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QUARTERLY PROGRESS REPORT
October 1, 1977 — December 31, 1977

PROGRESS ON ECC BYPASS SCALING

Paul H. Rothe
Christopher J. Crowley
James A. Block

MARCH 1978

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ABSTRACT

Recent results of a continuing program to develop an analytical and empirical model of plenum filling in a 1/15-scale model of a pressurized water reactor are presented. The topical section of this report updates a previous assessment of methods to scale ECC bypass phenomena. It has been possible to unify virtually all existing data for countercurrent flow in reactor vessel models and to develop the prescription that complete bypass of saturated water occurs at $J^*_{gc} \approx 0.4$ in small scale facilities. Methods to extrapolate to full scale remain equivocal, however. This report also describes the past quarter's efforts, which included continued analysis development for ramped transient steam supply tests with superheated walls, various tests with an unheated lower plenum in order to bound the effect of lower plenum heat transfer, further analysis of lower plenum entrainment, and scoping tests attempting to quantitatively assess wall-generated steam in superheated wall tests by measuring the separator vessel steam outflow.

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NOMENCLATURE

C	dimensionless constant in Equation (1)
c_p	specific heat capacity at constant pressure
D_c	core inner diameter
f	ratio of the steam condensed in the lower plenum and downcomer to the amount of steam that could be condensed to heat the liquid phase to saturation at equilibrium
g	acceleration due to gravity
h	water level depression
h_{fg}	latent heat of vaporization
J^*_{fd}	dimensionless liquid flow delivered to lower plenum
J^*_{fin}	dimensionless liquid flow injected
J^*_{gc}	dimensionless steam flow rate out of core (to the lower plenum)
P_{LP}	lower plenum pressure
P_{man}	steam flow orifice pressure
P_{sep}	separator vessel pressure
Q_T	total injected liquid mass flow rate
T_w	wall temperature

[redacted]

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1 INTRODUCTION

This is a Quarterly Progress Report on the Creare Downcomer Effects Program. The general context of this work is a postulated Loss-of-Coolant Accident (LOCA) in a Pressurized Water Reactor (PWR), although many of the basic processes being studied may also apply to Boiling Water Reactors (BWRs). The program is a continuing effort to develop analytical and empirical tools which will contribute to best-estimate and licensing predictions of lower plenum filling during postulated LOCAs in PWRs and to assist in the design and specification of larger scale plenum filling tests and the predictions of those test results.

1.1 Preview of This Report

This report is organized in three sections. The remainder of this section previews the report and gives an overview of the program. Section 2 describes the activities of the past quarter in the context of previous and planned work. Section 3 is a brief technical status report on the scaling of flooding in countercurrent flow.

Activities During the First Quarter of FY78

In the period October-December 1977 primary analytical efforts centered on upgrading both the ramped transient and condensation-induced transient analyses described in previous Quarterly reports. Alternative analyses for lower plenum voiding were also assessed. Experimental efforts included superheated wall tests with an unheated lower plenum to provide a bounding condition for testing analyses. The initial series of lower plenum voiding experiments in a six inch tube were completed. Various geometries, fluid/thermal conditions and test procedures were studied in order to make a general assessment of the voiding behavior. Finally, countercurrent flow tests with ECC of very low subcooling (order 10°F) were performed to provide critical data with a minimum of condensation effects.

Progress on Flooding Scaling

Various methods to extrapolat countercurrent flow data from facilities which are a small fract on of PWR scale have been suggested previously. During the past two years key data have been obtained and new approaches to data analysis developed which provide needed insight. Our ability to characterize the existing subscale data has improved significantly and this has brought the scaling questions into sharper focus. Despite these gains, it is plain that the existing facilities are simply too small to resolve the scaling questions satisfactorily. Section 3 of this report summarizes the new information, points out weaknesses in earlier thinking, assesses the status of research in this area, and identifies needed work, some of which is already planned.

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1.2 Program Overview

The Creare Downcomer Effects Program is a separate-effects model study of the two-phase flow behavior in the downcomer and adjacent regions of a PWR during the later stages of blowdown and during refill of the lower plenum in the event of a LOCA. Recognizing the complexity of the underlying phenomena and the limitations imposed by the state of the art of two-phase flow analysis, a balanced program of research experiments and semi-empirical analysis is being pursued. Efforts are divided into 11 interrelated topics:

A. Model Synthesis

B. Ramped Transients

C. Condensation-Induced Transients

D. Countercurrent Flow

E. Extended Superheated Walls

F. Lower Plenum Voiding

G. Boundary Conditions and Internal Idealizations

H. Refill Modeling in RELAP

I. System Effects

J. Technical Assistance and Review Group Participation

K. Downcomer Flow Topography Instrumentation

Primary effort (Task A) is focused on synthesis of a semi-empirical analysis whose main purposes are to gauge our understanding of the physics of downcomer effects at 1/15 scale, to suggest scaling relationships, and to help display data trends. The model synthesis activities control analytical and experimental efforts on the remaining tasks.

Tasks B and C are key activities leading to the development of models of lower plenum filling during ramped transients (of the steam supply and lower plenum pressure) and during condensation-induced transients. These tasks made major inputs to the model synthesis at the end of FY77 (preliminary models) and are expected to do so again at the end of FY78 (upgraded models).

Tasks D, E, F, and G are support activities, pursued at a somewhat lower level of effort individually than Tasks B or C, which address specific separate effects or boundary conditions required to improve the synthesized model incorporating separate effects. Information from these tasks is fed to the model synthesis at staggered intervals.

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A supplementary activity (Task H) seeks to test the model against integral tests performed in LOFT and Semiscale through the use of RELAP. This activity will also guide the development of the correlations by testing the compatibility of the correlations with a systems code such as RELAP. In addition, preliminary analysis of system effects (Task I) and Special Technical Assistance and Review Groups (Task J) activities continue.

Downcomer flow topography instrumentation has as its broad objective the development of a system to monitor and track the steam/water flow regimes in a downcomer. By mid-FY78 it is planned that the feasibility of the system will be demonstrated and that some sample data using this technique will be obtained and displayed.

Overall, the program strives to achieve a balance between attempting to develop a full understanding of the underlying phenomena and providing timely information in a form suitable for direct use by other research programs and by licensing. It is recognized that despite over a decade of research by various groups, the underlying mechanisms of even the most studied phenomena (e.g., flooding in countercurrent flow, or condensation during steam-water mixing) remain intransigent. Some of the topics (e.g., lower plenum voiding or condensation-induced transients) have received only limited study heretofore. Adequate understanding of some of the component phenomena may prove elusive. Therefore, the program continues to be highly flexible in its planning and implementation and the need for continued development and refinement of component models in future years is anticipated.

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2 STATUS SUMMARY

2.1 Previous Work

Work was begun on this program in FY74. The key report summarizing the experimental efforts of FY74 is Reference 1 presenting superheated wall tests in a planar geometry with top flood and single-loop injection. FY75 experimental work is summarized in Reference 2 and includes separate effects tests of countercurrent flow, superheated walls, and cold leg steam and also examines combinations of these effects in a planar, multi-loop injection configuration at near-ambient pressure. Reference 3 reports the experimental work performed during FY76 and FY76TQ, including lower plenum voiding, ramped transient, and coupled effects tests at elevated pressure (up to 75 psia) in a cylindrical multi-loop injection geometry.

The major analytical topical report is Reference 4 which is based on the FY74 and FY75 data with superheated walls and countercurrent steam flow. That report presents a time-dependent flooding/heat transfer model for ECC penetration with superheated walls and a steady reverse core steam flow. A subsequent Quarterly Report [5] describes a preliminary analysis treating ramped transients in reverse core steam supply and vessel pressure, with superheated walls. Another Topical Report [6] discusses the scaling of countercurrent flow separate effects, a subject which is updated in the Topical Section of this Quarterly Report.

The previous Quarterly Report dealt with the topic of condensation-induced transient (CIT) tests performed with a "soft" steam supply which is closely coupled to the vessel by a large pipe. This situation is believed to be more typical of PWR behavior than earlier tests. (Previous countercurrent tests have been conducted with the steam passing through a choked orifice thereby ensuring steady flow.) Results of CIT tests showed that experimental steam flows established themselves at new, much larger values when the ECC was injected. However, the ECC penetration rate was the same as in previous countercurrent flow tests at the same steam flow. Slug delivery observed in the choked steam flow tests did not occur with the soft steam supply. A separated-flow model for the broken cold leg pressure drop was developed and compared successfully with available data.

2.2 Work During the Quarter

Primary efforts during the quarter October 1-December 31, 1977 centered on further ramped transient analysis and lower plenum voiding (LPV) experiments and analysis. In addition, special experiments with superheated walls and countercurrent flow were performed to test key features of our superheated wall analysis.

Ramped Transient Analysis

During the third quarter of FY77 Reference 5 discussed a preliminary analysis which built upon the work of the analysis in Reference 4 but extended it to treat the additional effects of lower plenum heat transfer and ramped transient steam supplies. A few initial comparisons with baseline data were also presented. During this quarter, comparison of the preliminary ramped transient analysis with a broadly representative sample of existing data [3] was completed. These comparisons investigated trends across the parameter ranges studied in the experiments.

In subsequent analytical efforts, alternative models for various components of the analysis have been proposed and efforts begun to assess the sensitivity of the analysis to the various assumptions. The sensitivity of the analysis to the choices of values for empirical coefficients is also being examined. These analytical studies are being supported by appropriate data comparisons and additional experiments. We have not attempted to describe the analytical results in this report, due to their highly preliminary status, but we present some of the additional experimental data below. A Topical Report on this subject is scheduled for the fourth quarter of FY78.

Additional Tests With Superheated Walls

Previous data have indicated that lower plenum heat transfer has a significant effect on plenum filling behavior. Examples of the delay times observed under baseline hydraulic and thermal test conditions with a deep plenum and a scaled plenum (both heated), and an insulated (unheated) plenum were shown in Figure 1 of Reference 7. The preliminary analysis [5] was shown to be a lower bound for the observed delays in the data with the heated and unheated plenum under these baseline conditions.

The unheated plenum data form a lower bound to the effects of plenum heat transfer in superheated wall tests since they include only the effects of annulus wall heat transfer. For that reason, these data are important in testing the sensitivity of the analysis. During the quarter, we have extended the superheated wall testing to include the important parameter variations of water flow rate and injected ECC temperature with an unheated lower plenum.

Unheated plenum tests are run in the deep lower plenum geometry but the plenum walls are prevented from becoming superheated as follows: On the outside of the vessel, heating air is diverted to flow only above the plenum while on the inside of the vessel, the lower plenum is kept filled with subcooled water--a steady trickle of cold water is circulated into the plenum--until just prior to the test when the plenum is drained. With the unheated plenum then, the effect of lower plenum hot walls is removed.

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Figure 1 shows sample plenum filling traces comparing heated and unheated plenum results at several ECC flow rates. The effect of the fully heated lower plenum surface area is to give a larger water delivery delay time, and hence increase the time it takes the plenum to fill. Frames (a) and (b) show that the delivery delay is approximately 2.5 times greater with the heated lower plenum for both 60 and 30 gpm injection, adding about 25 seconds to the plenum filling time. Frame (c) shows that the delay time is increased by a factor of about 7 times with 10 gpm. Thus, the effect of the lower plenum is strongest with a very small injection rate.

Figure 2 compares heated and unheated lower plenum filling data with two ECC temperatures. Again, plenum filling is seen to be delayed significantly with the heated plenum. (Both tests are without reverse core steam flow.) With T_{ECC} = 80°F, the delay time is about doubled, adding four seconds to the plenum filling time. With T_{ECC} = 212°F, while it is difficult to assign a delay time to both cases, the plenum filling time is much longer--about 30 seconds longer--with the heated lower plenum.

Lower Plenum Voiding

During the refill stage of a PWR LOCA the reverse core steam flow may impact, entrain and ultimately bypass fluid stored in the lower plenum. This process, termed lower plenum voiding (LPV), is distinguished from potential entrainment, level swell and fluid bypass due to flashing. Although these processes are assumed to occur simultaneously during a hypothetical LOCA, they are first being isolated for individual study in the Creare program.

Figure 3 shows the highly idealized lower plenum voiding situation under study at Creare in vessels of 6, 12, and 18 inch diameters. Over the years, lower plenum voiding has been studied intermittently by several groups. The problem was first treated by Wallis and Block in 1975 [8] and led to a simple jet-impact model. Block [9] later proposed an alternative data correlation based on a critical Weber number concept. In subsequent years a considerable body of data was accumulated in various geometries, mainly by Creare [3,10,11], Dartmouth [12,13], and Battelle Columbus Laboratories [14,15]. Curiously, different data sets from different groups, and occasionally even from the same group, appeared inconsistent. The data spread was appreciable, spanning an order of magnitude in equilibrium water level and best displayed on logarithmic scales. Plainly no simple theory could predict all of the data, though conversely every theory seemed to agree with some of the data. Recent efforts at Creare and parallel studies at Dartmouth have clarified the situation somewhat. Of necessity, the discussion in this progress report is limited to a very cursory description of our findings and current efforts. We plan to describe the data base in detail in the Topical Section of our next Quarterly Report and we will report on development of basic analytical models and comparisons with data in a future report.

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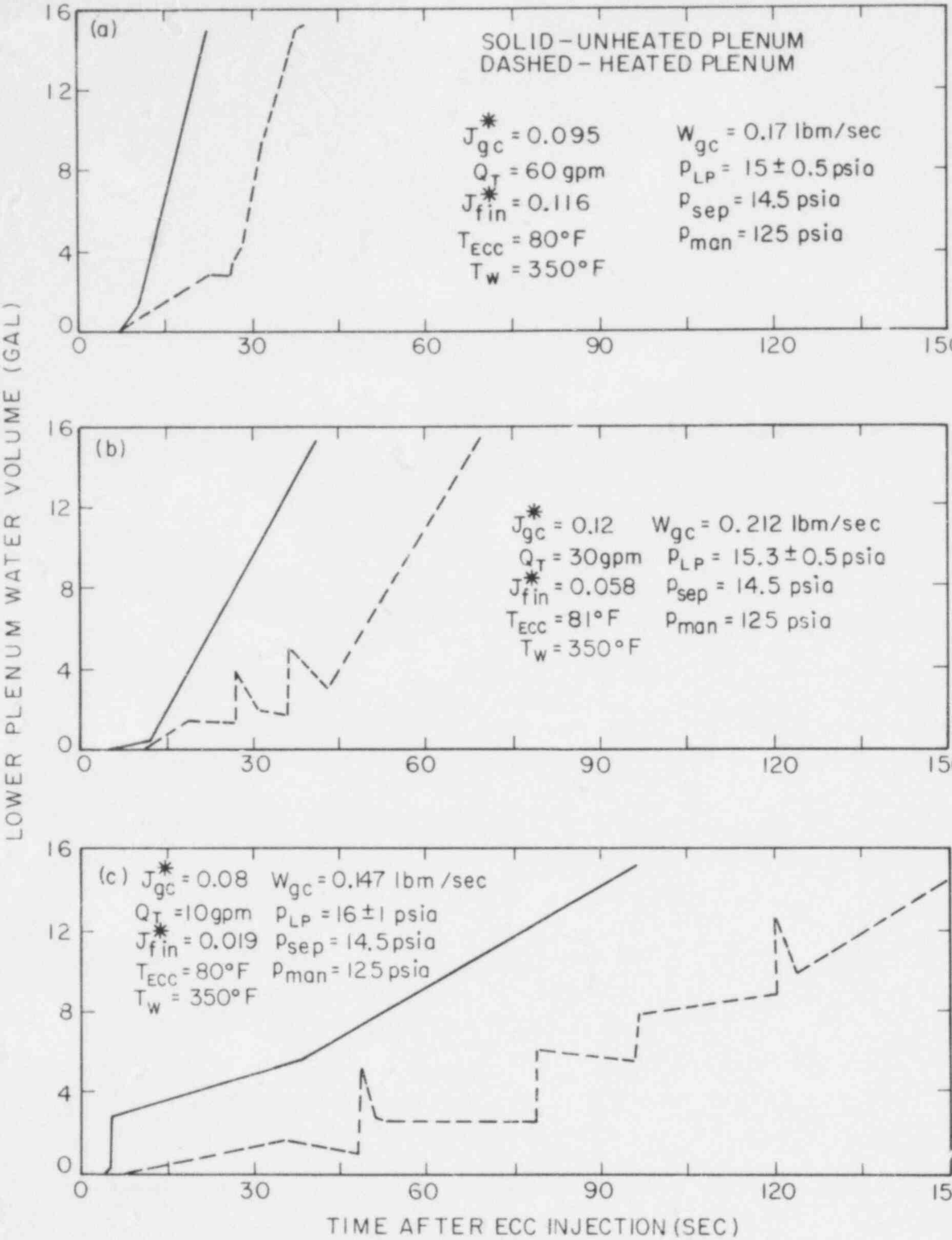

Figure 1. EFFECT OF HEATED PLENUM ON PLENUM FILLING AT VARIOUS ECC FLOW RATES

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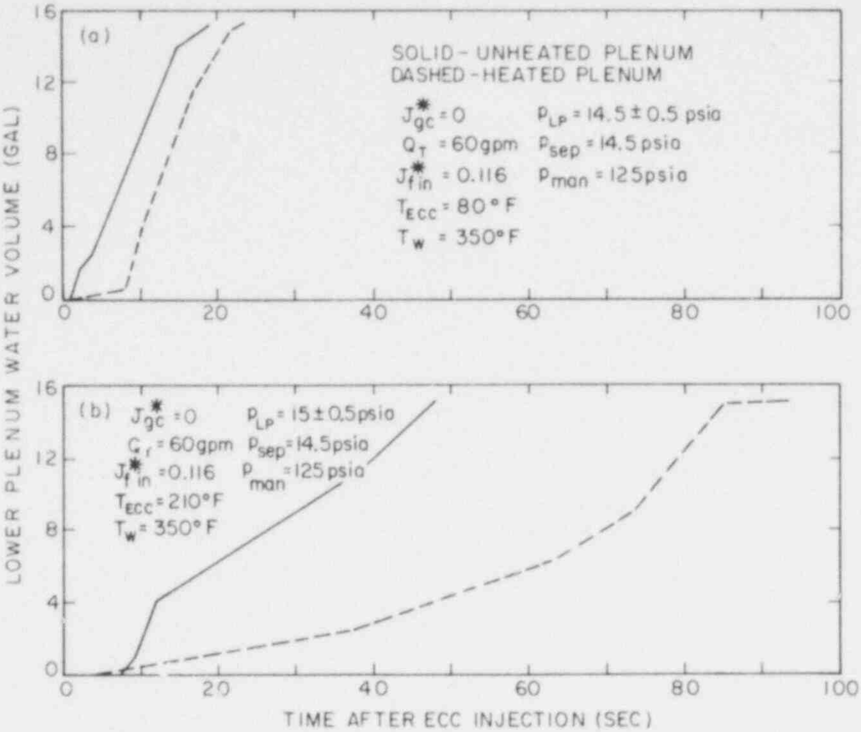

Figure 2. EFFECT OF HEATED PLENUM ON PLENUM FILLING WITH T_{ECC} = 80°F AND 212°F

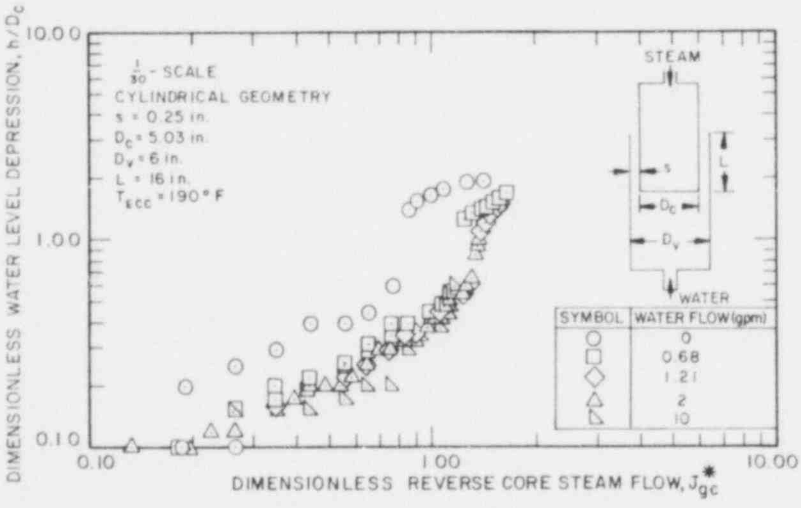

Figure 3. SAMPLE LOWER PLENUM VOIDING DATA FROM 6" ID TRANSPARENT VESSEL

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Why were early data apparently inconsistent? First, it must be appreciated that there are a large number of geometric parameters. Vessel diameter, annulus gap, annulus length, annulus obstructions, core open area, core hole pattern, lower plenum hardware, and lower plenum depth have all been varied. Secondly, there are many fluid/thermal parameters. Tests have been conducted with air or steam, with various liquids, with lower plenum injection or cold leg injection, at various lower plenum pressures, water temperatures, water injection rates and steam supply rates. Lastly, but most importantly, the phenomena are much more complex than was hoped for initially and are sensitive to the test procedures. Depending on the geometry and flow situation the liquid may be entrained as a film or in slugs. The steam water interface may be quiescent, uniformly rough, churning or wavy. At high steam velocities a steam jet impales the liquid surface. At moderate steam velocities, large liquid waves form, become unstable, and are voided. At high voiding rates the liquid in the vessel undergoes bulk sloshing, which reinforces the voiding. Major flow regime transitions and hysteresis have been identified. Recent test data suggest that early tests differed in significant parameters and in test procedures and that these differences were directly responsible for the apparent data inconsistencies.

During the Quarter, testing of lower plenum voiding in simple, transparent vessels proceeded along the lines described in the previous Quarterly Progress Report [7]. In addition to exploratory parameter variation and flow visualization a considerable body of equilibrium-level data has been amassed. These data have been found to be not only self-consistent, but also are consistent with virtually all existing data. It has therefore been possible to view earlier data from a broader perspective and establish consistent data trends. We are now just completing extensive data comparisons which will be reported in detail in our next Quarterly Report.

In parallel with fundamental tests we have been developing analytical models of the behavior. Several of these have been suggested by the flow visualization. In addition to the earlier models based on jet-impact and critical Weber number, analyses have been carried out for the growth of a surface wave subject to a constrained gas flow (Bernoulli effect) and for liquid entrainment based on the Kutateladze criterion for wave instability. Also, the correlation derived by Steen for entrainment in co-current vertical flow has been adapted to the lower plenum voiding situation. Initial comparisons with the tests show that the more recent analyses are consistent with the flow observations and data in specific parameter ranges. We are in the process of refining the analytical models and making extensive comparisons with data in order to assess the alternative models.

Boundary Conditions and Internal Idealizations

In an attempt to experimentally quantify the amount of steam generated during a test with superheated walls, and in order to gain a better understanding of the process of steam generation in superheated wall tests, the steam flow out of the separator vessel exhaust piping was measured for a limited number of tests.

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Under test conditions with no reverse core steam flow and 212°F ECC, steam generated from the superheated walls is the only source of steam. This steam cannot condense in the broken leg or separator vessel because the ECC is saturated. Similar tests with highly subcooled ECC are of marginal use in quantifying wall-generated steam because of the possibility of condensation in the broken cold leg and the separator vessel.

Figure 4 illustrates the results of a test with T_{ECC} = 210°F, no reverse core steam flow, and a heated annulus (but unheated plenum walls). The geometry in this test also included an enlarged broken cold leg, three inches in diameter. The filling trace in frame (a) of the figure shows that there is an initial delay in filling lasting about seven seconds, followed by a five second period of filling at just slightly less than the injected rate, and then (at 12 seconds) a decrease in the filling rate to approximately 25% of the injected rate. The filling rate gradually increases as the plenum fills. Also shown in frame (a) is the broken leg pressure drop (between the inlet annulus and the separator vessel). (The separator pressure remained less than 0.5 psi above atmospheric over the course of the test.) In the first couple seconds of this test, the pressure drop first increases to 2-3 psi, gradually decreases to zero at approximately the time the plenum begins to fill, increases again to 1 psi by 12 seconds, then gradually decreases over the remainder of the test.

The measured gas outflow from the separator vessel is presented in frame (b) of this figure. It is assumed that the outflow is entirely steam, although some fraction of the flow could be air which was initially part of the gas mixture in the separator vessel. The test procedure involved purging the vessel and separator with steam prior to the test; however, since the separator was open to the atmosphere, the separator may have contained a small amount of air. The outflow from the separator was measured using an orifice plate in the 4 inch (ID) pipe connecting the separator to the atmosphere. The indicated flow shows an initial surge in the first three seconds to a steam flow value $J^*_{gc} > 0.075$, which is in the steam flow range able to bypass most of the ECC under these conditions (c.f. Figure 11(a)). Between seven and 12 seconds the indicated flow increases from near zero to $J^*_{gc} \approx 0.05$, gradually decreasing for a long time thereafter as the plenum fills. The penetration of ECC is very sensitive to the steam upflow in the range $J^*_{gc} \approx 0.05$. A 30% uncertainty in the steam flow in this range can mean the difference between 20% and 100% water delivery since the penetration curve is very flat in this range (Figure 11(a)). The fluctuations in the indicated flow in Figure 4(b) are of this order of magnitude, therefore the observed filling rate may or may not be consistent with CCF penetration data (with unheated walls) since the uncertainty makes it difficult to tell.

Qualitatively, the superheated wall analysis [4] would predict that the steam flux would remain at a value high enough to bypass the injected water during the delay period and then decrease thereafter. Compared with the measured steam flow, the experimental and predicted analytical behavior are reasonably consistent qualitatively, except between three and seven seconds. Neither a vessel pressure increase of 1-2 psia nor a separator vessel pressure increase of less than 0.5 psia (given the volume of each vessel, the average steam flow measured and hence the compliance) accounts for this drop in measured steam flow.

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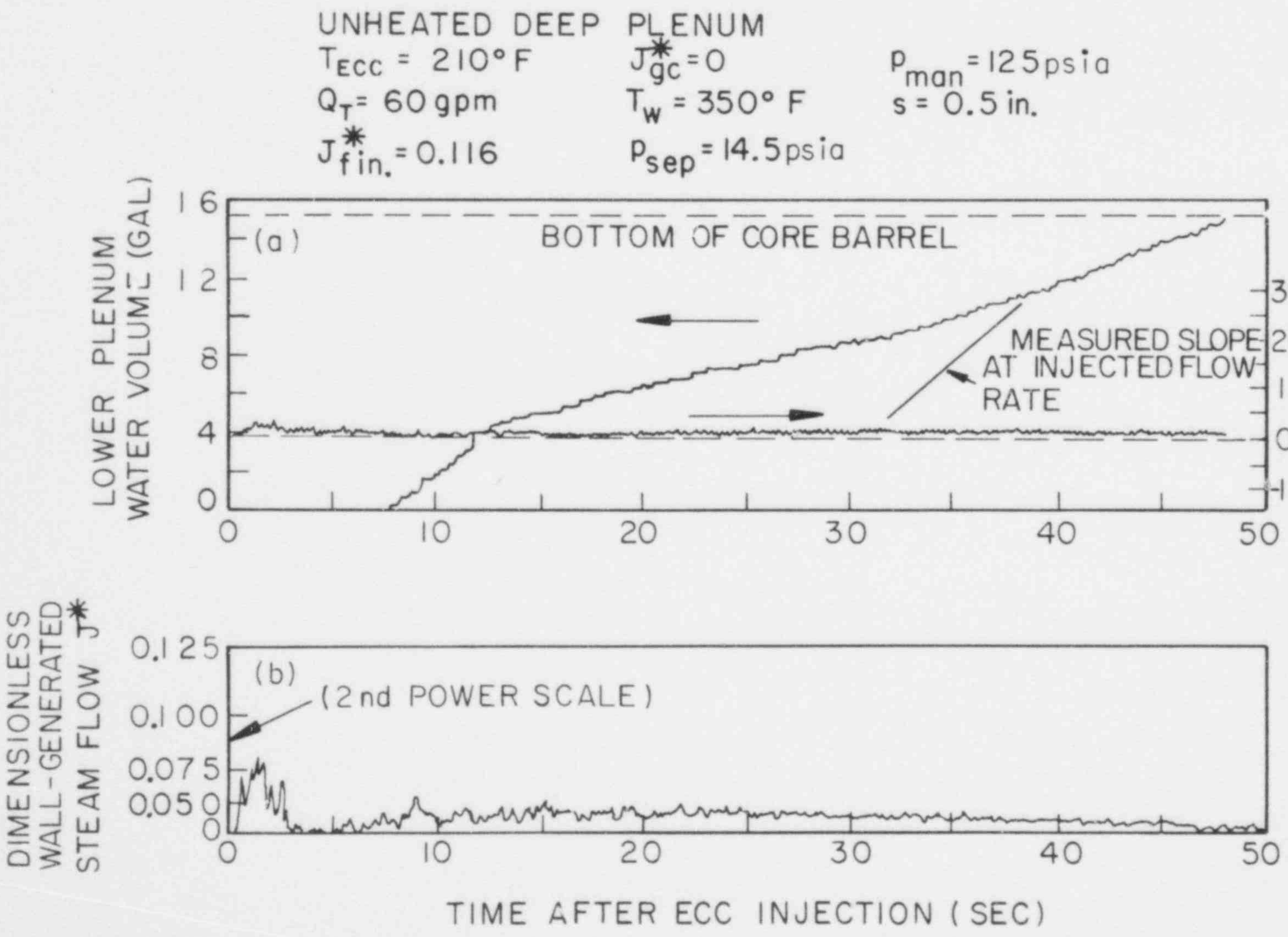

Figure 4. MEASUREMENT OF SEPARATOR VESSEL STEAM OUTFLOW WITH UNHEATED PLENUM (T_{ECC} = 210°F)

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For comparison, a test was performed under the same conditions as the test in Figure 4 but with a heated lower plenum. The results are shown in Figure 5. Frame (a) shows that the plenum filling rate was very small initially, but increased gradually over the course of the test. The measured separator outflow in frame (b) was $0.075 \leq J^{*}_{gc} \leq 0.10$ for most of the first 10 seconds of the test, though it did drop almost to zero between three and five seconds, similar to the behavior in Figure 4(b). After 30 seconds, the indicated flow gradually decreases to zero out to 80 seconds.

In comparison with Figure 4(b), the indicated steam flow behaves the same in the first five seconds of the test. This is probably the effect of the annulus heat transfer. The effect of the lower plenum heat transfer is seen in the higher measured steam flows with a heated plenum over the remainder of the test.

Clearly, measurement of the steam outflow in a few tests yields useful information--if only qualitatively--to guide analytical efforts. Continued efforts along these lines are planned.

2.3 Future Work

Future work on the topic of condensation-induced transients will include further development of the preliminary analysis presented in Reference 7. Ramped transient analytical efforts involving model sensitivity studies and data comparisons will continue with a Topical Report on this subject expected during the fourth quarter of FY78.

Lower plenum voiding studies will also continue. Data from a simplified 1/10 scale vessel will be obtained and compared with the analyses, and the effect of experimental methods used in LPV tests will be explored. The topical section of the next Quarterly Report will feature LPV.

The effects of pressure control techniques and boundary conditions in countercurrent flow tests will be also explored during the upcoming quarter.

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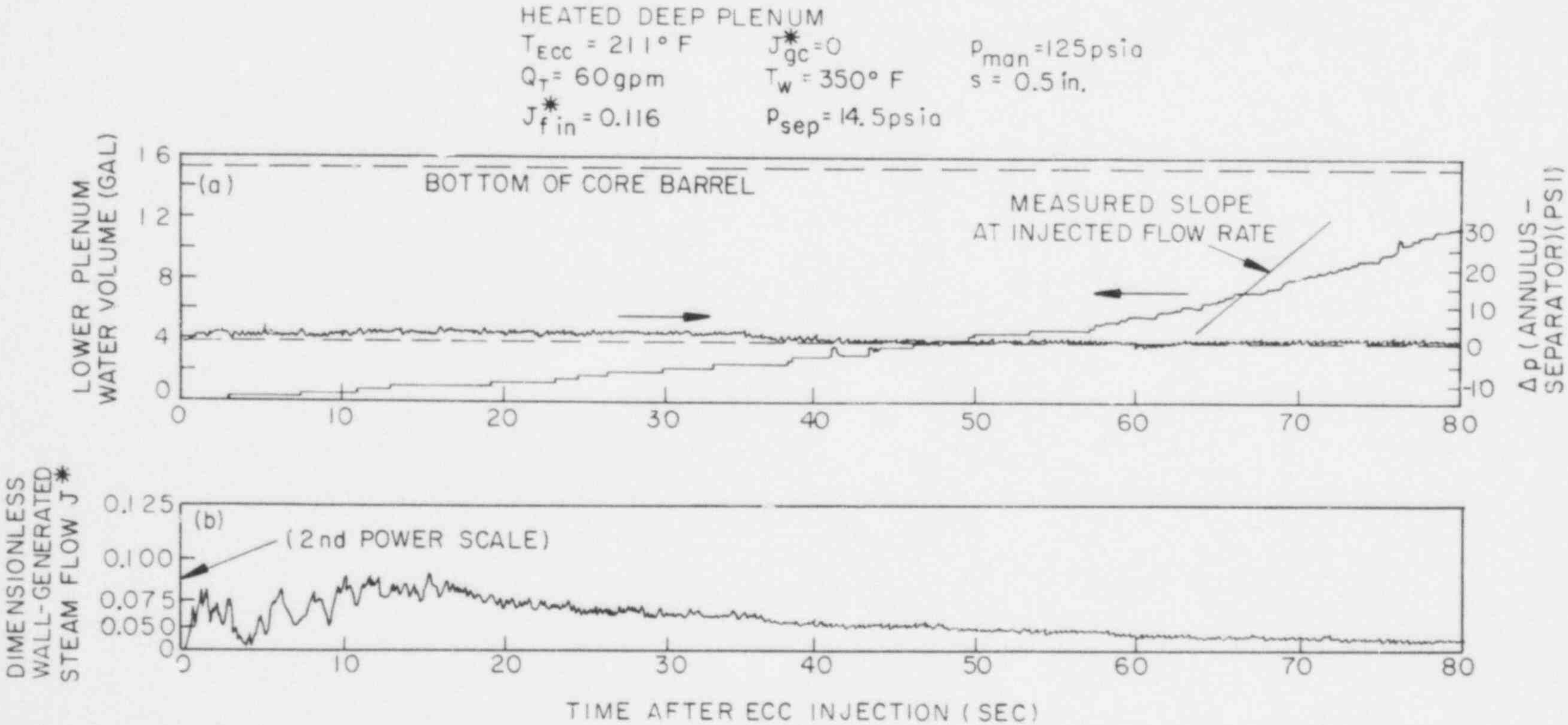

Figure 5. MEASUREMENT OF SEPARATOR VESSEL STEAM OUTFLOW WITH HEATED PLENUM (T_{ECC} = 210°F)

3 PROGRESS ON ECC BYPASS SCALING

3.1 Introduction

As described in the Introduction to this report, a number of effects have been identified as being important to the delivery of the ECC to the lower plenum of a PWR in the event of a LOCA. Among these are countercurrent flow flooding, condensation, boiling (due to superheated walls), lower plenum voiding and flashing. This topical section of the report is limited mainly to countercurrent flow flooding although several remarks on condensation and superheated wall effects are also made. Since ECC bypass testing has been performed only in subscale facilities, the concept of "scaling" arises in methods to predict full-scale, PWR behavior. Explicit analyses based on first principles have not as yet led to adequate predictions of the complex downcomer behavior in countercurrent flow although recent results of advanced code efforts are promising. Countercurrent flow test results have generally been expressed therefore as data correlations written in terms of dimensionless parameters. This report re-addresses the question of which parameters are appropriate.

An earlier Topical Report [6] addressed this same question and summarized the information available during 1976. The main conclusion of that report was that data are needed from facilities which are significantly larger than 1/15 scale. That remains our main conclusion. However, recently acquired evidence has provided valuable physical and scaling insight which leads us to modify some of the tentative conclusions in Reference [6]. In addition, the earlier report spoke only to the scaling of the flooding phenomenon with saturated water. Here we begin to address the scaling of condensation effects with subcooled water and superheated wall effects as well.

3.2 Background on Flooding in Tubes

"Flooding" is a term used in the chemical and nuclear engineering literature to describe a phenomenon which limits the rates of countercurrent flow, under gravity, of two phases with differing densities. It can be the result of either flow instability or the reaching of an envelope of the normal steady flow characteristics. For a given flow regime the flow rates at a flooding point are related and can be plotted as functions of each other to give a "flooding line" outside which operation is impossible.

The typical characteristics of a simple system limited by flooding are shown in Figure 6. Gas is supplied to a vertical tube at a controlled flux j_g (the volumetric flow rate divided by the cross-sectional area of the tube). Liquid is supplied at the top of the tube at a flux j_{fin}. The liquid flux leaving the bottom of the tube is j_{fd}. For a given value of j_{fin}, the behavior as j_g is varied is as follows. Up to a critical value of j_g called the "the complete penetration limit", all of the liquid flows down the tube and $j_{fd}=j_{fin}$. Above the complete penetration limit, j_{fd} decreases with further increase in j_g often following along or close to the "flooding line" which is the locus of

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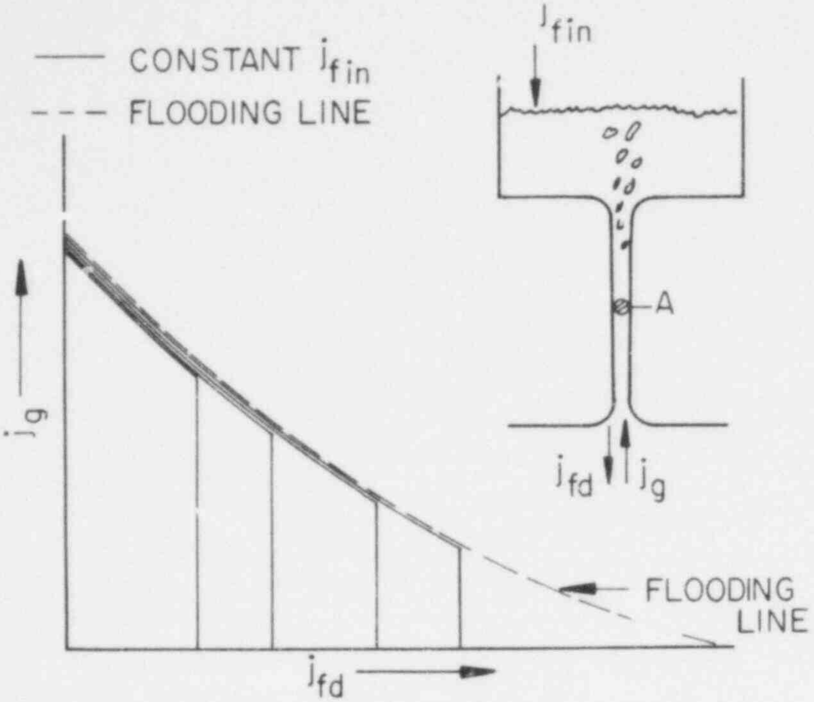

Figure 6. TYPICAL COUNTERCURRENT FLOW CHARACTERISTICS FOR A VERTICAL TUBE

the limit of allowable combinations of countercurrent flow rate. The difference ($j_{fin}-j_{fd}$) overflows at the top of the tube. At sufficiently high j_g the water is held up completely and the "complete bypass limit" has been reached. Such experiments can be performed in various ways and significant hysteresis zones have been reported.

Flooding in tubes has been studied by numerous authors without clear agreement having yet been reached about how to correlate the data. Wallis [16] studied flooding in vertical tubes for a limited range of diameters D (1/2 inch to 2 inches) using air and water at atmospheric pressure. He correlated his results with the equation

$$j_g^{*\frac{1}{2}} + j_f^{*\frac{1}{2}} = C \tag{1}$$

in which

$$j_g^* = j_g \rho_g^{\frac{1}{2}} [gD(\rho_f-\rho_g)]^{-\frac{1}{2}} \tag{2}$$

$$j_f^* = j_f \rho_f^{\frac{1}{2}} [gD(\rho_f-\rho_g)]^{-\frac{1}{2}} \tag{3}$$

The coefficient C varied depending on the end conditions, being 0.725 for sharp-edged flanges and 0.875 for smooth flanges, with some scatter in between.

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There is little theoretical basis for Equation (1). The dimensionless groups represent "balances between inertial forces and buoyancy" assuming that D is the appropriate characteristic length. The symmetrical square root correlation is merely something which has been "found to work" for similar systems such as packed towers and wetted wall columns [17].

Hewitt and Wallis [18] studied flooding in a 1.25-inch diameter tube using porous sintered tubular sections for introducing and removing the liquid. Equation (1) with C=1 fits the data. Further support for Equation (1) is given by Wallis [19]. A detailed study by Hewitt et al [20] of the effect on flooding of changing the tube length between porous sintered sections, at which liquid was added and removed, revealed that the situation was not so simple. Results depended on L/D ratio and did not seem to tend to any limit as L/D was increased beyond 100. Grolmes et al [21] studied flooding using nitrogen and water in tubes ranging from 4 mm to 25 mm in diameter and found no effect of either L/D or tube diameter. The critical gas velocity appeared to depend on liquid film thickness.

Pushkina and Sorokin [22] performed flooding experiments using various methods of introducing the liquid and correlated all of their data, independent of liquid flow rate, with the equation

$$K^* = j_g \rho_g^{\frac{1}{2}} [g\sigma(\rho_f - \rho_g)]^{-\frac{1}{4}} = 3.2 \tag{4}$$

K^* has been called the "Kutateladze Number" and can be obtained from Equation (2) by substituting the characteristic dimension

$$D_\sigma = \sigma^{\frac{1}{2}} [g(\rho_f - \rho_g)]^{-\frac{1}{2}}$$

determined from a balance between surface tension and buoyancy, for D in Equation (2). Defining a dimensionless diameter $D^* = D/D_\sigma$, the Kutadeladze number and the Wallis flux parameter can be related by $K^* = j^* D^{*\frac{1}{2}}$. In these experiments D^* ranged from 2 to 120 (0.25 to 12 inch tubes).

Wallis and Makkenchery [23,24] studied the gas velocity necessary to support a liquid film hanging above a dry tube wall. They found that j_g^* = constant correlated the data over a limited range of dimensionless tube diameters ($3 < D^* < 20$) while the criterion $K^* = 3.2$ was more appropriate for large tubes ($D^* > 30$). This finding has since been supported by Richter and Lovell [25] who extended the data base up to $D^* = 100$ (10 inch tubes).

One explanation for the observed failure of D as the characteristic dimension in large tubes is that the characteristic dimension is scaled by surface tension through its influence on the size of the "discrete protuberances" on a liquid film. The typical size of these protuberances is about 5 mm. It seems that small waves might dominate the idealized research situation with water injection by quiescent top-flooding. However, it is hard to imagine such a small dimension being important under realistic ECC injection conditions in which large masses of water with dimensions of the order of several feet are involved and are subject to intense condensation, boiling, and flashing.

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This review of simple studies in tubes has served to reveal both uncertainties and inconsistencies in what appear at first sight to be simple phenomena. While the use of some dimensionless groups for correlation purposes has been suggested, it can by no means be claimed that the phenomena, even in a simple tubular geometry and situation, are sufficiently well understood for routine analysis. Additional effects such as steam condensation on subcooled water remain to be studied in tubes. Direct application of these results to the PWR situation is highly questionable.

3.3 Saturated Water Flooding in Reactor Vessel Models

Conventional formulations for calculating delivery rate to the lower plenum in reactor vessel experimental models rely on a modified version of the Wallis correlation. Once such formulation, proposed by Creare in 1976 [4], is:

$$J_g^{*\frac{1}{2}} + mJ_{fd}^{*\frac{1}{2}} = C \tag{5}$$

where J^* is simply j^* with the annulus circumference used as the characteristic dimension. (It has been shown repeatedly [2,3] that annulus gap or hydraulic diameter are unsatisfactory as characteristic dimensions to correlate existing data.) In Equation (5), J_g^* is taken to be the difference between the experimentally supplied reverse core steam flow J_{gc}^* and an "effective" amount of steam condensed $J_{g,cond}^* = fJ_{g,eq}^*$, where $J_{g,eq}^*$ is the amount of steam that would be condensed at thermodynamic equilibrium, raising the entire flux of injected water J_{fin}^* from injection temperature T_{ECC} to saturation

$$J_{g,eq}^* = J_{fin}^* \frac{c_p(T_{sat}-T_{ECC})}{h_{fg}} \sqrt{\frac{\rho_f}{\rho_g}} \tag{6}$$

The factor f represents both departure from thermodynamic equilibrium in setting the <u>amount</u> of condensation and the incomplete fluid-dynamic effectiveness of the condensation that occurs as a means to suppress flooding. The coefficients proposed in Reference [4] are:

$$C = 0.32 \tag{7}$$

$$m = \exp[-5.6J_{fin}^{*\,0.6}] \tag{8}$$

$$f = \frac{p^{\frac{1}{4}}}{1+30J_{fin}^*} \quad \text{(p in atmospheres)} \tag{9}$$

This report identifies several general findings which will enable us to upgrade the correlation at a later time. However, our emphasis here is on scaling. Information on methods to better correlate the available subscale data is treated only incidentally as is necessary.

1816 353 ~~349~~

Reference [6] summarized contemporary experimental results for saturated water on a single scaling plot. Since that time several new experiments have been performed which provide new scaling insight. Figure 7 is a new scaling plot intended to supercede that in Reference [6].

In the remainder of this section we point out two specific weaknesses of earlier data analysis. We next review the data underlying Figure 7 to illustrate methods of data analysis and to summarize the current state of knowledge.

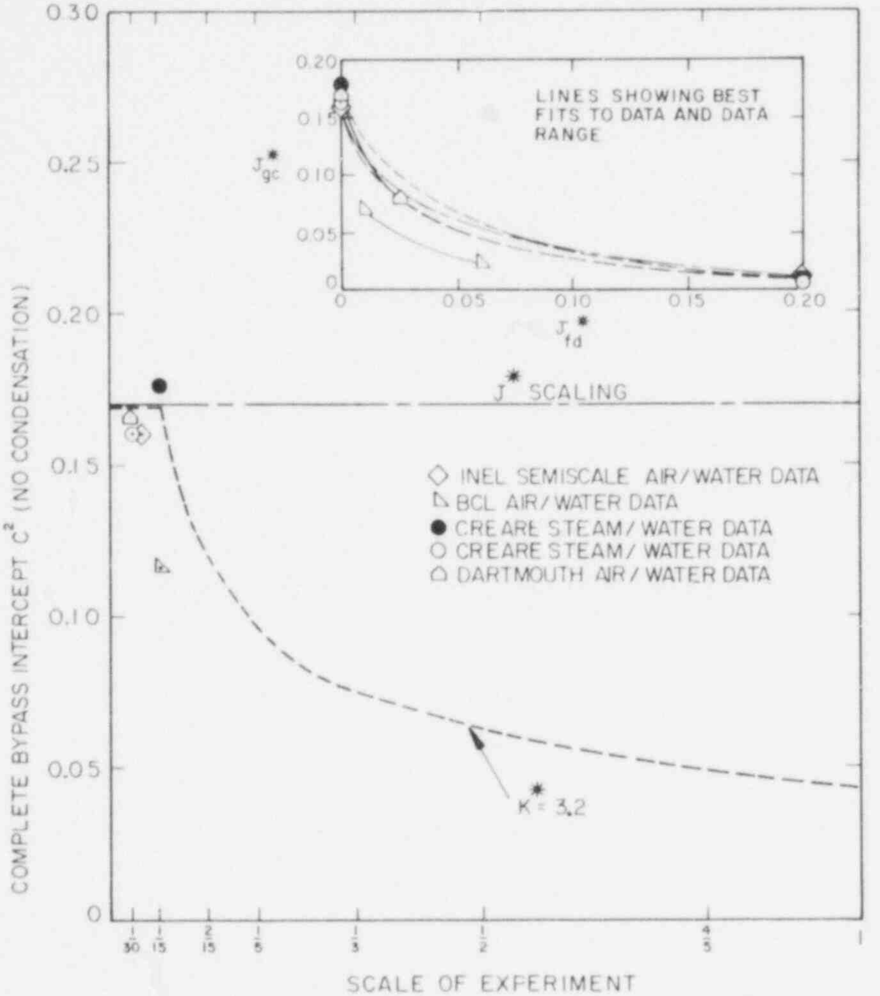

Figure 7. SUMMARY OF EXPERIMENTAL RESULTS FOR COMPLETE BYPASS OF SATURATED WATER AT SEVERAL SCALES

354

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The Difficulty of Extrapolation to Complete Bypass

Many early data sets lack data at and near complete bypass and in some cases most of the partial penetration range is missing as well. Specific examples will be shown in the data review which follows. (The reasons for this lack of data vary from the need to scope other phenomena in a limited time period to concern about overpressuring fragile glass vessels.) Figure 8 shows a recent set of saturated water data in the usual J^* coordinates and in the $J^{*\frac{1}{2}}$ coordinates that are useful for visual comparison with the Wallis correlation. About half of the data near complete bypass are presented with open rather than solid symbols to support our point here.

If only the solid symbols were available, graphical extrapolation in $J^{*\frac{1}{2}}$ coordinates (Figure 8(b)) or numerical fitting of the data to the Wallis correlation gives about $C \approx 0.32$. Neither of these methods can hope to reveal the inherent uncertainty of the extrapolation, which is made obvious in this example where the complete data set can be viewed. Plainly, the actual value of C should be about 0.40. Although only 25%, this sort of uncertainty is very important because it is of the order of the change expected between different small-scale experiments.

Since present licensing calculations are based solely on the "end of bypass", why do we care about the location of the complete bypass point? Our reasons are both scientific and practical. Firstly, we are striving to make best estimate calculations which are perhaps more critically dependent on the complete bypass point than on the complete delivery point. In particular, the superheated wall delay is sensitive mainly to the complete bypass point and in a realistic steam flow transient, the integrated delivery to the lower plenum during refill is much more sensitive to the partial penetration range of the flooding curve than to the literal "end of bypass" point. Secondly, due to data irregularities frequently seen near the complete delivery point, it is more useful to characterize the entire flooding curve than to choose a conservative end-of-bypass point.

The Difficulty of Extrapolation of Subcooled Water Data

Figure 9 shows a modern set of data from a currently operating facility. The open symbols were reported in our last Topical Report [3] and the filled symbols are reported here for the first time. The numbers by each data point show the actual subcooling. The filled symbols were obtained recently using an oversized (three inch diameter) broken leg which gave low pressure drop, kept the vessel near atmospheric pressure, and kept the subcooling low (less than 20°F) even at complete bypass. The subcooling was less than 10°F for most of these data. Only data similar to the open symbols were available at the time Reference [6] was written and these were obtained with a scaled (1.875 inch diameter) broken leg. Since the break area is fixed, the pressure and hence the subcooling increases significantly (50°F or more) as the amount of liquid bypassed (and hence the break pressure drop) is increased with 212°F ECC. It is therefore very difficult to achieve anything remotely approaching saturated water (say within 10°F) at complete bypass in tests with 212°F water and a scaled broken leg.*

---

*By closing down a valve in the broken leg, it is possible to <u>raise</u> the subcooling of the data near complete delivery and thereby maintain a constant, though high subcooling (say 50 to 60°F). Although this procedure is useful to data analysis, it does not provide saturated water data. The valve was wide open to the full pipe diameter for all the data of Figure 9.

1816 355

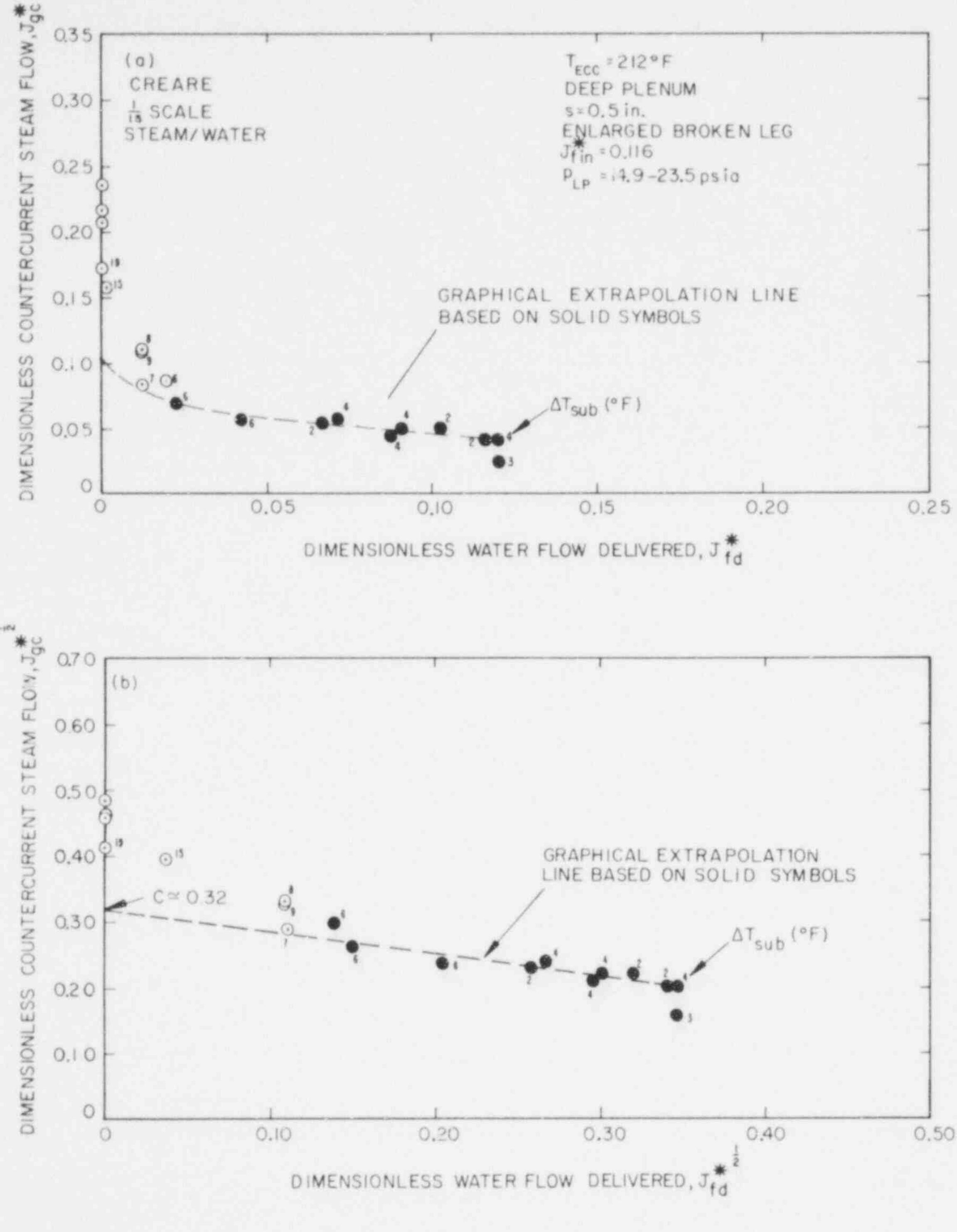

Figure 8. ILLUSTRATION OF THE DIFFICULTY OF DATA EXTRAPOLATION TO COMPLETE BYPASS

1846 356

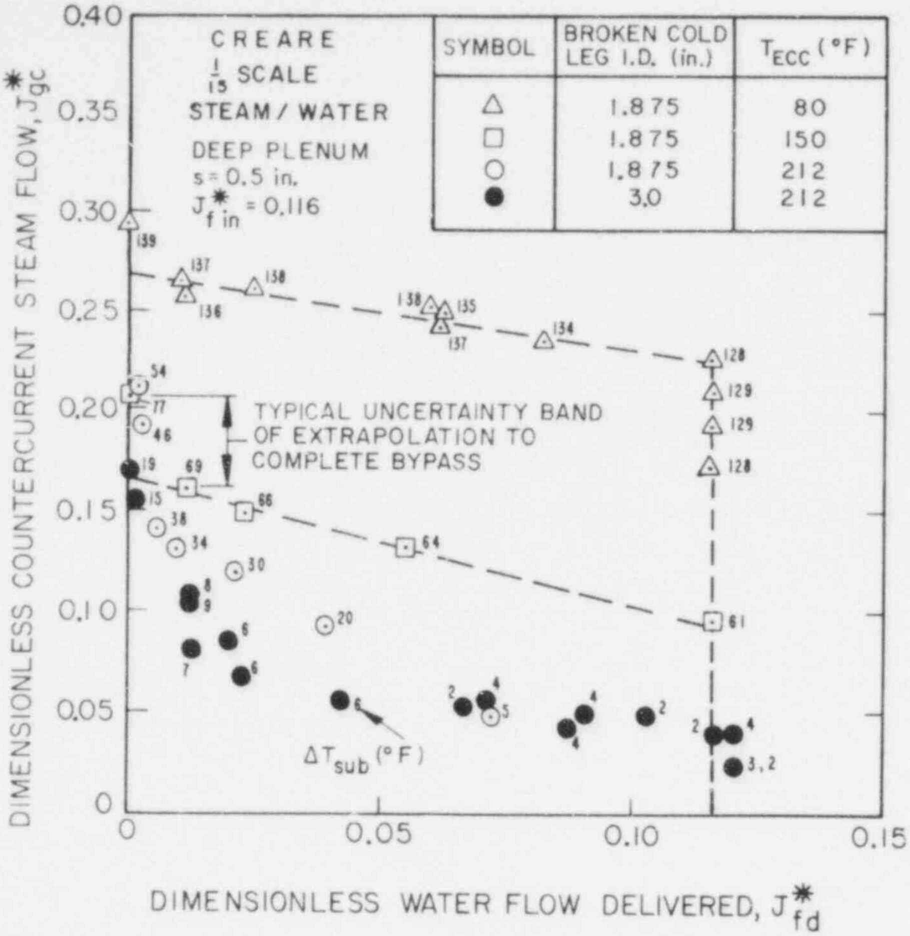

Figure 9. ILLUSTRATION OF THE DIFFICULTY OF SUBCOOLED WATER DATA EXTRAPOLATION TO SATURATION

Since saturated water data have been lacking, it has been customary to extrapolate data at different, but high subcoolings down to saturation. This exercise has been performed by various groups both approximately and with rigorous application of numerical statistical analysis. (In the latter case the "extrapolation" occurs when the coefficient C in the Wallis correlation is determined.) Below we show how this approach can fail.

Crudely, the complete bypass points on Figure 9 are about J^{*}_{gc} = 0.28 for 85°F water (139°F subcooling) and J^{*}_{gc} = 0.18 for 150°F water (77°F subcooling) based on the simple straightline extrapolations on Figure 9. (The minimum uncertainty of this extrapolation, apart from the raw data uncertainty, is indicated.) Linear extrapolation of the complete bypass points to zero subcooling suggests that complete bypass of saturated water would be at

$$J^{*}_{gc} = 0.18 - (0.28 - 0.18)\,\frac{77}{150-77} = 0.08$$

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Inspection shows that the open symbols for 212°F water (which is also highly subcooled due to the break pressure drop pressure) are roughly consistent with this extrapolation. Yet the filled symbols, which very nearly represent saturated water, are blatantly discrepant with the extrapolation of the subcooled water data since they give complete bypass at $J^*_{gc} \approx 0.17$, not $J^*_{gc} = 0.08$.

To be sure, different data sets can be invoked (and have been in References 3,4,6,10, and 26) to represent different water injection rates, vessel pressures, or data from different facilities. Additional data have been obtained to more closely characterize the complete bypass points, the uncertainty of which propagates dramatically into the extrapolated value for C. More sophisticated methods of data analysis have also been employed. Sometimes a reasonable result is obtained. However, having carried out these exercises and having reviewed similar efforts by others, we are led inevitably to the conclusion that saturated water behavior is far better represented by data for very nearly saturated water than by extrapolation of data for highly subcooled water.

Since subcooled ECC is injected in a PWR following a postulated LOCA, why do we care about saturated water behavior? There are again two reasons, one scientific and the other practical. First, there is a need in ECC bypass testing to isolate the several processes such as flooding, condensation and boiling for independent study in order to better assess the phenomena and to develop scaling criteria. In particular, as we show later in this report, condensation can be bounded in some respects by lines representing the limits of "no condensation" and "thermodynamic equilibrium". In contrast, criteria to bound flooding on comparable physical grounds have not yet been established. Secondly, since the ECC is heated by steam condensation in the cold legs and by heat transfer from superheated walls, perhaps to saturation in some circumstances, there is good reason to understand saturated water behavior. (Thermocouple data from some tests in Semiscale and LOFT show ECC temperatures close to saturation during refill.) On the other hand, the effects of condensation also require study and here we stress the importance of saturated water testing mainly to ensure that it is not overlooked. Later in this report we comment on the scaling of other phenomena such as condensation.

In pointing out the difficulties of extrapolation to complete bypass and to saturated water behavior, the stage has been set for the review of available data below. We first review the data which we feel are most useful and we then comment on the remaining data. Table I lists all the data in groups as used in this report to assess saturated water flooding separately from the effects of subcooling.

Data for Steam and Nearly Saturated Water

The only full test series to date with steam and nearly saturated water (achieved by an oversized broken leg) have been performed by Creare. Such tests at 1/30 scale were first performed in 1976 [27] for a program sponsored by EPRI. Additional data at 1/15-scale are reported here for the first time.

Figure 10 shows the 1/30-scale data in the usual J^* and $J^{*\frac{1}{2}}$ coordinates. Although the time-average vessel pressures are essentially atmospheric, the subcooling is about 7°F because the water injection temperature is 205°F. The data extend to complete bypass.

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TABLE I

SUMMARY OF DATA FOR ASSESSING SATURATED WATER COUNTERCURRENT FLOW

Contractor	Scale	Gas	Subcooling	Reference
Data on Saturated Water Behavior				
Creare	1/30	Steam	≈ 7°F	[27]
Creare	1/15	Steam	0-20°F	here
Dartmouth	1/30	Air	—	[28]
INEL	1/25	Air	—	[29]
Battelle	1/15	Air	—	[30]
Subcooled Countercurrent Flow Data				
Dartmouth	1/30	Steam	15-170°F	[12]
Creare	1/30	Steam	7-150°F	[27]
Creare	1/30	Steam	0-135°F	[6]
Creare	1/15	Steam	0-135°F	[3]
Battelle	1/15	Steam	10-170°F	[14]
Battelle	2/15	Steam	110-235°F	[26]
CE	1/5	Steam	95-170°F	[31]
Expected Data on Saturated Water Behavior				
Battelle	1/15	Air	—	Unpublished
Dartmouth	1/10	Air	—	Planned
Battelle	2/15	Steam	≤ 30°F	Planned
Battelle	2/15	Air	—	Under Consideration

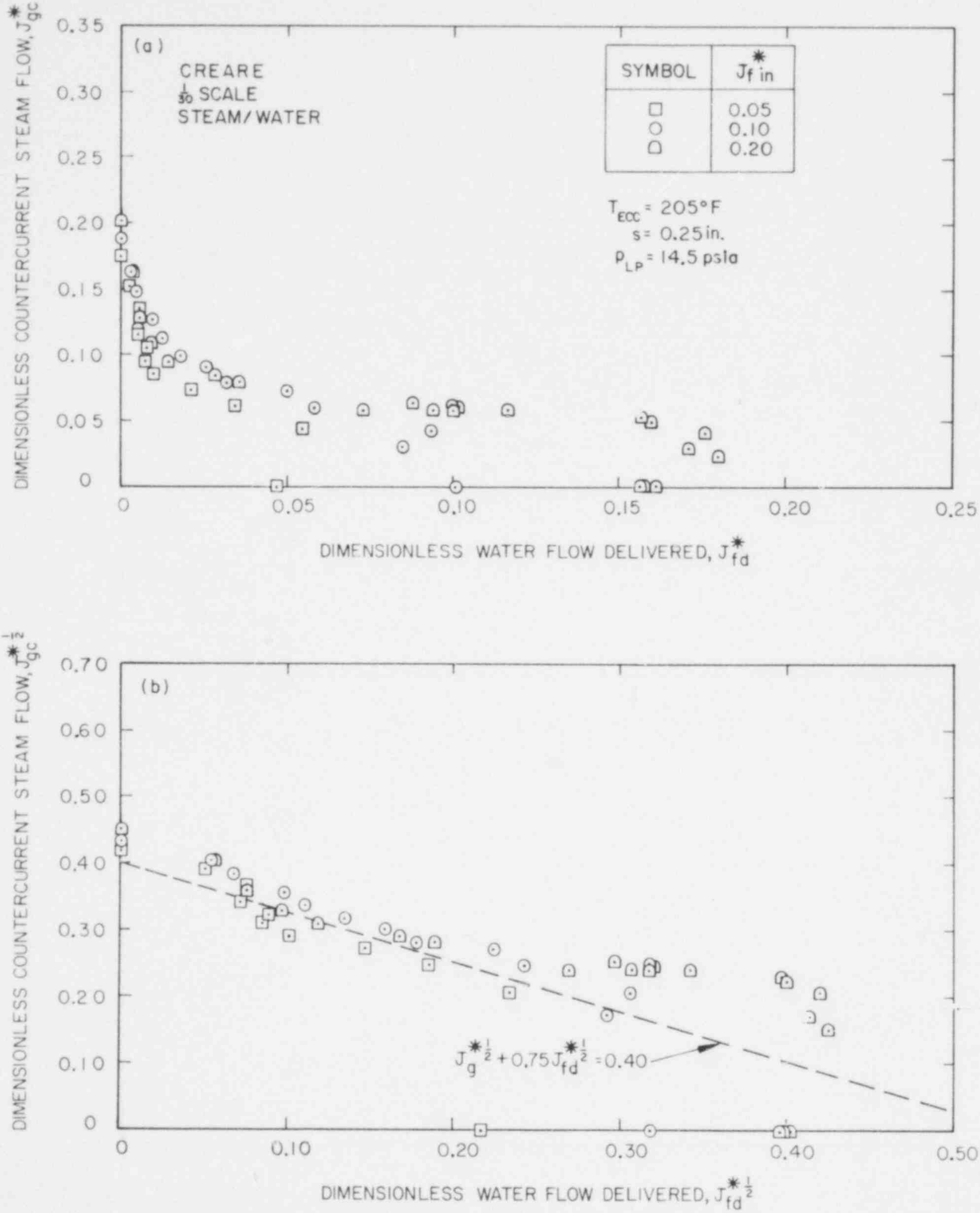

Figure 10. CREARE 1/30 SCALE SATURATED WATER DATA [27]

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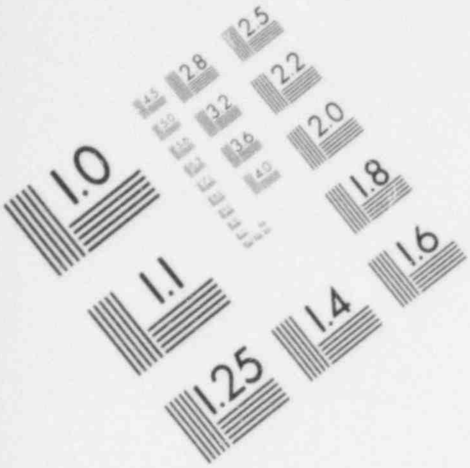
IMAGE EVALUATION
TEST TARGET (MT-3)

6″

MICROCOPY RESOLUTION TEST CHART



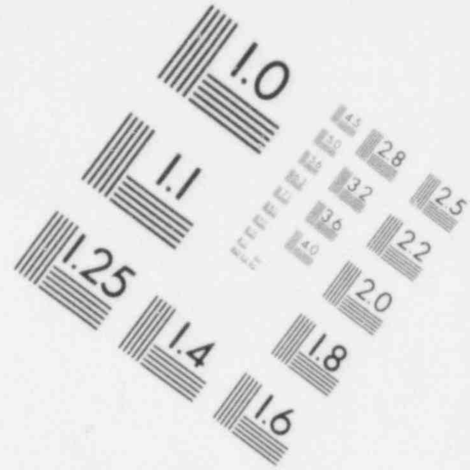
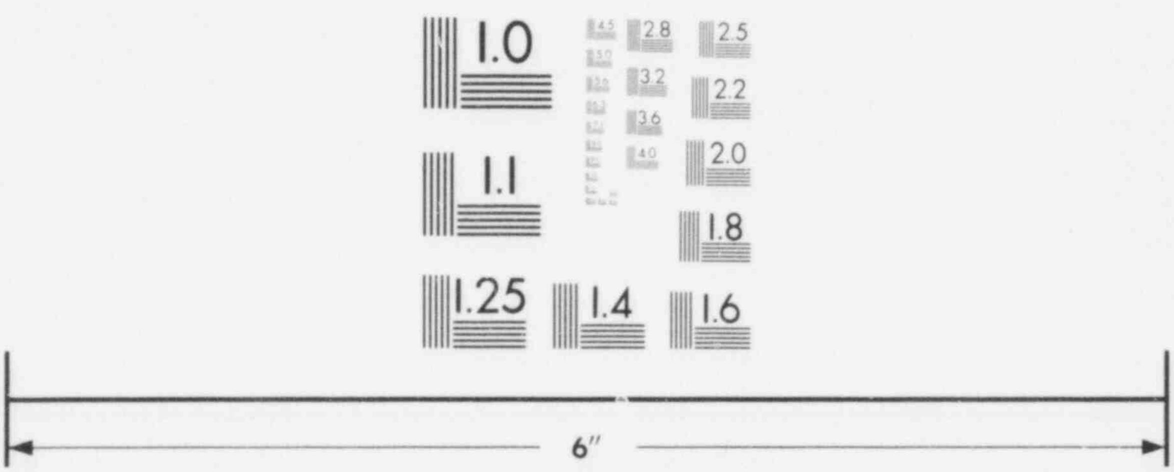


IMAGE EVALUATION
TEST TARGET (MT-3)



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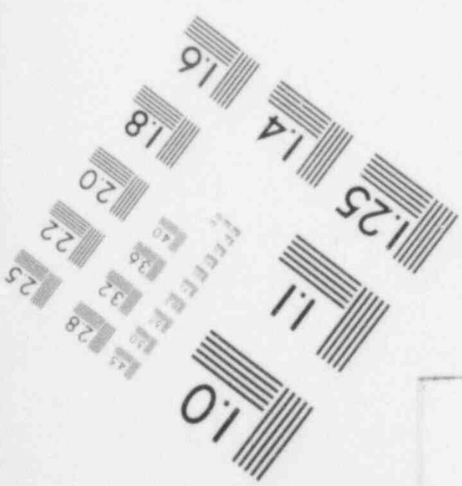
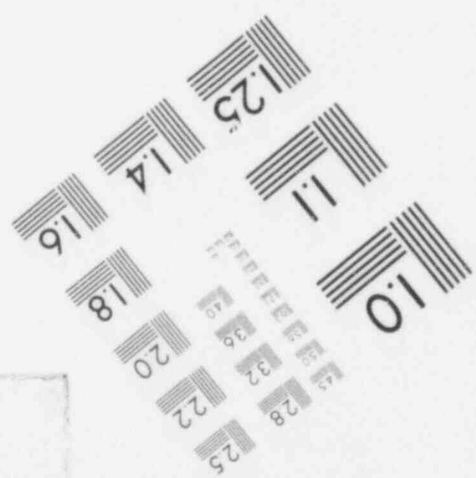
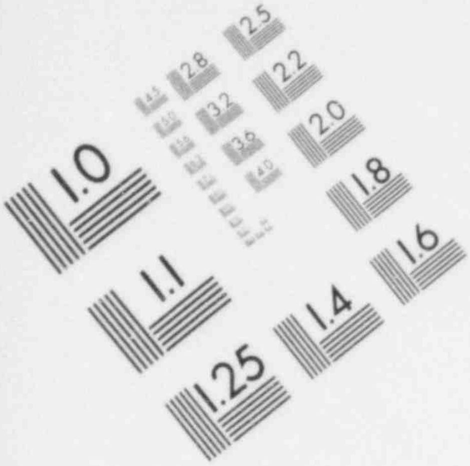






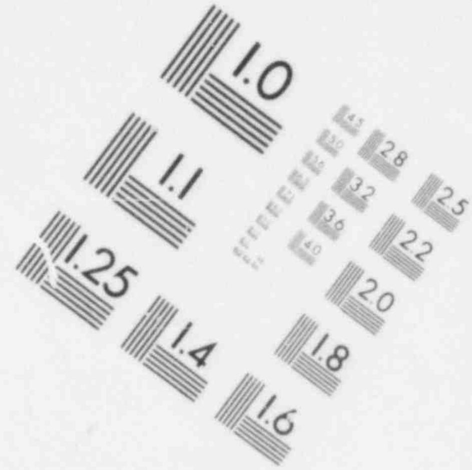
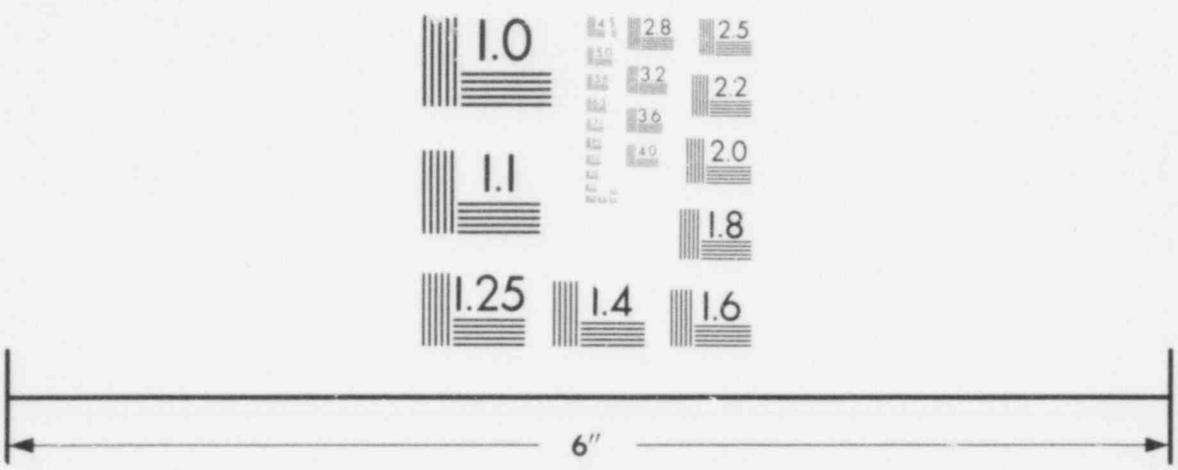


IMAGE EVALUATION TEST TARGET (MT-3)



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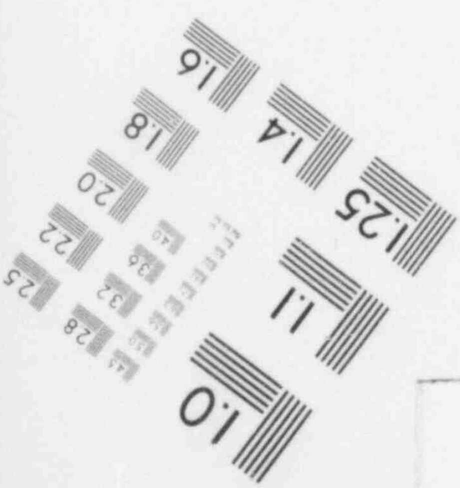
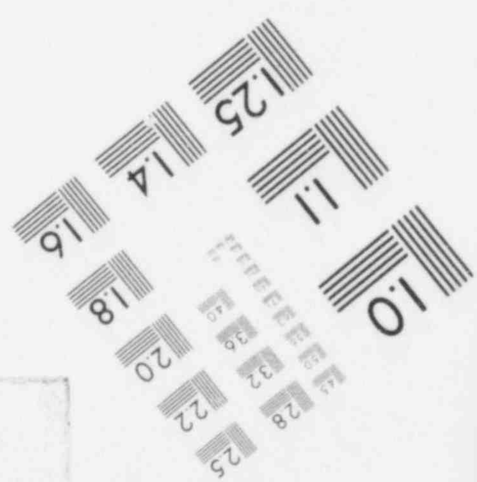
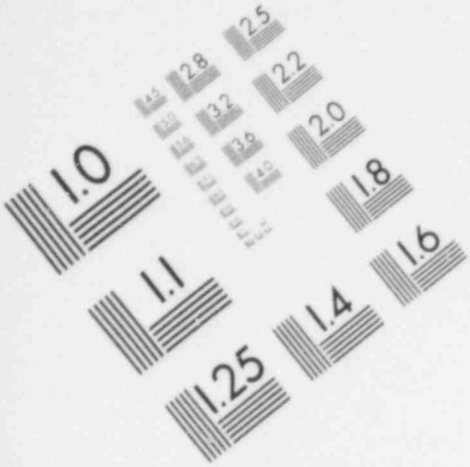






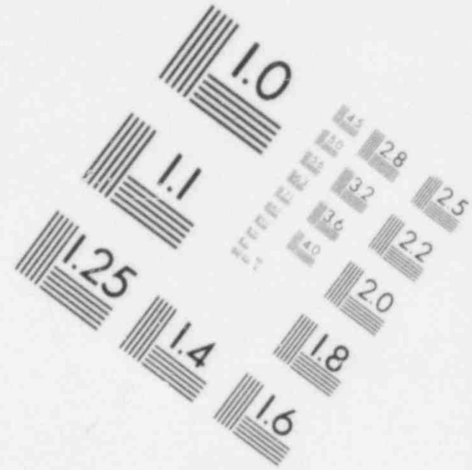
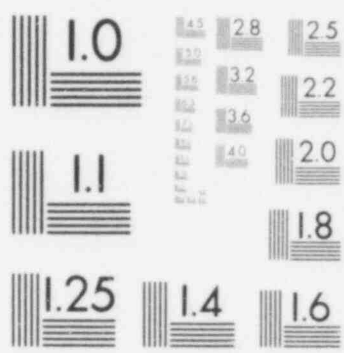


IMAGE EVALUATION
TEST TARGET (MT-3)



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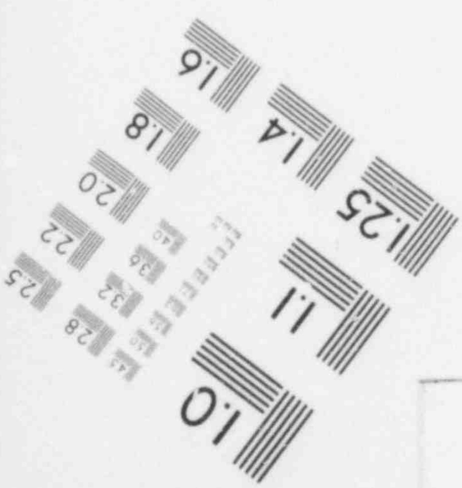
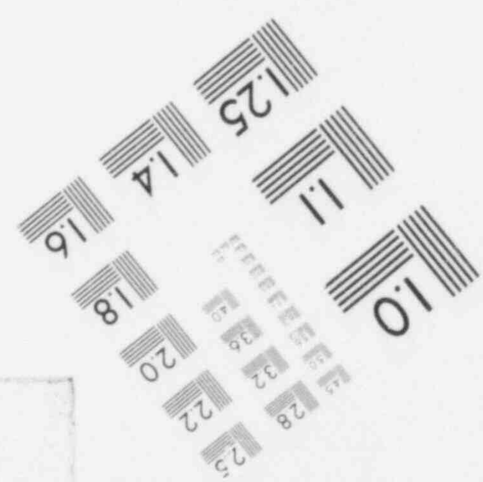
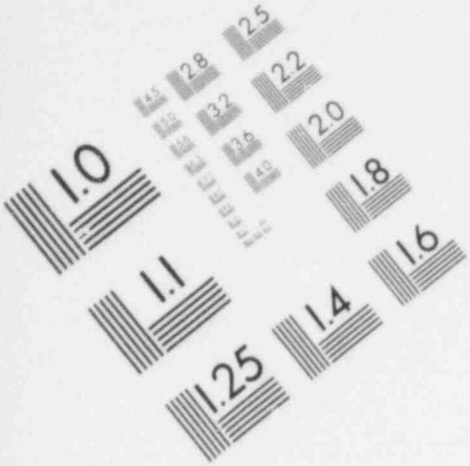
MICROCOPY RESOLUTION TEST CHART







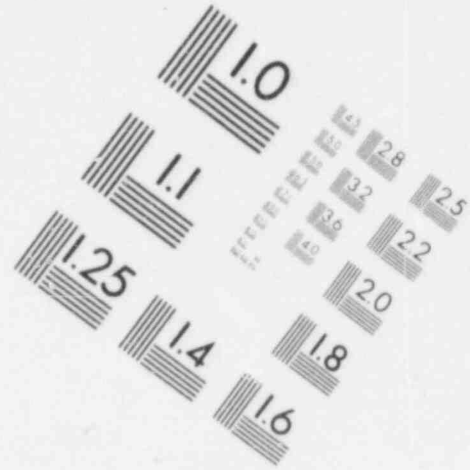
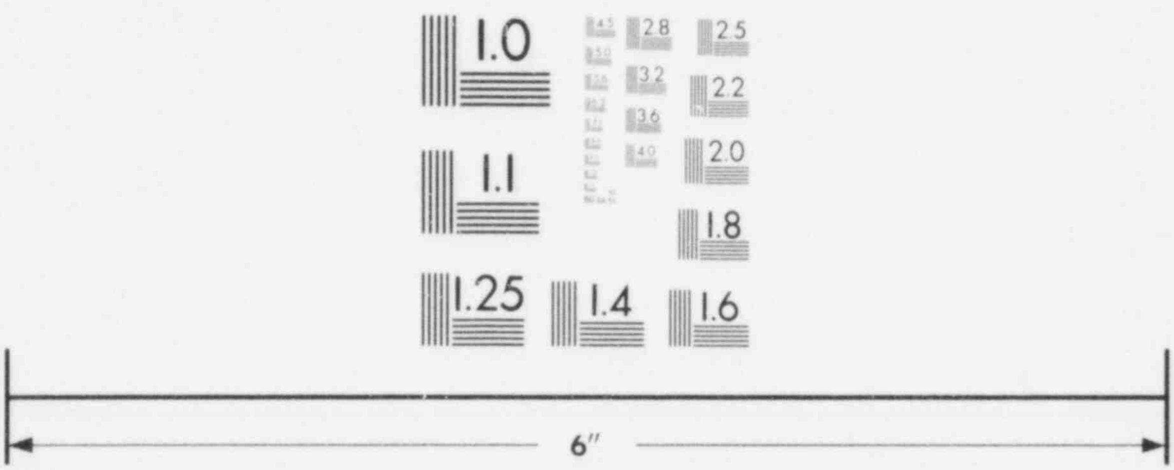


IMAGE EVALUATION TEST TARGET (MT-3)



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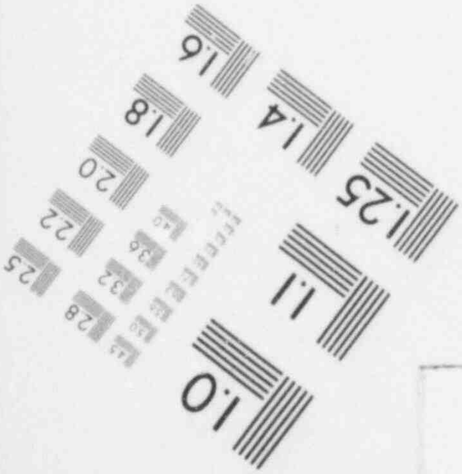

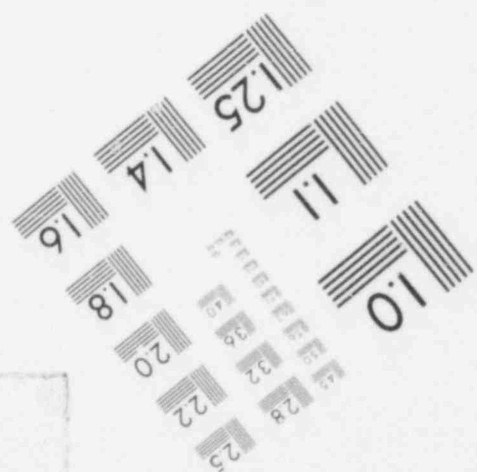

Two features of this data set should be noted:

1) For data near saturation, the effect (if any) of water injection rate is small and of the order of the data scatter.

2) Transition to complete delivery occurs abruptly at $J^*_{gc} \approx 0.05$. Specifically, the data with $J^*_{fin} = 0.2$ are nearly horizontal (at $J^*_{gc} = 0.05$) over the range $0.05 < J^*_{fd} < 0.16$.

Thus, the coefficient m is relatively insensitive to water injection rate. On the other hand, the data near complete delivery, particularly for the highest water injection rate, are poorly represented by the Wallis correlation as shown in Figure 10(b). Although representing m as a function of J^*_{fin} would probably improve a least-squares fit to all of the data, this type of m factor is inconsistent with the conclusions reached by this detailed examination of the data. A graphical fit to the data (Figure 10(b)) gives $C = 0.40 \pm 0.02$ and $m = 0.75 + 0.1$. In making this fit, data on the complete bypass line or near complete delivery are ignored because they are not well characterized by the Wallis correlation. (The latter data are, however, well represented by $J^*_{gc} \approx 0.05$. for $J^*_{fd} < J^*_{fin}$.) A negligible correction to C of only 0.005 to 0.01 is calculated using the values of f derived in Reference 4 and a subcooling of 7°F.

Figure 11 shows the Creare 1/15-scale data obtained recently with an oversized broken leg. These data are similar to the 1/30-scale data. Again the data near complete bypass are relatively insensitive to J^*_{fin} and the transition to full delivery is abrupt at $J^*_{gc} \approx 0.05$. The data with $J^*_{fin} = 0.15$ do lie a very small amount above the other data on Figure 11, perhaps due to minor differences in subcooling or normal data scatter.

A graphical fit to these 1/15-scale data gives $C = 0.42 \pm 0.02$ and $m = 0.75 \pm 0.15$ as shown on Figure 11. These numbers are the same as those obtained for the 1/30-scale data within the uncertainty of fitting the data. Figure 12 directly compares the 1/30 and 1/15-scale data to confirm the high degree of agreement between the two data sets.

In summary, independent sets of data for steam and saturated water at 1/30 and 1/15 scale have displayed qualitative similarity and have given complete bypass at $C \approx 0.40 \pm 0.02$ and a single slope coefficient $m = 0.75 \pm 0.2$ independent of water injection rate. The uncertainty in determining the complete bypass point is of the order of the data scatter. We have restrained in this presentation from fitting the data numerically, preferring to display the data fit graphically for direct assessment by the reader. Although some refinement may be achieved in future work by statistical data fits, the main need is for additional data at larger scale. Similar tests at 2/15 scale are planned by Battelle Columbus Laboratories (BCL).

Air/Water Data

Testing with air and water eliminates questions about the effects of condensation, but introduces the new question of whether air and steam behave in a similar fashion. To cite but one example, if K* scaling of flooding applies, then the different surface tensions of air/water and steam/water should cause a shift in the flooding point. Nonetheless, air/water tests provide information that complements the steam/water data and warrants presentation.

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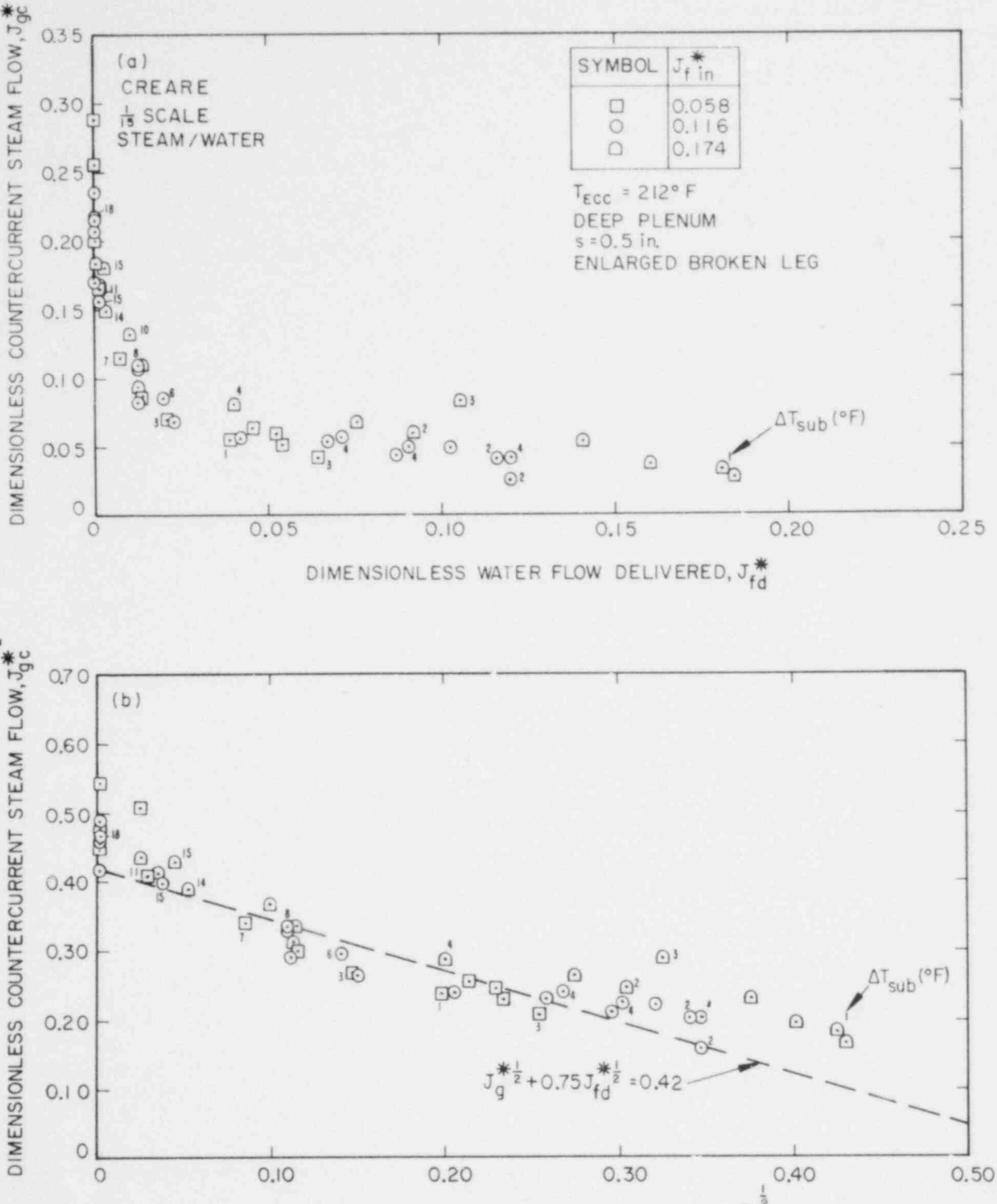

Figure 11. CREARE 1/15 SCALE SATURATED WATER DATA

1847 008

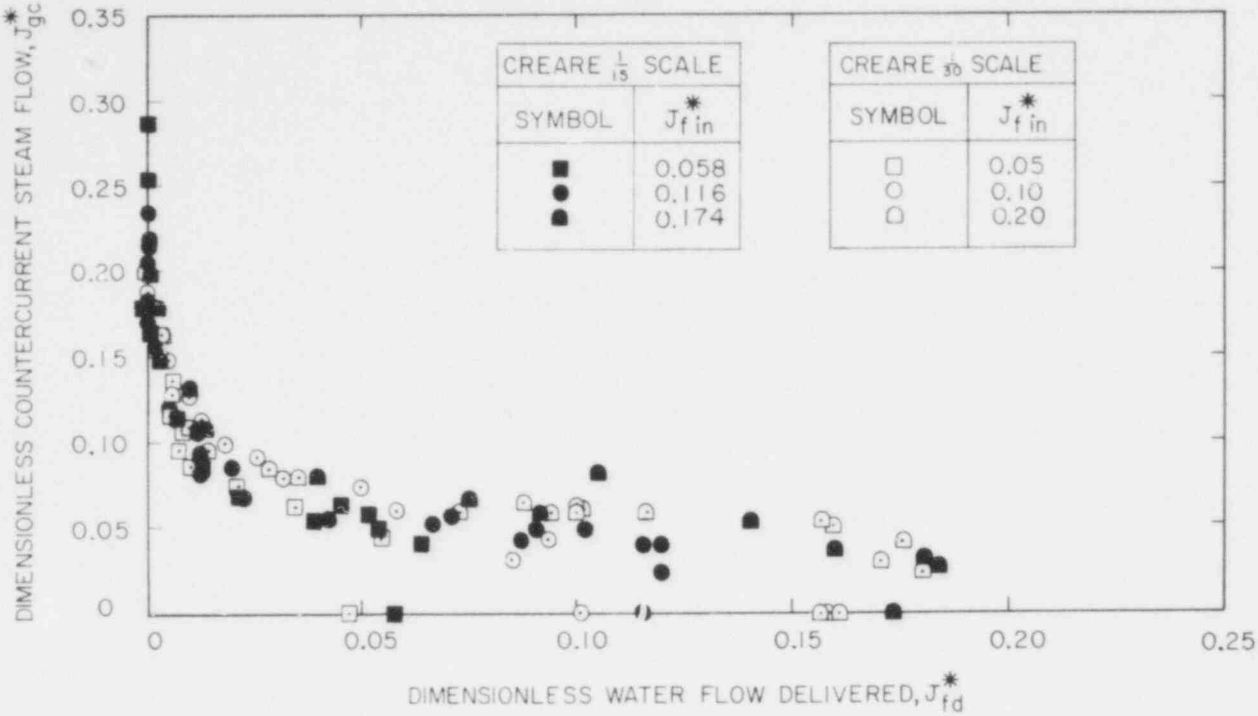

Figure 12. COMPARISON OF CREARE 1/30 AND 1/15 SCALE FACILITY WATER DATA

Wallis et al present air/water data from a 1/30-scale facility at Dartmouth [28]. These data are shown in Figure 13 and are compared in Figure 14 with the Creare 1/30-scale steam/water data. Near complete bypass the two data sets agree well and a fit to the Dartmouth data gives $C = 0.43 \pm 0.02$ and $m = 1.0 \pm 0.2$. Additional air/water tests at Dartmouth are planned at 1/10 PWR scale.

Air water tests have also been performed in the Semiscale vessel which, though quite tall, has a diameter only 1/25 of PWR scale. Reference [29] reports a total of 11 baseline test series according to the parameter categories cited in Table I of that report.

All but four of the test series were for geometries with a downcomer filler piece which distorts the physical situation. The remaining data sets (without a filler piece) all are similar to the sample data set shown in Figure 15 where it is compared with the correlation derived by INEL [29]. The INEL correlation gives $C = 0.40$ and $m = 0.70$, in good agreement with the data of Figure 15 and the remaining data except for one anomalous set of data with 0.35 inch gap (shown in Figure 19 of Reference 6) which are slightly lower than the correlation line.

The Semiscale air/water data are compared in Figure 16 with the Creare 1/30-scale steam/water data. In general, the two data sets agree closely. A minor discrepancy is that the Semiscale air/water data do not display the abrupt transition to complete delivery seen in the Creare steam/water data. It is unclear whether this difference is due to different behavior of air and steam or simply different experimental conditions or geometries. No other data speak to this issue.

1847 003

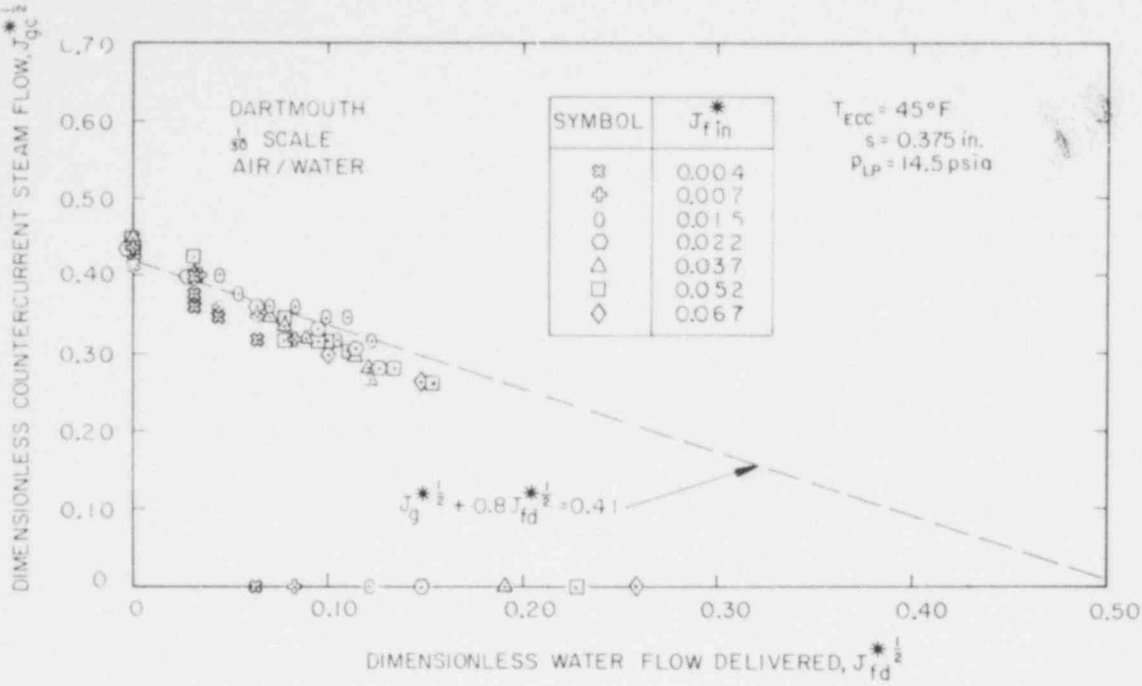

Figure 13. DARTMOUTH 1/30 SCALE AIR/WATER DATA [28]

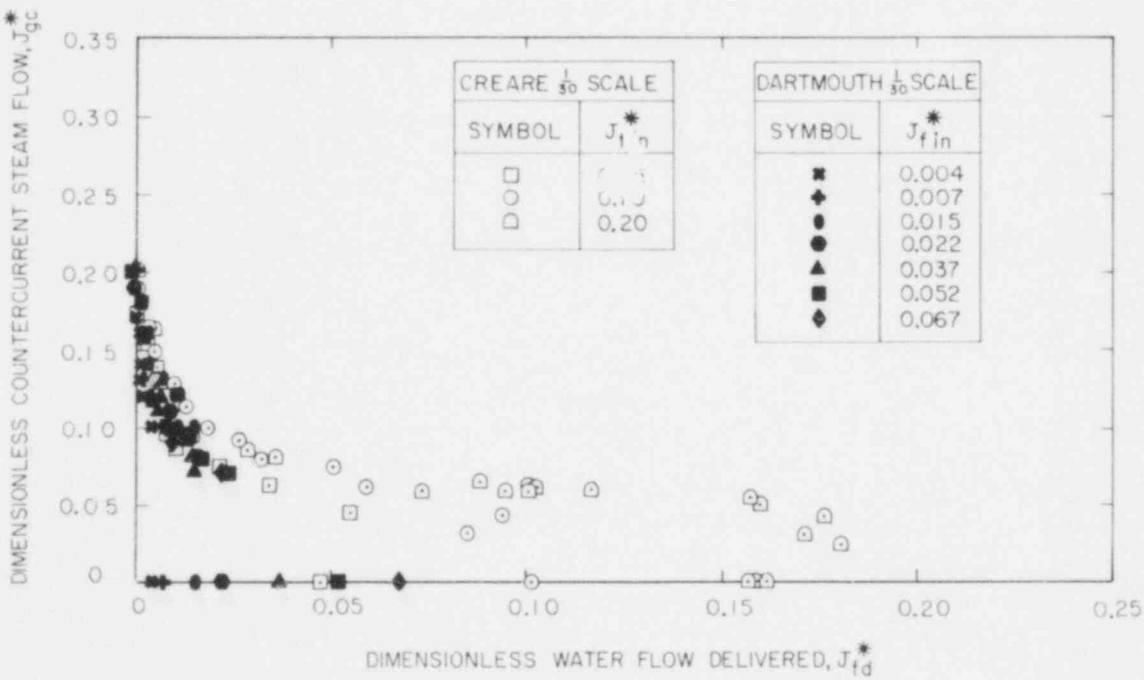

Figure 14. COMPARISON OF CREARE AND DARTMOUTH 1/30 SCALE DATA

1847 004

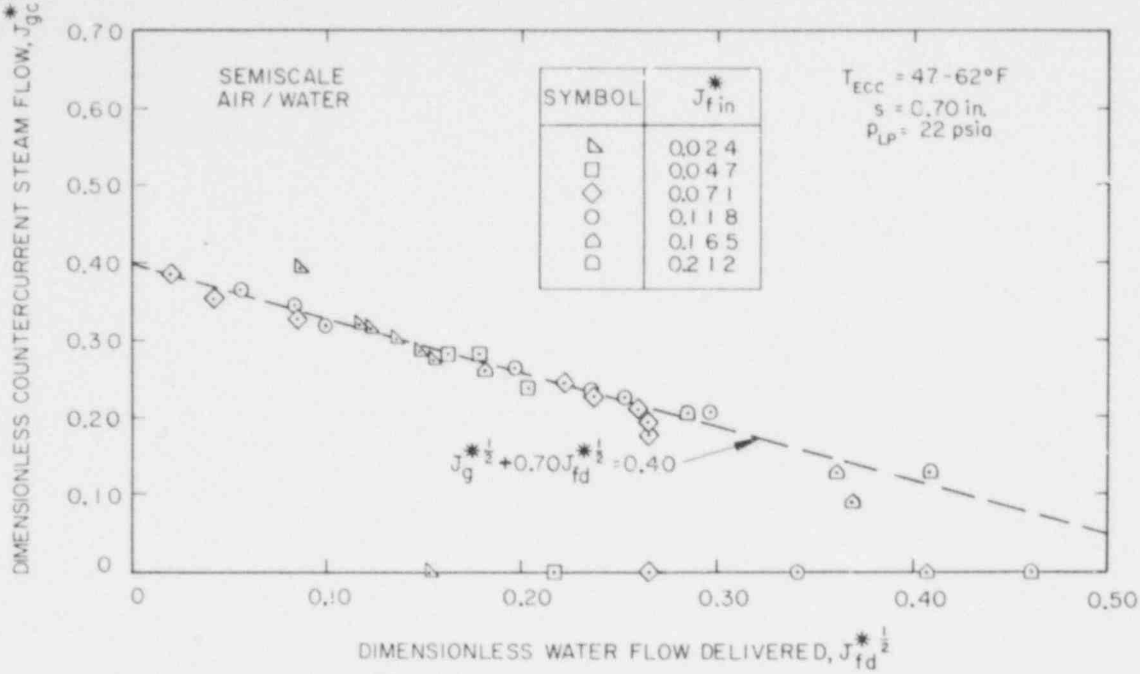

Figure 15. INEL AIR/WATER DATA FROM SEMISCALE FACILITY [29]

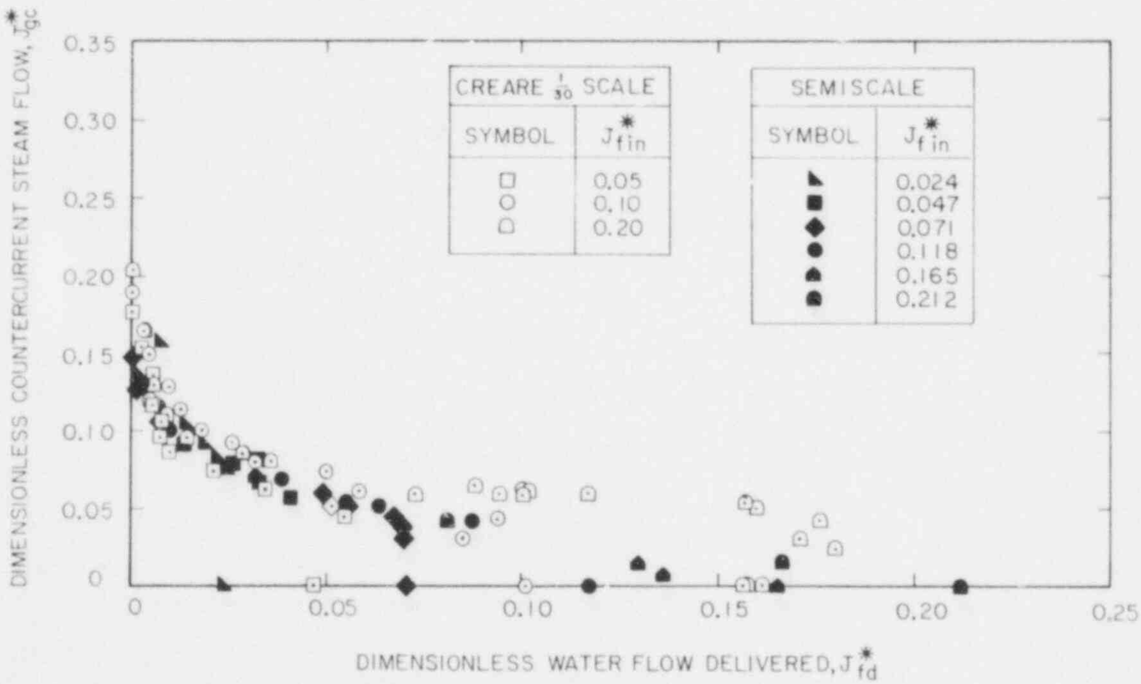

Figure 16. COMPARISON OF INFL DATA WITH CREARE 1/30 SCALE DATA

1847 005

Battelle Columbus Laboratories performed air/water tests in their 1/15-scale vessel and obtained the data compared in Figure 17 with the Creare 1/15-scale steam/water data. Battelle's correlation [30] gives C = 0.34 and m = 0.77 which represents the data well as seen in Figure 18. The Battelle data are appreciably below all of the foregoing data. An explanation for this discrepancy is lacking. Battelle has recently repeated these tests and the [illegible] data may clarify the situation when they are published.

Table II and Figure 7 summarize the air/water and steam/water data cited above. The values of C on Table II are also presented graphically in Figure 7, presented previously. Apart from the Battelle air/water data, the saturated water data indicate a nearly constant value of C at small scale. Even the fact that the Creare 1/15-scale steam/water data are slightly higher than the rest can perhaps be explained by the slight subcooling in these tests. Thus, it has been possible to provide a unified description of virtually all available data, which could not be achieved previously. Below we comment on the subcooled water data we chose not to include in this scaling figure.

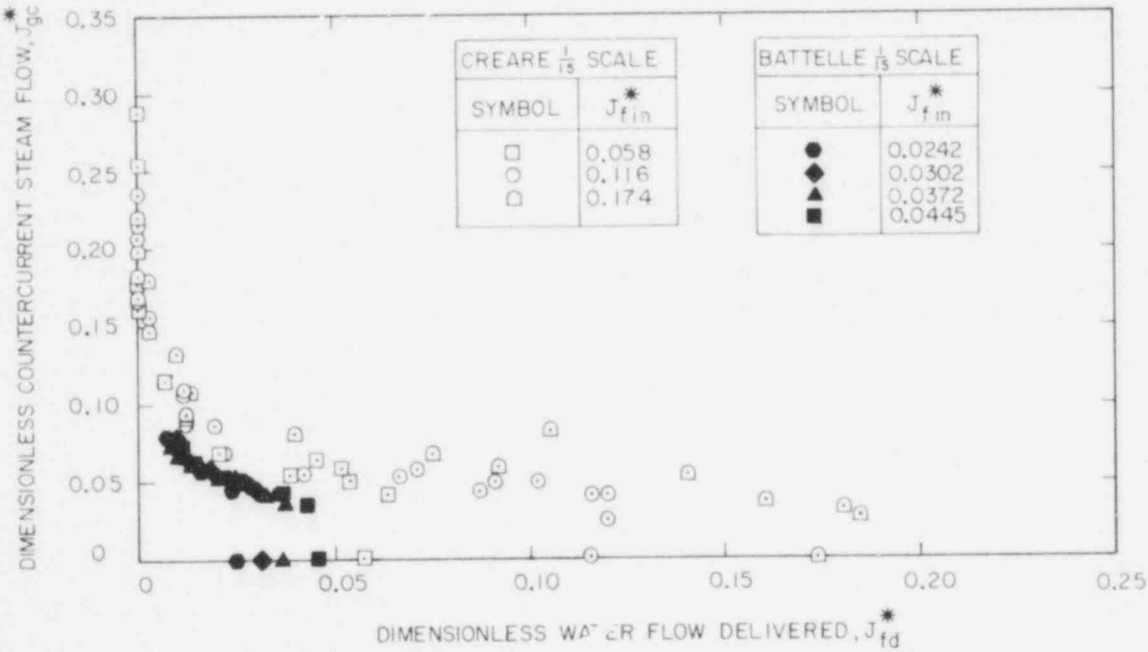

Figure 17. COMPARISON OF BATTELLE 1/15 SCALE AIR/WATER DATA WITH CREARE 1/15 SCALE DATA

1817 006

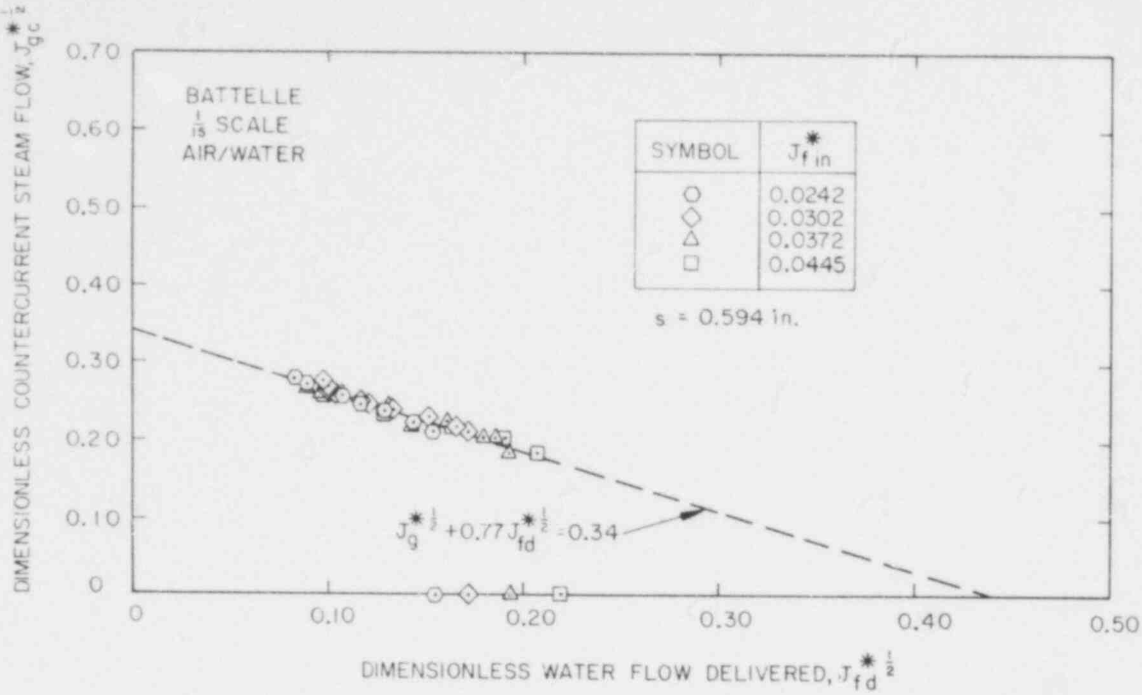

Figure 18. BATTELLE 1/15 SCALE AIR/WATER DATA [30]

TABLE II

ESTIMATED CORRELATION COEFFICIENTS

Contractor	Scale	Gas	Complete Bypass Limit C	Slope m	Figure Number
Creare	1/30	Steam	0.40 $\pm$ 0.02	0.75 $\pm$ 0.10	10
Creare	1/15	Steam	0.42 $\pm$ 0.02	0.75 $\pm$ 0.15	11
Dartmouth	1/30	Air	0.41 $\pm$ 0.04	0.80 $\pm$ 0.3	13
INEL	1/25	Air	0.40	0.70	15
Battelle	1/15	Air	0.34	0.77	17

1847 007

Other Countercurrent Flow Data

Several groups have amassed a large quantity of data on the countercurrent flow behavior of steam and highly subcooled water in reactor-model geometries. Briefly, these include tests at Dartmouth at 1/30-scale [12], Creare at 1/30 scale [27] and 1/15 scale [2,3] and Battelle at 1/15 scale [14] and 2/15 scale [26]. It is our view that such data are necessary to determine the effects of condensation on ECC bypass and have considerable value once saturated water data have provided a baseline for comparison. Taken alone, data for highly subcooled water are less useful for assessing either flooding of saturated water or the effects of condensation.

Battelle plans to do saturated water or low subcooling tests at 2/15 scale soon and they have assessed the existing 2/15-scale data which has subcooling ranging from 110°F to 235°F [26]. They find that a least-squares fit to the data yields C = 0.43 in excellent agreement with the conclusion reached in the previous section on saturated water behavior. This number is, however, based only on an initial data survey which rather incompletely fills the matrix of pressure, ECC injection rate, and temperature, as shown in Table III. Since many of these tests were performed at vessel pressures near the BCL supply capability, the steam flow was often unchoked and therefore unsteady. Figure 19 shows a typical set of 2/15-scale data. The Battelle correlation is also shown on this plot to illustrate the degree of extrapolation to saturated conditions, which in this case is relatively severe. It should be possible to improve our understanding considerably as additional data are obtained. However, it is not unreasonable to expect that a value of the coefficient C of order 0.4 will result as predicted by Battelle.

Combustion Engineering has obtained countercurrent steam/water data in the largest vessel tested to date, 1/5 of PWR scale [31]. Unfortunately, these very early data are too scanty to be of appreciable value here. Figure 20 shows all of the CE data, excluding only nine uninformative test repetitions. Since these data have been reviewed thoroughly in Reference [32], we simple cite the main points in that report:

- There are only 13 data points (exclusive of test repetitions).
- The limited data can only be viewed as a survey. Most of the data are either on or very near the complete bypass line or the complete penetration line; they provide only minimal information. The test parameters of flow, pressure and subcooling vary erratically, making it very difficult to identify sets of data at common conditions.
- Data at subcoolings below about 100°F are lacking. Therefore, the correlating coefficient C cannot be determined reliably.

1847 008

TABLE III

BATTELLE 2/15-SCALE TEST CONDITIONS, REFERENCE [26]

A. $p_{LP} \approx$ ambient (choked)

	ECC Subcooling (°F)				
J^*_{fin}	≈ 0	60	110	170	235
0.035					
0.061					
0.071					
0.089					
0.107					
0.12					
0.143					

B. p_{LP} = 30 psia (choked)

	ECC Subcooling (°F)				
J^*_{fin}	≈ 0	60	110	170	235
0.035				X	
0.061			X	X	
0.071					
0.089			X	X	
0.107					
0.12			X	X	
0.143				X	

C. p_{LP} = 60 psia (unchoked)

	ECC Subcooling (°F)				
J^*_{fin}	≈ 0	60	110	170	235
0.035					
0.061					
0.071					
0.089				X	
0.107					
0.12					
0.143					

D. p_{LP} = 75 psia (unchoked)

	ECC Subcooling (°F)				
J^*_{fin}	≈ 0	60	110	170	235
0.035				X	
0.061					X
0.071				X	
0.089			X	X	X
0.107					
0.12				X	
0.143				X	X

1817 009

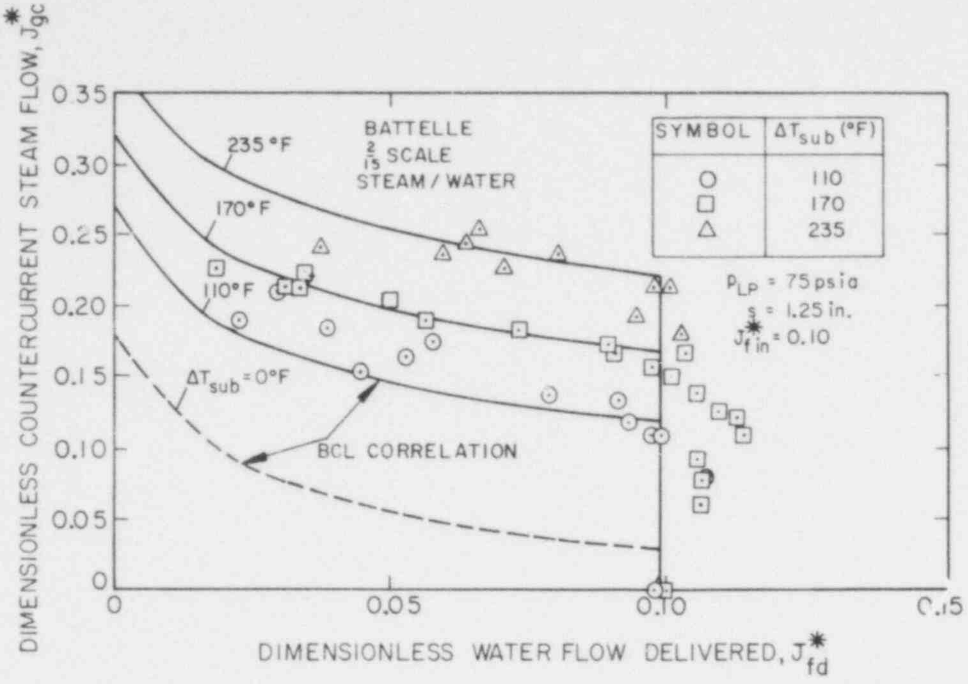

Figure 19. BATTELLE 2/15 SCALE DATA WITH HIGHLY SUBCOOLED WATER [26]

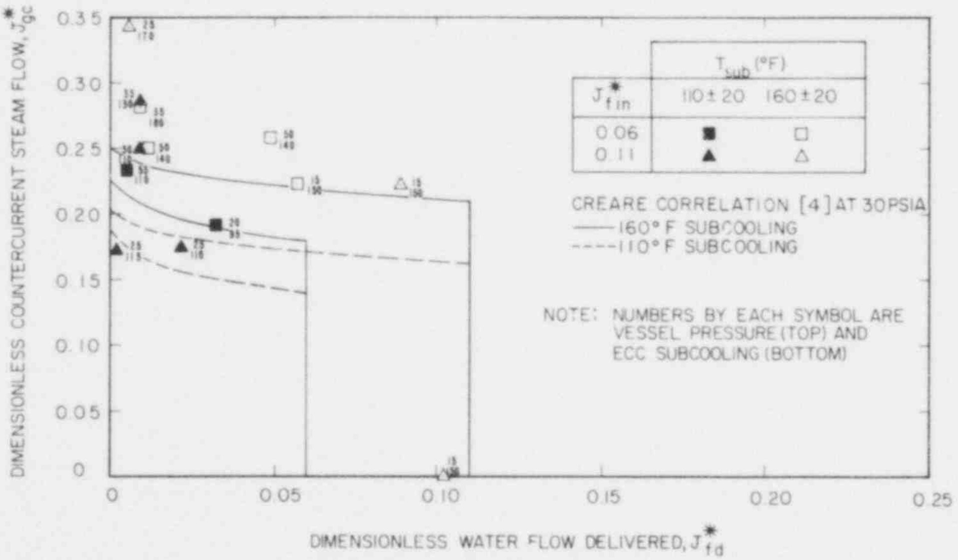

Figure 20. COMBUSTION ENGINEERING 1/5 SCALE DATA WITH HIGHLY SUBCOOLED WATER [31]

1847 010

- Although the location of a penetration curve is suggested by some of the highly subcooled data, there is insufficient information to assess the effects of condensation even by data interpolation at high subcooling.

- The Creare correlation is reasonably consistent with the available data, as shown on Figure 20. However, this may be coincidence since Reference [32] shows that widely divergent choices of the correlating parameters give equally reasonable agreement with the data.

In summary, while the CE data provide useful information at 1/5 scale, they are too scanty to answer any scaling questions satisfactorily.

Extrapolation to Larger Scale

The scaling (extrapolation) hypotheses are compared in Figure 7 with the available saturated water data. To provide an alternative perspective, the same information is repeated on logarithmic coordinates on Figure 21. The solid line in each figure represents the use of J* as the governing dimensionless parameter. The dashed line represents the hypotheses advanced by Wallis and Makkenchery and supported by Richter and Lovell, namely that J* scaling applies only at small scale but that at sufficiently large scale, complete bypass of saturated water occurs at $K^* = 3.2$. Although these two hypotheses figure most prominently in current thinking, another possibility warrants mention. The number 3.2 in the K* criterion lacks a sound fundamental basis; a different value for critical K* might be appropriate. This possibility prevents significant gains in understanding by small increases in test scale.

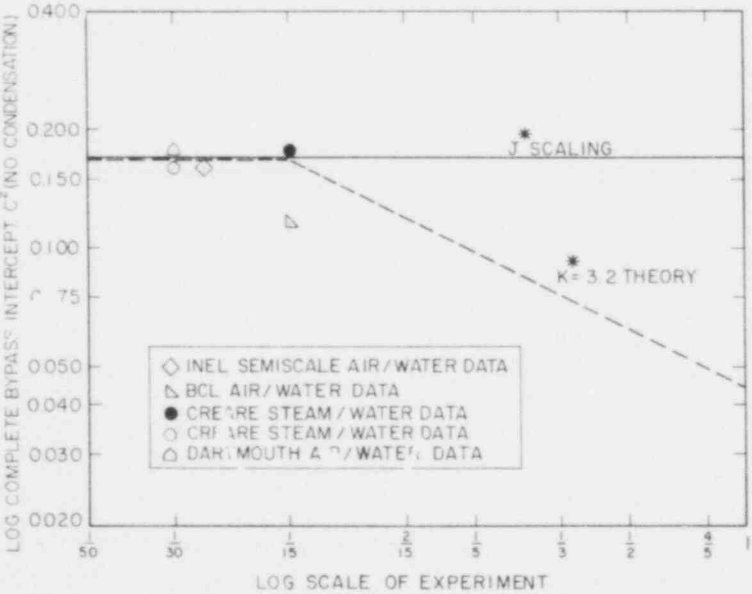

Figure 21. SUMMARY OF PRESENT EXPERIMENTAL RESULTS FROM FIGURE 7 IN LOGARITHMIC COORDINATES

1847 011

More importantly, all of present thinking relies on observations in extremely small facilities. While such experiments provide very useful modeling insight, they offer no hope of addressing the scaling question satisfactorily. It has been argued by some that at larger scale the flow regime will probably be vertically stratified with a river running down one side of the vessel and a gas flow streaming up the other side. Such an argument is certainly plausible and suggests that all present thinking may be overly conservative. On the other hand, if the annulus does run full at larger scale, the assumption that K* scaling is conservative cannot be justified on fundamental grounds. The simple answer is that we do not know how to extrapolate to larger scale, nor can we bound it short of $J_{gc}^{*} = 0$ for delivery. Thus, we can only speculate on scaling at the present time.

For these reasons, our earlier conclusion [6] remains unchanged today; experiments are still needed at a scale significantly larger than 1/15 of PW[illegible]le. Although tests at 2/15 scale have value, it is our opinion that 2/15 scale is also not large enough to address scaling questions satisfactorily. (To appreciate our concern, the reader should add a 2/15 scale data point with reasonable uncertainty at an arbitrary location in Figure 7 and subjectively assess the degree his confidence is increased.)

Summary Comments on Saturated Water Flooding

The available data have been assessed and separated into data on saturated water flooding and data which had appreciable subcooling. Difficulties in previous data interpretation have been identified and a new assessment of saturated water flooding behavior at small scale has been achieved. Alternative methods to extrapolate to larger scale have been brought more sharply into focus by Dartmouth data from experiments in large tubes. However, our main conclusion remains that tests at a scale significantly larger than 1/15 are needed.

It must be emphasized that the foregoing review addresses only the flooding of saturated water. Additional effects such as condensation, boiling due to superheated walls or lower plenum voiding may have equal importance. Although the available space and the status of the work precludes a comparable treatment of these topics in the present report, the following section provides brief comments to establish an overall perspective.

3.4 Comments on Refill Phenomena Impacting Flooding

Certain phenomena such as lower plenum voiding or flashing or steam-water mixing in the cold leg can be studied as effects isolated from countercurrent flow behavior in the downcomer, although during a LOCA these effects might occur simultaneously and interact. However, condensation and the effects of superheated downcomer walls are intimately coupled with flooding in the downcomer. Here we comment on the latter two phenomena and their scaling relative to the scaling of flooding.

1847 012

Scaling of Condensation Effects

During a controlled countercurrent flow experiment, where steam is supplied independently to the vessel at a fixed rate, the amount of condensation and its effect on water delivery can be bounded. (Although a PWR LOCA is certainly not a controlled experiment, such tests are the usual way that countercurrent flow effects have been studied.) The minimum amount of condensation that can occur is none. The maximum amount of condensation is that which will raise all of the injected water from injection temperature T_{ECC} to saturation, given previously by:

$$J^*_{g,eq} = J^*_{fin} \frac{c_p(T_{sat}-T_{ECC})}{h_{fg}} \sqrt{\frac{\rho_f}{\rho_g}}$$

However, we are interested here more in the effect of condensation on countercurrent flow behavior, for which there is considerable data, than on the actual amount of condensation itself, for which few data exist. The steam flow rate necessary for complete bypass is given by:

$$(J^*_{gc})_{CB} = C^2 + fJ^*_{g,eq}$$

where f can be no more than unity (f=1 corresponds to achievement of complete thermodynamic equilibrium without any contribution to flooding). Typical countercurrent flow data give values of f ranging from 0.1 to 0.5.

Best estimate and bounding calculations can now be made for full scale (as long as we recall that this is a controlled experiment, not a PWR). One limiting assumption is f=0. Depending on the scaling assumption made for flooding, complete bypass might occur at $J^*_{gc} \approx 0.16$ (J^* scaling), $J^*_{gc} \approx 0.04$ ($K^* = 3.2$) or some lower or higher number if neither of these scaling ideas are correct. This scaling uncertainty due to flooding may be compared with that introduced by different assumptions for f. With $J^*_{f,in} = 0.1$, typical of calculated ECC injection rates, $J^*_{g,eq}$ is 0.38 at 15 psi and 0.31 at 600 psia. Taking the larger number, a reasonable best estimate might be $fJ^*_{g,eq} = 0.1$ ($f \approx 0.25$) and an upper bound is $fJ^*_{g,eq} = 0.38$. The value of these calculations is to show that at full scale, the uncertainty introduced by condensation has a comparable order-of-magnitude effect on the steam flow needed for complete bypass as the (assumed but unbounded) uncertainty in the scaling of flooding.

In the event of a LOCA in a PWR, other effects of condensation may be more important than the adjustment to the complete bypass point described above. Condensation can contribute to the steam flows throughout the system, for example by altering the break pressure drop or by inducing an annulus upflow, as reported in Reference 7. Condensation may impact the steam flow split between the core and the cold legs. Condensation also can trigger flow oscillations throughout the system. Thus, although separate effects studies provide valuable information on condensation behavior, its effects and their scaling must also be assessed in system experiments and analyses.

1847 013

Scaling of Superheated Wall Effects

A closed form expression for hot-wall delay time under certain restrictions can be derived by combining equations (13) and (22) of Reference 4:

$$t_d = \left[\frac{\pi k^2 (T_w - T_{sat})^2 [1 + m(\rho_f - \rho_g)^{\frac{1}{4}}]^4}{\alpha C^4 h_{fg}'^2 [\rho_g g(\rho_f - \rho_g)]}\right] \left[\frac{L^2}{s^2 w}\right] \qquad (10)$$

where the first large bracket on the right-hand side contains physical constants and properties and the second bracket contains dimensions. It has been argued by some using a similar formulation or on qualitative grounds that hot wall effects (i.e., delay time) decrease as scale is increased because Equation (10) indicates that delay time is inversely proportional to scale. However, alternative conclusions can be derived by recognizing that the analysis of Reference 4 and specifically Equation (10) above assumes J* scaling of flooding. If instead K* scaling of flooding is assumed, calculated delay time is insensitive to scale. Thus, additional information on the scaling of flooding (and condensation) is needed to assess the geometric scaling of the effects of superheated downcomer walls.

3.5 Conclusions

The main conclusion of this report is that flooding and countercurrent flow experiments are needed in facilities considerably larger than those in use today, which range from 1/30 to 2/15 of PWR scale, in order to answer scaling questions satisfactorily.

A second important conclusion is that it has been possible to unify all existing flooding data, except for one early set of air/water experiments that are being repeated, by the assertion that J* scaling applies at small scales (where Kutateladze number is less than 3.2). Data from both simple tubes and model PWR vessels fit this prescription.

A best estimate of how flooding data should be extrapolated to scales larger than about 1/15 is highly equivocal. Existing data for 6 and 10 inch tubes suggest that the criterion K* = 3.2 is reasonable, although additional data in somewhat larger tubes would be desirable to strengthen this conclusion. Initial data correlations from the Battelle 2/15-scale tests suggest that J* scaling may apply to downcomer models up to 2/15 of PWR scale. Additional data should soon clarify the latter claim. None of these data, however, are at a sufficiently large scale to address fundamental issues such as the potential for flow regime transition.

The reader is reminded that these conclusions apply only to the scaling of flooding without the additional effects of condensation or superheated walls. We plan to report on these topics in the near future.

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APPENDICES

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APPENDIX A

CREARE 1/15-SCALE DATA WITH SATURATED WATER

The tabulated data for the Creare 1/15-scale saturated water countercurrent flow tests are presented below. The test geometry included an enlarged broken cold leg. The data tabulation includes the following:

TEST ID - identification number

W_{gc} - reverse core steam mass flow (lbm/sec)

Q_{DEL} - water flow rate delivered to plenum (gpm)

Q_{fin} - water flow rate injected (gpm)

T_{ECC} - injected water temperature (°F)

SUB - injected water subcooling (°F)

P_{LP} - lower plenum pressure (psia)

P_c - separator vessel pressure (psia)

J^*_{fin} - dimensionless water flow injected

J^*_{gc} - dimensionless reverse core steam flow

J^*_{fd} - dimensionless water flow delivered to plenum

GEOMETRIC PARAMETERS:

Annulus Gap Size = 0.5 in.

Annulus Circumference = 34.56 in.

Broken Cold Leg Diameter = 3.0 in.

Deep Plenum

1847 019

TABLE A-I

CREARE 1/15-SCALE DATA WITH SATURATED WATER

TEST ID	WGC(#M/S)	QDEL(GPM)	QFIN(GPM)	TECC(F)	SUB(F)	PLP(PSIA)	PC(PSIA)	JFIN*	JGC*	JFD*
2.0999	0.1016	27	30	209.5	2	14.9	14.5	0.0578	0.0584	0.052
2.1000	0.0712	33.3	30	209.5	2	14.8	14.5	0.0578	0.0411	0.0642
2.1001	0.0866	28	30	209.5	2	14.7	14.5	0.0578	0.0502	0.054
2.1002	0.1224	11	30	209.5	2	15	14.5	0.0578	0.0701	0.0212
2.1003	0.2049	3.6999	30	208.5	5	15.8	14.5	0.0578	0.1145	0.0071
2.1004	0.3046	0.3999	30	208.5	9	17	14.5	0.0578	0.1644	0.0007
2.1005	0.1529	6.8	30	208.5	4	15.3	14.5	0.0578	0.0868	0.0131
2.1006	0.1104	23.4	30	211.5	0	14.8	14.5	0.0578	0.0637	0.0451
2.1007	0.0949	20.2	30	211.5	0	14.9	14.5	0.0578	0.0546	0.0389
2.1024	0.5074	0.3	30	210	16	20.1	14.5	0.0578	0.2532	0.0005
2.1025	0.6046	0	30	209.5	22	22.2	14.5	0.0578	0.2878	0
2.0813	0.4284	0	60	210	20	21.6	14.5	0.1157	0.2066	0
2.0814	0.3453	0	60	210	17	20.5	14.5	0.1157	0.1707	0
2.0815	0.2022	6.1	60	210.5	7	17.1	14.5	0.1157	0.1089	0.[illegible]17
2.0816	0.1016	21.7999	60	209.5	5	15.9	14.5	0.1157	0.0566	0.042
2.0817	0.0435	62.0999	60	211	1	15	14.5	0.1157	0.0249	0.1197
2.0818	0.0712	60	60	211	1	14.9	14.5	0.1157	0.041	0.1157
2.0819	0.0866	53	60	211	1	15.1	14.5	0.1157	0.0495	0.1022
2.0820	0.0929	34.5	60	211	1	15.1	14.5	0.1157	0.0531	0.0665
2.0821	0.1516	6.3	60	211	5	16.5	14.5	0.1157	0.083	0.0121
2.0990	0.1529	10	60	208.5	5	15.7	14.5	0.1157	0.0857	0.0192
2.0991	0.1016	36.8	60	208.5	3	15.1	14.5	0.1157	0.058	0.0709
2.0992	0.0435	62.0999	60	208.5	3	14.8	14.5	0.1157	0.0251	0.1197
2.0993	0.0712	62.0999	60	208.5	3	15	14.5	0.1157	0.0408	0.1197
2.0994	0.0866	46.9	60	208.5	3	14.9	14.5	0.1157	0.0498	0.0904
2.0995	0.2049	6.1	60	212.5	6	17.3	14.5	0.1157	0.1098	0.0117
2.0996	0.3046	0.7	60	209.5	14	19.1	14.5	0.1157	0.1557	0.0013
2.0997	0.0775	45.1999	60	209.5	2	15.2	14.5	0.1157	0.0441	0.0871
2.0998	0.1224	11.5	60	209	4	15.7	14.5	0.1157	0.0686	0.0221
2.1026	0.5074	0	60	208.5	26	23.5	14.5	0.1157	0.2351	0
2.1027	0.4563	0	60	208.5	24	22.7	14.5	0.1157	0.2149	0
2.1039	0.1459	54.5	90	211	1	15.2	14.5	0.1736	0.0831	0.1051
2.1040	0.0924	72.8999	90	211	1	14.9	14.5	0.1736	0.0531	0.1406
2.1041	0.0654	83	90	210.5	1	14.8	14.5	0.1736	0.0377	0.1601
2.1042	0.0463	95.5	90	210.5	1	14.6	14.5	0.1736	0.0269	0.1842
2.1043	0.0567	93.6	90	210	2	14.7	14.5	0.1736	0.0328	0.1805
2.1044	0.2061	6.6999	90	210	8	17.3	14.5	0.1736	0.1104	0.0129
2.1045	0.1725	6.3999	90	213	4	17	14.5	0.1736	0.0932	0.0123
2.1046	0.1221	38.9	90	213	1	15.8	14.5	0.1736	0.0683	0.075
2.1047	0.1073	47.6999	90	213	0	15.7	14.5	0.1736	0.0602	0.092
2.1048	0.3557	1	90	213	12	19.5	14.5	0.1736	0.1802	0.0019
2.1049	0.2521	4.8999	90	212.5	8	18.1	14.5	0.1736	0.1322	0.0094
2.1050	0.1459	20.5	90	212.5	2	16.1	14.5	0.1736	0.0809	0.0395
2.1051	0.4472	0	90	211.5	16	20.7	14.5	0.1736	0.2201	0
2.1054	0.4051	0	90	212.5	15	20.5	14.5	0.1736	0.2003	0
2.1055	0.3659	0.3	90	212.5	13	19.8	14.5	0.1736	0.1839	0.0005
2.1056	0.3314	0.6	90	212	12	19.4	14.5	0.1736	0.1682	0.0011
2.1057	0.2909	1.4	90	209.5	14	19.1	14.5	0.1736	0.1487	0.0027

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