Flow Visualization Study of Inverted U-bend Two-phase Flow *

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CONF-861204--5

DE87 004706

ABSTRACT

A hot-leg U-bend experiment was performed. The experimental condition simulated the two-phase flow in a B&W primary loop during a small break loss of coolant accident or during some other abnormal transients. The loop design was based on the scaling criteria developed previously and the loop was operated either in a natural circulation mode or in a forced circulation mode using nitrogen gas and water.

The two-phase flow regimes at the hot-leg were identified on the basis of visual observation. The phase separation at the top of the inverted U-bend was observed at low gas flow rate. The void fractions were measured using differential pressure transducers and compared with the prediction from the drift-flux model. The natural circulation flow interruption occurred in two different modes, namely, quasi-periodic and semi-permanent modes. This phenomenon is mainly dependent on the difference in the hydrostatic head in the riser and downcomer, and the flow regime at hot-leg. Besides this flow interruption phenomenon, dynamic flow instabilities of considerable amplitudes have been observed.

NOMENCLATURE

C_o	Distribution parameter
D	Hydraulic diameter
g	Gravity
j	Total volumetric flux
j_f	Superficial liquid velocity
j_g	Superficial gas velocity
v_{gj}	Drift velocity
α	Void fraction
ρ	Density
σ	Surface tension

Subscripts

f	Liquid
g	Gas

DISCLAIMER

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* 4th Miami International Symposium on Multi-phase Transport and Phenomena, December 15-17, 1986, Miami Beach, Florida.

MASTER

INTRODUCTION

The accident at the Three Mile Island Unit 2 on March 28, 1979 has raised many problems in reactor safety and has resulted in greater emphasis on the thermal-hydraulic behavior during small break loss of coolant accidents or during some other abnormal transient related to them. Since the TMI-2 accident occurred, numerous issues have been addressed in regards to the B&W 2 x 4 loop NSSS designs. Some of the issues are generic in nature and others are design specific. In particular, some concern has been raised relevant to the B&W NSSSs largely because of some unique components and hardware features in the plant design in addition to the 2 x 4 loop geometry. It has been suggested that unique design features of the B&W reactor may produce unique and complex thermo-hydraulic behavior during system transients.

Perhaps the most particular feature of the B&W plant design relative to the other PWR vendor designs is the once-through steam generator (OTSG) as illustrated in Fig. 1. In the OTSG system, primary fluid flows downward through the tubes in the steam generator. The secondary feed enters the steam generator secondary riser section from the bottom. The design is such that superheated steam can be produced, whereas the U-tube in-shell design used by other vendors can only produce saturated steam. However, use of the OTSG in the B&W NSSS necessitates the use of large vertical hot legs with a 180 degree U-bend at the top to route the primary fluid from the reactor vessel to the top of the steam generator.

FIGURE 1. Babcock & Wilcox low loop plant design arrangement

In view of the inherent difficulties associated with full-scale testing, scale models of prototype systems have been extensively used to predict the behavior of nuclear reactor systems during normal and abnormal transients, as well as under accident conditions. The severity of the TMI-2 accident has increased interest in this area. New scaling criteria for a two-phase system have been developed based on a rigorous perturbation method by Ishii et al. [1,2]. This new approach has been used to evaluate the design parameters of the 2 x 4 simulation loop under the MIST program. In view of certain scaling difficulties and

scale distortions of the integral test facility, a supporting experimental study to investigate the hot-leg U-bend two-phase behavior and associated scaling problem has been initiated.

A simulation loop for studying the hot-leg U-bend two-phase flow in a B&W plant has been constructed based on the scaling criteria developed by Ishii et al. [1,2]. The main objectives are to construct a model for the hot leg and U-bend simulating a B&W plant and to study the natural circulation phenomena. Mechanisms for flow interruption and restart are investigated during natural circulation. The phase separation at the U-bend and its effect on the flow interruption are also studied. The effects of gas flow rate, loop frictional resistance and thermal center are examined by parametrically changing the operational conditions.

HOT-LEG U-BEND EXPERIMENT

Apparatus

The overall loop schematic is shown in Fig. 2. This two-phase flow loop is designed such that it can be operated either in a natural circulation mode or in a forced circulation mode using nitrogen gas and water. The loop design is based on the scaling criteria developed by Ishii et al. [1,2]. However, enough flexibility is built into the design such that certain scaling distortions can be studied by changing some components. One of the important aspects is that the height of the separator, as well as the liquid level within the separator, can be changed in order to study systematically the effect of the thermal center of the steam generator.

FIGURE 2. Overall loop schematics of hot leg U-bend simulation experiment

There are several important differences between the present loop and the prototype. These are listed below:

Item	Present Loop	Prototype
Loop	Single Loop	2 x 4 Loop
Core	No Simulation	Core and Steam Dome
Hot Leg	No Horizontal Section	Horizontal Section
Vapor Source Sink	Gas Injection Gas Ejection	Boiling Condensation

However, the effect of the horizontal hot-leg section will be examined in the later experiments.

Test Section

The test section comprises five basic components; the bubble injector, riser, inverted U-bend, downcomer and separator. The 5 cm ID riser simulates the vertical section of the hot leg. At the end of the riser section there is the inverted U-bend and the flow is turned downward into the gas-liquid separator which simulates the once-through steam generator. At present the loop is 5.5 m in height with a U-bend radius of 9 cm and the test section is made of Corning Pyrex glass pipes and fittings, except the separator. The height and diameter of the riser is determined, based on volume scale factor 1/815 of the scaling model developed by Ishii et al. [1,2].

The test section is designed such that it can be easily fitted with smaller or larger diameter glass pipes and fittings. The height of the hot-leg can also be reduced to test the phenomena under different scale factors. The test section inlet is composed of the connector, tee and reducer. The air is injected from the gas injector through the connector and the recirculating water enters from the tee side. The air-water is mixed at the tee and rises to the riser through the reducer. The riser consists of several sections of the glass pipes and the pressure taps. At present, 15.2, 30.5, 122, 152.4, 152.4, and 30.5 cm long straight glass pipes are used and between each glass pipe seven pressure taps are installed, as shown in Fig. 2. The pressure taps are connected to the differential pressure transducers by polypropylene tubing to measure the pressure drop and the void fraction in each section.

The downcomer below the inverted U-bend is connected to the separator with the flexijoint bellows. The bellows is to permit small deflection in the loop and to isolate small vibration.

The separator is made of a lucite tube of 23 cm ID and 91 cm long. The main function of the separator is to separate two-phase mixture into gas and water. The water is recirculated. The gas is vented to the atmosphere through control valves which adjust the gas flow rate. These valves are used to control the separator water level which simulates the thermal center in the steam generator.

One of the main features of this test section is that most of the sections are transparent such that flow visualization, high speed still photography and high speed cinematography (50-10,000 fps) are possible.

Gas Supply System

For gas flow, high pressure nitrogen tanks are used as the gas supply. These tanks are connected to a high pressure manifold from which a pressure regulator feeds the gas into 0.3 m³ gas accumulator. The accumulator dumps out variations in pressure and temperature as the gas is delivered from the regulator. From this accumulator, the gas flows through one of three variable area flowmeters, and then through a needle valve controlling the flowrate. For low nitrogen flowrates, Matheson Flowmeter, tube number 604 (range approximately 0.5 l/min - 15 l/min at STP) is used. The other flowmeters, Brooks Fullview 1110, number R-8M-25-4 (range 10 l/min - 90 l/min at STP), and Brooks Fullview 1110, number R-9M-25-3 (range 46 l/min - 460 l/min at STP) are used for high flowrates. The gas pressure is measured at the flowmeter exit using Matheson Pressure Gauge Model 63-5622.

The gas then passes into a small gas injector reservoir. The reservoir is constructed by cutting a 10.2 cm (4") diameter schedule 40 stainless steel pipe to a 34 cm length and welding a 150 psig stainless steel flange on each end. Through the bottom flange two holes are drilled to accommodate a line for the nitrogen gas flow and a line for drainage. Sandwiched between the lucite flange of the connector at the test section and the top flange on the reservoir is a pressure flange. The epoxy plate fits between this pressure flange and the top of the reservoir and by tightening down on the bolts which go through the three flanges.

The hypodermic tubing which carried the nitrogen gas from the reservoir to the test section was molded into the epoxy plate. These stainless steel capillary tubes having a nominal 0.015 cm ID and a nominal 0.03 cm OD are arranged in different patterns to achieve various injection modes. The number of nozzles per plate is varied from 49 to 621. However, most of the tests are carried out by using the 621 nozzle plate. For over a wide range of gas flow rates, it is possible to produce a bubbly flow with a quite uniform bubble size using this plate. The typical bubble size at the tee intersection with the cold leg return is about 2 to 3 mm diameter. Some nozzle plates are constructed to achieve a volumetric injection of the gas to the water flow. This is achieved by arranging the tubes so that their ends are symmetrically spaced at nine different heights over a 10 cm axial length. This plate permits very high void fraction bubbly flow at the inlet. The gas is injected vertically into the riser through these nozzles.

Water Recirculation System

The water from the separator is recirculated to the test section inlet through the recirculation line. The loop is designed to operate either in a natural circulation mode with the hydrostatic head difference between the downcomer and the riser, or a forced circulation mode using a pump. The water recirculation section consists of the 5 cm ID (2") PVC tubing, paddle wheel flowmeter with a magnitude pickup similar to those of a turbine flow meter, inlet friction control valve and pump.

The water recirculation flowrate is measured using the Signet Paddlewheel Flosensor for 2.5 cm (1") pipe. The flowrate is displayed at the flow indicator and is also recorded at a chart recorder using a signal conditioner. This flow meter has very low friction loss which is almost zero and can measure relatively low flowrates (the minimum monitoring flowrate is 174 cm³/sec or 2.75 GPM). The flowmeter is installed on the bronze T-fitting which is connected to 5 cm ID (2") PVC tubing through the 2.5 cm ID (1") copper tube at both sides.

A plastic tank (diameter, 57 cm; height, 87 cm; capacity, 0.21 m³) is used for the expansion tank, which is located at the highest position in the loop. The main function of the expansion tank is to stabilize the system pressure and control the water inventory in the loop. The water comes from an industrial water line through a fine filter.

Void Fraction Measurement

Knowledge of the void fraction in two-phase flow is very important, since it is one of the most fundamental geometrical parameters characterizing the topology of the flow. It is known that the two-phase pressure drop and the void fraction are closely related, particularly for low velocity vertical flow [3,4]. Furthermore, pressure fluctuations or variations can be produced by changes in the void fraction such that they may characterize two-phase flow regimes and regime transitions [3,4].

The relationship between the pressure drop and the void fraction is given below. The pressure drop over one cycle of a slug flow is given by

$$\begin{aligned}\Delta p &= \Delta p_b + \Delta p_s \\ &= L_b \left\{ \left[\alpha_{gb} \rho_g + (1 - \alpha_{gb}) \rho_f \right] g + \frac{4\tau_{wb}}{D} \right\} \\ &\quad + L_s \left\{ \left[\alpha_{gs} \rho_g + (1 - \alpha_{gs}) \rho_f \right] g + \frac{4\tau_{ws}}{D} \right\} + \Delta p_R\end{aligned}\quad (1)$$

Here the subscripts b and s denote the large bubble and liquid slug reactions, respectively. Thus Δp_b is the pressure drop over a large bubble section and Δp_s is the one over a liquid slug section. Similarly, α_{gb} and α_{gs} represent the void fractions in these two sections. L and τ_w stand for the length and wall shear stress. Δp_R is the irreversible loss associated with the momentum changes in the liquid as it accelerates and decelerates around a large bubble. For low velocity flow the static head dominates the pressure drop and the effects of wall shear and Δp_R are relatively small. For a 5 cm diameter pipe, the frictional pressure drop may be neglected if the velocity is in the order of 2 m/sec or less which is the typical velocity under a natural circulation condition in the loop. Then Eq. (1) can be used to measure the mean void fraction. In general, the large bubble length and liquid slug length are not uniform, therefore the pressure drop between two axial locations should fluctuate with passing of each bubble and liquid slug. These fluctuations are more pronounced as the distance between the two pressure taps decreases because the pressure drop represents instantaneous void fraction between the two points. However, by taking temporal averaging of the instantaneous pressure drop, the mean void fraction can be measured.

Hence,

$$\overline{\Delta p} = L \left\{ \overline{\alpha} \rho_g + (1 - \overline{\alpha}) \rho_f \right\} g \quad (2)$$

where $\overline{\Delta p}$ is the mean pressure drop over length L and $\overline{\alpha}$ is the mean void fraction.

The differential pressures are measured at five locations as indicated in Fig. 2. The pressure taps at the test section are connected to the differential pressure transducers by polypropylene tube lines through some valves. The valves are installed to set zero pressure differential in the transducer. Furthermore,

demineralized water supply lines are installed to purge the air in the pressure lines.

The output signals from the Sensotec pressure transducers are in mV units, so it is amplified to 0-5 V signal using a signal conditioner. All of the D.P. transducer signals and the flowmeter signal are displayed using two digital voltmeters and recorded at three channel chart recorders through the switching panel.

The system pressure is measured at the pressure tap number 1 using a mercury manometer. At low liquid flow (< 2 m/sec) these pressure transducers give very accurate measurement of void fraction.

Experimental Procedure

The experiments were carried out with nitrogen-water two-phase flow. In the natural circulation mode, the water was filled in the riser and bubbly flow was generated by injecting nitrogen gas through multiple nozzles. This gas injection simulated the boiling process in the prototype. The difference in the hydrostatic head in the riser section and downcomer section induced a natural circulation along the loop. The initial flow regime was always bubbly flow by the design of the nozzles and gas flow rates. As the gas flow rates increased, flow regime transitions as well as the interruption and resumption of natural circulation were observed.

In a forced circulation mode, the pump was turned on. The water flow rates were controlled by the pump by-pass flow. In this mode, two-phase flow regimes and flow regime transitions were observed. The operational ranges of these experiments in terms of fluxes were in the ranges of:

Nominal gas flux ; 0 to 1 m/sec

Nominal liquid flux; 0 to 1 m/sec

EXPERIMENTAL RESULTS AND DISCUSSION

Hot Leg Flow Regimes and Inverted U-bend Two-phase Flow

Preliminary tests have been performed under bubbly and slug flow conditions under the forced circulation mode, i.e., with the pump turned on, and the natural circulation mode. Flow regimes were classified on the basis of visual observation. At low gas flow rates, the entire hot-leg was in the bubbly flow. As the gas flow rates increased, formation of cup bubbles and slug bubbles could be observed. It appeared that the transition to slug flow was gradual and depends on axial locations. This indicated the significant entrance effect on the flow regime development.

The flow regimes which were observed at the upper part of the hot leg were compared with the flow regime map of Mishima and Ishii [5], as shown in Fig. 3. This map indicates the form of flow at various combinations of superficial velocity of the liquid, j_f , and that of the gas, j_g . In the comparison for the bubbly-to-slug transition, there are some discrepancies, i.e., the transition in the experiments occurred at lower gas flow rate than the model. The discrepancy may be attributed mainly to the length of the hot leg and the residence time of bubbles. Under the present experimental conditions, the volumetric fluxes were relatively low at less than 1 m/sec. Then the residence time of bubble was larger, particularly at lower fluxes. The large bubble residence time lead to increased bubbly coalescences and formation of cup bubbles, and eventually to slug bubbles. This tendency is clearly seen in Fig. 3. At the higher fluxes, the flow regime transition from bubbly flow to slug flow approaches that predicted by the model, see the data at higher j_f . The other important factor may

FIGURE 3. Comparison to the flow regime map of Mishima and Ishii

be the liquid turbulence. At extremely low liquid flux, the coalescences seem to be suppressed such that the bubbly to slug flow transition occurred at near the critical void fraction of 0.3 predicted by the model [5].

The definition of the bubbly flow is somewhat ambiguous at high superficial velocity of the liquid, that is, whether the bubbly flow should include cap bubbles or not. The slug to churn flow transition is also shown in Fig. 3. There is also some discrepancy which may be attributed to the difficulty in discriminating between the churn and slug flow. It was pointed out that measurements of wall pressure fluctuations and pressure drop fluctuations could be used to identify the flow regime transitions between bubbly, slug, churn and annular flow [3,4]. However, the pressure transducers used in this experiment have a low frequency response, so it is difficult to accurately distinguish the flow regimes using the pressure drop fluctuation signal.

On the other hand, the bubbly to slug flow transition along the test section can be determined from the changes in the mean void fraction as well as from a visual observation using a strobe light (3 μ s). It is well-known that the average slip between phases depends on the flow regimes [6,7]. For given liquid and gas flow rates, the mean void fraction is a simple function of the mean slip between phases across the flow area. For the present test section geometry, the mean void fraction should decrease at the bubbly to slug flow transition, because the relative velocity in slug flow is larger than that in bubbly flow for a 5 cm diameter vertical pipe. However, this difference is relatively small for this particular diameter pipe.

In the experiments, the initial flow regime was always bubbly flow by the design of the gas inlet nozzles and gas flow rates. Thus the bubbly to slug flow transition is the first flow regime transition to be observed along the vertical riser section. The transition point in the riser was a function of the liquid and gas flow rates as shown in Fig. 4. The axial elevations where the flow regime transition occurred were plotted against the liquid superficial velocity (volumetric flux) with the gas superficial velocity as a parameter. It indicates that the transition point strongly depends on the liquid flux, particularly at low gas fluxes. On the other hand, at high gas fluxes the transition occurred very near the gas entrance.

FIGURE 4. Entrance effects in the bubbly to slug transition

In the typical flow regime map shown in Fig. 3, these high gas flux data fall within the slug flow area. Thus very rapid bubble coalescences and development of slug bubbles are expected. However, for data belonging to the left side of the bubbly to slug flow transition boundary, the transition is caused by a relatively slow coalescence process of low concentration bubbly flow ($\alpha < 0.3$). As the model of Mishima and Ishii [5] indicates, the bubble collision probability decreases significantly at or below the void fraction value of 0.3.

The increase in the slug flow development length with the increasing liquid flux at a fixed gas flux can be explained by the required time for coalescence or bubble residence time. On the other hand, the decrease in the length with increasing gas flux at a fixed liquid flux can be explained by the higher void fraction and increased coalescence probability. Figure 4 clearly demonstrates these intricate mechanisms of flow regime transition and the entrance effect on flow regime development.

The measurements of void fraction were carried out at several locations as shown in Fig. 2, and the void fraction was compared with the prediction using the drift flux model [7]. The mean drift velocity, V_{gj} , is defined by

$$V_{gj} = v_g - j = \frac{j_g}{\alpha} - j \quad (3)$$

The constitutive relations for the drift velocity are as follows:

Bubbly Flow Regime (Distorted Particle)

$$v_{gj} = (C_o - 1)j + \sqrt{2} \left(\frac{\sigma g \Delta \rho}{\rho_f^2} \right)^{1/4} (1 - \alpha)^{1.75} \quad (4)$$

Slug Flow Regime

$$v_{gj} = (C_o - 1)j + 0.35 \left(\frac{g \Delta \rho}{\rho_f} \right)^{1/2} \quad (5)$$

Churn-turbulent Flow Regime

$$v_{gj} = (C_o - 1)j + \sqrt{2} \left(\frac{\sigma g \Delta \rho}{\rho_f^2} \right)^{1/4} \quad (6)$$

where the distribution parameter C_o is given by

$$C_o = 1.2 - 0.2 \sqrt{\rho_g / \rho_f} \quad (7)$$

From these correlations the void fraction α for each flow regime can be calculated at given j_g and j_f . The predicted void fractions from the drift flux correlation for slug flow are generally lower than the experimentally measured values. This implies that the actual average relative velocity between phases were smaller than that predicted by the above correlation given by Eq. (5). Figure 5 compares the experimental results for the average gas velocity with those predicted from the drift-flux model based on the slug flow correlation and the homogeneous flow model. It can be seen that most data fall between these two models. The tendency of the data to fall below the slug flow correlation may be attributed partially to the existence of many small bubbles even in slug flow.

The predicted bubbly flow gas velocity for distorted particles [7] at $\alpha = 0.3$ is also shown in Fig. 5. It is noted here that the local contribution of the drift velocity, i.e., the second term in Eqs. (4) to (6), has similar values for bubbly, slug and churn-turbulent flows at $\alpha = 0.3$ for these experiments. Hence, it is expected that most data fall between the slug flow line and bubbly flow line at $\alpha = 0.3$.

However, Fig. 5 indicates that nearly one half of the data do not fit into the category. This may be attributed to the effect of the phase and velocity distribution. The distribution parameter value used was for a fully developed flow in a relatively small diameter pipe. In the present experiment the value of the distribution parameter could have been smaller than the one given by the correlation.

The inverted U-bend two-phase flow tends to produce complicated phenomena [8], which involve a combined action of centrifugal and gravitational forces. The centrifugal force would shift the gas toward the zone of smaller curvature radius of the bend, and would throw the liquid toward the outer zone. The gravity effect tends to pull the liquid toward the inner wall of the bend and

FIGURE 5. Comparison with the drift flux model in the velocity-flux plane

rise the gas phase toward the outer wall. Accordingly, these forces would bring about the separation of phases. Furthermore, the change of direction from upflow to downflow in curved part would have an effect on the flow. The flow structure in the bend would also be influenced by the flow regime as the mixture entered the bend. The phase separation was observed at low liquid and gas flow rate but it needs much more research to interpret the condition for the onset of separation and the mechanism of the flow separation.

Natural Circulation Characteristics

By injecting nitrogen gas through multiple nozzles at the bottom of the hot leg, the difference in the hydrostatic head in the riser (hot leg) section and down-comer section was produced. This induced a natural circulation along the loop. Typical natural circulation flow characteristics are shown in Figs. 6 and 7. At low gas flow rates, the natural circulation was not induced. The top level of the two-phase mixture in the riser was lower than the inner curvature of the inverted U-bend. As the gas flow rates increased, the natural circulation started at certain gas flow rate and then the recirculation flow rate increased. Figure 7 reveals the effect of the separator water level. When the friction control valve in the water recirculation loop is fixed the natural circulation starts earlier and the recirculation flow rate increases more as the separator water level increases. However, at the small recirculation flow rates, flow oscillations were detected, which made it difficult to establish a clear relation

FIGURE 6. Effect of the separator water level in the natural circulation flow characteristics

FIGURE 7. Effect of the inlet friction loss in the natural circulation flow characteristics

between the gas flow rates and the recirculation flow rates. Figure 7 shows the effect of the inlet friction loss of the test section. The beginning of the natural circulation is at almost the same point regardless of the valve opening position, but the recirculation flow rates decrease with the increasing inlet friction loss. From Figs. 6 and 7, it can be concluded that the recirculation flow rates are mainly a function of the gas flow rate, the hydrostatic head difference and the system frictional resistance.

By changing the system conditions, it was found that the natural circulation flow interruption occurred in two different modes, namely, quasi-periodic and semi-permanent modes. Appearances of large slug bubbles led to the quasi-periodic flow interruption. However, the natural circulation can be sustained if there is sufficient hydrostatic head in the downcomer. One of the most important parameters determining the flow interruption is the water level in the separator. When the water level was sufficiently low, the semi-permanent flow interruption occurred. Then the two-phase level in the hot leg could not reach the U-bend section. This indicates that accurate knowledge of the void fraction in the hot leg is very important for the prediction of the flow interruption.

The flow oscillation which was observed under certain conditions as shown in Figs. 6 and 7 was quite periodic. The period was in the order of 10 to 25 sec. At present, the nature of this flow instability is not clear, but it depends on the pressure drops across the test section inlet as shown in Figs. 6 and 7. The void and pressure drop data appeared similar to those of the density wave instability [8,9].

CONCLUSIONS

Experiments were performed for the simulation study of hot-leg U-bend two-phase flow and some preliminary data were obtained. The following conclusions can be derived from the experimental results:

- Compared with the existing flow regime criteria, the bubbly-to-slug transition and slug-to-churn transition occurred at lower gas flow rates.
- The entrance effect predominated the bubbly to slug transition in the test section particularly at low flow.
- The complete phase separation at the top of the inverted U-bend occurred under certain conditions. However, the phase separation was not the cause of the permanent flow interruption.
- In a natural circulation mode, the recirculation flow rates were characterized by gas flow rates, separator water level and system friction loss.
- The natural circulation flow interruption occurred in two different modes, namely, quasi-periodic and semi-permanent modes. The quasi-periodic interruption was induced by large slug bubble and was recovered if there was sufficient hydrostatic head in the downcomer. The semi-permanent interruption occurred when the difference in the hydrostatic head was sufficiently low.
- The flow oscillations of a considerable amplitude were encountered near the flow termination. This type of flow instability may lead to loop-to-loop oscillations or flow excursions in a prototype system which has a multiloop configuration.

ACKNOWLEDGMENTS

The authors would like to express their sincere appreciation to Dr. Novak Zuber of NRC for valuable discussions. This work was performed under the auspices of the U.S. Nuclear Regulatory Commission.

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