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SIMULATION EXPERIMENTS FOR HOT-LEG U-BEND TWO-PHASE FLOW PHENOMENA*

by

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ABSTRACT

In order to study the two-phase natural circulation and flow termination during a small break loss of coolant accident in LWR, simulation experiments have been performed. Based on the two-phase flow scaling criteria developed under this program, an adiabatic hot leg U-bend simulation loop using nitrogen gas and water and a Freon 113 boiling and condensation loop were built. The nitrogen-water system has been used to isolate key hydrodynamic phenomena from heat transfer problems, whereas the Freon loop has been used to study the effect of phase changes and fluid properties. Various tests were carried out to establish the basic mechanism of the flow termination and reestablishment as well as to obtain essential information on scale effects of parameters such as the loop frictional resistance, thermal center, U-bend curvature and inlet geometry. In addition to the above experimental study, a preliminary modeling study has been carried out for two-phase flow in a large vertical pipe at relatively low gas fluxes typical of natural circulation conditions.

I. INTRODUCTION

In view of the impracticality of full-scale testing, scale models of a prototype system have been extensively used to predict the behavior of nuclear reactor systems during normal and abnormal operations as well as under accident conditions. The severity of the accident that occurred at the Three Mile Island Unit-2 plant 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 approach has been used [3,4] to evaluate the design parameters of the new 2 x 4 simulation loop under the MIST program [5]. In view of certain scaling difficulties and scaling distortions in the integral facilities [5,6], a supporting experimental study to investigate the hot leg U-bend two-phase behavior and associated scaling problems has been initiated at Argonne National Laboratory.

The major issues addressed under this project are the interruption and reestablishment of the loop two-phase natural circulation. The void distribution contributes to the natural circulation force and is one of the major factors in determining the flow rate, interruption and resumption. Therefore, a precise understanding of the two-phase flow regimes, regime transition points and relative motion between phases are indispensable for accurate

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predictions of the void fraction in the hot leg and overall loop flow behaviors. It is noted that in the prototype system, the diameter of the hot legs is about 90 cm and the length to diameter ratio relatively small at about 20. This indicates that the two-phase flow in the hot leg can be quite different from the standard small scale experiments. There is a great uncertainty in describing the flow because the conventional two-phase flow models and correlations are developed based on small diameter and large ℓ/d system experiments. In view of this, the two-phase flow regimes in a hot leg is studied in detail in terms of the effect of the inlet geometry, axial flow regime development and length to diameter ratio.

II. BASIC SCALING CONSIDERATION AND SCOPE

The available approaches for developing scaling criteria for two-phase flow systems have been reviewed by Ishii and Jones [7]. The similarity analysis for system dynamical phenomena has been carried out by Ishii and Zuber [8] and for some local hydrodynamic phenomena by Zuber [9]. The results based on the one-dimensional drift flux model [10,11] and the perturbation method [8] were used by Ishii and Kataoka [1,2] to develop integral scaling criteria for overall loop thermal-hydraulic simulations.

In the present study, these scaling criteria for single and two-phase flows [1,2] are utilized. The two different flow visualization loops were designed according to the above scaling criteria. However, enough flexibility is built into the design such that various parametric effects and scale distortions can be studied by changing some components. The experiments are carried out in an adiabatic nitrogen gas-water loop and in a Freon-113 boiling and condensation loop.

For two-phase systems, phase change, subcooling, drift flux, Froude, friction, time ratio and heat source numbers are important [1,2]. The results of the scaling study for the B&W 2 x 4 loop design, see Fig. 1, show that the following scaling criteria should be satisfied [3,4].

The velocity ratio is given by

$$u_R = \ell_R^{1/2} \tag{1}$$

and the time scale ratio by

$$t_R = \ell_R^{1/2} \tag{2}$$

Here the subscript R denotes the ratio between the values for the scale model and the prototype, thus $\psi_R \equiv \psi_m/\psi_p$ where ψ is an arbitrary variable.

From the phase change number and subcooling number similarity, it can be shown that

$$\left(x \frac{\Delta\rho}{\rho_g}\right)_R = 1 \tag{3}$$

where x is the steam quality. This implies that the quality should be scaled by the density ratio $\rho_g/\Delta\rho$. In addition to the above similarity, if the drift-flux number similarity exists, then it can be shown that

$$\left(\alpha \frac{\Delta\rho}{\rho_f}\right)_R = 1 \tag{4}$$

Thus the void fraction is scaled by the density ratio $\rho_f/\Delta\rho$ which is almost always near unity. From this, the model void fraction should be very close to that of the prototype system.

In an adiabatic simulation, a gas phase is injected into a system instead of boiling. The injection rate should be related to satisfy the quality similarity given by Eq. (3). Then the injection rate in terms of the gas volumetric flux is given by

$$\left[\frac{(j_g)_{inj}}{u_f}\right]_m = \left(\frac{\Delta\rho}{\rho_g} x\right)_p \tag{5}$$

By knowing the steam quality in a prototype system $(j_g)_{inj}$ can be determined.

A detailed scale model study for the B&W plant design has been carried out using single phase and two-phase scaling criteria [3,4]. The most severe condition in terms of the thermo-hydraulic simulation is imposed by the friction number similarity, because in a scaled model the hydraulic diameter can be much smaller in a piping system. Therefore, for a given value of a_R, calculations are centered to determine ℓ_R to meet $F_{iR} = 1$ for each section.

Then the maximum possible ℓ_R for given a_R is given [3,4] by

$$\ell_R = 10.0\ (1/a_R)^{-0.67} \tag{6}$$

and the volume ratio by

$$V_R = 10.0\ (1/a_R)^{-1.67} \tag{7}$$

Hence, for a sample case of V_R = 1/815, one obtains for the practically optimum case as

$$a_R = 1/218$$

$$\ell_R = 0.27 \qquad (8)$$

And in this case, the time scale is reduced by

$$t_R = \frac{t_m}{t_p} = \sqrt{\ell_R} = 0.52 \qquad (9)$$

Therefore, the key timings of various transients will be reduced by a factor of 0.52 in the scale model. The prototype hot leg diameter is 91.5 cm, vertical rise 14.25 m and total length 21 m. By using these numbers, the corresponding model dimensions are 6.2 cm, 3.84 m and 5.6 m, respectively. In view of the commercially available glass tube sizes, d_m of 5.1 cm and 10.2 cm have been chosen. The vertical elevation of 3.5 m and 5.5 m are chosen to simulate the prototype flow as well as to study the scale distortion caused by using a too long hot leg such as in MIST [5].

Using these criteria, the data on void fractions, flow rates and pressure drops can be translated into prototype values. Furthermore, the information on hot-leg flow regime, U-bend flow separation, flow interruption and resumption can be recasted in terms of the prototype values. Same can be done for MIST and other simulation facilities. Furthermore, the experimental parametric study on the frictional resistance, thermal driving head, and various geometries such as the hot leg diameter, height and U-bend radius will clearly show the effects of scale distortions on these variables in definite numbers.

Another focus of the tests is the hot leg flow regimes and flow regime transitions. In the first series of tests, the gas is injected into the vertical section of the hot leg directly. The inlet section is always in the bubbly flow with a relatively uniform bubble size. From this controlled inlet condition, the entrance effect on the two-phase flow regimes and regime transitions can be easily studied visually. It is considered that the bubbly flow is the predominant flow regime in the hot leg of the prototype system. Hence these tests are very important for understanding the flow in the prototype system.

On the other hand, in the second series of tests, the vessel outlet and horizontal section of the hot leg are also simulated. This geometry may tend to produce a slug flow at the bottom of the vertical section of the hot leg. Although in the prototype system these slug bubbles should disintegrate immediately due to interfacial instabilities [12,13], this may not occur in the integral simulation facilities such as MIST, UM and SRI loops. Therefore, it is quite important to identify the effect of the vessel outlet and horizontal section on the two-phase flow regimes.

The third series of experiments are carried out in the Freon-113 boiling and condensation loop. The effects of phase changes and fluid properties can be studied in detail in comparison with the adiabatic loop experiments. Only preliminary tests are carried out in this boiling loop. However, several important differences have already been observed.

The data from these parametric study will be used to develop a two-phase flow model for hot leg and U-bend flow. A parallel analytical study is currently carried out to determine the pipe diameter and entrance length effects on the flow regime. From the combination of the data and analysis, the final two-phase flow model will be recommended. In this report, a limited number of data and flow observations are reported.

III. EXPERIMENTAL FACILITY

A. Adiabatic Simulation Loop

The test facility for studying hot leg U-bend two-phase flow was built in accordance with the scaling criteria developed by Ishii et al. [1-4]. As shown in Fig. 2, this two-phase flow loop consists of the bubble injection chamber simulating the core, 5 cm ID riser, inverted U-bend, gas separator simulating the once through steam generator, and cold leg return. The bubble chamber, riser and U-bend section were made of Corning Pyrex glass tubes and fittings, whereas the gas separator was made of plexiglass. The maximum riser (hot leg) height was about 5.5 m. The radius of the initial U-bend was 8.8 cm. However, the loop was designed such that the hot leg diameter, U-bend radius and hot leg height could be easily changed to study the parametric effects.

To model the steam/water flow in an actual LWR, in this experimental facility the tested fluids were nitrogen and water, working as the vapor phase and liquid phase, respectively. The gas was injected into the riser through nozzles which were made of stainless steel tubes, having a nominal 0.015 cm ID and 0.03 cm OD. These 625 nozzles were molded into an epoxy plate which was held by a plenum at the bottom of the riser. The gas flowrate and pressure were measured between the plenum and the gas accumulator. Downstream of the U-bend, there was a separator where the gas was vented to the atmosphere from the loop through a valve. This separator, made of transparent plastic, was 91 cm high and 20 cm in diameter. To direct the gas and liquid carry over from the U-bend into the separator, the vertical section was extended into the separator. This extension was made of a plastic tube of 5.1 cm diameter and 46 cm length. It was mounted to the separator cover and had many perforated holes of 1 cm in diameter such that the separation of gas from the gas-water mixture could be quickly achieved without disturbing the water level in the separator. Above the separator, a bellow type flexible coupling of 5 cm length was used to reduce the stress on the glass test section. Beneath the separator, there was a 60 cm long glass tube through which entrainment of gas phase into the cold leg was monitored. Beyond this point, a plastic tube of 5 cm in diameter was used instead of a glass tube since single phase flow could be expected. In the downcomer (cold leg) section there was a friction control valve which could be used to alter the loop frictional resistance. Furthermore, a liquid flow meter was installed in the horizontal section of the cold leg with a sufficient straight entrance length. This flow meter is a paddle wheel type with magnetic pick-up and has special characteristics of very low pressure drops.

This loop can be operated either in a natural circulation mode or in a forced circulation mode. The natural circulation can be induced by a hydrostatic head difference between the riser section and the downcomer section. No external power is necessary under this mode. For a forced circulation mode, a centrifugal pump with the capacity of 76 litre/min was used. By properly adjusting the control valve and bypass valve, a forced circulation with a desired flowrate can be obtained.

In the riser section, seven pressure taps were installed for measurement of the differential pressure at five locations as indicated in the figure. These pressure taps were made of brass plate. The inside diameter is 5.1 cm and outside diameter is 8.9 cm. A small hole of approximately 0.4 mm in diameter was drilled to measure the pressure. At the low flowrates of interest to this experiment, these pressure taps give accurate void fraction measurements through differential pressure transducers because the frictional losses are negligibly small.

The experimental loop is designed to simulate the prototype system under natural circulation conditions. Thus the pump rotor is considered to be locked in the stationary position. The frictional valve fully opened position corresponds to the prototype system with the locked pump rotor.

In order to study the effect of vapor phase inlet section on the two-phase flow regimes and flow interruption three different inlet sections were used, see Figs. 3 and 4. The first type had no horizontal hot leg section to force the inlet flow to be in a bubbly flow. The latter two had a horizontal section of different lengths. A detailed description of the loop is given in Refs. [14] and [15].

B. Freon 113 Boiling and Condensation Loop

The basic dimensions of this loop are similar to the adiabatic loop described above. However, the boiling and condensation phenomena can be studied in addition to the capability of the nitrogen-water loop. As can be seen from Fig. 5, the loop has the boiler section with seven electrically heated rods of the total power of 4.2 KW and the condenser section cooled by the secondary Freon-113 loop. The heat is transferred to the secondary loop at the simulated steam generator from the primary loop. The heat sink of the secondary loop consists of the heat exchanger cooled by water and coils submerged in a cold bath within a large chest-type freezer. The coolant in the secondary loop is pressurized to stay in the liquid phase and circulated by a pump. The loops have various power and temperature measurements in addition to the hydrodynamic measurements such as the differential pressure transducers, pressure gauges and flow meters. The pressure lines have special bubble purging devices to eliminate gas or vapor from the transducers and pressure lines. All the two-phase flow sections are made of pyrex glass tubes and fittings such that the flow visualization experiments are possible.

IV. EXPERIMENT IN ADIABATIC LOOP

A. Range of Flow Parameters

Generally, this experiment was conducted on the basis of three varying parameters; they were gas flowrate, friction valve opening and water level in the separator. Also, in order to study the effect of vapor phase inlet section on the flow regimes and flow interruption, two horizontal sections of different lengths were tested, see Figs. 3 and 4. Table I lists the ranges of parameters in this experiment.

Table I. Range of Flow Parameters

gas volumetric flow	0 ~ 50 cm/sec
friction valve opening	1, 1/4, 3/16, 1/8
separator water level	18 cm, 45 cm, 80 cm
horizontal section length	0, 15 cm, 91 cm

Two U-bends with different curvatures, R/d = 1.78 and 3, were tested at several separator water levels against different friction valve openings and vapor flowrates for analyzing its effect on the flow termination as well as natural circulation flow.

A detailed description of experimental data are given in Refs. [14] and [15]. Only the summary of the results are given below.

B. Natural Circulation and Flow Interruption

In general, the induced liquid natural circulation rate decreases with the decreasing gas flow rate. As the gas flow rate decreases further, eventually the liquid circulation rate becomes zero corresponding to the flow interruption. When the permanent flow termination occurs, the two-phase level in the hot leg stays at or below the lower surface of the top of the U-bend. Due to the insufficient hydrostatic head difference between the hot leg and cold leg, the two-phase level cannot rise to flow over the U-bend section, thus there is no carryover liquid flow. Only the gas phase is transported over the U-bend. Two-phase flow oscillations are observed at near the flow termination condition. The amplitudes of the oscillations can be very significant. The period of the oscillations is about 20 sec.

Besides the permanent flow interruption discussed above, intermittent flow interruptions have also been observed in the slug or churn turbulent flow regime. As a large slug bubble passes over the U-bend, the section is temporarily voided and the liquid carryover flow becomes very small. However, with the passing of a liquid slug, the carryover flow is fully recovered. The liquid natural circulation rate measured by the flow meter in the cold leg return shows that the flow is quite steady and not much influenced by the intermittent carryover at the U-bend. It appears that the liquid mass has sufficient inertia, thus the total liquid flow is not sensitive to the disturbances caused by each slug bubble. The time scale of the intermittency is about 1 sec whereas the flow oscillations have a period of approximately 20 sec. Thus it can be concluded that these two phenomena are not related.

The intermittent flow interruption does not lead to the permanent flow termination. This indicates that the phase separation in the U-bend is not the cause of the permanent flow termination. The present experiments have demonstrated that the natural circulation termination occurs when there is insufficient hydrostatic head in the downcomer side. As long as the two-phase level in the hot leg can be raised to the top of the U-bend, the carryover flow can be reestablished. This points to the importance of the thermal center in the once-through steam generator and the void fraction distribution in the hot leg.

C. Effect of Separator Water Level (Thermal Center)

The induced liquid flow rate increases with the increasing water level in the separator at a fixed gas flowrate and friction valve opening. The vertical distance between the U-bend and the bottom of the hot leg is fixed, thus an increase of water level in the separator results in an increase of the hydrostatic head in the downcomer. Since the natural circulation is induced by the static head difference in the hot leg and cold leg downcomer, the circulation rate increases with the level.

The induced liquid flow rate depends on the separator water level, frictional loss along the loop and void fraction distribution in the hot leg. The gas flow at the flow termination is reduced as the water level in the separator increases. Thus the flow termination condition conforms to the general parametric dependences of the natural circulation rate. This shows that at higher water levels, less gas rates are required to induce the same liquid flow rate.

D. Effect of Frictional Resistance

The changes in the frictional resistance of the test loop was achieved through adjusting the opening of the gate valve which was of screw type with a diameter of 5 cm. The openings of the gate valve was varied over fully, 1/2, 1/4, 3/16 and 1/8 open in terms of the valve stem rotations. For each position, tests were run with three different water levels in the separator and three different geometries of the core exit section. It has been observed that as the friction valve opening decreases (implying increases in the single phase friction resistance) the induced liquid flowrate decreases. However, such effect was not pronounced when the friction valve opening was at fully, 1/2 and 1/4 open, because over this range the frictional resistance does not change considerably. The extent of the effect of the friction valve opening on the induced liquid flowrate also depends on the separator water level. Furthermore, a decrease of the friction valve opening has a tendency to stabilize the flow oscillation. This effect applies to all three different geometries of a core exit. Most importantly, the friction valve opening has no influence on the relation between liquid flowrate and gas flowrate when the flow termination is reached.

E. Effect of Inlet Section Geometry

Three different geometries of a core exit section were tested to compare their effect on the flow interruption and induced liquid flowrate. One had a vertical inlet where the gas flowed vertically into the hot-leg as shown in Figs. 2 and 3. Two of them had a simple mixing chamber, horizontal section and elbow, as shown in Fig. 4. The horizontal section had a length of 15 cm or 91 cm.. A 5 cm pipe diameter elbow of 90° and 18 cm radius was used between the vertical hot-leg and the horizontal section. The two-phase mixture of nitrogen and water flowed horizontally through this section before entering the vertical hot-leg.

With the vertical inlet section, the flow regime transition from bubbly to slug flow showed strong entrance effect. The axial transition position was a function of the gas flux. However, at the top of the hot leg the general trend of flow regimes can be predicted by existing criteria [16].

In the present experiments, the hot leg flow with a horizontal section is always in the cap bubbly or slug flow regime. This is due to the flow stratification at the horizontal section. The flow regime in the horizontal section is either elongated bubbly flow or stratified flow with a propagating interfacial wave front. The stratification occurred within about one diameter of a pipe from the simulated core exit plane. However, in general this length depends on the bubble rise velocity and liquid flux. At the elbow the horizontal two-phase flow is turned 90° into a vertical flow. At this point quasi-periodic slugging occurred. This slugging produced either cap bubbles or slug bubbles depending on the gas flux. Also it has been observed that smaller cap bubbles tend to catch-up the preceding ones and agglomerate into slug bubbles.

According to a recently developed theory by Kocamustafaogullari and Ishii [12,13], the maximum cap bubble size is about 40 $\sqrt{\sigma/g\Delta\rho}$. Thus for a vertical pipe much larger than this value (~10 cm), the stable slug flow cannot be sustained. Due to the instability, the initial large bubbles should disintegrate into smaller cap bubbles of stable sizes. It is expected, therefore, in the prototype system with a diameter of 91 cm the slug flow is unstable in the vertical hot leg section. A typical flow regime should be a bubbly or dispersed cap bubble regime. On the other hand, in the integral test facilities, the slug flow is more stable. Thus both the diameter of the hot-leg and the inlet geometry have significant influence on the flow regimes, void distribution and flow behaviors.

F. Effect of U-bend and Its Curvature

In this experiment most of the experimental trials were performed with the same U-bend, however a modified U-bend of different curvature was also tested at separator water level of 45 cm and 18 cm under varied friction valve openings to compare the effect on the flow behavior and flow termination. The ratio of the curvature radius to diameter was 1.78 and 3 where the one with 1.78 was considered as the standard.

Comparisons of the amplitudes of the induced flow oscillation and superficial liquid velocities between tests with these two U-bends show no significant differences when the separator water level was 45 cm. The average behaviors were quite similar in terms of the flow termination and natural circulation rate. Only some differences in dynamical behaviors have been observed. It shows that the U-bend with larger curvature tends to broaden the range of the superficial liquid velocity over which the flow oscillation can occur. The experimental data and the results of the flow visualization have confirmed that the flow termination is mainly governed by the loopwise hydrostatic head balance and not by the local phase separation phenomena at the U-bend. It appears, therefore, the detailed geometrical scaling of the U-bend section may not be very important for studying the overall loop behavior.

G. Simple Model for Flow Termination

A simple model for the prediction of the flow termination can be developed from a force balance. For a steady state natural circulation flow, the hydrostatic head difference between two legs should balance the frictional pressure drop along the loop. Thus

$$\rho_f \ell_w g - \int_0^{\ell_{max}} \rho_m g \, dz = \left[\frac{f_{SP} \ell_{SP}}{2D} + \frac{K}{2} \right] \rho_f u_f^2 + \int_0^{\ell_{max}} \frac{f_{TP}}{2D} \rho_m u_m^2 \, dz \qquad (10)$$

Here ρ_w and ρ_{max} are the height of the separator water level and hot-leg U-bend from the bottom of the loop, respectively.

At the point of the flow termination $u_f = 0$, thus it reduces to

$$\rho_f \ell_w g - \rho_m \ell_{max} g = \left[\frac{f_{TP} \ell_{max}}{2D} + \frac{K_{TP}}{2} \right] \rho_m u_m^2 \qquad (11)$$

Here it has been assumed that the mixture density ρ_m is approximately uniform along the hot leg for simplicity. Under the low gas flux condition typical of the flow termination, the two-phase frictional pressure drop may be neglected with respect to the gravitational terms.

Then from Eq. (11) it can be shown that

$$\alpha \simeq \frac{\rho_f}{\Delta\rho} \left[1 - \frac{\ell_w}{\ell_{max}} \right] \qquad (12)$$

The comparison of the predicted void fraction at the flow termination to the experimental values under different conditions are given in Table XII. As can be seen from the table, the experimental mean void fractions in the hot-leg agrees with the predicted values from the simple model. In Table II, the experimentally measured void fractions at five different levels are given. The predicted void fraction is the overall average void fraction along the entire hot leg section.

Table II. Comparison of Void Fraction at Flow Termination Between Empirical Data and Prediction with Friction Valve Fully Open and without Horizontal Hot-Leg Section

Separator Water Level	j_g (cm/sec)	α_1	α_2	α_3	α_4	α_5	α_{pre}
80 cm	3.3	0.108	0.130	0.142	0.140	0.145	0.151
45 cm	5.4	0.244	0.309	0.185	0.198	0.200	0.215
18 cm	7.0	0.375	0.291	0.218	0.222	0.325	0.264

H. Flow Instabilities

At low gas flow rates under the natural circulation condition, large amplitude flow oscillations have been observed. The period of oscillation was between 10 and 25 sec. It was a weak function of the gas flux or liquid natural circulation rate. The period decreased as the gas flux increased. On the other hand, the amplitude strongly depends on the gas flux and inlet flow restriction. The general tendency was that the amplitude increased as the gas flux decreased until it hit the maximum value near the flow termination point. However, as the gas flux was further reduced toward the liquid flow termination, the amplitude slightly decreased. The inlet flow restriction stabilizes the flow both in terms of the amplitude and unstable range. With a larger flow restriction, this flow oscillation can be basically eliminated.

The period of the oscillations and parametric dependencies show that this instability is related to the void propagation phenomena [17,18]. The characteristic time can be related to the kinematic wave velocity and the system axial length. This implies that the period of oscillation is in the order of the mixture residence time. It is considered that the observed phenomenon is either the density wave oscillation or its coupling with the compressible volume in the separator.

In terms of the safety analysis for the prototype system, the occurrence of this flow instability is important. The dynamical behavior of the loop near flow termination can be considerably influenced by the flow oscillations. This is particularly so in the prototype system because the loop configuration is more complicated than the model due to the existence of two hot legs, four cold legs and a common core. Thus any flow instability has a potential of leading the system to loop to loop flow oscillations or flow excursions which may complicate the accident sequences and lead to more unreliable predictions. However, this phenomena should be studied in more detail until a comprehensive understanding can be obtained.

V. PRELIMINARY OBSERVATIONS FROM FREON-113 BOILING AND CONDENSATION LOOP

Several preliminary experiments were run using the new Freon-113 boiling and condensation loop. Because of the flexibility of the system a wide range of experimental conditions are possible, however for testing the loop simple initial and boundary conditions have been chosen. The initial conditions of the experiments for the primary side were

the single phase liquid state throughout the loop,
no initial flow,
an uniform temperature throughout the loop, and
no cooling in the simulated steam generator.

At the start of an experiment a constant power was supplied to the simulated core, then it was kept at this value until the end of the experiment. The secondary loop was kept in the shut-down mode with no cooling to the primary loop until a considerable amount of vapor accumulated in the primary side of the steam generator. Then constant subcooled liquid flow was initiated in the secondary loop to activate the heat sink to the primary side.

During the experiments several different loop-wise phenomena were observed. In the first stage, no loop-wise natural circulation of liquid was observed. The hot liquid from the core simply built up in the hot-leg by natural convections within the hot-leg. A plume of hot liquid rising in the hot-leg was visible. This stage was followed by a stable single phase natural circulation over a fairly long period. The loop wise natural circulation started when a sufficient head difference was established between the hot-leg and cold-leg return. It was observed that the flow rate was nearly constant except at the beginning and end of this stage. Both the onset and termination of the single phase natural circulation happened quickly. In the latter part of the single phase natural circulation stage, subcooled boiling was observed in the heater rod section. However, very small bubbles generated by the subcooled boiling collapsed as they rose in the vessel and no vapor accumulation was observed.

The sudden termination of the single phase natural circulation was followed by boiling in the core. This lead to the gradual build-up of a vapor space above the core. Until this vapor space reached the top of the horizontal section of the hot-leg, no vapor was transferred to the hot-leg and no loop-wise circulation was observed. The bubbles in this saturated boiling were much bigger than the ones from the subcooled boiling.

The two-phase natural circulation was established as the vapor flowed from the vessel and a sufficient void fraction was established in the hot leg. Most of the vapor came from the vapor space above the core. At the inlet of the horizontal section, the flow pattern was quite similar to the adiabatic experiment discussed in the previous section. At the bottom of the vertical hot leg, slugging occurred due to the flow stratification in the horizontal section. However, the phase interfaces were much more unstable in the Freon experiment. The slug or cup bubbles immediately disintegrated into small bubbles. The flow regime was, therefore, mostly in churn turbulent bubbly flow even at moderate vapor fluxes. Significant turbulent motions were observed up to 2 to 3 m from the bottom. The void fraction in this section seemed to be much higher than the ones in the downstream section. Above this quite turbulent section, a typical bubbly flow was established up to the U-bend section. The flow over the U-bend section was similar to the ones in the adiabatic experiments. The flow patterns were strongly dependent on the vapor flux. The duration of the two-phase natural circulation was a function of the heat flux and the condensation rate. Without sufficient condensation in the steam generator, the vapor phase accumulated rapidly in the U-bend and upper part of the simulated steam generator. This lead to the complete flow termination. However, unlike the adiabatic experiments, this was not a permanent flow termination.

It was observed that the bubbly flow in the hot leg was maintained and gradually the liquid levels in the hot leg and steam generator came down. During this stage, occurrences of sudden flashing at the upper 1/3 of the hot leg were observed. The flashing started both within the liquid and at the pressure taps. Once the flashing started, the two-phase flow regime changed dramatically from bubbly to slug flow. A slug bubble was generated by very rapid growth of a nucleated bubble. Often the bubble growth was so rapid that the flow could not be accelerated sufficiently and the motion of the slug bubble slowed down considerably. Several cycles of the slug bubble generation lead to a very much increased natural circulation rate.

Due to this increased rate, a large amount of subcooled liquid entered into the core. Because of this, the boiling in the core was completely suppressed. The vapor volume decreased considerably and the liquid level rose above the bottom of the hot leg, thus it shut down the vapor flow to the hot leg. This also lead to the termination of the natural circulation. At the end of this flashing phenomena, the stagnated liquid was observed in the hot leg. The vapor phase filled the upper part of the hot leg and U-bend section. The subcooled boiling started during this stagnated period and the whole process could repeat with a period of a few minutes.

It is noted that the cooling by the secondary loop can be initiated any time during the experiment. For example, the condensation of accumulated vapor at the upper part of the steam generator can be promoted by starting the secondary loop after the termination of the two-phase natural circulation. The rapid condensation can reduce the pressure in the hot leg and may help the flashing process. However, the flashing could happen without the secondary loop circulation. The main cause of the flashing appears to be the hydrostatic pressure decrease within the hot-leg as the liquid moves up from the bottom to the top. This pressure reduction is considerable at the order of 10 psi (~69 kPa). As the saturated liquid enters into the hot-leg and rises due to natural circulation or natural convection within the hot-leg, it can be superheated. This superheating can lead to flashing at the upper part of the hot-leg. Overall, the flow phenomena in the Freon loop are more complicated and unstable due to thermal non-equilibrium effects on phase changes.

VI. DRIFT FLUX MODEL FOR LARGE DIAMETER PIPES

In the prototype system, the diameter of the hot legs is about 90 cm and the length to diameter ratio relatively small at about 20. Thus the two-phase flow in the hot legs under natural circulation conditions can be quite different from the standard experiments. Thus the conventional two-phase flow models developed based on small diameter and large ℓ/d system experiments may not be adequate for accurately predicting the two-phase flow phenomena in the hot legs. In view of this, the drift flux model applicable to large diameter pipes at relatively low fluxes has been developed [19]. Based on the detailed analysis of bubble behaviors the drift velocity correlations have been obtained in collaboration with a large number of experimental data. The air-water and steam-water data over the pressure range of 0.1 to 18 MPa and the diameter range of 2 to 61 cm have been used. The preliminary results [19] are summarized below.

The area averaged drift velocity $\overline{V}_{gj}$ or the relative velocity $\overline{v}_r$ is given in the standard form by

$$\overline{V}_{gj} = (1-\alpha)\ \overline{v}_r = (C_o - 1)\ j + \langle\langle V_{gj} \rangle\rangle \tag{13}$$

where the distribution parameter C_o represents the effect due to the phase and velocity distributions in the cross section and $\langle\langle V_{gj}\rangle\rangle$ the average local slip between phases.

For low gas flux conditions given by $j_g < 0.5\ (\sigma g \Delta\rho/\rho_f^2)^{0.25}$ the standard correlations [10,11] can be used. Thus

$$\langle\langle V_{gj} \rangle\rangle = \begin{cases} \sqrt{2}\left(\dfrac{\sigma g \Delta\rho}{\rho_f^2}\right)^{0.25} (1-\alpha)^{1.75} & ;\ \text{Bubbly} \\ \sqrt{2}\left(\dfrac{\sigma g \Delta\rho}{\rho_f^2}\right)^{0.25} & ;\ \text{Churn-Turbulent} \\ 0.35\sqrt{gD\Delta\rho/\rho_f} & ;\ \text{Slug} \end{cases} \tag{14}$$

However the slug flow is limited [12,13] to $D \lesssim 40\sqrt{\sigma/g\Delta\rho}$, and the distribution parameter is given by

$$C_o = 1.2 - 0.2\sqrt{\rho_g/\rho_f} \tag{15}$$

For higher gas flux conditions given by $j_g > 0.5\,(\sigma g \Delta\rho/\rho_f^2)^{0.25}$, the newly developed drift flux model has the following form for low viscous fluids.

$$\langle\langle V_{gj}\rangle\rangle = \begin{cases} 0.0019\, D^{*0.809}\left(\dfrac{\rho_g}{\rho_f}\right)^{-0.157} N_{\mu f}^{-0.562} & \text{for } D^* \le 30 \\ 0.030\left(\dfrac{\rho_g}{\rho_f}\right)^{-0.157} N_{\mu f}^{-0.562} & \text{for } D^* > 30 \end{cases} \quad (16)$$

where $D^* = D/\sqrt{\sigma/g\Delta\rho}$ and $N_{\mu f} = \mu_f/(\rho_f \sigma \sqrt{\sigma/g\Delta\rho})^{0.5}$.

The above results are compared to a large number of experimental data. The present correlations fit to these data over wide ranges of gas flux, diameter, system pressure and liquid physical properties. The accuracy of the prediction of void and liquid fractions is within ±20%. This is a significant improvement over the existing correlations.

VII. SUMMARY AND CONCLUSIONS

The two-phase natural circulation and flow termination in the hot-leg and U-bend have been experimentally investigated. The nitrogen-water simulation loop and Freon 113 loop were designed and constructed according to the scaling criteria developed under the program. These loops are a partial scale model of a typical B&W 2 x 4 nuclear reactor system and the main focus of the research is the natural circulation phenomena during a small break loss of coolant accident.

The phenomena were studied in detail by focussing on the simulation and scale distortion effects in terms of the hot leg U-bend phase separation, two-phase flow regimes and void distribution. The effects of parameters such as the thermal center (separator water level), loop frictional resistance, inlet section geometry and U-bend curvature on the natural circulation flow termination were experimentally analyzed. The void fraction distributions along the hot-leg were obtained from differential pressure transducers. A simple criterion for the prediction of the flow termination condition was proposed in terms of the gas superficial velocity. Important conclusions obtained from the adiabatic experiments are summarized below.

(1) In general the induced liquid natural circulation rate increased with the increasing gas flow rate. This natural circulation rate strongly depended on the loop frictional resistance and gravitational driving head.

(2) As the gas flow rate was reduced, eventually the liquid flow was terminated. This flow termination was basically governed by the hot leg void distribution and the separator water level. The frictional resistance of the loop had almost no effect on the flow termination. A higher liquid level in the separator implied higher hydraulic head, thus a smaller void fraction in the hot leg was required to sustain the natural circulation leading to a smaller gas flux at the flow termination.

(3) Temporal voiding of the U-bend section happened quasi-periodically in the slug or churn-turbulent flow regime. This was caused by the passage of large slug bubbles. Under this condition the liquid flow through the U-bend was intermittent. However, the loop natural circulation was not strongly influenced by this intermittency and quite stable. Thus the phase separation at the U-bend had no important effect on the overall natural circulation. As long as there was enough hydraulic driving head, the two-phase mixture level could recover up to the U-bend and the liquid flow was reestablished.

(4) Near the flow termination point, flow oscillations with a considerable amplitude had been observed. The period of the oscillation was between 10 to 25 sec. This indicated that the instability was related to the kinematic wave propagation. It could be stabilized both in terms of the amplitude and unstable range by increasing the single phase flow restriction.

(5) The inlet geometry effects were examined by using three different configurations, i.e., straight vertical-up, short horizontal section with a 90 degree elbow and long horizontal section. The phase separation in a horizontal section lead to the stratification. This stratified two-phase flow caused the slugging at the elbow. Thus the flow regime in the vertical section was always either in cap-bubble or slug flow. On the other hand, with the straight vertical-up inlet geometry, bubbly flow was possible. It is expected that in the prototype system, similar slugging can happen at the elbow. However, very large cap or slug bubbles are unstable [11,12], thus they should disintegrate into a large number of smaller cap and deformed bubbles.

(6) The effect of the U-bend curvature on the natural circulation was not significant. This is consistent with the second and third conclusions.

(7) A very simple criterion for predicting the flow termination point was derived from a force balance. This criterion was in good agreement with the data.

(8) There was basically no hysteresis effect between the flow termination and reestablishment.

The preliminary tests in the Freon 113 loop showed significant effects of heat transfer and phase changes. The two-phase flow regime in the hot leg was mostly churn-turbulent bubbly flow in the lower section and bubbly flow in the upper section. The horizontal slugging rarely lead to the formation of stable slug flow in contrast to the adiabatic case. This should be due to the difference in the surface tensions and the phase change. The most significant phenomenon was the flashing in the upper part of the hot leg which could induce two-phase natural circulation.

In addition to these experiments, an analytical study has been carried out to develop a two-phase flow model for large diameter pipe flow. The present correlations fit to a large number of data over wide ranges of gas flux, diameter and system pressure.

From the present experimental study, an understanding of the basic mechanism of the natural circulation termination has been established. The loop friction and thermal center play key roles in determining the natural circulation rate. The hot-leg flow regime and void distribution are also very important in predicting the phenomena. Both of these strongly depend on the inlet geometry. Several scale distortion effects in a small scale model have been pointed out. These will affect the analysis of the data from the present loop as well as the other integral facilities such as MIST and UM. In order to clarify these points, the present experimental program is continued to cover such effects as larger diameter hot leg, different fluid properties and phase changes.

NOMENCLATURE

a	Area scale
C_o	Distribution parameter for drift-flux model
D	Hydraulic diameter
f_{TP}	Two-phase friction factor
f_{SP}	Single phase friction factor
g	Gravity
j	Total volumetric flux $(j_g + j_f)$
j_g	Gas volumetric flux
K	Orifice loss coefficient
ℓ	Axial length scale
ℓ_w	Separator water level from bottom of loop
ℓ_{max}	Hot leg height from bottom of loop
t	Time scale
u	Velocity scale
u_f	Liquid velocity
u_m	Mixture center of mass velocity
$\overline{v}_r$	Mean relative velocity
V	Volume scale
$\overline{V}_{gj}$	Mean drift velocity

$\langle\langle V_{gj} \rangle\rangle$ Average of local drift velocity

x Vapor quality

z Axial coordinate

Greek Symbols

α Void fraction

$\Delta\rho$ Density difference $(\rho_f - \rho_g)$

ρ_f Liquid density

ρ_g Gas density

ρ_m Mixture density

σ Surface tension

Subscripts

$(\ )_m$ Model value

$(\ )_p$ Prototype value

$(\ )_R$ Ratio of model to prototype values

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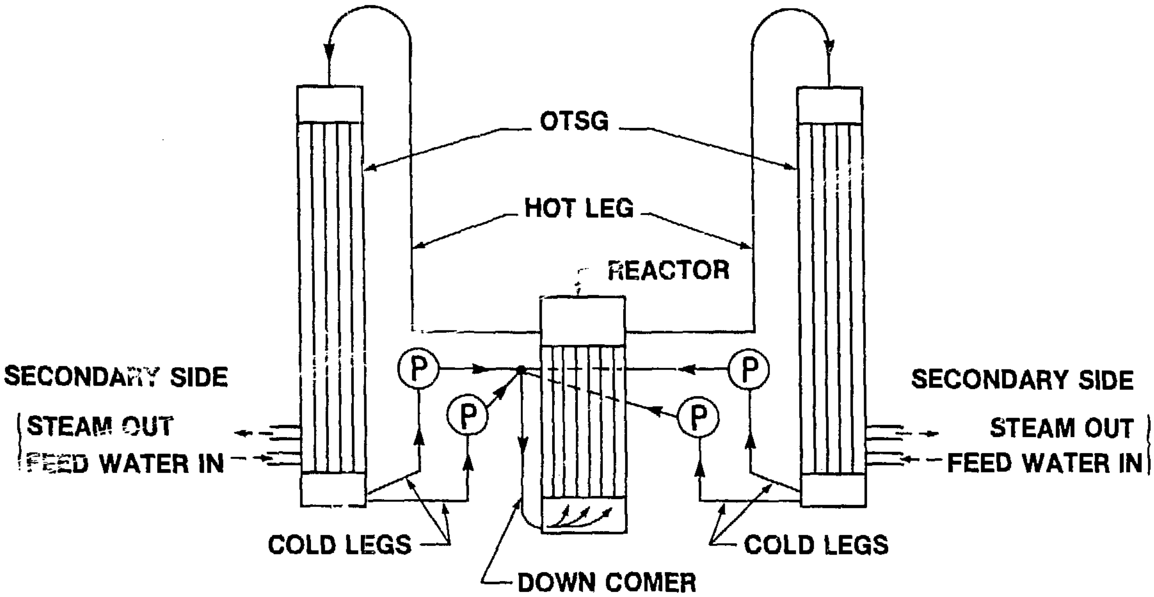

Fig. 1. Schematic of B&W 2x4 Loop Nuclear Reactor

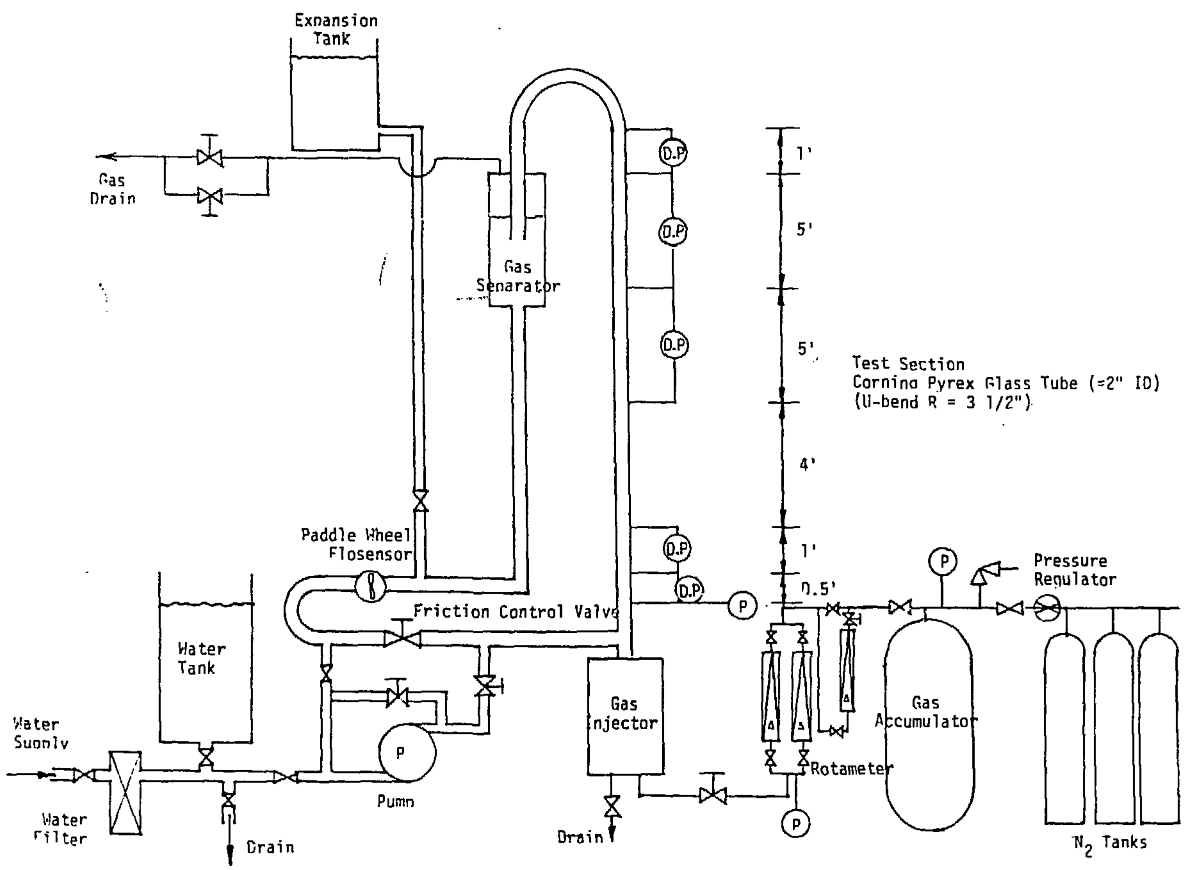

Fig. 2. Schematics of Hot-leg U-bend Simulation Loop for Nitrogen Gas-water Experiments

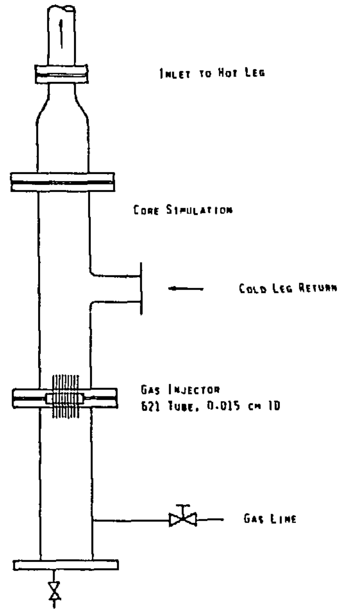

Fig. 3. Hot-leg Inlet of Vertically Straight Geometry without Horizontal Hot-leg Section

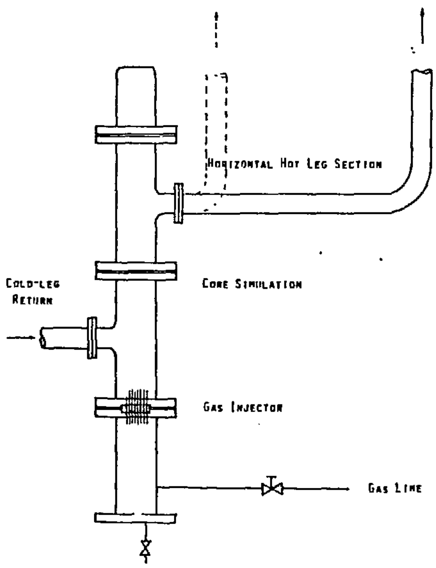

Fig. 4. Hot-leg Inlet with Horizontal Section Simulation Reactor Vessel Exit Geometry (short and long horizontal sections shown)

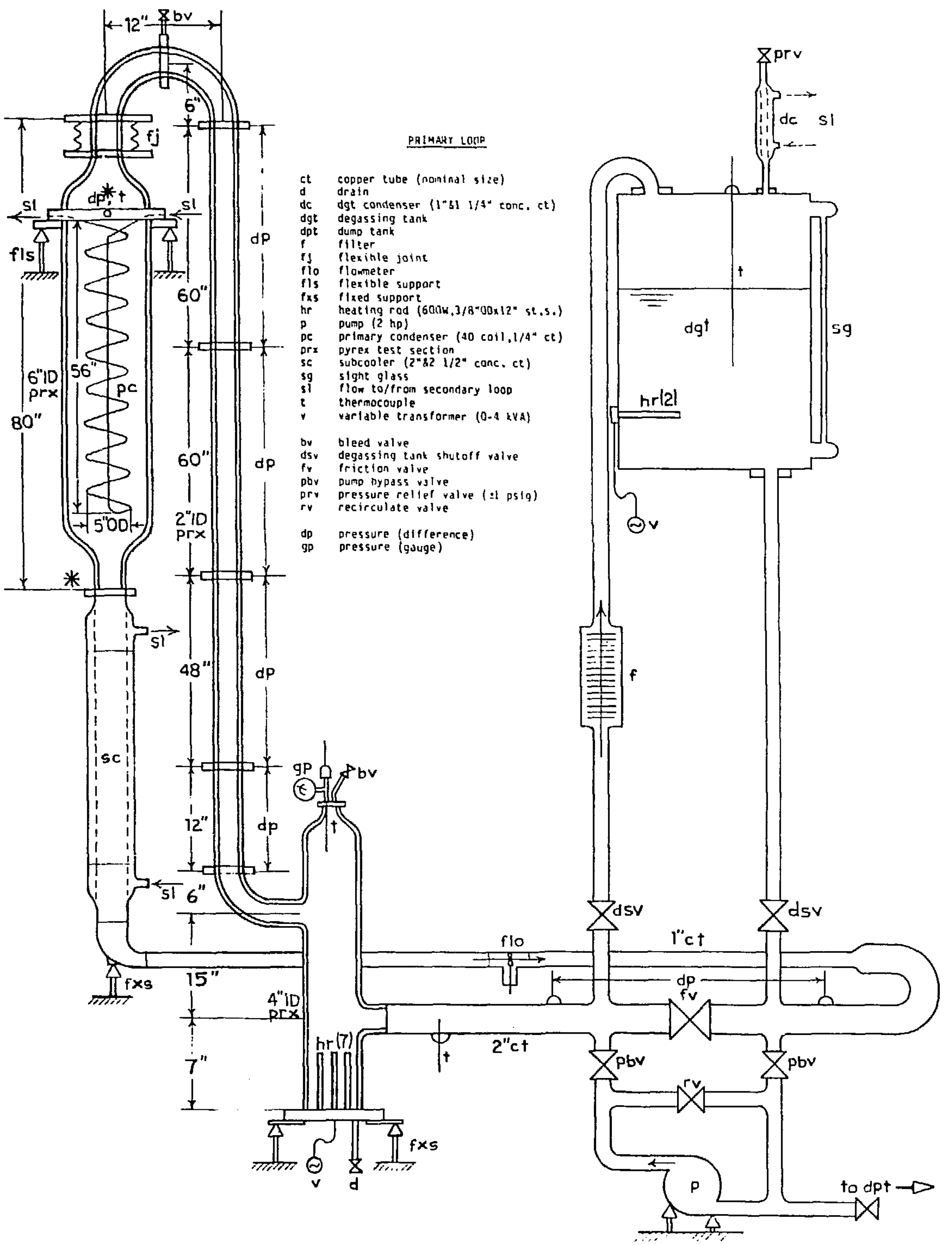

Fig. 5. Schematic of Freon 113 Boiling and Condensation Loop for Hot-leg U-bend Natural Circulation Study