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

FROM: Saul Levine, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER # 67 - REFLOODING OF SIMULATED PWR CORES AT LOW FLOW RATES

This Research Information Letter describes the cooling of electrically heated rods during bottom flooding. The information presented is considered applicable to the evaluation of emergency cooling system performance in pressurized water reactors.

## 1.0 Introduction

This letter summarizes results and analyses of bottom flooding experiments conducted at constant inlet flooding rates. The primary information base has been provided by the PWR Full Length Emergency Cooling Heat Transfer (FLECHT) experiments which are continuing with separate effects and system effects tests in FLECHT SEASET. Supplementing this data base are significant results from several other programs including Semiscale and programs conducted in Germany by KfK and KWU.

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The goals of this ongoing research are:

A. To study heat transfer at the low reflood rates (less than one inch per second) that have been predicted to occur in LPWRs and that require restrictive modeling assumptions by Appendix K of 10 CFR 50;

B. To provide a clearer understanding of reflood flow regimes and heat transfer mechanisms, and to develop best estimate methods for predicting heat transfer coefficients, quench front velocities, liquid carryover, cladding temperatures and other features of reflood behavior; and

C. To examine the effects of geometry and system parameters such as bundle blockages, grid spacers, fuel array design, and loop and steam generator operating conditions.

The information available to date provides a substantially improved understanding of emergency core cooling, especially with respect to Items A and B, and allows the calculation of more realistic peak cladding temperatures. The FLECHT SEASET program will study particularly the questions listed in Item C.

Typical FLECHT results are reported in this letter and the data from other programs are presented in order to provide perspective on the effects of test facility and heater rod design. A summary of the current predictive capabilities for reflood behavior, as provided by both computer codes and empirical correlations, is also included.

The FLECHT tests utilized electrically heated rods with nominal external dimensions equivalent to those employed in standard 15 x 15 PWR nuclear fuel arrays. Axial heater profiles peaked near the midplane ('cosine-shaped') and peaked near the top ('skewed-shaped') were employed. More than 200 reflooding experiments were conducted with a systematic variation of inlet flooding rate, system pressure, rod power, and other important parameters. The test section was well-instrumented, providing data for calculation of heat transfer coefficients and detailed mass distributions.

The information presented is considered applicable to 10 CFR 50.46, paragraphs (a)(1), (c)(2) and to Appendix K of Part 50, paragraphs ID3 and ID5. Subsection ID5 allows use of reflood heat transfer coefficients based on the unblocked FLECHT results when flooding rates are one inch per second or higher. For lower flooding rates, steam cooling and blockage must be considered:

> "During refill and during reflood when reflood rates are less than one inch per second, heat transfer calculations shall be based on the assumption that cooling is only by steam, and shall take into account any flow blockage calculated to occur as a result of cladding swelling or rupture as such blockage might affect both local steam flow and heat transfer."

FLECHT SEASET will address these broader issues and will provide data needed for a reevaluation of Appendix K.

## 2.0 Summary

Significant conclusions supported by reflood research at constant inlet flooding rates include the following:

### A. Experiment Results for Low Flooding Rates

1. Substantial heat transfer is available below 2.5 centimeters (1 inch) per second in unblocked bundles. Cooling by dispersed droplet flow is observed even for reflood rates of 1 centimeter per second. Appendix K is conservative in requiring that only cooling by steam can be considered at low flooding rates.

2. Evidence to date from heater rod experiments indicates that reflooding behavior of stainless steel-clad rods is conservative with respect to reflooding of zircaloy-clad rods. Conduction models predict that conservatism is due to differences in cladding thermal properties and that it may be enhanced by the existence of a thermal resistance as caused by a design gap or by moderate ballooning.

### B. Analytical Predictions of Reflood Behavior

1. Basic aspects of reflood behavior including quench front velocity, liquid carryover rate, void fraction, and heat transfer coefficients

can be better predicted by semiempirical or empirical correlations than by phenomenologically-based calculations.

2. Early temperature behavior including the cladding temperature increase during reflood and the time that the maximum temperature occurs can generally be well-predicted by phenomenologically-based codes. Later temperature behavior, heat transfer in the dispersed droplet flow regime, and the quench time cannot yet be described well by mechanistic models.

These conclusions are supported by: Parametric studies in the FLECHT program and results of other U.S. and German reflood tests, and predictions using empirical correlations and computer codes. These topics are discussed in Appendices A through C and are highlighted in Sections 2.1 and 2.2.

## 2.1 Experiment Results for Low Flooding Rates

### 2.1.1 Parametric Effects Found in FLECHT Tests

The effectiveness of emergency cooling is indicated by studies of cladding temperatures, heat transfer, rod quenching times and bundle mass effluent fraction. These variables have been studied extensively in FLECHT as a function of the parameters listed in Table I. Many of the basic tests that were performed with a cosine-shaped axial power profile were repeated with a skewed-shaped axial power profile.

Variation of the parameters has qualitatively predictable effects on reflooding behavior:

A. Higher inlet flooding velocity, pressure, or inlet subcooling cause a lower cladding peak temperature rise, a higher quench front velocity, and a shorter quench time; and

B. Higher power, initial cladding temperature, or housing temperature cause a lower quench front velocity, a longer quench time, and (except for the case of initial temperature) a higher temperature rise.

Increases in cladding temperature are terminated by cooling due to dispersed droplet flow. A significant quantity of liquid in droplet form exists above the quench front which aids in cooling the upper rod elevations. FLECHT movies indicate typical droplet sizes of 1 - 2 mm, requiring steam velocities on the order of 5 m/sec for entrainment. Heat transfer coefficients are determined by the amount of water in the vapor, and both heat transfer and water content generally increase with quench front velocity. Except for the highest velocities, vapor superheat is found to increase sharply with distance above the quench front in the central portion of the rods.

Figure 1 shows that the sensitivity of peak cladding temperature to flooding rate increases as the flooding rate decreases, and there is not a dramatic deterioration in heat transfer at 2.5 centimeters per second.

### 2.1.2 Results of Other Reflooding Experiments

The primary FLECHT data for full length stainless steel rods agree well or are conservative in comparison with results of other experimental programs. The experiments compared include tests with shorter rods in the Semiscale Facility (INEL), tests using a very large bundle at KWU (Erlangen, Germany), tests with unpressurized zircaloy-clad rods in the FLECHT facility, tests with pressurized zircaloy-clad rods at KfK (Karlsruhe, Germany), and tests with partially blocked channels in FLECHT.

A. Semiscale. In spite of substantial geometrical differences between Semiscale and FLECHT, the same parametric trends are found, and the magnitudes of the cladding midplane peak temperature rise and the quench front velocity for comparable test conditions are very similar.

B. KWU. The KWU tests using a 340 rod bundle resulted in similar heat transfer coefficients, and all differences can be explained in terms of differences in test design and conduct.

C. KfK. The experiments with zircaloy-clad heater rods by KfK and in FLECHT each resulted in higher quench front velocities than found for stainless steel-clad rods tested under similar conditions. The difference appears to be enhanced when the zircaloy cladding balloons, and may approach the theory-predicted enhancement factor of two in such cases as suggested by both theory and experiment (see Appendices B, C).

D. FLECHT Blockage Tests. The FLECHT tests with plate blockage resulted in better cooling immediately downstream of the blockage than experienced in the unblocked tests. These experiments were nonconclusive, however, due to the unrealistic blockage geometry and the limited parameter range (including limited flow bypass area).

## 2.2 Analytical Predictions of Reflood Behavior Based on FLECHT Results

Predictions of cladding temperature rise, quench front velocity, and liquid carryover to the upper plenum are especially important for assessing safety margins during reflood. Modeling approaches tend to emphasize either (1) the fuel rod side and heat conduction, or (2) the fluid side and heat convection. The former approach can result in closed-form analytical expressions for key variables, while the latter generally involves empirical models or phenomenologically-based computer codes. FLECHT data have played a key role in developing or assessing models of each type.

### 2.2.1 Conduction-Controlling Models

Simple models are available for quench front velocity and liquid carryover and tend to be of the conduction-controlling type. The "classical" conduction model for quench front velocity (Appendix C) lacks a convection mode of heat transfer and assumes that no heat transfer occurs above the quench front. This is more conservative than Appendix K regulations which allow heat transfer to steam above the quench front and it may be used to determine a bound for reflood behavior.

Figure 2 shows the FLECHT low and high flooding rate data as a function of the dimensionless temperature parameter that controls the quench front velocity in conduction models. Also shown is the quench front velocity as predicted by the classical one-dimensional conduction equation with boundary conditions of a constant heat transfer coefficient in the wet region and zero heat transfer in the dry region. These boundary conditions are only slightly more conservative than would exist under steam cooling restrictions and result in substantially lower predicted velocities than found in the experiments. The calculation must be considered to be semiquantitative since it depends on an "effective wall thickness," which is somewhat uncertain (Appendix C).

### 2.2.2 Convection-Controlling Models

#### 2.2.2.1 Empirical Models

Empirical FLECHT correlations for heat transfer coefficients and quench times have been generated (Appendix D) which are highly successful in fitting their data base. When these correlations are employed in evaluation model computer codes, the peak cladding temperature is substantially lower than obtained by assuming that cooling is due to dry steam. Application of the FLECHT correlation to other geometries or to an expanded parameter range has uncertain validity, however, due to its high degree of empiricism, providing rationale for development of more phenomenologically-based models.

#### 2.2.2.2 Phenomenological Models

A number of best-estimate, phenomenologically-based codes having various degrees of complexity have been developed including RELAP4, REFLUX2, FLOOD4, SUPERH (all NRC/RSR-sponsored) and UCFLOOD (EPRI-sponsored). The reflood heat transfer and entrainment model parameters in the systems code RELAP4/MOD6 were determined by a parametric study and comparison with FLECHT data. Good agreement with data was obtained by variation of these parameters, and guidelines for their choice were established. Consistently reliable guidelines could not be found, however, indicating a need for further modeling work on reflood heat transfer.

The single channel core codes, REFLUX2, FLOOD4 and SUPERH, were developed to provide a mechanistic description of the reflood phenomena specifically observed in FLECHT. Figure 3 compares the predictions of REFLUX2 for a FLECHT test in a best-estimate calculation and in a calculation that only allows dry steam cooling above the quench region. This calculation must be considered qualitative in nature due to its many modeling assumptions (Appendix C). It is also important to note that there is no steam cooling requirement in licensing calculations for reflood rates above one inch per second, and the actual steam cooling penalty below one inch/second is subject to details of each vendor's modeling approach. Phenomenological modeling of heat transfer above the quench front has not yet reached a satisfactory state, although the calculation of cladding temperature increase and turnaround time by REFLUX2, FLOOD4, SUPERH, RELAP4, or UCFLOOD is often good.

### 2.2.2.3 Semiempirical Models

A number of semiempirical models have been developed for the prediction of quench front velocities during reflooding at constant inlet flooding rates (Appendix C). A successful model developed within RSR employs initial system parameters rather than transient thermal-hydraulic conditions and constitutes a simple tool for making pretest estimations of reflood velocity, quench time and mass carryover.

The correlation was developed using both low and high flooding rate data from the FLECHT program and is given by:

$$u_q = 20.\ u_{in}\ \Gamma^{-\frac{1}{2}} \left(\frac{T_{min} - T_{sat}}{T_{init} - T_{sat}}\right)^{0.15} \qquad (1a)$$

where $u_q$ = quench front velocity

$u_{in}$ = inlet flooding velocity

$T_{min}$ = minimum film boiling temperature

$T_{sat}$ = saturation temperature

$T_{initial}$ = initial cladding temperature

The dimensionless number ($\Gamma$) in Equation (1a) is given by:

$$\Gamma = \frac{D\ q\ \rho_f}{H_{fg}\rho_v\mu_v} \qquad (1b)$$

It is approximately proportional to initial local heat flux (q) and inversely proportional to pressure. A higher number by Equation (1b) tends to indicate greater turbulence in the froth region, enhanced droplet entrainment and reduced quench front velocity.

Figure 4 shows a comparison of measured and predicted velocities for the FLECHT experiments. The data base includes a wide range of test parameters: inlet velocities of 1 - 45 cm/s, peak rod power of 1.7 - 4.6 kW/m, pressures of 0.1 - 0.6 MPa, initial peak cladding temperatures of 140 - 1100°C, inlet subcooling of 72 - 90°C, and both cosine and "skewed" axial power profiles. The average percent discrepancy between the measured and predicted velocities is 20%.

The model provides good predictions of quench front velocities for other facilities. Semiscale tests performed with system parameters similar to those of FLECHT tests resulted in similar actual and predicted quench front velocities, in spite of different core lengths of 1.7 and 3.7 m. The reflood rate for zircaloy-clad rods in LOFT is nearly twice that predicted by Equation 1 for stainless steel-sheathed heater rods. This enhancement factor is due only to differences in rod design and is expected according to conduction model theory and the results of small-scale experiments (such as those sponsored by EPRI at UCLA).

The mass carryover rate fraction for low flooding rates, exclusive of fall back, is given by unity minus the ratio $u_q/u_{in}$ calculated by Equation (1). Refinements to this calculation can be made by application of Yeh's void fraction correlation or by the treatment of Sun and Duffey (Appendix C).

Details of this calculation are given in Appendix C. Further results and analyses are presented in Appendices A - D as outlined in Figure 5. Nomenclature is described in Appendix E.

## 3.0 Discussion

Results of the FLECHT program have been widely exposed to technical review through documentation and presentation at numerous meetings, including the Water Reactor Safety Research Information meetings. NRR staff utilize FLECHT data and consult with RES heat transfer staff when making licensing decisions. The general consensus is that the FLECHT program has been conducted well and that the data are valuable and important for consideration in the licensing of pressurized water reactors.

The FLECHT program has served as a model for programs in other countries and has produced benefits in addition to an understanding of low flood rate behavior and a data base for model development. All reactor vendors have utilized FLECHT data to improve their reflood models. Computer code development groups at RSR-sponsored laboratories have made extensive use of the data, including the unique FLECHT measurements of steam temperature above the quench front. These measurements demonstrated the thermal nonequilibrium nature of the fluid, and have allowed more detailed model assessments. The program also provided valuable flow visualization data and demonstrated its importance in the interpretation of recorded measurements. In addition it was demonstrated that differential pressure cells could be used to calculate void fractions in the test section and mass distributions throughout the system.

An understanding of scaling effects, blockage effects, and system behavior will be gained in the FLECHT SEASET tests. Original system effects tests (FLECHT-SET) verified the parametric trends observed in FLECHT (Section 2.1.1). Those tests also indicated the importance and complexity of steam generator effects and upper plenum design on system behavior. Such behavior must be understood for the analysis of gravity feed reflood (with continuously varying reflood rates) and will be examined in the FLECHT SEASET program.

Other areas of continuing research involve: (1) the investigation of reflood behavior for zircaloy-clad rods; and (2) analytical modeling efforts. Reflooding with zircaloy-clad rods is now being investigated in out-of-pile tests at the German KfK Rebeka Facility. Parametric reflood studies are also being planned for late 1980 in the NRU reactor at Chalk River, Canada, as part of the RSR fuel behavior research program. Analytical efforts are continuing by many organizations, including RSR in-house correlation work giving quench velocity and time as a simple function of physical variables, and Westinghouse work to somewhat simplify the accurate FLECHT heat transfer correlation by using elevation above the quench front rather than time as an independent variable.

## 4.0 Recommendation

The results presented above are recommended for consideration in the application and appraisal of evaluation models for reflood heat transfer. The following points are of particular note:

A. The low flooding rate (less than 1 inch per second) FLECHT data can be used in the preparation of a future Appendix K revision; and

B. Simple tools can be used to evaluate vendor calculations of reflood behavior, such as the RSR correlation for quench front velocity and the upper plenum carryover fraction, and existing phenomenologically-based codes for the increase in peak cladding temperature during reflood.

For further clarification or evaluation of these results, L. B. Thompson or Y. Y. Hsu of the Separate Effects Research Branch of the Division of Reactor Safety Research may be contacted.

Saul Levine

Saul Levine, Director
Office of Nuclear Regulatory Research

Enclosures:
1. Appendix A
2. Appendix B
3. Appendix C
4. Appendix D
5. Appendix E

## TABLE I

## RANGE OF PARAMETERS IN THE FLECHT EXPERIMENTS

| Parameter | Range (SI Units) | Range (British Units) |
|---|---|---|
| Inlet Flooding Rate | 1.0 - 46 cm/sec | 0.4 - 18 inch/sec |
| System Pressure | 0.1 - 0.62 MPa | 15 - 90 psia |
| Peak Power | 0.7 - 4.6 kW/m | 0.2 - 1.4 kW/ft |
| Initial Cladding Temperature | 150 - 1200°C | 300° - 2200°F |
| Coolant Inlet Subcooling | 9 - 105°C | 16 - 189°F |
| Local Channel Area Blockage | 0 - 100 Percent | Same |
| Bundle Area Blockage | 0 - 80 Percent | Same |
| Decay Power | ANS + 20% -- ANS-15% | Same |
| Axial Power Profile | cosine, skewed | Same |
| Bundle Radial Power Profile | 'FLECHT', uniform | Same |

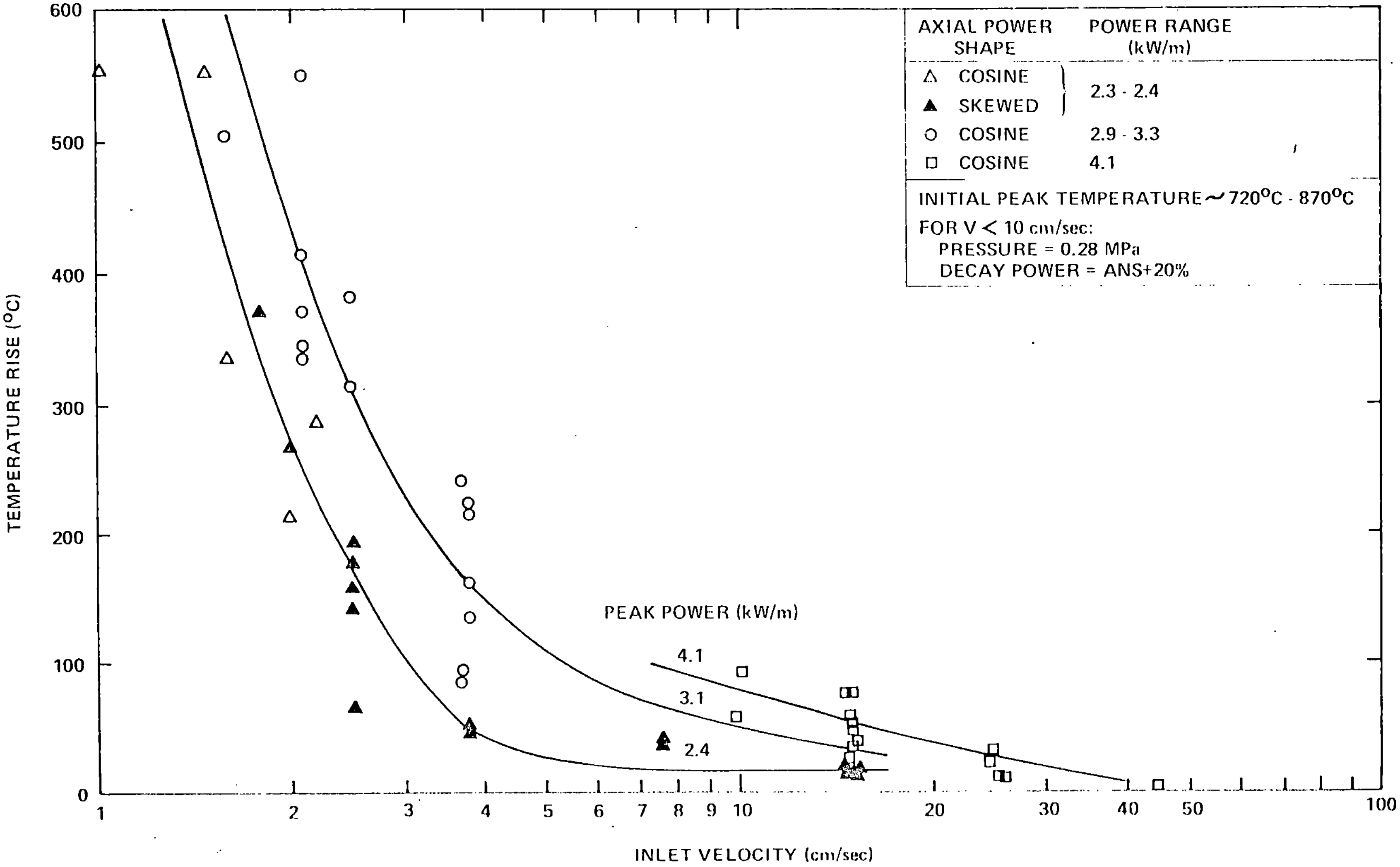

Figure 1. Temperature Rise at Location of Highest Temperatures during Reflood as a Function of Inlet Flooding Velocity.

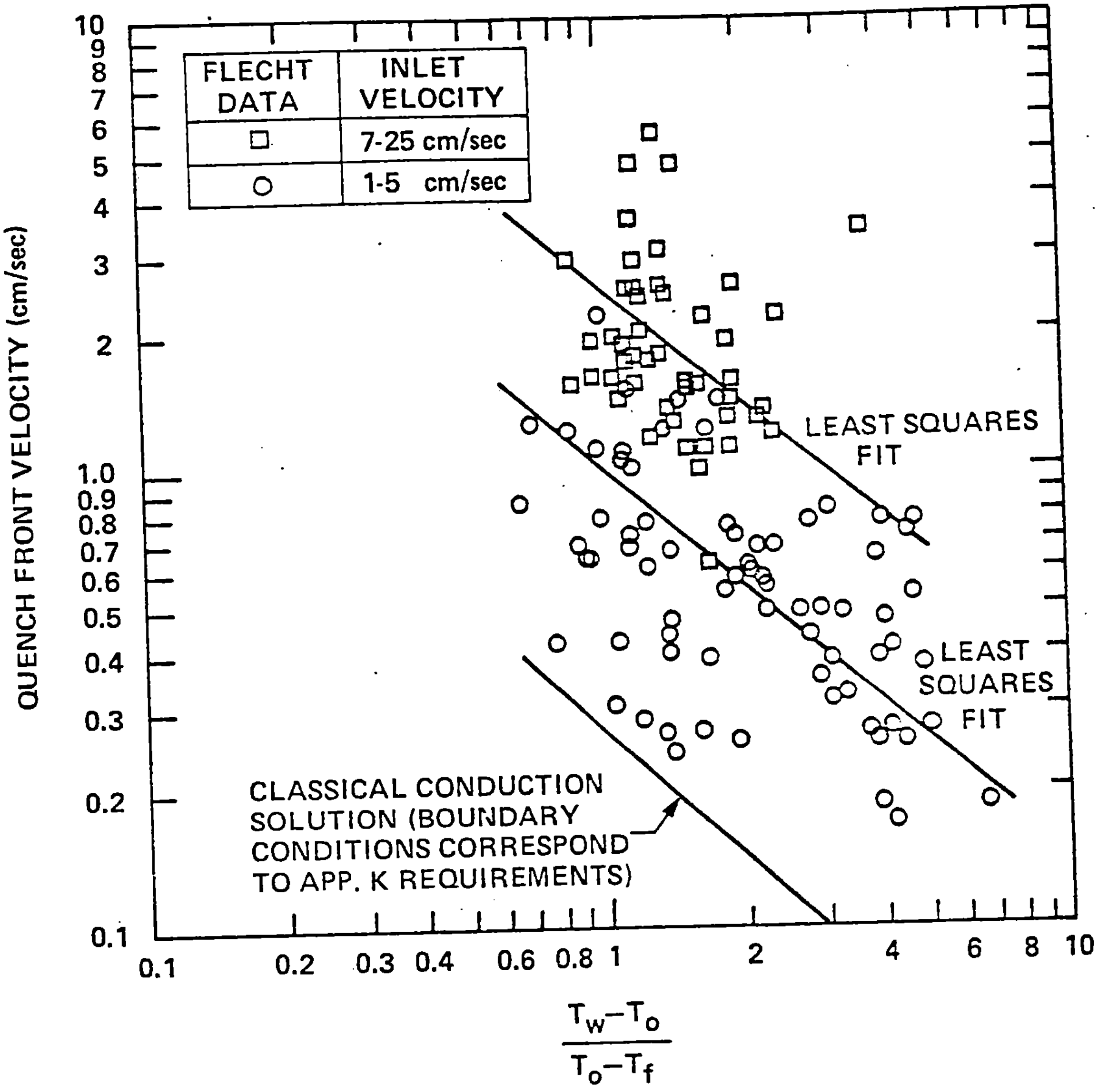

Figure 2. Quench Front Velocities for FLECHT Data and for Conduction-Solution Approximation to Appendix K Requirements, Given as a Function of Wall, Rewetting, and Fluid Temperatures $T_w$, $T_o$, and $T_f$.

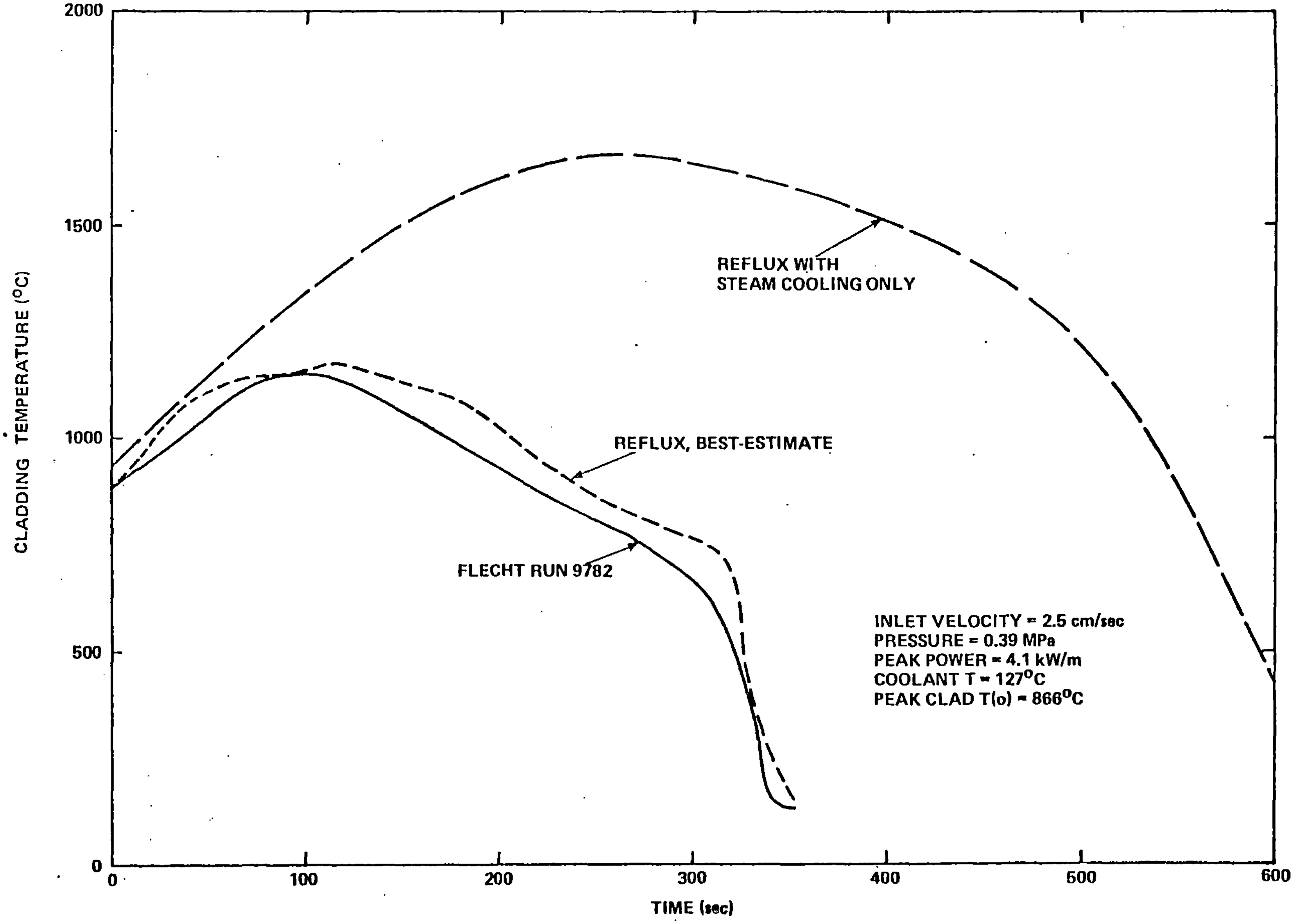

Figure 3. Best-Estimate and Steam-Cooling Calculations Using the MIT Code REFLUX.

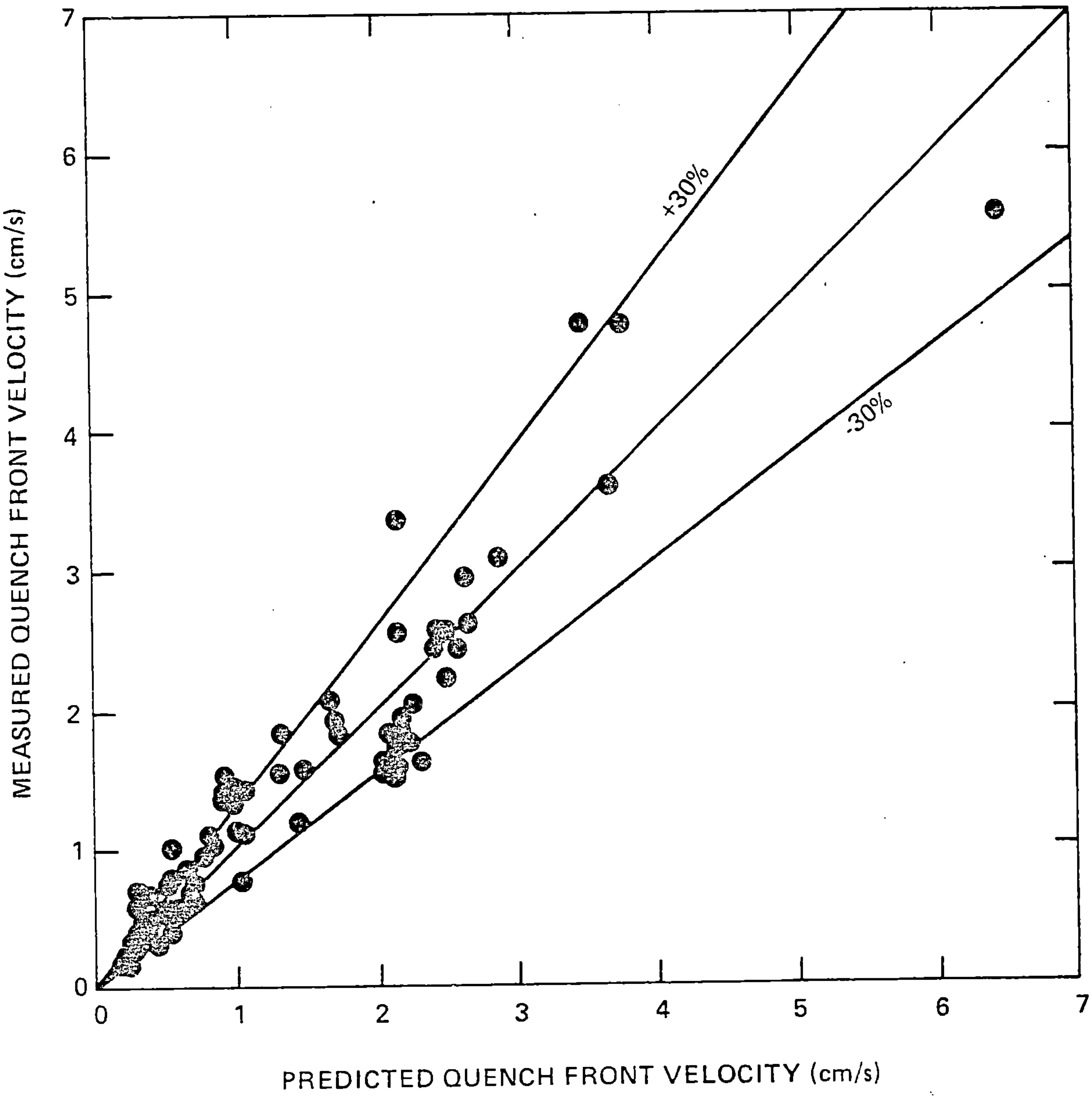

Figure 4. Comparison of Measured and Predicted Quench Front Velocities for FLECHT Tests with Inlet Velocities of 1 to 45 cm/s.

## Figure 5. Appendices to the Reflood RIL

Appendix A Westinghouse FLECHT Results

- I. Facility Description
- II. Program and Procedure
- III. Effects of Inlet Velocity and other Parameters on Reflooding Behavior
- IV. Comparison of Tests with Cosine and Skewed Axial Power Profiles
- V. Heat Transfer Information
- VI. Mass Entrainment Information
- VII. Correlations
  - 1. Heat Transfer and Quench Time
  - 2. Effect of Variable Flooding Rate

Appendix B Results of Other Reflooding Experiments and Comparison with FLECHT Data

- I. Semiscale Constant Flooding Rate Experiments
- II. KWU Constant Flooding Rate Experiments
- III. FLECHT Tests Using Unpressurized Rods with Zircaloy Cladding
- IV. KfK Tests Using Pressurized Rods with Zircaloy Cladding
- V. FLECHT Flow Blockage Tests

Appendix C Analytical Predictions of Thermal-Hydraulic Behavior During Reflood

- I. Convection-Controlling Models
  - 1. FLECHT Correlations
  - 2. REFLUX
    - a. Models
    - b. Comparison of REFLUX Predictions with Data
    - c. Conservative Predictions by REFLUX
    - d. Prediction of Peak Cladding Temperatures
  - 3. RELAP4
- II. Conduction-Controlling Models for Quench Front Velocity
  - a. One-Dimensional Models
  - b. Two-Dimensional Models
  - c. Multi-Region Model
- III. Semi-Empirical Approach for Quench Front Velocity
  - a. Murao Equation for High Flooding Rates
  - b. RSR Correlation for High and Low Flooding Rates
- IV. Conclusions

Appendix D The FLECHT Quench Time and Heat Transfer Correlations

- I. Correlations for Quench Time

Figure 5 (Continued)

II. Correlations for Heat Transfer Coefficient
  1. The 'FLECHT' Correlation
  2. The $Z-Z_q$ Correlation

Appendix E Nomenclature

For further clarification or evaluation of these results, L. B. Thompson or Y. Y. Hsu of the Separate Effects Research Branch of the Division of Reactor Safety Research may be contacted.

Original Signed By
Saul Levine

Saul Levine, Director
Office of Nuclear Regulatory Research

Enclosures:
1. Appendix A
2. Appendix B
3. Appendix C
4. Appendix D
5. Appendix E

RECORD NOTE; Review comments have been received from W. Hodges (NRR), L. Hochreiter (W), K. H. Sun (EPRI), R. Shumway (INEL) and P. Griffith (MIT) and have been largely incorporated. Appendices are intended for distribution to a select list or on request.

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|---|---|---|---|---|---|
| RSR:W:SE | RSR:W:SE | RSR:W:SE | RSR:W CEJ | RSR:W LST | RSR TM |
| LBThompson | YYHsu | LHSullivan | CEJohnson | LSTong | TEMurley |
| 09/07/79 | 09/7/79 | 09/11/79 | 09/19/79 | 09/24/79 | 10/1/79 |
| RES:PCB | RES RJB | RES SL | | | |
| JTLarkins | RJBudnitz | SLevine | | | |
| 10/27/79 | 10/29/79 | 11/6/79 | | | |