UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

DEC 8 1981

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert B. Minogue
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER NO. 128, "PWR LOWER PLENUM REFILL RESEARCH RESULTS"

This memorandum transmits the final results of the completed lower plenum refill research performed by Battelle Columbus Laboratories (BCL) and Creare, Incorporated. It updates and extends the results reported in a previous Research Information Letter (RIL No. 57), "Small-Scale ECC Bypass Research Results."

The purpose of NRC's Emergency Core Coolant (ECC) Bypass research programs was to develop best estimate models of the ECC bypass phenomenon in pressurized water reactors. These models have been developed and are presented in the Appendix to this memorandum. The models can be used in best estimate codes and demonstrate that current licensing "end of bypass" definitions and evaluation models are conservative. In addition, the data generated through these programs can be used to assess the modeling capabilities of codes such as RELAP4, RELAP5 and TRAC.

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No additional ECC bypass work is planned for either the Creare or BCL programs. However, the data has been cataloged and will be maintained at their respective facilities. Both BCL and Creare will be available to respond to any inquiries which may arise concerning the data. Any questions concerning the Appendix should be directed to Jose N. Reyes (427-4260).

Robert B. Minogue, Director
Office of Nuclear Regulatory Research

Enclosure: As stated

APPENDIX TO RESEARCH INFORMATION LETTER NO. 128

"PWR LOWER PLENUM REFILL RESEARCH RESULTS"

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December 8, 1981

PWR LOWER PLENUM REFILL RESEARCH RESULTS

Introduction

Emergency core coolant (ECC) injection during a large-break loss-of-coolant accident (LOCA) in a pressurized water reactor (PWR) involves the complex process of countercurrent flow of ECC fluid into the vessel against the upward flow of steam and water escaping to the break. This upward flow of fluid may divert the injected ECC fluid out the break (ECC bypass) and thus delay refilling of the lower plenum (LP) and subsequent reflooding of the core. Figure 1 illustrates the complex processes during bypass and refill. LOCA calculations used in the licensing process typically divide the early LOCA into distinct periods. The blowdown period ends at some time designated as end-of-bypass. The refill period begins at end-of-bypass because the escaping primary fluid no longer impedes the ECC fluid from reaching the lower plenum. The time to refill the LP prior to starting reflood is determined in a separate refill calculation used to link the blowdown and reflood codes. Most codes used in the licensing process (RELAP4 or similar) do not have the ability for continuous calculation through the blowdown, refill, and reflood periods.

The objective of the previous RIL was to show that the definitions of end-of-bypass were conservative because they are based on a conservative extrapolation of small-scale tests to full scale. This work concentrated on defining the point that upward flowing steam and additional steam generated by hot vessel walls no longer bypasses injected ECC fluid. The present RIL updates and reinforces the previous RIL by providing data at a larger scale size to strengthen scaling theories and by providing an alternate method of calculating an area of uncertainty in the previous hot-wall calculation.

The primary objectives of this RIL are: 1) to provide a realistic and continuous analysis of the entire refill process, 2) to evaluate the capability of existing codes (such as RELAP4) to realistically calculate LP refill, 3) to recommend upgraded RELAP4 models, and 4) provide data for assessing advanced codes such as RELAP5 and TRAC. To obtain a realistic estimate of refill, it is necessary to determine the amount of LP liquid swelling up into the downcomer and to understand the process by which it flows up the downcomer and out the break. It is also necessary to determine to what extent the upward flowing two-phase mixture interacts with the downward flowing ECC (previous ECC bypass research only investigated single-phase steam upflow). By taking these effects into account, the amount of original liquid remaining in the lower plenum and the amount of injected ECC fluid that reaches the LP can be calculated. The research performed since the previous RIL has concentrated on testing and analyses that treat the blowdown/refill process as a continuous transient which combines the complex processes of level swell and expulsion of LP liquid and the countercurrent flow of ECC fluid in the downcomer and into the LP.

Update of Previous ECC Bypass Results

The previous RIL presented results of testing to determine the amount of ECC fluid penetrating into the LP against a steady-state upflow of steam and

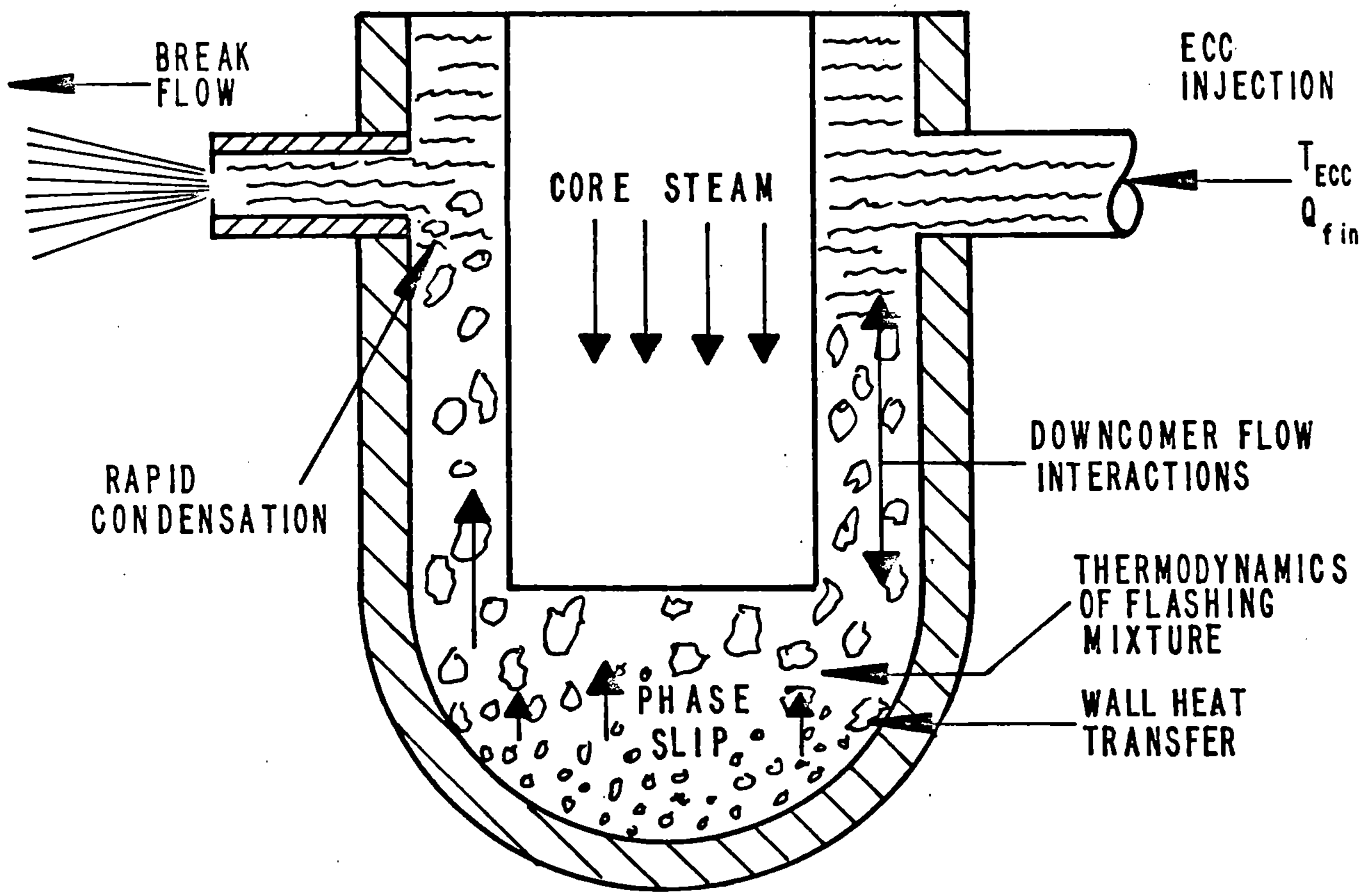

Figure 1. SKETCH OF FLASHING TRANSIENT PHENOMENA

against a transient upflow of steam both with and without additional steam produced by superheated vessel walls. Parametric studies were performed to investigate how the ECC bypass process could be scaled as a function of geometric scale size and pressure. While the effect of pressure was well understood, scaling of size was less certain due to the limited range of test vessel sizes (1/30 - 2/15 scale). Based on the data then available, it appeared that either $J^* \sqrt{s}$ or K^* (constant momentum flux of steam) scaled the data better than J^* (momentum flux increases with scale). The effect of steam condensation by subcooled ECC appeared to be increasing with scale size. This would tend to allow more ECC penetration for a given amount of steam upflow. Thus it was recommended that the more conservative scaling method continue to be used in licensing calculations until large scale data are available. However, in view of the observed increase in condensation effects which accompanied the increase in scale size, some credit for condensation could be given.

The previous RIL also presented a transient hot-wall delay model that combined the effect of steam upflow and additional hot wall steam. This model showed that current licensing models are conservative, even when conservative limits were placed on all scaling parameters that could be realistically bounded. However, one parameter could not be realistically bounded -- the partition of the wall heat used to produce steam and that used to heat liquid. This did not cause great concern since testing and analysis has shown a decreasing effect of hot walls as scale size increases.

Since the previous report, additional data from a larger size vessel has been obtained. One-fifth (1/5) scale tests continue to show $J^* \sqrt{s}$ scaling and the increasing effects of condensation. Equations I and II and Tables I, II, and III include correlations of small-scale data and recommend a method of extrapolating ECC bypass data to a larger scale. Reference 2 presents the detailed scaling analysis and the additional 1/5 scale data.

An alternate transient hot-wall model has also been developed that treats the heat partition in a more mechanistic manner. This new transient hot-wall model is summarized in Reference 3. Both the additional data and analysis have strengthened the findings of the previous RIL in areas where further support was desirable.

New Lower Plenum Refill Results

Tests have been conducted that treat the blowdown and refill in a more realistic and continuous manner. Typical tests consist of filling and pressurizing a scale model of a PWR vessel and blowing the vessel down while injecting ECC fluid. While these tests are still separate-effects tests and do not attempt to exactly duplicate conditions expected in a PWR, these tests produce the most typical conditions of a LOCA blowdown available in a facility that is well controlled and specifically instrumented to measure refill. Two key differences exist in these tests over previous tests: 1) they include the swelling of liquid in the lower plenum and its effect on the amount of primary fluid remaining in the vessel after the blowdown and 2) ECC fluid penetrates to the LP against an upward flow of a two-phase mixture rather than single-phase steam. Tests have systematically investigated various important parameters including scale sizes of 1/30, 1/15, 2/15, and 1/5 and pressures up to 250 psia. Analysis efforts have concentrated on three areas: 1) observation of trends to better understand the important processes and to identify any effects of scale size, 2) testing the ability of RELAP4 codes to perform a continuous calculation through refill, and 3) developing and using an independent, lumped-parameter model with various "DIALS" or adjustments to test the effect of various modeling assumptions and to test the modeling assumptions used in other codes such as TRAC or RELAP5.

ECC BYPASS SCALING EQUATIONS

Equation I

$$[J_g^* - F\,J^*_{g,T}(\mathrm{COND})]^{\frac{1}{2}} + [M - Z\,J^*_{g,T}(\mathrm{COND})\exp(-a\sqrt{(J_\ell^*)_{in}})]J_\ell^{*\frac{1}{2}} = C$$

Equation II

$$J_g^{*\frac{1}{2}} - F\,J^*_{g,T}(\mathrm{COND})^{\frac{1}{2}} + [M - Z\,J^*_{g,T}(\mathrm{COND})\exp(-a\sqrt{(J_\ell^*)_{in}})]J_\ell^{*\frac{1}{2}} = C$$

Table 1 Empirical Constants Calculated for the Traditional ECC Bypass Formulation of Equation I

Coefficient	Creare 1/5 Steam	BLC 2/15 Steam	BCL 1/15 Steam	Creare 1/15 Steam	Creare 1/30 Steam
C	0.369±0.015	0.455±0.010	0.523±0.012	0.434±0.017	0.388±0.014
F	0.281±0.113	0.297±0.014	0.119±0.013	0.146±0.019	0.084±0.64
M	0.896±0.136	0.987±0.078	1.18±0.086	1.009±0.094	0.395±0.091
Z	0.451±1.54	11.73±2.80	19.13±2.04	11.22±2.48	2.58±1.40
a	0.0	9.5	8.0	6.0	3.0

*95% Confidence Limits (±two standard errors).

Table II Empirical Constants Calculated for the Modified ECC Bypass Formulation of Equation II

Coefficient	Creare 1/5 Steam	BLC 2/15 Steam	BCL 1/15 Steam	Creare 1/15 Steam	Creare 1/30 Steam
C	0.344±0.014	0.328±0.012	0.417±0.013	0.401±0.017	0.390±0.016
F	0.209±0.047	0.382±0.022	0.233±0.019	0.155±0.027	0.036±0.048
M	0.822±0.092	0.666±0.053	0.877±0.059	0.816±0.091	0.417±0.090
Z	1.49±0.42	4.05±1.29	16.91±2.22	5.33±0.91	3.35±1.13
a	0.0	7.5	9.0	4.5	3.0

*95% Confidence Limits (±two standard errors).

Table III Recommended Methods to Extrapolate Correlational Coefficients in Table I and II to Larger Scale

Coefficient	Value at Large Scale	Scaling Basis
C	Use values from Creare 1/5 or BCL 2/15 data (whichever is smaller for conservatism) modified to decrease by the 1/4 root of scale size (circumference)	Observed scaling behavior (also more conservative of scaling theories)
F	Use values from Creare 1/5 or BCL 2/15 (smaller 1/5 values for more conservatism)	Observed increase in F with scale size. Thus values no larger than at small scale should be conservative.
M	Use values from Creare 1/5 or BCL 2/15 (larger value is more conservative)	Constant or slightly decreasing value observed.
z	ZERO	Observed decrease with scale size (also more conservative)
a	Not used when z = 0.0	

Caution--values of coefficient derived for one equation should not be used in the other equation. We currently have no basis to support one equation over another.

The effect of level swell and fluid flowing up the downcomer on the liquid remaining in the vessel is very well predicted for these tests using a Wilson Bubble Rise Model and a homogeneous (no slip) flow model in the downcomer. The Wilson Model has a void fraction dependence that appears more appropriate than a constant bubble rise velocity. The Wilson model adequately predicts a variety of test results without modification while the constant bubble rise velocity must be empirically adjusted to match different pressures and void fractions. Thus, if the Wilson model is used and the correct depressurization rate is calculated, RELAP4 series codes should correctly calculate the swelled LP level and the fluid remaining in the LP after the blowdown. RELAP4 MOD5 successfully calculates LP mass and level history from various tests without simulated ECC injection. Care should be exercised in implementation of this model, however, since instabilities have been observed when the Wilson model is used in a number of vertically stacked nodes.

By comparison, tests conducted with ECC injection depressurized more rapidly due to condensation and resulted in increases in the amount of initial LP liquid being removed from the vessel prior to refill by the ECC fluid than tests conducted without ECC injection which were otherwise identical. RELAP4 MOD5 had difficulty calculating the tests with ECC injection due to numerical problems with water packing. Use of RELAP4 MOD7 indicated that the improved numerics allow the code to calculate the transients with ECC injection (minor code modifications were required). The nonequilibrium option of MOD7 also provides additional modeling flexibility although for most tests the equilibrium and nonequilibrium calculations are nearly identical.

The latter portions of these blowdown/refill tests with ECC injection provide a more realistic simulation of ECC penetration to the lower plenum since a two-phase mixture flows up the downcomer and impedes the penetration of ECC fluid. Calculation methods can be assessed by comparison with measured transients of lower plenum inventory, lower plenum liquid level, vessel pressure, and separator pressure used to simulate the containment. Analyses can also calculate the downcomer flows that are not directly measured in these experiments. These tests were successfully related to previous steam-only ECC bypass tests by relating the momentum flux of the two-phase mixture with the known momentum flux of steam required for bypass. The momentum flux of the steam alone for these tests was not large enough to cause bypass based on previous steam-only tests, even though bypass did occur. However, when the two-phase mixture was treated as a homogeneous fluid (with zero phase slip), ECC penetration occurred at a momentum flux similar to that expected from single-phase steam testing. This provides our first indication of how to analyze countercurrent flow when the upward flowing stream is two-phase and provides a link between the realistic case and more controlled single-phase tests.

Reference 4 demonstrates that RELAP 4/MOD 7 can adequately predict the blowdown/refill tests. Application of the code to LOFT tests shows good agreement with time-dependent LP and downcomer mass histories as shown in Figure 2. A summary of the blowdown/refill testing and analysis is included as Reference 5.

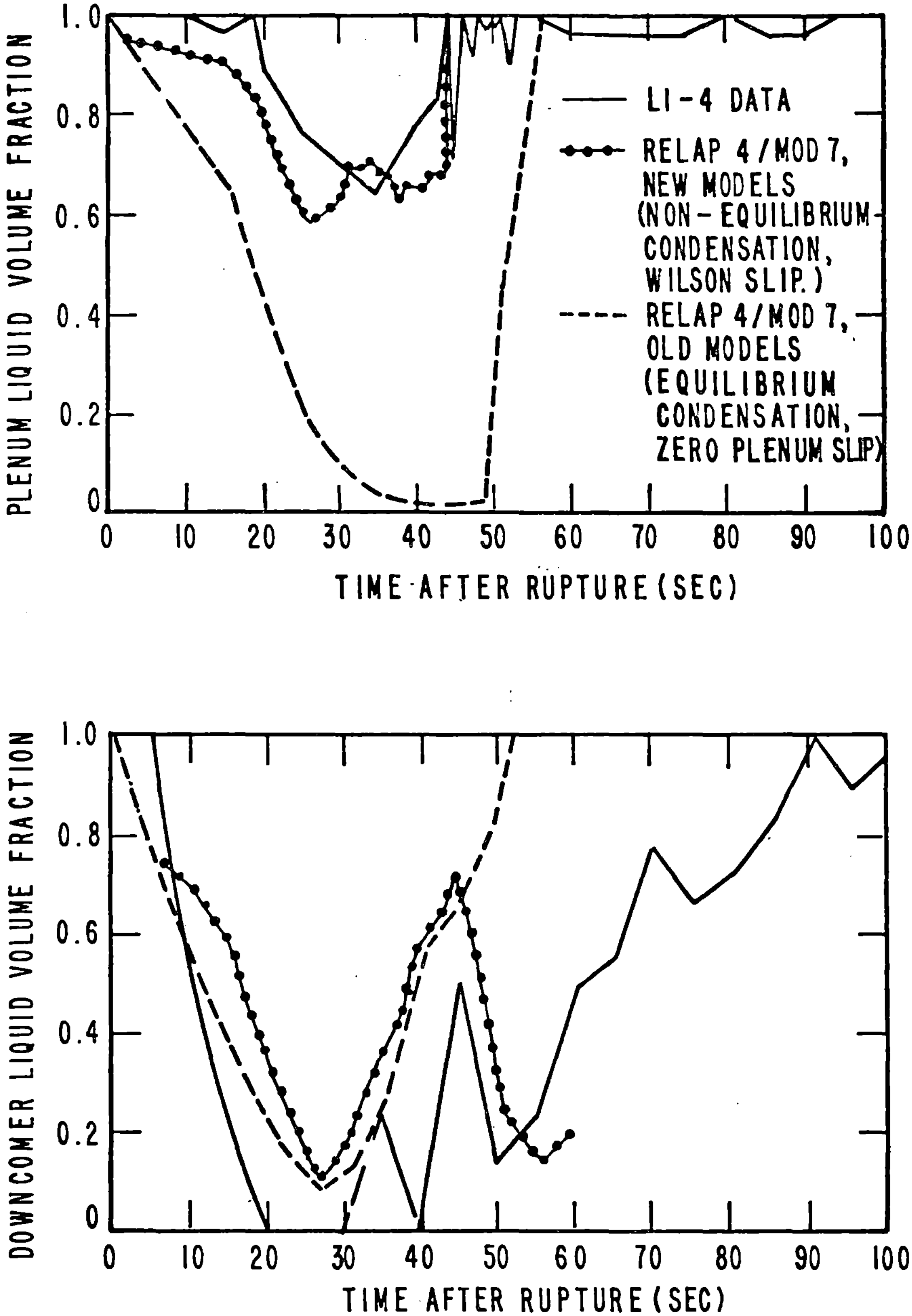

Figure 2. COMPARISON OF LOFT TEST L1-4 EXPERIMENTAL DATA AND RELAP4/MOD7 CALCULATIONS (FROM ATTACHMENT IV)

Applicability of Results

This work provides an evaluation of the ability of codes in the RELAP4 family to calculate the integrated blowdown and refill period of the large-break LOCA. Confidence in the ability to correctly calculate refill at full scale is demonstrated by the code's ability to calculate a wide range of scale sizes without empirical changes. In addition, data are available to assess the advanced nonequilibrium codes such as TRAC and RELAP5. This work is also indirectly applicable to transients other than the PWR large-break LOCA. Level swell is important in boiling water reactor large- and small-break LOCAs and condensation is important in many reactor transients. Assessing the ability of codes to predict the tests described herein will provide an indication of their applicability to other types of transients containing the same general phenomena.

This work supports the end-of-bypass definition required in Appendix K calculations by virtue of its support of the previous RIL. A model has also been approved by NRR for the Yankee Rowe LOCA Evaluation Model. This submittal uses a LP-phase separation model to take credit for liquid remaining in the LP after the blowdown. Some of the early data reported here was used in support of the licensing submittal. Reference 5 contains a discussion of how the work reported herein could be applied as an evaluation model calculation of refill.

Future Work

No additional work is planned for either the CREARE or BCL programs. Both these contracts will be terminated at the end of FY 1981. However, continued use of these results are planned under other programs. Tests similar to the blowdown/refill tests are planned under the 2D/3D program for the cylindrical core test facility (CCTF) and the upper plenum test facility (UPTF). These results can be used as a scoping tool to plan testing in these facilities. This data will also be used in the assessment programs planned for the advanced codes.

This work was reviewed by the ECC Bypass Review Group and comments are provided in Reference 6. Any questions concerning this report should be directed to William D. Beckner (427-4260).

References

(1) Memo from S. Levine to H. Denton, dated 8/10/79, "Small Scale ECC Bypass Research Results," RIL #57.

(2) NUREG/CR-2106 dated 4/81, "1/5-Scale Countercurrent Flow Data Presentation and Discussion."

(3) NUREG/CR-2030 dated 3/81, "Application of Battelle's Mechanistic Model to Lower Plenum Refill."

(4) NUREG/CR-2085 dated 4/81, "RELAP 4/MOD7 Analysis of Flashing Transient Effects During Refill."

(5) NUREG/CR-2058 dated 3/81, "Summary of Refill Effects Studies with Flashing and ECC Interactions."

(6) Minutes of the Refill Effects Research Review Group Meeting - June 30, 1981.

TN-329

NUREG/CR-2058
CREARE TN-329

SUMMARY OF REFILL EFFECTS STUDIES WITH FLASHING AND ECC INTERACTIONS

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Prepared for
U. S. Nuclear Regulatory Commission

TN-333

NUREG/CR-2106
CREARE TN-333

1/5-SCALE COUNTERCURRENT FLOW DATA PRESENTATION AND DISCUSSION

TOPICAL REPORT

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Creare TN-328
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RELAP4/MOD7 ANALYSIS OF FLASHING TRANSIENT EFFECTS DURING REFILL

Topical Report

Christopher J. Crowley

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Creare Inc.
Hanover, New Hampshire

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Washington, D.C. 20555

SUMMARY

RESEARCH INFORMATION LETTER NO. 128

"PWR LOWER PLENUM REFILL RESEARCH RESULTS"

FIN A4048
FIN A4070

This letter summarizes the results of the lower plenum refill research performed by Battelle Columbus Laboratory and CREARE, Inc. It extends RIL No. 57. Best Estimate ECC Bypass models are presented in the appendix which indicates that current licensing evaluation models are conservative.

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DEC 8 1981

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Original Signed by

Denwood F. Ross, Jr.

Robert B. Minogue, Director
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Enclosure: As stated

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