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UNCERTAINTY IN PREDICTED LOFT REFLOODING RESPONSE: INFLUENCE ON CLADDING OXIDATION

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Semiscale gravity feed reflood and FLECHT-SET tests have been reviewed to determine phenomena which may be important during LOFT reflood. FLOOD4 and RELAP4/MOD6 predictions for Semiscale and FLECHT-SET tests were compared to experimental data. Based on these comparisons, uncertainties were estimated for the LOFT reflood predictions; these uncertainties were then utilized to bound the extent of cladding oxidation expected for the LOFT L2-3 and L2-4 tests.

DISPOSITION OF RECOMMENDATIONS

No disposition required.

ABSTRACT

Semiscale gravity feed reflood and FLECHT-SET tests have been reviewed to determine phenomena which may be important during LOFT reflood. FLOOD4 and RELAP4/MOD6 predictions for Semiscale and FLECHT-SET tests were compared to experimental data. Based on these comparisons, uncertainties were estimated for the LOFT reflood predictions; these uncertainties were then utilized to bound the extent of cladding oxidation expected for the LOFT L2-3 and L2-4 tests.

SUMMARY

Semiscale gravity feed reflood tests and FLECHT-SET tests have been reviewed to determine phenomena which may be important during LOFT reflood. The tests evaluated generally show little cladding temperature rise during reflood. The tests also indicate that water vaporization in the steam generator or upper plenum will cause insignificant steam binding.

The FLOOD4 and RELAP4/MOD6 reflood codes generally predicted peak cladding temperatures to within 100^{o}F. Calculated quench times may differ from experimental measurements by as much as 100 seconds. It is predicted that little rise in cladding temperature will occur during reflood. The complex geometry of the LOFT upper plenum should ensure that little liquid will reach the steam generators and result in steam binding.

The comparison of model predictions to the Semiscale and FLECHT-SET data provide uncertainty bounds on the predicted L2 Series peak cladding temperature histories. These uncertainties in peak cladding temperature ($\pm$ 100^{o}F) and quench time ($^{+100}_{-20}$ sec) were utilized to evaluate and bound the extent of cladding oxidation expected for each L2 series LOCE. The oxidation limit established for LOFT cladding is not exceeded even for the most severe cladding temperatures which will ensure at least partial ductility of the cladding during the test sequence. Thus cladding oxidation is not predicted to be a limiting factor during the L2 tests.

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I. INTRODUCTION

Current reflood predictions for the high power LOFT tests indicate peak cladding temperatures in excess of 2000^{o}F may be maintained for 100-200 seconds. Cladding oxidation will result at these temperatures causing some degradation of cladding strength.

In order to place bounds on the cladding oxidation expected during the LOFT L2 test series, the ability to model the reflood phase of a LOCE has been studied to identify important parameters which influence cladding temperature.

This report reviews gravity feed reflood experiments (FLECHT-SET, Semiscale) and two codes used to predict pressurized water reactor reflood behavior, FLOOD4 and RELAP4/MOD6. Phenomena which may be of importance during the reflooding of the LOFT L2 tests and the ability of the codes to predict such phenomena are discussed. Reflood code uncertainties are combined with cladding oxidation characteristics to place bounds on potential oxidation of the LOFT cladding.

Section II presents a general description of reflood phenomena. Section III discusses FLECHT-SET and Semiscale gravity feed tests; Section IV discusses current modeling capability in the FLOOD4 and RELAP4/MOD6 codes and compares the model predictions with FLECHT-SET and Semiscale results. In addition, potential three dimensional effects which may be important during reflood are also discussed. Section V presents bounding limits on cladding temperature response and on cladding oxidation for the LOFT L2-2, L2-3 and L2-4 tests. Section VI summarizes the major conclusions regarding the reflood behavior expected for LOFT.

II. GENERAL REFLOOD DESCRIPTION

The nuclear core of a reactor may be cooled following the blowdown phase of LOCA by injecting the ECC water directly into the lower plenum or by injecting the coolant into the downcomer or cold leg. Systems utilizing downcomer or cold leg injection, such as LOFT, are referred to as gravity feed reflood systems.

The core flooding rate for gravity feed systems is dependent on the difference between the core pressure and the downcomer gravity head.

Gravity feed systems are characterized by oscillations in the core inlet flow. Contact between the ECC water and the hot fuel rods results in vigorous boiling and steam generation. The steam generation increases the core pressure until the coolant inertial effects are overcome and the ECC flow is reversed. The steam generation rate then decreases allowing steam to vent which results in a drop in the system pressure. Positive flow is then re-established and the oscillatory cycle is repeated. Semiscale tests and FLECHT gravity feed tests have exhibited these flow oscillations.

As the coolant contacts the fuel rods, a frothy two-phase mixture in advance of the quench front is formed. As more steam is generated and the steam velocity increases, liquid from the froth layer is entrained in the steam flow and carried up past the fuel rod. The entrained droplets may cool the upper elevations of the fuel rod by physical contact on the rod and/or by serving as a radiant heat sink. The entrained droplets and steam are not in thermodynamic equilibrium so it is possible to have the droplets entrained in superheated steam. The heat transfer mechanisms associated with the cooling of rods during reflood are not well understood[1].

In the upper plenum, the steam may exit through the broken loop or through the intact loops. The intact loops offer less resistance to the steam flow so most of the steam passes into the intact loops. It has been calculated that approximately 80% of the flow for LOFT will pass through the intact loops. The entrained droplets can be either de-entrained in the upper plenum (deposited and form a liquid film on upper plenum internal structures) or be carried along with the steam into the broken or intact loops. The droplets which are de-entrained may remain on the upper plenum surfaces, may be reentrained, or may fall back into the core thereby providing additional cooling to the upper core elevations. The droplets which are not de-entrained and are carried into the intact loop may be partially or totally vaporized in the steam generators. Vaporization of the entrained droplets creates a higher system pressure which retards the flooding rate. This leads to higher peak cladding temperatures and longer quench and temperature turnaround times.

As a result of liquid entrainment and fallback from the upper plenum to the core, the core cooling process proceeds from both the bottom and top of the core. As time progresses, enough reflooding water has been added to the system that the fuel rod is cooled and brought to the saturation temperature of the water.

The major phenomena controlling the fuel rod response during the reflood phase of a LOCA are (1) fuel rod stored energy and decay power generation, (2) fuel rod internal pressure, (3) thermal and mechanical properties of the fuel and cladding, and (4) cladding surface heat transfer characteristics.

The initial steady state fuel rod stored energy will strongly influence peak cladding temperatures during blowdown; current calculations indicate from 50-75% of the initial stored energy still remains within the fuel rod at initiation of reflood. An important parameter is the fuel cladding gap which influences heat removal from the fuel pellet to the cladding and surrounding coolant. Internal fuel rod pressure strongly influences cladding deformation (ballooning or collapse). The thermal and mechanical properties of the cladding are important in characterizing both heat transfer from the fuel rod and cladding deformation and potential failure.

System related parameters which affect the the cladding surface heat transfer are ECC fluid subcooling, flooding rates, containment pressure, loop flow resistances, upper plenum geometry effects on droplet de-entrainment and liquid fallback, two-phase heat transfer, liquid entrainment and carryover fraction, and droplet vaporization in the steam generators.

A considerable amount of research has been and is being performed to identify and quantify the controlling hydrodynamic effects and heat transfer during reflood. Two of these programs, the Westinghouse FLECHT-SET Phase B1 experiments and the Semiscale gravity feed reflood tests have been reviewed and important parametric effects will be summarized in the next section.

III. EXPERIMENT DATA REVIEW

1. FLECHT-SET RESULTS

The FLECHT-SET B1 tests [2] were designed to simulate the gravity feed reflood behavior of a commercial PWR. The test assembly contained a 10 x 10 array of 12-foot, electrically heated rods. System volumes, heights, and loop resistances were scaled to that of a PWR. Steam generators were included in both the broken and intact loops.

The influence of upper plenum flow area, system pressure, coolant subcooling, peak power, core inlet resistance, and intact and broken loop resistance on quench time, cladding temperatures and temperature turnaround times were examined. Of the parameters investigated, the rod power and system pressure were found to have the greatest effect. These results are consistent with earlier PWR FLECHT experiments[3].

Increases in fuel rod power generation at the start of reflood were shown to result in higher cladding temperature rises and delay in achieving temperature turnaround and quench as shown in Figure 1. The higher cladding temperatures at the start of reflood caused higher steam generation rates and more entrainment early in reflood. While the increased entrainment led to an initial increase in heat transfer, it also resulted in less fluid accumulation in the core. This produced a decrease in quench front velocity and caused lower heat transfer later in reflood as shown in Figure 2.

System pressure was found to significantly effect the peak cladding temperature characteristics as shown in Figure 3. The system pressure directly influences the specific volume of the two-phase mixture. Increases in system pressure decrease the coolant specific

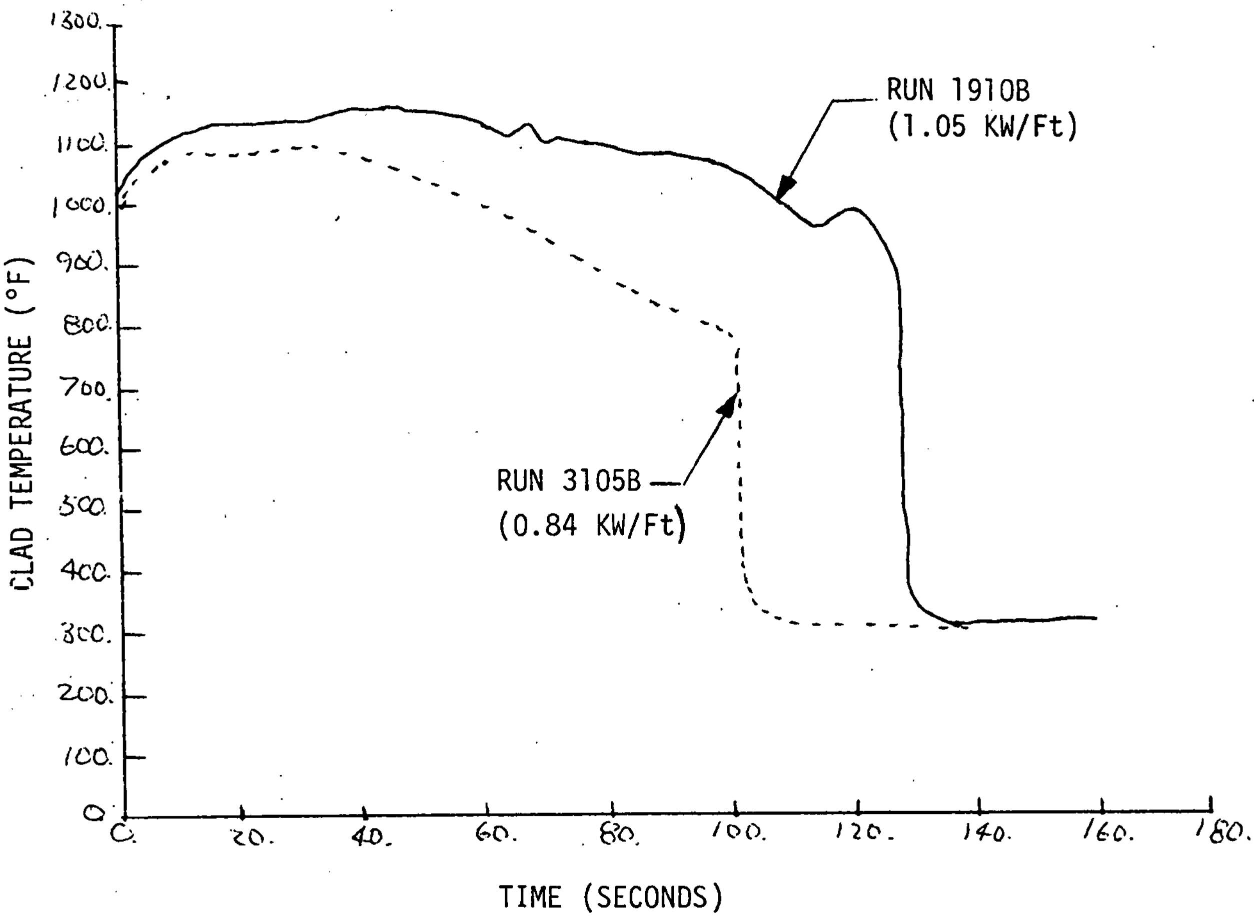

Figure 1. Effect of Initial Power on Midplane Reflood Cladding Temperatures (FLECHT-SET)

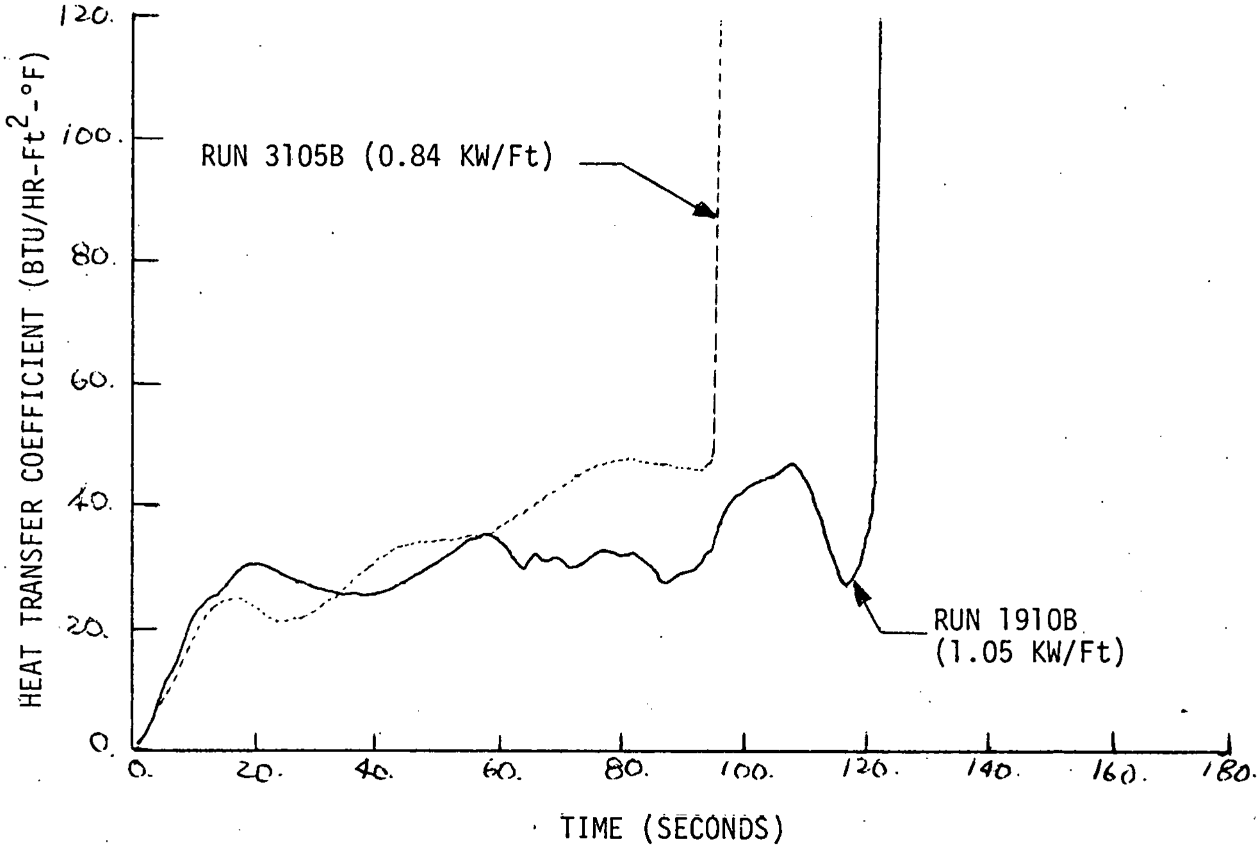

Figure 2. Effect of Initial Power on Midplane Elevation Reflood Heat Transfer Coefficients (FLECHT-SET)

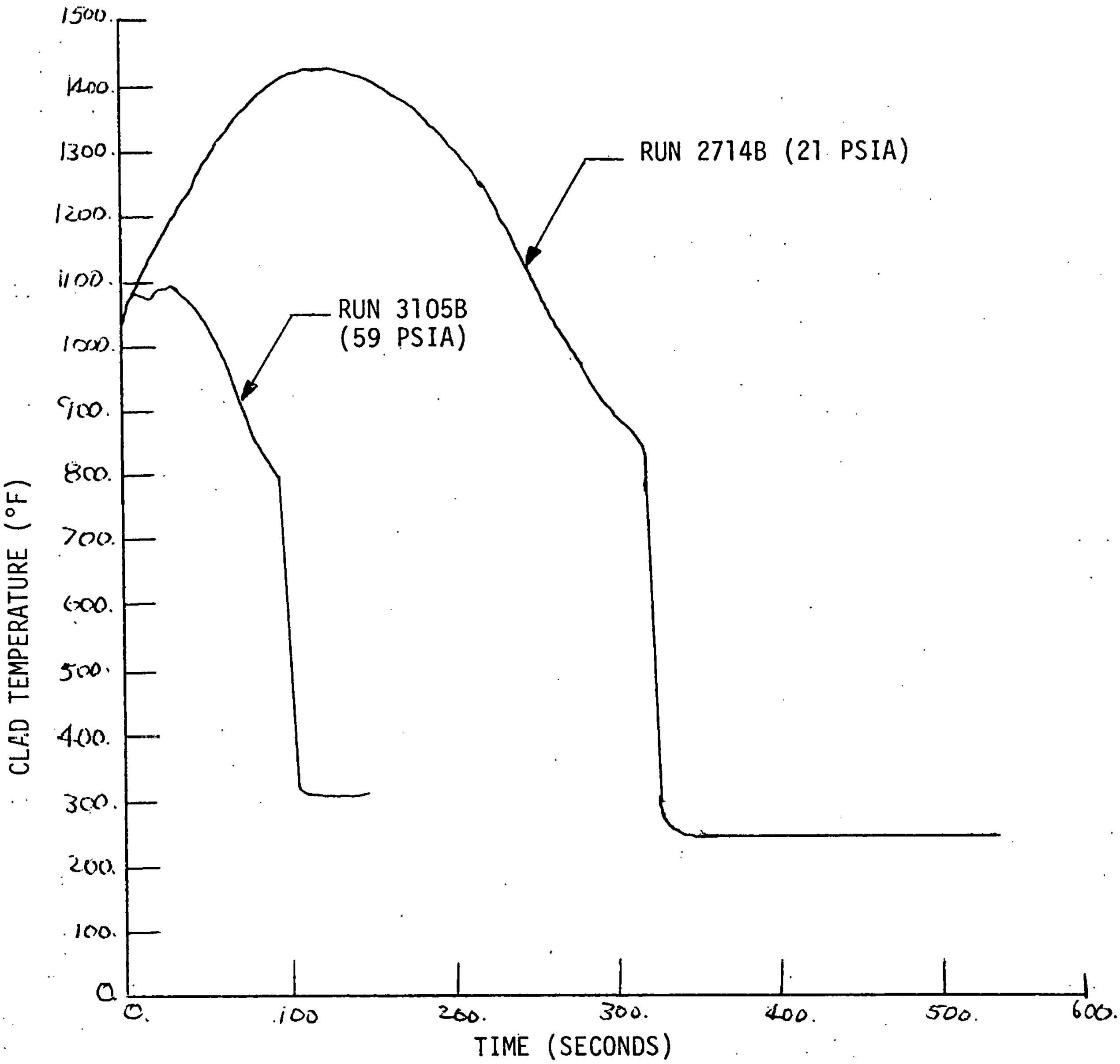

Figure 3. Effect of System Pressure on Midplane Elevation Reflood Cladding Temperatures (FLECHT-SET)

volume. A lower specific volume permits a larger mass flow. The increased mass flow increases the heat transfer which decreases quench and turnaround times and reduces the cladding temperature rise.

Coolant subcooling was shown to have a small influence on midplane heat transfer characteristics as shown in Figure 4. Decreasing the subcooling resulted in earlier boiling of the coolant. The early boiling produces early entrainment and good initial heat transfer, but reduced heat transfer at later times. A decrease in subcooling resulted in small increases in quench times.

Increases in core inlet and broken loop resistances were shown to have negligible effect on midplane heat transfer characteristics as shown in Figures 5 and 6 respectively. The core inlet resistance comprises a small fraction of the loop resistance. Hence, the mass flow and loop pressure drop is insensitive to changes in core inlet resistance. Similarly, the broken loop flow is much less than the intact loop flow. Changes in the broken loop did not significantly affect reflood. Increases in the intact loop resistance did retard the reflooding rate and caused lower steam flow and longer turnaround and quench times due to a reduction in the flooding rate.

Changes in upper plenum flow area had negligible effect on cladding temperature, turnaround time, or quench time.

2. SEMISCALE RESULTS

A series of gravity feed reflood tests were conducted in the Semiscale MOD1 system[4]. The tests encompassed a broad range of conditions and provided a data base for the development of the FLOOD4 code and reflood information to LOFT.

The Semiscale gravity feed reflood tests were conducted with the initial system conditions matched to the conditions expected following a blowdown. The system pressure was established by controlling the

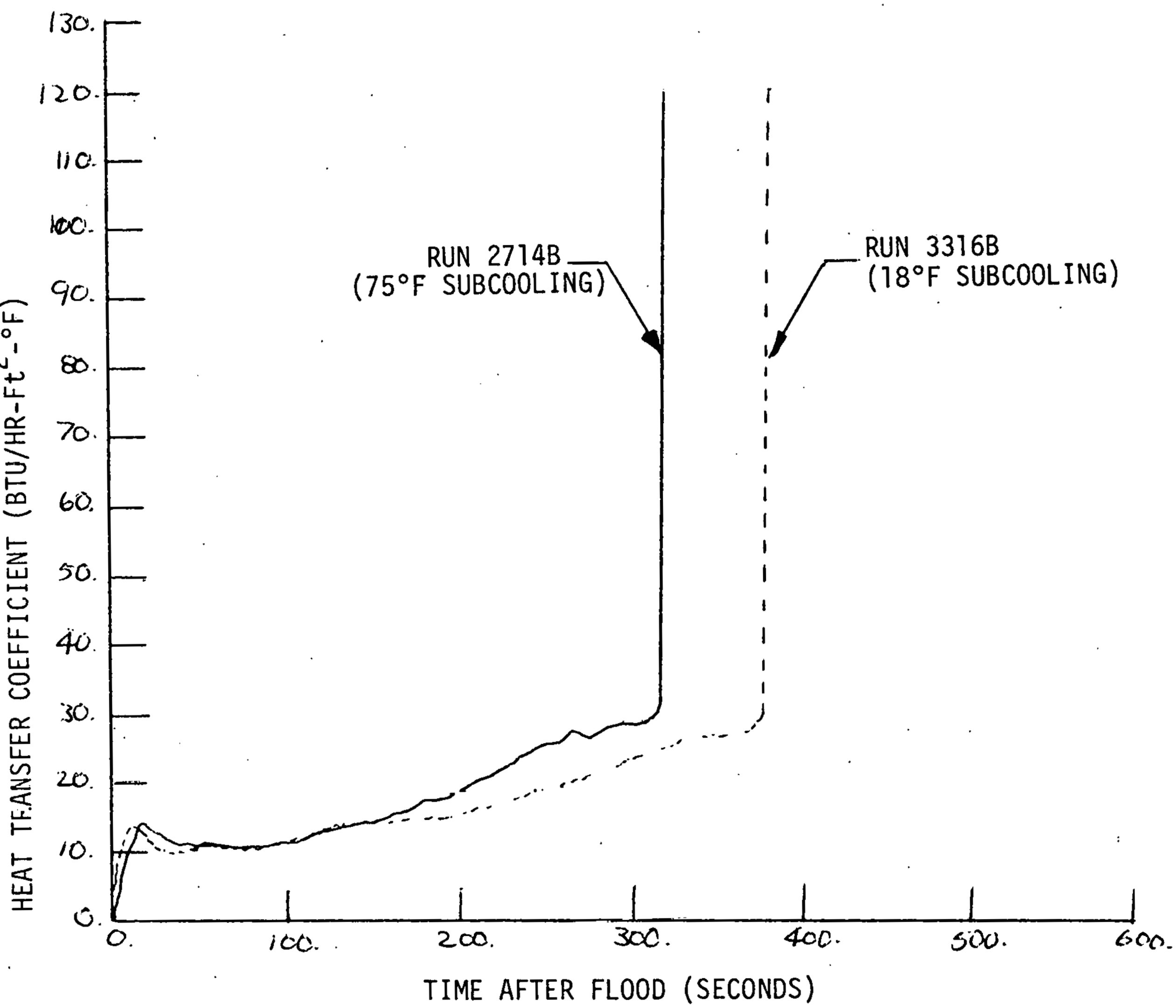

Figure 4. Effect of Coolant Subcooling on Midplane Elevation Reflood Heat Transfer Coefficients (FLECHT-SET)

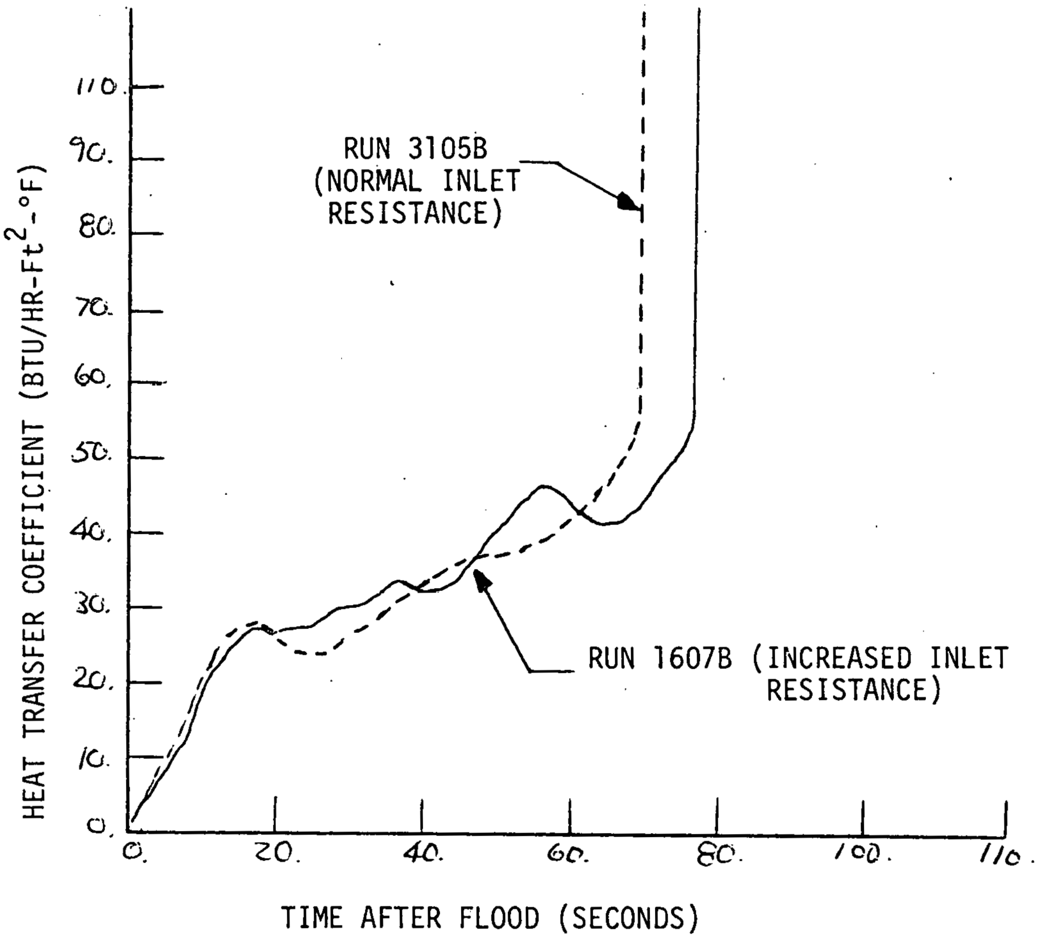

Figure 5. Effect of Core Inlet Resistance on Midplane Elevation Reflood Heat Transfer Coefficients (FLECHT-SET)

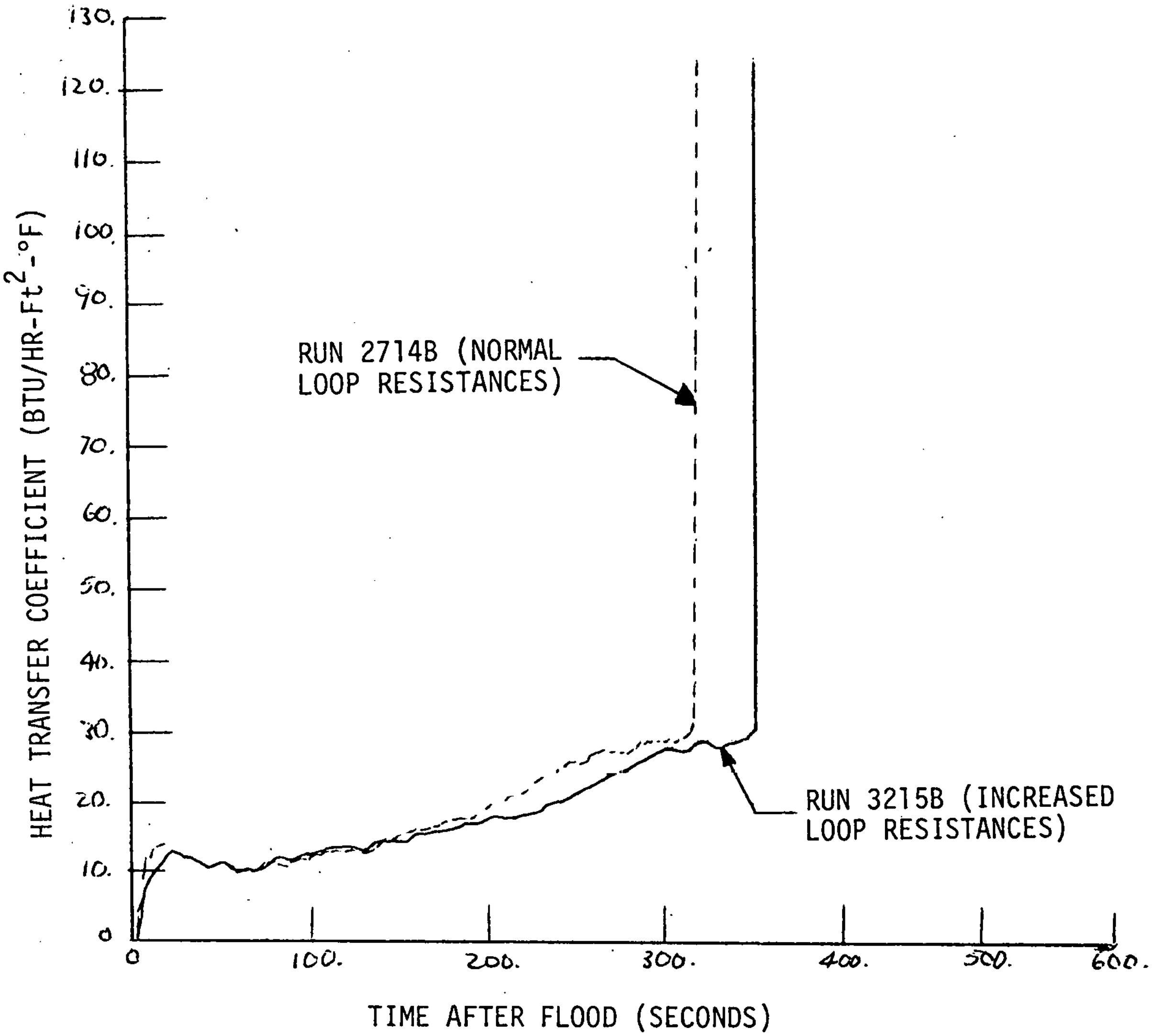

Figure 6. Effect of Loop Resistance (Broken and Intact) on Midplane Elevation Reflood Heat Transfer Coefficients (FLECHT-SET)

pressure in the pressure suppression system. The initial water level in the lower plenum was established and the core power was set at the desired value. The ECC injection was initiated when the desired peak cladding temperature was achieved.

The core inlet oscillations observed in the FLECHT-SET tests were also observed in the Semiscale gravity feed tests. The oscillation in the surface heat transfer coefficient, shown in Figure 7, closely followed the coolant oscillations. For the initial 25 seconds, the heat transfer coefficient oscillated between 0 and 60 BTU/ht-ft^{2o}F. From 25 seconds until just prior to quench, heat transfer coefficients vary from 20-100 BTU/hr-ft^{2o}F. At quench, a large increase in heat transfer occurs.

Figure 8 is a typical plot of quench time as a function of elevation. Quenching occurs at the top and bottom of the rod and progresses towards the rod midplane. The bottom quenching is due to the advancement of the cooling liquid while droplet de-entrainment and fallback from the upper plenum, coupled with lower power, results in top quenching. From Figure 8, three regions of approximately equal quench front velocities can be constructed. The quench velocities ranged from 0.5 in/sec in region I to 0.2 in/sec in region II to 0.16 in/sec in region III. The quench velocity decreased somewhat with increased cladding temperature. The occurrence of top quenching suggests that the peak cladding temperature will not migrate up the rod as reflood progresses. Once the midplane temperatures have turned around, the thermal rise of the fuel rod has been effectively terminated.

A reflood boiling curve was constructed from experimental data. From this curve, five heat transfer regimes were identified. They were (1) forced convection to steam, (2) dispersed flow, (3) film boiling with some forced convection between vapor and liquid, (4) transition boiling, and (5) nucleate boiling. The regimes are identified in Figure 9. Region I includes convection to steam and

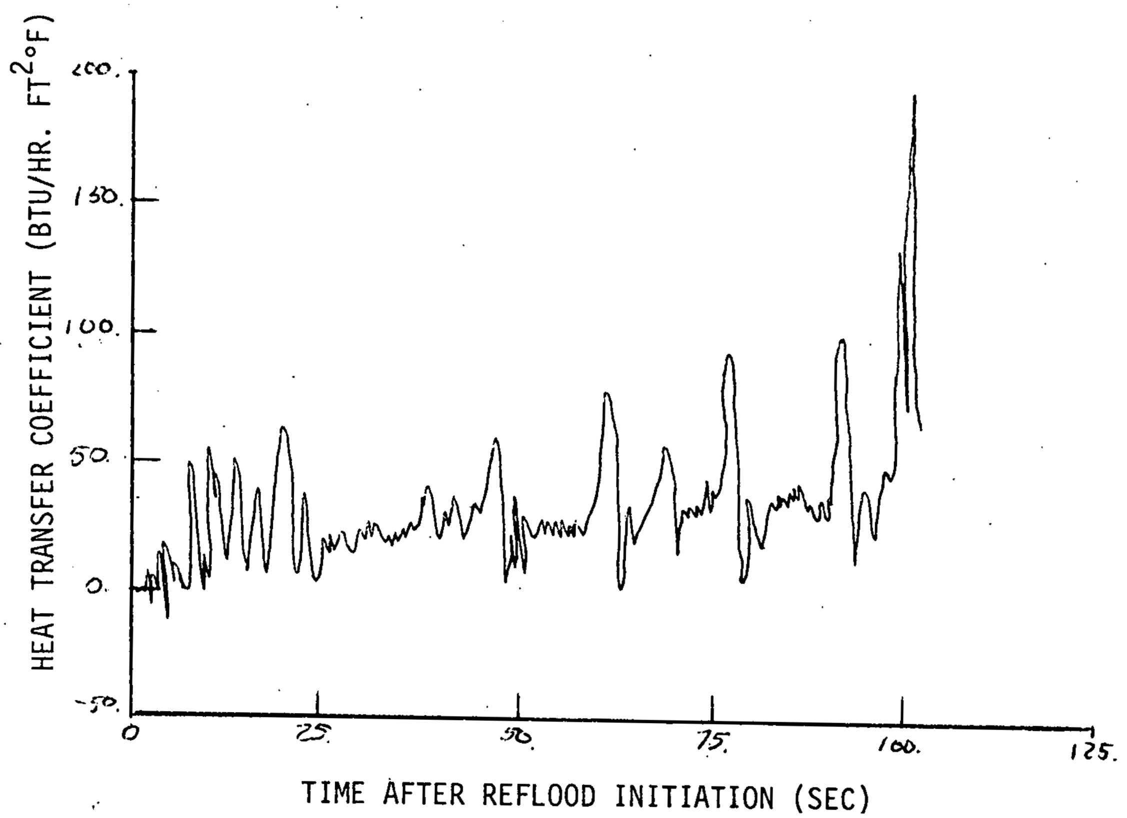

Figure 7. Midplane Elevation Reflood Heat Transfer Coefficients (Semiscale, S-03-8).

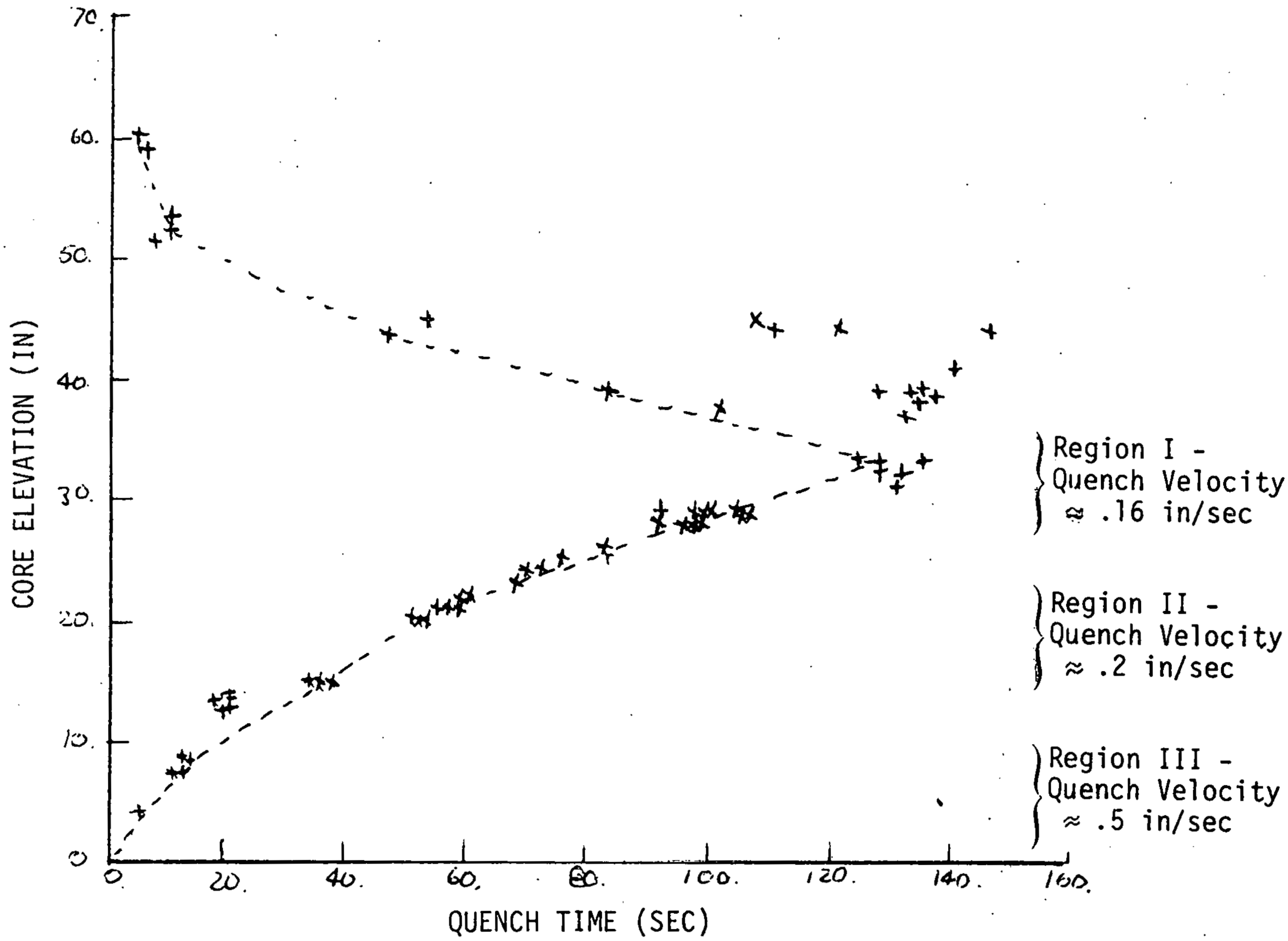

Figure 8. Quench Times as a Function of Axial Elevation (Semiscale, S-03-8)

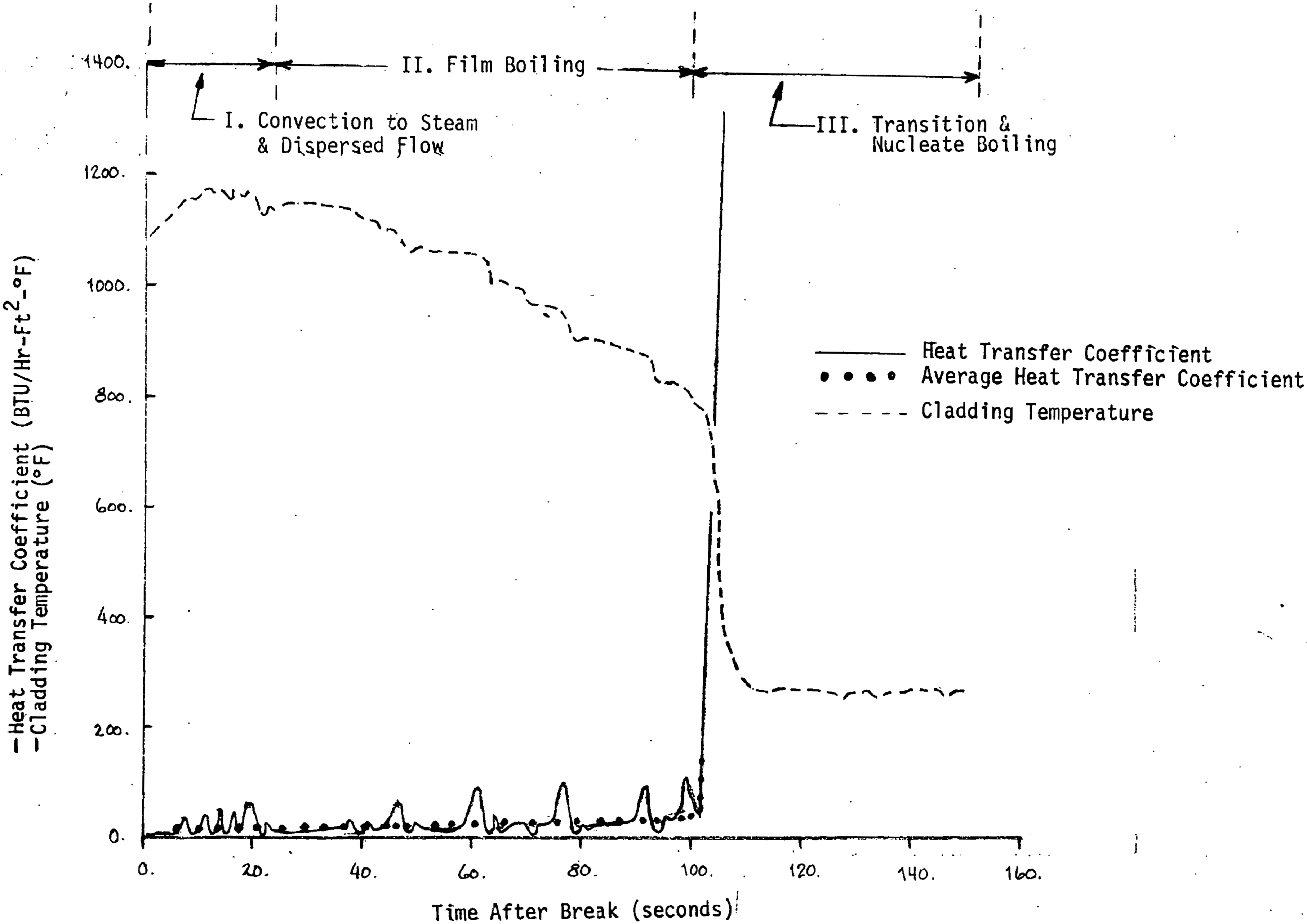

Figure 9. Overlay of Midplane Elevation Surface Heat Transfer Coefficients and Cladding Temperature (Semiscale, S-03-8).

dispersed flow boiling. Region II is film boiling while region III encompasses the end of film boiling, transition boiling, and the start of nucleate boiling.

The peak cladding temperature increases slightly during the first few seconds of reflood when the surface heat transfer is characterized by convection to steam. As the liquid entrainment increases in the dispersed flow regime, the cladding temperature rise is terminated and the rod begins to cool. The end of film boiling and start of transition boiling marks the commencement of quench. Quench is achieved when the cladding surface heat transfer returns to nucleate boiling. Semiscale results indicated that for midplane peak power elevations that the majority of the time is spent in the film boiling mode. From Figure 9, it is observed that the cladding temperature does not reflect large temperature oscillations as would be expected from the oscillating heat transfer coefficients. This is a result of the near adiabatic state of the rod. Thus, a valid approximation to the heat transfer coefficient is a smooth curve which averages the oscillations as shown in Figure 9.

Parameter studies such as the effect of power and pressure were not performed in the Semiscale tests although comparison of various tests do give an indication of the influence of certain parameters on reflood behavior. These results were consistent with the FLECHT parameter studies.

In general, the experimental data shows that system related parameters and physical properties do not greatly affect peak cladding temperatures; however, some effect on quench times due to these parameters has been observed.

System stored energy and heat transfer related paramenters are the key parameters influencing cladding temperature and coolant behavior during reflood. Of particular interest are the heat transfer parameters. The fuel rod stored energy related quantities are understood and are known or can be specified with some degree of accuracy. The heat transfer related parameters, in particular the specification of heat transfer regimes and droplet entrainment and vaporization cannot, at present, be accurately specified [5,6,7].

IV. MODELING CAPABILITY

RELAP4/MOD6 [8] and FLOOD4 [9] are the computer codes presently available at INEL for reflood analysis.

1. FLOOD4

FLOOD4 was developed from FLECHT data to calculate the core and system behavior during Semiscale reflood tests. FLOOD4 couples the system hydraulic response with core heat transfer and steam generation. Four heat transfer correlations are used to simulate the boiling curve and the mode of heat transfer depends upon the fuel rod elevation, water elevation, and the surface temperature.

Below the quench elevation, the heat transfer is forced convection to liquid. At the quench front, nucleate boiling and the Hsu transition boiling correlation are used. Further, from the quench front in the dispersed flow region, a heat transfer correlation developed from the FLECHT data is used.

The entrainment correlation used by FLOOD4 depends upon the steam flow, the system pressure, the hydraulic diameter, the elevation (length) of the collapsed liquid level above the quench front, and an entrainment multiplier.

The film boiling correlations for dispersed flow heat transfer and entrainment require user input constants. FLOOD4 also requires the user to input the entrained liquid fraction which is vaporized in the steam generator. Accurate specification of these constants is necessary for reasonable predictions. To some extent, the input constants are system specific. The constants associated with the dispersed flow and film boiling correlations do not seem to vary much between Semiscale and FLECHT tests. The input quantity describing the liquid vaporization fractions in the steam generators may vary from system to system. For Semiscale and FLECHT, the FLOOD4 liquid vaporization fractions are identical.

Figures 10 and 11 compare FLOOD4 predictions with Semiscale results. FLOOD4 fairly well predicts peak cladding temperatures but underpredicts quench times and overpredicts heat transfer coefficients. The optimized constants resulted in good predictions of peak cladding temperatures, but flow oscillations, heat transfer coefficients and core inlet mass flow are still overpredicted. Peak cladding temperatures are predicted to within $100^{o}F$ and quench times are predicted to within ± 60 seconds.

2. RELAP4/MOD6

RELAP4/MOD6 was developed to model a broad spectrum of reflood situations. Consequently, many of the correlations used in the reflood model require user specified constants. The appropriate value of the constants are not always readily apparent and experimental data is necessary to accurately specify the constants.

Figures 12 through 17 presents results from reference 10 comparing baseline RELAP4/MOD6 predictions (using default values of input constants) and best-fit RELAP4/MOD6 predictions (input constants optimized to give best fit between prediction and experiment with Semiscale and FLECHT data). Table 1 summarizes and compares the RELAP4/MOD6 calculations with experimental measurements from Semiscale test S-03-2.

Considerable scatter exists in the RELAP4/MOD6 predictions. The best-fit predictions are usually more accurate than baseline predictions. But even best-fit predictions may miss quench times by $^{+100}_{-20}$ seconds.

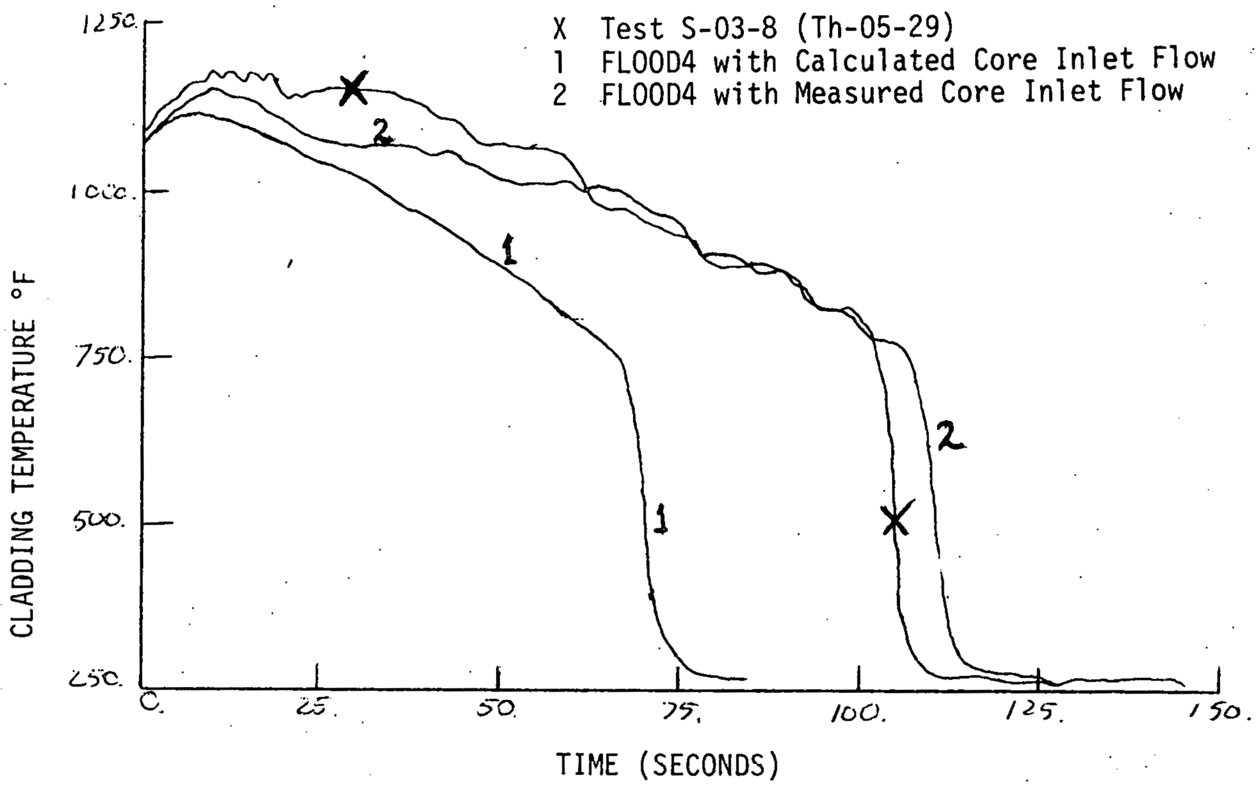

Figure 10. Comparison of Semiscale S-03-8 Measured Cladding Temperatures with Baseline and Best Fit (Optimized Multipliers) FLOOD4 Predicted Cladding Temperatures

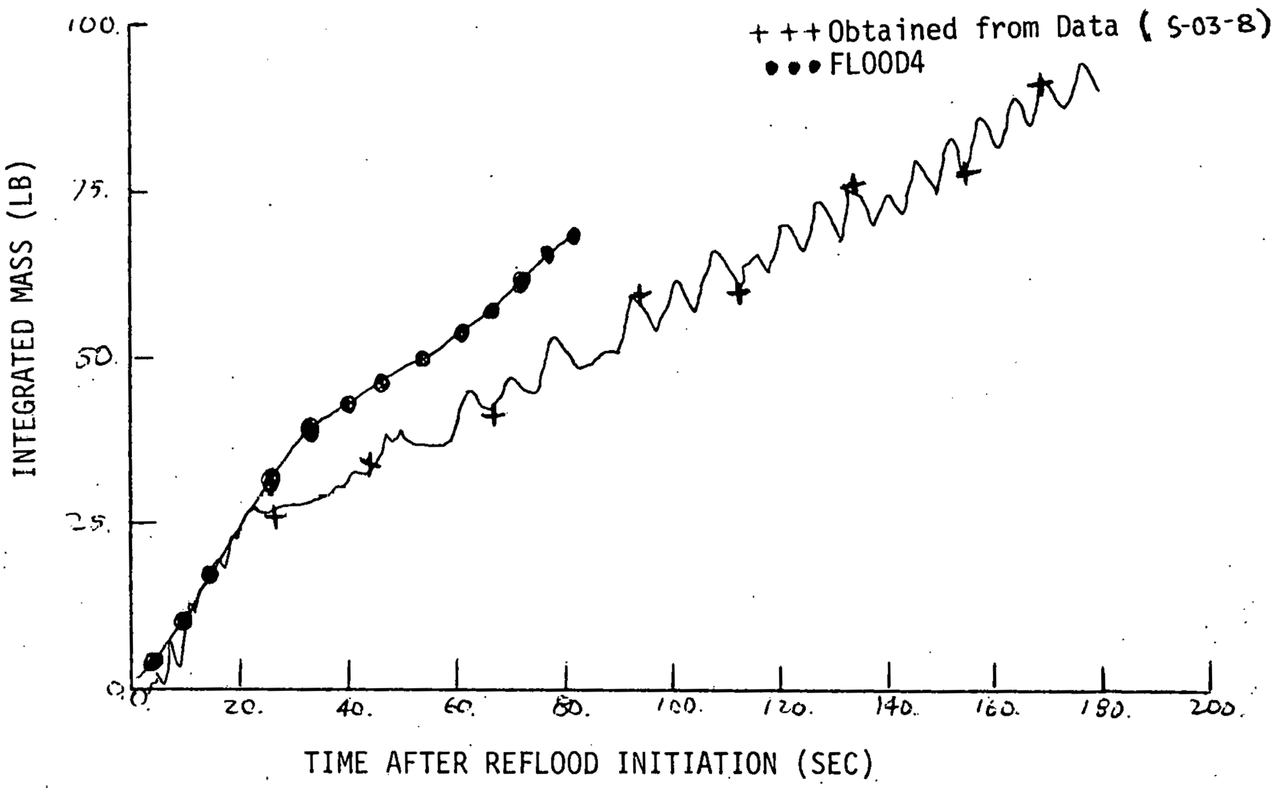

Figure 11. Comparison of Measured Core Total Mass with FLOOD4 Prediction using Optimized Multipliers (Semiscale, S-03-8).

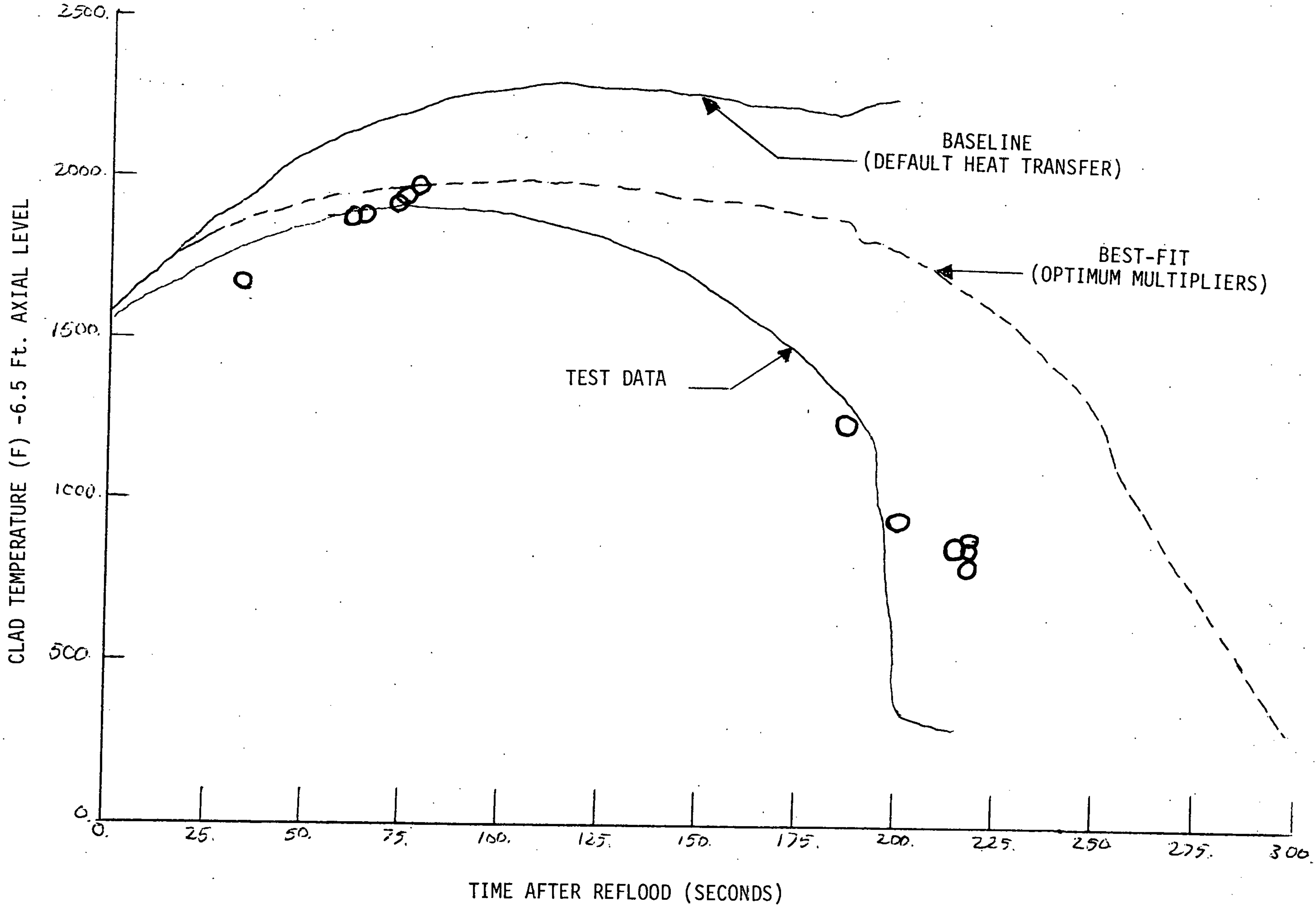

Figure 12. Comparison of FLECHT Test 4831 Cladding Temperature With Baseline (Default Heat Transfer) and Best-Fit (Using Optimized Multipliers) RELAP/MOD6 Predictions.

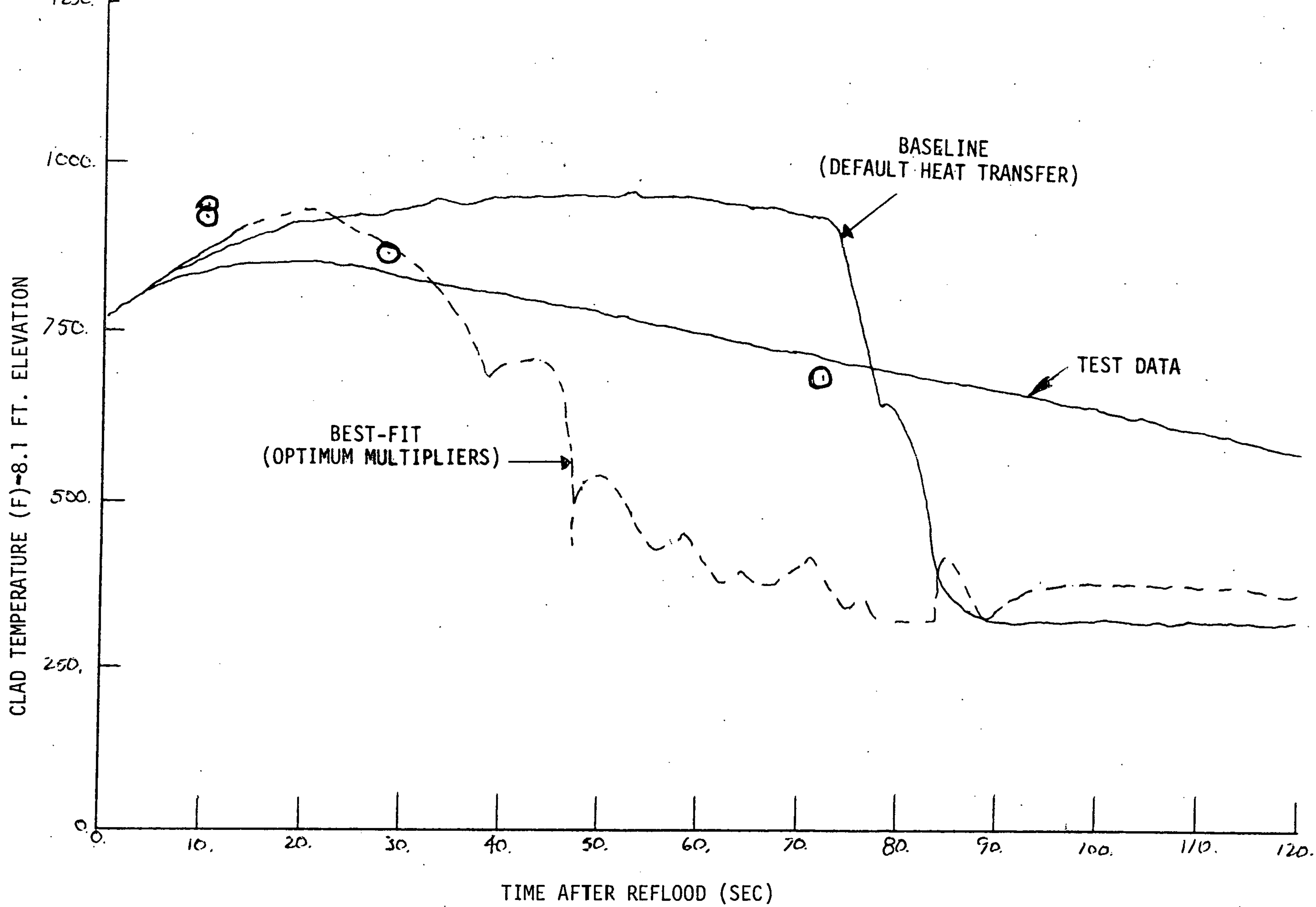

Figure 13. Comparison of FLECHT Test 3105B Cladding Temperature With Baseline (Default Heat Transfer) and Best-Fit (Using Optimized Multipliers) RELAP/MOD6 Predictions.

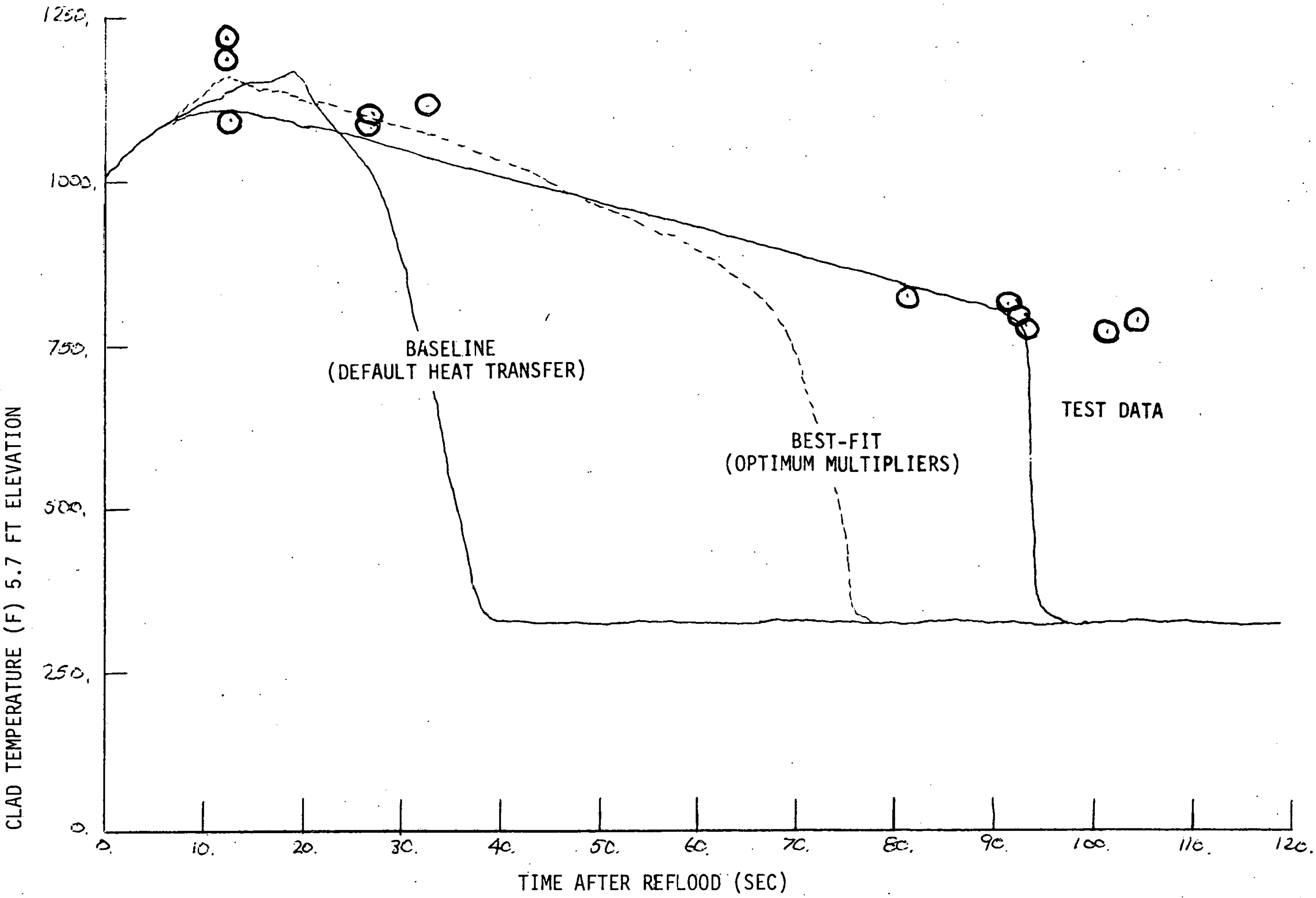

Figure 14. Comparison of FLECHT Test 3105B Cladding Temperature With Baseline (Default Heat Transfer) and Best-Fit (Using Optimized Multipliers) RELAP/MOD6 Predictions.

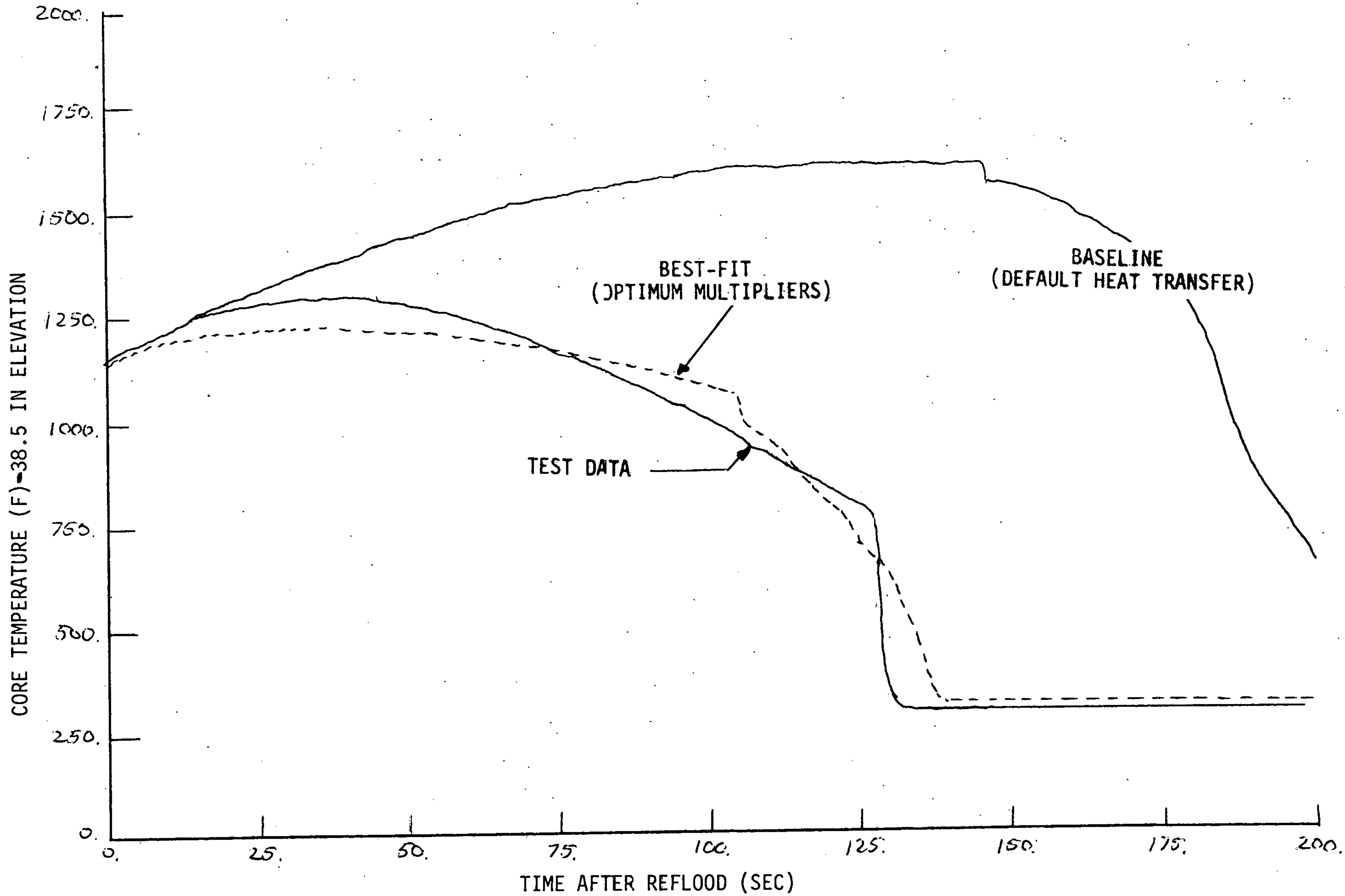

Figure 15. Comparison of Semiscale Test S-03-2 With Baseline (Default Heat Transfer) and Best-Fit (Using Optimized Multipliers) RELAP/MOD6 Predictions.

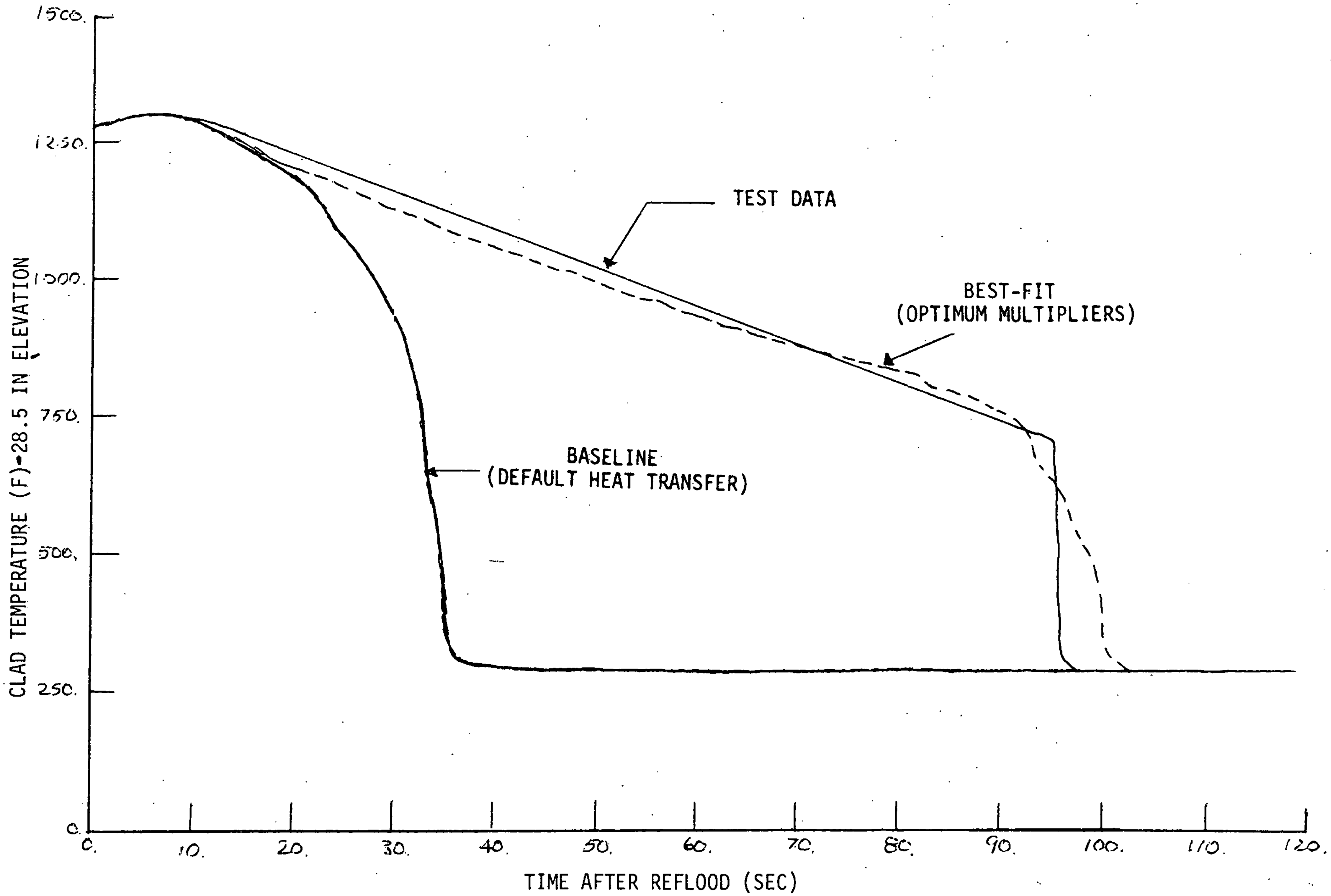

Figure 16. Comparison of Semiscale Test S-03-6 With Baseline (Default Heat Transfer) and Best-Fit (Using Optimized Multipliers) RELAP/MOD6 Predictions.

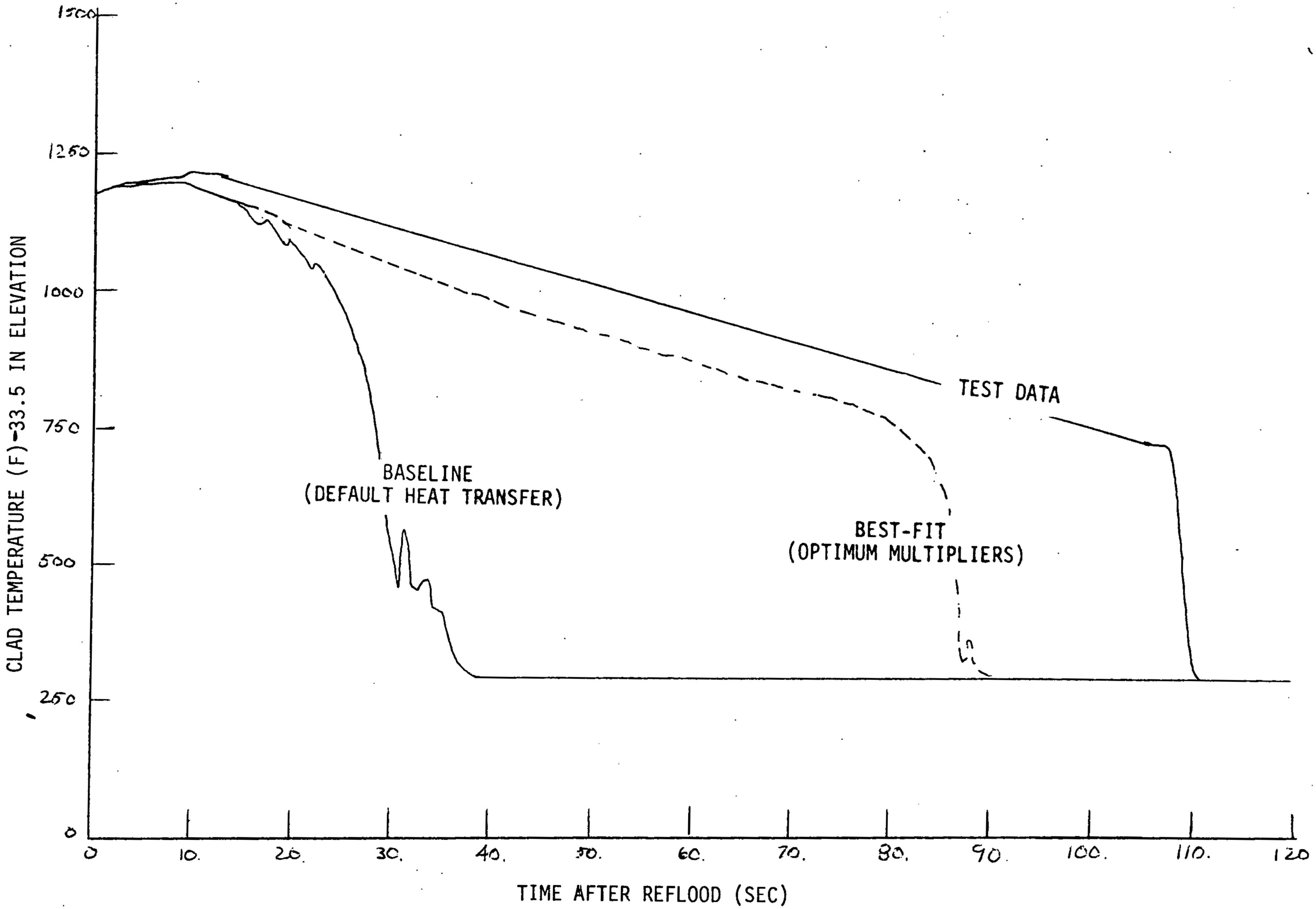

Figure 17. Comparison of Semiscale Test S-03-6 With Baseline (Default Heat Transfer) and Best-Fit (Using Optimized Multipliers) RELAP/MOD6 Precitions.

Table 1. Comparison of Semiscale Reflood Parameters with Basecase and Best Match RELAP4/MOD6 Calculations

	ELEVATION m (in)					
	0.216(8.5)	0.597(23.5)	0.724(28.5)	0.851(33.5)	0.978(38.5)	1.321(52.0)
PEAK TEMPERATURE: K (°F)						
Test	816.5(1010)	1060.9(1450)	1097.0(1515)	1038.7(1410)	1035.9(1405)	790.4(963)
RELAP with Guideline Input	812.0(1002)	1227.6(1750)	1264.3(1816)	1227.0(1749)	1147.0(1605)	817.6(1012)
RELAP with Adjusted Input	782.0(948)	1061.5(1451)	1067.6(1462)	1009.8(1358)	937.0(1227)	673.2(752)
TIME OF PEAK TEMPERATURE (s):						
Test	6.0	17.0	24.0	25.0	31.0	37.0
RELAP with Guideline Input	17.4	64.2	85.8	112.2	129.0	156.6
RELAP with Adjusted Input	0.6	20.6	24.2	31.4	31.8	0.2
TIME OF QUENCH (s):						
Test	27.0	84.0	111.0	124.0	138.0	119.0
RELAP with Guideline Input	46.0	139.0	164.0	187.5	>200	>200
RELAP with Adjusted Input	28.0	98.0	110.0	132.0	138.0	32.5

Peak cladding temperatures during reflood are normally predicted within 100^{o}F. Until LOFT reflood data becomes available, much uncertainty will exist in the LOFT RELAP4/MOD6 reflood calculations.

3. POTENTIAL 3-D EFFECTS DURING REFLOOD

A study of the important parameters influencing reflood characteristics of a large PWR has been recently completed by EG&G [11]. The effects of three-dimensional hydrodynamic effects within the core region, and the behavior of entrained liquid in the upper plenum, hot leg, and steam generator were examined. Steam binding, the creation of a system back pressure due to steam generation, retards the flooding rate and can increase both the cladding temperature rise and the time to quench. Steam generation due to droplet vaporization in the upper plenum or steam generators was identified as a potential major contributor to the steam binding problem. Calculations indicate that heat transfer from the upper plenum structures to the two-phase mixture is important for only a short period of time early in reflood. The energy stored in the upper plenum internals is small and is quickly removed. The net effect of upper plenum heat transfer on steam binding is small.

The determination of liquid vaporization in the steam generators is difficult. The amount of vaporization is a function of initial droplet entrainment, subsequent de-entrainment in the upper plenum, the droplet size and the transit time of the drops through the steam generator tubes.

A computer simulation of the flow paths in the upper plenum indicates that most droplets will impinge on some surface in the upper plenum. Upon impinging, the droplets may deposit (de-entrain) on the surface or possibly shatter into smaller droplets and remain entrained. It is doubtful if the shattering process occurs to an appreciable extent. Two mechanisms have been postulated by which the liquid may reach the steam generators, (1) the liquid in the upper core region may once again be entrained and carried to the steam generators, or (2) the de-entrainment process may produce a frothy mixture which may be transported to the steam generators. It is highly likely, however, that once de-entrainment occurs the liquid will remain deposited or fall back into the core.

Droplet vaporization in the steam generators depends primarily on the droplet size and on the time the droplet spends in the steam generator. Small droplets, due to their large surface area/volume ratio, are more easily vaporized and slower velocities which result in longer transit time enhance vaporization. Table II summarizes the FLECHT predicted transit time through the steam generator as a function of droplet size and estimates the fraction of each droplet converted to steam for several droplet diameters.

TABLE II

Water Droplet Size Versus Steam Generator Transit Time and Fraction of Dropplet Converted to Steam While Traversing the Steam Generator

Droplet Diameter - in	0.1544	0.0977	0.0564	0.0178
Transit Time - sec	1.7	1.5	1.3	1.05
% decrease in droplet dia.	1.95	3.24	6.0	24.0

As can be seen in Table II, the transit time through the steam generators is small, even for large diameter drops, so that vaporization can only occur for extremely small droplets. FLECHT-SET B1 results support these estimates and indicate very little vaporization occurs in the steam generators.

Figures 18 and 19 present calculations to estimate evaporation in the steam generators for the Semiscale tests. The figures show that little increase in quality, and therefore, little evaporation, occurs in the steam generator.

The Semiscale experimental results tend to confirm these calculations. Apparently little liquid from the Semiscale reflood tests reached the steam generators and vaporization in the steam generators was insignificant.

Radiation is expected to be an important mode of heat transfer during refill and the early stages of reflood for the high powered LOFT tests [12]. The presence of numerous unheated guide tubes in the core, which act as radiant heat sinks, may cause circumferential temperature gradients to be established both on the central rod guide tubes and the adjacent fuel rods. Some bowing of the fuel rods and the guide tubes may result from the circumferential temperature gradients. The effect of the bowing on fuel response has not been evaluated. Guide tube and/or fuel rod bowing may affect fuel module movement.

The LOFT Test L2-6 will contain fuel rods prepressurized to 350 psi and will provide valuable data concerning the extent of ballooning[13]. Reference 14 discusses the potential for coplaner ballooning and resulting fluid channel blockage. It was concluded that in a PWR, coplaner ballooning was possible but not likely due to statistical variations in the cladding temperatures as a result of fuel rod stored energy, fuel rod rewetting resulting during blowdown, and local cladding temperature variation during the ballooning process.

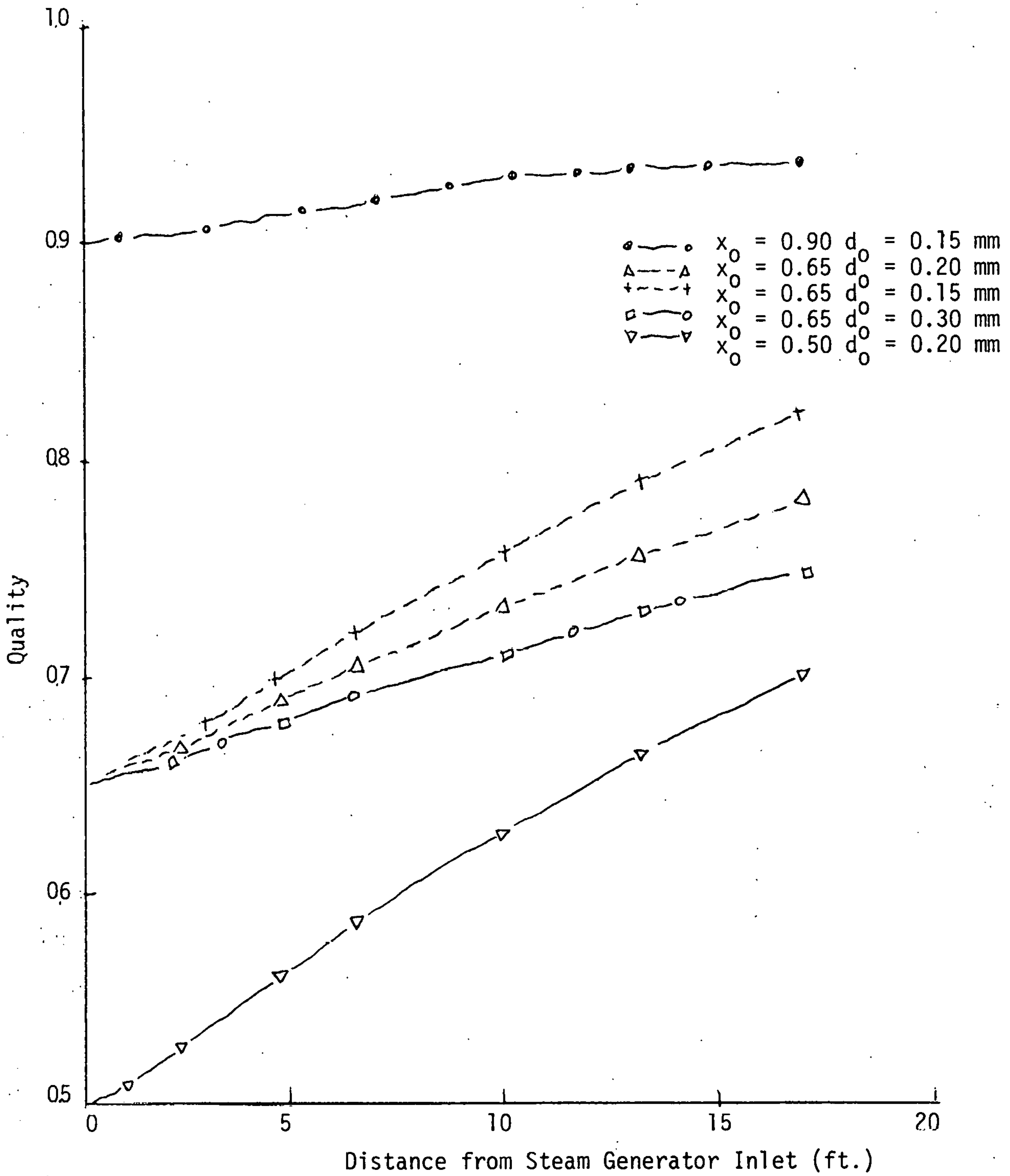

Figure 18. Calculated Increase in Quality in Traversing Steam Generator as Function of Droplet Diameter for Semiscale Test S-03-7

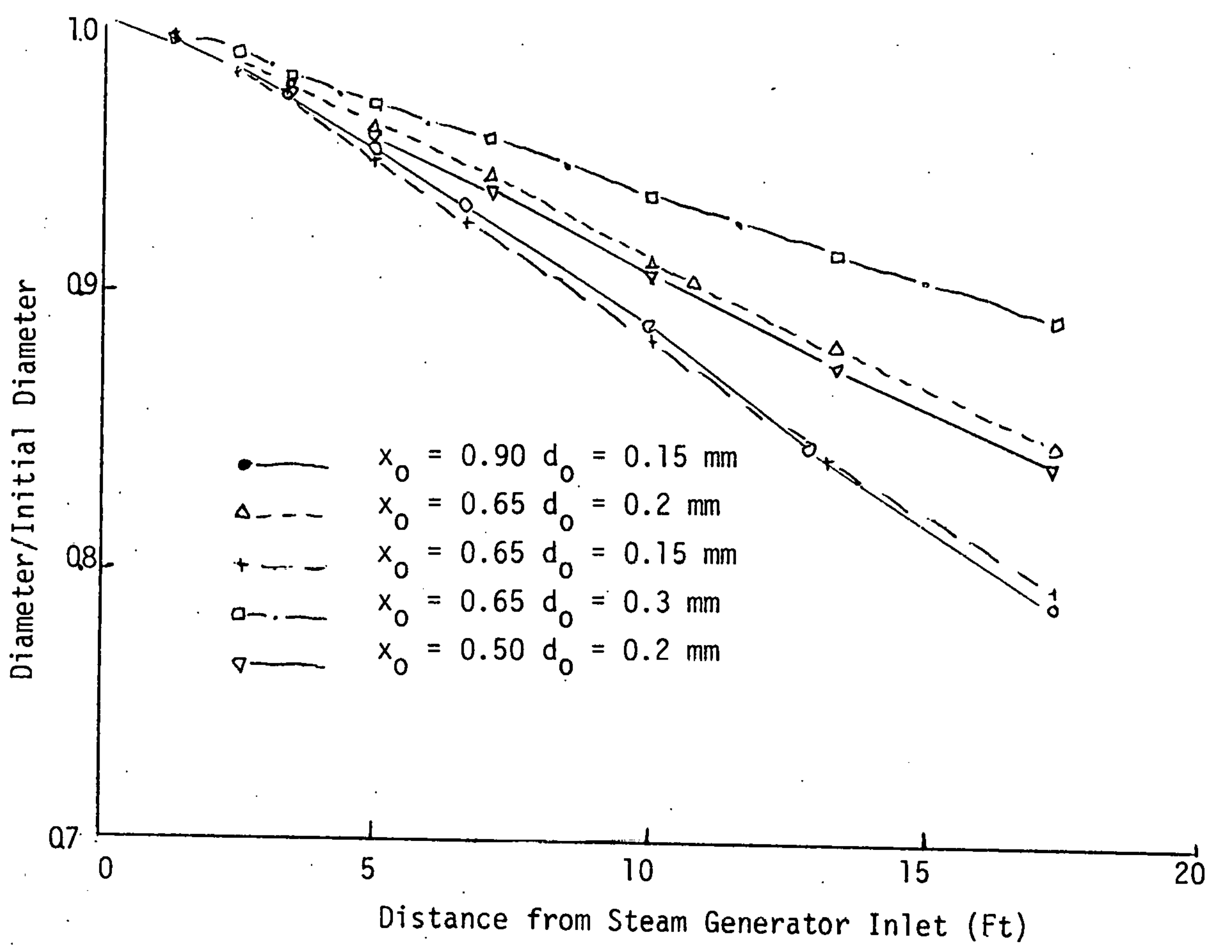

Figure 19. Decrease in Droplet Diameter as a Function of Distance Traveled Within Steam Generator For Semiscale Test S-03-7.

V. CLADDING OXIDATION

The previous sections have reviewed FLECHT-SET and Semiscale gravity feed reflood experiment results and summarized reflood modeling capabilities. From these sections, it is expected that peak reflood cladding temperatures for the LOFT LOCE's will be predicted to within 100 ^{o}F. Quench time will be predicted to within 100 seconds and the contribution to core steam binding due to liquid vaporization in the LOFT steam generators will be minimal.

The peak cladding temperature and quench time uncertainties were combined with best estimate calculations of LOFT reflood behavior to construct bounding cladding temperature histories. These temperature curves were then used to calculate cladding oxidation expected for the LOFT L2 tests.

The reflood calculations were performed with the FLOOD4 reflood dynamics code. The power-time histories and the ECC injection rates used in the FLOOD4 calculation were taken from RELAP4/MOD6 blowdown and refill predictions. The entrainment and heat transfer constants used were those which allowed the best match between FLOOD4 predictions and Semiscale gravity feed test data.

The best estimate FLOOD4 predictions of LOFT center module cladding surface temperatures for tests L2-2, L2-3 and L2-4 are given in Figure 20. Several trends are apparent from these curves. Only a small cladding heatup occurs and the heatup period is confined to the first 10 seconds of reflood. After this period, the cladding slowly cools until quench occurs.

During refill and the early portions of reflood, nearly adiabatic heat transfer conditions are predicted to exist. During this period, the surface heat transfer may not be sufficient to remove the energy generated by the decay of accumulated fission products. Cladding

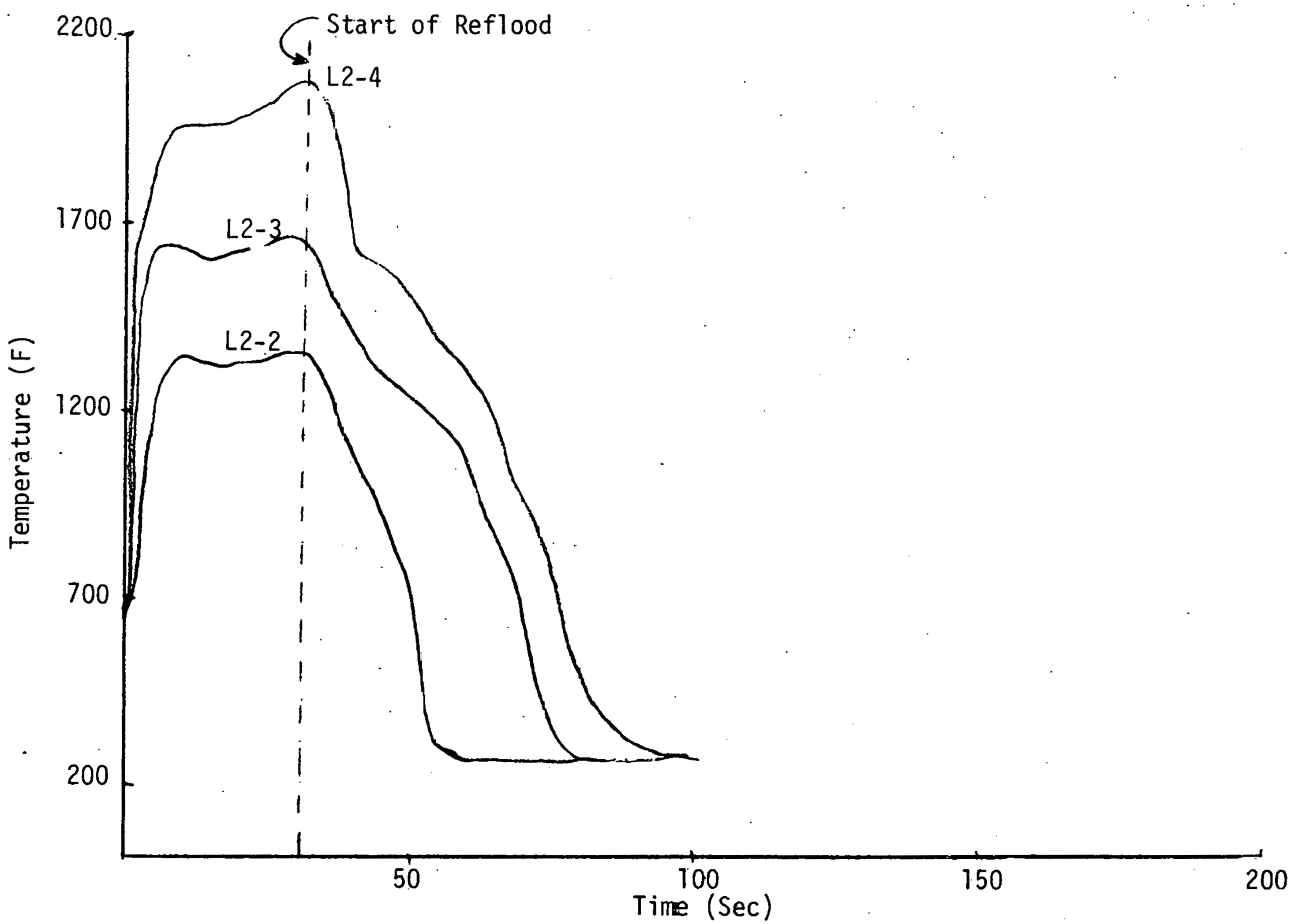

Figure 20. Nominal Predicted Peak Cladding Temperatures for LOFT Tests L2-2, L2-3, and L2-4. (MLHGR of 26, 39, 52 Kw/M respectively)

heatup is therefore possible. As a result of the near thermal equilibrium in the fuel rod, and the large resistances to heat flow within the rod, limited energy can be transferred to the cladding during the first few seconds of the reflooding period when surface heat transfer conditions may permit cladding heat up.

Zircaloy cladding oxidation characterstics have been evaluated and LOFT cladding temperature and time-at-temperature limits have been established in Reference 15 and are shown in Figure 21.

These limits are based on:

(1) The need to retain at least partial ductility of the cladding during the LOFT tests.

(2) ORNL oxidation data for zircaloy tubing in a steam environment[16,17].

(3) UO_2-zircaloy oxidation data[18,19,20].

The limiting oxidation correlation presented in Figure 21 (from Reference 15) was utilized to estimate the expected cladding oxidation which would result from the FLOOD4 calculated best estimate and upper bound LOFT cladding temperature histories. The upper bound temperature histories based on the uncertainties in peak cladding temperatures and quench times which were determined by comparing the model predictions to experimental results, are shown in Figure 22. The percentage of the allowable cladding oxidation limit was calculated and the results are given in Table III for the L2-2, L2-3 and L2-4 tests. In no case, even for the upper bound temperature response, was the cladding oxidation calculated to exceed the partial ductility retention limit.

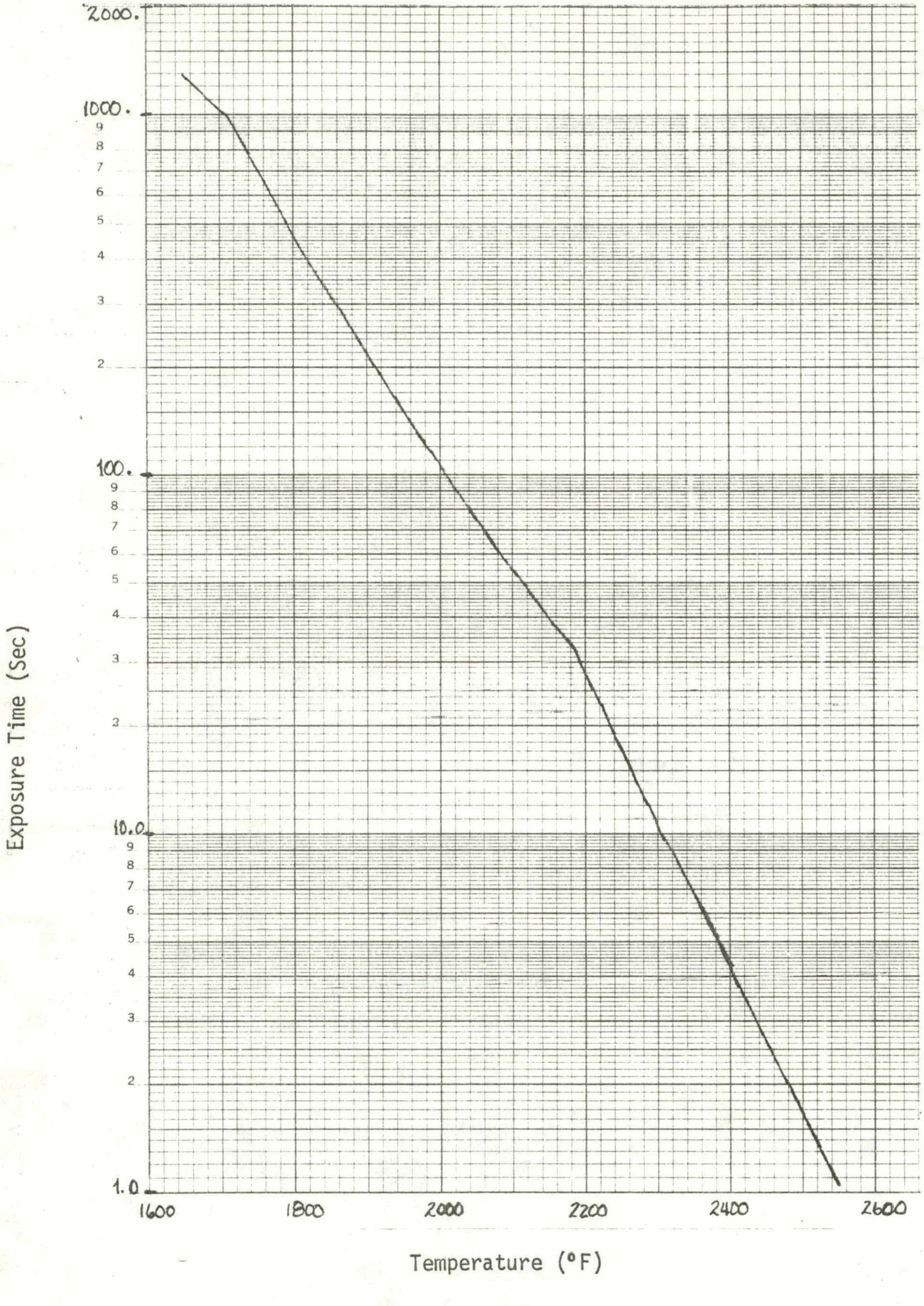

Figure 21. Criterion For Limiting Cladding Oxidation During LOFT LOCEs.

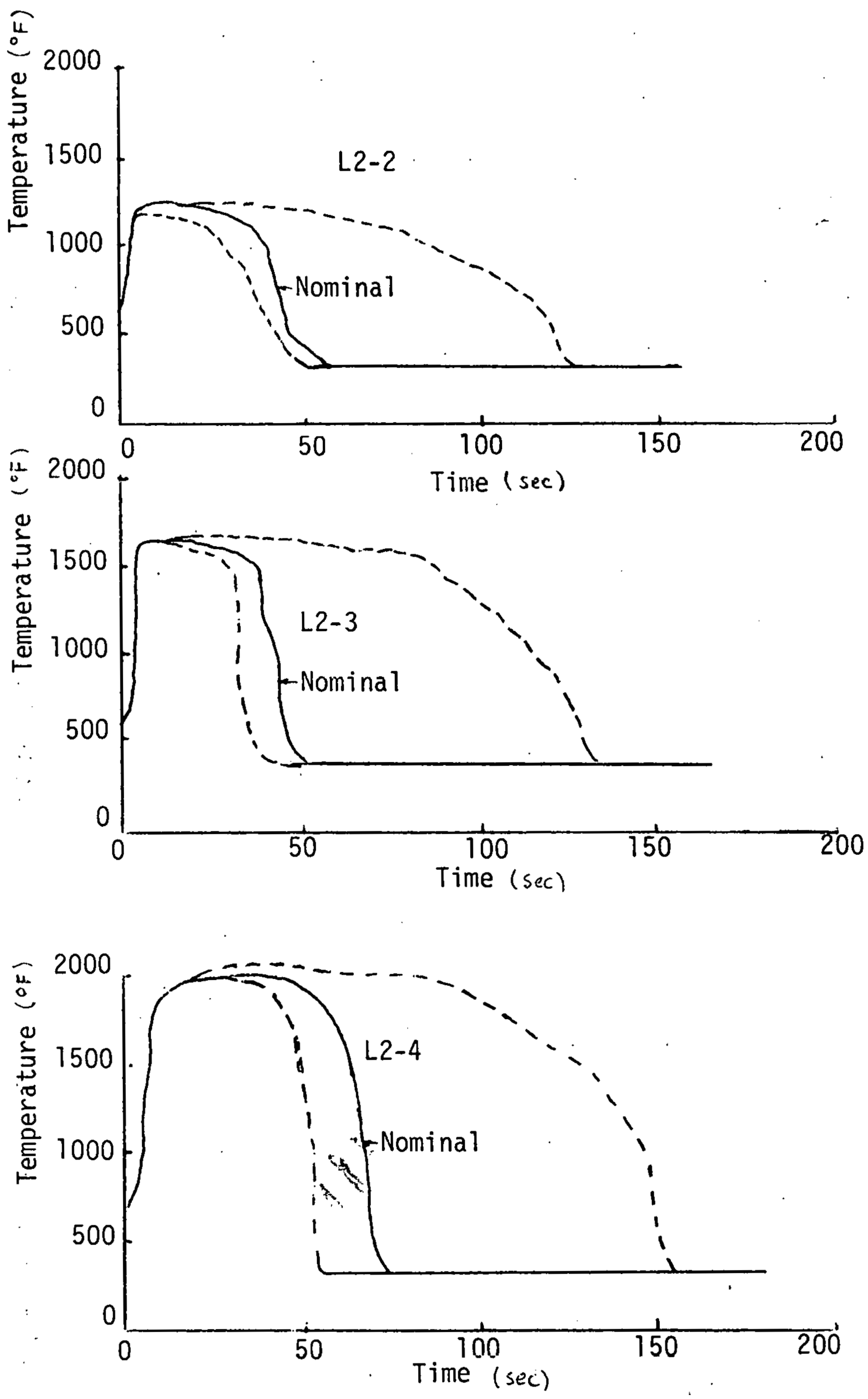

Figure 22. Peak Cladding Temperature Bounds Expected for L2-2, L2-3, and L2-4 Tests. Used for Estimating Extent of Cladding Oxidation.

TABLE III

Expected Peak Cladding Oxidation for the LOFT L2 Series LOCE's

Test	Fraction of Allowable Oxidation Limit (1)
L2-4 Extended Quench	0.896
L2-4 Best Estimate	0.2625
L2-4 Enhanced Quench	0.221
L2-3 Extended Quench	0.054
L2-3 Best Estimate	0.031
L2-3 Enhanced Quench	0.023
L2-2 Extended Quench	0.0245
L2-2 Best Estimate	0.0083
L2-2 Enhanced Quench	0.0083

(1) 1.0 means the allowable oxidation limit (partial cladding ductility) has been reached.

VI. CONCLUSIONS

The following conclusions can be made as a result of this study:

1. FLECHT-SET and Semiscale reflood tests for reflood conditions similar to those expected for LOFT showed little cladding temperature rise. The contribution to steam binding due to liquid vaporization in the steam generators and upper plenum is expected to be small.

2. Current code capability to predict reflood response generally predicts peak cladding temperatures to within 100^{o}F and quench times to within 100-200 seconds.

3. Three-dimensional effects may be important for the LOFT tests. The more important 3-D effects may include, (1) liquid entrainment phenomena which will effect core heat transfer, (2) radiation heat transfer for the higher power tests, and (3) cladding ballooning and/or cladding bowing which may effect core flow distributions.

4. Cladding oxidation for the L2-Series tests is not expected to result in nil-ductility (brittle) cladding even for upper bound cladding temperatures.

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