# TEST PREDICTION OF THE SEVENTH SEMISCALE MOD-1 TEST SERIES STEAM GENERATOR TUBE RUPTURE TESTS TEST S-28-5

SEMISCALE PROGRAM

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# TEST PREDICTION OF THE SEVENTH SEMISCALE MOD-1 TEST SERIES STEAM GENERATOR TUBE RUPTURE TESTS TEST S-28-5

by

C. P. Fineman

SEMISCALE PROGRAM

Approved: DJ Olson by DJH
D. J. Olson, Manager
Semiscale Program

Approved: DJ Hanson
D. J. Hanson, Manager
Semiscale Experiment Specification & Analysis Branch

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SUMMARY

This document contains a pretest prediction of the Semiscale Mod-1 system thermal-hydraulic response for Test S-28-5. Test S-28-5 will be the fifth integral blowdown reflood test to be performed in the steam generator tube rupture test series. The primary objectives of this test are to aid in defining the core temperature response for large numbers of steam generator tube ruptures and to probe into the range of steam generator tube ruptures shown by the analysis used to specify Test Series 28 to result in high peak cladding temperatures.

The initial conditions for Test S-28-5 will be as specified in Appendix 28 of the Semiscale Experimental Operating Specification (EOS)[1]. Injection from an accumulator into the intact loop hot leg just upstream of the steam generator inlet plenum will begin at 40 seconds after rupture to simulate the steam generator tube ruptures. The test will be run with an injection rate of 0.181 kg/s to simulate the rupture of 20 steam generator tubes.

The break configuration will represent a full size (200%) double-ended offset shear cold leg break. The test will be initiated at an initial core power of 1.44 MW (with 36 powered rods) and the ANS power decay curve will be used during the reflood portion of the test. Emergency core coolant (ECC) from the intact loop high pressure injection system (HPIS), the accumulator, and the low pressure injection system (LPIS) will be injected into the intact loop cold leg. Accumulator, HPIS, and LPIS injection will also be used in the broken loop pump simulator discharge. The pressure suppression system pressure will be maintained at about 241 kPa during the blowdown and the reflood portions of the test.

The predictions for Test S-28-5 were developed from Test S-04-6 test data (the baseline test) and from calculations performed with the FLOOD4 computer code. The system response during the first 40 seconds of Test S-28-5 is expected to be the same as the system response in Test S-04-6. Therefore, Test S-04-6 data is provided to give an indication of the expected system thermal-hydraulic response for the first 40 seconds of Test S-28-5. The FLOOD4 computer code was used to provide predictions for the remainder of the transient. Since the heat transfer and entrainment correlations used in the FLOOD4 code have not been extensively tested against data, the prediction is expected to follow the trends of the data, but may not exactly calculate the oscillating flows and the rod temperatures. Also, the calculation of quench times is strongly dependent on the rod temperature distribution and system pressure at the initiation of reflood. Small differences in these parameters can significantly affect the reflood calculations. In addition, the FLOOD4 code does not account for downcomer wall heat transfer during the refill and reflood transient. Previous test data indicates that liquid depletion in the downcomer, which is due to downcomer wall heat transfer, can also significantly affect the core response during refill and reflood.

The peak temperature in the core during blowdown should be approximately 1075 K at 8 seconds after rupture based on Test S-04-6 results. This temperature is expected to occur on a rod on the perimeter of the core. The peak temperature should be about 994 K when the injection simulating the tube ruptures begins. However, data from previous tests in Test Series 28 have shown that some of the rods may quench during blowdown. If quenching during blowdown does occur in Test S-28-5, lower cladding temperatures in the core may occur during reflood than

were predicted because the temperatures at the start of refill would be lower. Test S-04-6 data indicates the system pressure should reach 241 kPa (containment pressure) by 40 seconds. Fluid saturation conditions at 6 MPa and 549 K should be present in the steam generator secondary at 40 seconds.

FLOOD4 calculations indicate the peak temperature in the core should increase from 994 K at 40 seconds to 1209 K at 321 seconds after rupture before turning over and declining to 1146 K at the end of the period of steam generator tube rupture flow. This temperature response is due to the calculation of a heat transfer coefficient from the Dittus-Boelter correlation (based on the reverse steam flow through the core caused by the injection simulating the flow from the ruptured tubes) which is just able to turn the rod temperatures over during this period. After the injection into the intact loop hot leg near the steam generator ended at 646 seconds after rupture (the time at which the steam generator secondary would empty if 20 tubes ruptured), the FLOOD4 model indicated that during lower plenum refill the peak temperature in the core would increase to 1277 K. Lower plenum refill was accomplished by the LPIS and HPIS only because the intact loop accumulator would be depleted of water at approximately 70 seconds after rupture. Reflood of the core by the LPIS and HPIS is expected to start at about 720 seconds after rupture. The core hot spot is expected to quench about 846 seconds after rupture (126 seconds after reflood) and the whole core is expected to quench by 861 seconds after rupture.

Comparison of previous Series 28 test results with the FLOOD4 calculations indicate that the calculated peak temperatures are, in general, conservative relative to the measured data. As a consequence,

the peak temperature calculated for Test S-28-5 (1277 K) is expected to be higher than the majority of the test data. As a safety precaution however, the core power trip point temperature will be set at 1255 K for Test S-28-5.

# 1. INTRODUCTION

This report contains the predictions of the Semiscale Mod-1 system thermal-hydraulic response for Test S-28-5 which will be the fifth integral blowdown-reflood test in the steam generator tube rupture test series. The report identifies the prerupture system conditions and presents the expected behavior of key variables with particular emphasis placed on the predicted response of the electrically-heated core. Test S-04-6 data[2] (the baseline test for Test Series 28) was used to indicate the expected system blowdown response, since the response in Test S-28-5 should be the same during this period. The FLOOD4[3] models used to predict the system response over the remainder of the transient are described.

The test conditions for Test S-28-5 are identical to those of the baseline test except for the introduction of accumulator injection into the intact loop hot leg just upstream of the steam generator inlet plenum to simulate the steam generator tube ruptures. The test will be run with an injection rate of 0.181 kg/s to simulate the rupture of 20 steam generator tubes. The change in heat transfer potential of the steam generator will be simulated by discharging the steam generator secondary fluid over the simulated tube rupture period. The water in the accumulator will be near saturation conditions at 547 K (approximately the average temperature of the pressurized water reactor (PWR) steam generator secondary fluid at rated load) and 5.9 MPa. The total volume of water injected to simulate the tube rupture flow is 0.144 $m^3$, which is core area scaled from three PWR steam generators at rated load. The injection will begin at 40 seconds after the cold leg break to simulate steam generator tube ruptures. During steam generator liquid injection,

the accumulator pressure will be maintained by a nitrogen supply. The injection will be terminated before the accumulator water is completely exhausted to prevent nitrogen injection into the primary system. The initiation of the tube ruptures at 40 seconds was selected because preliminary analysis showed that when the tube ruptures occurred at this time the highest peak cladding temperatures occurred (see Figure 1). The highest temperatures occurred because tube rupture at this time was assumed to prohibit refill of the downcomer and lower plenum and was followed by an assumed period of adiabatic heatup in the core while the lower plenum was refilled after the steam generator secondary was emptied.

Emergency core coolant (ECC) for Test S-28-5 will be injected into the intact loop cold leg and broken loop pump simulator discharge. The Mod-1 ECC systems in operation in both loops will include the accumulator injection system (AIS), the high pressure injection system (HPIS), and the low pressure injection system (LPIS).

The operating conditions for Test S-28-5 are summarized in Table I. The test will be conducted at an initial core power of 1.44 MW and an initial flow rate of $9.5 \times 10^{-3}$ $m^3/s$. The radial core power profile will be peaked for this test. The three high power rods will have a peak power density of 39.7 kW/m and the other 33 low power rods will have a peak power density of 37.7 kW/m. Four rods will be unpowered with their locations chosen to give the same core configuration as in Test S-04-6. The fluid temperature at the core inlet will be 558 K and the core outlet fluid temperature will be 594 K. The axial power profile will be skewed toward the bottom of the heated core as shown in Figure 2.

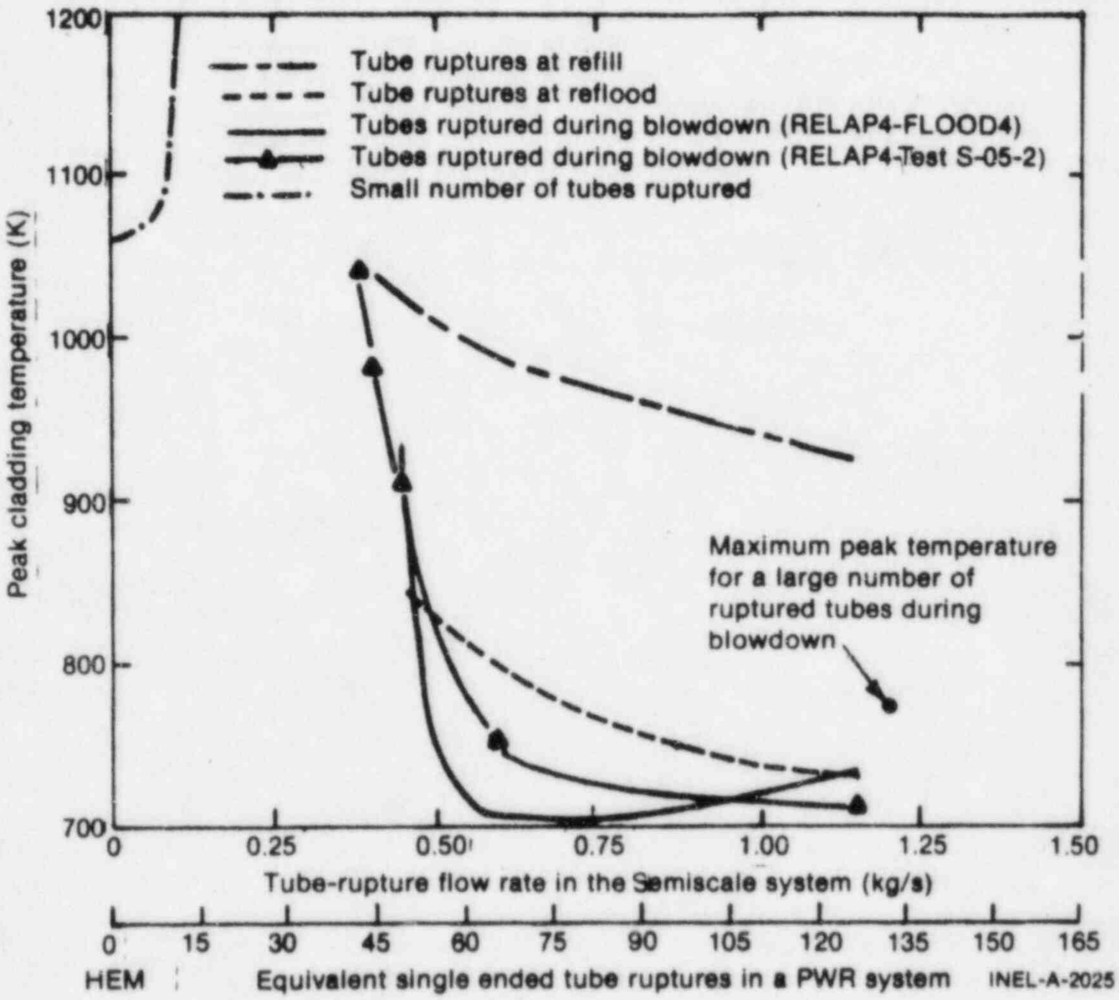



Figure 1. The Influence of the Tube Rupture Flow Rate or the Number of Ruptured Rubes on the Peak Cladding Temperature

Table I

Test S-28-5 Description and Initial Conditions

| Parameter | Initial Value |
|---|---|
| Break Size | 200%[a] |
| Break Type | Cold Leg |
| Intact Loop Resistance | Low[b] |
| Nominal Initial System Pressure | 15.5 MPa |
| Hot Leg Fluid Temperature | 594 K |
| Cold Leg Fluid Temperature | 558 K |
| Core Temperature Difference | 36 K |
| Core Power | 1.44 MW |
| Core Initial Inlet Flow Rate | 7.1 kg/s |
| Power Decay | Figure 3 |
| Pump Speed Control | Allowed to coast down to approximately 61% of initial rpm, then maintain at 61% of initial rpm. |
| **ECC Injection** | |
| Accumulator | |
| Location | Intact Loop Cold Leg |
| Actuation Pressure | 4.1 MPa |
| Liquid Volume | 0.08 $m^3$ |
| Gas Volume | 0.053 $m^3$ |
| Line Resistance | $659 \frac{MPa\ sec^2}{kg\ m^3}$ |
| Injection Rate | $1.45 \times 10^{-3}\ m^3/s$ |
| Nitrogen Valve | Open for 24 seconds after accumulator empty of water |

Table I (contd)

Test S-28-5 Description and Initial Conditions

| Parameter | Initial Value |
|---|---|
| HPIS | |
| Location | Intact Cold Leg |
| Actuation Pressure | 12.4 MPa |
| Injection Rate | $1.96 \times 10^{-5}$ $m^3/s$ |
| LPIS | |
| Location | Intact Cold Leg |
| Actuation Pressure | 1.03 MPa |
| Injection Rate | $2.52 \times 10^{-4}$ $m^3/s$ |
| Tube Rupture Simulator | |
| Steam Generator Accumulator | |
| Location | Just Upstream From The Intact Loop Steam Generator Inlet Plenum |
| Actuation Time | 40.0 Seconds |
| Closure Time | 646 Seconds |
| Liquid Volume | 0.144 $m^3$ |
| Gas Volume | $4.8 \times 10^{-2}$ $m^3$ |
| Temperature | 547 K |
| Injection Rate | $2.38 \times 10^{-4}$ $m^3/s$ |

(a) 200% break refers to a simulated double-ended offset shear break in the broken loop with each break nozzle having an area of 0.000243 $m^2$. The 200% break has a break area-to-system volume ratio equivalent to that ratio for a double-ended offset shear break in the cold leg of one loop of a four-loop pressurized water reactor.

(b) Low system resistance refers to the size of orifices located at the inlet and outlet of the intact loop steam generator. The low system resistance orifices have an approximate 4.06 cm diameter hole. The total system resistance with the low resistance orifices is properly scaled to the LOFT system.

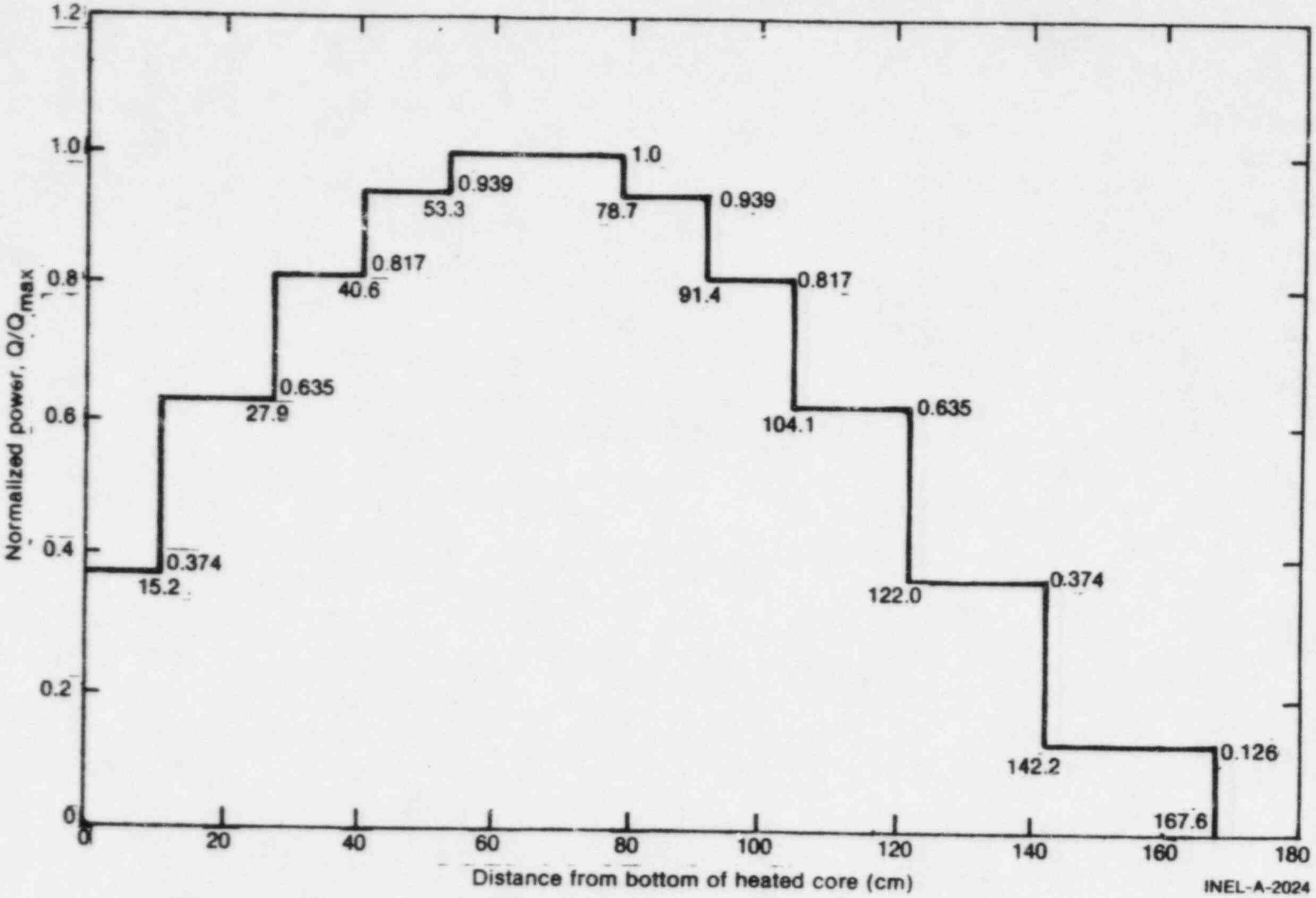



Figure 2. Normalized Axial Power Profile for Test S-28-5

The power decay will follow the electrical power decay curve shown in Figure 3. The pressure suppression system for Test S-28-5 will be controlled to maintain a containment pressure of 241 kPa throughout the blowdown and the reflood portions of the test.

Section II of this report presents a brief description of the analysis methods and FLOOD4 models used in these predictions, and the results of the calculations. Section III presents the more significant conclusions arising from the predictions. A more detailed discussion of the FLOOD4 model is included in Appendix A.

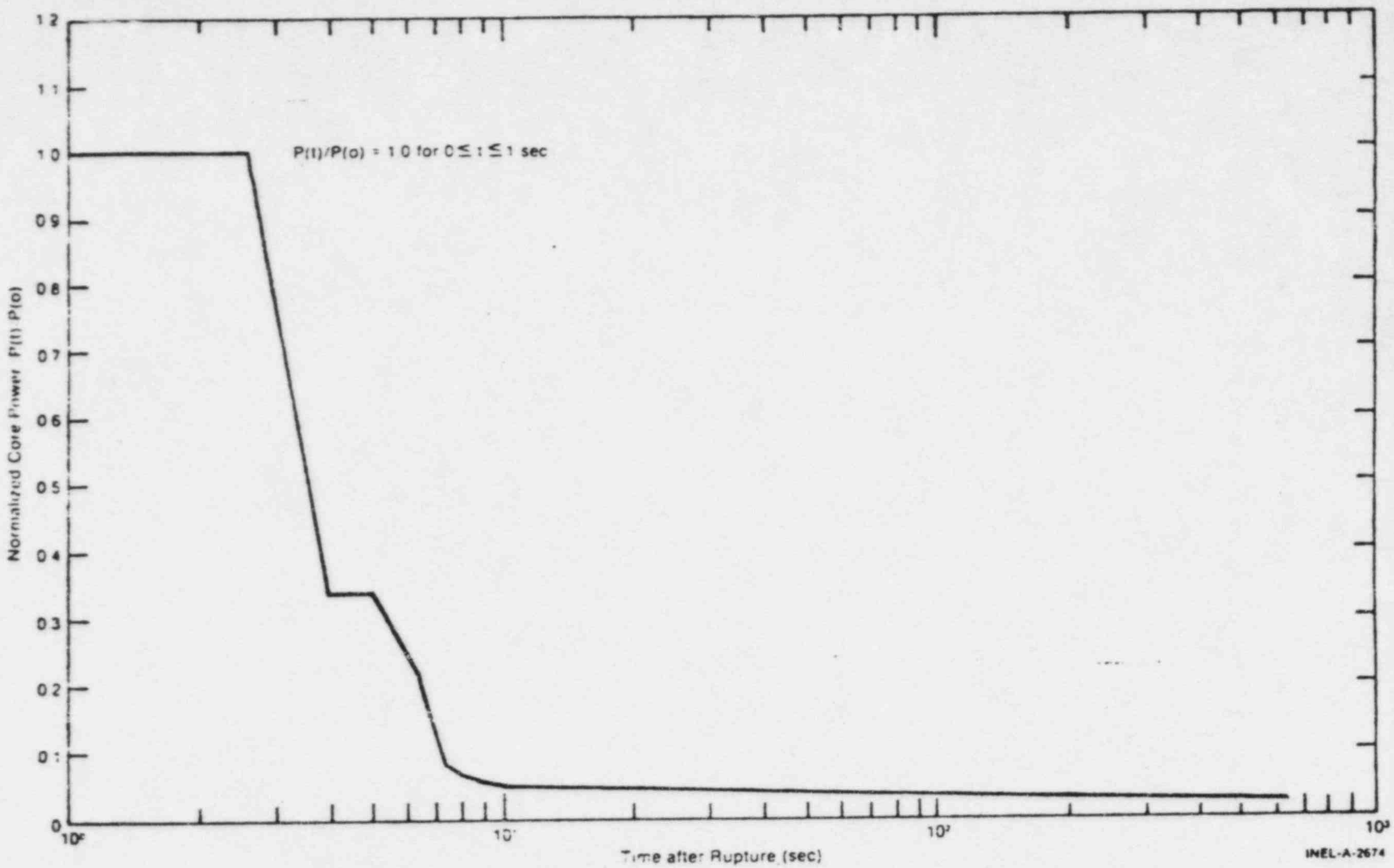



Figure 3. Decay Heat Curve for Test S-28-5

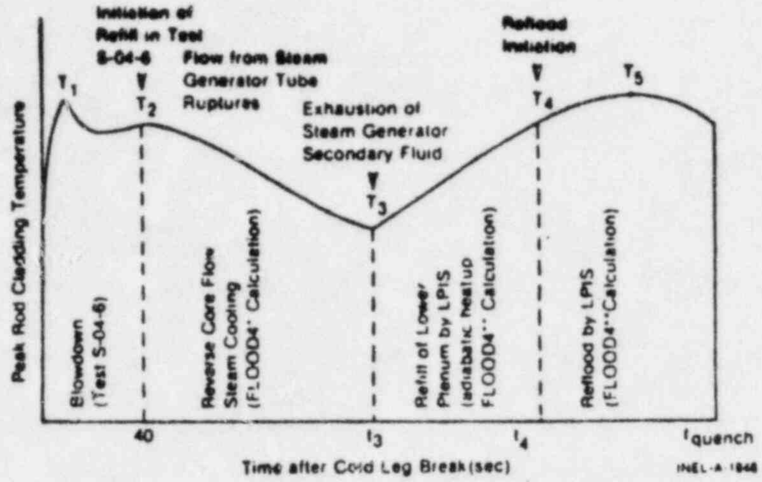
## II. PREDICTIONS OF STEAM GENERATOR TUBE RUPTURE TEST S-28-5

### 1. METHOD OF ANALYSIS

The analysis of a loss-of-coolant accident (LOCA) involving steam generator tube ruptures required that a different method of analysis be used to predict the response of the Semiscale Mod-1 system because of the long transient (over 720 seconds to initiation of reflood) expected for this type of LOCA. The long transient was a factor in deciding against using the analysis methods used for previous pretest predictions which consisted of using RELAP4 to predict the blowdown and refill response and FLOOD4 to predict the reflood response of the system. An initial study of the type of phenomena expected in Test S-28-5 and the type of calculations required indicated that the best way to proceed would be to use the methods developed for the scoping analysis described in EOS Appendix 28, Addendum 28-A (see Reference 1). This method is described below and summarized in Figure 4.

The transient for Test S-28-5 can be divided into four main time periods. These periods consist of: (1) the blowdown period prior to the steam generator tube rupture, (2) a period of reverse core flow after the tubes rupture and lasting until the steam generator secondary empties, (3) heat-up of the core as the lower plenum is refilled by the LPIS, and HPIS, and (4) core reflood by the LPIS and HPIS.

The baseline test for Test S-28-5 is Test S-04-6. Test S-28-5 will differ from Test S-04-6 only in that Test S-28-5 will include steam generator accumulator injection into the intact loop hot leg just upstream of the steam generator inlet plenum beginning at 40 seconds after rupture




| Total Rupture Mass Flow (kg/s) | Temperature (K) | | | | | Time (sec) | | | Heat Transfer # Coefficient (kW/m$^2$ - K) |
|---|---|---|---|---|---|---|---|---|---|
| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $t_3$ | $t_4$ | $t_5$ | |
| 0.181 | 1075 | 994 | 1146 | 1277 | 1279 | 646 | 720 | 726 | 0.060 |

* For historical configuration control, load module FLOOD4 102 (configuration control number HB00120IB) was used for this section of the study.

** Load module FLOOD4 103 (configuration control number HB00121IB) was used for this section of the study.

\# Steam cooling heat transfer coefficient

Figure 4. Analysis Technique Used in Pretest Prediction for Test S-28-5

to represent the flow from the ruptured tubes. Since the initial conditions for Tests S-28-5 and S-04-6 will be the same, the Mod-1 system response during the first 40 seconds of the transient of Test S-28-5 should be the same as the system response in Test S-04-6. Because of the similarity expected between the two tests, Test S-04-6 data is used to indicate the expected system thermal-hydraulic response prior to 40 seconds.

The period of reverse steam flow through the core, which is caused by the injection simulating the tube ruptures, lasts until 646 seconds after rupture. This injection duration is based on how long it would take to empty the steam generator secondary at a tube rupture flow rate of 0.181 kg/s (20 tubes ruptures). It was assumed during this period that the heat transfer mechanism in the core would be single phase forced convection heat transfer to steam. To estimate the core temperature response, the FLOOD4 program (load module FLOOD4/102)[a] was used in the following manner. From Test S-04-6 data, the peak temperature in the core at 40 seconds was 994 K. This temperature was used as input into the FLOOD4 code, and a cosine curve fit was used to calculate an initial axial temperature profile at the start of the reverse core flow period. The heat transfer from the rods to the steam during the period of reverse core flow was calculated by the FLOOD4 program using a heat transfer coefficient calculated from the Dittus-Boelter correlation. The heat transfer coefficient that was calculated for a tube rupture flow rate of 0.181 kg/s was 0.060 $kW/m^2$-K. Since the current version of FLOOD4 is

[a] For the purpose of historical configuration control, FLOOD4/102 is referenced as program number H001201B.

not able to calculate sustained periods of negative core flow, a special version of FLOOD4 (FLOOD4/102), in which the initial axial temperature profile was reversed and positive core flow was modeled, was constructed to perform this calculation. The magnitude of the steam flow through the core was estimated by assuming that 30% of the water injected to simulate the flow from the ruptured tubes flashed to steam on entering the intact loop hot leg, and that a flow split between the intact loop, core, and broken loop occurred where 65.2% of the steam flowed through the core. The flow split was estimated on the basis of the intact and broken loop and core hydraulic resistances. This core flow was then used in the calculation of the heat transfer coefficient from the Dittus-Boelter correlation and in the FLOOD4 calculation. The assumption of single phase heat transfer to steam from 40 to 646 seconds is probably a conservative assumption as the core flow during this period is expected to be a two-phase mixture of water and steam and heat transfer to the liquid portion of the flow in the core was neglected in the analysis of the heat transfer during this period.

The temperature distribution at the end of the reverse core flow calculation was assumed to be the rod temperature distribution at the initiation of the refill period. All intact loop ECC injected during the period of tube rupture flow is assumed to bypass out the break. The time period for refill was estimated by assuming that the lower plenum must be refilled by the LPIS and HPIS flow alone. (The refill period was calculated to be about 74 seconds). The rod temperature distribution at the initiation of refill was input into the FLOOD4 code (load module

FLOOD4/103)[a] and an adiabatic heat-up option (h = 0.0) was used for 74 seconds to calculate the temperature at the initiation of reflood. The reflood of the core using LPIS and HPIS flow was then calculated with the FLOOD4 code (load module FLOOD4/103).

It is anticipated that several of the assumptions used in the analysis of the refill and reflood periods may result in higher calculated rod cladding temperatures than would actually occur. The use of an adiabatic heat-up (h = 0.0) may be somewhat conservative and, therefore, result in higher predicted peak rod cladding temperatures than would occur in the experiment. The use of a heat transfer coefficient of 30 $W/m^2$-K during the heat-up would decrease the peak rod cladding temperature by about 83 K. The potential accumulation of water in the lower plenum during the emptying of the steam generator was not included in estimating the volume of water that must be supplied by the LPIS and HPIS to completely fill the lower plenum. If a smaller volume of LPIS and HPIS liquid were needed to fill the lower plenum, the adiabatic heat-up would occur for a shorter period of time, which would also result in lower calculated rod cladding temperatures.

The FLOOD4 code does not account for liquid depletion in the downcomer because it does not calculate downcomer wall heat transfer. This downcomer wall heat transfer, noted in previous Semiscale tests, could impede the refilling of the lower plenum by the LPIS and HPIS. In this case, the experimental refill and reflood response could be somewhat different that the predicted response.

[a] For the purpose of historical configuration control, FLOOD4/103 is referenced as program number H00121IB.

## 2. FLOOD4 MODEL DESCRIPTION

The FLOOD4/102 computer code was used to predict the core thermal response during the reverse steam flow portion of Test S-28-5 (40 to 646 seconds after rupture) and FLOOD4/103 was used to predict the refill and reflood portions of the test (646 to 882 seconds after rupture). The FLOOD4 code is a recently developed reflood analysis tool and, therefore, is undergoing evaluation and improvement as more test data becomes available. Figure 5 shows the FLOOD4 model of the Semiscale system. A more detailed discussion of the code and a listing of the input to the models is contained in Appendix A.

FLOOD/102 is a modified version of the FLOOD4 code. It was modified to allow the FLOOD4 heat-up option to be used to predict the rod cladding and core fluid temperature response during the period of reverse steam flow. Since the current version of the FLOOD4 heat-up option is not able to model sustained periods of negative core flow, the code was modified internally to invert the initial axial temperature profile and then positive core flow was used in the FLOOD4 model to enable it to calculate the heat transfer from the rods to the steam flow. In this way, the response of the rod temperatures to the reverse steam flow from 40 to 646 seconds after rupture was calculated. The temperature profile at 646 seconds was then input into the FLOOD4 model to calculate the refill and reflood response. FLOOD4/103 was the version of the FLOOD4 code used to make this calculation. The FLOOD4 heat-up option was used to model the assumed adiabatic heat-up of the rods while the lower plenum was refilled by the LPIS and HPIS. The temperature profile at the end of the adiabatic heat-up was used as the initial temperature

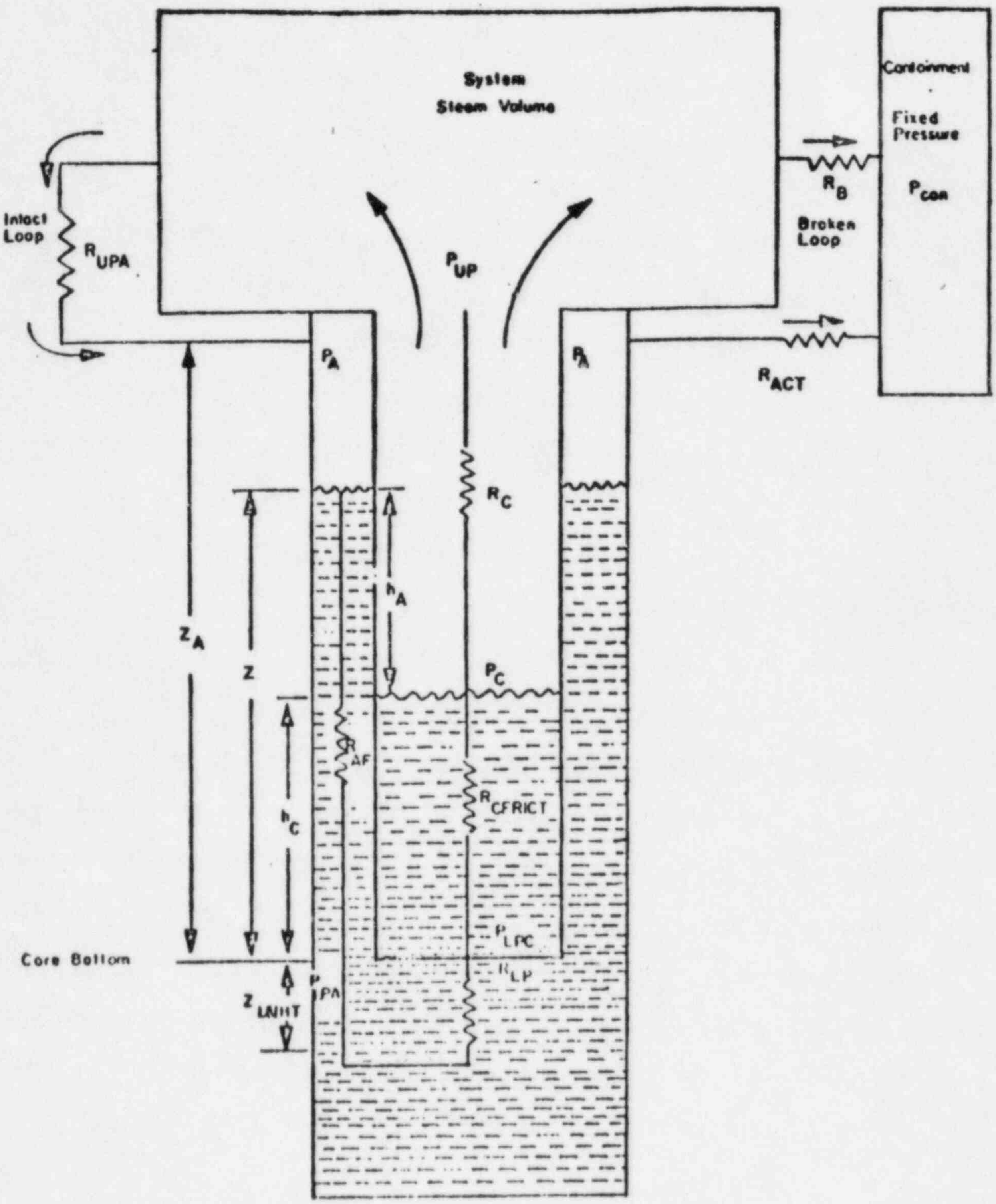



Figure 5. FLOOD4 Model of Semiscale System

profile at the start of reflood. The reflood of the core by the LPIS and HPIS was then calculated with the FLOOD4 code. The rod axial temperature distribution at 40 seconds after rupture is shown in Figure 6, and at the start of refill in Figure 7. The rod axial temperature distribution used at the start of reflood is shown in Figure 8. Table II lists the initial conditions used in the FLOOD4 model at the start of reflood for Test S-28-5. The FLOOD4 calculations for Test S-28-5 provide a prediction of the thermal-hydraulic response for the reverse core flow, refill, and reflood processes over the time period from 40 seconds to 882 seconds following rupture.

## 3. PREDICTIONS OF THE SEMISCALE MOD-1 SYSTEM RESPONSE

Predicted behavior of key system parameters for Test S-28-5 are presented and discussed in this section.

### 3.1 Blowdown Response Prior to Steam Generator Tube Rupture

Since the initial conditions for Tests S-04-6 and S-28-5 are the the same, the system response in Test S-28-5 should be essentially the same as in Test S-04-6 until steam generator injection into the intact loop between the pressurizer and the steam generator inlet plenum begins at 40 seconds after rupture. A detailed discussion of the system thermal-hydraulic response in Test S-04-6 is contained in Reference 2 and, therefore, only a brief discussion is included here. Several results from the blowdown period of Test S-04-6 which are of interest in Test S-28-5 are described below.

The peak temperature in the core during the blowdown period of Test S-04-6 occurred on a rod located on the perimeter of the core and reached approximately 1075 K at 8 seconds after rupture. Test data

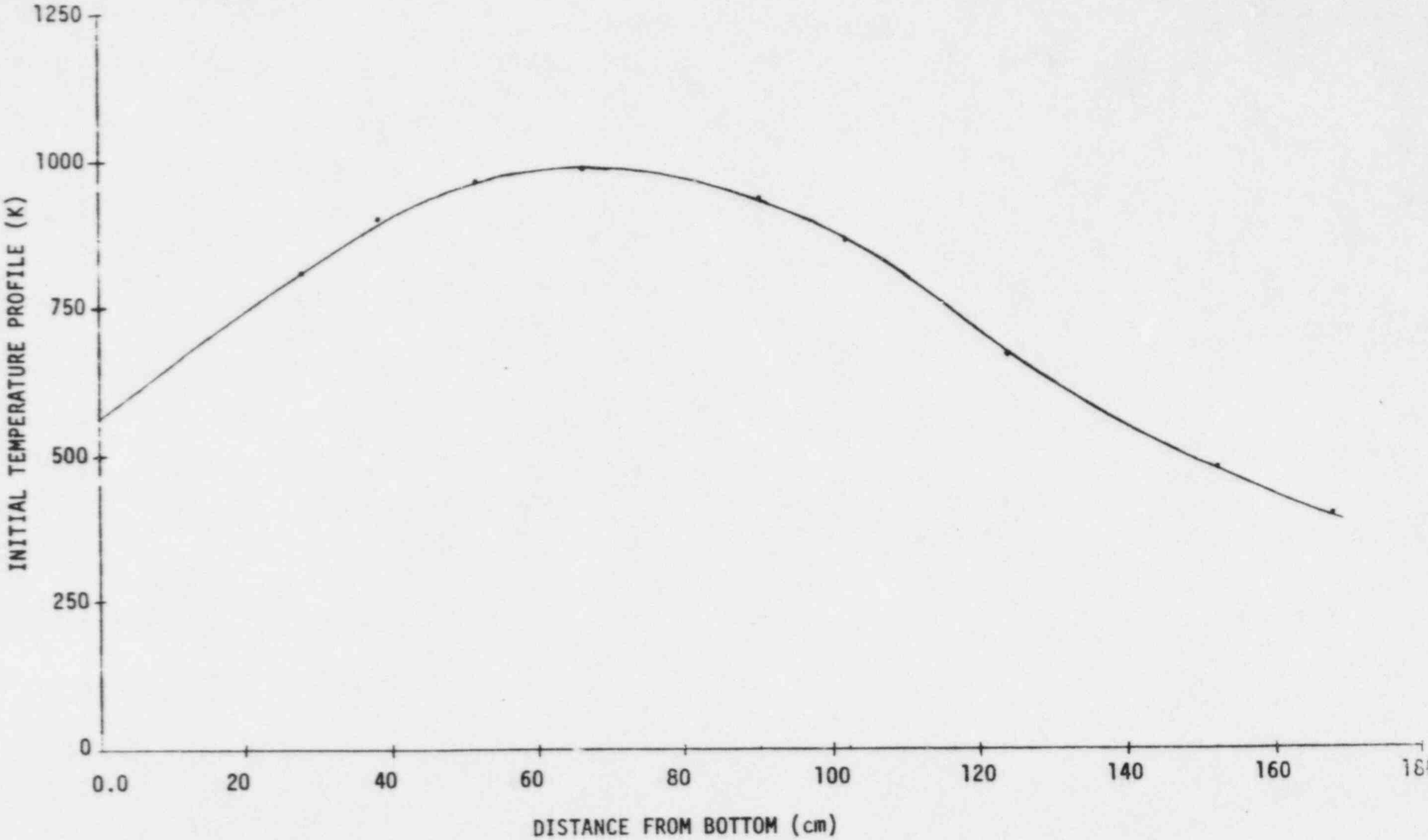



Figure 6. Rod Temperature Profile at Initiation of Simulated Tube Rupture Flow

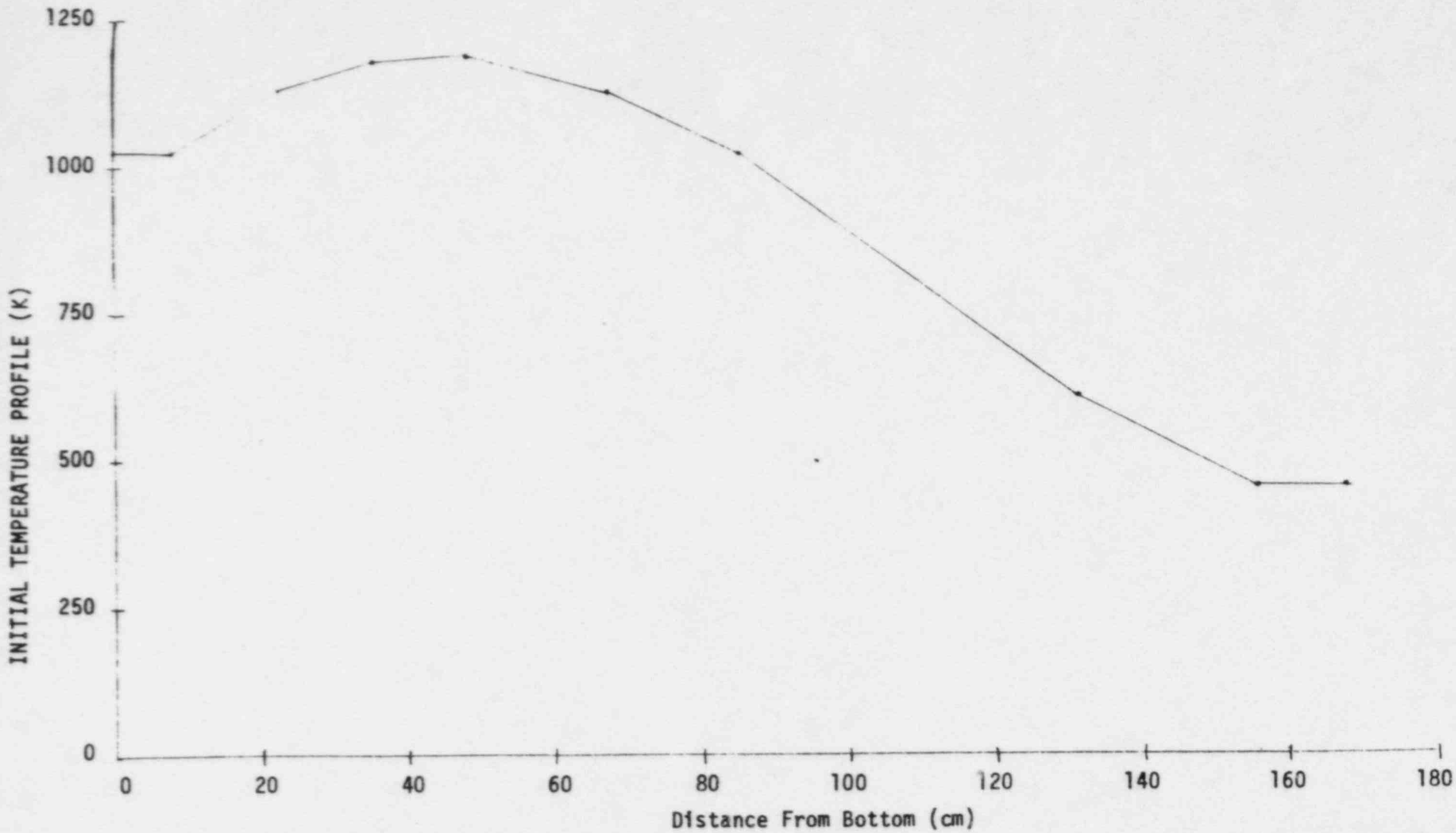



Figure 7. Rod Temperature Profile at Start of Refill

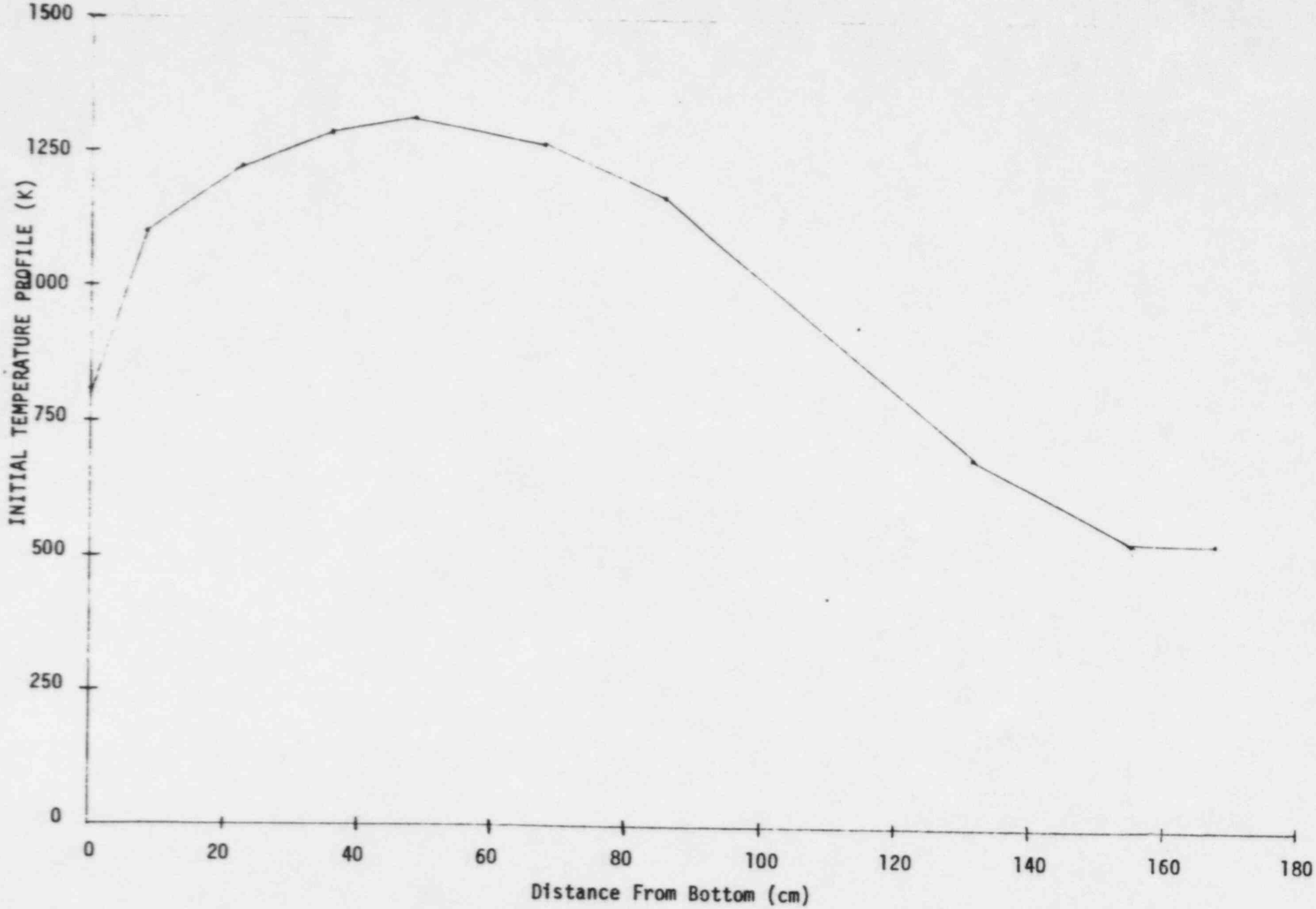



Figure 8. Rod Temperature Profile at Start of Reflood

Table II

Semiscale Mod-1 Initial Conditions At The

Start of Reflood for Test S-28-5

| Parameter | Initial Value |
|---|---|
| Containment Pressure | 241 KPa |
| Temperature of ECC | |
| At Bottom of Heated Length | 411 K (saturated) |
| ECC Injection Rate Cold Leg Intact Loop | |
| 720 Seconds to Completion | $2.72 \times 10^{-4}$ $m^3/s$ |
| Peak Rod Power Density | 0.79 kW/m |
| Power Profile | Stepped (Figure 2) |
| Power Decay | Refer to Figure 3 |
| Peak Initial Rod Temperature | 1277 K |
| Temperature Profile | Refer to Figure 8 |

shows this temperature declined to 994 K at 40 seconds as shown in Figure 9. Test S-04-6 data indicated the system pressure had reached containment pressure (241 kPa) at 40 seconds after rupture (Figure 10). The mass flow at the core inlet (see Figure 11) at this point in time is negative (flow out of the core) and approximately 0.25 kg/s in magnitude. The steam generator secondary pressure (Figure 12) at 40 seconds was approximately 6.0 MPa and the secondary fluid temperature (Figure 13) was 549 K (saturation conditions).

### 3.2 System Response During Reverse Core Flow and Refill

The FLOOD4 calculation of the period of reverse steam flow through core predicted that the peak temperature in the core would increase from 994 K at 40 seconds after rupture to 1209 K at 321 seconds after rupture before turning over and declining to 1146 K at the end of the period of steam generator tube rupture flow. At 646 seconds the injection representing the tube rupture flow ended. During the heat-up of the core while the lower plenum was refilled by the LPIS and HPIS, the FLOOD4 model showed the peak temperature rising from 1146 K to 1277 K at the beginning of reflood (compare Figures 7 and 8). Reflood from the bottom is estimated to start at 720 seconds after rupture.

### 3.3 System Response During Reflood

The FLOOD4 code was used to predict the system response during reflood for Test S-28-5. Hand calculations were performed to determine the time at which reflood would commence, based on the time required for the steam generator secondary to empty and for the lower plenum to refill by the LPIS and HPIS. The results indicated core reflood in

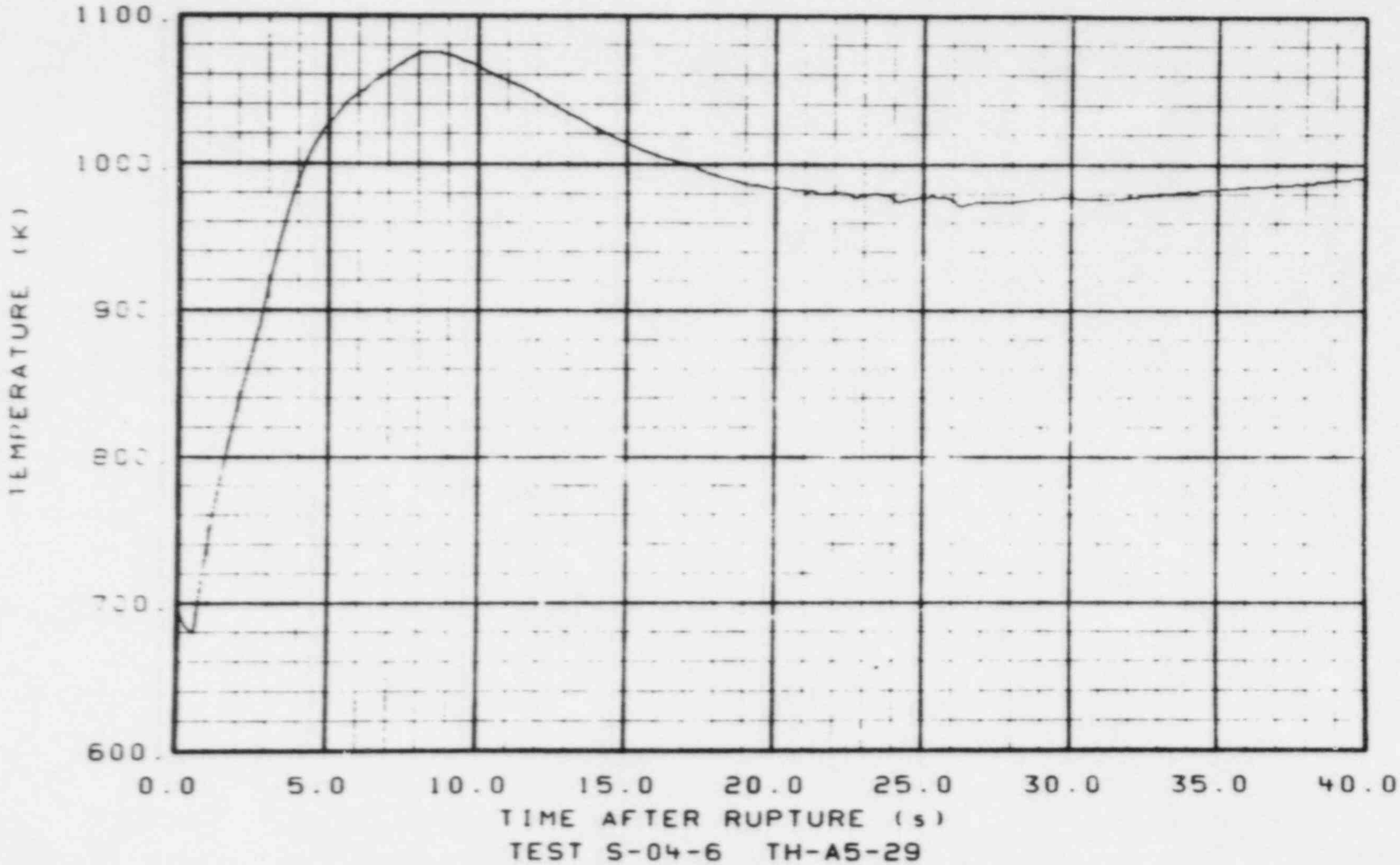



Figure 9. Measured Cladding Temperature Rod A5 (74 cm Elevation) During Blowdown in Test S-04-6

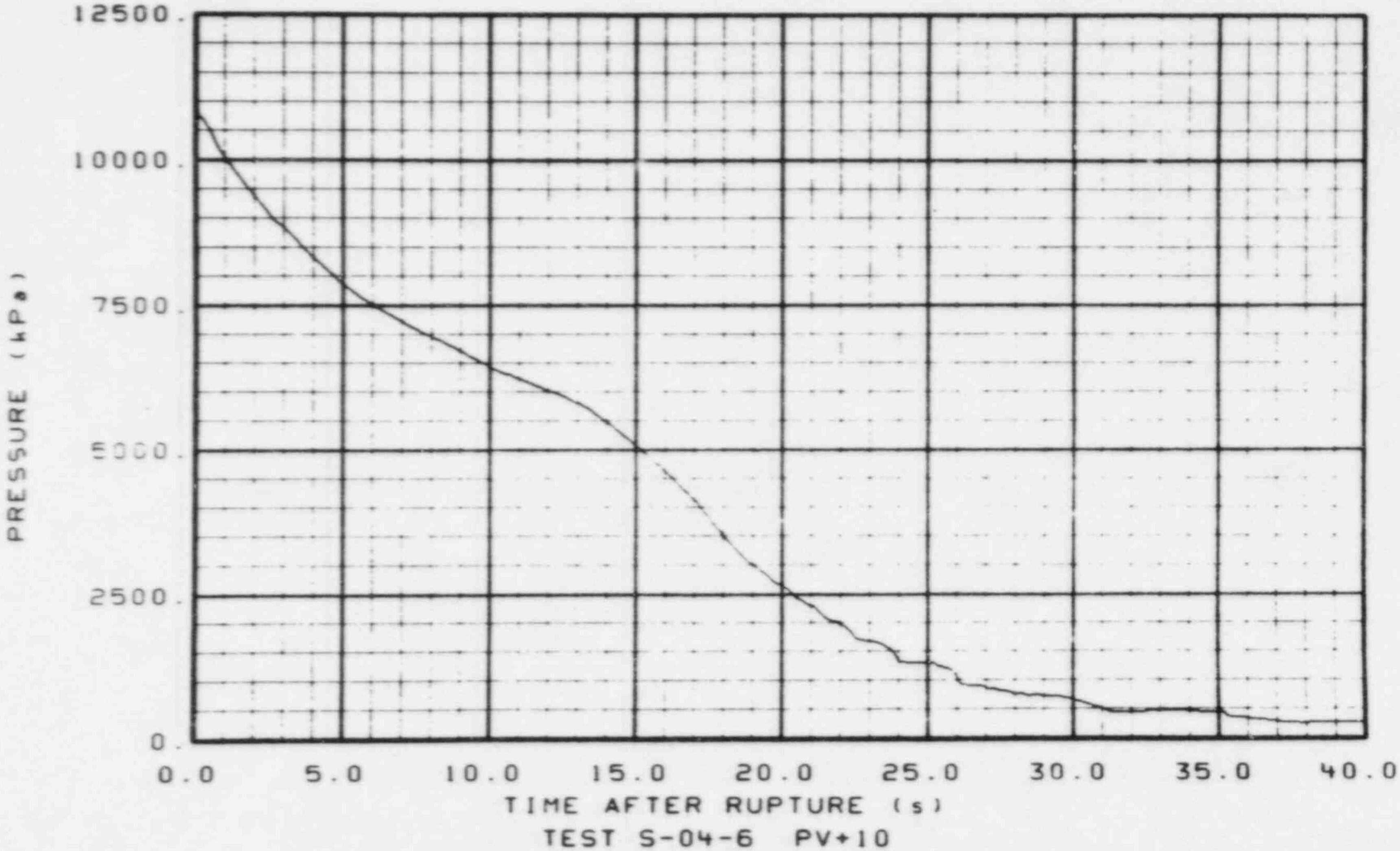



Figure 10. Measured Pressure in the Upper Plenum During Blowdown in Test S-04-6

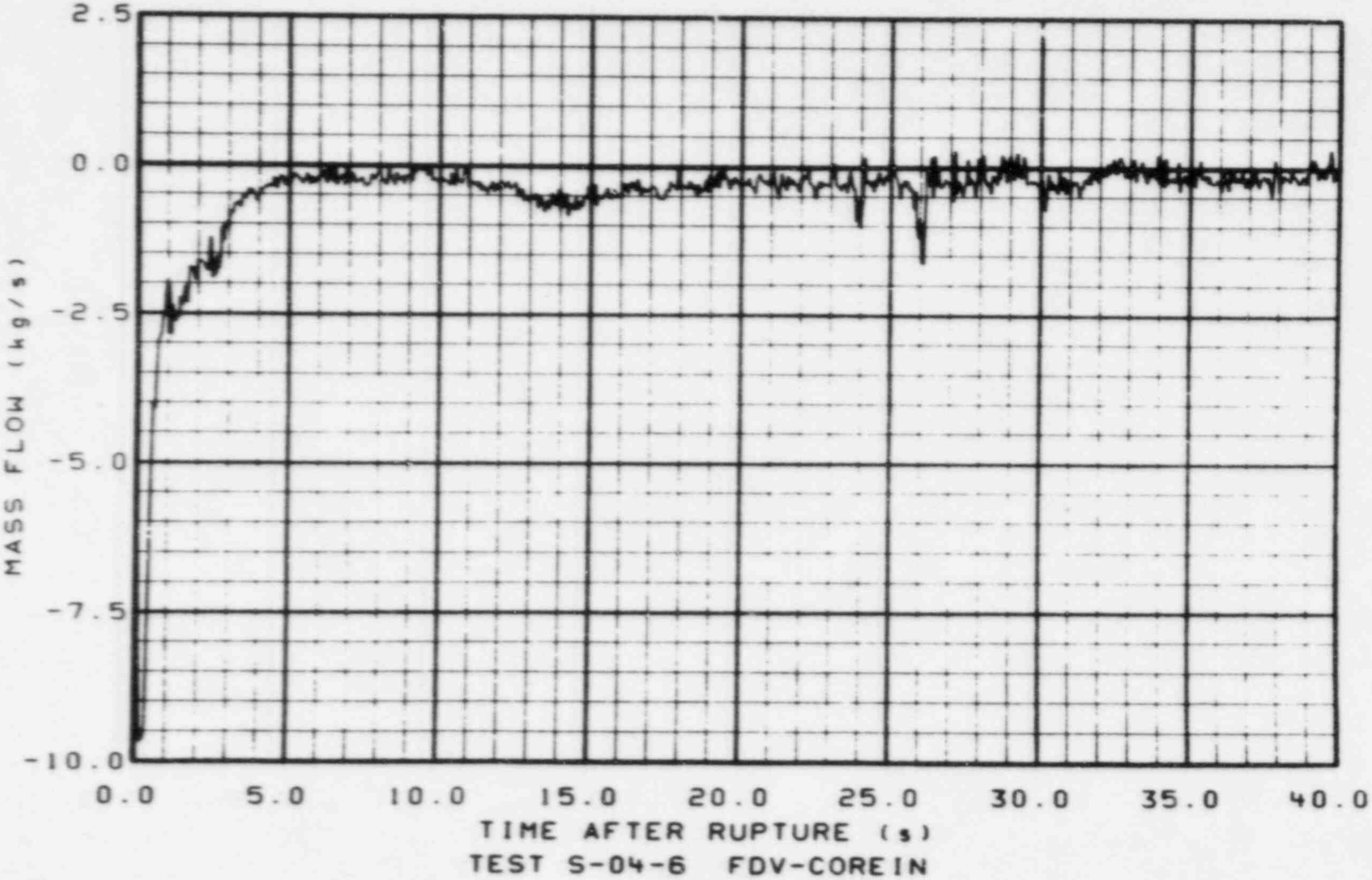



Figure 11. Measured Mass Flow at the Core Inlet During Blowdown in Test S-04-6

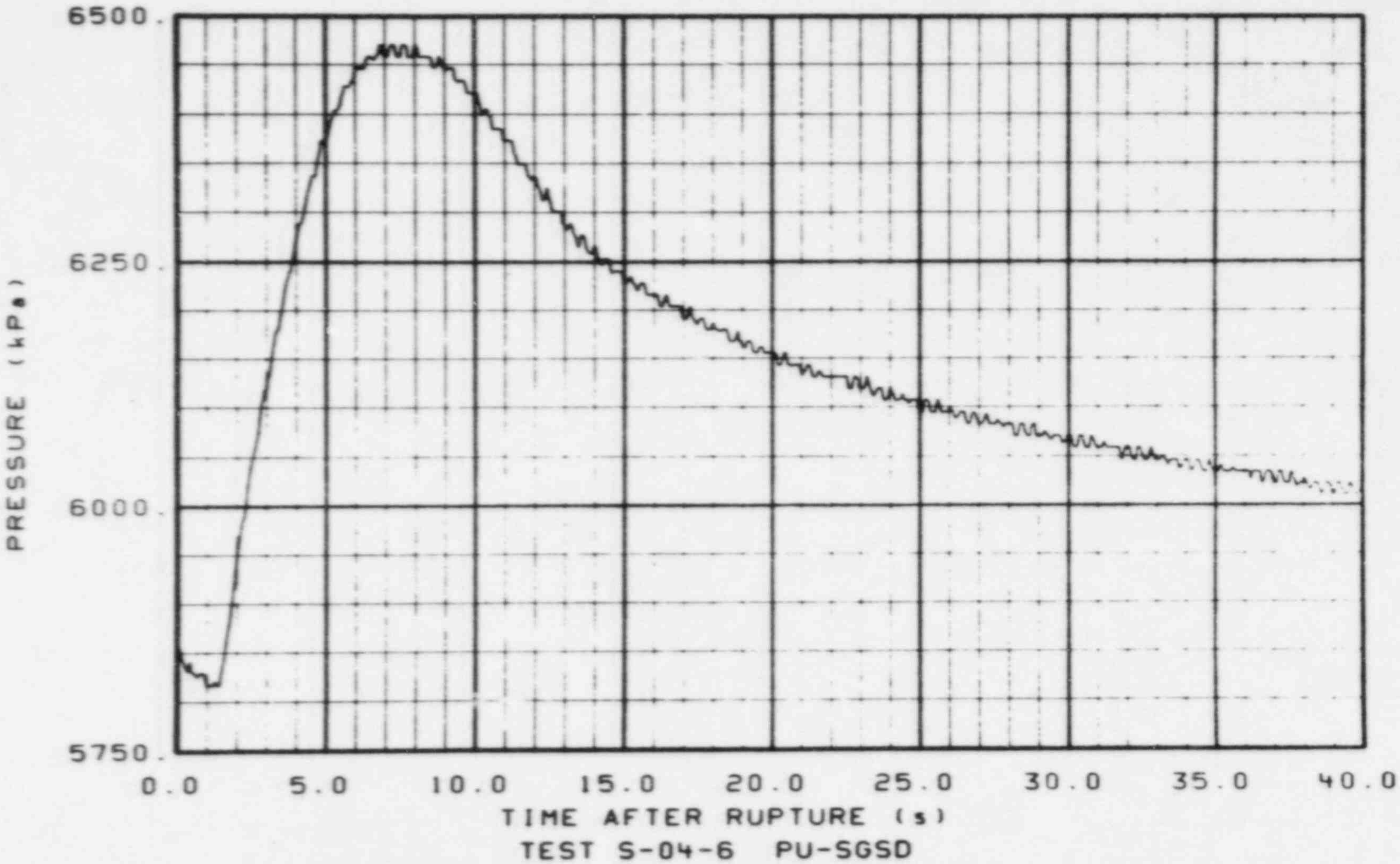



Figure 12. Measured Pressure in the Steam Generator Secondary During Blowdown in Test S-04-6

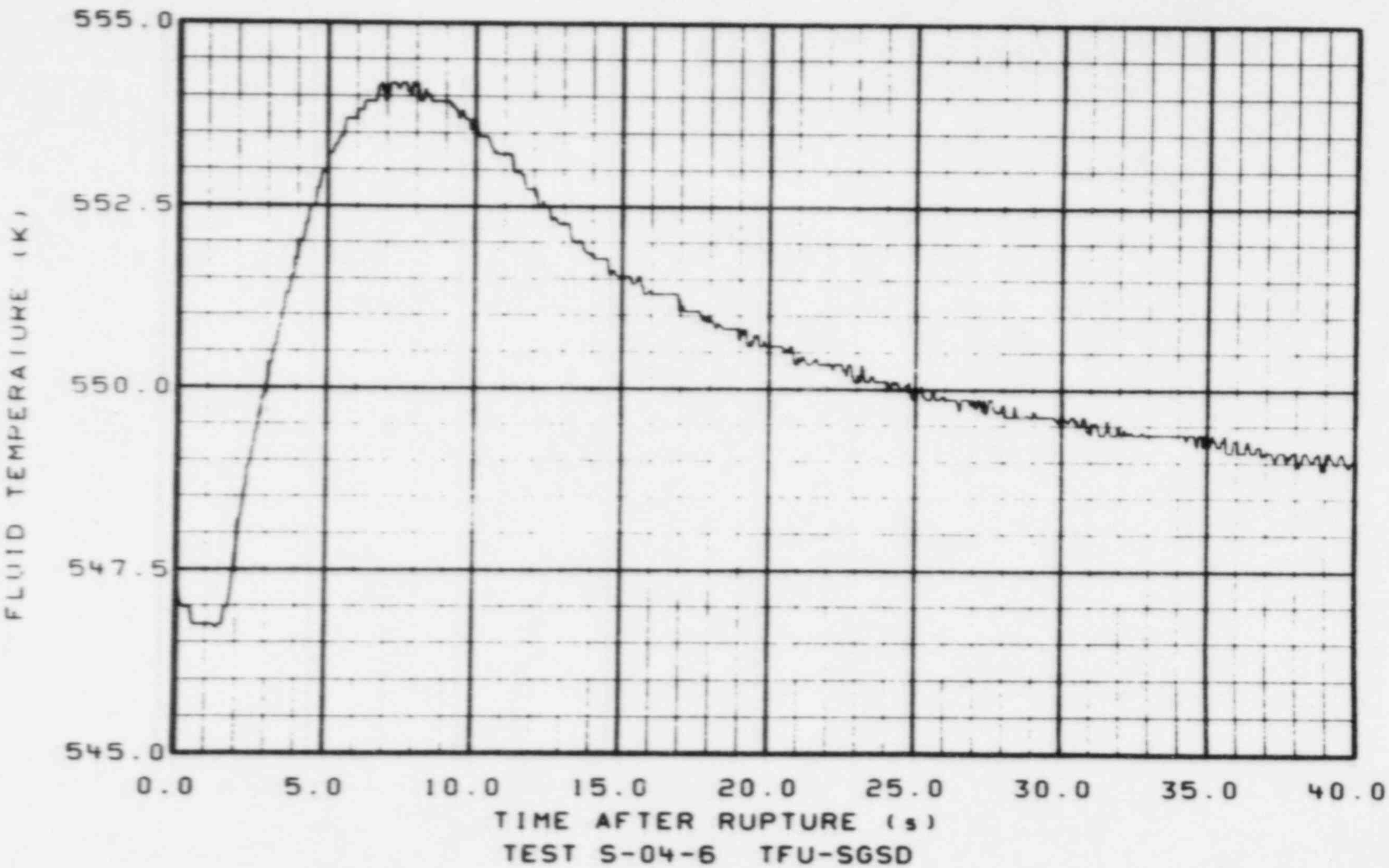



Figure 13. Measured Fluid Temperature in the Steam Generator Secondary During Blowdown in Test S-04-6

Test S-28-5 would start at approximately 720 seconds. The calculated reflood results presented in this section were obtained assuming the rod power densities at the time of reflood were representative of the high power rod power density.

Figure 14 shows that the FLOOD4 calculations predict that the core inlet flow oscillates both positively and negatively as for previous predictions. A comparison of the calculated differential pressure between the upper plenum and the inlet annulus (Figure 15), with the steam flow from the upper plenum (Figure 16), shows that the differential pressure between the upper plenum and the inlet annulus follows the steam generation in the core. The oscillations in the steam flow from the upper plenum are related to the oscillations in the core flow rate shown in Figure 14. A comparison of the data in these figures shows that the amplitude of the steam flow and differential pressure are directly related to the amplitude of the core flow oscillations as expected. The downcomer annulus liquid level shown on Figure 17 also shows oscillations. These oscillations are primarily responsible for the oscillations in the core flow and steam generation in the core. The manometer type oscillations result when the liquid level builds up in the downcomer and forces liquid into the core. Some of the liquid forced into the core is vaporized to steam on contact with the heater rods. This steam generation causes a small pressure increase which tends to force some fluid out of the core and also entrain some liquid up the core. The level in the downcomer then builds up again and the process is repeated causing the oscillatory flows and levels shown in Figures 14 through 17. The core quench levels shown in Figure 17 indicate

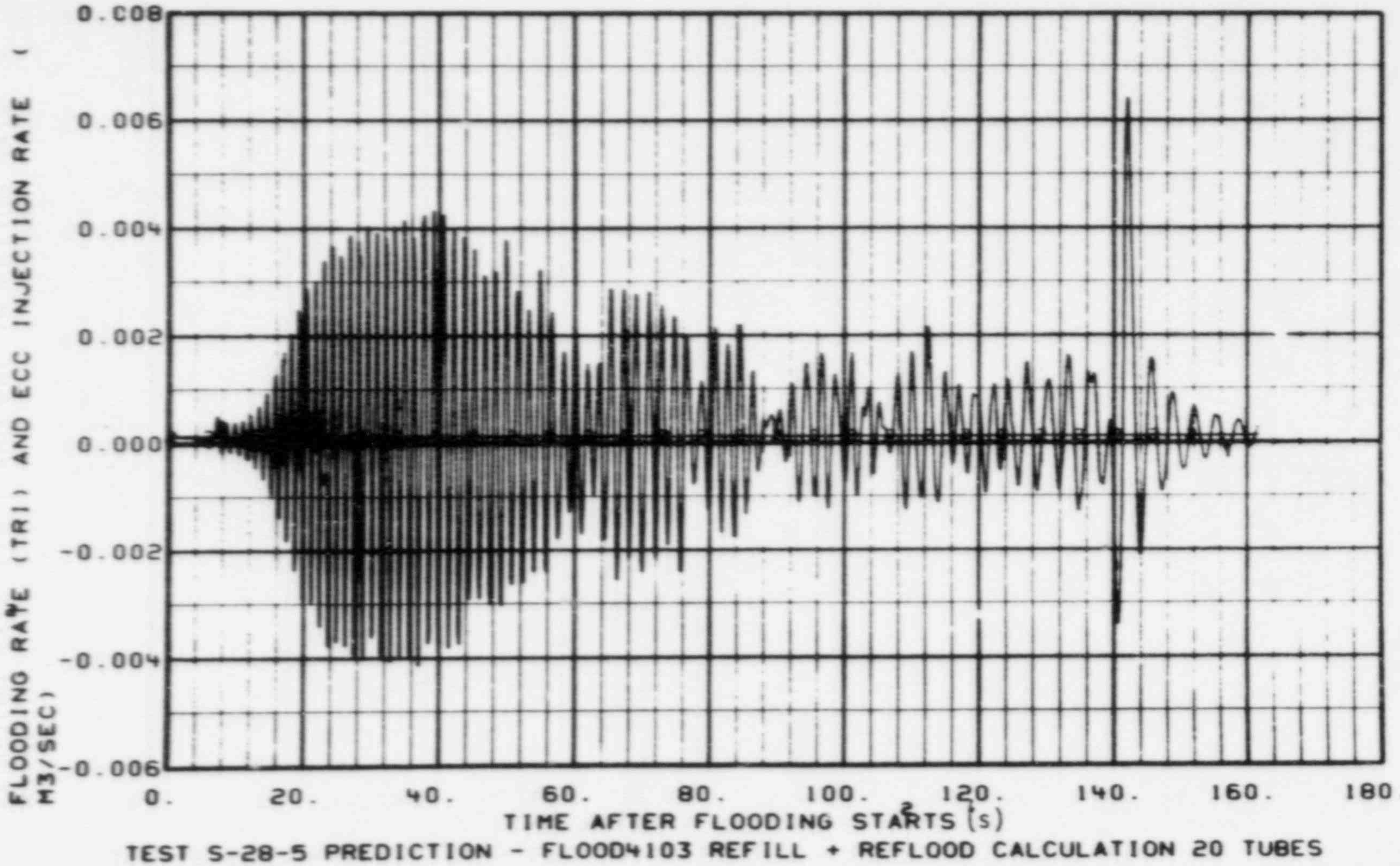



Figure 14. FLOOD4 Prediction of Core Inlet Volumetric Flow Rate

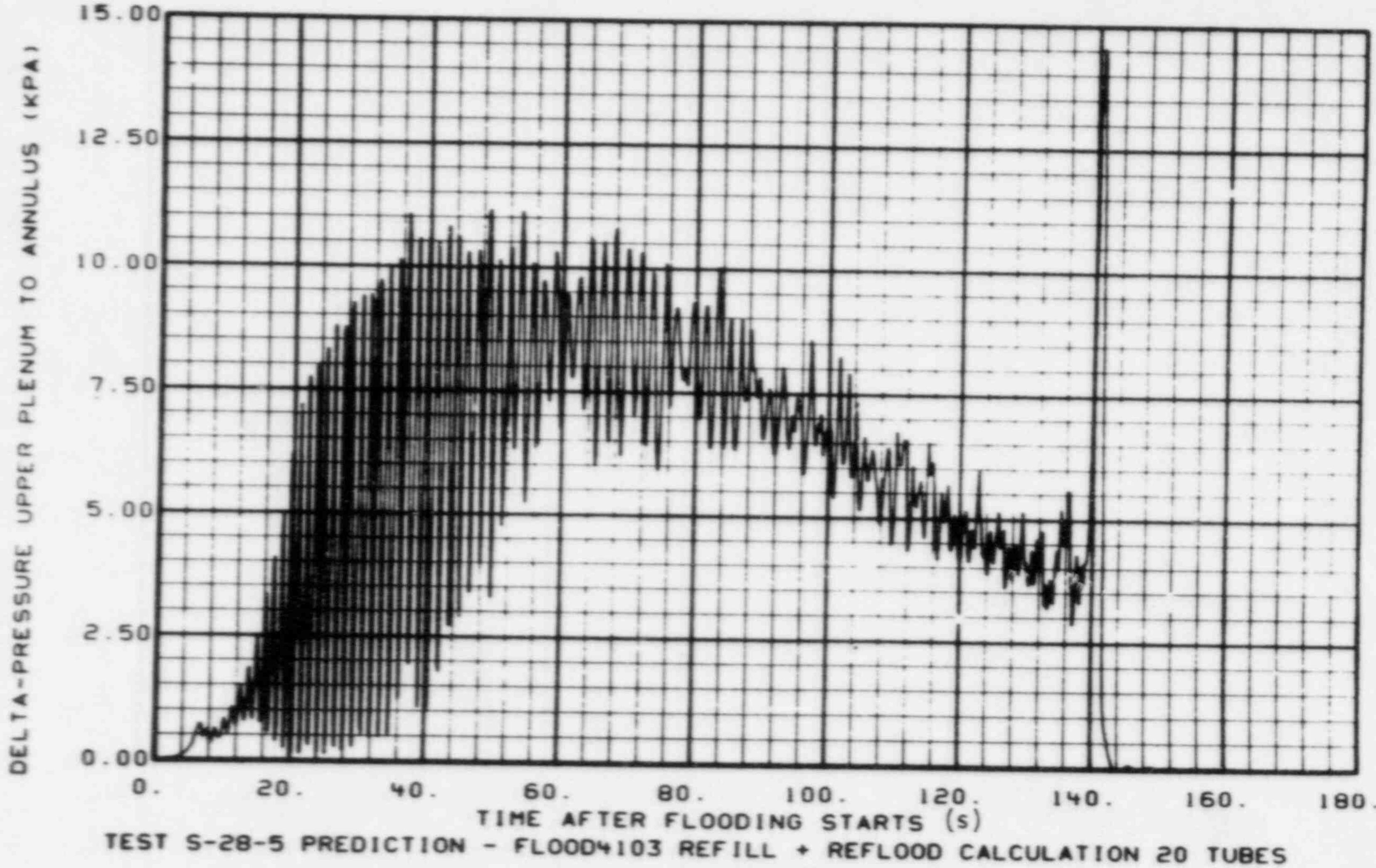



Figure 15. FLOOD4 Prediction of Differential Pressure Between the Upper Plenum and Inlet Annulus

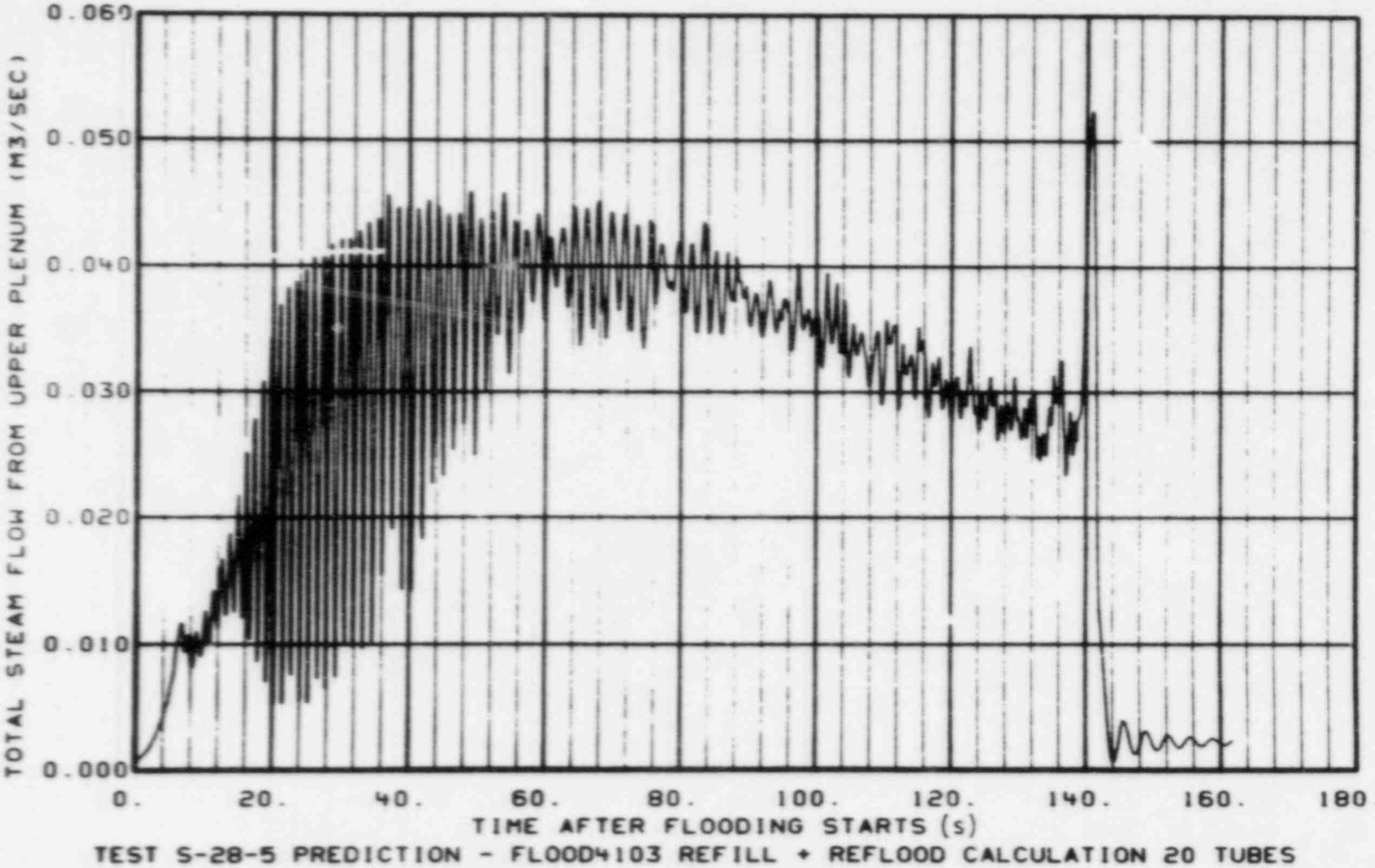



Figure 16. FLOOD4 Prediction of Total Steam Flow from the Vessel Upper Plenum During Reflood

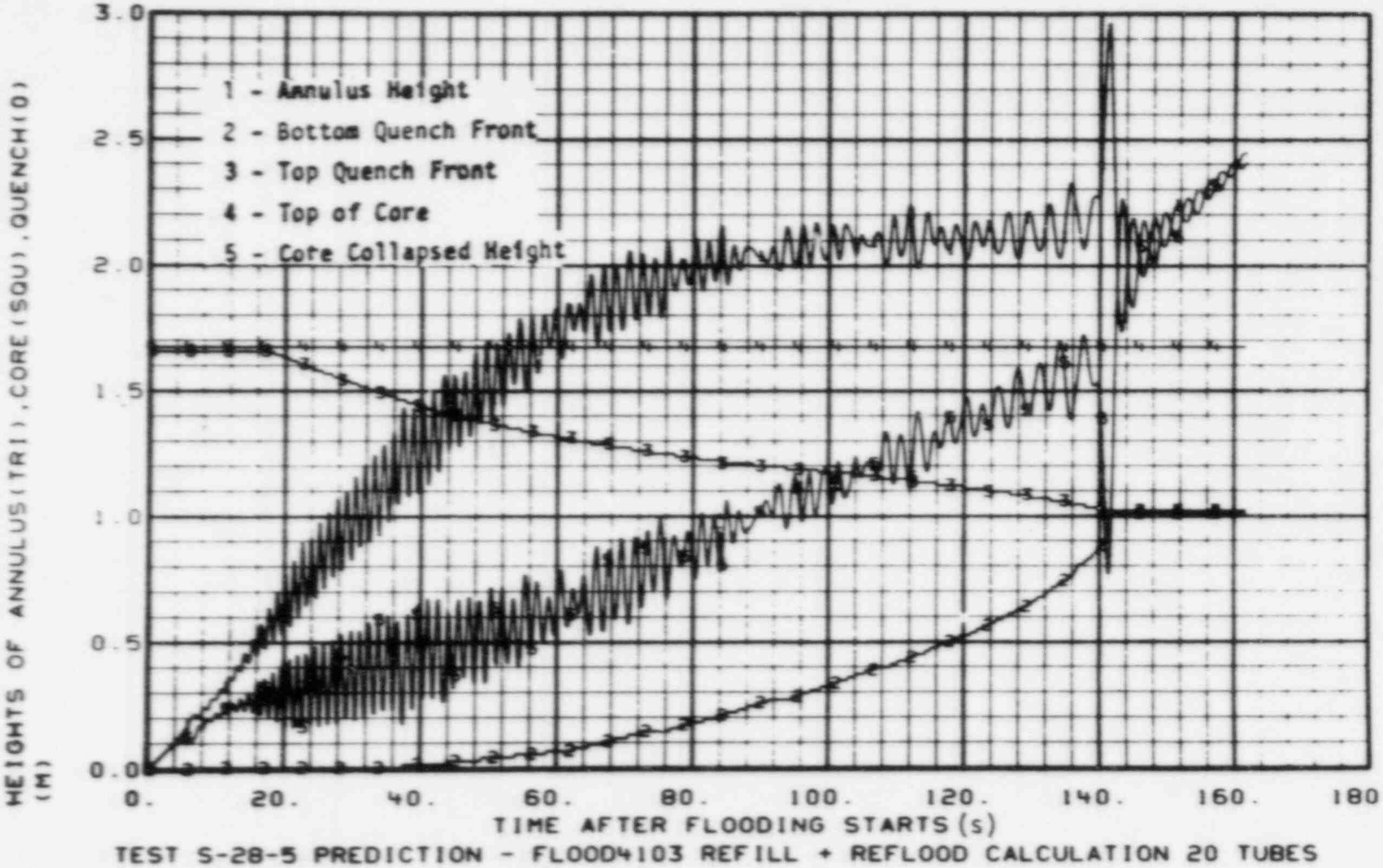



Figure 17. FLOOD4 Prediction of Water and Quench Front Heights During Reflood

that the core quenched from both the top and the bottom and that all rod surfaces are quenched by about 141 seconds after the initiation of reflood, or 861 seconds after rupture. The rate of change of liquid level for the downcomer annulus relative to the core is slightly different because the annulus water that enters the core and is evaporated to steam is not included in the core collapsed level calculation. The collapsed core liquid level is used only as a calculational parameter for heat transfer specification. That the core collapsed liquid level is shown to be higher than the heated length does not indicate that the core is completely full of liquid. The collapsed liquid level includes liquid in the regions above the heated length which would fill the core if collapsed. This collapse will not occur because steam flow in the core causes entrainment.

The FLOOD4 code cannot account for the downcomer mass depletion phenomena noted in previous Semiscale tests. This phenomena is a result of an excessively large amount of energy transfer from the downcomer walls to the fluid in the downcomer gap after the liquid is depleted from the accumulator. The mass depletion from the downcomer causes a reduction in the downcomer liquid head which in turn causes a reduction in the core reflood driving potential (the annulus water level shown in Figure 17 would be lower if mass depletion were taken into account). The depletion could cause the measured reflood phenomena to be somewhat different than the predicted reflood response.

The FLOOD4 predicted thermal response of the Semiscale Mod-1 core for the reflood portion of Test S-28-5 is presented in Figures 18 and 19. Core elevations of 20, 36, 53, 63.5, and 99 cm above the heated

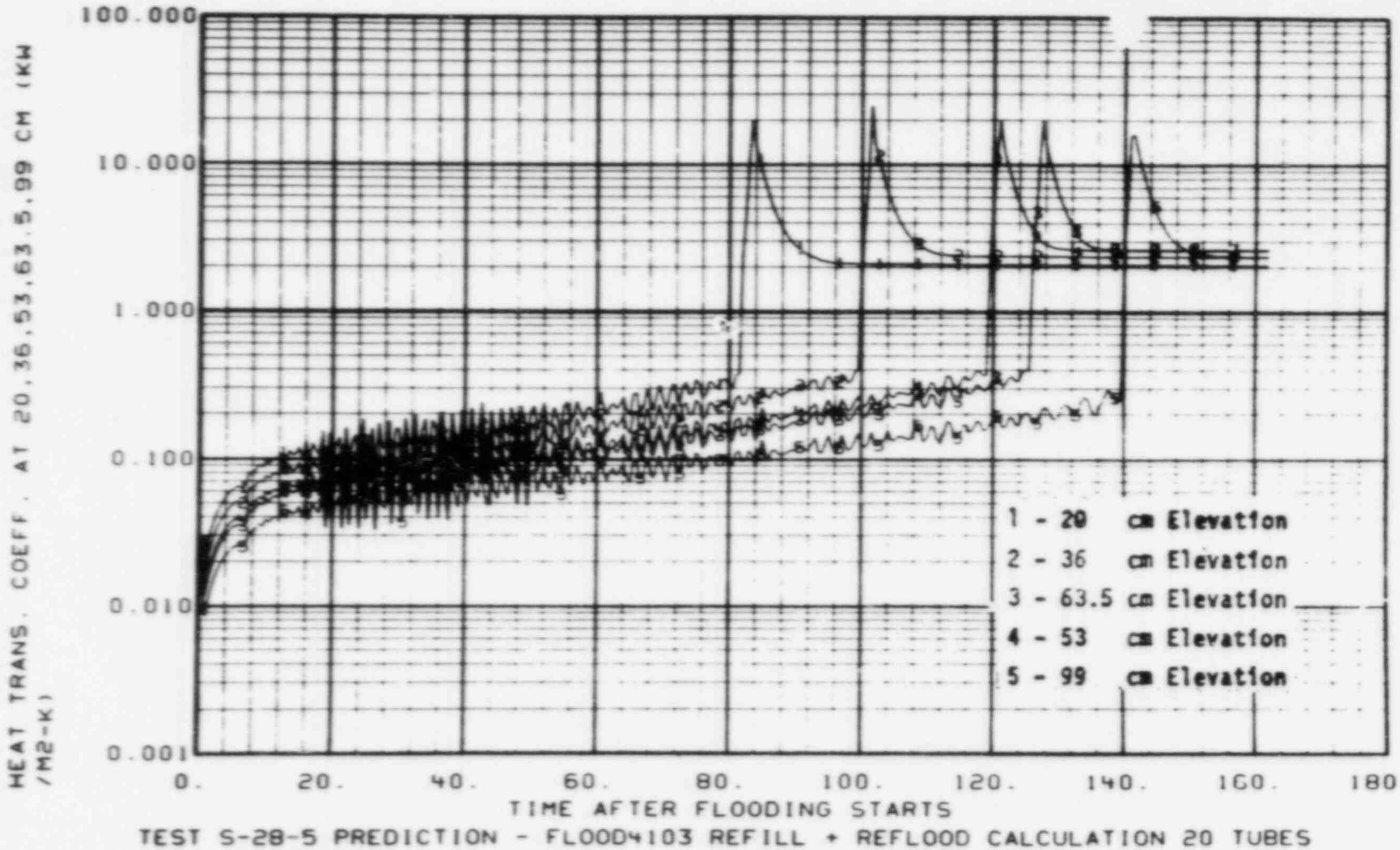



Figure 18. FLOOD4 Prediction of the Heat Transfer Coefficient at the 20, 36, 53, 63.5 and 99 cm Elevations


Figure 19. FLOOD4 Prediction of the Rod Temperatures at the 20, 36, 53, 63.5 and 99 cm Elevations During Reflood

length were chosen for presentation of predicted parameters because they correspond to existing core heater rod thermocouple measurements. The predicted heat transfer coefficients rapidly increase to a fairly constant value (Figure 18) similar to the dispersed flow heat transfer coefficients observed in previous tests. In Figure 18, the lower elevations are shown to have the higher heat transfer coefficients in this dispersed flow film boiling regime because the fluid quality in the lower core region is lower relative to the fluid quality in the upper core region. When the quench front approaches an elevation, the heat transfer coefficient increases very rapidly as the heat transfer regime switches to transition boiling. After a rod position is quenched the heat transfer regime is nucleate boiling and forced convection to liquid with fairly constant heat transfer coefficients between 2.0 and 3.0 $kW/m^2$-K. The predicted rod surface temperature response for various elevations is shown in Figure 19. The temperature at each elevation shows a continual decrease while in the dispersed flow film boiling regime until the quench front approaches that elevation; then the rod surface temperature decreases very rapidly. This rapid decrease in temperature is a result of the prediction of transition boiling. All the predicted rod surface thermocouple responses approach a constant value corresponding to nucleate boiling and forced convection to liquid. The predicted surface heat flux at the hot spot (63.5 cm elevation) is shown in Figure 20. The quench time is about 846 seconds after rupture (126 seconds after reflooding starts) for this location and the critical heat flux during quench is about 1250 $kW/m^2$.

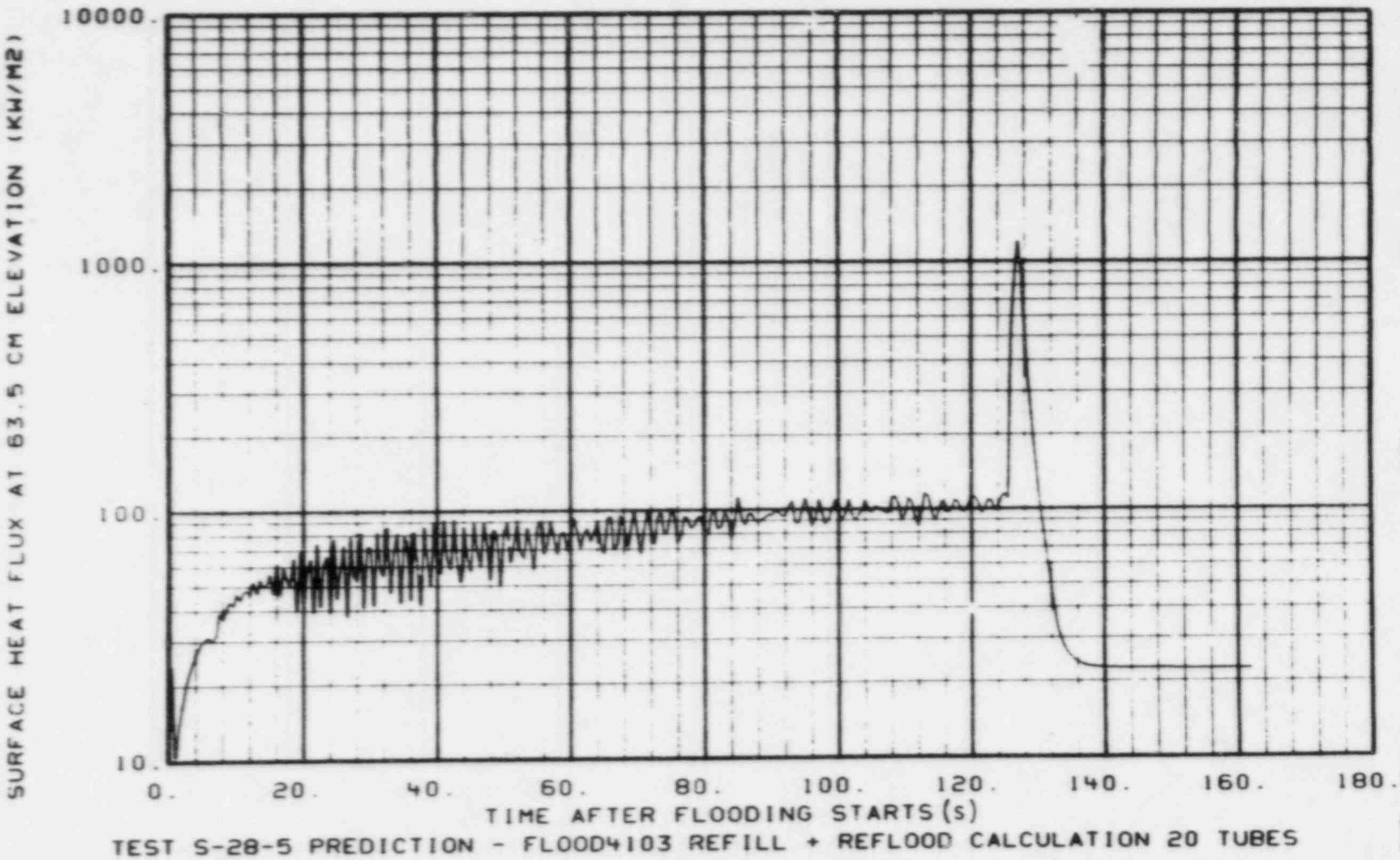



Figure 20. FLOOD4 Prediction of the Surface Heat Flux at the Rod Hot Spot (63.5 cm Elevation) During Reflood

In summary, the peak rod temperature in the core during blowdown should be approximately 1075 K at 8 seconds after rupture. This peak temperature should decline to 994 K at 40 seconds after rupture. During the period of reverse steam flow through the core, the peak rod temperature should increase to 1209 K before turning over and declining to 1146 K at 646 seconds. During the refill period the calculations indicated the peak core temperature would increase to 1277 K at the beginning of reflood. The peak temperature increases slightly during reflood to 1279 K before the rod hot spot quenches at 126 seconds after reflood or 846 seconds after rupture. This rod surface temperature response is summarized in Figure 21.

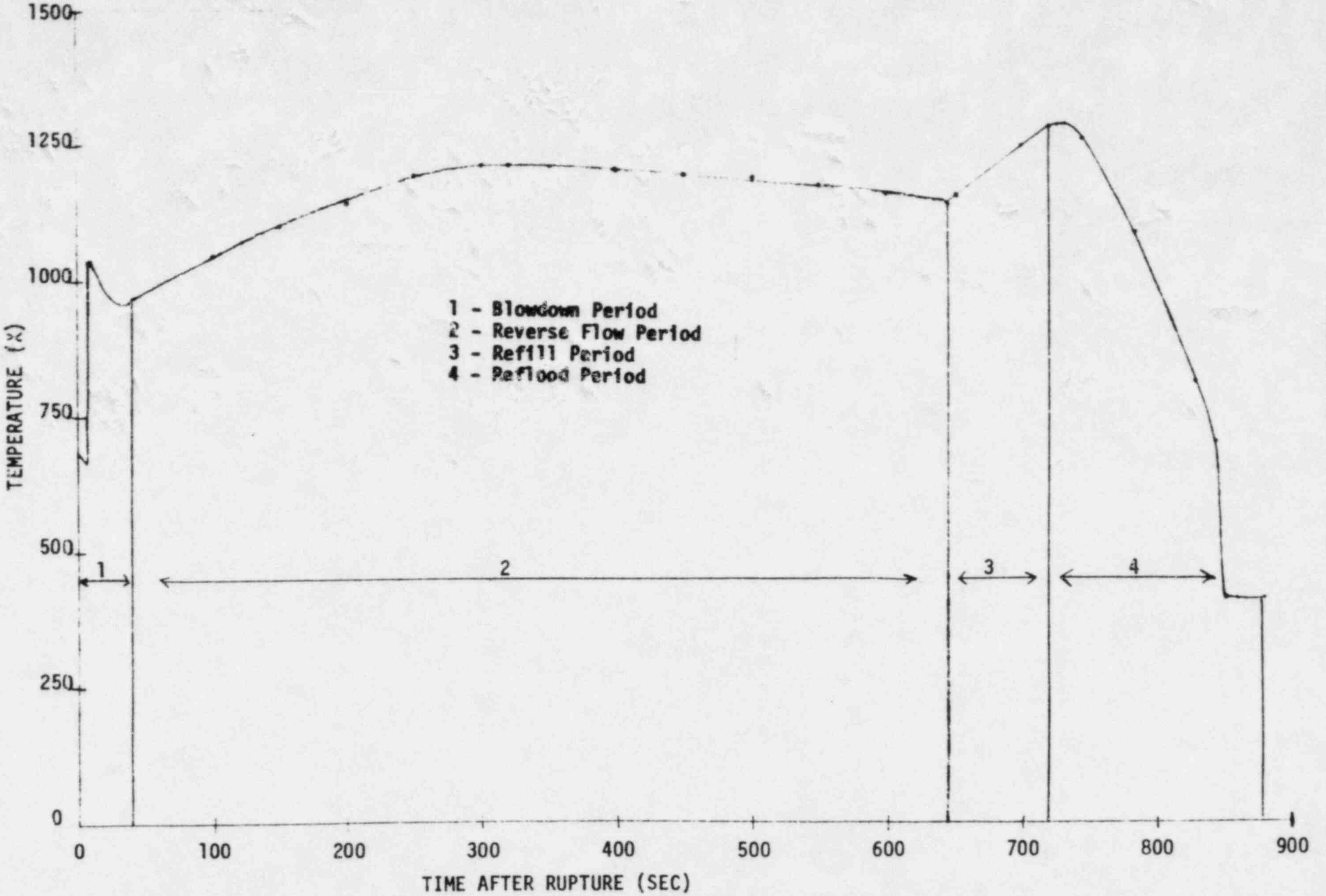



Figure 21. Peak Rod Cladding Temperature During Test S-28-5

# III. CONCLUSIONS

The conclusions relative to the use of Test S-04-6 data to indicate the blowdown response and the FLOOD4 predictions over the rest of the transient for the Semiscale Mod-1 Test S-28-5 are as follows:

(1) The system and core thermal response should be essentially identical for Tests S-28-5 and S-04-6 until 40 seconds after rupture because the initial conditions for the two tests are the same.

(2) The peak temperature during blowdown should be approximately 1075 K at 8 seconds after rupture and should occur on a rod located on the core perimeter. This temperature should decline to 994 K at 40 seconds after rupture.

(3) The reverse steam flow through the core, which is caused by the tube ruptures, occurs during the period from 40 to 646 seconds after rupture. The peak temperature at 646 seconds should be approximately 1146 K. This predicted response was based on single phase heat transfer to steam and did not account for any heat transfer to the liquid present in the core flow. Better cooling in the core may result from any liquid present in the flow.

(4) Heat-up of the core while the LPIS and HPIS refill the lower plenum should result in a peak temperature rise from 1146 K to 1277 K over the period of 646 to 720 seconds after rupture.

(5) The start of reflood from the bottom is estimated to begin at 720 seconds after rupture.

(6) The hot spot elevation (63.5 cm from the bottom of the heated length) is expected to quench at about 846 seconds after rupture or about 126 seconds after the start of reflood. The whole core is predicted to quench by 141 seconds after the start of reflood (861 seconds after rupture).

## IV. REFERENCES


(1) D. J. Olson Ltr to P. E. Litteneker, DJO-125-77, Transmittal of EOS Appendix 28, June 3, 1977.

(2) J. O. Zane Ltr to P. E. Litteneker, Zan-250-76, Transmittal of Quick Look Report for Semiscale Mod-1 Integral Blowdown Reflood Tests S-04-5 and S-04-6, October 15, 1976.

(3) J. O. Zane Ltr to R. E. Swanson, Zan-235-75, Test Prediction of the Third Mod-1 Semiscale Test Series, Reflood Heat Transfer Tests, Tests S-03-1, S-03-2, and S-03-3, November 19, 1975.

# APPENDIX A

# FLOOD4 COMPUTER CODE

## APPENDIX A

## FLOOD4 COMPUTER CODE

The FLOOD4 computer code is a recently developed analysis tool used to predict core reflood behavior in water reactors. The methods and models used in FLOOD4 are currently undergoing evaluation and improvement.

The FLOOD4 code couples the system hydraulics using the momentum equation for the core, lower plenum, and downcomer with the heat transfer and steam generation in the core region. Liquid which rises in the downcomer to a height greater than the cold leg is assumed to be lost from the system. The steam within the system is lumped into one gas volume and the perfect gas law is used to calculate the relationship between the steam pressure, mass, volume, and temperature. Figure A-1 illustrates the hydraulic coupling of the Semiscale system used in the FLOOD4 model. The core is represented in FLOOD4 by a series of axially stacked conduction nodes which have a specified initial temperature and energy generation rate. The heat transfer coefficient applied to a node depends on the mode of heat transfer which is determined from the elevation of the node, the elevation of the water, and the temperature of the node. Four different heat transfer modes are used to define the boiling curve and one mode is defined for forced convection to single-phase liquid below the quench level. The reference temperature used for the heat transfer calculation is $T_{sat}$ for nodes above the water level in the core and $T_{bulk}$ for nodes below the quench level core.

The fluid entering the upper plenum is a mixture of the steam generated in the core and entrained water. The amount of steam is determined from the heat flux at the nodes above the quench front and

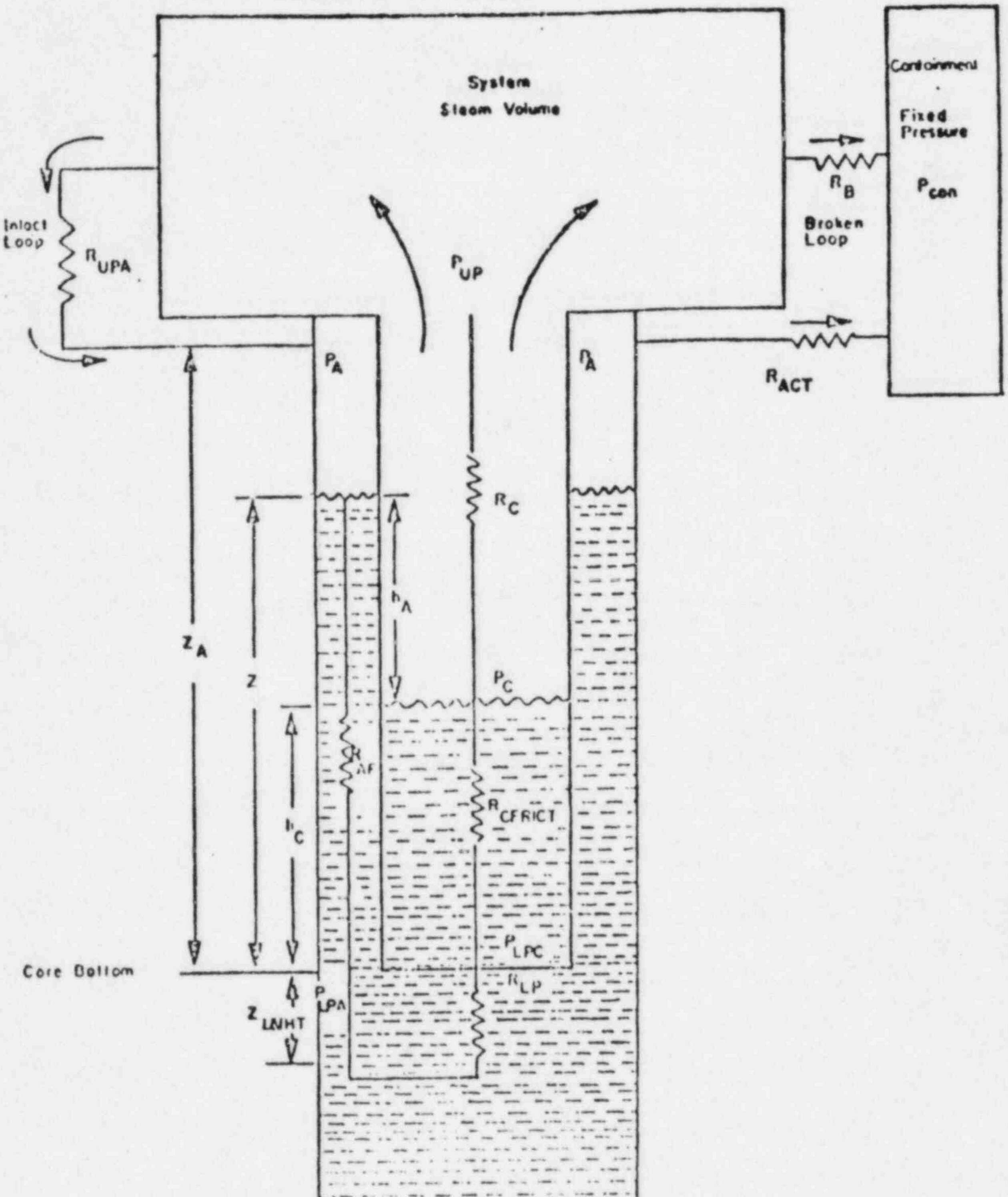



Figure A-1. FLOOD4 Model of Semiscale Mod-1 System

the amount of entrained water is a function of the steam flow rate, the collapsed water level above the quench front, the pressure, and the core hydraulic diameter. Since all of the rods are assumed to be identical, the calculation is performed for one subchannel and rod and then multiplied by the number of rods in the core to obtain the total steam flow. The axial temperature distribution at the start of the injection simulating the tube ruptures (40 seconds) was determined by using the peak temperature in the core at that time and using a cosine curve fit to determine the temperature distribution. The initial axial temperature distribution of the rods at the start of reflood was determined by using temperature distribution at the time the FLOOD4 reverse core flow steam cooling calculation terminated as input into FLOOD4 and performing a core heat-up calculation.

FLOOD4 has several new features which are still experimental and include: (1) capability for upper plenum injection which include a condensation mode, (2) capability to have liquid fall back from the upper plenum if the core steam velocity goes below a certain value, and (3) vaporization of entrained liquid in the intact loop steam generator. Future predictions will attempt to include these features where applicable in an effort to better simulate expected behavior.

Table A-1 is a copy of the input to the FLOOD4 calculation for reverse core flow steam cooling calculation and Table A-II is a copy of the input to the refill and reflood calculation for Test S-28-5.

Table A-I. FLOOD4 Input Listings for the Reverse Core Flow Steam Cooling Calculation

```
      TEST S-28-5 PREDICTION - FLOOD4102 REVERSE STEAM FLOW CALC  20 TUBES
    1 TIME AFTER FLOODING STARTS (SEC)
    2 FLOODING RATE(TRI) AND ECC INJECTION RATE (IN/SEC)     -100.      100.
    3 HEIGHTS OF ANNULUS(TRI),CORE(SOL),QUENCH(O) (FT)       -2.        12.0
    4 TOTAL STEAM FLOW FROM UPPER PLENUM (GPM)
    5 DELTA-PRESSURE UPPER PLENUM-ANNULUS (PSI)               0.0        2.0
    6 THERMOCOUPLE TEMPERATURE AT 8,14,21,25,39 IN. (F)      0.         2200.
    7 SURFACE HEAT FLUX AT 25 INCH ELEVATION (BTU/HR-FT2)    1000.      1000000.
    8 HEAT TRANS.COEFF.AT 8,14,21,25,39 IN. (BTU/HR-FT2-F)   1.         10000.
    9 DISTANCE FROM BOTTOM (IN)                              0.         70.
   10 INITIAL TEMPERATURE PROFILE (F)                        0.         1600.
   11 FLOODING RATE(TRI) AND ECC INJECTION RATE (GPM)
   12 LIQUID LEVEL AND CORE EXIT QUALITY                      0.0        1.0
   13 LIQUID LEVEL AND CORE EXIT STEAM FLOW (LBS/SEC)
   14 CORE EXIT LIQUID VAPORIZED IN STEAM GENERATOR (LB/SEC)
   15 CORE EXIT AND COLLAPSED LEVEL STEAM VELOCITY (FT/SEC)
 -1
       0.55       0.55       50.        0.55     300.00
      .0513       .05      .0589       35.0        6.        58.4  .0001408      264.0
       11.8       2.63      1.67      .0445      .085
    0          .00376       .05         1.       .760         .6       0.0        0.3
        5.5       0.0       0.0        .07    1.E+06        3.5       3.0
       .001      500.   200      .001      500.   200       .001      500.  200  100
      266.6       11.0
 -1
        9.6       11.0
 -1
       5.63       11.9
 -1
       0.52       11.0
 -1
    2          .00465      0.00       175.      940.        1.0      0.00
        0.6       0.25    75380.       0.0      264.       38.0      264.      1330.
    1     1    0            40.0       0.5     645.0        .05      2.00        0.2
     36.       940.        1.0       1.0       1.0       .995      .039
    1     1    2       .055       0.
    2     2    4       .045       1.
    3     4    2       .036       0.
    5     5    1       .010       0.
    6     6    1       .029       0.
 -1
   17    22   50   43   78    4     2    2   10     5    5
    1    12        0.5      0.374     859.
   13    22        0.5      0.635     959.
   23    32        0.5      0.817    1013.
   33    42        0.5      0.939    1030.
   43    62        0.5      1.000     984.
   63    72        0.5      0.939     876.
   73    82        0.5      0.817     769.
   83    96        0.5      0.635     642.
   97   112        0.5      0.374     466.
  113   132        0.5      0.126     326.
 -1
```

Table A-II. FLOOD4 Input Listing for the Refill and Reflood Calculation

```
     TEST S-28-5 PREDICTION - FLOOD4103 REFILL + REFLOOD CALCULATION  20 TUBES
   1 TIME AFTER FLOODING STARTS (SEC)
   2 FLOODING RATE(TRI) AND ECC INJECTION RATE (IN/SEC)    -100.      100.
   3 HEIGHTS OF ANNULUS(TRI),CORE(SCU),QUENCH(O) (FT)      -2.        12.0
   4 TOTAL STEAM FLOW FROM UPPER PLENUM (GPM)
   5 DELTA-PRESSURE UPPER PLENUM-ANNULUS (PSI)              0.0        2.0
   6 THERMOCOUPLE TEMPERATURE AT 6,14,21,25,39 IN. (F)     0.         2200.
   7 SURFACE HEAT FLUX AT 25 INCH ELEVATION (BTU/HR-FT2)   1000.      1000000.
   8 HEAT TRANS.COEFF.AT 6,14,21,25,39 IN. (BTU/HR-FT2-F)  1.         10000.
   9 DISTANCE FROM BOTTOM (IN)                             0.         70.
  10 INITIAL TEMPERATURE PROFILE (F)                       0.         1600.
  11 FLOODING RATE(TRI) AND ECC INJECTION RATE (GPM)
  12 LIQUID LEVEL AND CORE EXIT QUALITY                     0.0        1.0
  13 LIQUID LEVEL AND CORE EXIT STEAM FLOW (LBS/SEC)
  14 CORE EXIT LIQUID VAPORIZED IN STEAM GENERATOR (LB/SEC)
  15 CORE EXIT AND COLLAPSED LEVEL STEAM VELOCITY (FT/SEC)
-1
    0.55        0.55        50.        0.55     300.00
   .0513         .05      .0569        35.0         6.       58.4   .0001403        264.0
   11.8         2.63       1.67       .0445       .085
 0             .00376       .05          1.       .760         .6        0.0          0.3
    5.5          0.0        0.0         .07    1.0E+06        3.5        3.0
   .001         500.   200        .001       500.  200       .001       500.   200   100
  266.5         11.0
-1
    9.6         11.0
-1
  , 5.63        11.9
-1
    0.52        11.0
-1
 2             .00468       0.00        175.       940.        1.0       0.00
    0.6          0.25     75380.         0.0       264.       38.0       264.       1672.
 0    1        0            646.0        0.5      720.0        .05       2.00         0.2
  36.          940.          1.0         1.0        1.0       .995
 1    1        2        .055        0.
 2    2        4        .045        1.
 3    4        2        .036        0.
 5    5        1        .010        0.
 6    6        1        .029        0.
-1
 17   28     50     43     78     4       7    2    10    5    5
  1    1            0.5       0.374    1000.
  2   12            0.5       0.374    1529.
 13   22            0.5       0.635    1733.
 23   32            0.5       0.817    1862.
 33   42            0.5       0.939    1903.
 43   62            0.5       1.000    1825.
 63   72            0.5       0.939    1625.
 73   82            0.5       0.817    1403.
 83   96            0.5       0.635    1116.
 97  112            0.5       0.374     769.
113  132            0.5       0.126     500.
-1
```

EG&G Idaho, Inc.

P. O. Box 1625
Idaho Falls, Idaho 83401

July 27, 1977

Sheron

Mr. R. E. Tiller, Director
Reactor Operation and Program Division
Idaho Operations Office - ERDA
Idaho Falls, Idaho 83401

TRANSMITTAL OF QUICK LOOK REPORT FOR SEMISCALE MOD-1 STEAM GENERATOR TUBE RUPTURE TESTS S-28-3 and S-28-4 - DJO-162-77

Dear Mr. Tiller:

Attached is the Quick Look Report for Semiscale Mod-1 Tests S-28-3 and S-28-4 which were performed June 28, 1977 and June 30, 1977, respectively. These integral blowdown-reflood tests were conducted with a break configuration representative of a 200% double-ended offset shear cold leg break, and included the injection of a heated liquid from a pressurized accumulator tank to simulate a steam generator tube rupture flow initiated at the start of vessel refill. The primary objective of Test S-28-3 was to determine the effect on the system and core thermal-hydraulic response of a simulated steam generator tube rupture flow rate equivalent to the flow associated with the singel-ended rupture of 12 tubes in a PWR steam generator. The primary objective of Test S-28-4 was to determine the effect on the system and core thermal-hydraulic response of a simulated steam generator tube rupture flow rate equivalent to the flow associated with the single-ended rupture of 30 tubes in a PWR steam generator. The secondary-to-primary flow rates for Tests S-28-3 and S-28-4 were within the upper and lower limits of an analytically determined range of tube rupture flow rates which could lead to high rod cladding temperatures.

The relatively small steam generator tube rupture flow for Test S-28-3 resulted in a system and core hydraulic response that was similar to the response observed for Test S-28-2 in which the tube rupture flow rate was about half that for Test S-28-3. As in Test S-28-2, the small secondary-to-primary flow for Test S-28-3 was not of sufficient magnitude to maintain a reverse core flow after the initiation of the intact loop accumulator nitrogen flow. The initiation of nitrogen flow at about 52 seconds after rupture forced the initiation of vessel refill and resulted in core reflood beginning at about 64 seconds. Reflood of the core continued during most of the period of the steam generator tube rupture flow. However, because of the increased steam binding in the intact loop resulting from the steam generator tube rupture flow, reflood of the core for Test S-28-3 occurred at a somewhat slower rate than for the Series 28 baseline test (Test S-04-6).

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The core thermal response for Test S-28-3 was influenced considerably by the secondary-to-primary flow. The reduced reflood rate resulted in a prolonged period of rod heatup which lead to considerably higher peak cladding temperatures (on the average) during reflood in the upper two-thirds of the core than were observed for Test S-04-6. The peak cladding temperatures during reflood for Test S-28-3, however, were not significantly different than the peak cladding temperature achieved during blowdown. A maximum cladding temperature of 1098°K was obtained during the reflood phase of the test.

During the period of simulated steam generator tube rupture flow for Test S-28-4, the secondary-to-primary flow was the dominant influence on the system and core thermal-hydraulic behavior. The steam generator tube rupture flow in Test S-28-4 resulted in a strong reverse core flow comprised of secondary fluid in a saturated liquid-vapor mixture. The good core cooling provided by the fairly low quality liquid vapor mixture passing downward through the core caused a top down quench of most of the core prior to the initiation of core reflood. Because of the good core cooling following the initiation of the secondary-to-primary flow, the peak cladding temperatures during the tube rupture flow period were signficiantly lower than the peak cladding temperatures achieved during the blowdown phase of the test.

Very truly yours,

D.J. Olson/jcm

D. J. Olson, Manager
Semiscale Program

JMC:kc

Attachment

cc:

R. W. Barber, ERDA
R. S. Brodsky, ERDA
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R. S. Boyd, NRC
S. Fabic, NRC
R. B. Foulds, NRC
R. F. Fraley, ACRS - 21
S. H. Hanauer, NRC
G. Kelly, NRC
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T. E. Murley, NRC
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R. Denning, BCL
R. B. Duffey, EPRI
G. Fader, CE
G. Farber, IfR
P. Griffith, MIT
R. W. Kiehn, EG&G Idaho, W/O Attach.
W. Kirchner, LASL
M. Levenson, EPRI
W. Loewenstein, EPRI - 2
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