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# FIRST QUARTER FY80 PROGRESS REPORT ON REFILL EFFECTS PROGRAM

Quarterly Progress Report
October 1 — December 31, 1979

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## ABSTRACT

This report describes work on the Creare Refill Effects Program during the first quarter of FY80. Calculations using a preliminary, semi-empirical analysis are compared against flashing transient data for the effects of wall heat transfer, break flow, downcomer slip, and non-equilibrium downcomer behavior. Results of parametric tests of flashing effects are briefly summarized for the effects of hot leg breaks, separator vessel pressure, initial plenum volume, annulus gap size, initial plenum liquid subcooling, and reverse core steam flow. Future plans are outlined.

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## NOMENCLATURE

| | |
|---|---|
| $D_b$ | broken cold leg diameter |
| $D_{bh}$ | broken hot leg diameter |
| $D_v$ | vessel diameter |
| $L_{LP}$ | height of lower plenum |
| $L_v$ | height of vessel |
| $m_{fp}(0)$ | initial mass of liquid in plenum |
| $P_{sep}$ | separator vessel pressure |
| $P_v$ | vessel pressure |
| $Q_{fin}$ | injected volumetric flow rate of ECC |
| $Q_w$ | rate of heat transfer from vessel wall |
| s | annulus gap size |
| $T_{ECC}$ | temperature of injected ECC |
| $T_s$ | saturation temperature |
| $T_f(0)$ | initial liquid temperature in lower plenum |
| $V_{mp}(0)$ | initial mixture volume in lower plenum |
| $V_{mp}(f)$ | final mixture volume in lower plenum |
| $W_{gc}$ | mass flow rate of reverse core steam |
| $\emptyset$ | slip velocity in lower plenum mixture |
| $\eta_m$ | condensation efficiency parameter in downcomer |

# 1 INTRODUCTION

This is a quarterly report on the Creare Refill Effects Program. The context of this effort is the blowdown and refill of a Pressurized Water Reactor (PWR) vessel during a postulated LOCA. The primary work in FY80 involves analysis and experiments related to flashing and swelling of fluid contained in scale model PWR vessels during depressurization transients with both large and small breaks. Although emphasis is on refill of a PWR vessel, many of the phenomena studied--such as phase slip in a flashing mixture and non-equilibrium mixing of subcooled water and steam--have broader applications during other phases of a LOCA or during operating transients in BWRs or PWRs. The major goals of these flashing studies are to assist in the development of LOCA analyses by

1) identifying the key phenomena,

2) organizing and contributing to the data base available for code developers to assess their analyses,

3) developing analysis tools which permit rapid, inexpensive calculations and sensitivity studies to assist advanced code development, and

4) suggesting scaling relationships and predicting the effects of alternative scaling models at full-scale.

As outlined in the previous quarterly report [1], the general structure of the program has been divided into four tasks with associated subtasks:

- Flashing Analysis and Assessment

  Analysis

  a. Identify physical models
  b. Develop CREFIL analysis
  c. Modify and use RELAP

  Assessment

  a. Understand data
  b. Comparisons of analysis with data
  c. Sensitivity calculations

- Flashing Experiments

  a. 1/30-scale modeling and flow visualization tests
  b. 1/15-scale parameter tests
  c. 1/5-scale scaling tests

- Reporting

- Program Coordination

In the period of October through December 1979, primary efforts focused on development of new models and assessment of alternate models added to the CREFIL analysis. Comparisons of the CREFIL analysis with RELAP4/MOD5 calculations and experimental data continued. Experimental work consisted of continued parameter experiments at 1/15-scale and flow visualization experiments with and without ECC injection in the 1/30-scale vessel. Section 2 summarizes the accomplishments on each of the program topics during the quarter. Highlights of these efforts include:

1) Development and assessment of models for the phenomena of wall heat transfer, break mass flow, and downcomer slip in the CREFIL analysis.

2) Preliminary CREFIL calculations of the flashing transient experiments with ECC injection.

3) Completion of the single-parameter scoping experiments at 1/15 scale.

4) Completion of a motion-picture film documenting flow behavior in flashing transients with and without ECC injection in a transparent (1/30-scale vessel) [2].

## 2 SUMMARY OF RESULTS

### 2.1 Reporting

During the period comprising the last two months of this quarter and the first two months of the following quarter, reporting is receiving emphasis. Two Topical Reports, an Interim Report, and two Quarterly Reports are scheduled to be prepared during this time. The two Topical Reports are on the FY79 tasks of Lower Plenum Voiding and Flow Topography. The Interim report covers work on flashing transients begun in FY79 and continuing in FY80.

During this quarter, the Topical Report on Lower Plenum Voiding was completed [3]. This report describes the results of FY79 separate effects tests studying equilibrium voiding in various vessels ranging in size from 1/30 to 1/10 of PWR scale. Among the findings described are identification of several flow regimes and the scaling of idealized equilibrium voiding. The effects of various geometric parameters as well as water injection, transient steam flows, and two-phase plenum mixtures are also described. A wave analysis developed by Wallis [4] is shown to predict data in the predominant wave regime while four other analyses by various investigators (with several scaling parameters) are shown to be inconsistent with the data. This report marks the completion of planned studies of lower plenum voiding as a separate effect.

Preparation of the Topical Report on Flow Topography [5] was started in this first quarter of FY80 and has since been completed. The report describes the instrumentation system of hardware and software invented to record, display, and analyze phase distributions in two-phase flows. Tests of the system in a 1/15-scale model PWR are reported. Work was also initiated on an Interim Report summarizing progress to date in testing and analysis of flashing transients and ECC interactions. This report will be completed in early February.

The Quarterly Report [1] for the fourth quarter of FY79 "Summary of FY79 Progress on Refill Effects Program" was also completed. This report summarizes the progress during FY79 relative to planned efforts. Plans for FY80 are also outlined. The present report constitutes the second quarterly report to be completed in this period.

### 2.2 Analysis and Model Development

A semi-empirical analysis of flashing effects is being developed. A key purpose of this analysis is to help organize the Creare flashing transient data base for code assessment. Similar analyses have also been useful in the past to permit rapid exploratory calculations and extensive sensitivity studies, to assist advanced code development and to suggest scaling relationships. During the quarter, primary emphasis was given to analysis development efforts over testing, in order to generate new models and to explore alternate models for various phenomena.

Reported progress thus far has included descriptions of baseline tests with [6,7] and without [7,8] ECC injection. The analysis of baseline tests without ECC injection was presented in Reference 6 and concentrated on the modeling of the slip velocity for phase-separation in the lower plenum. An early version of the analysis, containing the basic building blocks was used. Since that time, the analysis (called CREFIL) has been upgraded to include alternate models and was restructured in a general revision of the coding. Analysis of the experiments without ECC injection has been performed for the phenomena of wall heat transfer, break flow modeling, and downcomer slip in addition to previous modeling of flashing and phase separation in the plenum. Analysis of the experiments with ECC injection has begun for the effects of condensation and upflow quality during flashing transients. The preliminary results of this analytical work are summarized here.

## Previous Results

Analysis comparisons with experimental data at 1/15-scale have shown [6] that plenum phase separation should be modeled with slip velocities on the order of 10 ft/sec. These are significantly higher than slip velocities based upon the concepts of rising bubbles (which are on the order of 2 ft/sec). Flow visualization in our transparent vessel has revealed vigorous two phase mixing during phase separation at moderate void fraction. The effect of phase slip was modeled across a spectrum of assumptions ranging from homogeneous to separated plenum mixtures using both CREFIL and RELAP4/MOD5. The Wilson correlation [9], expressing slip velocity as a function of mixture void fraction, gave the necessary slip velocities required to match experimental data. A second model, the Labuntsov correlation [10], has subsequently been shown to give similar good results. The two codes CREFIL and RELAP agreed closely in all calculations.

## Heat Transfer

In order to bound the possible effects of wall heat transfer in the flashing transients, a model which assumes conduction-limited wall heat transfer was incorporated into the analysis. This model also assumes that the entire surfaces of the lower plenum and downcomer are involved in heat transfer and that the wall surface temperature is always at the saturation temperature corresponding to the current vessel pressure (the entire vessel having initially been at saturation temperature corresponding with and without this "maximum" heat transfer against typical experimental data for vessel this "maximum" heat transfer against typical experimental data for vessel pressure, plenum mass, plenum mixture level, and steam outflow transients. As shown, the calculation which includes heat transfer better matches the pressure, level, and outflow transients with only a small effect on the vessel mass transient. Heat transfer therefore improves comparisons with these specific data. Further calculations assessing more realistic heat transfer models are planned. The effect of wall heat transfer is expected to decrease with scale as the ratio of fluid volume to metal surface area increases.

## Effect of Break Mass Flow

In previous comparisons [6], the break mass flow model was shown to primarily determine the rate of vessel depressurization. However, if the depressurization transient is not matched exactly, there are secondary effects on fluid mass and level which somewhat obscure the direct effects of the plenum phase slip models. To remove these modeling uncertainties, the CREFIL analysis was modified to accept experimental pressure data as input and calculations were performed without a break model. As shown in Figure 2, when the pressure transient is matched by inputting experimentally measured pressures, both the Wilson and Labuntsov correlations continued to match other transient parameter data well. The Zuber-Findlay correlation [11] consistently underpredicts the vessel mass.

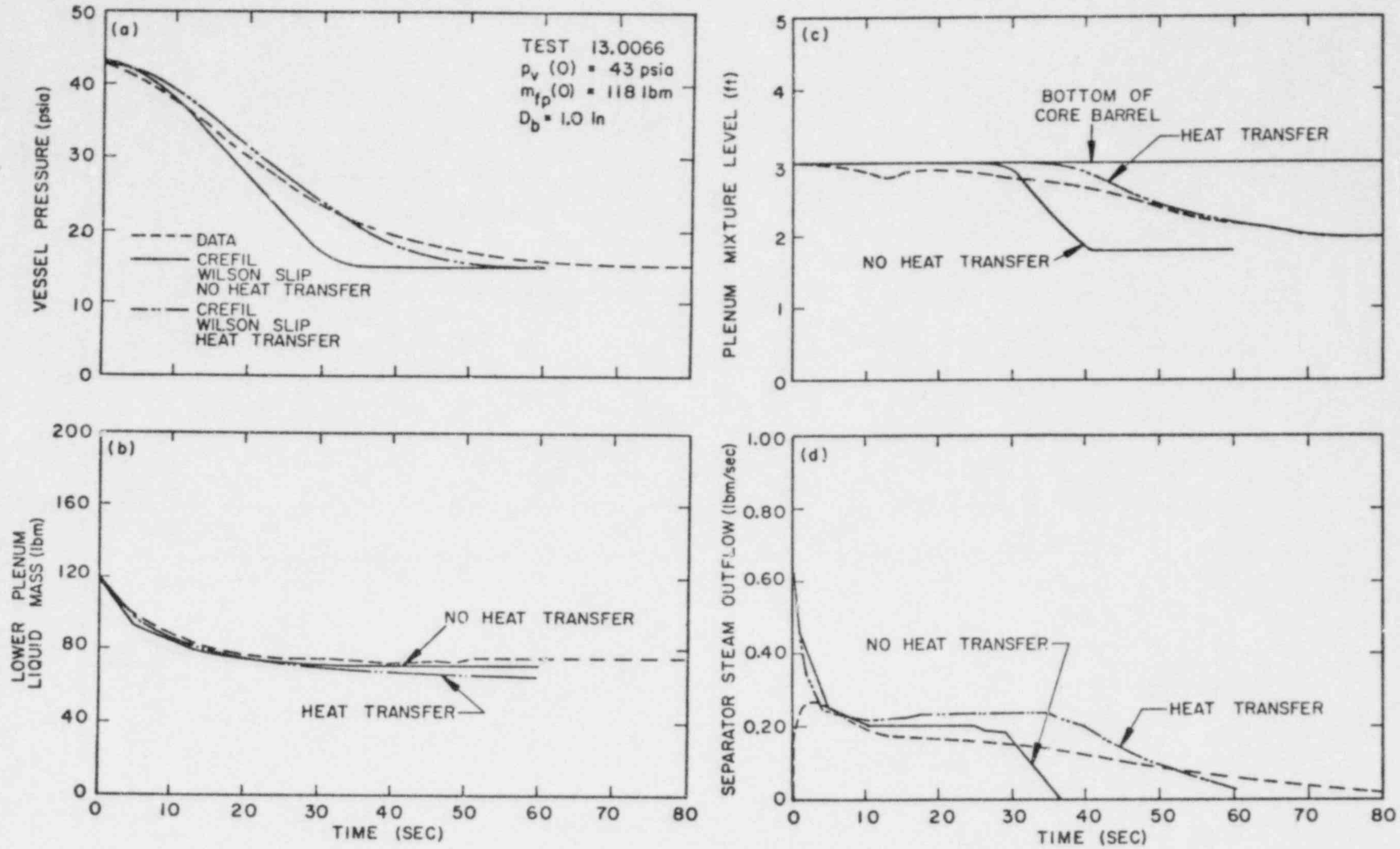


Figure 1. EFFECT OF WALL HEAT TRANSFER IN CALCULATION OF A TYPICAL FLASHING TRANSIENT

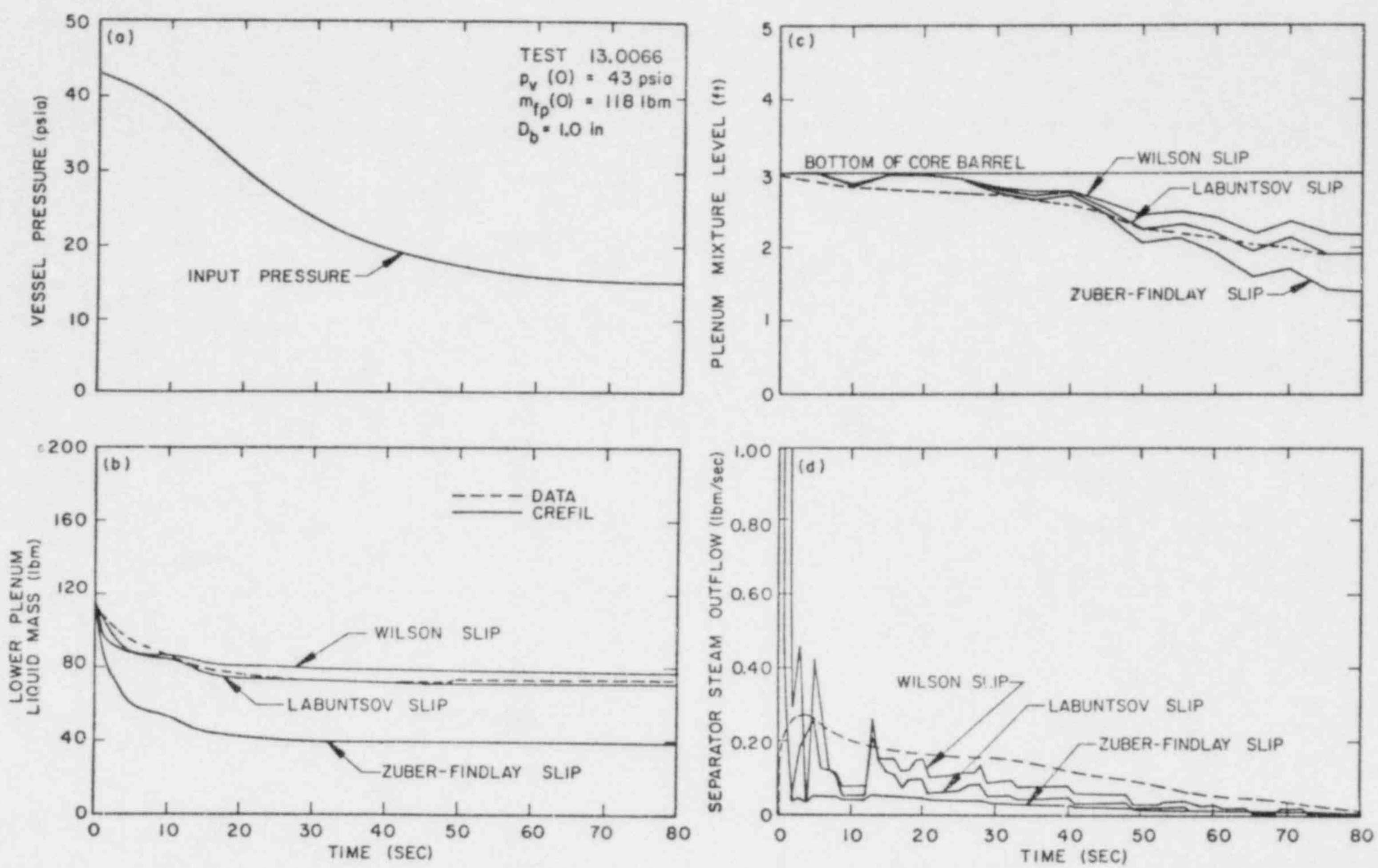


Figure 2. EFFECT OF VARIABLE SLIP VELOCITY IN FLASHING TRANSIENT CALCULATIONS WITH PRESSURE INPUT

Various critical flow models, including the Moody [12], Henry-Fauske [13] and Homogeneous Equilibrium Models [14] can be used for critical flow. Since development of critical flow models is beyond the scope of this project, the modified Henry-Fauske/Homogeneous Equilibrium Model recommended for RELAP4/MOD5 [15] is used for our critical flow calculations. This model performs acceptably as shown in Figure 1. Additional break flow models including the effects of slip or nonequilibrium thermodynamics may be assessed, though no model development involving critical flow is planned.

## Downcomer Slip

Besides slip in the lower plenum, additional slip may also occur in the downcomer. In RELAP for example, default models allow further slip between phases at the junction between the lower plenum and downcomer. Slip velocities are typical of the Zuber-Findlay correlation [15]. As shown in Figure 3, downcomer slip has a negligible effect in the calculations when the Wilson correlation is used for plenum slip. Downcomer slip is only important when the plenum slip velocity is small, as shown by the homogeneous calculation in Figure 3. Even applying the Wilson correlation to slip in the downcomer and the lower plenum has a negligible effect in the calculations. This is because the effect of slip is approximately proportional to the cross-sectional flow area in each region. Since the area of the downcomer is one-sixth of the plenum area, velocities having equivalent effects are six times larger for the downcomer than for the plenum. Therefore, at high plenum slip velocities, downcomer slip may be neglected in the calculation of these tests. This is confirmed by RELAP4/MOD5 calculations performed with and without slip at the plenum-downcomer junction.

## ECC Injection

During the quarter the first analysis comparisons involving ECC injection were performed. Experimentally, the combined effects of flashing, condensation, and ECC bypass have been shown [6] to have complex effects on the timing and rate of filling of the lower plenum.

The preliminary analysis models the effects of thermal nonequilibrium in the downcomer with an adjustable coefficient $\eta_m$ to reflect the degree of thermal nonequilibrium during condensation. A value $\eta_m=0$ signifies no condensation while $\eta_m=1$ implies complete equilibrium. Results of calculations reveal that the highest and lowest estimates for the effects of ECC injection occur when $\eta_m=0$ without heat transfer and $\eta_m=1$ with heat transfer. The calculations are presented in Figure 4 for the vessel pressure and mass transients in a typical test with ECC injection. The two estimates bound the pressure transient, but do not bound the mass transient, though the trend of the transient is matched fairly well with $\eta_m=1$.

Figure 5 illustrates the calculations and experimental data for a test where the ECC subcooling has been significantly reduced and thus the effects of condensation reduced. With $T_{ECC}=200°F$, the difference in pressure calculations between the $\eta_m=0$ and $\eta_m=1$ estimates becomes smaller, as expected. The mass calculations bear about the same relationship to the data as with colder ECC (Figure 4(b)) with the $\eta_m=1$ calculation again coming closer to the data. For this test, it is noted that the filling rate of the vessel is much less than the injection rate and the analysis correctly predicts the trend toward reduced filling rate. Further sensitivity studies are required varying the condensation model and other phenomena (e.g., break flow, ECC bypass, heat transfer) in the calculations. The purpose of the figures here is only to illustrate our preliminary results and the directions of our work. No conclusions should be drawn yet.

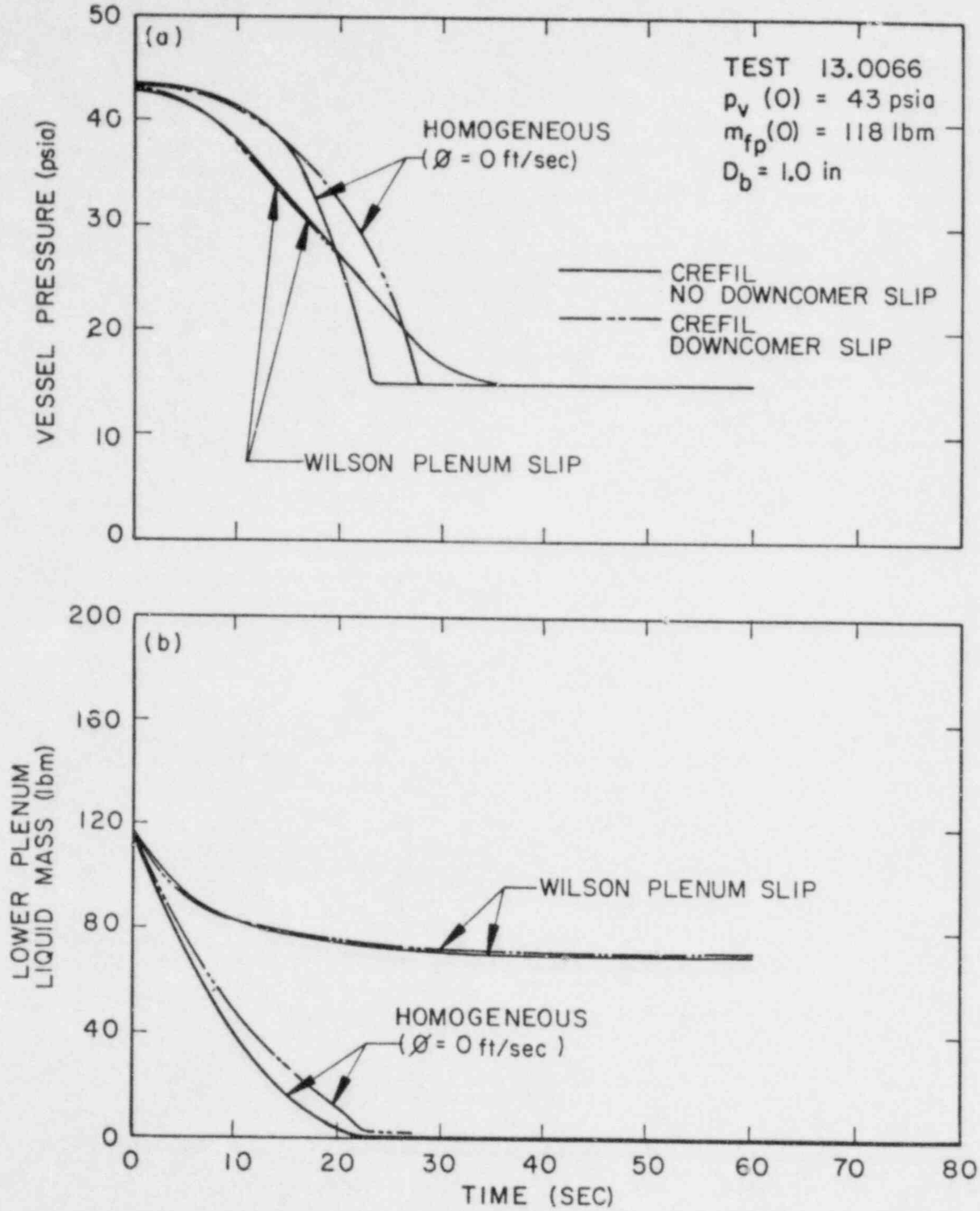


Figure 3. EFFECT OF DOWNCOMER SLIP IN FLASHING TRANSIENT CALCULATIONS

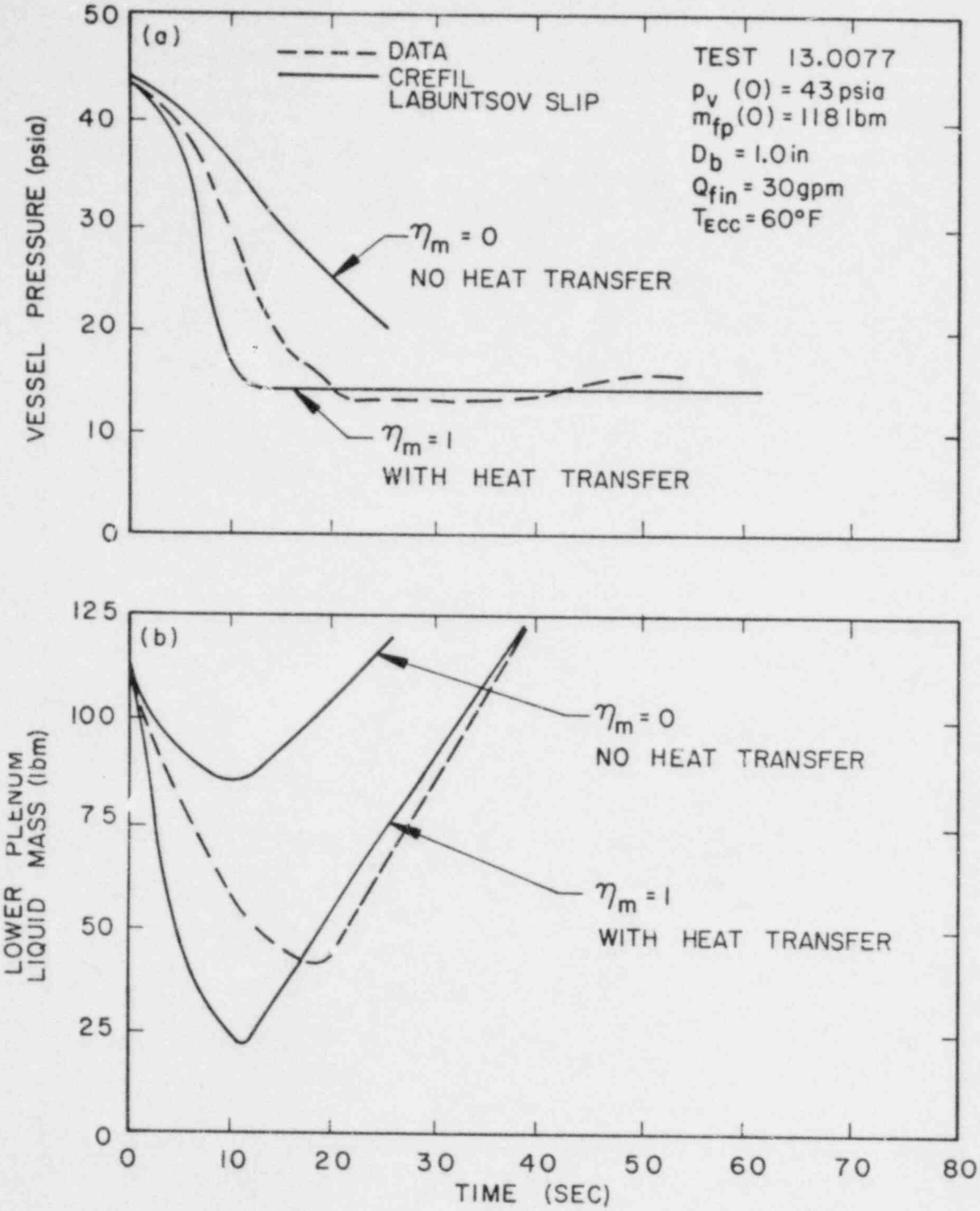


Figure 4. CALCULATION OF FLASHING TRANSIENT WITH HIGHLY SUBCOOLED ECC INJECTION ($Q_{fin}$=30 gpm, $T_{ECC}$=60°F)

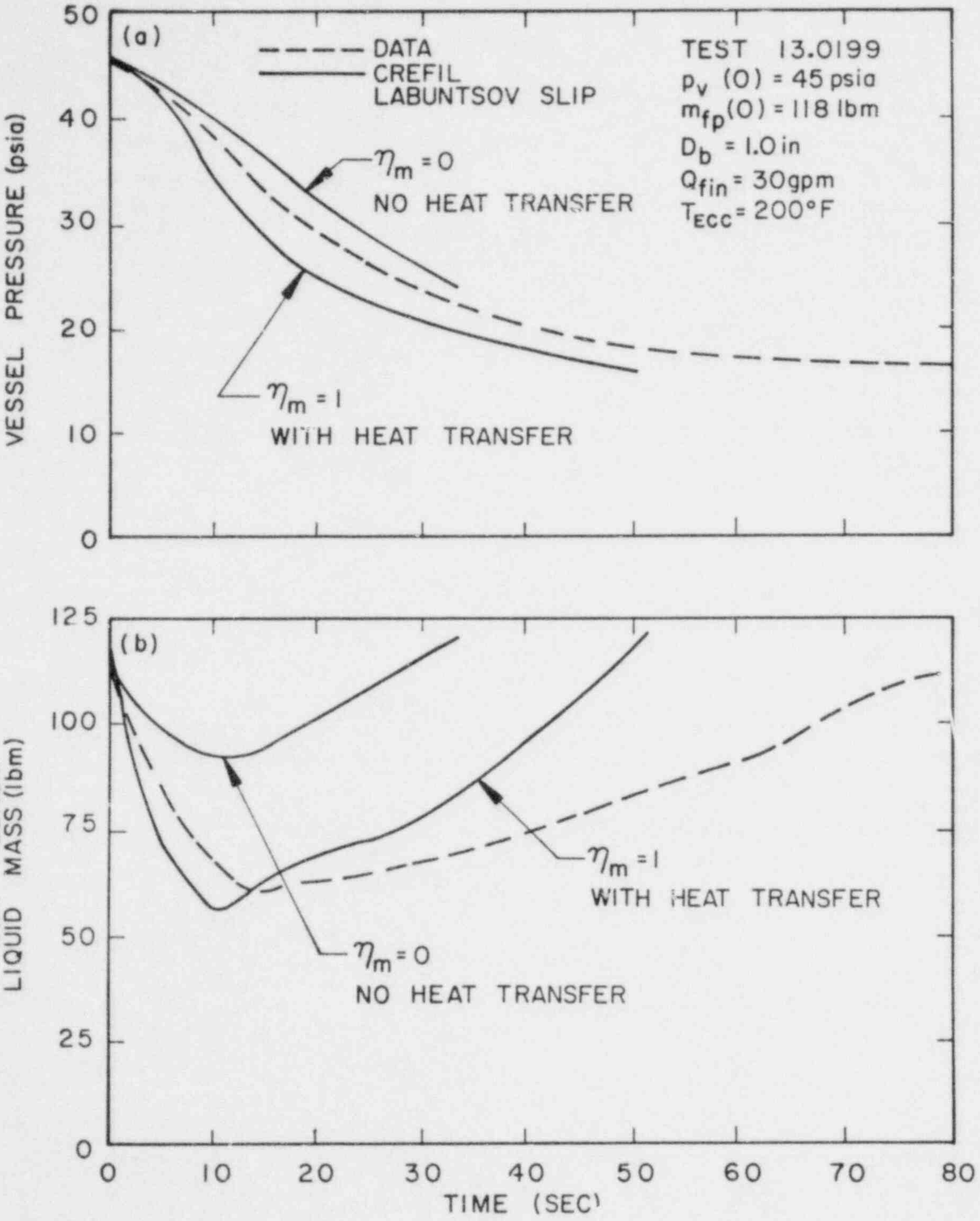


Figure 5. CALCULATION OF FLASHING TRANSIENT WITH LOWER SUBCOOLING OF INJECTED ECC ($Q_{fin}$=30 gpm, $T_{ECC}$=200°F)

Although not illustrated here, our calculations also show that the liquid component of the two-phase upflow needs to be accounted for in modeling flooding and ECC bypass. Initial calculations used correlations for ECC bypass based on single-phase (steam) upflow [6] and predicted no ECC bypass although significant bypass is seen to occur in the tests. Two modifications were made to the correlation to account for two-phase upflow effects and the more successful model was used here. Further study of this effect is needed and should be greatly assisted by analysis of experiments with an enlarged downcomer gap (see Section 2.3) and other experiments performed at larger scale.

### Future Work

Generally, it is expected that model development efforts will concentrate on further assessment of alternate models for some of the phenomena described here, (e.g., condensation and ECC bypass), with some changes to the CREFIL program needed to model effects of parameters not yet analyzed. During the following quarter, the analysis will be compared with additional blowdown test data from sources outside of Creare. Data from vessels ranging in size from 1/15 [17] to 1/5 [18] PWR scale will be analyzed and presented as part of the Interim Report on flashing transients. Comparisons with additional Creare data will also be made.

## 2.3 Flashing Experiments

During this quarter, the remaining parameter tests of the initial scoping series were completed. Reference [19] is a description of the test facility and reference [8] includes a discussion of the flashing test procedures. Table 1 includes the parameters which have been investigated to date. Previous reports [6,8] have discussed the effects of cold leg break size, initial pressure and injected water flow rate. Wall heat transfer and ECC temperature were discussed above. In this section, the effects of hot leg break size, separator vessel pressure, initial plenum volume, annulus gap size, initial plenum liquid temperature, and reverse core steam flow are reviewed.

### Hot Leg Break Size

Figure 6 presents partial results of cold leg and hot leg break tests without ECC injection. Even though the flow area in the passage approaching the break is of different geometry and twice as large on the hot leg side as on the cold leg side (core vs downcomer area), similar amounts of liquid remain in tests of hot leg and cold leg breaks of the same size. The distribution of effluent discharge is also about equal between the hot leg and cold leg sides when both legs have breaks of the same size. Therefore, the flow area and geometry upstream of the break are not critical parameters determining the remaining liquid volume or outlet flow distribution for this geometry.

Figure 7 shows that the remaining liquid volume decreases monotonically with increasing total break area. The data in Figure 7 also show that with the 2.3 in. diameter break in one leg (or $A>0.03$ ft$^2$), the remaining volume is about the same independent of what size break is in the other leg. This suggests that a limit is approached for the amount of liquid lost as the break size is increased.

Tests have also been done with combined hot and cold leg breaks and ECC injection. The plenum water inventory behavior shows the same trends as results obtained with cold leg breaks alone [6].

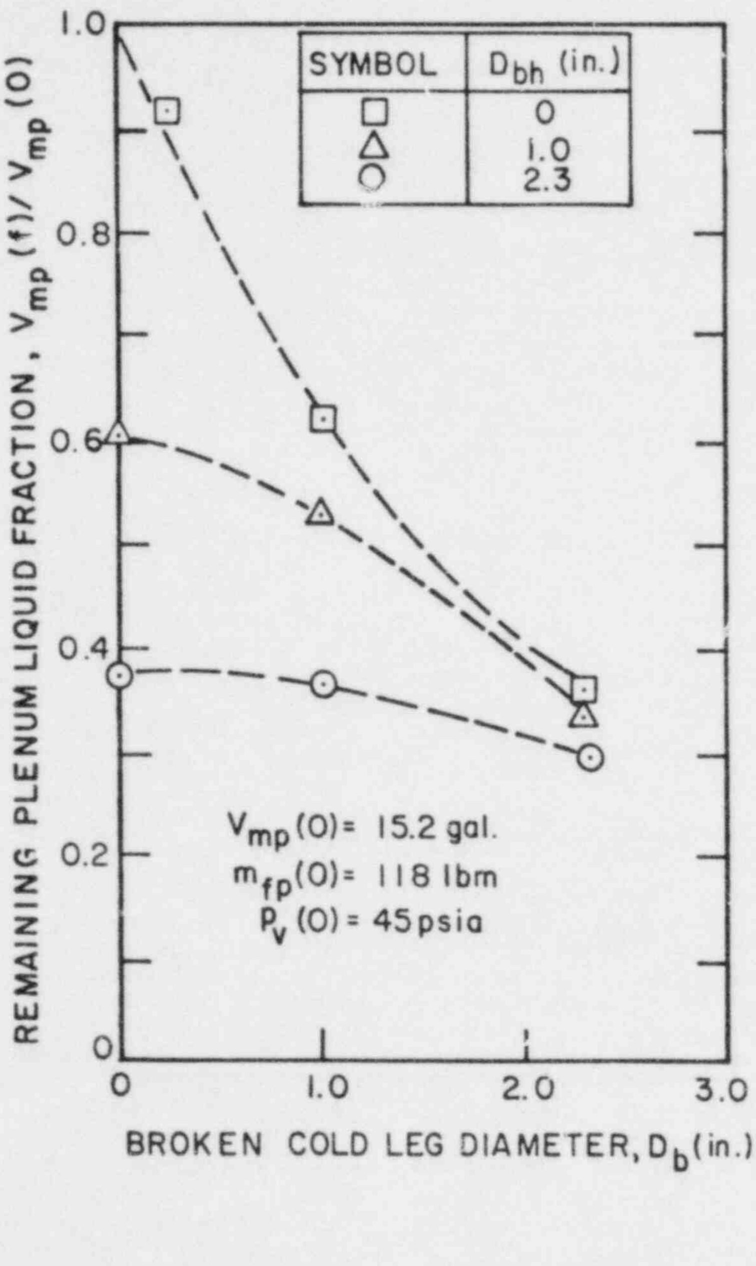


Figure 6. EFFECT OF BROKEN HOT LEG SIZE ON REMAINING PLENUM LIQUID FRACTION

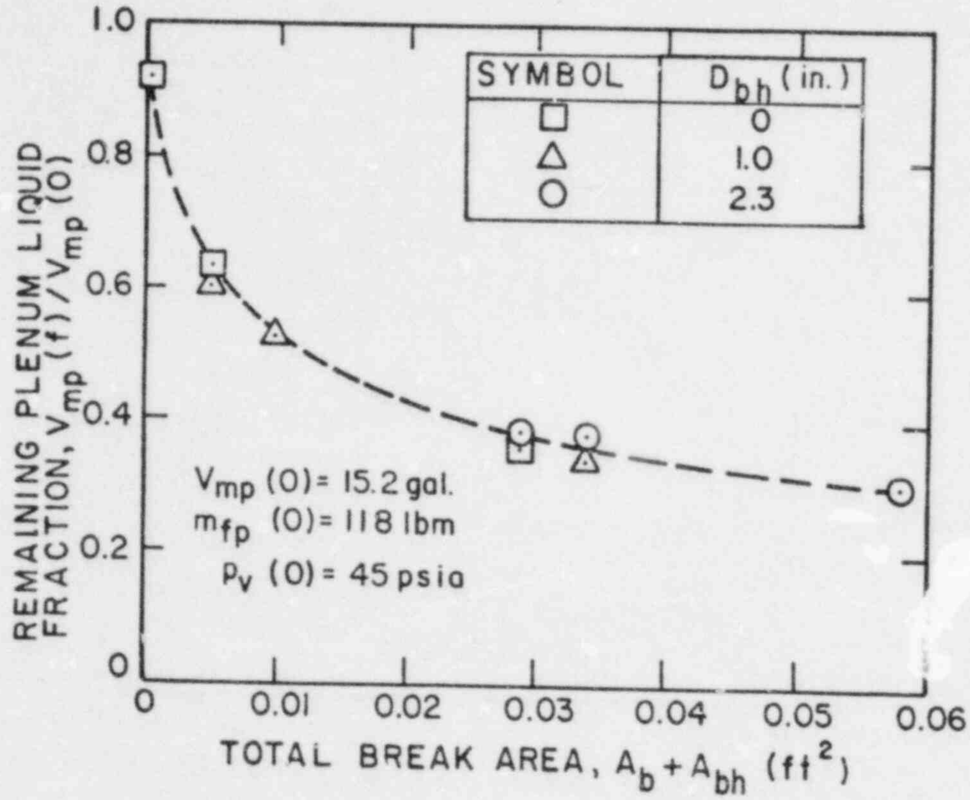


Figure 7. REMAINING PLENUM LIQUID FRACTION AS A FUNCTION OF TOTAL COLD AND HOT LEG BREAK AREAS

| TABLE 1<br>FLASHING TRANSIENT PARAMETERS | | |
|---|---|---|
| Parameter | Symbol | Range |
| Cold Leg Break Size | $D_b$ | 0.25 - 2.3 in. |
| Hot Leg Break Size | $D_{bh}$ | 0.25 - 2.3 in. |
| Initial Pressure | $p_v(0)$ | 15 - 120 psia |
| Separator Vessel Pressure | Psep | 15 - 75 psia |
| Initial Plenum Volume | $V_{mp}(0)$ | 0 - 15.3 gal. |
| Injected Water Temperature | $T_{ECC}$ | 60 - 200°F |
| Injected Water Flow Rate | $Q_{fin}$ | 0 - 90 gpm |
| Annulus Gap Size | s | 0.5, 1.0 in. |
| Initial Plenum Liquid Temperature | $T_f(0)$ | 212-358°F |
| Vessel Height | $L_v$ | 30, 60 in. |
| Plenum Height | $L_{LP}$ | 6, 36 in. |
| Vessel Diameter | $D_v$ | 11.5 in. |
| Reverse Core Steam Flow | $W_{gc}$ | 0 - 1.5 lbm/sec |
| Wall Heat Transfer | $Q_w$ | — |

## Separator Vessel Pressure

The purpose of the tests described here was to determine the effect that the separator vessel pressure had on the key test variables. In one test series the initial vessel pressure was always 100 psia while the separator pressure was 15, 35, 55, or 75 psia. In a second series the initial vessel pressure was 25 psi greater than the separator pressure which was held steady at values from 15 to 75 psia.

Figure 8 presents results of the first series and shows that with an initial vessel pressure of 100 psia, increasing the separator pressure from 15 to 75 psia causes a 30% increase in the fraction of water left in the plenum. This is expected since as the driving vessel-to-separator pressure difference becomes smaller, less of the fluid energy is released to cause flashing, swelling and liquid carryover. The second series of tests showed that a constant initial vessel-to-separator pressure difference of 25 psid results in approximately a constant amount of liquid remaining in the vessel (62-68%), independent of the initial vessel pressure.

## Initial Plenum Volume

This series of tests was done to investigate the effect of initial plenum liquid volume. The results indicate that the amount of liquid lost depends on if, and for how long, the mixture is able to swell to the downcomer height. Figure 9 compares the remaining liquid volume with the initial liquid volume. Very little mass is lost in the test with an initial volume of four gallons because the mixture did not reach the down-

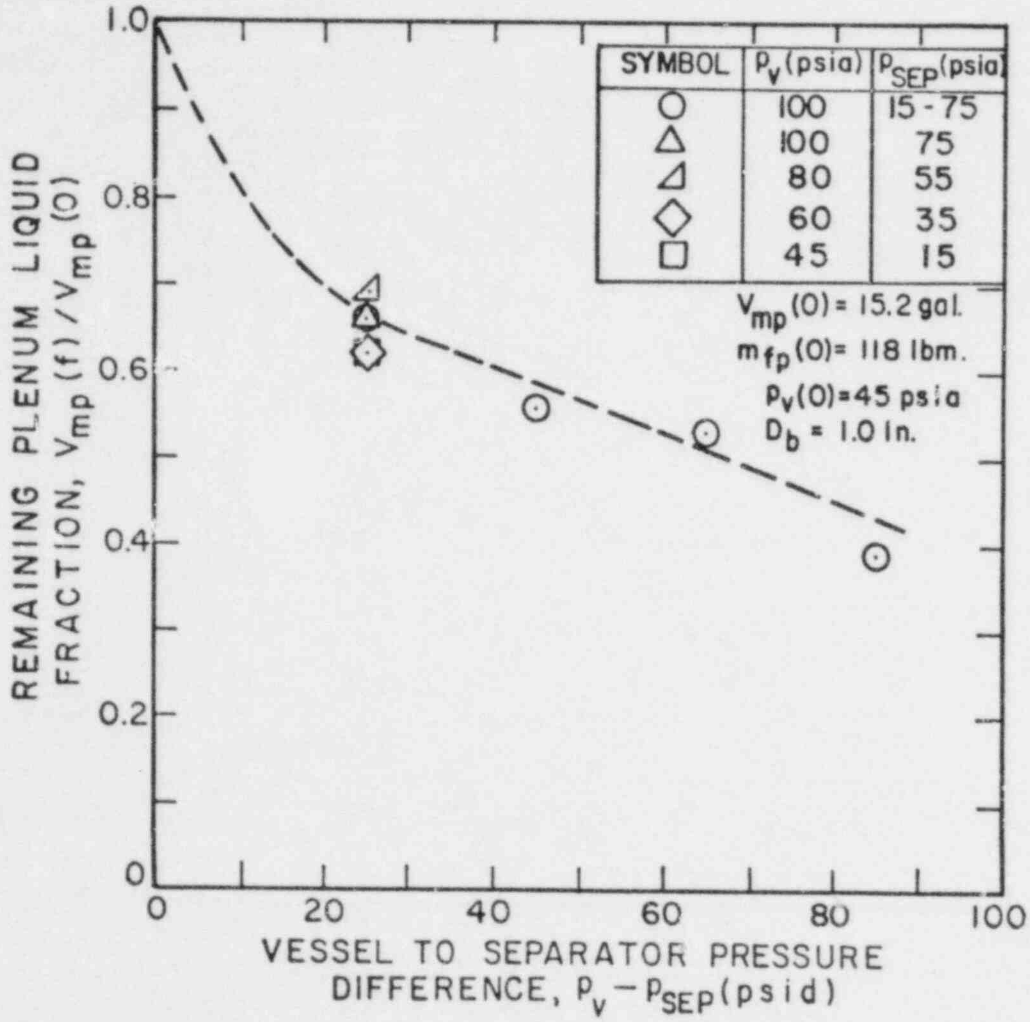


Figure 8. EFFECT OF SEPARATOR PRESSURE ON REMAINING PLENUM LIQUID FRACTION

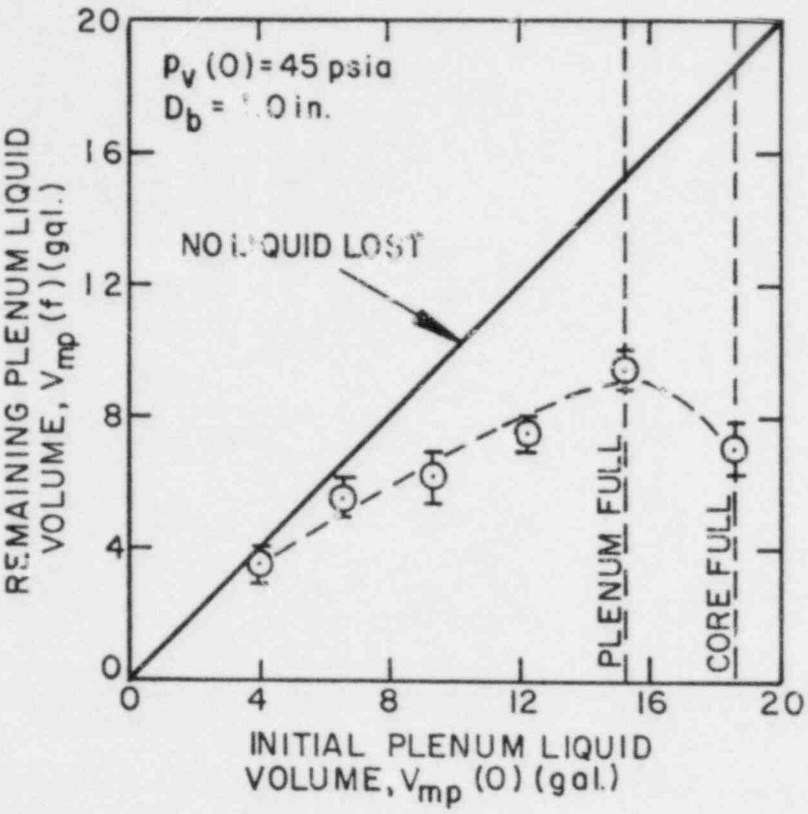


Figure 9. EFFECT OF VESSEL INITIAL LIQUID VOLUME ON REMAINING PLENUM LIQUID FRACTION

comer height. Increasing the initial volume up to the full plenum volume results in a greater fraction of liquid lost, but more liquid remaining. If the initial volume is further increased so the core is nearly full initially, less liquid remains than with a full plenum. The reasons for the decrease in remaining liquid when the core is filled require further study.

## Annulus Gap Size

Tests have been done with an oversized gap (1.0 in.) to compare with tests in the baseline vessel geometry (0.5 in. gap). Without ECC injection, preliminary results suggest that the flashing behavior is insensitive to gap size based on tests with a 1.0 in. diameter break. However, gap size may become important with other break sizes, since the volume increase caused by swelling is on the order of the downcomer volume and may mean the difference between liquid carryover and complete phase separation. Additional oversized gap tests are planned for next quarter.

Significant differences exist between data obtained with the oversized gap and data obtained with a scaled gap when subcooled ECC is injected. Depressurization is more rapid and the vessel begins to fill earlier with the oversized gap. Figure 10 illustrates that a similar trend in the minimum vessel inventory with injection rate exists for each gap size but that the minimum is always greater for the oversized gap. This trend is expected since the swelling mixture generated from flashing in the lower plenum has less momentum in the downcomer with the oversized gap and therefore less ability to bypass ECC.

## Initial Plenum Liquid Subcooling

The subcooled liquid tests were performed primarily to determine the sensitivity of the flashing behavior to deviations of the liquid temperature from the saturation temperature at the initial test pressure. Figure 11 presents the final liquid volume fraction for tests done at 45 psia and 100 psia with initially subcooled liquid. Although there is some scatter in the data, there is little effect of 10°F to 20°F subcooling on remaining liquid fraction. There is a trend to have more liquid remaining with increased subcooling at values greater than 20°F.

The liquid temperature for the test conditions of 100 psia and 55°F subcooling is about equal to the saturated liquid temperature at 45 psia. As expected, the final liquid volume fractions are very similar for the 55°F, subcooled 100 psia test and the saturated, 45 psia test. Similarly, the 31°F, subcooled test at 45 psia results in about the same amount of liquid left as the saturated fluid test from 25 psia.

## Reverse Core Steam Flow

Figure 12 presents results of tests where a constant mass flow rate of reverse core steam is initiated at the start of blowdown. The remaining liquid volume fraction is larger in tests with higher core steam flow. Physically, increasing the steam flow increases the break pressure drop for fixed liquid flow. During a blowdown transient, increased steam flow reduces the rate of vessel depressurization. In turn, a reduced depressurization rate reduces the degree of level swell, the gas flux entering the downcomer, and the entrainment of liquid so that less liquid tends to be lost from the vessel. Furthermore, the final pressure of the vessel is above ambient when there is a steam flow out of the vessel. Thus increased steam flow lessens the pressure reduction experienced by the vessel, an effect which also tends to reduce the loss of liquid.

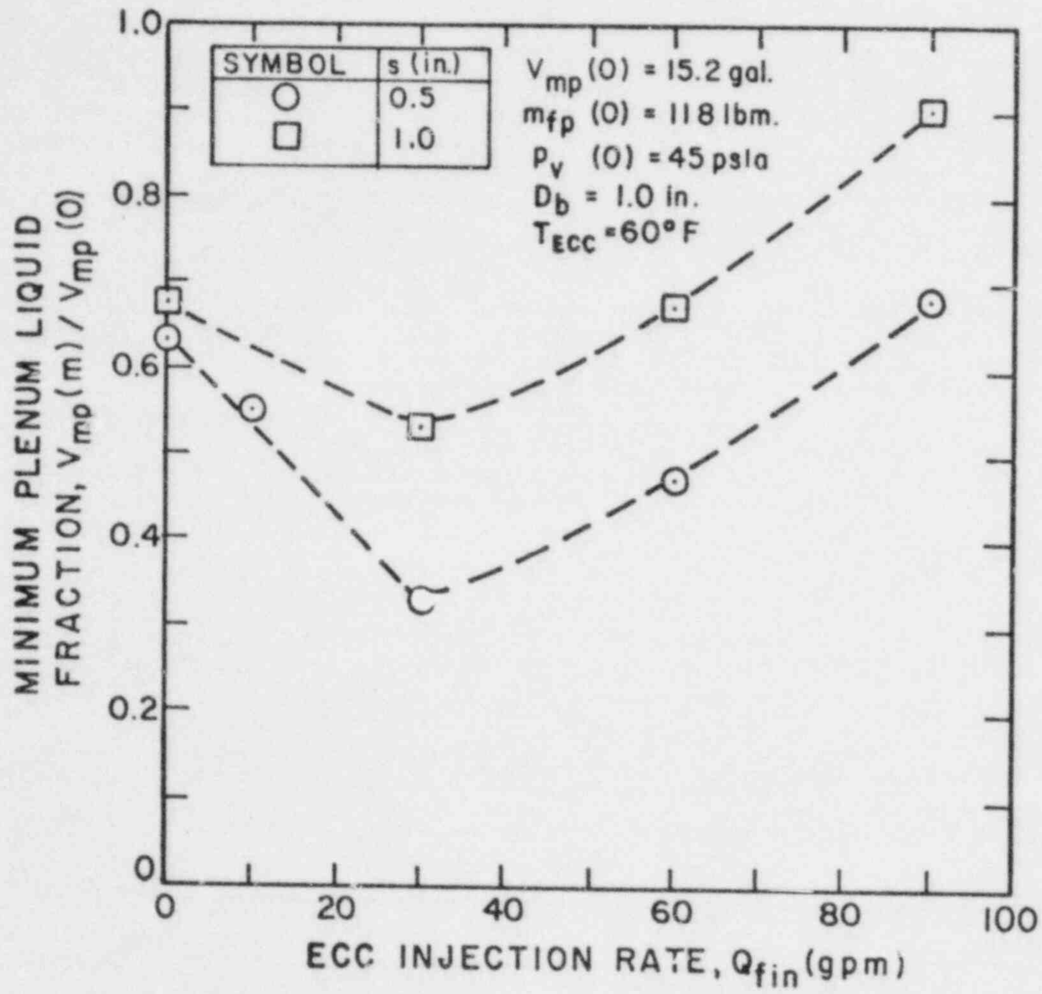


Figure 10. EFFECT OF ANNULUS GAP SIZE ON MINIMUM PLENUM LIQUID FRACTION IN FLASHING TRANSIENTS

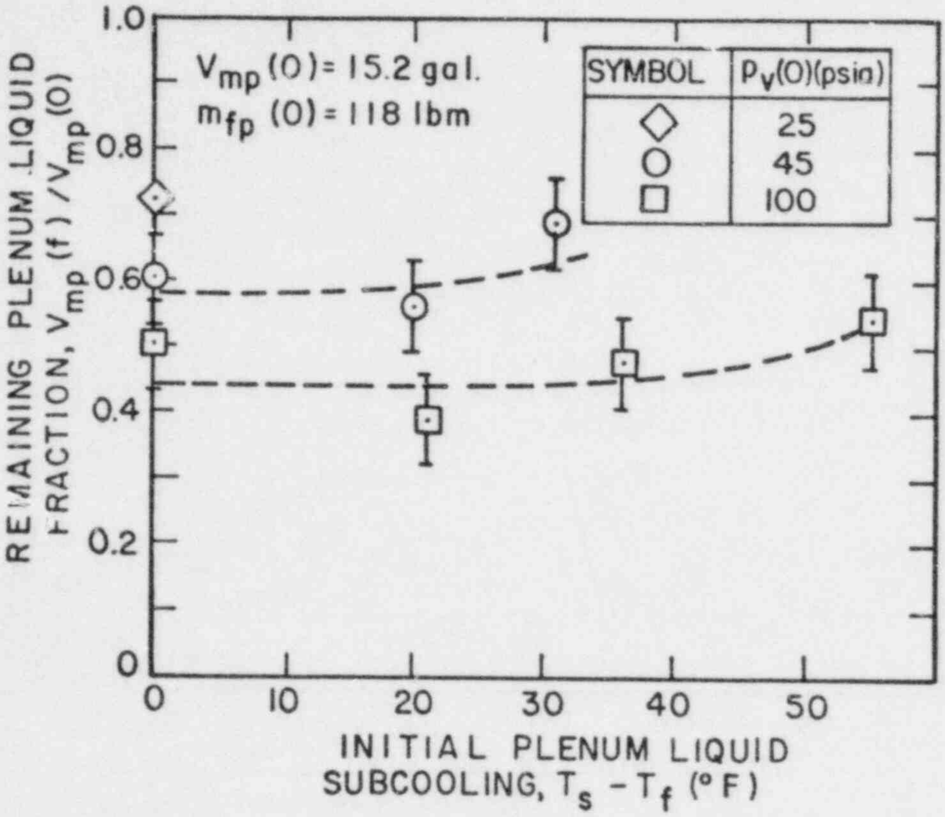


Figure 11. EFFECT OF INITIAL PLENUM FLUID SUBCOOLING ON REMAINING LIQUID FRACTION

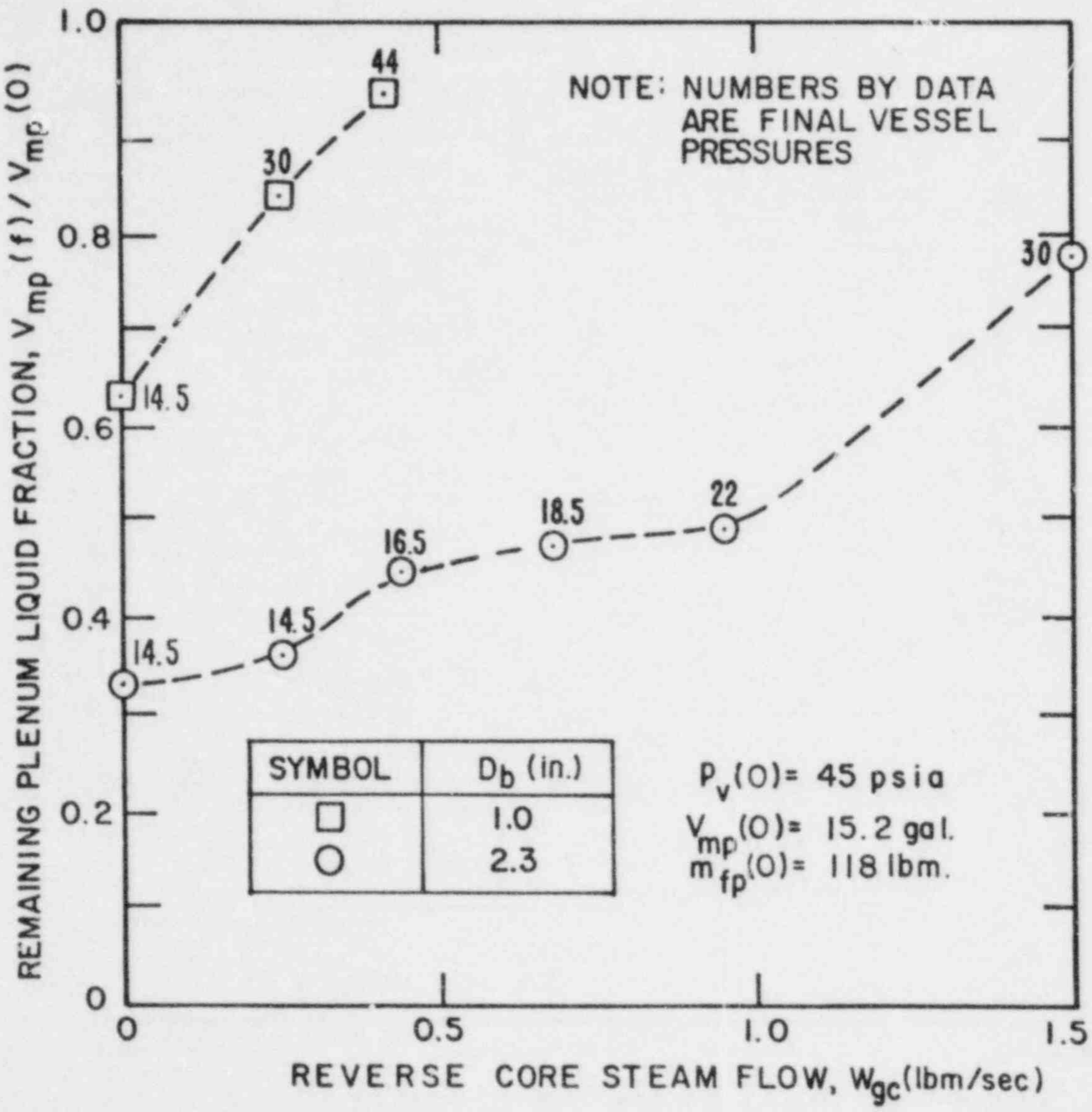


Figure 12. EFFECT OF REVERSE CORE STEAM FLOW ON REMAINING PLENUM LIQUID FRACTION

Acting in opposition to the effects described above is the tendency for the reverse core steam flow to entrain liquid from the plenum by impacting it and sweeping waves out of the plenum. Called lower plenum voiding [3], this effect was not significant in the tests described here, but can be important in vessels with a more shallow lower plenum.

## Future Work

In the 1/15-scale vessel, planned testing during the upcoming quarter will be minimal, and will primarily involve repeating a few of the key parameter tests where instrumentation or procedure errors occurred. A few tests extending the range of pressure and ECC temperature parameters are also being considered. The 1/30-scale vessel will be used for instrumentation verification tests coordinating instrument measurements with flow visualization (and filming). This vessel will also be used for model development tests for the effects due to a full core barrel. There is presently on site a 1/5-scale model PWR vessel which will be used for flashing transient experiments during the third quarter of FY80. These experiments of the effect of scale are the most important element of planned testing.

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ABSTRACT

This report describes work on the Creare Refill Effects Program during the first quarter of FY80. Calculations using a preliminary, semi-empirical analysis are compared against flashing transient data for the effects of wall heat transfer, break flow, downcomer slip, and non-equilibrium downcomer behavior. Results of parametric tests of flashing effects are briefly summarized for the effects of hot leg breaks, separator vessel pressure, initial plenum volume, annulus gap size, initial plenum liquid subcooling, and reverse core steam flow. Future plans are outlined.


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