cases where two independent measurements were made for a single variable. These cases show that there is a considerable variability in the data when measurements are made by different instruments at the same location. In making comparisons with FLASH6 calculations, further variability is introduced in comparing the node and flow path volume averaged quantities calculated by FLASH6 with experimental measurements made at a single point. By locating the FLASH6 nodes and flow paths optimally relative to a given measuring gage it is probable that the comparison of calculation and data could be improved. However, when only a few comparisons are made, as is the case here, then many of the gages will be located away from the centers of nodes and flow paths and this will affect the comparisons.

Figures 3 through 21 show comparisons between FLASH6 calculations and experimental data for Standard Problem 2. Figures 22 through 42 show similar comparisons for Standard Problem 3. Each figure shows plots of experimental data on the top of the page and corresponding FLASH6 predictions at the bottom of the page. FLASH6 predictions are plotted on a scale approximately the same as that of the experimental data. The FLASH6 plots were generated from information edited every 0.1 seconds, while the experimental data were sampled every 0.05 seconds. FLASH6 calculations were made over the entire time range, 0 to 45 seconds for Standard Problem 2 and 0 to 90 seconds for Standard Problem 3, for which experimental data are given.

Three of the variables for which experimental data are given are not edited directly by FLASH6, namely the momentum flux, fluid velocity and volumetric flow rate. These are evaluated from FLASH6 calculated quantities as follows:

$$\text{momentum flux (lbm/ft-sec}^2\text{)} = w^2/\rho A^2 \quad (1)$$

$$\text{volumetric flow rate (gal/min)} = 60w/0.1337\rho \quad (2)$$

$$\text{fluid velocity (ft/sec)} = w/\rho A \quad (3)$$

where ρ is flow path density, w is mass flow rate and A is flow path area. Differential pressures are predicted as the difference between pressures in the FLASH nodes where the gauges are located. With the exception of elevation head adjustments, no account is made for location of a gauge within a FLASH node. Density in the vessel is calculated as the average density of node 9, i.e. total mass divided by total volume. All other densities shown in the comparisons are flow path densities.

A. Comparisons for Standard Problem No. 2

Fluid Temperatures

Figure 3 shows comparisons of FLASH6 calculated fluid temperatures with test data. The FLASH6 calculated temperatures all follow the saturation line. That is, all temperatures are saturation temperatures at the node pressure except during the very early subcooled portion of the blowdown. The data, however, show temperatures above saturation for some locations later in the transient. Fluid temperature at the pressurizer outlet (TF-40 in Figure 3) shows the greatest departure from saturation. This discrepancy between data and calculations is due to two factors, 1) the equilibrium node assumption in FLASH6, and 2) the metal plant heat capacity model wherein no heat is transferred to the steam in a node. With the FLASH6 detailed plant metal heat capacity model the heat transfer from metal to node is related to the nodal mixture height. When the mixture height reaches zero no heat is transferred from the metal to the node fluid. Also when there is any amount of liquid in a node the steam in the node must be saturated because of the equilibrium assumption. The differences between calculated and actual fluid temperatures are apparently not a major concern for LOCA analysis where fuel temperatures are of primary interest. However, if steam temperature is underpredicted then resistance to steam flow in a loop could also be slightly underpredicted.

Metal Temperatures

Figures 4 and 5 show metal temperatures at two locations in the Semiscale system. In FLASH6, heat is conducted to the node fluid from a maximum of two heat slabs associated with the detailed and simple heat capacity models. The detailed model has two axial layers and three radial layers for a total of six metal nodes. The simple model has all of the metal lumped into a single node. Most of the metal is represented using the detailed model. The simple model is used only in nodes 1, 3, 5, 8 and 9. The temperatures plotted in Figures 4 and 5 are calculated using the detailed model. For the cases where several experimental temperature curves are shown, they represent measurements at various locations which are all represented in the FLASH model by a single metal slab conducting heat to the liquid.

Temperatures in the metal surrounding the downcomer annulus are shown in Figure 4. Note that the experimental data show an increase in temperature at some locations. The point at which the temperature starts to increase apparently corresponds to the time when effective cooling of the surface is terminated. Since the entire downcomer and lower plenum are represented in the FLASH model by a single node and the lower plenum never completely empties of liquid, the FLASH calculations do not show this increase in temperature. Some heat continues to be transferred to the liquid in the lower plenum. In Figure 5 some of the temperatures are overpredicted while others are underpredicted, however, the trends are correct. The differences between predictions and data are apparently due to the rather wide variation in temperatures within the metal associated with a single FLASH node. This variation in temperature is obvious from the experimental data. Use of a greater number of nodes would yield a better representation of the metal temperature details.

Momentum Flux

Figures 6 and 7 show plots of momentum flux at two locations in the system. Overall the FLASH6 calculations have the same trends as the data in both cases. Where more than one location is plotted on a single graph, the FLASH calculations show the same relationship to one another as do the experimental data.

The momentum flux is not calculated directly in FLASH6 but is determined from the mass flow rate and the density. Hence the momentum flux results contain errors from both the density and the mass flow rate calculations. An examination of comparisons for the mass flow rates and densities in Figures 11-15 shows that a larger portion of the error seems to be due to the density calculations. Also the flowmeter and densitometer measurements assume homogeneous flow. Even if this assumption were satisfied, the measurement errors could still be as large as $\pm 1930 \text{ lb/ft-sec}^2$ for momentum flux. Considering the measurement errors and the assumption of homogeneous flow which was made in reducing the experimental data, the FLASH predictions show reasonable agreement with the data trends.

Volumetric Flow Rate

Figures 8, 9 and 10 show comparisons of predicted and measured volumetric flow rates. The plots show that FLASH6 correctly predicts the data trends, particularly early in the transient. Later in the transient the volumetric flow rate is overpredicted in the pressurizer surge line. In the FLASH6 model, the surge line is connected to the pressurizer at an elevation slightly above the bottom. Hence, a small amount of water remains in the bottom of the node after the first steam starts to flow out of the pressurizer at about 5 seconds in the transient. As the pressure drops the remaining water flashes to steam and flows out of the surge line. The surge line is connected above the bottom of the node in the FLASH6 model to avoid calculating negative mass or energy at the time when the water empties from the pressurizer. In the test apparatus, the surge line connects to the bottom of the pressurizer.

The experimental operating loop flow (Figure 8) is calculated most accurately late in the transient. The flow rate spike in the experimental data at 37 sec. is not reproduced in the calculation. The blowdown loop hot leg flow rate is underpredicted late in the transient.

Mass Flow Rate

Figures 11 and 12 show comparisons of measured and predicted mass flow rates at two locations in the test apparatus. Note that the mass flow rate was not measured directly but was calculating from the fluid velocity and density. Hence this variable has a higher probable error than some of the directly measured variables.

There is a tendency for the predicted operating loop cold leg flows to drop off more quickly than the experimental data early in the

transient and hang up longer later in the blowdown. Overall the predictions are good.

Fluid Density

Density at various locations is shown in Figure 13 through 15. Although FLASH6 provides a fairly good prediction of the data trends, the fluid density is clearly one of the more difficult variables to predict. In particular, the fluid density in the operating loop cold leg is underpredicted early in the transient and in the vessel the density is underpredicted late in the transient. The FLASH6 predictions are flow path densities except in the case of Figure 15 where the average nodal density in node 9 is plotted.

Pressure

Pressure predictions are compared to experimental data in Figures 14 and 15. In general, FLASH6 gives a very good prediction of the pressure transient.

Differential Pressures

Figures 18 through 21 show comparisons between predicted and measured differential pressures. Again FLASH6 gives a very good prediction of the data trends. Note that the scales on the ordinate are slightly different for the experimental data and predictions of Figures 19, 20 and 21. The main reason for differences between the predictions and the data is the location of the measuring stations relative to the node hydraulic center where the FLASH pressure is calculated. Although elevation head corrections are accounted for in the plotted FLASH results, the friction pressure drop along a length of pipe represented by a FLASH6 node is not. Therefore, if a measurement station is not located at the midpoint of a FLASH6 node, pressure at the measuring station and the location of the FLASH6 node hydraulic center will differ by the pressure drop between the two points. In general, the measurement locations are not at node centers. This is particularly true for the blowdown loop.

B. Comparisons for Standard Problem No. 3

Most of the variables plotted for Standard Problem No. 3 are identical to those plotted for Standard Problem 2. Until the small accumulator begins to discharge at approximately 13 seconds, the response for Standard Problem No. 3 is almost identical to that of Standard Problem No. 2. After accumulator injection begins the response changes significantly compared to Standard Problem No. 2. Discussion will therefore be centered around response later in the transient, i.e. after accumulator injection begins.

Fluid Temperatures

Fluid temperature comparisons are shown in Figure 22. Generally the comparisons are good except that FLASH6 does not predict that fluid temperatures will rise above saturation except as the result of the numerical difficulties. As with Standard Problem No. 2, the fluid temperatures do not rise above saturation in general because the plant metal heat capacity model has a mixture level dependent heat transfer coefficient. When the mixture level is zero, as in the case of a steam filled node, then no energy is transferred from the metal to the node fluid. Overall the comparisons are good.

Metal Temperature

Figures 23 and 24 show comparisons of predicted and measured metal temperatures. The previous discussion accompanying Standard Problem No. 2 comparisons is also relevant here.

Momentum Flux

With the exception of a number of flow spikes, the momentum flux calculations shown in Figures 25 and 26 compare favorably with the experimental data. Note in particular the good agreement on the complicated blowdown loop momentum flux transient shown in Figure 26. Momentum flux spikes calculated by FLASH6 are at least partially the result of predicted pressure fluctuations. Notice that the experimental data also shows momentum flux spikes although to a lesser degree than the FLASH6 calculations.

Volumetric Flow Rate

Figures 27 through 30 show comparisons of FLASH6 predictions and measured volumetric flow rates. Volumetric flow rates are not calculated directly in FLASH6, but rather they are computed from flow path density and mass flow rate. As discussed later, the flow path density calculation shows more departure from the experimental data than other variables. Since the volumetric flow rate is calculated from the density one would expect to see some differences between calculations and measurements.

In Figures 27 and 28, the most significant difference between calculations and experimental data is the predicted fluctuations that occur in the calculations after 30 seconds. These fluctuations in the predictions are due at least in part to the pressure and flow fluctuations discussed earlier.

As with Standard Problem No. 2, the volumetric flow out of the pressurizer is overpredicted during the steam flow portion of the transient as shown in Figure 29. Again, the FLASH6 flow path is connected slightly above the bottom of the node, so some liquid is trapped in the bottom. As the pressure drops this liquid flashes and flows out as steam, thus resulting in the overprediction of volumetric flow between 15 and 30 seconds.

Figure 30 shows plots of volumetric flow rate out of the accumulators. The FLASH6 accumulator model does not account for the flow of cover gas into the system following the emptying of liquid. The flow rate is set to zero when the supply of cooling water is exhausted. This occurs in the calculations at approximately 58 seconds. Hence, the departure of the calculations and the predictions is due to neglecting the flow of cover gas in the FLASH6 model. During the liquid flow portion of the accumulator injection, the flow rate is slightly underpredicted by FLASH6. The oscillations in blowdown loop accumulator flow rate are due to the pressure oscillations in node 12 into which the accumulator empties. Similarly the small spikes in operating loop accumulator flow are due to rapid dropoff of the downstream node pressure (node 2) as a result of the rapid unrealistic condensation of steam described earlier.

Mass Flow Rate

Comparison of measured and predicted mass flow rates are shown in Figures 31 and 32. Overall the comparisons are adequate particularly in light of the uncertainties in the experimental measurements. For example, Figure 31 shows mass flow rate in spool piece 1 of the operating loop as determined from turbine meter and drag disc measurements. Note the rather large differences between the two measured values of the same variable. The large calculated flow spikes in Figure 32 result from the prediction of unrealistic interactions of injection water and steam near the operating loop injection location.

Fluid Density

Figures 33, 34 and 35 are comparisons of measured and calculated fluid density at various locations in the Semiscale test apparatus. FLASH6 flow path densities are plotted in Figures 33 and 34. The density in the vessel shown in Figure 35 is calculated as the average nodal density of node 9 which represents the downcomer and lower plenum.

The data trends are well represented by the FLASH6 calculations, however, fluid density appears to be the variable most difficult to predict. This is due at least in part to the large differences in density which can exist in a region represented by a FLASH6 node or flow path. In the Semiscale experiment, density is measured along a line between two points using gamma densitometers.

Differences between predictions and experimental data are due mainly to the location of measuring stations relative to FLASH nodes and flow paths. For example, Figure 35 shows that density in the vessel is underpredicted during the later portion of the transient. In the FLASH6 predictions the average nodal density of node 9 decreases after the fill water is exhausted as the water boils and flows out of the downcomer. However the density measurement is made in the lower plenum which remains filled with liquid.

Pressure

Pressures at various locations are compared in Figures 36, 37 and 38. Agreement between FLASH6 predictions and experimental data is favorable. Note that the predicted pressure oscillations in node 12 (P-76) are due to the leak flow model predictions as discussed earlier.

Figure 38 shows transient pressures in the accumulators. Note that after the fill water is exhausted at about 55 seconds the FLASH6 predictions show no further drop in pressures. This reflects the fact that FLASH6 does not account for the flow of cover gas into the system. The data show that the pressures continue to drop as the cover gas flows out of the accumulators.

Differential Pressures

Comparisons of measured and predicted differential pressures are shown in Figures 39 through 42. FLASH6 predicts the data trends well, but again predicts more fluctuations (i.e. spikes) than are measured. These predicted fluctuations are due to the steam-water interaction and leak flow oscillations discussed earlier. Note that the scales of the last two differential pressure plots are significantly different for the experimental data and FLASH6 predictions. The ordinate scale was made larger so as to include the entire FLASH6 predictions. Although FLASH6 tends to overpredict the magnitude of the differential pressures (due partly to locations of gages relative to node centers) the trends are well represented.

VII. CONCLUSIONS

Extensive comparisons of FLASH6 predictions with experimental data from 1 1/2 Loop Semiscale Tests 1011 and 1009 (Standard Problems No. 2 and No. 3) show that FLASH6 adequately describes the test data. In making comparisons with a large number of measured variables several factors should be considered including the accuracy of the experimental data, the nodalization of the FLASH6 model with respect to the prediction of each variable, and variability of the measured quantity within the lumped volumes used in FLASH6. Comparisons with experimental data show that FLASH6 predicts the blowdown data well. FLASH6 predictions also compare favorably during the reflood portion of the Standard Problem No. 3 transient.

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1-1/2-LOOP SEMISCALE SYSTEM AND INSTRUMENTATION - ISOMETRIC
FIGURE 1

SCHEMATIC OF FLASH MODEL OF SEMISCALE
ISOTHERMAL TEST 1011-STANDARD PROBLEM TWO

FIGURE 2

FLUID TEMPERATURES IN OPERATING LOOP

FIGURE 3

METAL TEMPERATURES IN CORE BARREL

FIGURE 4

METAL TEMPERATURES IN VESSEL WALL

FIGURE 5

MOMENTUM FLUX FROM DRAG DISCS IN OPERATING LOOP HOT LEG

EXPERIMENTAL DATA

FLASH6 PREDICTIONS

FIGURE 6

MOMENTUM FLUX FROM DRAG DISCS IN BLOWDOWN LOOP

FIGURE 7

VOLUMETRIC FLOW RATE FROM TURBINE METERS IN OPERATING LOOP

EXPERIMENTAL DATA

FLASH6 PREDICTIONS

FIGURE 8

VOLUMETRIC FLOW RATE FROM TURBINE METER IN BLOWDOWN LOOP HOT LEG

FIGURE 9

VOLUMETRIC FLOW RATE FROM TURBINE METER AT PRESSURIZER OUTLET

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 10

MASS FLOW RATE IN OPERATING LOOP HOT LEG SPOOLS 1 AND 5

FIGURE II

MASS FLOW RATE IN OPERATING LOOP COLD LEG SPOOL 22

EXPERIMENTAL DATA

FLASH 6 PREDICTION

FIGURE 12

FLUID DENSITY IN OPERATING LOOP HOT LEG

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 13

FLUID DENSITY IN OPERATING LOOP COLD LEG

EXPERIMENTAL DATA

FLASH6 PREDICTIONS

FIGURE 14

FLUID DENSITY IN VESSEL

EXPERIMENTAL DATA

FLASH6 PREDICTIONS

FIGURE 15

PRESSURE IN BLOWDOWN LOOP

FLASH 6 PREDICTIONS

FIGURE 16

PRESSURE IN VESSEL

FIGURE 17

DIFFERENTIAL PRESSURE ACROSS STEAM GENERATOR

EXPERIMENTAL DATA

FLASH6 PREDICTIONS

FIGURE 18

DIFFERENTIAL PRESSURE ACROSS CORE

FIGURE 19

DIFFERENTIAL PRESSURE ACROSS SIMULATED PUMP

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 20

DIFFERENTIAL PRESSURE ACROSS SIMULATED STEAM GENERATOR

FIGURE 21

FLUID TEMPERATURES IN OPERATING LOOP

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 22

METAL TEMPERATURES IN CORE BARREL

FIGURE 23

METAL TEMPERATURES IN VESSEL WALL

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 24

MOMENTUM FLUX IN OPERATING LOOP HOT LEG

FIGURE 25

MOMENTUM FLUX IN BLOWDOWN LOOP

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 26

VOLUMETRIC FLOW RATE IN OPERATING LOOP

FIGURE 27

VOLUMETRIC FLOW RATE IN BLOWDOWN LOOP

FIGURE 28

VOLUMETRIC FLOW RATE AT PRESSURIZER OUTLET

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 29

VOLUMETRIC FLOW RATE FROM ACCUMULATOR TANKS

FIGURE 30

MASS FLOW RATE IN OPERATING LOOP
HOT LEG - SPOOL PIECE I

FIGURE 31

MASS FLOW RATE IN OPERATING LOOP COLD LEG-SPOOL PIECE 22

EXPERIMENTAL DATA

FLASH 6 PREDICTION

FIGURE 32

FLUID DENSITY OPERATING LOOP HOT LEG

FIGURE 33

FLUID DENSITY IN OPERATING LOOP COLD LEG

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 34

FLUID DENSITY IN VESSEL

FIGURE 35

PRESSURE IN BLOWDOWN LOOP

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 36

PRESSURE IN VESSEL

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 37

PRESSURE IN ACCUMULATORS

FIGURE 38

DIFFERENTIAL PRESSURE ACROSS STEAM GENERATOR

FIGURE 39

DIFFERENTIAL PRESSURE ACROSS CORE.

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 40

DIFFERENTIAL PRESSURE ACROSS SIMULATED PUMP

FIGURE 41

DIFFERENTIAL PRESSURE ACROSS SIMULATED STEAM GENERATOR

EXPERIMENTAL DATA

FLASH 6 PREDICTIONS

FIGURE 42

Accuracy of the Experimental Data

An error analysis of the test data for the 1-1/2 Loop Semiscale Isothermal tests is given in Reference 6. The analysis was performed to obtain confidence limits on the published data. Total maximum error was obtained by adding the individual error components, while total probable error was obtained by the root-sum-square technique of adding the individual error components. The individual error components were assumed to be independent and normally distributed with known variance. Also, homogeneous flow conditions were assumed for the determination of certain error components for the flowmeter and densitometer measurement systems. Errors associated with the data acquisition and processing system were considered separately and used as an individual error component when the error associated with the total measurement system was analysis.

Table A.1 gives the total maximum and total probable errors which were considered to be typical of each type of measurement.

In using this table it is worth remembering that the values given for maximum error are not absolutes because of the assumptions made in reducing the data. Another manner of estimating the probable error is to compare the several cases where two independent measurements are made of the same variable. For example, both drag discs and turbine meters were used at some locations in the test apparatus. By comparing the two independent measurements and the total probable error band, one gets a feeling for the true variability of the experimental data. For example, Figure A.1 shows the hot leg mass flow rate for Standard Problem No. 3 as determined from turbine meter and densitometer measurement together with the total probable error band. Figure A.2 shows the same measurement of hot leg mass flow rate along with a measurement of the same variable determined from drag disc data. Note that during the first 20 seconds of the transient, the measurement based upon drag disc data is generally outside of the error band for the turbine meter based measurement.

Several other cases where two independent measurements were made for a single variable are shown in the comparison plots in the text. Comparing these measurements shows that there is considerable variation of the measured variable even at a single point along the cold leg pipe. FLASH6 variables

are averages over node and flow path volumes so that some further variation is introduced when these averaged quantities are compared to data measured at one point. Also, measured metal temperatures tend to vary considerably within metal represented in the FLASH6 predictions by a few lumped nodes.

TABLE A.1: Total Maximum and Total Probable Error for
1 1/2 Loop Semiscale System Experimental Data

PRESSURE

Total maximum	$\pm 1.4\%$ transducer full scale
Total probable	$\pm 1.0\%$ transducer full scale

DIFFERENTIAL PRESSURE

Total maximum	$\pm 2.4\%$ transducer full scale
Total probable	$\pm 1.3\%$ transducer full scale

FLUID TEMPERATURE

Total maximum	$\pm 10^{\circ}\text{F}$
Total probable	$\pm 5^{\circ}\text{F}$

METAL TEMPERATURE

Total maximum	$\pm 15^{\circ}\text{F}$
Total probable	$\pm 7^{\circ}\text{F}$

DENSITY

Total maximum	$\pm 1.9 \text{ lb/ft}^3$
Total probable	$\pm 0.9 \text{ lb/ft}^3$

VOLUMETRIC FLOW

Total maximum	± 1.1 to ± 21 gpm, depending on transducer range
Total probable	± 0.6 to ± 10.2 gpm, depending on transducer range

FLOW VELOCITY

Total maximum	$\pm 0.7 \text{ ft/sec}$
Total probable	$\pm 0.5 \text{ ft/sec}$

MOMENTUM FLUX

Total maximum	± 640 to $\pm 1930 \text{ lb/ft-sec}^2$, depending on transducer range
Total probable	± 320 to $\pm 920 \text{ lb/ft-sec}^2$, depending on transducer range

MASS FLOW RATE

Total maximum ^(a)	
Total probable	± 4.5 to $\pm 13\%$ of reading, depending on transducer range

HOT LEG MASS FLOW RATE FOR STANDARD NO. 3 WITH PROBABLE ERROR BANDS

FIGURE A.1

HOT LEG MASS FLOW RATE FOR STANDARD PROBLEM NO. 3 DETERMINED BY DRAG DISC AND TURBINE METER MEASUREMENTS

FIGURE A.2