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TECHNICAL SUMMARY ATTACHMENT TO ECC BYPASS RIL
VOLUME I: REVIEW OF FINDINGS

TOPICAL REPORT

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TECHNICAL SUMMARY ATTACHMENT TO ECC BYPASS RIL VOLUME I: REVIEW OF FINDINGS

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ABSTRACT

This Topical Report is a contractor attachment to the Research Information Letter (RIL) entitled "Small Scale ECC Bypass Research Results". The RIL, and this report, deal with countercurrent flow and superheated wall behavior in PWR downcomers. The topics of lower plenum voiding, flashing, and refill are deferred to later documents. In this report we:

1) review the purposes of our work,

2) summarize the work performed by Creare,

3) identify significant findings in all available work,

4) discuss the applicability of the findings to licensing,

5) recommend further research.

A companion volume of technical appendices to this report addresses three topics:

1) sensitivity calculations at PWR scale,

2) assessment of countercurrent flow data,

3) comparisons of calculations with LOFT data.

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EXECUTIVE SUMMARY

Extensive analytical and experimental studies have been performed at Creare to identify and assess phenomena that may occur while attempting to refill a pressurized water reactor (PWR) vessel following a loss of coolant accident. The major purposes of the separate-effects studies at small scale are to:

1) identify phenomena,
2) establish a data base for testing computer codes,
3) develop simple, semi-empirical analyses to aid model-development and licensing evaluations, and
4) propose scaling hypotheses and calculation methods.

This report summarizes Creare's efforts and also reflects related findings of NRC staff and other investigators.

Downcomer flow behavior has been addressed mainly by tests in models of vessels ranging from 1/30 to 2/15 of PWR scale. An analysis method has also been developed by Creare to calculate plenum filling by accounting for countercurrent flow and superheated wall effects during prescribed transients of steam flow and pressure in the vessel. This method has been assessed by comparison with the small-scale experiments and LOFT; and it has been applied to predict behavior at PWR scale and to display the sensitivity to alternate modeling assumptions.

In our transient calculation method, the wall-generated steam flow is limited at the flow just necessary to sustain complete bypass. In contrast, the sequential calculation recommended in 10CFR50 Appendix K, based on then existing methods, uses up steam too rapidly in the blowdown period. (Blowdown proceeds to end of bypass and is followed by a separately calculated "steady state" hot wall delay.) Thus, the Creare transient calculation of superheated wall effects during refill is more accurate than the sequential calculation and tends to be more conservative over the range of possible transients and modeling assumptions.

The basic scaling of countercurrent flow in the downcomer remains fundamentally at issue because the available data are from vessels that are too similar in size and too small relative to reactors. Basic uncertainties about two-phase flow regimes, the potential for beneficial "channelling" of steam and water flow at large scale, and incomplete knowledge of rapid condensation make extrapolation to PWR scale difficult. All evidence at 1/30 and 1/15 scale consistently points to J* scaling of saturated water "flooding" (momentum exchange) at all pressures and injection rates tested. Questions arise at scales larger than 1/15 as the effects of ECC subcooling are considered. Some empirical evidence or analysis approaches support J* scaling up to 2/15 scale while other approaches indicate divergence to more conservative K* scaling of flooding for scales larger than 1/15. The benefit of ECC subcooling in reducing ECC bypass has been characterized by a factor f which may range from zero to unity. S[illegible] evidence indicates $f \approx 0.2$ independent of scale while a statistical analysis performed at NRC indicates that f increases from

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f=0.16 at 1/15 scale to 0.33 at 2/15 scale. A scaling approach that is conservative relative to the data trend at small scale is to combine K* scaling with a constant value f=0.2; letting f=0 is an even more conservative approach that may be warranted in view of the large extrapolation from small-scale models to full scale.

The start of plenum refill during LOFT L1-4 is calculated within a second by our analysis using J* scaling and f=0.2. The EM model proposed in the RIL (K*=3.2 scaling with f=0.3) is conservative with respect to the start of refill in L1-4 by 5 seconds.

Initial demonstration calculations for selected blowdown transients at PWR scale have been performed. They reveal that superheated wall delays are negligible if J* scaling of flooding is used but become significant if K* scaling of flooding is used. Except at the extreme value f=1.0, the calculated delays are relatively insensitive to the subcooling factor f under all conditions for the particular blowdown transients input to the model. However, the interaction between condensation and ECC bypass may significantly lengthen the blowdown transient and thus may lead to longer delays in PWR refill.

Cold leg steam-water mixing and condensing behavior has been addressed in isolated-component analyses and in extensive experiments ranging from 1/30 to 1/3 of PWR scale. Methods to predict two-phase flow regimes and oscillatory fluid-thermal interactions between momentum exchange and condensation heat transfer have been developed. Calculations have shown that these flow oscillations amplify resistances in the intact loops, such as the primary coolant pump. The developed methods also permit identification of circumstances, involving the dispersed flow regime or noncondensibles, when dramatically reduced condensation may occur. These two effects should be factored into evaluation models.

Studies of lower plenum voiding, flashing, and refill are in progress at Creare and are therefore not major topics of this report on work completed through FY78. Of interest are the generation of steam in the lower plenum and introduction of low quality fluid in the downcomer during ECC bypass and subsequent refill and also the voiding of ECC after it has been delivered to the lower plenum. To date, the voiding flow regimes have been established during steady-state and transient tests with both water and two-phase mixtures as the lower plenum fluid. Since two-phase mixtures void much more rapidly than water alone, they are receiving emphasis in our studies. At the same time, systematic studies of flashing depressurization and level swell are underway. Improved understanding of these several phenomena, identified in the Semiscale and LOFT integral tests, is a major objective of our planned efforts for FY79 and FY80.

Ultimately, methods are needed to perform transient calculations continuously, throughout the course of the event, for various hypothesized accidents. These calculations must consider the integrated behavior of the blowdown flows in the vessel and their interaction with the coolant system. Advanced codes are being developed and assessed for this purpose under other programs. Our contribution to this effort is the acquisition and analysis of data from tests where elements of the relatively simple scale-model system at Creare are coupled in various ways. For example, in a postulated LOCA, the steam flow rate up the downcomer annulus depends on condensation rate (on the cold ECC) there and in the cold legs. As more ECC (or more subcooled ECC) is injected, a greater countercurrent steam flow is induced and thus the length of time bypass can be sustained may be changed. Similarly, introduction of cold ECC during a flashing transient causes more rapid depressurization of the system and a more rapid boiling of the lower plenum fluid. Experimental and analytical work on these and other coupled transients during ECC injection are underway.

The most pressing research needs on ECC bypass are for development and assessment of analytical approaches that properly calculate the effects of condensation, boiling and entrainment on transient, system fluid flows through the refill (ECC-injection) period. Separate effects experiments are also needed to assess these approaches. An additional major need is for a few countercurrent flow experiments at significantly larger scale. These needs are being addressed by the advanced code, separate effects, and 3D programs.

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1 PURPOSES OF SMALL SCALE STUDIES

Purposes stated in NRC Buff Books for the Creare Refill Effects Program are:

1) Develop phenomena-based, semi-empirical models for best-estimate prediction of transient plenum refill rates and phenomena affecting system behavior during the ECC injection phase.

2) Provide information to code developers to assist code development and assessment.

3) Develop scaling hypotheses relating to transient plenum refill phenomena to assist code development and PWR evaluation.

4) Provide technical assistance as required to support WRSR's steam-water mixing and ECC bypass program and planning activities.

5) Extend and demonstrate at small scale an instrumentation system developed by Creare to map steam/water topographies under simulated transient LOCA conditions in experiments such as 3D.

Unique features of the small scale studies are their emphasis on identification and assessment of physical phenomena and their rapid iteration of controlled experiments, instrumentation development, and analysis to derive predictive tools. The small-scale studies serve a variety of needs. For the designer of a test program in a large scale facility we:

1) identify phenomena to be anticipated in testing,

2) establish appropriate test procedures and develop necessary instrumentation.

3) identify facility design constraints,

4) develop scaling hypotheses and simple analytical tools to permit rapid, easy estimates of the large scale test results,

5) perform a large number of tests over broad ranges of all major test parameters, rapidly and at low cost, to reduce the number of tests needed at large scale,

6) identify key issues to be resolved by tests at large scale.

For the developer of an advanced numerical code for the prediction of reactor loss of coolant accidents, we:

1) identify phenomena to be analyzed,

2) provide a large base of small-scale data for comparison with analysis,

3) calculate and predict our own data to assure the utility of the data base as a test of an analysis,

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4) iterate calculations and experiments until an adequate basic understanding of small-scale behavior as been achieved,

5) develop simple analysis tools and closed-form equations where possible to permit rapid, inexpensive calculations to assist advanced code development,

6) perform extensive sensitivity comparisons with the small-scale data to assist advanced code assessment.

For NRC staff responsible for reactor licensing, we:

1) identify phenomena and system effects that may need to be considered in the licensing process,

2) establish a base of small scale data for testing LOCA code calculations,

3) develop simple, easy to use, predictive tools for comparison with LOCA code calculations,

4) quantify uncertainties in physical modeling and display their impact on PWR LOCA analysis,

5) propose scaling hypotheses and best-estimate calculations methods,

6) identify research that may be needed to assist reactor licensing.

In this report we emphasize licensing needs and address the needs of large scale tests or advanced code development only where it is germane to licensing.

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2 OVERVIEW OF CREARE RESEARCH ON ECC BYPASS

Guided by integral tests in the Semiscale and LOFT facilities, LOCA code calculations, and our own separate effects testing, Creare has experimentally and analytically assessed refill of a 1/15-scale model reactor vessel and has identified and studied a number of separate effects:

1) cold leg ECC flow regimes, flow oscillations, and pressure drop,
2) downcomer countercurrent flow and condensation,
3) downcomer and lower plenum superheated wall effects,
4) ramped transient steam supply and vessel pressure,
5) condensation-induced transients (coupling the downcomer behavior with the steam supply),
6) lower plenum voiding,
7) lower plenum flashing transients (coupling lower plenum, downcomer and break behavior),
8) downcomer and core level swell, and
9) integral vessel and loop steam flows.

In the course of this work, basic information has emerged on a number of underlying phenomena:

1) countercurrent flow,
2) condensation,
3) boiling,
4) two-phase entrainment,
5) flashing,
6) transient and oscillatory flow,
7) waterhammer and structural interactions.

Creare has also invented and applied instrumentation for level measurement (sequentially coupled conductivity probes) and two-phase distributions and velocities (topography grid of conductivity probes) using unique sensors of our own design as well as commercially available sensors.

To date over 40 technical reports and publications have resulted from this work. Recognizing the difficulty in easily digesting all of this material and the tendency for earlier reports to become obsolete as additional knowledge is gained, we geared our FY78 efforts and reports to completing certain key areas of work and summarizing the results. This approach was designed specifically to coordinate with preparation of the RIL. Thus, at this time we can identify seven specific documents (Table 1) which summarize all previous work by Creare and also review relevant information by other groups. Each document is discussed briefly below.

TABLE 1

KEY DOCUMENTS ON CREARE ECC BYPASS RESEARCH

Reference	Date	Title
1) TN-291 (NUREG/CR-0600)	January 1979	Summary of FY78 Progress on Creare Refill Effects Program
2) ASME Special Publication G00127	November 1977	Thermal and Hydraulic Aspects of Nuclear Reactor Safety
3) TN-272 (NUREG/CR-0048)	March 1978	Progress on ECC Bypass Scaling
4) TN-282 (NUREG/CR-0464)	October 1978	Scaling of Pressure and Subcooling for Countercurrent Flow
5) TN-287 (NUREG/CR-0599)	March 1979	Analysis of Superheated Wall Effects During Refill at Small Scale
6) TN-252 (NUREG-0291)	February 1977	Downcomer Effects in A 1/15-Scale PWR Geometry - Experimental Data Report
7) Letter to A. W. Serkiz	March 1978	Review of Creare Reports

Reference 1 is a review of our status at the end of FY78 and our plans for FY79. Briefly, we have brought our studies of cold leg flows, downcomer countercurrent flow, superheated wall effects, and ramped transients to acceptable levels of understanding of small scale behavior. We at Creare are not presently working on these areas except to assist RIL preparation or to assist other efforts. Studies of condensation-induced transients, voiding, flashing transients, and level swell are at a much earlier stage of work and are being emphasized in our FY79 program.

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Reference 2 is a collection of technical papers dealing broadly with nuclear reactor safety. Two of these papers, by Creare authors, are specifically germane to this RIL. Block provides a historical perspective and overview of the refill period of a loss of coolant accident and Rothe describes studies of cold leg flow.

References 3 and 4 summarize available studies of countercurrent flow behavior including our own research. Reference 3 deals with countercurrent flow "flooding" and is restricted to data and analyses for saturated water and steam (or water and air). Reference 4 builds on Reference 3 by treating the additional effects of ECC subcooling on flooding.

Reference 5 reports extensive research on the effects of superheated walls on the initial refill process. (This report is summarized in a recent technical paper [8].)

Reference 6 reports most of the Creare 1/15-scale data although additional countercurrent flow and superheated wall tests are reported in References 3, 4, and 5. Table 2 displays the main test parameters.

TABLE 2

PARAMETERS OF CREARE REFILL EFFECTS TESTS

Geometric Parameters	
Number of Vessels	8
Downcomer Gap	0.25 to 2.0 inches
Downcomer Length	6 to 36 inches
Cold Leg Diameter	0.5 to 2 inches
Break Diameter	0.1 to 3 inches
Vessel Diameters	4 to 18 inches (1/45 to 1/10 scale)
Thermodynamic Parameters	
Vessel Pressure	15 to 120 psia
Vessel Wall Temperature	210 to 550°F
ECC Temperature	60 to 300°F
ECC Subcooling	0 to 220°F
ECC Injection Rate	0 to 180 gpm (J^*_{fin}=0.35)
Core Steam Flow	up to 3 lbm/sec (J^*_{gc}=1.7)
Test Modes	
Countercurrent Flow	Superheated Walls
Core Steam Only	No Steam
Core plus Cold Leg Steam	Core Steam
Coupled Loop Steam	Ramped Steam
Ramped Core Steam	Lower Plenum Voiding
Ramped Steam/Pressure	No ECC
	Cold Leg ECC
Condensation Transients	Lower Plenum ECC
Break Controlled	
Containment Controlled	

Finally, Reference 7 is an annotated review of all Creare reports to that date. Reference 1 contains an updated bibliography of Creare reports.

This report also includes three technical appendices. The first reports model sensitivity calculations at PWR scale. The second reviews the data available for assessing countercurrent flow models. The third provides comparisons of calculations with LOFT L1-4.

Each of these documents is self-complete and covers a specific review, or technical area in detail. The remainder of this report summarizes the significant findings of this work and relies on these documents as base references.

3 SUMMARY OF SIGNIFICANT FINDINGS ON REFILL

3.1 Downcomer

An important aspect of PWR refill, which is also relevant to certain phases of ECC injection in BWRs, is the countercurrent flow in the downcomer of the reverse core steam flow and the ECC liquid injected through the cold legs. This countercurrent steam flow tends to hold up the ECC liquid in the downcomer and may bypass it out the break. Due to the number and complexity of the phenomena occurring in the downcomer and their interaction with effects in adjacent components such as the lower plenum and the break, specific effects have been isolated for independent study:

1) condensation

- saturated ECC (no condensation)
- subcooled ECC

2) steam-flow mode

- controlled steady
- controlled transient
- condensation-induced transient
- cold leg steam

3) wall heat transfer

- saturated walls
- superheated downcomer walls
- superheated plenum walls

Table 3 summarizes the main scale-model downcomer tests performed by Creare and Battelle according to the type of test. Additional countercurrent flow tests have been performed in flow visualization facilities at Creare and Battelle and in 1/30, 1/10, and 2/15 scale models at Dartmouth.

TABLE 3

SUMMARY OF DOWNCOMER MODEL TESTS PERFORMED

(Number of Each Type Performed)

	Creare		Battelle	
	1/30	1/15	1/15	2/15
1. TRANSIENT TESTS				
a) Hot Wall Ramped Transients	0	100	0	30
b) Countercurrent Flow Ramped Transients	0	170	0	40
c) Condensation Induced Transients	0	30	0	0
2. STEADY CORE STEAM				
a) Hot Wall Tests	0	250	0	50
b) Countercurrent Flow Delivery Curves	20	50	70	60
c) Tests With Cold Leg Steam	0	40	310	240

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3.1.1 Countercurrent Flow Without Condensation or Superheated Walls

Almost two decades of research on countercurrent flow are outlined in References [3] and [4]. Despite numerous attempts by various authors, reliable methods of analysis have not yet been developed to predict even the simplest situation of steady countercurrent flows of air and water in an unheated tube, due to the multiplicity of possible flow regimes. The relatively recent efforts of the small-scale studies in PWR models at Dartmouth, Creare and Battelle have been directed to developing semi-empirical models blending data correlations with analysis. Considerable attention has been given to the countercurrent flow situation with steady flows, saturated water and without superheated walls. A large base of data has been established at 1/15 scale and more limited data have been obtained at 2/15 scale. Correlations have been developed to describe available data. Emphasis is placed here on correlation of flow and pressure parameters and physical size (scaling) because geometric details (such as number of loops, annulus length and cold leg arrangement) have not had significant effects.

For countercurrent flow of steam and saturated water a clear, relatively simple picture has emerged for facilities up to 1/15 of PWR scale. Figure 1 compares Creare saturated water data at 1/30 and 1/15 scales on the J* coordinates described in Reference [3]. Excellent overlay of the data is seen. Previous tests in different 1/30-scale and 1/15-scale vessels provide independent confirmation of these tests. These data have been correlated by the equation:

$$J_{gc}^{*\,1/2} + mJ_{fd}^{*\,1/2} = C \qquad (1)$$

with: $C = 0.40$
$m = 0.8$

Equation (1) describes the portion of the curve near complete bypass ($J_{fd}^{*}<0.05$). At large values of ECC delivery rate J_{fd}^{*}, the data approach the limiting lines $J_{gc}^{*}=0.04$ and $J_{fd}^{*}=J_{fin}^{*}$ shown on the figure. Figure 1 shows that saturated water data are independent of ECC injection rate J_{fin}^{*}. Similarly, Figure 2 shows that the effect of pressure is properly accounted in the J* parameters at least up to 65 psia.

References [3] and [4] show that these data are consistent with:

1) Dartmouth 1/30-scale air-water data,

2) INEL/Semiscale air-water data, and

3) Dartmouth air-water data from a 1/10-scale annulus.

In addition, recent Battelle 1/15-scale air-water data [9] obtained in the plenum filling mode agree closely with the Creare 1/15-scale saturated water data of Figure 1. Thus, all available evidence supports J* scaling of saturated water up to 1/15 of PWR scale.

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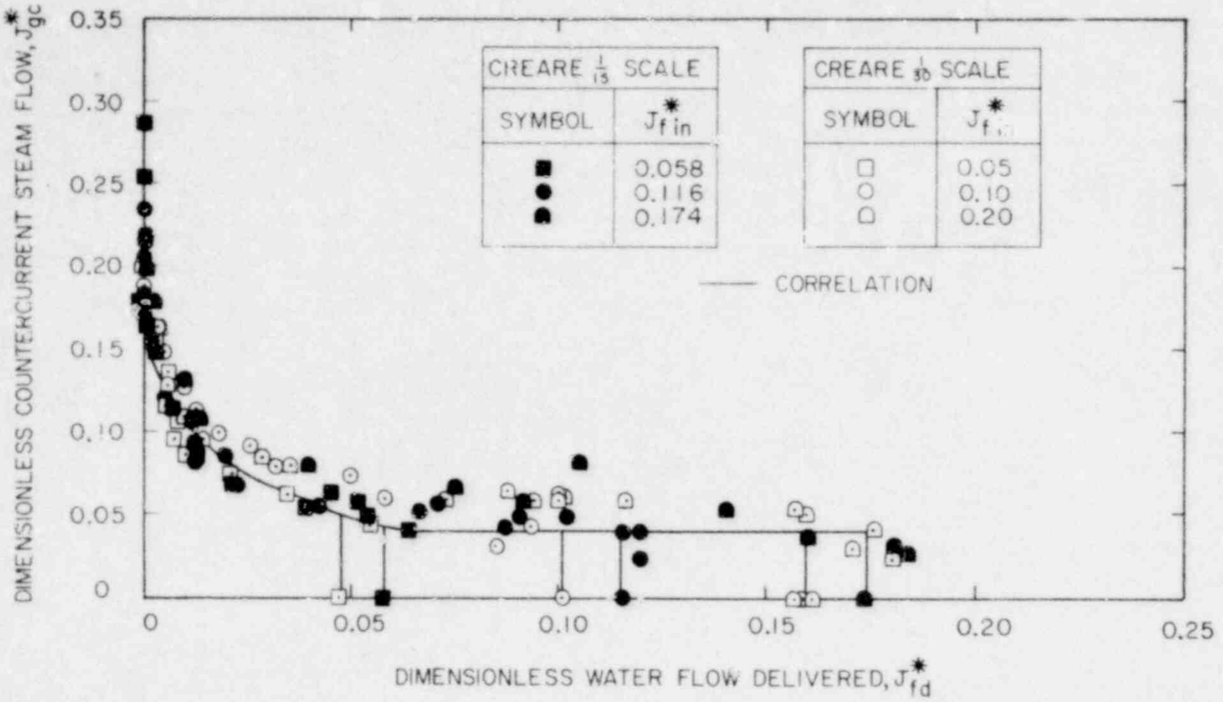

Figure 1. SATURATED WATER COUNTERCURRENT FLOW DATA AT 1/30 AND 1/15 SCALES

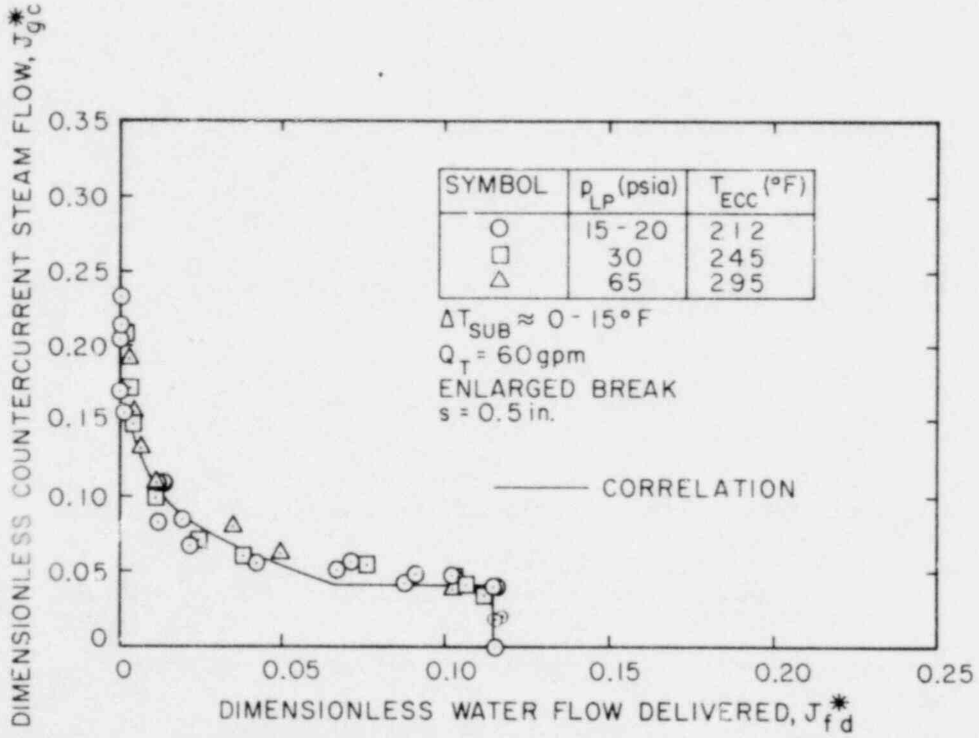

Figure 2. SATURATED WATER COUNTERCURRENT FLOW DATA AT 1/15 SCALE FOR VARIOUS PRESSURES [CREARE REFERENCE 4]

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At scales larger than 1/15, the situation is not as clear. Battelle 2/15-scale, air-water data are significantly below all other data and support $K^*=3.2$ scaling. Beckner et. al. [10] present statistical analyses of 2/15-scale air-water and steam-water data, using a new correlation form, and support K^* scaling. However, they point out that this conclusion is based primarily on the Battelle 2/15-scale air-water data. Battelle 2/15-scale steam-water data at low subcooling contain enough scatter and variation of subcooling that they are consistent with both J^* scaling [4], and also with the analysis of Beckner et. al. Comparison of Dartmouth air-water data in 1/10-scale and 2/15-scale annulli supports J^* scaling and the 2/15-scale Dartmouth data are clearly inconsistent with $K^*=3.2$ at complete bypass [11].

Based on present results it is our best estimate that the J^* scaling approach will ultimately correlate all saturated water data in the range 1/30 to 2/15 scale. There are some indications that the constant velocity criterion $K^*=3.2$ may be more appropriate at larger scales, perhaps even at 2/15 scale, and Battelle has suggested an alternate correlation method that relies on an I^* parameter to blend these limits. However, regardless of the correlation developed for small scale data, the major licensing uncertainty is the application of any correlation at PWR scale. The available test facilities are simply too similar in size and too small by comparison with PWRs for their data to be extrapolated reliably to PWR scale. Thus, a few critical tests are needed in a facility much closer to PWR size, although these tests need not be performed over the entire pressure range experienced by PWRs during ECC injection. In the interim, there are good reasons to continue to use the relatively conservative $K^*=3.2$ scaling criterion for flooding.

3.1.2 Countercurrent Flow With Condensation

Unlike the situation for saturated water, a number of thermodynamic parameters impact condensation and its effects on countercurrent flow processes. A correlation technique has been devised [4] which in effect accounts for condensation by reducing the reverse core steam flow J^*_{gc} to an "equivalent" flow J^*_g that is "effective" in bypassing the water:

$$J^*_g = J^*_{gc} - f\lambda J^*_{fin} \tag{2}$$

where the coefficient λ is simply a combination of fluid properties:

$$\lambda = \frac{c_p(T_s - T_{ECC})}{h_{fg}} \sqrt{\frac{\rho_f}{\rho_g}} \tag{3}$$

This relation amounts to an energy balance on the system where the empirical factor f may range from zero to unity. The latter extreme would correspond to the idealized situation of thermodynamic equilibrium by condensation only in the lower plenum. Thus, the factor f accounts for <u>both</u> deviation from thermodynamic equilibrium (incomplete mixing and condensation) and also distribution of condensation through the downcomer (rather than only in the lower plenum. In fact, f is found empirically to be approximately 0.2 rather than 1.0.

We refer to these processes with fixed steam supplies as "subcooled flooding" to distinguish them from tests with condensation induced transients of steam flow.

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A unique set of data has been obtained in 1/15-scale tests at Creare where the subcooling has been varied from zero to about 200°F for each of several pressures in the range 15 to 65 psia. While these data are consistent with those from previous tests, they considerably extend the range of pressure and subcooling studied and have been carefully controlled to extend to and beyond complete bypass in each instance. These data have been correlated [4] with the results:

1) C=0.40, a constant,

2) f=0.16, a constant,

3) the most reliable data, namely at complete bypass, have been analyzed independently of partial delivery data,

4) the partial delivery range is represented in terms of a single dimensionless parameter, the product λJ^*_{fin} or the related parameter R_{Tb} (i.e., not dimensional parameters like subcooling, pressure, and injection rate independently as in early schemes).

Since this approach was developed very recently, it should be further assessed and refined by comparison with available data from a number of facilities.

Appendix B of this report is a self-complete review and preliminary assessment of all data available for developing and testing correlations. Its purpose here is to assist the reader in assessing the data base.

Beckner et. al. [10] have performed statistical analyses of all available data over the range 1/30 to 2/15 of PWR scale. This is the most current and comprehensive analysis of countercurrent flow data that has been performed. A number of functional forms have been examined, including those used by Creare, and alternate statistical approaches have been employed. Beckner et. al. have identified a trend in the factor f which increases from about 0.16 to 0.33 as scale is increased from 1/15 to 2/15 (based on the available BCL 2/15 scale data). They note, however, that the scaling of condensation is relatively less certain than the scaling of flooding.

Figure 3 is a set of plots representing all Battelle countercurrent flow data in the ECC flow ranges indicated. Each data point represents the midpoint of a penetration curve determined by simple interpolation of neighboring points on the curve. These midpoints are then plotted as functions of the condensation potential λJ^*_{fin} to correspond with the plots of Beckner et. al. [10]. Figure 3 shows that the data at the two scales overlay within the data scatter. Thus, in fitting these data within their uncertainty it is unnecessary to invoke a condensation coefficient that increases with scale. However, the results of Beckner et. al. indicate that the fit to the data may be improved somewhat and a "best fit" obtained, if such a coefficient trend is chosen.

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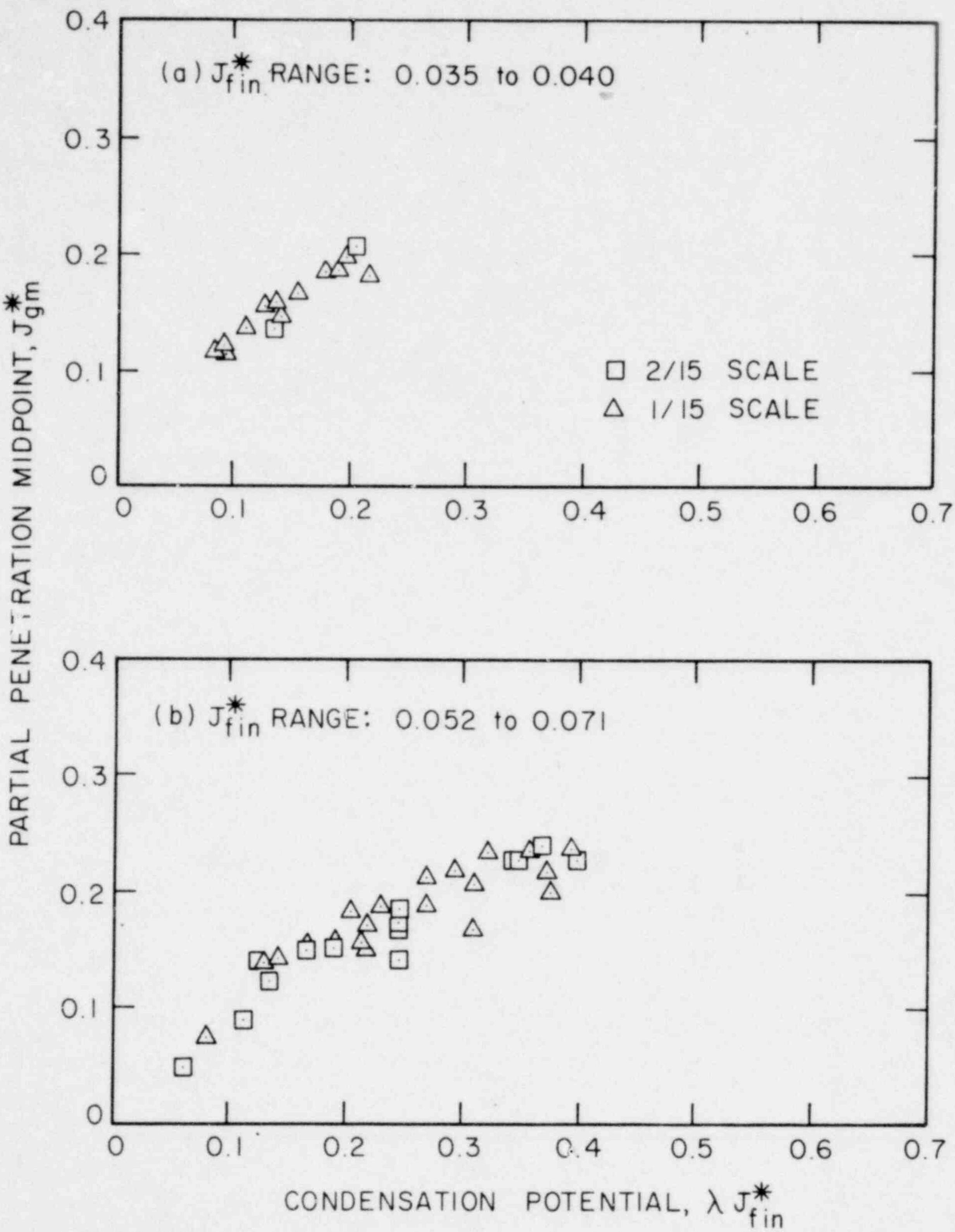

Figure 3. BATTELLE ECC BYPASS DATA AT TWO SCALES (continued)

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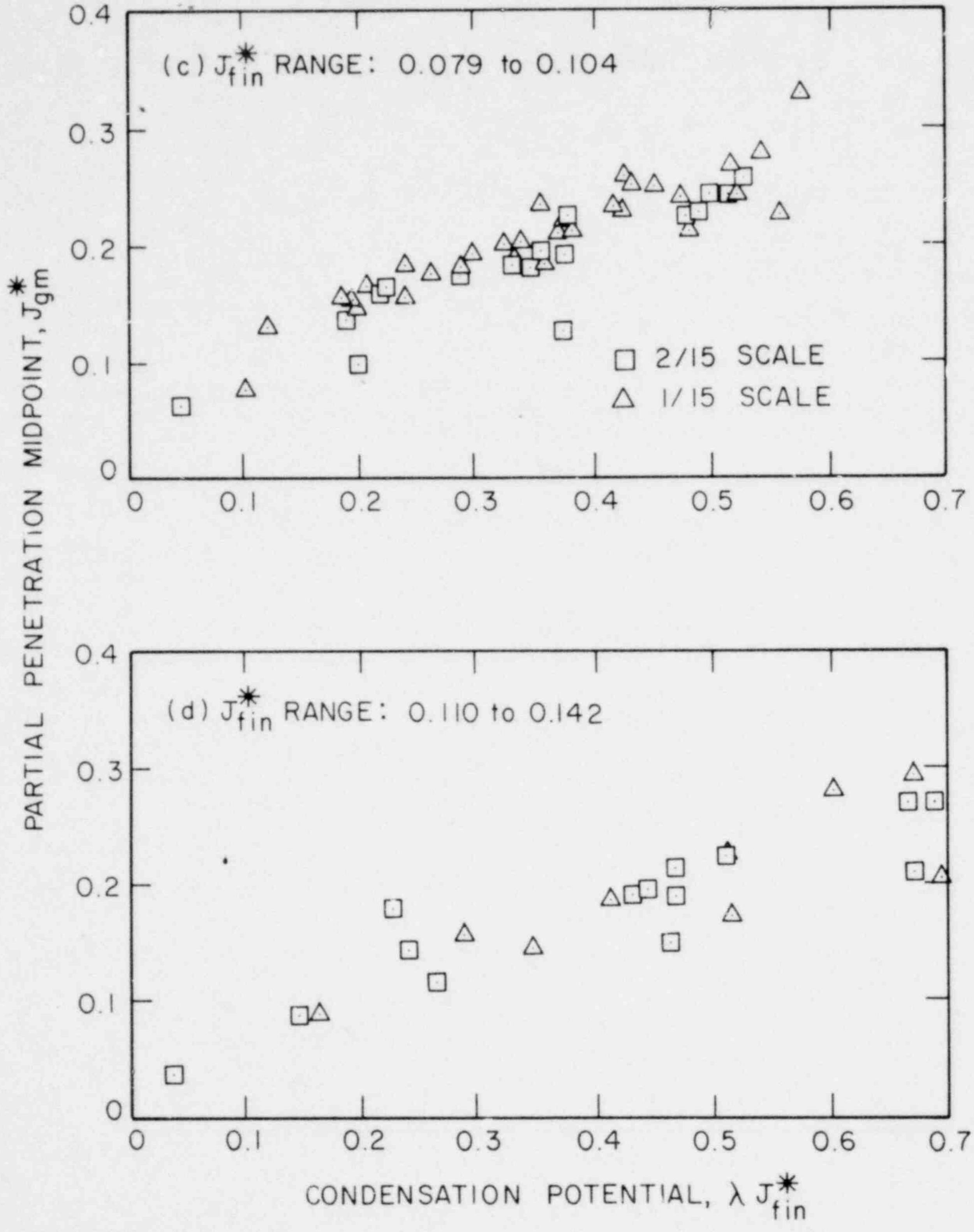

Figure 3. BATTELLE ECC BYPASS DATA AT TWO SCALES (concluded)

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Since the scale model downcomers are very small compared with PWRs and since the basic scaling laws for condensation are ill-resolved [12] a conservative modeling approach is warranted until experiments are performed at significantly larger scale. If $K^*=3.2$ scaling of flooding is assumed, the constant value $f=0.2$ is conservative relative to the trend of small scale data. The more conservative assumption $f=0$ may be necessary in view of the large extrapolation from small scale to full scale.

3.1.3 Countercurrent Flow With Steam Flow Transients

Scale model countercurrent flow tests have been performed with controlled ramps of steam flow and vessel pressure and also with so-called condensation-induced transients of steam flow. The ramped transients have been conducted at Creare using a 1/15-scale vessel and Battelle using a 2/15-scale vessel; the condensation-induced transients have been conducted at Creare.

The ramped transient experiments have demonstrated that a quasi-steady analysis can accurately predict refill during steam flow transients. Crudely, the countercurrent flow correlations map the transition between complete bypass and complete delivery. During a transient calculation, the main need is ability to predict the steam flow at which delivery begins. The more detailed information contained in the delivery curves (e.g., Figure 1) is also of value, but is secondary to prediction of the end of complete bypass. Allowance is easily made for storage of liquid in the downcomer volume.

The details of plenum filling, particularly slug delivery, are an artifact of the scale model experiments. Slug delivery occurs mainly in experiments with steady steam flow from a choked steam supply system. Repeated slug delivery has not been observed with transient steam flows or compliant steam supplies more like the situation in reactors. Slug delivery has also been mitigated when superheated walls are present although an initial storage period (hot wall delay) and subsequent single dump is usually observed. Special experiments performed for EPRI with a very stiff steam supply dramatically accentuated the slug delivery behavior. At the other extreme, the slug delivery behavior was eliminated altogether when a very compliant steam supply was used. Direct comparison of plenum filling under identical conditions except for steam supply demonstrated the existence of a "universal" flooding curve independent of the steam supply compliance or the presence or absence of slug delivery. Thus slug delivery need not be analyzed to assess PWR refill.

Our main concern for prediction of the effects of condensation lies in prediction of the steam flow transient in reactors. Condensation-induced transient experiments have indicated that ECC injection may interact with the steam supply and break in such a way as to maximize the bypass effect. Specifically, condensation on the ECC has been demonstrated to induce a steam flow sufficient for bypass; in effect, the ECC blows itself out the break as was observed compellingly in Semiscale S-01-1B (hot-leg break). Conversely, large two-phase pressure drops across the break, which occur during ECC bypass, tend to restrict the blowdown. Thus, the system tends to converge at a steam expulsion rate just sufficient to sustain ECC bypass for long periods.

Present best-estimate calculation procedures such as RELAP4 isolate the blowdown calculation from the bypass period and have difficulties in modeling condensation. Specifically, in assuming thermodynamic equilibrium, RELAP4 significantly overpredicts the benefits of condensation in removing steam from the system, particularly if condensation is suppressed by non-condensible gases. Advanced codes are being developed to better model condensation effects and small-scale tests are being performed to help assess these codes. However, it must be recognized that application of the present findings depends on calculated steam flow transients that may not properly reflect the effects of condensation. The sensitivity calculations in Appendix A reveal that condensation-induced transients and their interactions with ECC bypass can extend the blowdown transient and bypass period dramatically.

3.1.4 Countercurrent Flow With Superheated Walls

The effect of superheated walls on countercurrent flow has been assessed by extensive tests at 1/15 scale and more recently by initial tests at 2/15 scale. A semi-empirical model has been developed and assessed at Creare to calculate the rate of delivery of ECC to the lower plenum of a PWR subject to specified transients of reverse core steam flow and vessel pressure. A set of assumptions leading to a "best-estimate" analysis of superheated wall effects has been established. Comparison with our data shows that this analysis accurately predicts the timing and rate of plenum filling for most of the data and also displays proper data trends as test parameters are varied.

The utility of this sort of semi-empirical model development is most compactly illustrated by the closed-form expression for annulus delay time t_{da} given below. On inspection, it reveals the effects of the major geometric and thermodynamic parameters, the interfacial momentum exchange in flooding reflected by the coefficient C, and the effects of subcooling (reflected in the coefficient f, the pool boiling coefficient n, and the pool temperature T_p calculated from an energy balance).

$$t_{da} = \left[\frac{\pi k^2 L^2}{\alpha s^2 [\rho_g g w(\rho_f - \rho_g)]}\right]\left[\frac{(T_w - T_p)}{h_{fg} + n c_p (T_s - T_p)}\right]^2 \left[\frac{1}{C^2\left[1 - \left(\frac{J^*_{gc}}{C^2 + f\lambda J^*_{fin}}\right)\right]}\right]^2 \qquad (4)$$

From this equation, the effects of increasing parameters such as downcomer length or initial wall temperature are seen to increase delivery delays while increasing the gap size, pool boiling coefficient, or flooding coefficient is seen to decrease delays.

The sensitivity of the calculations to the major assumptions in the analysis has been studied. Extensive comparisons of alternative models and coefficient values with 1/15-scale data reveal the latitude available in attempting to match the data [5]. The single most important factor is the flooding coefficient C, which appears to the fourth power in the equation above for delay time. The value C=0.4 determined from independent

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countercurrent flow experiments without superheated walls is shown to be a good choice by the good agreement obtained with superheated wall data. The remaining coefficients f and n, and the parameter T_p all represent effects of ECC subcooling. Unlike the situation with C, high and low estimates of the effects of subcooling can be derived by letting subcooling take on the limiting values of zero (saturated water) or its maximum value (corresponding to injection temperature) in various parts of the model. These high and low estimates easily bound the data obtained with highly subcooled ECC. Thus, the uncertainty range in modeling the effects of subcooling has been quantified and the best-estimate analysis has been shown to be accurate by comparison with 1/15-scale data.

Our best-estimate analysis calculates heat transfer limited only by wall thermal conduction. Although this simple assumption is sufficient for prediction of most of our 1/15-scale data, improved agreement is achieved with some 1/15-scale data at extremes of high wall superheat or low ECC subcooling by including the recently developed transition boiling correlation of Cheng in the model. Since available evidence indicates that transition boiling is suppressed as gap size (i.e., scale) increases, we have not incorporated a transition boiling model in our best-estimate analysis.

Comparison with initial experiments in the Battelle 2/15-scale facility shows that the measured hot wall delays are even lower than those predicted using J* scaling of flooding and best-estimate assumptions elsewhere. Thus, these 2/15-scale data are inconsistent with K* scaling of flooding. The data can be calculated correctly if J* scaling is used and either f=0.3 is assumed or T_w is reduced by 40°F.

Data from other programs have not yet contributed significantly to our development of separate-effects models. In particular, Semiscale and LOFT are intended mainly to study integral behavior and of necessity have not been designed or adequately instrumented to provide the comprehensive information needed to examine separate effects such as ECC bypass. The test L1-2 intended to isolate the hot wall effect did <u>not</u> do so because the core was not simulated and steam upflow in the core mitigated the hot wall effect in an atypical manner.

The LOFT non-nuclear series does provide some evidence to assess superheated wall effects and ECC bypass scaling concepts since L1-4 and L1-5 indicate significant ECC bypass. Calculations in Appendix C show that our best-estimate model predicts the start of refill in L1-4 closely while the evaluation model proposed in the RIL is conservative with respect to L1-4. The lack of measured core steam flow rate in L1-4 reduces confidence in these comparisons, however.

3.1.5 PWR Sensitivity Calculations

The paragraphs above have described the major countercurrent flow effects in the downcomer and the models used in their analysis. One result of this effort has been development of a computer code that can be used for the calculation of the transient refill period following a loss of coolant accident. Appendix A is a self-contained technical report describing the application of this code analysis at PWR scale and displaying the sensitivity to alternate modeling and scaling assumptions.

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Our calculation procedure requires as input a transient blowdown calculation from a system code such as RELAP. Our analysis then calculates the transient ECC delivery delay and subsequent refill subject to countercurrent flow and superheated wall effects. This contrasts with the sequential method described in 10CFR50 Appendix K where an experimentally determined "hot wall delay" is simply added to the time for end of bypass from a calculated blowdown transient. Although either method is dependent on the input blowdown transient, the transient calculation properly limits the wall-generated steam during the blowdown whereas the sequential calculation does not.

Demonstration calculations are presented in Appendix A for a few large-break blowdown transients. In these particular examples we find that superheated wall effects are negligible if J* scaling of flooding is used, but become significant if K* scaling of flooding is used. Except at the extreme value f=1, the calculated delivery delays are relatively insensitive to the subcooling factor f under all conditions for these blowdown transients. However, the potential for significant interactions berween condensation and ECC bypass during the blowdown has been identified and requires further evaluation.

3.2 Cold Leg

The calculation of cold leg flow regime, cold leg steam flow, and ECC temperature is of interest to the prediction of the refill and reflood portions of a LOCA and to the assessment of fluid-structure interaction and structural integrity. Cold leg ECC flow and pressure oscillations and slug impact have been observed in a number of separate effects experiments and in Semiscale and LOFT.

Creare has developed an analytical model of cold leg behavior that unifies and explains available component data [2]. Unique among components, the cold leg has an exceptional base of data spanning the range from 1/20 to 1/3 of PWR scale. Prime contributions have been made by Westinghouse, who performed elevated pressure experiments at 1/14 and 1/3 scale and developed pressure drop correlations under contract to EPRI, Combustion Engineering who performed experiments at 1/5 and 1/3 scale and developed a momentum balance, and Creare who performed transparent model studies and developed analyses under contract to NRC and EPRI.

Analytical capability has been developed to predict the cold leg flow regime (dispersed two phase, slug oscillations, or stable slug) the cold leg pressure drop, the steam flow rate and the effluent temperature. Figure 4 displays calculated and measured flow regimes in some of the Westinghouse experiments and Reference 2 displays a number of comparisons with detailed pressure and flow data. Since the calculations and data agree relatively well over a large range of size (1/20 to 1/3 of PWR scale) there is some evidence that reasonable predictions at PWR scale can be made. While the analysis successfully treats the cold leg as an isolated component, it has not yet been extended to treat fluid-system interactions with other components. Such interactions strongly impact, and thereby render uncertain, present ability to predict flow regimes.

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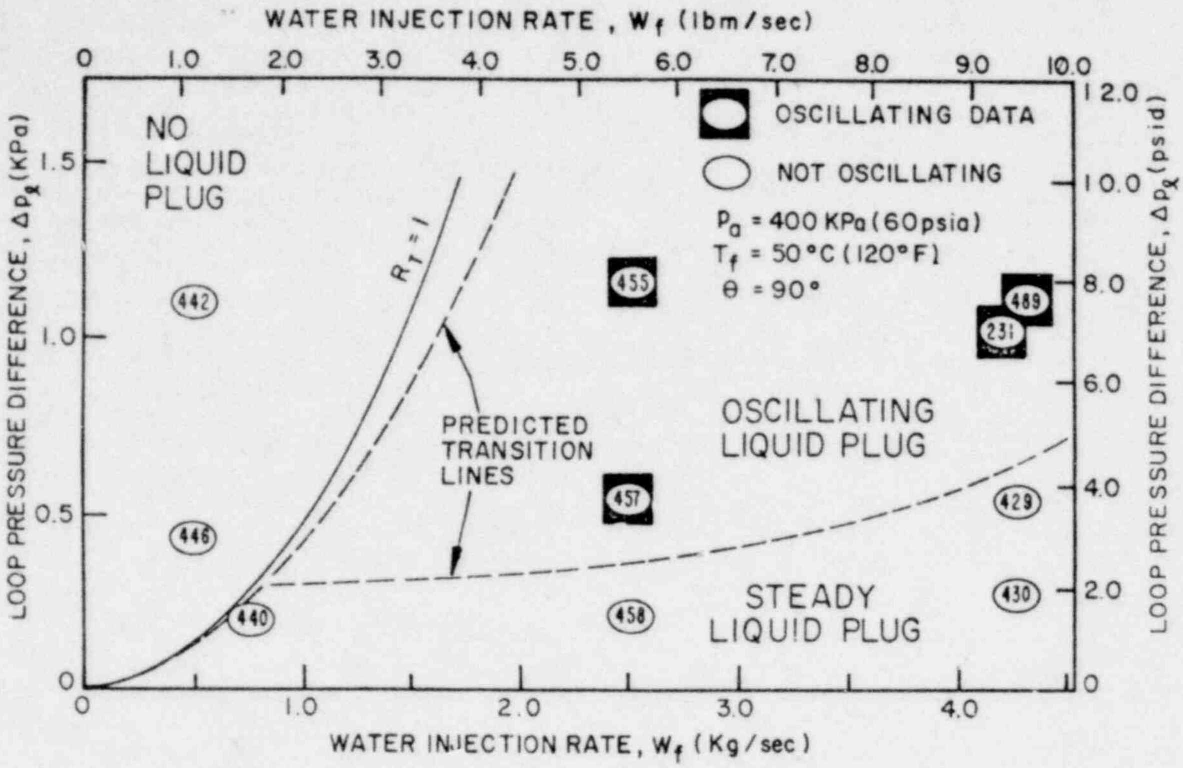

Figure 4. COLD LEG FLOW REGIMES

Research needs include:

1) the prediction and execution of tests in simple coupled systems,

2) the inclusion of the present analytical model or its equivalent in a system code such as RELAP or TRAC followed by comparison of the calculations with data from systems such as Semiscale and LOFT which have complexities comparable to PWRs, and

3) assessment of the potential for and significance of the slug impact on the core barrel and primary coolant pump that has been reported for Semiscale and observed in small scale models.

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3.3 Lower Plenum

Our efforts on lower plenum effects such as voiding and flashing are at an early stage [1]. Several flow regimes and distinct entrainment phenomena have been identified, preliminary data have been obtained at several scales, and data analysis is underway. These topics are the main subjects of study in FY79. Identified phenomena include:

1) removal of liquid from the lower plenum by impact and entrainment due to reverse core steam flow,

2) removal of liquid from the lower plenum by level swell due to flashing and lower plenum heat transfer,

3) coupling of the above two effects,

4) repeated emptying and filling of the lower plenum due to coupling of condensation in the downcomer and voiding by reverse core steam flow,

5) production of steam by lower plenum flashing,

6) geysering of lower plenum fluid promoted by downcomer level swell such as identified in the Semiscale experiments,

7) level swell into the core promoted by lower plenum flashing and flow resistance in the downcomer and break which helped early cooling in LOFT L2-2.

Recent experiments have revealed much more rapid voiding of two-phase mixtures than in similar experiments with only water in the lower plenum. Strong effects of ECC injection on flashing transients have also been identified. Briefly, condensation on the ECC promotes more rapid depressurization and flashing. In turn, the more rapid flashing enhances voiding of lower plenum fluid. Thus, in effect, ECC injection promotes a rapid reduction of lower plenum inventory prior to refill.

3.4 Integrated Vessel Steam Flows

Preceding sections have described separate effects studies of isolated components subject to controlled initial and boundary conditions. Ultimate application is the prediction of transient behavior of an entire system. Our emphasis is on prediction of processes occurring in the vessel, exclusive of the core, during the period of ECC injection and vessel refill. Here we point to studies tending to integrate the behavior in the vessel.

The condensation-induced transient studies described above amount to a coupling of the downcomer with the steam supply and the break during the ECC bypass period. It is a class of experiment requiring prediction of transient steam flow by modeling the combined break and downcomer behavior. Similarly, the flashing experiments underway involve interaction with the break, ECC, and prediction of transient steam flows and vessel pressures. These sorts of separate-effects experiments, where transient steam flows in the vessel are variable, provide a critical test of the predictive capability of LOCA codes and their underlying physical models.

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4 APPLICATION TO LICENSING

Here we assess the significant findings relative to the purposes identified in Section 2.

Findings on a number of phenomena are cited above. Certain effects, notably cold leg steam binding, ECC bypass by countercurrent flow in the downcomer, and the hot wall effect have been addressed extensively at small scale and are reflected in present licensing procedures. Other phenomena such as lower plenum voiding and flashing, level swell in the downcomer and core, effects of noncondensibles, transient steam flow splits (driven by condensation, flashing and two-phase pressure drops), and structural interactions are receiving attention. Here we address those areas where well established findings may impact licensing rules or approaches.

4.1 Downcomer Countercurrent Flow

Reference [8] cites the rule that "all emergency cooling water injected into the inlet lines of the reactor vessel during the bypass period shall in the calculations be subtracted from the reactor vessel calculated inventory." "...The end of bypass definition used in the calculation shall be justified by a suitable combination of analysis and experimental data. Acceptable methods for defining 'end of bypass' include, but are not limited to, the following: 1) Prediction of the blowdown calculation of downward flow in downcomer for the remainder of the blowdown period; 2) Prediction of a threshold for droplet entrainment in the upward velocity, using local fluid conditions and a conservative critical Weber number."

Complete subtraction of all cooling water injected during bypass may be non-conservative. A scenario can be envisioned where some cooling water is delivered to the lower plenum or downcomer, heated to saturation, and later flashed to steam as the depressurization continues. Such flashing can be eruptive (geysering) or may be sustained for long periods. Such a scenario occurred due to downcomer level swell in the semiscale facility during tests S-04-1, -2, -3, -4, and S-07-6 where it was actuated by sudden repressurization due to accumulator noncondensibles.

Status reports on conformance to 10CFR50, Appendix K, reveal that after end-of-bypass, vendor calculations include addition of a delay comprised of (1) a free-fall time, and (2) hot wall delay displayed in Figure 30 of Creare TN-188 [13]. Rather than dealing with these effects sequenti it is preferable, and more likely to be conservative, to perform a complet transient calculation combining the effects. That analytical capability now exists. In the transient calculation the wall-generated steam flow is limited to sustain the critical flow rate just sufficient for bypass whereas the sequential calculation permits the steam to be used up too rapidly in the early blowdown period.

Either the end-of-bypass criterion or the transient calculation pr cedure requires analytical and experimental justification. Prediction o downward flow in the downcomer may be non-conservative if the calculatio are performed as a simple blowdown without proper treatment of condensat driven flows toward the ECC water. Assuming the steam flows in the down can be accurately calculated, there is ample analytical and experimental

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justification for calculating ECC delivery rate as a function of steam upflow. While small scale studies point to the modified Wallis correlation described herein (J* scaling) as an appropriate flooding formulation, sufficient scaling uncertainties remain that a more conservative criterion should be employed. Dukler [14] has shown analytically that the critical Weber number concept is functionally equivalent to the K*=3.2 complete bypass criterion proposed by Pushkina and Sorokin [15] and supported by Richter and Lovell [16]. Each is a "constant velocity" scaling approach and Dukler's contribution has been, in effect, to reveal that either modeling idea leads to about the same critical velocity. Since no one has suggested a still more conservative criterion, despite extensive study, we urge use of the K*=3.2 criterion for complete bypass. This criterion also matches 1/15-scale saturated water data. Delivery calculations in the partial delivery range may be performed following the K* scaling of 1/15 scale data described in Reference [5] or the recently developed model of Richter, Wallis and Speers [17]. Either of these approaches are easily implemented in a transient calculation procedure.

It is our best estimate that some benefit results from condensation in the downcomer in the sense that an empirical value of f=0.20 or more in countercurrent flow correlations is justified by comparison with small scale data. However, there is sufficient uncertainty in the prediction of this benefit, particularly extrapolation to full scale, for us to recommend that it be ignored in transient delivery calculations until it can be justified by large scale experiments. Thus, we urge the use of flooding formulations based on saturated water behavior, such as those above, in ECC delivery calculations.

Our best estimate is that superheated wall effects on initial PWR refill are negligible if J* scaling of flooding applies. More conservative flooding formulations may lead to significant hot wall delays. A transient calculation procedure for combined countercurrent flow and superheated wall effects is described in Reference [5]. A set of conservative assumptions for use in this model are:

1) K*=3.2 flooding
2) f=0
3) n=1
4) $T_p = T_{ECC}$
5) L=A/w

Here A is the total exposed surface of superheated walls and heat transfer is limited by wall conduction and the flooding criterion. This combined set of physically based assumptions strikes us as somewhat extreme and overly conservative. Less conservative combinations might be employed by relaxing individual coefficients to the best-estimate assumptions. Conservatism could be demonstrated relative to the trend of the small scale data and safety margin provided by K* extrapolation of flooding.

Licensing evaluations should require assessment of the sensitivity of the calculated blowdown transient to alternate assumptions about the interaction between condensation and ECC bypass.

4.2 Cold Leg Steam-Water Mixing

The Rule Making Hearing [8] addressed the issue of interference between steam flowing through the primary coolant pipes and injected ECC water. Allowances were made for incorporating future models of momentum and energy exchange to permit steam flow in the primary coolant pipes during ECC injection. Such models have been introduced by the vendors based on correlations of pressure and flow data and first order momentum and energy balances. Of particular interest in calculations of ECC bypass and subsequent refill are the flow regime in the intact cold legs, the cold leg steam flow rate, and the temperature of the liquid entering the downcomer. Status reports on vendor conformance to 10CFR50, Appendix K, reveal that:

1) the cold leg steam flow is calculated using a very small cold-leg flow resistance (by comparison with the flow resistance of other components such as the primary coolant pumps), and

2) the cold leg steam flow is assumed to condense entirely just downstream of the accumulator injection point.

While the cold leg flow resistance is small when the cold leg is treated as an isolated component, it tends to amplify flow resistances of upstream components such as the pump. In the regime of slug flow in the cold leg, the cold leg steam flow oscillates, typically from zero to twice the average value. These oscillations in steam flow tend to increase the time-average steam flow resistance of upstream components.

The assumption of complete steam flow condensation is invalid in the dispersed flow regime. This regime has been observed at low thermodynamic ratio (less than about 2) or when noncondensible concentrations in the gas approach 1% [2]. Incomplete condensation tends to introduce additional steam flow into the downcomer and promote ECC bypass. Available data for cold leg flow regimes and the effects of cold leg steam on ECC bypass should be incorporated in evaluation model calculations.

4.3 Research Needed for Licensing

Here we attempt to recommend areas of research useful to assist NRR staff in assessing PWR refill. This report has shown that there is a well developed understanding of cold leg behavior, countercurrent flow in the downcomer and superheated wall effects on countercurrent flow in small scale systems. Methods of analysis have been developed and scaling approaches proposed.

Downcomer Effects

For downcomer effects, we are able to rank several recommendations for futher work. These are discussed in order of importance.

Confident predictions of system pressure and steam flow transients are needed for licensing. Small scale studies of refill have usually employed external steam supplies such that the core steam flow rate is an independent test parameter. Conversely, best-estimate calculations using RELAP have calculated steam flow rates and distribution without integrating ECC bypass

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and condensation effects. For example, predictions of LOFT L2-2, L2-3, and L2-2 [18] required fixes because "the thermodynamic equilibrium assumption causes excessive condensation and significant underprediction of system pressure. These condensation effects also cause the code to calculate sequential filling of control volumes..." Methods of analysis are being implemented in advanced codes to properly include downcomer ECC behavior and condensation in the steam flow calculations and these methods need to be assessed by comparison with various experiments where transient core, lower plenum, and cold leg steam flows are test variables. Such experiments are now underway at small scale.

A major need is for at least a few countercurrent flow experiments in a facility close to PWR scale. Initially these experiments need not test superheated wall effects or cover the entire pressure range encountered by reactors during ECC injection. However, they must provide sufficient ECC flow and subcooling to replicate the ranges found in PWRs and include capability to test nearly saturated water. The steam supply should be sufficient to completely bypass the ECC for approximately 100 seconds. Experiments along these lines are being planned as part of the International 3D Program.

In the eventuality that countercurrent flow experiments in the 3D program demonstrate that the $K^*=3.2$ scaling criterion is appropriate for countercurrent flow bypass, then further studies of boiling and heat transfer at large scales might be useful to quantify conservatisms, if any, deriving from transitional and film boiling behavior which tend to mitigate the hot wall delay in small scale tests at high wall superheats typical of reactor transients. Large scale justification of this benefit would be needed because small scale evidence indicates suppression of transient boiling as gap size is increased. This testing is not recommended at this time, pending the results of the planned countercurrent flow research.

Cold Leg Effects

Analytical efforts involving advanced codes are needed to assess the current models developed to describe steam-water mixing in cold leg injection sections. Comparisons with separate effects and integral system results (i.e., LOFT and Semiscale) should be included. Further experimental work is not recommended at this time.

Lower Plenum Effects

Continuing effort is needed and is ongoing at small scale to assess a number of phenomena described in this report. Knowledge of lower plenum voiding is needed to determine the inventory at the start of refill and to ensure that ECC once delivered to the lower plenum will remain there. Knowledge of lower plenum flashing is needed to predict its impact on lower plenum voiding and its contribution to downcomer steam flow. Certain phenomena identified in integral tests, specifically level swell in the downcomer and core, need to be analyzed and assessed by appropriate separate-effects experiments. Finally, the potential effects of noncondensible gases on condensation and hence on blowdown, repressurization, ECC bypass, and flashing need to be addressed more fully.

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ABSTRACT

This Topical Report is a contractor attachment to the Research Information Letter (RIL) entitled "Small Scale ECC Bypass Research Results". The RIL, and this report, deal with countercurrent flow and superheated wall behavior in PWR downcomers. The topics of lower plenum voiding, flashing, and refill are deferred to later documents. In this report we:

1) review the purposes of our work,
2) summarize the work performed by Creare,
3) identify significant findings in all available work,
4) discuss the applicability of the findings to licensing,
5) recommend further research.

A companion volume of technical appendices to this report addresses three topics:

1) sensitivity calculations at PWR scale,
2) assessment of countercurrent flow data,
3) comparisons of calculations with LOFT data.

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