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SUMMARY OF REFILL EFFECTS STUDIES WITH FLASHING AND ECC INTERACTIONS

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ABSTRACT

This report summarizes the results of an experimental and analytical program which has modeled blowdown and refill in scale model PWRs in a more realistic and continuous manner than previous separate effects experiments in the Creare program. These experiments are intended to complement and contribute to a fuller understanding of integral experiments such as LOFT. Experiments have been performed at 1/30, 1/15, and 1/5-scale vessel sizes. The latter is approximately LOFT scale. An independent analysis was developed to explore various modeling options for the phenomena observed in the experiments and to identify the most important phenomena to model. Bounding and sensitivity calculations were also performed. Finally, a RELAP4 code (MOD7) was used to demonstrate that best-estimate calculations can be performed continuously through refill and to calculate refill behavior.

EXECUTIVE SUMMARY

This report summarizes the results of an experimental and analytical program which has modeled blowdown and refill in scale model PWRs in a more realistic and continuous manner than previous separate effects experiments in the Creare program. These experiments are intended to complement and contribute to a fuller understanding of integral experiments such as LOFT.

These flashing transient experiments consist of filling and pressurizing a scale model of a PWR vessel and blowing the vessel down while injecting ECC fluid. Although the tests are combined effects tests and may not exactly duplicate conditions expected in a PWR, these tests produce typical conditions of a LOCA blowdown in a facility that is well controlled and specifically instrumented to measure refill. There are two key differences between these "Refill" tests and previous "ECC bypass" tests. First, they include the swelling of liquid in the lower plenum and its effect on the amount of primary fluid remaining in the vessel after the blowdown. Secondly, the ECC fluid must penetrate to the lower plenum against an upward flow of a two-phase mixture (rather than single-phase steam). The tests systematically varied important geometric, thermal, and hydraulic parameters, including pressures up to 200 psia and scale sizes of 1/30, 1/15 and 1/5 of a PWR.

Analysis efforts have concentrated on three areas

- Observations of trends to better understand important processes and to identify any effects of scale size.
- Development of an independent analysis (CREFIL) with various adjustable parameters and model options to explore the sensitivity to analytical methods and confirm best-estimate models by comparison with data.
- Use of RELAP4 codes to test the ability of these codes to perform a continuous calculation through refill and to calculate refill behavior.

Modeling assumptions for various phenomena were implemented in the independent analysis CREFIL. The sensitivity of the calculations to alternate assumptions established the relative importance of certain phenomena and the range of their effects. Best-estimate comparisons with experimental data were then performed to confirm the use of three important models. First, the Wilson slip correlation can be used to calculate the correct mass and level history in the lower plenum. Implementation of this model eliminates the need to select independent plenum slip velocity parameters in the analysis. It also better accounts for the effects of pressure and void fraction compared with earlier models and allows the lower plenum to be modeled more simply as a single volume. Secondly, the momentum of the liquid component in two-phase upflow contributes significantly to ECC bypass when compared to results with single-phase steam upflow. Two equally successful models were developed. Finally, condensation and thermal-mixing processes can be modeled as approximately equilibrium processes. Relative to the phenomena modeled by these analyses, other effects such as wall heat transfer, density gradients, coefficients for countercurrent flow in the downcomer, and non-equilibrium vapor generation are of secondary importance.

When each of these modeling ideas is incorporated, calculations of parameters important to refill such as the mass in the vessel at the start of refill, the time to depressurize the vessel, and the time to refill the vessel are in very good agreement with the Creare experimental data over the range of parameters tested, including scale size.

Using RELAP4/MOD7 to analyze the Creare experiments, continuous calculations through refill were performed. For most tests, analytical results from RELAP4/MOD7 and CREFIL were found to be very similar using the Wilson slip correlation and the thermal equilibrium option in RELAP4/MOD7. Although RELAP4/MOD7 models two-phase upflow in a different way than does the special-purpose code CREFIL, RELAP4/MOD7 is usually similarly successful in calculating the experimental results. However, in a few cases RELAP4/MOD7 calculations disagreed severely with both the data and the CREFIL calculations. By comparison with CREFIL we traced the causes of these discrepancies and devised simple modifications to RELAP4/MOD7 that positively eliminated them. Like CREFIL, RELAP4/MOD7 also has a capability to model thermal non-equilibrium between gas and liquid phases. This non-equilibrium option is useful in achieving somewhat improved comparisons with Creare data in some cases. However, in cases where highly subcooled ECC is injected, the results are similar for equilibrium and non-equilibrium models.

These modeling ideas were subsequently applied to a RELAP4/MOD7 calculation of LOFT experiment L1-4. The Wilson slip correlation improved the calculation of the lower plenum liquid inventory measurement compared with previous modeling assumptions. Use of the non-equilibrium option also improved the calculation of the vessel inventory by permitting steam voids to exist in the downcomer. Thus, RELAP4/MOD7 capabilities to calculate blowdown/refill have been assessed by comparison with Creare and LOFT data. The physical models in RELAP4/MOD7 have also been examined and their behaviors compared with the simpler models in CREFIL.

Relative to licensing, this program has laid the groundwork for upgrades in current evaluation model approaches under existing rules, if desired by applicants. Comparisons with data display the physical realism and accuracy of best-estimate models in continuous calculations. By adjusting the models in the best-estimate calculations, it is possible to develop a continuous evaluation model calculation. Some preliminary model concepts are presented here, and an approach to develop an evaluation model is suggested.

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1 INTRODUCTION

The primary context of the work described here is a large cold leg break in a pressurized water reactor. The problem was to understand and to model the phenomena and interactions which may occur during the later stages of blowdown and refill. These included vapor generation, phase-separation, two-phase countercurrent flow, condensation, ECC bypass, wall heat transfer, and critical flow. No combined effects experiments including both blowdown and refill effects with ECC injection into a vessel existed prior to these experiments, though integral experiments did exist. In order to implement various licensing assumptions and due to numerical difficulties which arose when modeling injection of subcooled ECC, previous analyses of refill were often unable to explore in a continuous calculation the modeling assumptions made in describing refill. This study has provided experimental data for events such as the end-of-bypass or time to refill and parameters such as plenum liquid inventory in scale model experiments simulating blowdown and refill. Achievement of a sufficient understanding of refill phenomena has been demonstrated by continuous best-estimate, bounding assumption, and model sensitivity calculations for these experiments and LOFT integral experiments.

This recent work represents the culmination of refill effects studies. In previous years the effects of countercurrent flow [1,2,3], superheated downcomer walls [4], and lower plenum entrainment [5], were studied in separate and combined effects experiments of ECC bypass. The previous experiments had not yet included the effects of flashing and swelling of plenum fluid and the resultant two-phase upflow in the downcomer. The present phase of the Creare Refill Effects Program has studied these effects during blowdown and refill of scale model PWR vessels up to 1/5 of reactor scale size. The Bibliography to this summary lists the Creare reports which are pertinent to the refill studies with flashing.

The contributions from this program include:

- Identification of refill phenomena. Among the phenomena which have been identified are non-equilibrium flashing thermodynamics, critical flow in the break, phase separation (slip) in the lower plenum, heat transfer from the vessel walls, downcomer flow interactions (e.g., cocurrent and countercurrent flow), non-equilibrium condensation, and two-phase mixing.

- Generation of a refill effects data base. For code developers. these tests are useful for assessing the ability of the codes to model refill. By isolating individual phenomena in some tests, evaluation of these tests is useful for developing modeling insights for the phenomena. Measurements of parameters such as pressure, vessel mass, mixture level, flows, and fluid temperatures have been recorded for 113 experiments varying 13 parameters. While the experiments are combined effects experiments that may not exactly duplicate conditions expected in a PWR, these tests produce the most typical conditions of a LOCA blowdown available in facilities that are well controlled and specifically instrumented for refill.

- Presentation of scaling information. Testing has been performed in 1/30, 1/15, and 1/5 scale vessels to provide scaling information. Further, the 1/5-scale vessel is comparable in size to the largest refill experiments performed up to this time (LOFT and CCTF), thus providing data directly applicable to interpretation of results of these experiments.

- Development of a "transparent", semi-empirical analysis and code (CREFIL). The analysis has been used to calculate the experiments and to perform sensitivity studies evaluating alternate and bounding models for the phenomena identified.

- Establishment of Relative Importance of Phenomena and Preferred Models. One key finding is that the Wilson correlation correctly predicts mass and mixture level histories when used to model slip in the lower plenum. Secondly, the effects of the liquid momentum in two-phase upflow must be accounted for in the analyses (two equally effective, alternate models were identified). Thirdly, condensation and thermal mixing processes are close to thermal equilibrium. Relative to plenum slip, downcomer upflow momentum, and condensation, the effects of wall heat transfer, plenum density gradient, non-equilibrium generation and downcomer momentum exchange modeling have lesser importance to determining vessel pressure and plenum mass histories.

  The modeling of break flow is also important and requires some modeling upgrades, but improvements of break flow models were not undertaken in this program.

- Demonstration of RELAP4/MOD7 effectiveness. The RELAP4/MOD7 [6] computer code can accurately calculate refill effects experiments without artificial noding approaches. In spite of certain limitations in modeling the physical processes of two-phase upflow during countercurrent flow in the downcomer RELAP4/MOD7 can predict the experimental behavior. The virtue of RELAP4/MOD7—as opposed to earlier MODs—lies mainly in improvements to the numerics (water-packing difficulties). The non-equilibrium model in MOD7 is a welcome addition to RELAP4 capabilities although it is not a critical factor in the calculation of available experimental results

In a broader, more basic sense the work has contributed to the understanding of diverse phenomena including countercurrent flow, critical flow, condensation, flow regimes and phase-separation in a pool and in an annular passage. These basic contributions may be useful in small break and BWR modeling as well as in the present large break PWR context. Similarly, the data are suitable to assess fundamental constitutive relations in advanced codes without being limited to a specific context.

This program has also led to development of concepts which might assist licensing. Application of the results of this program to calculation of a LOFT experiment has shown that both best-estimate and "evaluation" models can be run continuously from blowdown through refill, whereas current licensing models involve discontinuity at an arbitrary point identified as the end of bypass. Suggestions for an "evaluation" model based on modified applications of the Wilson plenum slip, downcomer slip, and non-equilibrium condensation calculations are made. Despite their identified conservatisms, these models would enable a relaxation of more stringent conservatisms that are presently required due to the lack of continuous calculation capabilities of EM codes.

In this report the experiments and analyses are briefly reviewed in Sections 2 and 3. Scaling comparisons are made in Section 4. The analytical results from Creare experiments without ECC and with ECC injection are reviewed in Sections 5 and 6, respectively. Calculations of LOFT experiment L1-4 are presented in Section 7. Finally, suggested concepts for an "evaluation" model approach suitable to licensing calculations of blowdown and refill are described in Section 8.

2 EXPERIMENTS

The region studied is limited to the vessel, and conditions at its boundaries are controlled. Even so, numerous phenomena and regions in the vessel interact as shown in Figure 1. As the vessel depressurizes, the saturated liquid flashes to steam, swells, and is carried out the break. In the downcomer, there is condensation on the subcooled ECC, thermal mixing, and momentum exchange between the ECC and the two-phase upflow. Some of the ECC is bypassed and some is heated and delivered to the plenum where it mixes with the liquid there. In turn this mixture flashes later in the transient. To isolate these behaviors, experimental parameters have been systematically varied.

Table 1 lists the parameters studied in the experiments. Our literature review revealed prior flashing and blowdown experiments in many simple vessels without simulated internals, but only a few tests in vessels including internals. Parameter variations such as cold leg break size, initial vessel pressure, and initial liquid mass were common in these tests. However, scaling of blowdown had been insufficiently explored [7]. Experiments with ECC injection in prototypical vessels were limited to a few tests in integral facilities such as LOFT and Semiscale. For these reasons we performed new experiments emphasizing ECC injection (with ECC flow and subcooling variations) in a model PWR vessel similar in size to LOFT [8]. We also addressed scaling questions by performing tests in a smaller but geometrically similar 1/15-scale vessel [9] and modeling questions by performing flow visualization studies in a transparent 1/30-scale vessel [10].

In Table 2, important dimensions and typical ECC flow rates for these three test facilities are compared with a PWR and with the LOFT vessel. Most of these parameters are in the same range for each of the vessels. It is seen that the time required to fill the lower plenum at the nominal ECC injection rate is within a factor of two at all scales. The lower plena in the Creare experiments are somewhat enlarged relative to a PWP and LOFT in order to preserve the timing of the plenum filling. References 8 and 9 present detailed descriptions of the Creare test facilities and instrumentation.

The number of tests performed at each vessel size is listed at the bottom of Table 1. Typical measurements in each experiment included pressures temperatures, liquid levels, and mass flow rates. Experimental measurements were digitally recorded for each test at sampling rates of about 100 samples/second using a computerized data acquisition system. The data from the 113 tests are documented in Reference 11. For code developers interested in calculating these experiments we have suggested a few key experiments for comparison in that Reference. In this summary we present comparisons of analysis with selected experiments and with only key measurements such as vessel pressure, liquid mass, plenum void fraction, and plenum fluid temperatures.

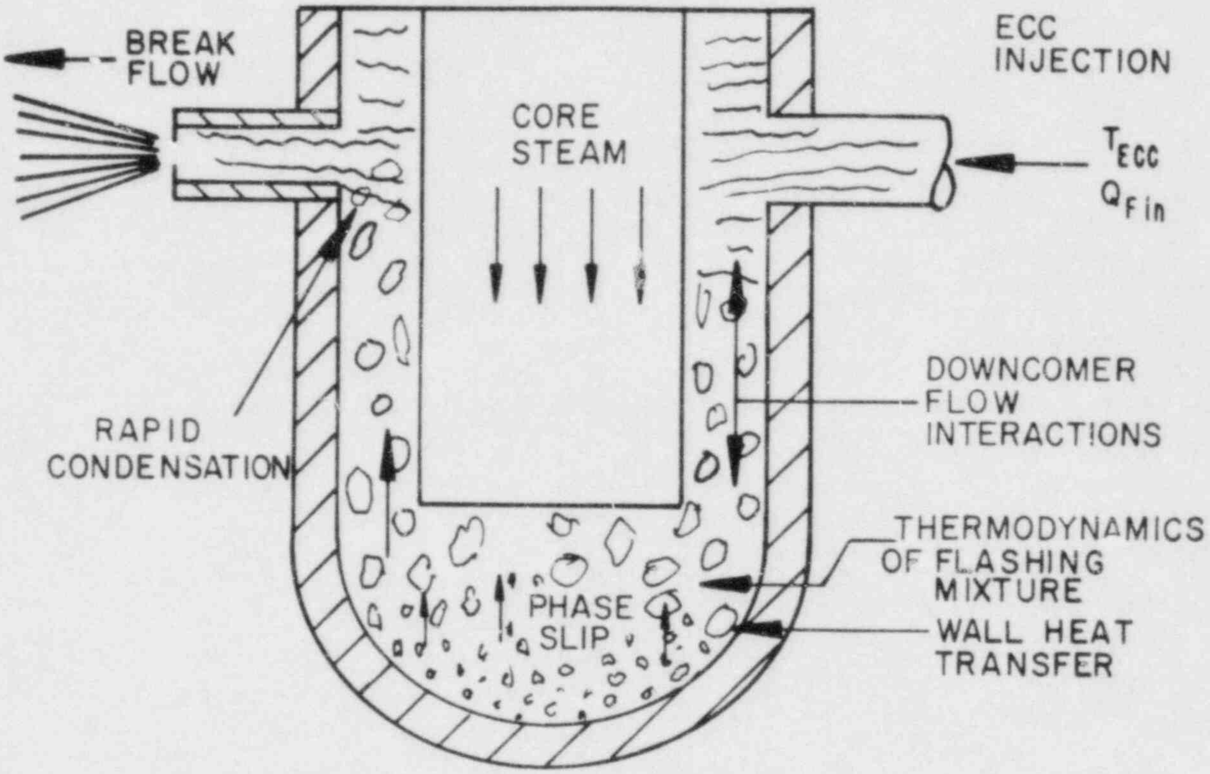

Figure 1. SCHEMATIC OF FLASHING TRANSIENT PHENOMENA

TABLE 1

PARAMETERS STUDIED IN FLASHING TRANSIENT EXPERIMENTS

Parameter	Parameter Ranges			
	Symbol	1/5 Scale	1/15 Scale	1/30 Scale
Cold Leg Break Size (in.)	D_b	1.0-6.0	0-2.3	0.25-1.5
Initial Pressure (psia)	$p_v(0)$	45-200	20-100	20-30
ECC Flow Rate (gpm)	Q_{fin}	0-1500	0-90	0-12
ECC Temperature (°F)	T_{ECC}	60-200	60-T_{sat}	60
Annulus Gap Size (in.)	s	1.5	0.5, 1.0	0.25
Vessel Diameter (in.)	D_v	35.1	11.5	6
Initial Temperature (°F)	$T_f(0)$	T_{sat}	60-T_{sat}	T_{sat}
Initial Inventory (lbm)	$V_{mp}(0)$	0-2000	0-120	0-20
Separator Pressure (psia)	p_{sep}	15	15-75	15
Plenum Volume (ft^3)	V_{LP}	33.2	0.27, 0.204	0.34
Core Flow Rate (lbm/sec)	W_{gc}	0-5.5	0-1.5	---
Hot Leg Break Size (in.)	D_{bh}	—	0-2.3	—
Number of Experiments		24	82	7

TABLE 2

PARAMETRIC COMPARISON OF SCALE MODEL EXPERIMENTS WITH TYPICAL PWR CONDITIONS

Parameter	"Typical" PWR	LOFT	1/5-Scale	1/15-Scale	1/30-Scale
Break Area/Plenum Volume [A_b/V_{LP}(1/ft)]	3.5×10^{-3} (max)	5×10^{-3}	0.16×10^{-3} to 5.9×10^{-3}	0.16×10^{-3} to 14×10^{-3}	1.0×10^{-3} to 36×10^{-3}
Time to Fill Plenum [V_{LP}/Q_{fin}(sec)]	10.5	9.5	9.6-58 (17.3)*	9.5-57 (17.1)	12.2-49 (14.7)
ECC Flow Rate [J^*_{fin}]	0.10	0.07	0.02-0.18	0.02-0.18	0.02-0.12
ECC Flow Rate [K^*_{fin}]	7.3	2.4	0-6.0	0-3.4	0-1.7
Annulus Gap Size / Vessel Diameter	0.058	0.056	0.043	0.043	0.042
Downcomer Volume / Plenum Volume	1.0	1.46	0.20	0.12, 0.90	0.09

*Nominal Value at $J^*_{fin}=0.10$.

3 ANALYTICAL MODELING

The analytical work in this program has been performed on several levels.

- scaling comparisons and bounding calculations,
- development of a phenomena-based, semi-empirical analysis (CREFIL) for best-estimate predictions, and
- use of the thermal-hydraulic code RELAP4/MOD7 to calculate the experiments.

Some of the scaling comparisons are shown in the next section. These compare first-order experimental results important to refill such as the time to depressurize the vessel, the minimum mass remaining in the plenum, and the time to refill the plenum at several scales. The CREFIL analysis was developed specifically to evaluate alternate models for the phenomena observed in the experiments. Lacking the generality of large best-estimate codes, the virtues of CREFIL are the transparency of its workings, ease of modification, and low run cost. Lastly, calculations of our experiments were done with RELAP4/MOD7 in order to assess the modeling capability of this code for the effects important to refill.

$$\boxed{\begin{aligned} \frac{dp_v}{dt} &= f_1\ (G, x_b, T_b, p_v) \\ G_a &= f_2\ (x_b, T_b, p_v) \\ x_d &= f_3\ (dp_v/dt) \\ x_b &= f_4\ (x_d, dp_v/dt) \\ T_b &= f_5\ (x_d, dp_v/dt) \end{aligned}}$$

The CREFIL analysis is an interactive numerical solution of lower plenum, downcomer, and break flow models. Functional forms are displayed at the right for blowdown exclusive of ECC injection. They relate the major variables: vessel pressure P_v, break flux G, break inlet quality x_b, downcomer inlet quality x_d and break inlet temperature T_b. ECC injection requires additional relations for condensation and liquid heating in the downcomer, flow regime and phase slip with the two-phase downcomer upflow, momentum exchange and split of the ECC to "bypass" and "delivery" paths, and thermal mixing in the plenum. Beyond these physical models, a certain amount of bookkeeping is required. Thus, this analysis amounts to simultaneous solution of some 20 differential and algebraic equations constructed in modular forms as dictated by the physics. The interested reader should see the full analysis development in Reference 12.

These flashing transients have also been modeled using RELAP4/MOD7 and the results are documented in Reference 13. RELAP4/MOD7 is a one-dimensional, single-fluid, thermal-hydraulic code in the RELAP4 series. Unlike earlier versions of this code, MOD7 contains a non-equilibrium condensation model which allows subcooled water to coexist with steam. We used RELAP4/MOD7 as an example of an advanced form of the RELAP4 or FLASH genre of codes still used for licensing. Here we demonstrate the ability of such a code to calculate effects important to refill.

The approach used in our analysis of refill effects was to employ the CREFIL analysis in sensitivity studies to discover which phenomena were most important in the modeling and to choose the most effective models in each case. The results guided the modeling choices used in RELAP4/MOD7 calculations. Sections 5 and 6 illustrate calculations with both analyses. The results of the analytical modeling with RELAP4/MOD7 were then applied to the LOFT integral system and the results of calculations of test L1-4 are displayed (Section 7).

4 EXPERIMENTAL SCALING CONSIDERATIONS

Most dimensions of the experimental vessels are linearly scaled from PWR dimensions. The lower plena are larger than linearly scaled, however, to preserve the time required to refill them. Similarly, the blowdown timing has been preserved by holding the Moody ratio M/D_b^2 constant as scale is decreased. In this formulation M is the lower plenum liquid mass and D_b is the break diameter. The same initial pressure is used at both scales and a range of ECC flow rates is tested to encompass alternate scaling laws.

This experimental approach worked. The time to depressurize the vessel is similar at all scales, both with and without ECC injection, as shown by the data in Figures 2a, 3a, and 4a.* The remaining mass fraction without ECC injection and the minimum mass during transients with ECC injection (Figures 2b, 3b, and 4b) are also seen to agree very well. Data from the two scales agree closely even on these simple coordinates. The shift to slightly higher values at 1/15-scale is correctly predicted by the analysis and is due to a stronger relative effect of heat transfer at the smaller scale.

With ECC injection, the time at which the plenum refills is an important consideration (Figures 3c and 4c). When highly subcooled ECC is injected, the time to refill is very similar at both 1/5 and 1/15 scale (Figure 3c). This is because the plenum usually fills at the injection rate under these conditions. When ECC of a low subcooling is injected, the time to refill the plenum is apparently shorter at 1/5-scale (Figure 4c). There is less wall surface area per unit volume in the plenum at large scale. Therefore, the effect of wall heat transfer is relatively smaller at large scale and filling is more rapid. This trend is predicted by the analyses. At both scales, however, the filling rate of the plenum is only a small fraction (20-30%) of the rate of injection with hot ECC. The time to refill is therefore very sensitive to small changes in the refill rate under these conditions.

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*The dimensionless break size is defined by $D^*=D/D_b$ where D is the break size in a given experiment and D_b is the scaled break size. The scaled break size is given by $D_b=D_{PWR}(M/M_{PWR})^{1/2}=D_{PWR}(V_{LP}/V_{LP\ PWR})^{1/2}$ according to the Moody ratio. Nominal values of $D_{PWR}=30$ in. and $V_{LP\ PWR}=1400$ ft^3 have been assumed.

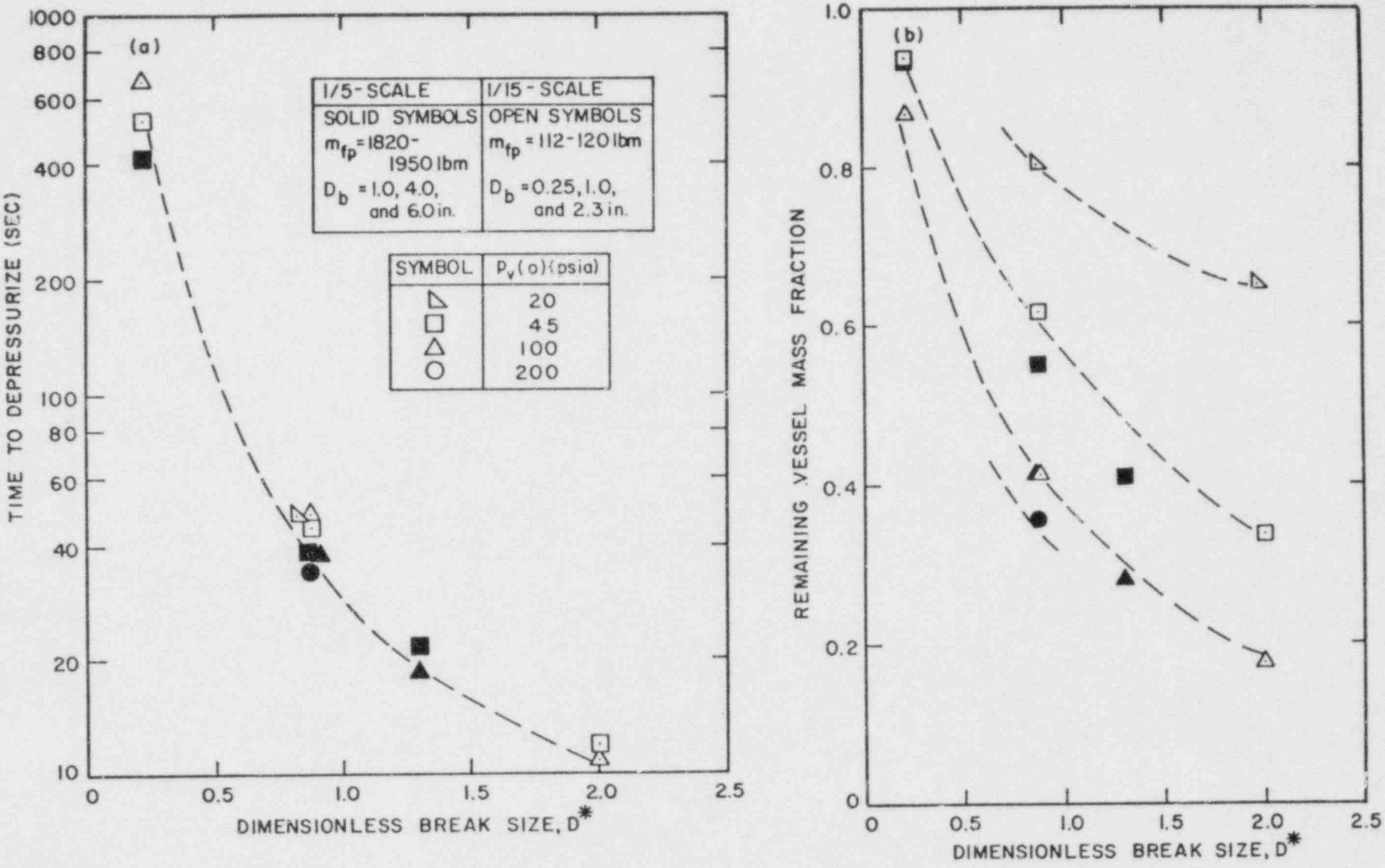

Figure 2. PARAMETER COMPARISONS FOR EXPERIMENTS WITHOUT ECC INJECTION

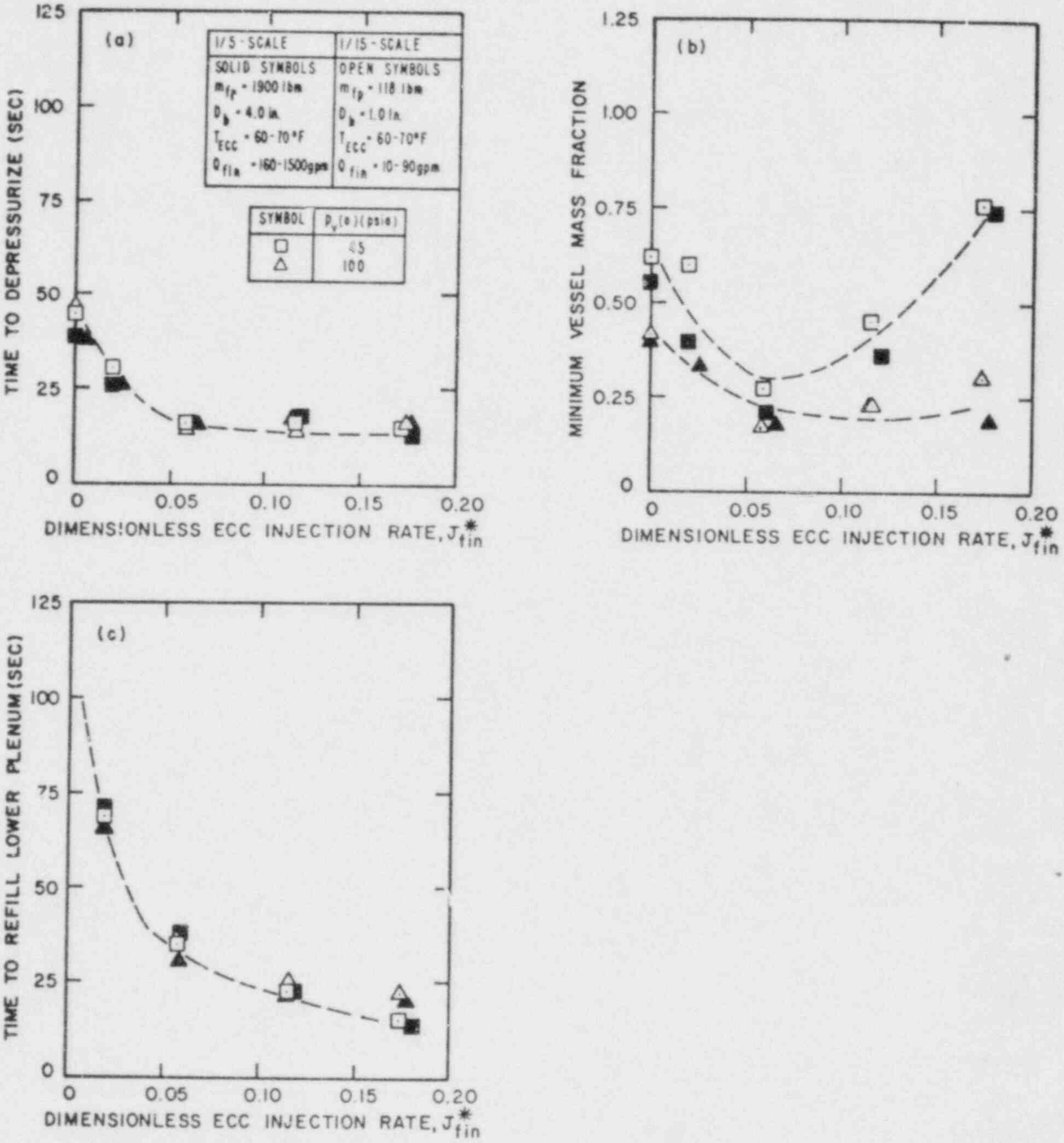

Figure 3. PARAMETER COMPARISONS FOR EXPERIMENTS WITH HIGH ECC SUBCOOLING

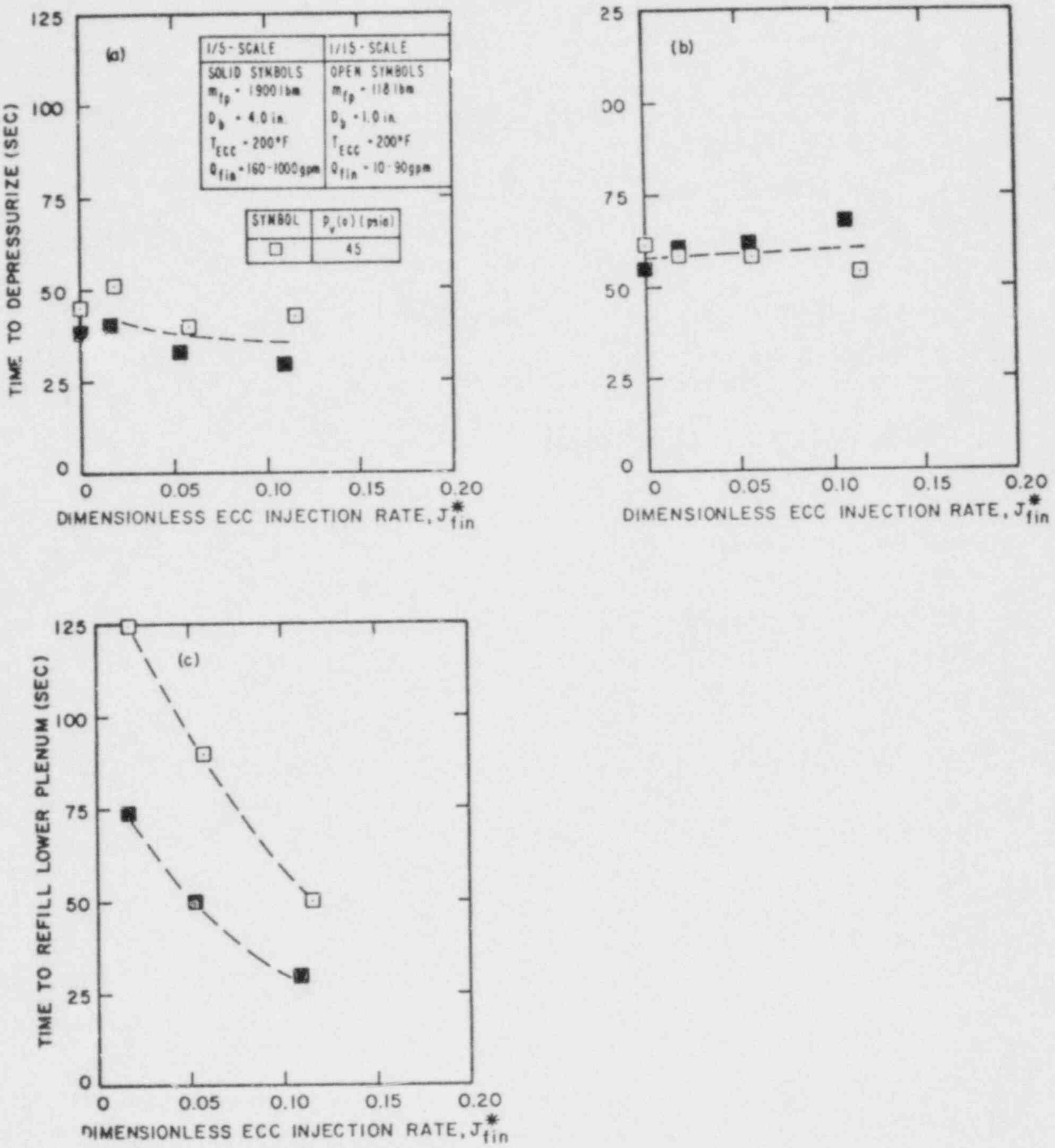

Figure 4. PARAMETER COMPARISONS FOR EXPERIMENTS WITH LOW ECC SUBCOOLING

5 RESULTS WITHOUT ECC INJECTION

5.1 Background

Extensive experiments were performed without ECC injection to isolate plenum behaviors from those related to ECC injection. Figures 5 and 6 display the key data from two typical experiments, one at 1/15-scale and one at 1/5-scale, respectively. The latter test began at the highest pressure tested, 200 psia.

The analytical studies performed with CREFIL and RELAP4/MOD7 encompassed the effects of

- lower plenum slip velocity
- plenum wall heat transfer
- plenum vertical density gradient
- slip at the plenum-downcomer junction

It was determined that the modeling of lower plenum slip had a large effect in the calculations as illustrated in Figures 5 and 6. The effect of wall heat transfer was readily modeled and, while it is important to include heat transfer effects at small scale, the effects become relatively unimportant at larger scale. The density gradient and downcomer slip models had minor effects in comparisons involving these tests.

At this point we must also mention that correct modeling of the critical flow through the break is important. However, in view of the large effort already expended on break flow modeling in other programs, we gave priority to the study of other phenomena. State-of-the-art break flow models such as the Henry-Fauske/Homogeneous Equilibrium Model [14] are applied in fully interactive calculations. We have identified many cases where these break flow models are accurate as well as some where they are deficient. In separate CREFIL calculations we have also circumvented dependence on the break flow modeling by using experimentally measured vessel depressurization as input [12].

5.2 Variable Plenum Slip Velocity Calculations

The rate of slip of the gas phase relative to the liquid phase in the plenum has a significant effect on the quality of the flow entering the break (hence the break pressure drop) and the fraction of the initial mass retained in the plenum during the transient.

An early technique for modeling plenum slip was to assume a constant slip velocity of about 2 ft/sec in the plenum volume [14]. This model was applied without regard to the parameters of

- plenum void fraction
- vessel pressure
- number of volumes used to model the lower plenum

The slip velocity in fact varied to some extent depending upon the experiment being modeled.

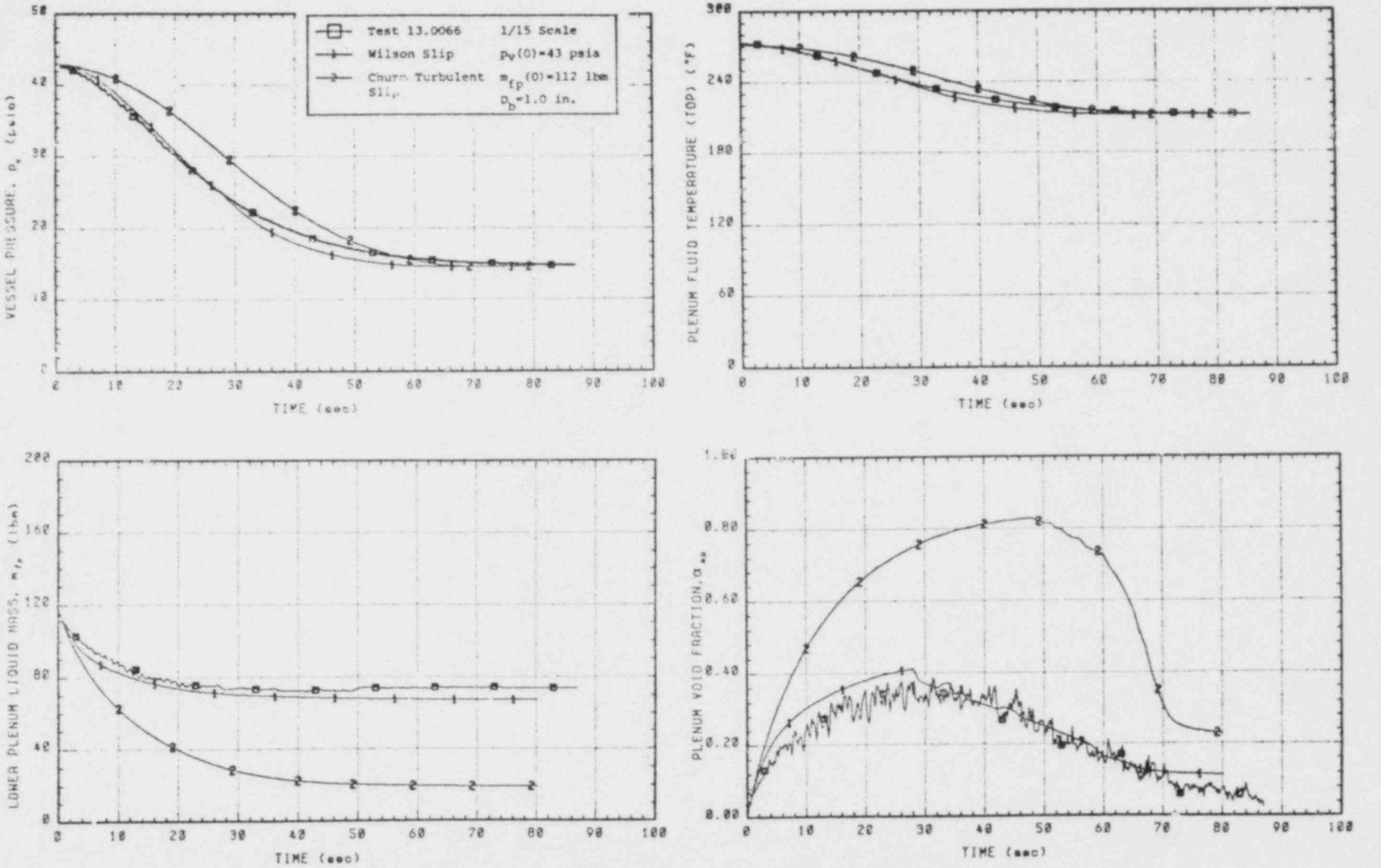

Figure 5. CREFIL CALCULATION OF 1/15 SCALE DATA WITHOUT ECC INJECTION (TEST 13.0066)

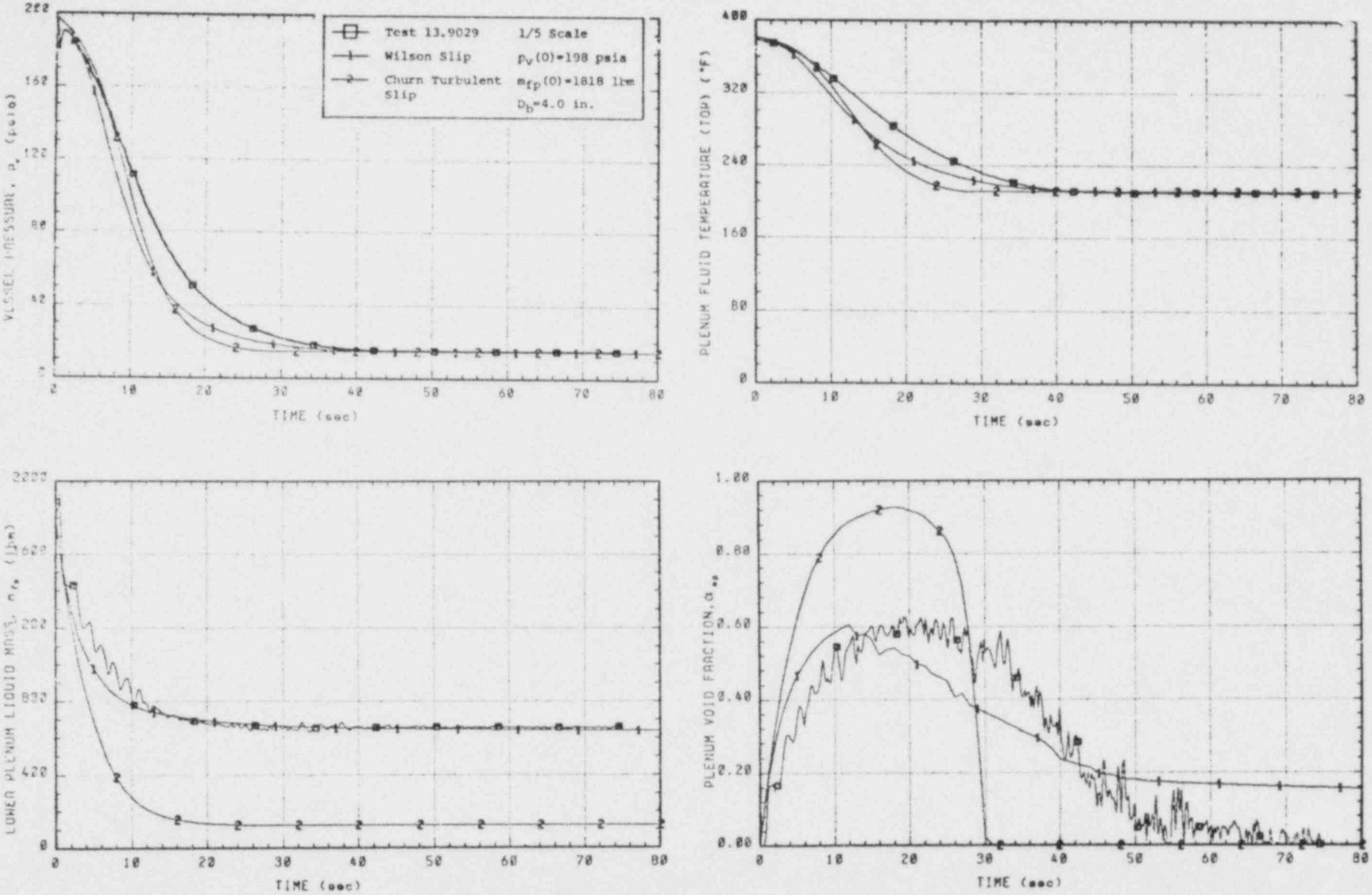

Figure 6. CREFIL CALCULATION OF 1/5-SCALE DATA WITHOUT ECC INJECTION (TEST 13.9029)

In comparisons with our experimental results at both 1/5 and 1/15-scale, and at pressures up to 200 psia, it is shown that this simple model tends to overpredict the time it takes for the vessel to depressurize and significantly underpredicts the amount of fluid in the plenum.

In order to more accurately model plenum slip effects, models in which the slip velocity is a function of plenum void fraction and vessel pressure (variable slip models) were evaluated. Various models are compared in Figure 7. Characterizing these models by their pressure dependency in Figure 7 we have two classes of models, one is the churn-turbulent correlation [15], the other includes the Wilson [16], Labuntsov [17], and Toshiba [18] correlations. The second group is represented by the Wilson correlation in our calculations.

At higher pressures, differences between the models are less pronounced, which explains the long history of use of the constant slip velocity model. The churn-turbulent model is based on the behavior of groups of bubbles rising in stagnant or flowing liquids. The Wilson correlation was developed from steady-state experimental measurements of slip for steam bubbles rising through a pool of saturated liquid. Kagawa et al. [19] obtained nearly the same results in a blowdown/flashing context (simple vessel) to support the Wilson correlation in that application.

The CREFIL calculations with the churn-turbulent correlation are also shown in Figures 5 and 6. These calculations are much like the results obtained when a constant slip velocity of 2 ft/sec is assumed. In particular, too much liquid is calculated to be removed from the plenum. Figures 5 and 6 also show that when the Wilson slip correlation is used both the vessel depressurization and the plenum liquid mass are more accurately calculated at both 1/5 and 1/15-scale. The mixture level is also calculated well, as can be inferred from the void fraction comparisons for the plenum mixture.

5.3 RELAP4/MOD7 Calculations

RELAP4/MOD7 calculations of these two experiments using the Wilson slip model show very good agreement with the experimental data (Figures 8 and (9) and are very similar to the CREFIL calculations (Figures 5 and 6). For these calculations, the lower plenum has been modeled as a single volume. Since all fluid is saturated, the equilibrium option of the code was also used.

At the time this program began, other data comparisons and sensitivity studies were performed [20] using the RELAP4/MOD5 code. It was necessary to modify that version of the code to implement the Wilson slip correlation since it did not appear as an option until the MOD6 version of RELAP4. Good agreement of the previous calculations with similar calculations using the RELAP4/MOD7 code (and the "official" Wilson slip option) supports the correctness of our earlier calculations.

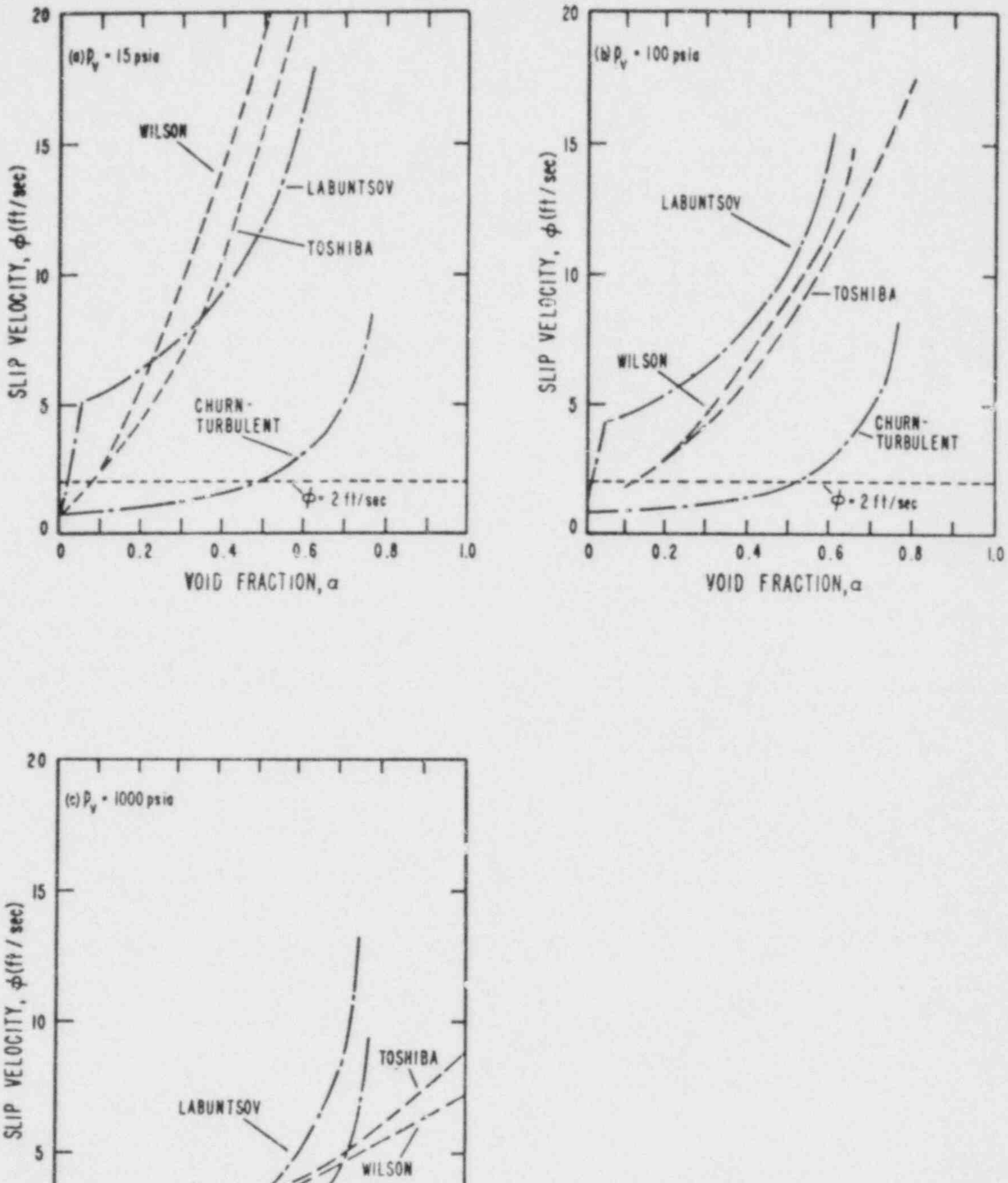

Figure 7. VARIABLE SLIP VELOCITY CORRELATIONS AT VARIOUS PRESSURES

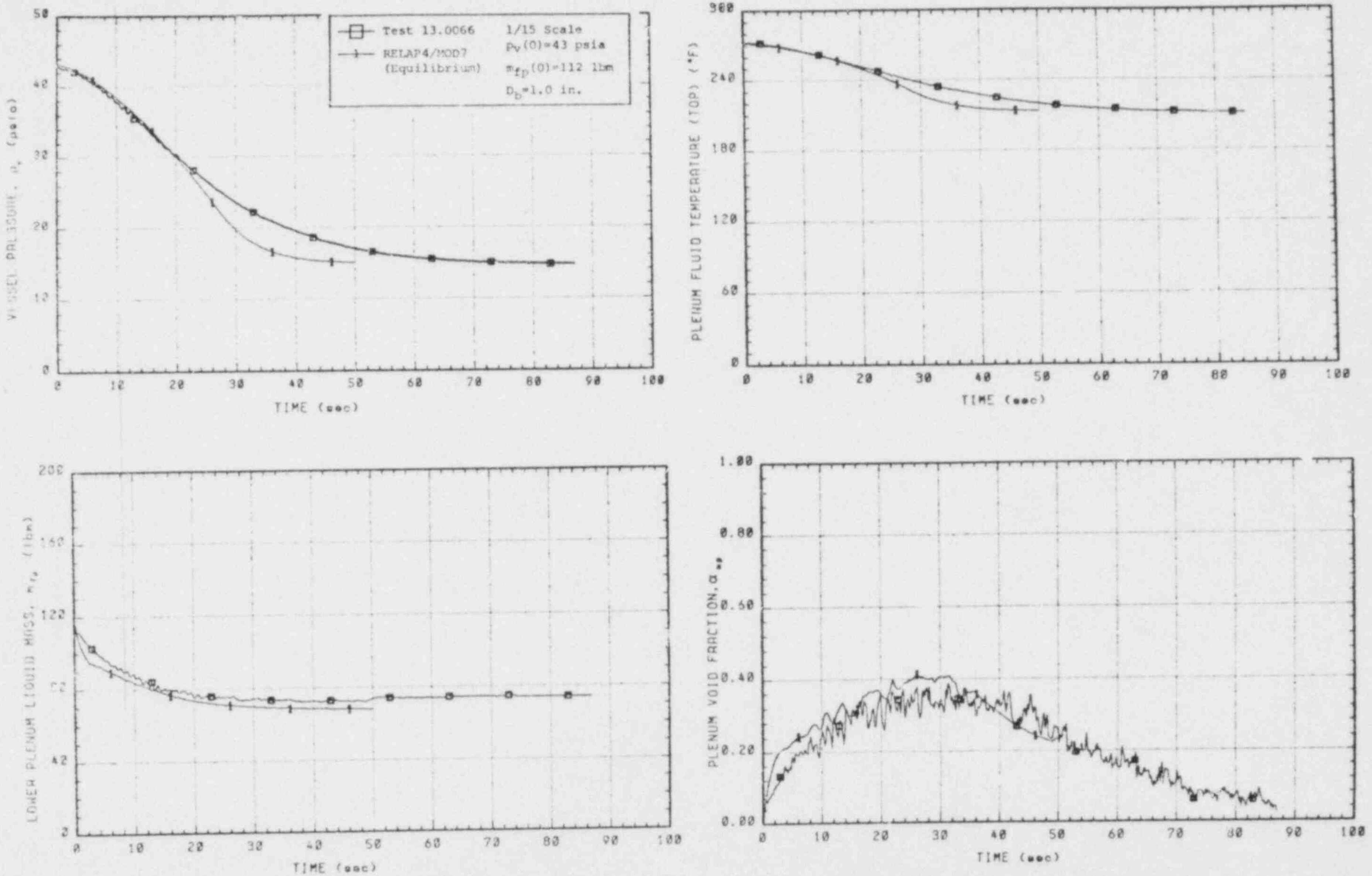

Figure 8. RELAP4/MOD7 EQUILIBRIUM CALCULATION OF 1/15-SCALE DATA WITHOUT ECC INJECTION (TEST 13.0066)

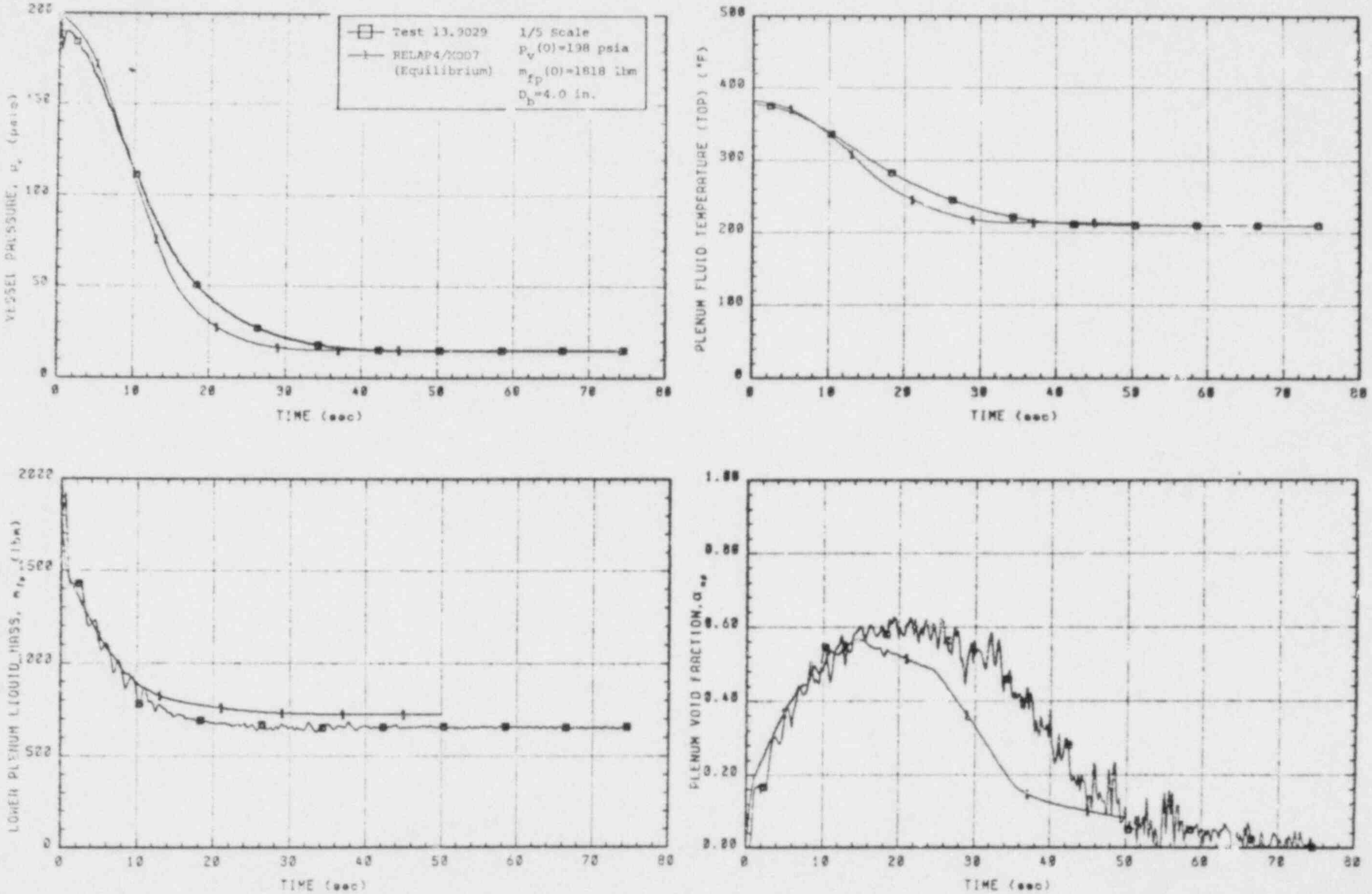

Figure 9. RELAP4/MOD7 EQUILIBRIUM CALCULATION OF 1/5-SCALE DATA WITHOUT ECC INJECTION (TEST 13.9029)

Various other ways to model the lower plenum behavior were also studied. RELAP4/MOD7 has two adjustable parameters for modeling phase separation in the lower plenum: the slip velocity and a "density gradient" parameter. Setting the density gradient parameter to its maximum value of unity effectively doubles the value of the slip velocity. With the churn-turbulent slip correlation it has been found [12] that this set of assumptions produces calculations which lie about midway between those in Figures 5 and 6 for Wilson and churn-turbulent slip (with no density gradient). The remaining plenum mass is underpredicted.

In other calculations, the plenum was divided into many homogeneous (i.e., zero slip) volumes with the RELAP vertical slip model [14]* in the junctions between the volumes. Both five and 20 lower plenum volumes were modeled. The results with both five and 20 volumes were nearly identical and also very close to the calculations with a density gradient parameter of unity.

The RELAP4/MOD7 calculations thus show that the best agreement with the Creare data is achieved with a single lower plenum volume using the Wilson slip correlation. Use of a single volume in modeling the lower plenum decreases computational costs as well.

5.4 Conclusions

Table 3 summarizes the results of additional CREFIL and RELAP4/MOD7 calculations of 1/5-scale experiments without ECC in terms of the time to depressurize the vessel and the remaining plenum mass. The actual transient comparisons for these tests may be found in References 12 and 13. The Wilson variable slip model predicts experimental results over a range of pressures, break sizes, and the factor of three change in scale. The break flow models are seen to be adequate for interactive pressure calculations for these experiments without ECC injection. There is a trend to underpredict the time to depressurize the vessel for large break sizes. In this connection we specifically point out that we have used a flow multiplier of unity. The remaining mass in the vessel is predicted well for all conditions. This plenum slip model is thus an improvement over previous slip models, eliminates the need to adjust slip velocity and density gradient parameters in the analyses, and allows the plenum to be modeled as a single volume.

The great similarity between CREFIL and RELAP4/MOD7 calculations strongly suggests that both analyses are equivalent for these tests without ECC injection. Therefore, the majority of the calculations with RELAP4/MOD7 were performed for experiments with ECC injection and are shown in the following section. Those comparisons are a more severe test of the modeling since the phenomena are more complex.

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*Equivalent to the churn-turbulent slip as used here.

TABLE 3

COMPARISON OF MEASURED AND CALCULATED PARAMETERS WITHOUT ECC INJECTION

Test #	Dimensionless Break Size, D*	Nominal Initial Vessel Pressure (psia)	Time to Depressurize (sec)			Remaining Mass (%)		
			Data	CREFIL	RELAP4/MOD7	Data	CREFIL	RELAP4/MOD7
1/15-Scale								
13.0035	0.22	45	530	600		94	92	
13.0034	0.22	100	675	800		87	85	
13.0051	0.88	20	48	54		81	73	
13.0066	0.88	45	45	40	33	62	57	58
13.0292	0.88	100	48	44		42	44	
13.0060	2.0	45	12	7.5		34	32	
13.0210	2.0	100	11	6		18	18	
1/5-Scale								
13.9024	0.22	45	460	730	460	94	92	88
13.9025	0.87	45	39	36	34	55	54	55
13.9021	0.87	100	38	35		41	44	
13.9029	0.87	200	34	32	28	36	35	39
13.9022	1.3	45	22	22	16	41	42	43
13.9023	1.3	100	19	14		28	31	

*The time for the vessel pressure to decrease to 18 psia.

6 RESULTS WITH ECC INJECTION

6.1 Background

Typical experimental results with injection of highly subcooled ECC are shown in Figures 10 and 11. Similar test conditions of initial pressure, ECC temperature, and dimensionless flow rates were used at 1/15 and 1/5 scale. Comparison of Figure 5 (no ECC injection) with Figure 10 shows that the injection of subcooled liquid has caused the vessel to depressurize much more rapidly. This more rapid depressurization causes the mass in the plenum to be significantly less just prior to refill (mass fraction of 0.27 at 16 seconds in Figure 10) than the remaining mass wtihout ECC injection (mass fraction of 0.[illegible] in Figure 5). In all of these experiments, there is a complicated effect of depressurization and filling behavior with ECC injection as a result of interplay between the phenomena sketched in Figure 1.

The analytical studies of experiments with ECC injection have addressed the models for

- condensation in downcomer and break
- two-phase upflow momentum (or slip) in downcomer
- momentum exchanger in downcomer (countercurrent flow)
- plenum phase separation
- wall heat transfer

The previous analytical work without ECC supports successful application of the Wilson slip correlation and wall heat transfer models to the modeling of experiments with ECC injection. The sensitivity studies show that condensation and plenum fluid mixing should be modeled as nearly thermal equilibrium processes. The modeling of the effect of the liquid component in two-phase momentum has a large effect on the calculated behavior. We therefore primarily discuss the modeling of downcomer flow processes but will also show the effects of condensation assumptions for the purpose of comparing with the non-equilibrium condensation model in RELAP4/MOD7.

6.2 Downcomer Flow Processes

CREFIL. There are three downcomer flows important to ECC bypass in the flashing transient: the upflow of steam, the upflow of liquid, and the flow of delivered (or bypassed) liquid determined by the first two flows. Analytically, the momentum of the upflowing mixture is determined first and considered separately. Then the momentum exchange between the upflowing and delivered (or bypassed) liquid is considered. The modeling of the momentum of the upflowing mixture is much more significant than the momentum exchange relationship.

Liquid Momentum in Two-Phase Upflow

The momentum contributed by the liquid component in two-phase upflow was found to be the most important factor. The relative effect of the liquid component on the momentum of the two-phase upflow was varied in the analysis by relating the effective liquid upflow in upward momentum to the actual liquid upflow through a slip velocity parameter V*, as in Equation (1).

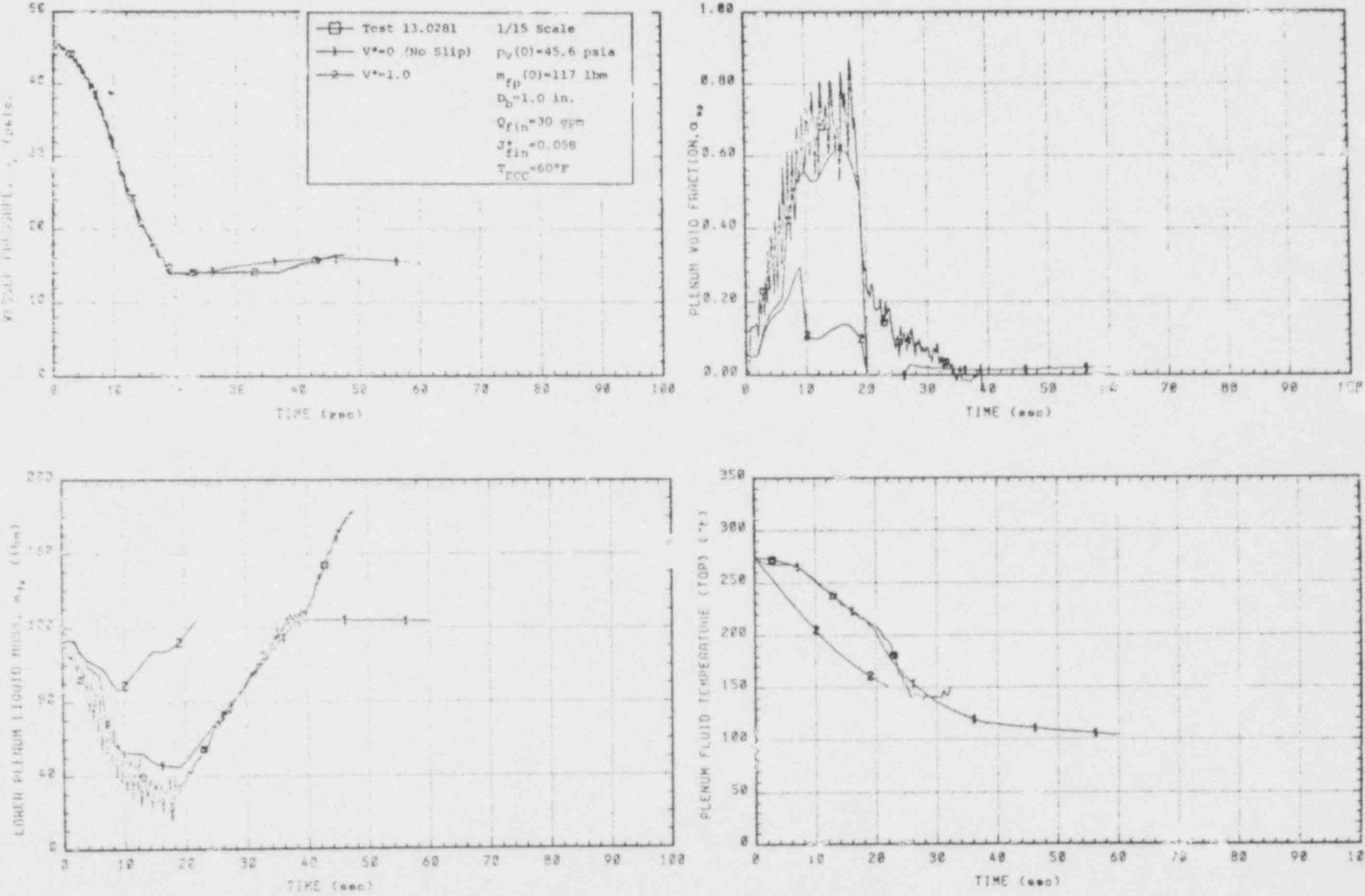

Figure 10. CREFIL CALCULATION AND 1/15-SCALE DATA WITH SUBCOOLED ECC INJECTION (TEST 13.0281)

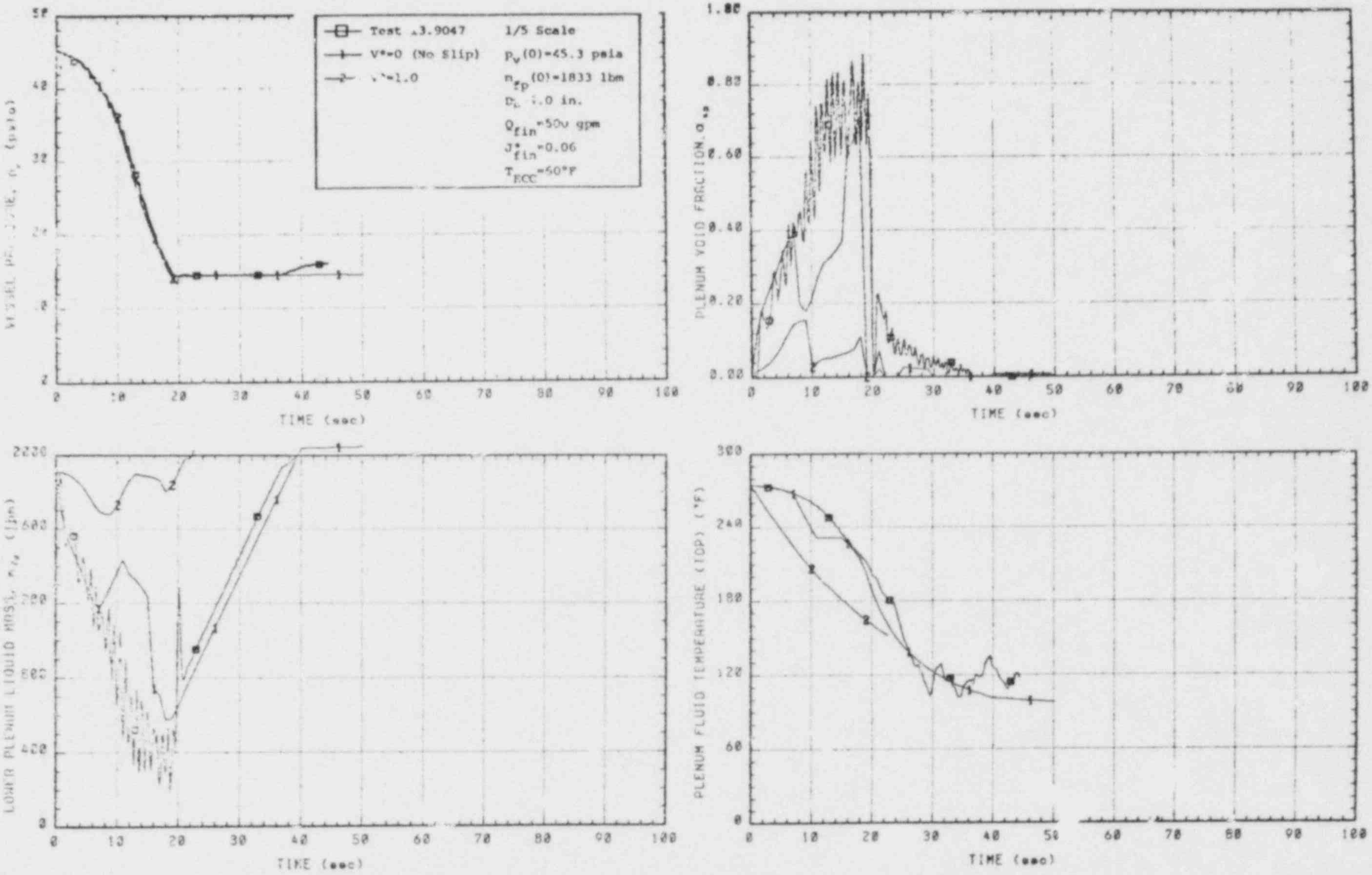

Figure 11. CREFIL CALCULATION AND 1/5-SCALE DATA WITH SUBCOOLED ECC INJECTION (TEST 13.9047)

$$W_{fd(eff)} = W_{fo}(V^*) \qquad (1)$$

Then the effective liquid upflow and the steam upflow were used to determine the momentum of the two-phase upflow

$$S_{2\phi} = f_1 \, (W_{fd(eff)}, W_{gd}) \qquad (2)$$

For the purposes here it is sufficient to recognize that the limit of zero slip in Equation (1) (signified by $V^*=0$) implies the maximum effect of liquid upflow. The limit of infinite slip (gas separated completely from liquid, $V^*=1$) implies no effect of the liquid upflow ($W_{fd(eff)}=0$) from Equation (1). In this case the momentum of the upflow is a function of the steam mass flow only.

Calculations with these limiting values of V^* are compared with the experimental data in Figures 10 and 11. The assumption of zero slip is plainly superior to that of infinite slip. Using the steam flow component alone by the $V^*=1$ assumption permits grossly premature delivery of the ECC to the lower plenum. These calculations demonstrate that the momentum of the liquid in the two-phase upflow cannot be ignored in modeling ECC bypass (ECC bypass cannot be based solely on the steam flow component).

In the analysis, two models for the two-phase upflow in Equation (2) were formulated. One was a Homogeneous Component and the other a Separated Component flow model [12]. These models gave the same results for the limiting values of the slip parameter V^* in Equation (2). Both models were equally successful in calculating the experimental data because of the large effect of the liquid component on the momentum.

Momentum Exchange

Once the momentum of the upflowing mixture was determined, a relationship was needed to calculate the ECC delivery (or bypass). Conceptually, this relationship is

$$W_{fdel} = f_2 \, (S_{2\phi}) \qquad (3)$$

This relationship was formulated based on using the two-phase upflow momentum (Equation (2)) in a correlation developed from single-phase upflow experiments [21,22]. Various choices for the exact formulation were possible based on dimensionless scaling approaches suggested in these references. However, sensitivity studies in Reference 12 show that alternate formulations have a negligible effect on the calculations. The liquid momentum is large and highly transient. Over a very short period of time the liquid momentum decreases from a large value to a negligible value when the mixture in the plenum can no longer swell to the core inlet level. Therefore, the effect of the liquid component on the momentum of the upflow overshadows the scaling of the momentum exchange except for transitional situations.

The calculations in Figures 10 and 11 were performed with the pressure transient input to the analysis and therefore closely match the pressure data. Figures 12 and 13 present comparable calculations with $V^*=0$ and interactive modeling of the break flow using the CREFIL analysis. There is a tendency for some of these calculations to predict an overly rapid depressurization with blowdown completed in about 70% of the measured time. Sensitivity analyses reveal that better modeling of subcooled break flow may be required. This warrants research beyond the scope of this program.

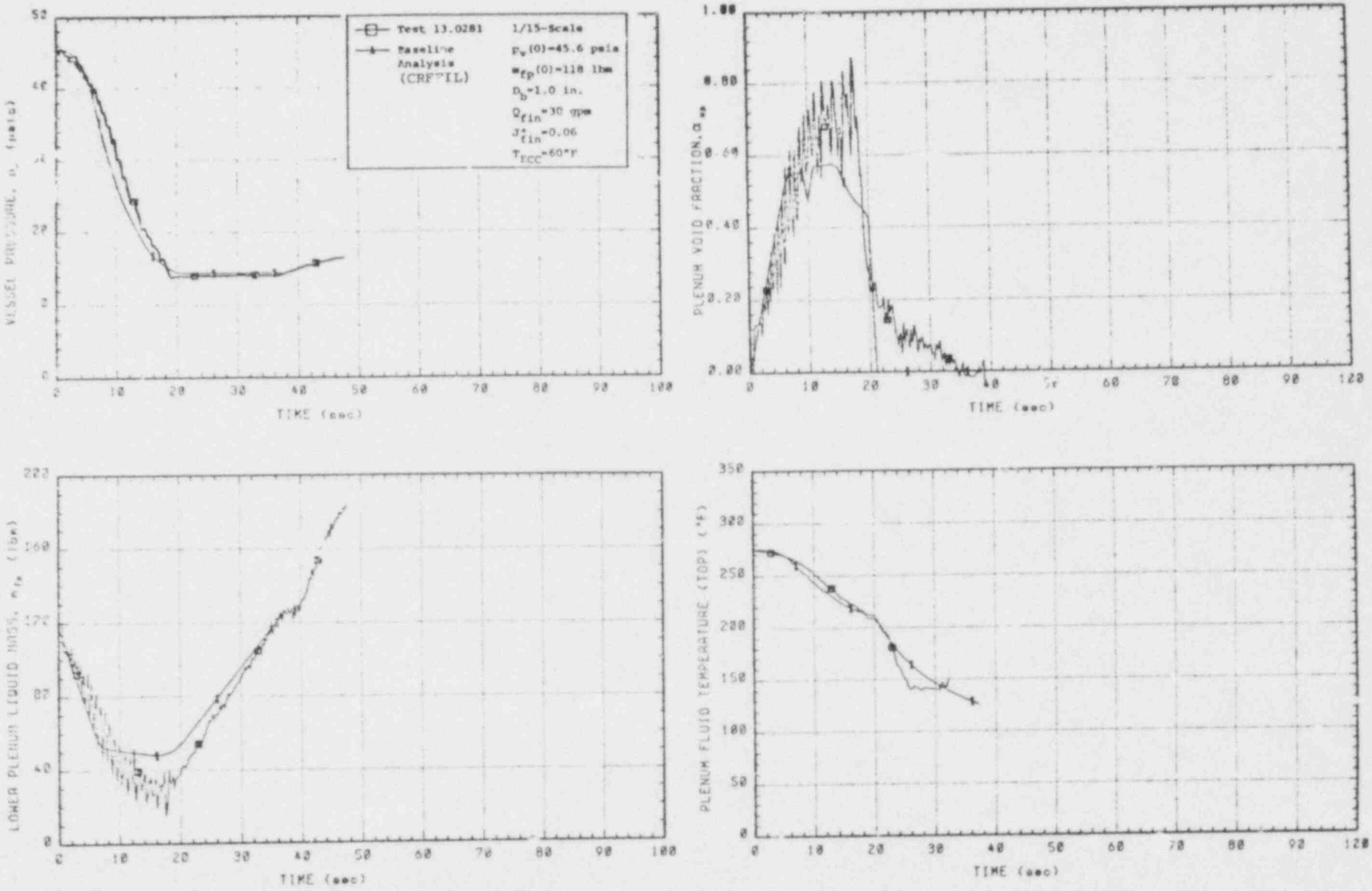

Figure 12. CREFIL BEST-ESTIMATE CALCULATION FOR A 1/15-SCALE EXPERIMENT (TEST 13.0281)

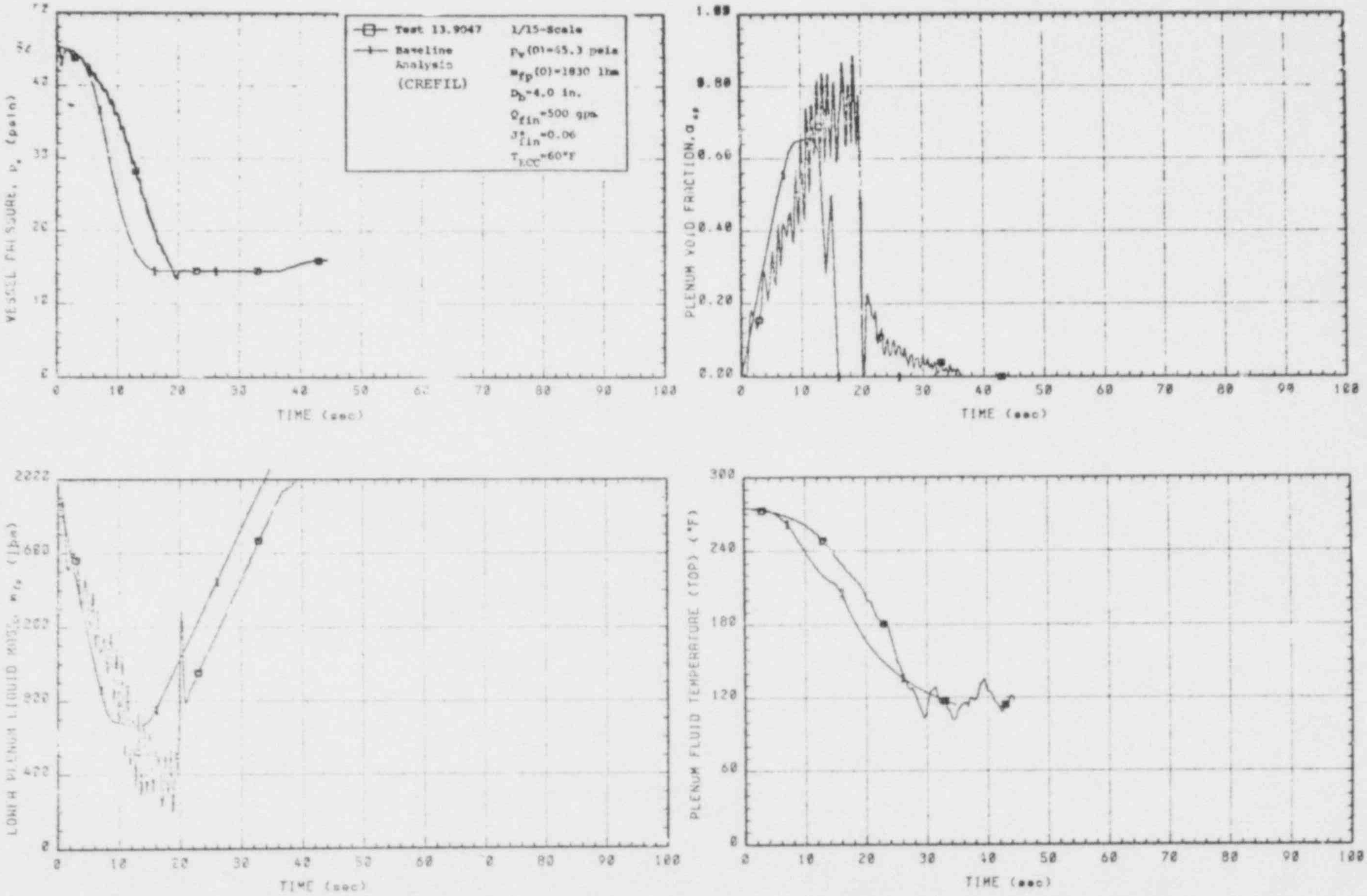

Figure 13. CREFIL BEST-ESTIMATE CALCULATION FOR A 1/5-SCALE EXPERIMENT (TEST 13.9047)

RELAP4/MOD7. Since RELAP is a single-fluid code, it can only recognize one gas and one liquid flow in any junction. RELAP therefore cannot model ECC bypass in exactly the same way as was done in the CREFIL analysis (with three flows).

RELAP uses the void fractions in the downcomer and/or lower plenum to calculate an average void fraction. This is used in turn to calculate a vertical slip velocity between the gas and liquid phases at a given junction. This sequence can be expressed by

$$\bar{\alpha} = f_3 \ (\alpha_{DOWNCOMER}, \alpha_{PLENUM}) \qquad (4)$$

$$V_{SLIP} = f_4 \ (\bar{\alpha}) \qquad (5)$$

The slip velocity is used to determine whether the flow is in a co-current or countercurrent flow regime. If the calculated slip velocity does not exceed the upward gas velocity, the flow is cocurrent. If the slip velocity is larger than the gas velocity, flow is countercurrent. In the countercurrent flow regime, the slip velocity is as calculated by Equation (5) unless limited to a maximum value found by simultaneously solving a flooding equation and the continuity equation.

Standard Vertical Slip

The Standard Vertical Slip calculation in RELAP4/MOD7 gives slip velocities similar to the churn-turbulent correlation for plenum slip shown in Figure 7. The void fraction used to calculate the slip velocity is found by volume-averaging the plenum and downcomer void fractions. Figures 14 and 15 display RELAP4/MOD7 comparisons with the Standard Vertical Slip model and a Modified Slip model discussed below.* As shown in these figures, the calculated time to depressurize the vessel is somewhat short at both scales. The calculated minimum mass is in good agreement with the experimental data. At 1/5-scale (Figure 15) the time to refill the vessel is also in good agreement with the data, but at 1/15-scale (Figure 14), the plenum does not refill within 100 seconds for the Standard Slip model (50 seconds are shown). Similar behavior was found for other tests with highly subcooled ECC at 45 psia initial pressure at 1/15 scale.** The behavior is a result of heat transfer effects which prevent a transition to countercurrent flow at small scale. Heat transfer effects are relatively larger than at 1/5 scale because of the surface area to volume ratio.

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*The equilibrium condensation model is also used for reasons discussed in the following section.

**Similar results are also obtained with any combination of the vertical slip models (churn-turbulent and flow-regime dependent) and the two void fraction options (volume-averaged and volumetric—flux-weighted) available in RELAP4/MOD7.

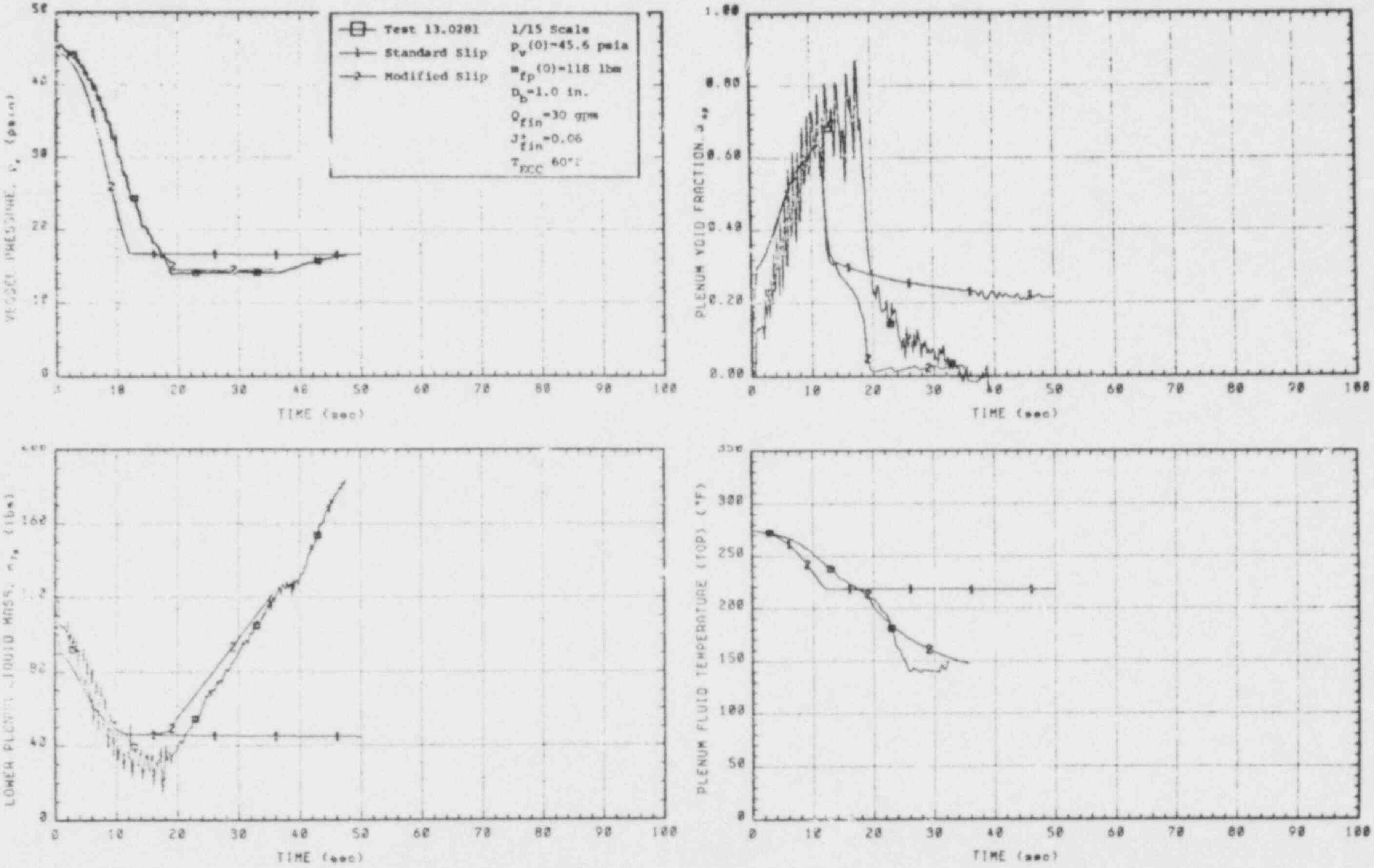

Figure 14. EFFECT OF VERTICAL SLIP MODEL IN RELAP4/MOD7 CALCULATION AT 1/15 SCALE (TEST 13.0281)

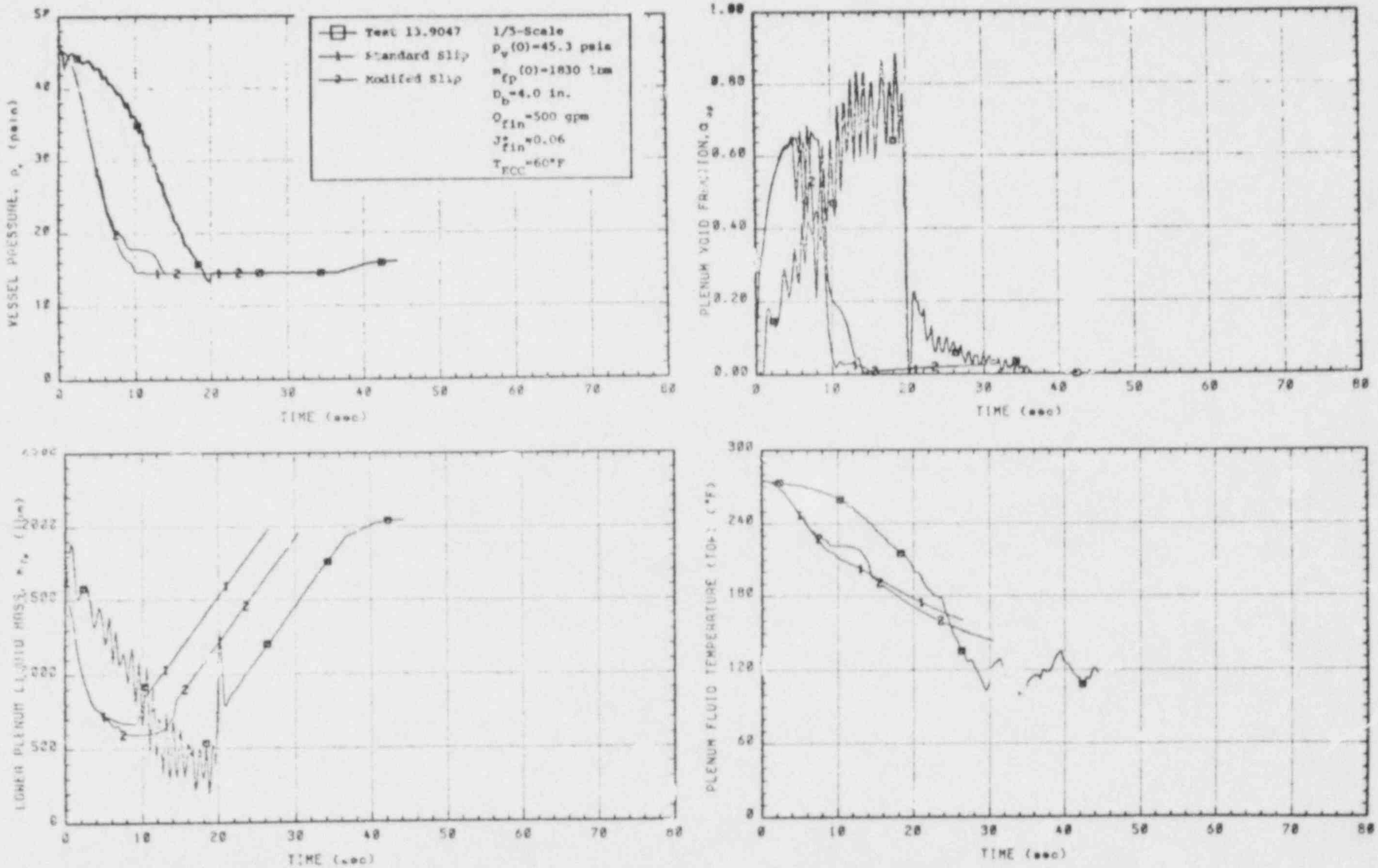

Figure 15. EFFECT OF VERTICAL SLIP MODEL IN RELAP4/MOD7 EQUILIBRIUM CALCULATION AT 1/5 SCALE (TEST 13.9047)

Qualitatively, during the period of flashing and level swell during a transient, RELAP calculates a cocurrent two-phase upflow with no ECC delivery, because the calculated slip velocity is small. (This has the same effect as the complete bypass calculated initially by the CREFIL analysis.) Eventually the calculated slip velocity increases to a value large enough to permit a transition to countercurrent flow, i.e., $V_{SLIP} = V_g$. Then the vessel refills as in Figure 15. Although the slip velocity correlation could be refined, the central problem in Figure 14 is the model for void fraction which is input into the correlation for slip velocity.

Modified Vertical Slip

To improve the calculations, a new option was created for determining the void fraction used in the RELAP vertical slip velocity equation. In the Modified Slip model, the void fraction of the flow in the junction between the plenum and downcomer is used to calculate the slip velocity

$$\bar{\alpha} = f_6 \; (\alpha_{junction}) \qquad (7)$$

as opposed to the available models which both use the void fraction in adjoining volumes. This model is suited for highly accelerating flows in a pipe [23]. As demonstrated by Figures 14 and 15, this modification allows refill to be predicted better for Figure 14 while the calculations of other tests are not changed significantly (see additional comparisons in Reference 13).

Thus, although RELAP4/MOD7 necessarily treats two-phase momentum effects differently than the CREFIL analysis, the approach is based on the same physical concepts and is similarly successful in calculating the experimental behavior once the Creare modified void fraction model is used.

6.3 Condensation

CREFIL. In the CREFIL analysis, condensation has been modeled as a constant fraction of thermal-equilibrium, η_m. This coefficient reflects the degree to which the condensation of steam approaches thermal equilibrium in the downcomer (or break). This in turn affects the enthalpy of the fluid entering the break and the depressurization rate when interactive break flow models are used.

The bounding limits of the effect of condensation were explored in the model sensitivity study with CREFIL. These limits are complete thermal equilibrium (η_m=1) and no condensation allowed (η_m=0). Figures 16 and 17 show the calculations for two experiments using the bounding limits for condensation and also the value η_m=0.6 (which was used in best-estimate calculations). The calculations near thermal equilibrium (η_m=0.6 to 1) come much closer to matching the experimental data. For these calculations, adjusting the non-equilibrium factor η_m to a value of 0.6 has possibly masked some deficiencies in the break flow model with highly subcooled liquid.

RELAP4/MOD7. The non-equilibrium model uses a constitutive package to calculate an effective rate of heat transfer during condensation. The constitutive package is described in Reference [25]. This non-equilibrium model does not have any adjustable dials in the standard form which has been used here. (Input variations may be used to apply a multiplier to the calculated condensation rate.) Figures 18 and 19 compare equilibrium and non-equilibrium calculations using RELAP4/MOD7.

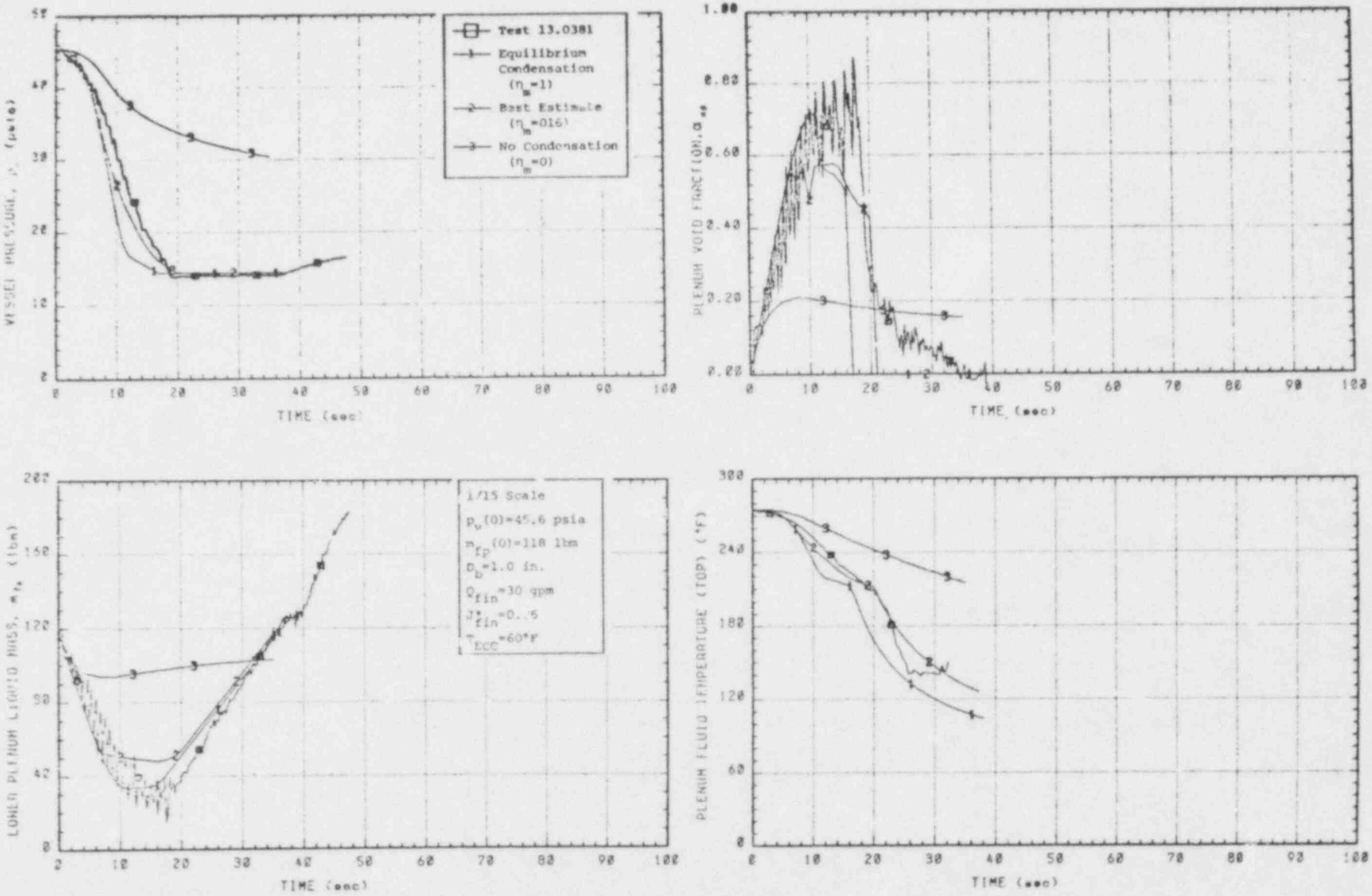

Figure 16. EFFECT OF CONDENSATION IN CREFIL CALCULATIONS AT 1/15 SCALE (TEST 13.0281)

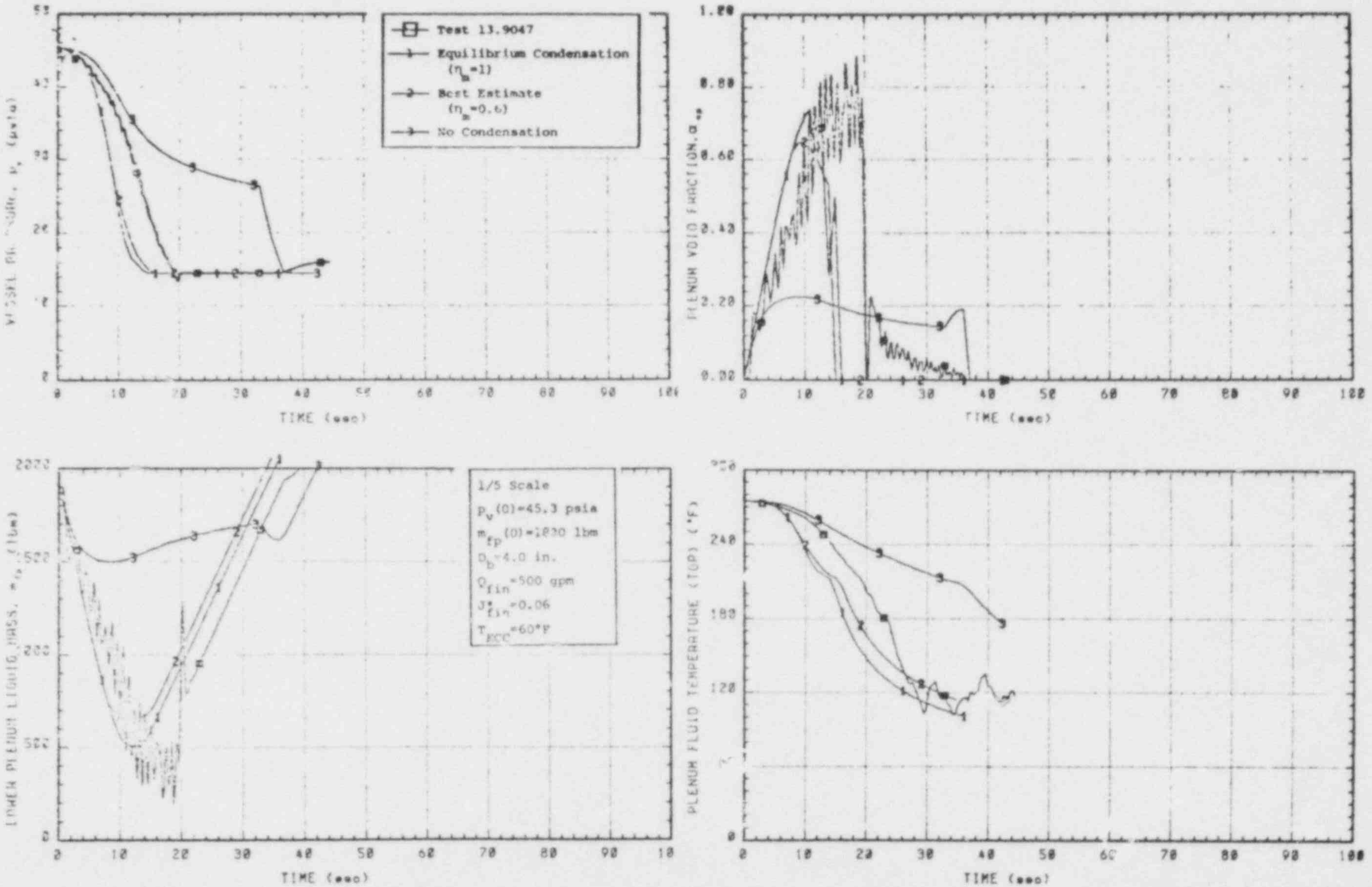

Figure 17. EFFECT OF CONDENSATION IN CREFIL CALCULATION AT 1/5 SCALE (TEST 13.9047)

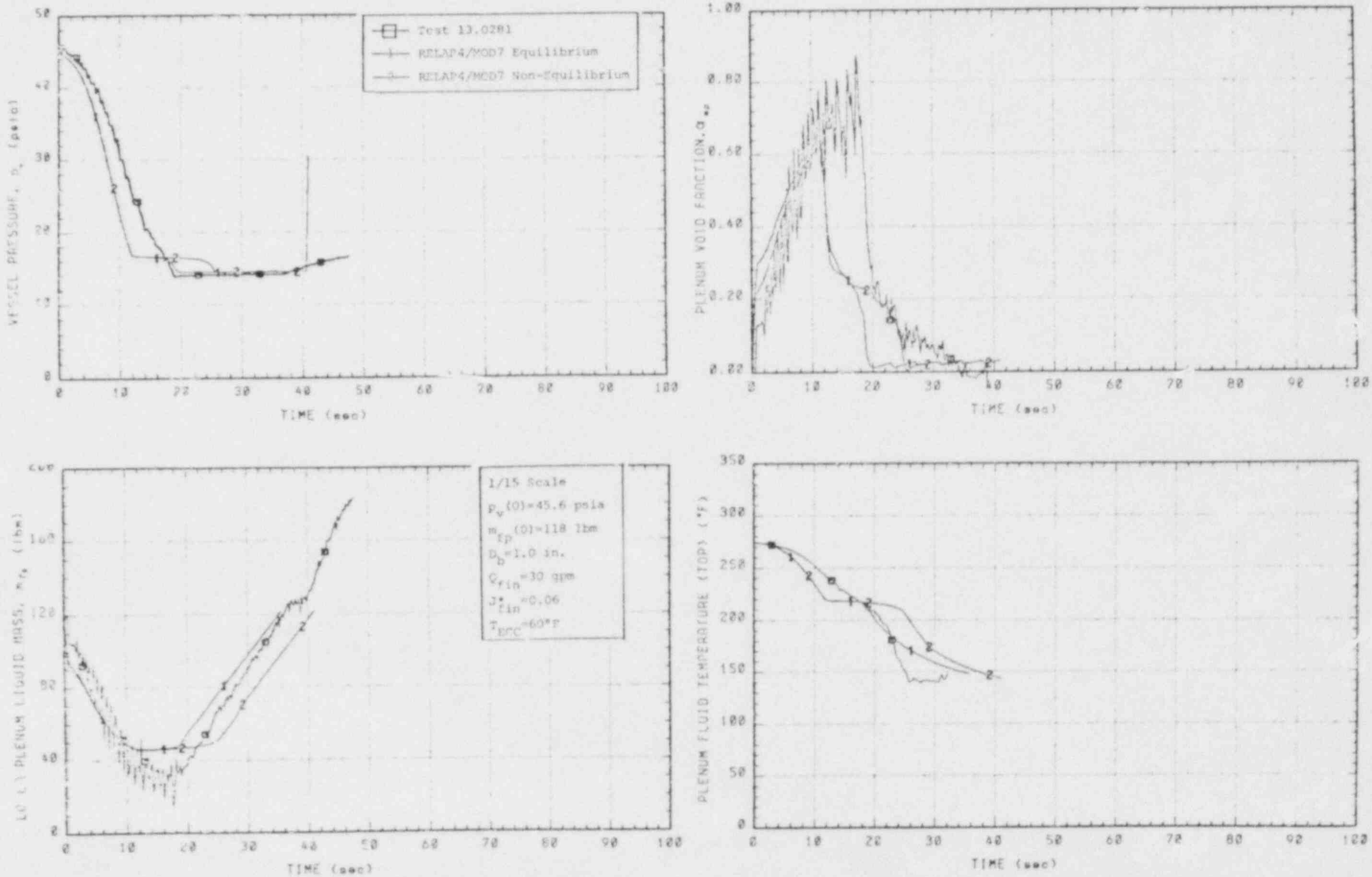

Figure 18. RELAP4/MOD7 EQUILIBRIUM AND NON-EQUILIBRIUM CALCULATIONS AT 1/15 SCALE (TEST 13.0281)

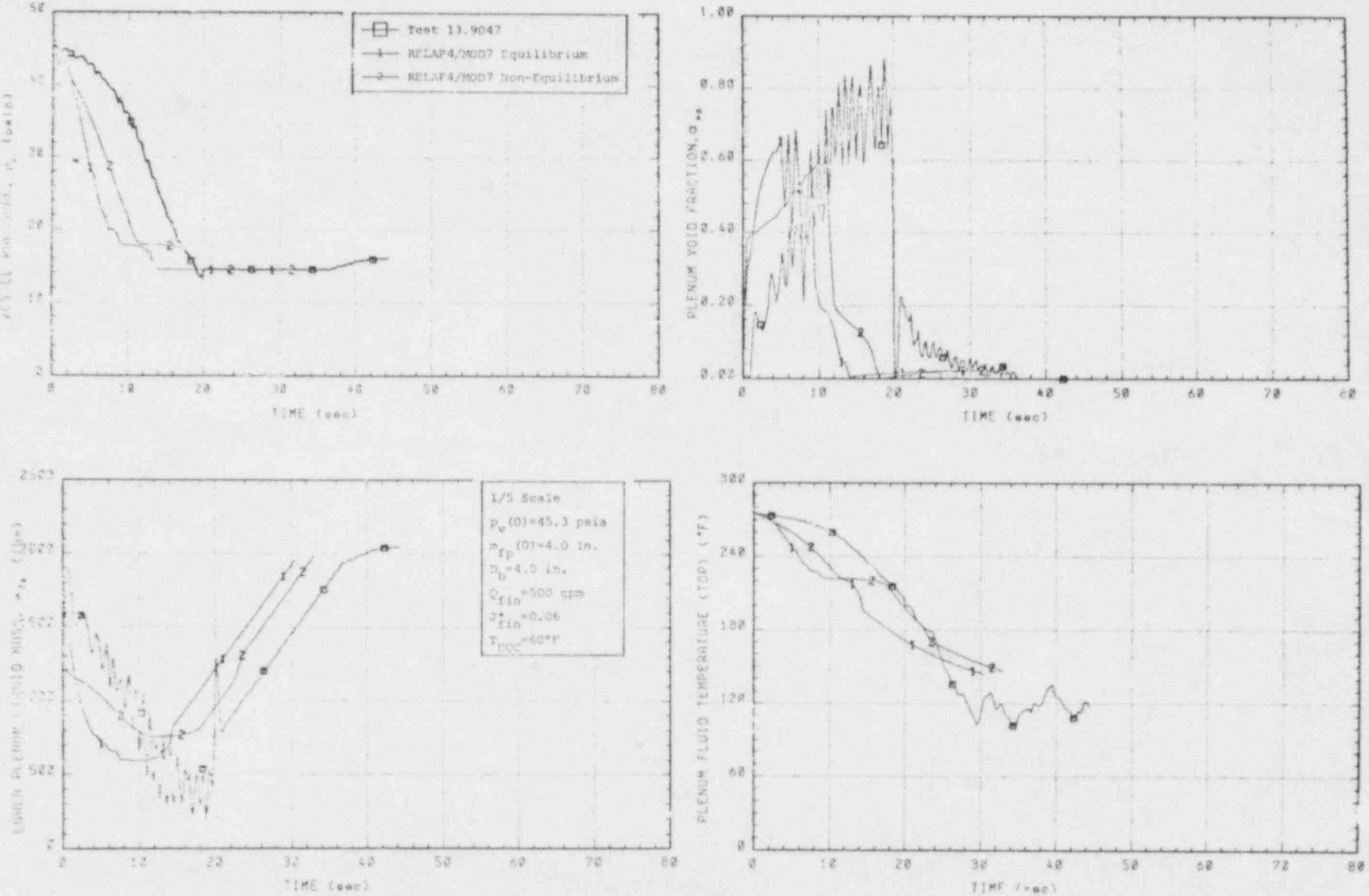

Figure 19. RELAP4/MOD7 EQUILIBRIUM AND NON-EQUILIBRIUM CALCULATIONS AT 1/5 SCALE (TEST 13.9047)

Relative to the calculations with the equilibrium model, the vessel depressurization is somewhat longer with the non-equilibrium model, the minimum plenum mass is typically somewhat higher (in poorer agreement with the data), while the time to refill is in slightly better agreement with the data.

There are some second-order differences apparent in the RELAP4/MOD7 non-equilibrium calculations. In the mass transient curves, there is an initial rapid loss of mass from the vessel, and a subsequent flat region in this curve at a somewhat higher value of the mass than the equilibrium calculation. The rapid loss of mass from the plenum may be a result of small deficiencies in the implementation of the non-equilibrium model. The non-equilibrium model causes the cold leg and downcomer volumes to fill with liquid from the plenum (reach void fraction of zero) in about 0.1 seconds, with the concurrent disappearance of the steam space initially present. This behavior is not related to the injection of subcooled ECC, since it occurs even if ECC injection is delayed. Program outputs show that some condensation is calculated to occur even though the liquid is not subcooled. Thus, this appears to be a small numerical problem with the non-equilibrium model. It explains the sudden loss of plenum mass however, and the difference in details between equilibrium and non-equilibrium calculations.

Study of the condensation rates calculated by the non-equilibrium model shows that in most cases, and in particular for the cases shown here, the non-equilibrium rates are equivalent to thermal equilibrium. Therefore, the differences in the calculations shown here are primarily numerical rather than related to the physics of the models. By the same token, the non-equilibrium model does not improve best-estimate physical modeling although it will provide a means for sensitivity calculations after the numerical problems are solved.

Comparisons with Figures 16 and 17 illustrate that the CREFIL and RELAP4/MOD7 equilibrium calculations produce about the same result. The non-equilibrium RELAP calculations and the CREFIL calculations show the same tendency toward a flattening in the mass transient, however, the initial rapid mass loss is not observed in CREFIL. A small step in the pressure transient due to heat transfer effects is observed with RELAP but not CREFIL.

The equilibrium calculations with RELAP4/MOD7 also demonstrate that earlier difficulties in calculating these experiments with ECC injection using RELAP4/MOD5 [22] was therefore not due to the equilibrium features of the code. The previous problems were primarily due instead to numerical instabilities (related to water-packing) which have since been improved in MOD7 although not yet definitively eliminated.

6.4 Parameter Sensitivity with RELAP4 and CREFIL

Table 4 summarizes additional experimental and analytical results in terms of the time to depressurize the vessel, the minimum mass in the lower plenum, and the time to refill the plenum. Experimental data at all scales can be well characterized by either the CREFIL analysis or RELAP4/MOD7 calculations. Full transient comparisons for these experiments may be found in References 10 and 11.

TABLE 4

COMPARISON OF MEASURED AND CALCULATED PARAMETERS WITH ECC INJECTION

Test #	T_{ECC} (°F)	J^*_{fin}	Nominal Initial Vessel Pressure (psia)	D*	Time to Depressurize (sec)*				Minimum Mass in Plenum (%)				Time to Refill (sec)**			
					Data	CPEFIL	RELAP4/MOD7		Data	CREFIL	RELAP4/MOD7		Data	CREFIL	RELAP4/MOD7	
							Eq.	Non-eq.			Eq.	Non-eq.			Eq.	Non-eq.
13.0076	60	0.019	45	0.88	31	30	18	28	60	59	58	63	69	74	70	65
13.0281	60	0.056	45	0.88	16	15	12	12	27	41	39	39	35	35	35	40
13.0074	60	0.116	45	0.88	16	22	17	25	51	49	45	43	23	28	25	34
13.0203	70	0.058	100	0.88	15	17	13	16	18	36	30	37	36	38	35	40
13.0204	70	0.116	100	0.88	14	15	12	16	24	25	31	37	23	23	22	40
13.0205	70	0.174	100	0.88	16	14	20	28	30	30	32	33	21	19	27	36
13.0128	100	0.058	45	0.88	28	30	19	20	44	56	52	50	43	52	46	53
13.0200	200	0.019	45	0.88	51	75	—	—	59	68	—	—	125	125	—	—
13.0254	200	0.058	45	0.88	42	64	25	37	58	64	53	62	90	110	80	—
13.0128	200	0.116	45	0.88	43	38	—	—	54	56	—	—	50	60	—	—
13.0300	70	0.058	45	2.0	7	6	5	—	17	26	22	—	31	30	28	—
13.0250	60	0.034	100	0.89	13	13	13	13	43	22	32	32	18	24	25	34
13.9050	70	0.019	45	0.87	27	24	19	24	40	53	50	57	72	67	60	61
13.9047	60	0.06	45	0.87	16	13	10	11	22	34	33	41	35	32	29	31
13.9048	65	0.12	45	0.87	17	20	16	16	36	46	45	45	23	27	22	23
13.9064	70	0.024	100	0.87	26	32	25	33	33	48	44	54	66	69	63	64
13.9057	75	0.066	100	0.87	15	15	14	11	18	33	36	33	31	35	33	26
13.9061	70	0.12	100	0.87	14	11	15	18	23	18	30	31	23	23	24	27
13.9042	200	0.017	45	0.87	40	47	—	—	61	64	—	—	74	—	—	—
13.9044	200	0.054	45	0.87	32	31	22	28	63	60	50	59	50	62	45	47
13.9046	200	0.11	45	0.87	30	27	—	—	68	52	—	—	30	45	—	—
13.9054	200	0.06	100	0.87	40	70	30	38	42	47	46	59	48	100	48	56

*Time to reach 18 psia or 20 psia.

**Time for plenum mass to equal initial mass.

The trend of the calculations with decreased ECC subcooling is to better calculate the time to depressurize the vessel. The non-equilibrium calculations of RELAP4/MOD7 better match the experimental depressurization transients than the equilibrium calculations for low ECC subcooling. The refilling of the vessel is more gradual with the non-equilibrium calculation for low ECC subcooling, in agreement with the data. The non-equilibrium calculation also does a better job of predicting the depressurization transient for low ECC flow rates at both scales. For high ECC subcooling both models are equivalent.

For larger initial vessel pressures, larger breaks, or larger gap sizes the equilibrium calculation of RELAP4/MOD7 tends to predict the time to refill the vessel and the minimum mass in the vessel better than the non-equilibrium calculation. The non-equilibrium calculations tend to predict too long a time to refill. Depressurization transients with subcooled ECC injection are also matched better by any of the analyses for larger initial pressures. The CREFIL calculations tend to compare with the best features of the RELAP4/MOD7 comparisons.

6.5 Conclusions

The major conclusions from this work are that:

- Both CREFIL and RELAP4/MOD7 analyses can adequately predict the trends of the experiments in continuous calculations of refill.
- The important phenomenon to be modeled in order to calculate the experiments is related to the momentum of the liquid component in two-phase upflow and subsequent ECC bypass. The good comparison between the CREFIL and RELAP4/MOD7 analytical results indicates that the simple concepts used in RELAP4/MOD7 can predict these experiments.
- Thermal equilibrium models in the analyses give good agreement with most of the experimental data. In a few cases (for low ECC subcooling or low ECC flows) the non-equilibrium model of RELAP4/MOD7 has some advantages and is otherwise equivalent to the equilibrium model. (Assuming that a small numerical problem with the non-equilibrium model is fixed.)
- The tendency of all the analyses to underpredict the depressurization transient with highly subcooled ECC at low pressure indicates that subcooled break flow models might be improved. CREFIL calculations with the experimental pressure transient used as an input support the conclusion that better calculation of other test results occurs when the pressure transient is matched. (A break flow multiplier of 0.63 has been used for all calculations with ECC injection.)

7 APPLICATION TO LOFT EXPERIMENT

The modeling ideas discussed in the previous sections of this summary have been applied to RELAP4/MOD7 calculations of LOFT experiment L1-4. Previously, a simplified nodalization of the LOFT experimental geometry was created [25]. This model used 13 nodes, 16 junctions and 8 heat slabs compared with 53, 59, and 47 elements, respectively, in LOFT pre-test predictions. The simplified nodalization agreed well with the pre-test predictions [26].* The agreement with experimental data from L1-4 was also good for system components (pressurizer, pumps, intact loop steam generator, accumulator, etc.). The calculated liquid inventories in the downcomer and lower plenum showed disagreement with experimental trends. It is shown here that using the Wilson slip correlation in the lower plenum and using the non-equilibrium condensation model improves the calculations with respect to plenum and downcomer inventories.

For both of the calculations shown here, the input parameters have been upgraded in accordance with LOFT L1-4 post-test calculations [27]. The nodalization of the system was not changed, however. (The suggested split-downcomer nodalization of Reference[27]was <u>not</u> used.) The only significant modeling concession which differs from the concepts in INEL calculations of L1-4 is that the coolant pump speeds have been regulated in order to match the experimental results. The calculations required 200 to 800 seconds of CPU time on a CDC machine.

The previous RELAP4/MOD5 calculations have also used a slip velocity of zero in the plenum and (of necessity) thermal equilibrium modeling. Typical results for the vessel pressure, plenum liquid fraction,** downcomer liquid fraction and core region liquid fraction are displayed by the dashed lines in Figures 20 to 23. The solid lines are the experimental results. (There are no experimental data for the core liquid fraction.) The vessel depressurization rate (Figure 20) is predicted quite well. The plenum is calculated to be nearly voided between 25 and 50 seconds with this set of assumptions (Figure 21) while the data indicate a greater amount of liquid present. The plenum is calculated to fill rapidly about ten seconds too late. The downcomer region is correctly calculated to void (Figure 22), but fills early (at 52 seconds) whereas the experimental data indicate that filling did not occur until approximately 90 seconds. The core region is calculated to remain voided while the downcomer fills. Finally, the core begins to fill once the plenum has been filled.

The calculations shown by the dotted lines in Figures 20-23 illustrate the effect of using the Wilson slip correlation in the vessel volumes (lower plenum, core, upper plenum and downcomer) and the standard non-equilibrium model of RELAP4/MOD7 (in the lower plenum, core, upper plenum, downcomer, and intact cold leg volumes). The calculated vessel depressurization is slightly faster than previously calculated (Figure 20). The behavior of system components is about the same. The major difference appears in vessel liquid inventories. Figure 21 shows that the plenum comparison is improved. Both the minimum value and the time at which the plenum is filled are in better agreement with the conductivity probe measurements. The downcomer (Figure 22) is approximately voided by 25 seconds, in agreement with the experimental results and the other calculations. The downcomer begins

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*The upper plenum to downcomer bypass path was not modeled in the Creare nodalization.

**The liquid mass distributions are derived from the plenum and downcomer conductivity probe sensors. We have reviewed the analysis of the data from these probes and have concluded that the interpretations shown in the figures here are consistent with the measurements. There are some additional questions involving the time response of the probes, but these are not expected to alter the major conclusions.

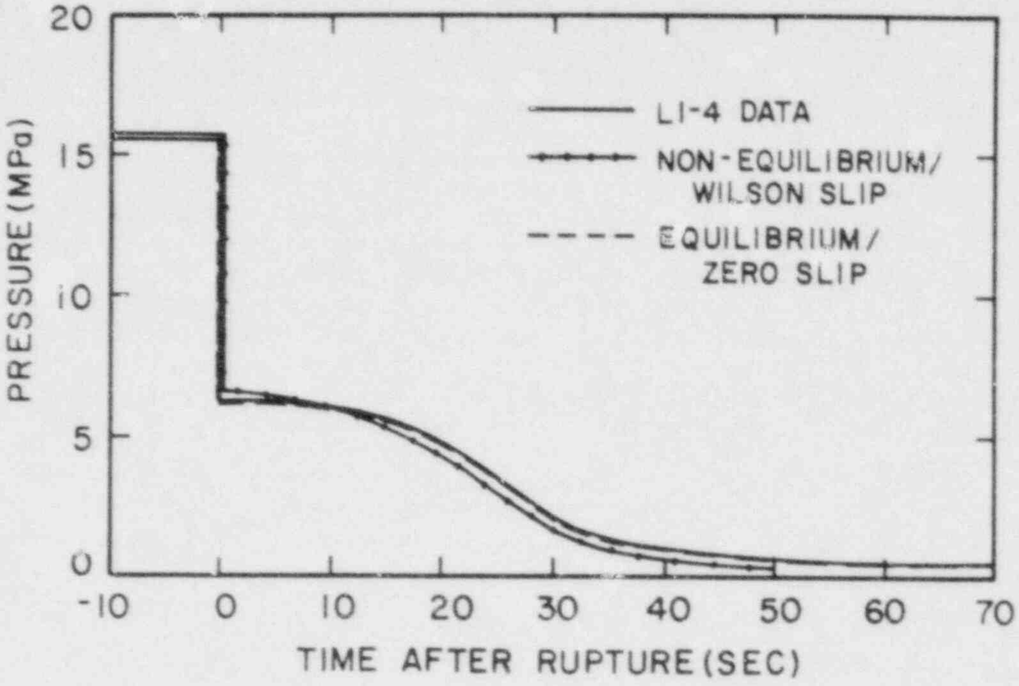

Figure 20. PRESSURE IN INTACT LOOP COLD LEG

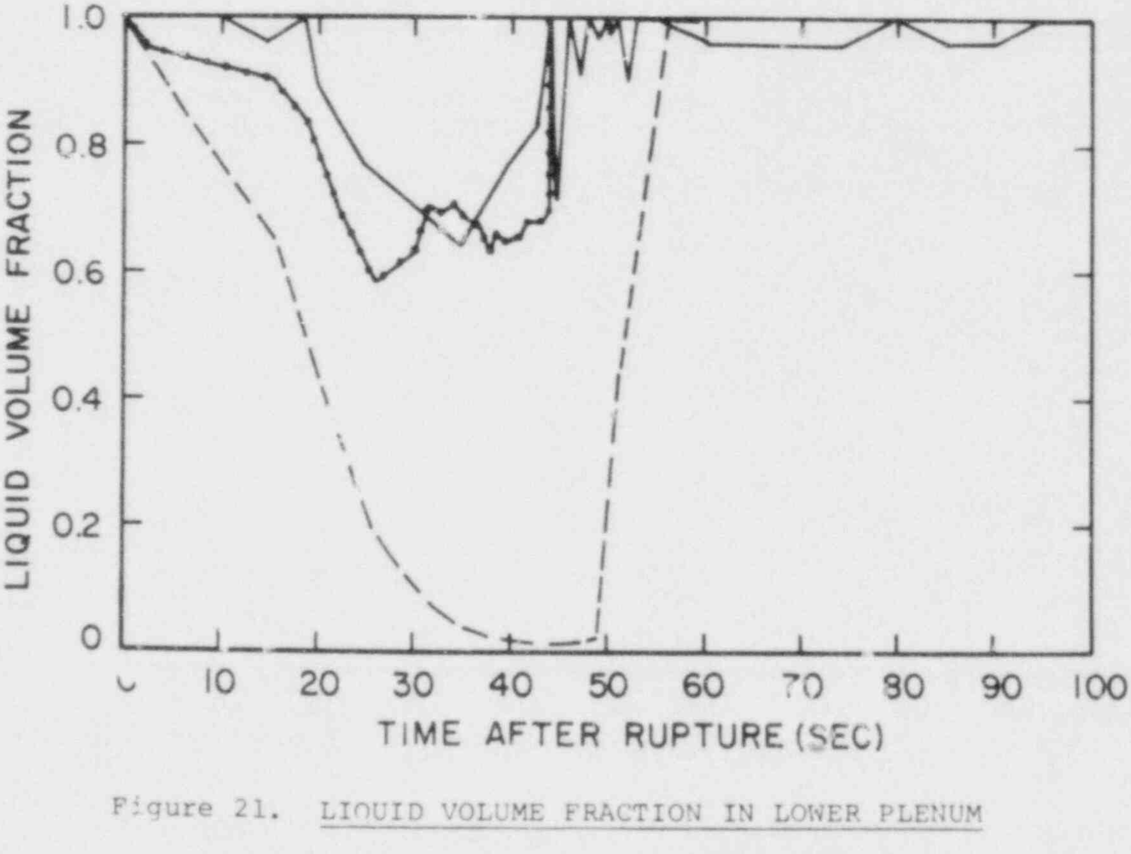

Figure 21. LIQUID VOLUME FRACTION IN LOWER PLENUM

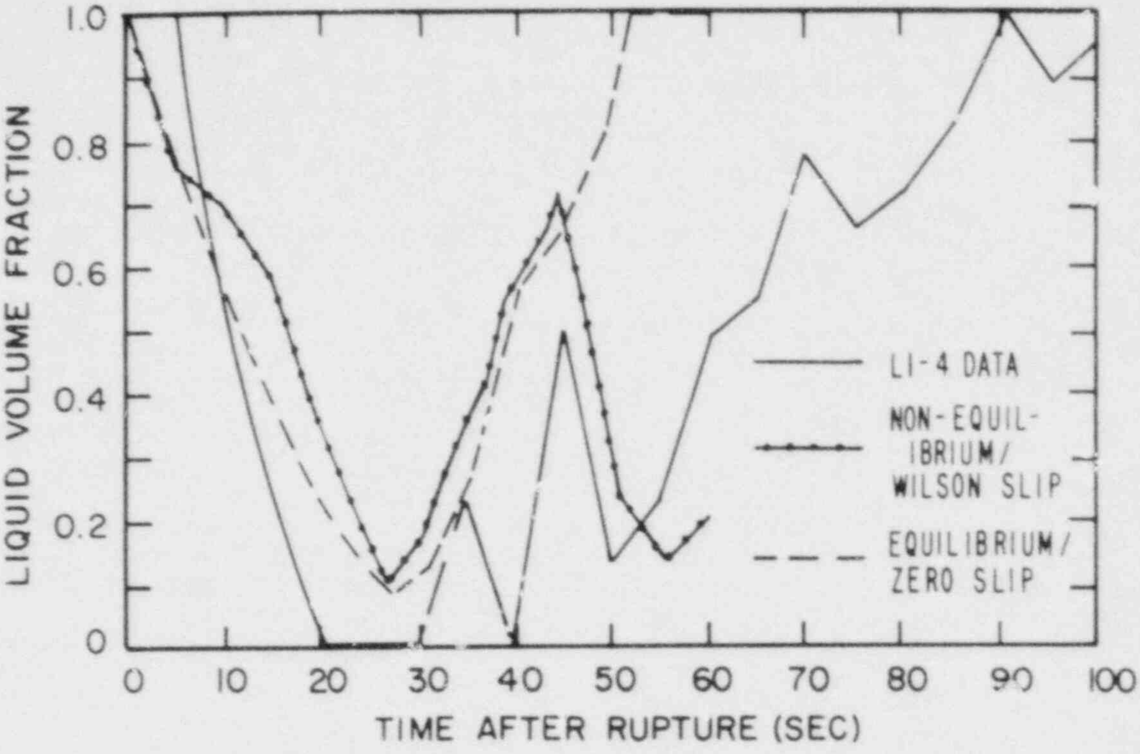

Figure 22. LIQUID VOLUME FRACTION IN DOWNCOMER

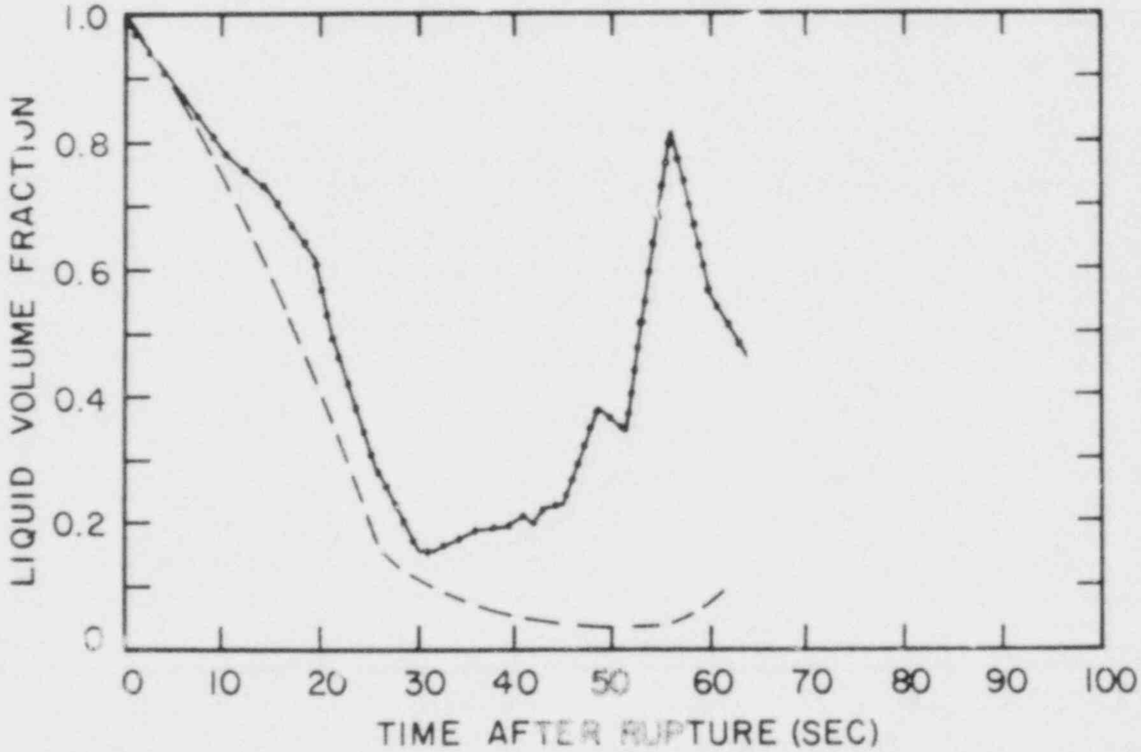

Figure 23. LIQUID VOLUME FRACTION IN REACTOR VESSEL

to fill somewhat between 24 and 44 seconds, and then voids again by 55 seconds. The experimental data show some filling of the downcomer during this period (24-44 seconds) though not as much as is calculated. The second period of voiding (44-55 seconds) is caused by delivery of downcomer liquid to the plenum (Figure 21) and core (Figure 23). Both the calculations and data indicate that the downcomer liquid fraction decreases when the plenum fills.

The non-equilibrium calculation shows that the voiding in the core region is not as great as in the equilibrium calculation. The core begins to fill much earlier in the non-equilibrium calculation.

The calculations shown in these figures were ended at 60 seconds. In the actual experiments, nitrogen from the accumulator enters the system at that time. The nitrogen injection has the potential to affect the experimental results in several ways: the addition of non-condensibles could reduce condensation rates, the system pressure could be increased, and the nitrogen flow could entrain fluid from the upper portion of the downcomer. RELAP4/MOD7 cannot model these effects, cannot in fact model the transport of air between system volumes, and therefore the calculations are not considered valid after 60 seconds. Note that the average rate of refill shown by the downcomer liquid fraction data after 60 seconds corresponds roughly to the rate of LPIS plus HPIS injection (Figure 22).

Use of the Wilson slip correlation permits a greater amount of liquid to remain in the lower plenum than the original zero slip assumption (for which the plenum is virtually voided at one point). This result is consistent with the Creare experiments described earlier. The minimum amount of fluid remaining in the plenum in test L1-4 is in good agreement with the calculation using Wilson slip in the plenum. Additional calculations have shown that this result is true for both equilibrium and non-equilibrium condensation assumptions.

Use of the non-equilibrium condensation model permits the downcomer to contain some steam voids despite the presence of subcooled liquid in the downcomer. During the period from 30 to 44 seconds, there is a net steam flow out of the lower plenum, i.e., into both the downcomer and the core, as a result of flashing of plenum fluid. (Note that with more fluid remaining in the plenum, the steam source from flashing is larger.) Some small amount of delivery occurs and the liquid in the plenum gradually becomes more subcooled. Between 44 and 48 seconds in the non-equilibrium calculation the plenum fluid becomes sufficiently subcooled that it can no longer flash. This is the point at which the plenum rapidly fills and the downcomer drains. This sequence in the calculations is similar to the behavior in calculations of Creare experiments. In the calculation with equilibrium condensation, since there is little plenum fluid remaining between 20 and 50 seconds, there is no significant contribution to steam flow from flashing. There is a sustained, large reverse core steam flow which passes through the plenum and flows upward in the downcomer, preventing ECC delivery. (The reverse core steam flow is probably induced by condensation on the downcomer ECC.) At about 50 seconds, the downcomer becomes full and subcooled ECC begins to enter the lower plenum. The downcomer remains filled with subcooled ECC. Because of the thermal equilibrium restriction the downcomer fluid cannot both be subcooled and contain steam voids.

During the period 30-44 seconds, the filling of the downcomer is calculated to be somewhat larger than was measured. Increased heat transfer, reduced condensation, or a reduced slip velocity in the downcomer might further improve the calculations. For example, heat transfer is mainly in the nucleate boiling regime, with heat transfer coefficients of around 3000 Btu/hr-ft^2°F. If heat transfer were wall conduction-limited, larger coefficients of about 10,000 Btu/hr-ft^2-°F would be implied. The non-equilibrium model contains several calculational assumptions about flow regimes, entity sizes, and heat transfer rates, any one of which might be upgraded to produce better agreement. Note that the downcomer volume at the time of N_2 injection is approximately correct, however (underpredicted slightly).

It is therefore a combination of both the Wilson slip correlation and non-equilibrium condensation model which leads to significant improvement in the overall agreement of RELAP4 calculations of test L1-4. Other model refinements can be identified which might lead to other secondary improvements. Rather than simply fine-tuning the models, additional comparisons with separate effects data, particularly condensation experiments, are needed first.

8 RECOMMENDATIONS

8.1 Introduction

In order to implement various licensing assumptions and due to numerical difficulties which arose when modeling injection of subcooled ECC, calculations of PWRs (or LOFT experiments) were often discontinuous using the RELAP4 code. That is, the calculations were halted, various assumptions employed to help the calculations over difficult periods, and then they were restarted. It has been demonstrated in various INEL reports and by Creare [13] that best-estimate (BE) calculations of blowdown and refill can be performed continuously with RELAP4/MOD7. Numerical problems related to ECC injection have been mitigated in RELAP4/MOD7. Given the improved understanding of refill effects demonstrated here, it is possible to develop a new "evaluation model" (EM) based on RELAP4 or similar 1D, HEM codes. which may also be run continuously from blowdown through refill. Plainly, advanced two-fluid non-equilibrium codes such as RELAP5 or TRAC possess similar capabilities and individual applicants must choose which code they prefer to use.

The two major elements of the Appendix K rules [28] for the modeling of ECC bypass are

- fluid injected prior to "end of ECC bypass" must be subtracted from the vessel liquid inventory, and
- the criterion for "end of bypass" must be identified and justified by a suitable combination of experimental data and analysis.

Within the structure of these rules, an accepted procedure for calculating refill in an EM code has been implemented [29]. This analysis involves keeping track of and subtracting ECC fluid injected before "end of bypass", discounting fluid which has filled the downcomer in excess of one-third full, and involving several time delays before refill is completed (time to fill the cold legs one-half full, a free fall time, a hot wall delay time, and time to fill the lower plenum). The end of bypass occurs "when the net flow through the downcomer is into the lower plenum". This implementation therefore involves sequentially inserting these various separate calculations into calculations of the refill process. In BE codes the processes being modeled may in fact overlap to some extent. Thus, the sequential implementation of models for these effects is very conservative.

The BE calculations presented in this report provide some of the tools to develop a continuous EM calculation based on RELAP4 which is still conservative but less ad hoc than the present sequential approach. This "evaluation model" could be justified by comparisons with experimental data like those shown in this report. This EM approach could be developed within the structure of the existing rules, just as the present EM code was, and at the same time it would be more in keeping with the spirit of the rules as well as relaxing unnecessary conservatisms.

In the following paragraphs we first describe some initial modeling concepts, suggested by the previous work with best-estimate models , that might be incorporated into an EM calculation. Then, general recommendations for a course of further work to develop and justify an EM code are made.

8.2 Initial Concepts for Development of Continuous EM Calculation

As a result of the BE calculations discussed in the previous sections of this report, a few specific modeling concepts were developed which might be part of an EM calculation. These concepts are initial ideas for the purpose of illustration and not the final answer. They have not been implemented in any calculations at this time. The individual concepts are quite easy to implement, but the development of a consistent, specific set of concepts needs structured development as outlined in Section 8.3.

Some of our initial model concepts are listed in Table 5 as examples. For each phenomenon in column 1, an associated parameter is identified in column 2, the direction of its effect in the models given in column 3, and its purpose relative to the models used in our BE calculations is listed in column 4. With these sorts of physical models in mind, consider the overall strategy recommended in Section 8.3 below.

TABLE 5

EXAMPLES OF PRELIMINARY MODEL CONCEPTS FOR EM CALCULATIONS

Phenomenon	Parameter(s)	Effect in Calculations	Purpose in EM Calculations
Phase Separation	Slip Velocity in Volumes (Relative Velocity Between Gas and Liquid Phases)	As slip velocity is increased, more liquid mass remains in the lower plenum	Remaining liquid mass in plenum flashes and swells, causing longer ECC bypass period relative to BE calculations.
Condensation	Rate of Heat Transfer In Condensation	As the rate of condensation is decreased (perhaps to zero), steam voids exist in volumes.	Liquid inventory in downcomer or cold legs may be reduced over BE calculations which tend to fill downcomer and cold legs. This may simulate "1/3 full downcomer" or "1/2 full cold legs" in present EM approach.
Wall Heat Transfer	Heat Transfer Coefficient or Boiling Regime	During ECC bypass and refill, heat is removed from downcomer walls at a rate limited by conduction in the wall. (During blowdown, little stored heat is removed from downcomer walls.)	During ECC bypass current BE calculations show heat transfer coefficients only a fraction of values implied by conduction - limited heat transfer. The effect of "hot walls" would be simulated by imposing conduction-limited heat transfer. This would cause extended ECC bypass and downcomer voiding, delaying refill relative to BE calculations. (The effect of wall heat transfer could be made more conservative by assuming zero wall heat transfer during blowdown for higher wall temperatures at the start of bypass.) The sequential "hot wall delay" in current EM calculations would be replaced.
Downcomer Momentum Effects	Vertical Slip Velocity or Void Fraction in Vertical Slip	As a vertical slip velocity (or the void fraction used in determining the vertical slip velocity) is decreased, the start of refill is delayed.	A time to refill which is conservative relative to BE calculations of small scale data would result.

8.3 Recommendations for EM Code Development

Assuming that an applicant decides to upgrade EM code methods to a continuous calculation methodology, a specific strategy is recommended here. We suggest that EM code justification should be based on two elements; namely, demonstration of

1) conservatism relative to available scale model data (e.g., Creare, LOFT), and

2) a conservative methodology for extrapolation to full scale.

This strategy will in turn justify the approach selected for the EM code.

In order to produce a continuous EM calculation from a continuous BE calculation (ours or any other), further work is suggested in several steps

- Develop physically motivated evaluation model concepts.

- Challenge the model concepts by comparison with experimental data.

- Develop a conservative scaling methodology.

- Demonstrate the scaling methods by comparison with data from different scales and confirmed basic physical principles.

- Apply the model to PWRs.

The following paragraphs clarify the above suggestions.

On development of a consistent EM calculation, Table 5 illustrates our suggested approach which would be to adjust existing parameters in demonstrated BE calculations. Qualitatively, we suggest as a criterion that the EM calculations should be a close lower bound to the available LOFT and Creare 1/5-scale data. Based on the present results, it should be easy to specify timing and inventory distribution criteria for such a comparison. Implementing individual model concepts is straightforward although some thought must be given to interactions among model elements.

On scaling, the usual strategy is to identify credible alternative approaches and justify a choice among them by comparison with data from facilities of different sizes. For the transition from end of blowdown through the refill period there are existing Creare data ranging from 1/30 to 1/5 of PWR vessel diameter as well as LOFT and forthcoming CCTF integral data at 1/5-scale diameter. The most conservative scaling methodology that is consistent with the data would be used in the EM code.

This suggested course of activity is expected to yield an EM code for continuous calculations used in licensing PWRs. The EM code will be conservative, but less conservative than current licensing approaches. It will be justified by comparisons with extensive Creare and LOFT data at 1/5-scale and scaling requirements for full-scale application will be understood.

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This report summarizes the results of an experimental and analytical program which has modeled blowdown and refill in scale model PWRs in a more realistic and continuous manner than previous separate effects experiments in the Creare program. These experiments are intended to complement and contribute to a fuller understanding of integral experiments such as LOFT. Experiments have been performed at 1/30, 1/15, and 1/5-scale vessel sizes. The latter is approximately LOFT scale. An independent analysis was developed to explore various modeling options for the phenomena observed in the experiments and to identify the most important phenomena to model. Bounding and sensitivity calculations were also performed. Finally, a RELAP4 code (MOD7) was used to demonstrate that best-estimate calculations can be performed continuously through refill and to calculate refill behavior.

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