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H. B. Robinson Unit 2
Extended Transfer To Cold Leg Recirculation Following a Large Break LOCA

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1.0 INTRODUCTION

This document presents the results of an analysis of the extended transfer to the cold-leg-recirculation phase from the safety-injection phase at the H. B. Robinson Steam Electric Plant Unit 2 (Robinson) following a postulated large break loss-of-coolant accident (LBLOCA). The analysis was performed to determine the magnitude of a second fuel cladding heatup when the source of the coolant for the Emergency Core Coolant System (ECCS) is transferred from the Refueling Water Storage Tank (RWST) to the containment sump. The analysis is an extension of an existing analysis (Reference 1) which evaluated the transfer to cold leg recirculation assuming the procedure required only 21 minutes. The current analysis extends this transfer time to 30.5 minutes.

The analysis supports operation with a nuclear enthalpy rise factor ($F_{\Delta H}$) of 1.80 and a total peaking factor (F_Q^T) of 2.50, as modified by an axially-dependent power peaking limit [K(z) curve], for fuel assemblies supplied by Siemens Power Corporation - Nuclear Division (SPC-ND).

2.0 SUMMARY

The analysis presented in this report demonstrates that the criteria set forth in Title 10, Part 50.46(b), of the Code of Federal Regulations, 10 CFR 50.46(b), which govern the acceptability of LOCA analyses are satisfied for Robinson for operation within the established power peaking limits, with an $F_{\Delta H}$ of 1.80 and an F_Q^T of 2.50, with the K(z) curve shown in Figure 2.1 applied to the peaking limits, with a full core composed of fuel assemblies supplied by SPC-ND, at the rated power of 2,300 MWt and with steam generator tube plugging of up to 6%.

The analysis presented in this report was performed assuming the LBLOCA was a double-ended cold leg guillotine break with a discharge coefficient of 0.8 (0.8 DECLG). This corresponds to a break with an area approximately 80% of the cold leg area. This particular break was previously identified as the limiting break for Robinson.[2] This analysis modeled the aftermath of the LBLOCA with only one High Head Safety Injection (HHSI) pump running and was essentially independent of the assumed break size. However, for consistency, the limiting break size from LBLOCA was assumed for this analysis also.

The analysis utilized two top-peaked axial power shapes corresponding to the Middle of Cycle (MOC) and to the End of Cycle (EOC), respectively. Figures 2.2 and 2.3 show the two power shapes. The MOC power shape was peaked at relative axial elevation (X/L) of 0.73, and the EOC power shape was peaked at X/L = 0.81. The Peak Cladding Temperatures (PCTs) during the second fuel rod heatup for the MOC and EOC cases were calculated to be 2,102°F and 2,097°F, respectively. The results presented bound the cross-flow and time-step sensitivity results. Metal-water reaction during this second heatup was calculated to be less than the 10 CFR 50.46(b) criteria.

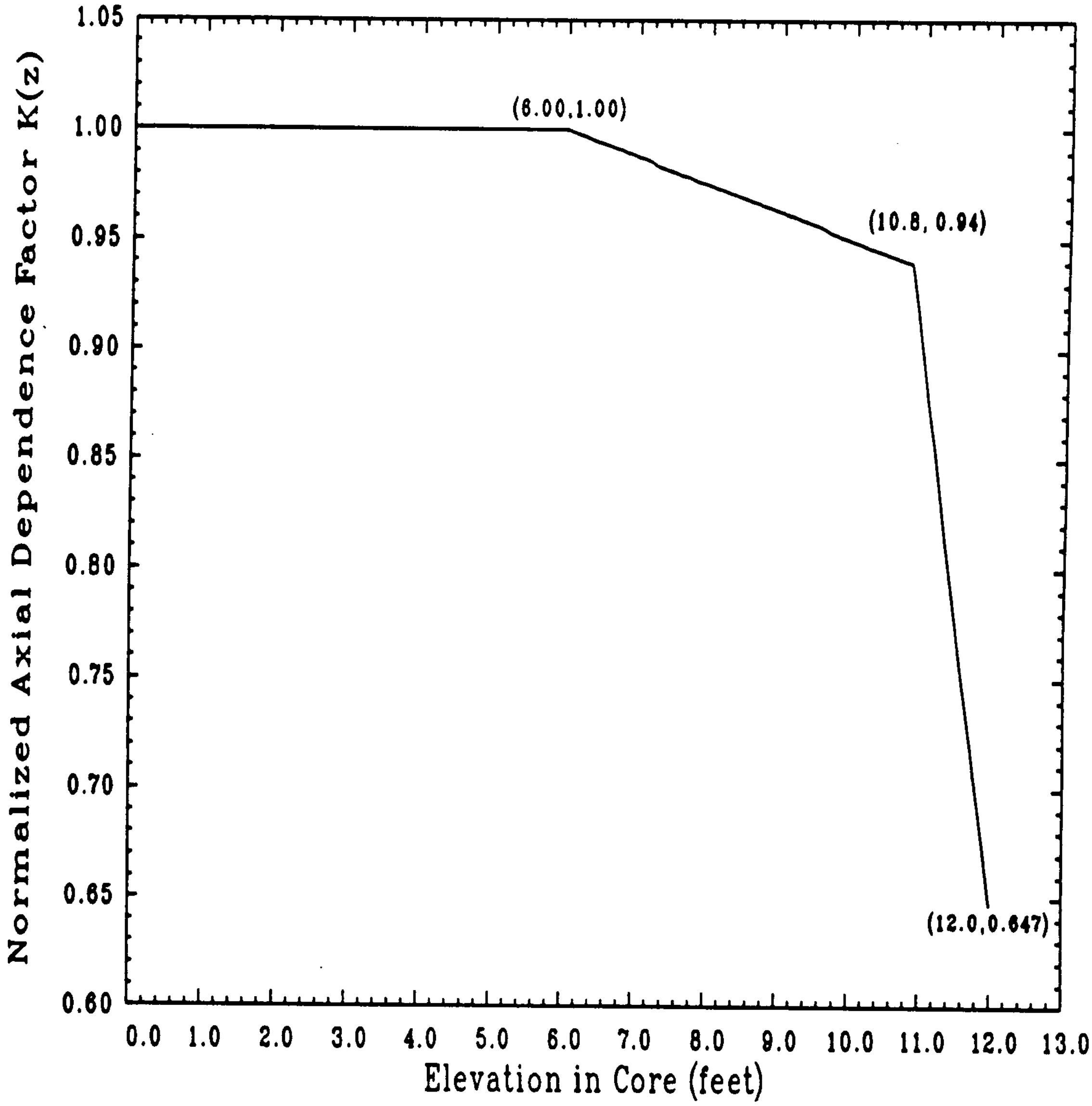

Figure 2.1 Normalized Axially-Dependent Peaking Factor for Robinson

Figure 2.2 Middle-of-Cycle (MOC) Axial Power Shape

Figure 2.3 End-of-Cycle (EOC) Axial Power Shape

3.0 ANALYSIS

The transfer to cold leg recirculation was analyzed to demonstrate that the criteria[3] stated in 10 CFR 50.46(b) will be met. These criteria are:

1. The calculated maximum fuel element cladding temperature (PCT) may not exceed 2,200°F.

2. The total amount of fuel element cladding which is calculated to react chemically with water or steam may not exceed 1% of the zircaloy within the heated length of the core.

3. The cladding temperature transient must be shown to terminate at a time when the core geometry is still amenable to cooling. The local fuel rod cladding oxidation may not exceed 17%.

4. The core temperature must be reduced and decay heat, resulting from the long-lived radioactivity remaining in the core, must be removed for an extended period of time.

Section 3.1 of this report provides a description of the transfer of the coolant supply for cold leg injection and containment sprays from the RWST to the containment sump. Section 3.2 describes the analytical models used by SPC-ND. Section 3.3 provides a brief description of Robinson and presents a summary of the system parameters considered in the analysis. Section 3.4 provides a summary of the results of the transfer analysis for both the MOC and EOC top-peaked axial power profiles.

3.1 Description of Safety Injection Transfer for LBLOCA

The Safety Injection (SI) coolant and containment sprays are supplied from the RWST during the early part of a LBLOCA. Eventually, the inventory in the RWST is depleted to the point that it is necessary to transfer the intake of the Low Head Safety Injection/Residual Heat Removal (LHSI/RHR) pumps from RWST to the containment sump. During this transfer, there is a potential for a second cladding heatup since the LHSI/RHR pumps are shut down to perform the transfer. The procedure controlling this transfer is Reference 4.

When the RWST level has been reduced to 27% of capacity during the injection phase of the LBLOCA, all but one of the HHSI pumps are turned off, as are all of the LHSI/RHR pumps. The earlier in the LBLOCA transient that this level is reached, the more decay heat is available and the lower the RCS inventories. Assuming early containment spray activation and maximum containment spray flow rate, the level of the RWST could reach 27% of capacity as early as 21 minutes after the initiation of the LBLOCA.

The remaining HHSI pump continues to inject RWST fluid into the primary system until the RWST level is reduced to 9% of capacity or 30.5 minutes, whichever is less. During the period when only a single HHSI pump is operating, the intake for the LHSI/RHR pump must be transferred from the RWST to the containment sump and the pump brought up to speed so that it comes on line without delay. By 51.5 minutes into the LBLOCA transient, one LHSI/RHR pump will be turned on and will remain on. This single LHSI/RHR pump draws water from the containment sump and injects into the cold leg of the primary system. At the same time, the remaining HHSI pump is turned off and remains off.

A single HHSI pump does not inject enough SI water into the primary system to match the break flow and, during the period when only one HHSI is operating, partial uncovery of the core occurs. This second core uncovery can produce a second fuel rod heatup. When the LHSI/RHR pump is brought on line 51.5 minutes into the LBLOCA transient, the core begins refilling and the second fuel rod heatup is terminated.

Partial core uncovery, followed by a core recovery, makes this event similar to a small break LOCA (SBLOCA) event. A typical SBLOCA transient involves a relatively small break in the reactor coolant system (RCS) which causes it to depressurize as the RCS fluid is lost through the break. As the primary pressure falls, the saturation pressure for the RCS fluid is reached and it begins to flash to steam. The quality of the break flow increases and once the break flow is essentially steam, the plant enters a fairly slow boiloff phase. The HHSI pumps inject water into the RCS cold legs when the RCS pressure drops below the shutoff head of the pumps. In spite of this SI flow from the HHSI, the liquid level in the reactor vessel eventually drops and at least partially uncovers the core for the limiting break sizes. As effective fuel

rod cooling is lost in the core, the fuel rods begin to heat up. The heatup is terminate only when SI (HHSI and/or accumulator) flow becomes greater than the break flow and is able to initiate core recovery. At this point, the heatup is mitigated and the fuel rods are quenched.

The system response during the transfer to the cold-leg recirculation phase following a LBLOCA is similar to that of the SBLOCA. For this reason, SPC-ND analyzed the transfer from the injection phase to the recirculation phase following a LBLOCA with the SPC-ND revised SBLOCA methodology.[5] A discussion of the analytical models SPC-ND uses for SBLOCA analysis models are presented below in Section 3.2.

3.2 Evaluation Model

The SPC-ND evaluation model for SBLOCA incorporates the appropriate conservatisms as mandated by Appendix K of Title 10, Part 50, of the Code of Federal Regulations (Appendix K) and consists of the following three computer codes:

1. **RODEX2**[6] - This code is used to determine the initial fuel stored energy and gap conditions for the initialization of the system blowdown and hot rod response calculations.

2. **ANF-RELAP** - SPC uses a version of RELAP5/MOD2 denoted as ANF-RELAP to model the primary system and secondary side of the steam generators. The governing conservation equations for mass, energy, and momentum transfer are used along with appropriate correlations consistent with Appendix K.

3. **TOODEE2** - This code is employed to simulate the behavior of the hot rod during a LOCA. The code uses core exit steam flow rate, saturation temperatures, and mixture level boundary conditions from the ANF-RELAP system calculation.

3.3 Model Description

Robinson is a PWR designed by Westinghouse which has an RCS with three hot leg pipes, three inverted U-tube steam generators, and three cold leg pipes with one Reactor Coolant Pump (RCP) in each cold leg. System response to the SI injection transfer transient was

modeled by the ANF-RELAP computer code. The governing conservation equations for mass, energy, and momentum transfer were used, along with the appropriate correlations consistent with the requirement of Appendix K, by ANF-RELAP to correctly model the system response.

The RCS of the plant was nodalized in the ANF-RELAP model into control volumes representing reasonably homogeneous regions, interconnected by flow paths or "junctions." The model included [ ] accumulators, one pressurizer, and [ ] steam generators with both primary and secondary sides. [ ] loops of the plant were simulated [ ] to provide an accurate representation of the plant. A steam generator tube plugging level of 6% was assumed.

The HHSI and LHSI/RHR pumps were modeled as fill junctions at the accumulator lines, with conservative flows given as a function of system back-pressure. The RCP performance curves were characteristic of pumps used in this plant design.

The core model of this ANF-RELAP model consisted of [ ] The heat generation rate used in the ANF-RELAP reactor core model was determined from reactor kinetics equations with actinide and decay heat curves constructed in accordance with the specific requirements of Appendix K.

The analysis was initialized for both MOC and EOC conditions. The initialization assumed that prior to the transfer to cold leg recirculation procedure only one HHSI pump and one LHSI/RHR pump were available, that the containment pressure was 25 psia, the reactor vessel inventory was approximately 100,000 lbm and the collapsed core height was 5.0 ft. The system was initialized, based on the assumed conditions at 21 minutes into the LBLOCA transient, at a steady condition with one HHSI and one LHSI/RHR pump injecting coolant into the cold leg from the RWST. Initializing the transfer calculations at 21 minutes after initiation of the LBLOCA will result in a conservatively severe transient, since the decay heat will be high and the RCS inventory low.

3.4 Results for Transfer Evaluations

The transfer from the injection phase to the recirculation phase results in a sequence of SI flow changes to the RCS. The operation of the LHSI/RHR pumps is terminated at the beginning of the transient (21 minutes after initiation of the LBLOCA) and the transfer of the LHSI/RHR pump intake from the RWST to the containment sump begins. At this time, SI flow to the RCS is provided by a single HHSI pump. The single HHSI pump flow continues for another 30.5 minutes at a flow rate of approximately 45 lbm/sec as shown in Figure 3.1. Operation of the HHSI pump flow is then terminated at 51.5 minutes into the LBLOCA (1,830 seconds in Figures 3.1 through 3.15) and the LHSI/RHR pump is brought on line at that time. Figure 3.1 shows this rapid increase in SI flow.

This transfer of the SI flow was analyzed for two different top-peaked axial power profiles, a MOC axial power profile and an EOC profile. Figures 3.2 through 3.8 present the system response results from ANF-RELAP using the MOC axial power profile and Figures 3.9 through 3.15 for the EOC profile.

[

] Core recovery occurs when the LHSI/RHR pump is brought on line at 1,830 seconds. The RCS pressure, shown in Figure 3.3, remains nearly constant near the initial value of 30 psia, which corresponds to a flooded core, with a slight reduction as the inventory in the RCS is reduced. With core recovery, the heat transferred to the coolant increases and the pressure recovers quickly. The collapsed liquid level, shown in Figure 3.4, shows a slow reduction in core inventory until the LHSI/RHR pump refloods the core. Figure 3.5, the reactor vessel inventory, shows this behavior a little more clearly. The decrease in coolant during operation with one HHSI and the rapid increase in coolant when the LHSI/RHR pump begins operation. The total break flow, shown in Figure 3.6, displays the same behavior as the RCS pressure. The break flow decreases during the period in which only one HHSI pump was operating and then dramatically increases when the core is reflooded and the RCS pressure returns to its initial value.

Figure 3.7 shows the void fraction at peak power node of the hot rod. The plot displays a significant amount of oscillation around mean values. The "dip" in the mean void fraction between 600 and 800 seconds is the result of water droplets, which had been accumulating in the plenum at the core outlet, separating from the steam in the plenum and dropping back into the top of the core. This separation can be seen in the void fraction at the core outlet shown in Figure 3.2. The void fraction at the core outlet rises in response to the water droplets falling back into the core; whereas, the void fraction at the hot node falls. The mean value of the void fraction at the hot node displays a rising trend from about 800 seconds until core recovery begins and exceeds 0.9 at about 1,050 seconds.

The TOODEE2 calculated temperature trace for the peak node in the hot rod, shown in Figure 3.8, shows a small response during the period from 1,000 seconds to 1,260 seconds. The temperature of the peak node rises rapidly to about 2,102°F before core recovery terminates the transient.

For the EOC profile, core uncovery begins at about 760 seconds and the void fraction at the core exit is higher than for the MOC case. Figure 3.9 shows this behavior. The plots of RCS pressure, collapsed liquid level, reactor vessel inventory, and break flow for the EOC profile, shown in Figures 3.10 through 3.13, are quite similar to those for the MOC profile. The void fraction at the peak node of the hot rod, shown in Figure 3.14, displays similar oscillations about the mean values. The "dip" in the mean void fraction between 600 and 800 seconds is the result of water droplets, which had been accumulating in the plenum at the core outlet, separating from the steam in the plenum and dropping back into the top of the core. This separation can be seen in the void fraction at the core outlet shown in Figure 3.9. The void fraction at the core outlet rises in response to the water droplets falling back into the core; whereas, the void fraction at the hot node falls. The mean value of the void fraction at the hot node displays a rising trend from about 800 seconds until core recovery begins and exceeds 0.9 at about 1,080 seconds.

The TOODEE2 calculated temperature trace for the peak node in the hot rod, shown in Figure 3.15, shows a small response during the period from 950 seconds to 1,210 seconds.

The temperature of the peak node rises rapidly to about 2,097°F before core recovery terminates the transient.

The TOODEE2 model, which calculates the hot rod heatup during the transient, was initialized with a fuel pellet and cladding temperature distribution at 21 minutes into the LBLOCA transient, equal to the saturation temperature of the core coolant. TOODEE2 uses the ANF-RELAP calculated transient hot assembly fluid conditions to determine the fuel rod PCT and metal-water reaction.

The highest second fuel clad heatup PCT for the extended transfer of SI injection, 2,102°F, was obtained with the MOC axial power profile (Figure 3.14). The PCT for the EOC axial power profile was calculated to be 2,097°F (Figure 3.15), which is slightly less than the MOC calculated PCT. The magnitude of the second heatup PCT for both the MOC and EOC axial power profile is less than the 10 CFR 50.46 (b) criterion of 2,200°F. The PCTs calculated for the two power profiles show that the metal-water reaction did not exceed 10 CFR 50.46(b) limits. The calculated PCT for the second fuel clad heatup transfer is fairly sensitive to the axial power profile. However, the use of conservative top-peaked MOC and EOC axial power profiles assures that the second fuel rod heatups in this report are bounding.

The results of the second heatup due to the extended transfer of SI flow for both the MOC and EOC axial power profiles are summarized in Table 3.1.

Table 3.1 Second Heatup Results

	MOC Peak X/L = .73	EOC Peak X/L = .81
Peaking Factors[a]		
Total Peaking Factor, F_Q^T	2.414	2.383
Nuclear Enthalpy Rise Factor, $F_{\Delta H}$	1.80	1.80
Axial Peaking Factor	1.341	1.324
Peak Clad Temperature		
Temperature, °F	2,102	2,097
Time, sec	1,831.6	1,836.4
Elevation, ft	9.0	10.5
Metal-Water Reaction		
Local Maximum, %	3.672	4.171
Elevation of Local Maximum, ft	9.0	10.5
Hot Pin Total, %	0.790	1.178
Core Maximum, %	< 1.0	< 1.0

(a) These peaking factors have been adjusted to reflect the K(z) curve shown in Figure 2.1.

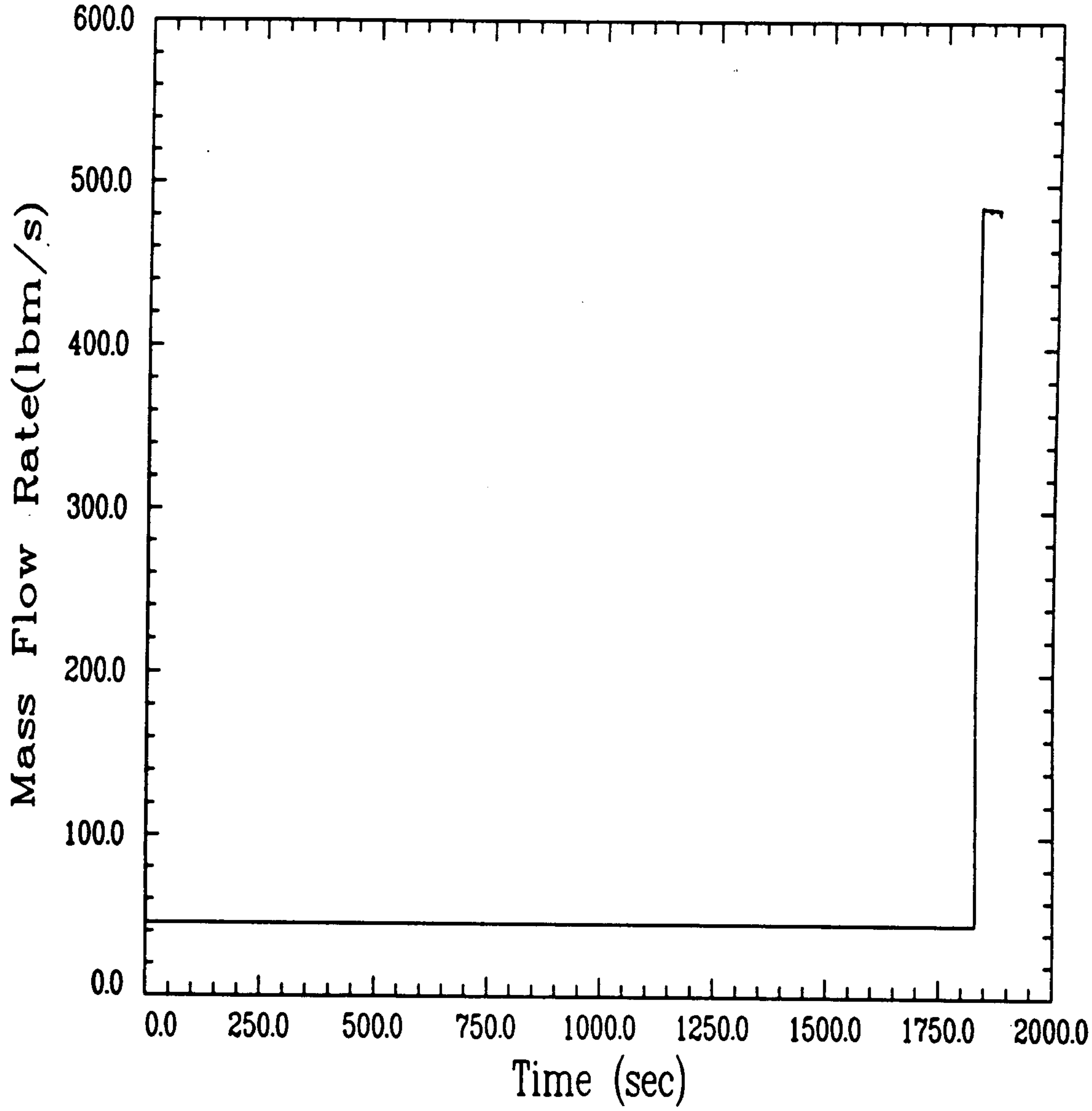

Figure 3.1 Flow to RCS during Transfer of SI following LBLOCA

Figure 3.2 Vapor Fraction at Core Outlet during Transfer of SI following LBLOCA (MOC)

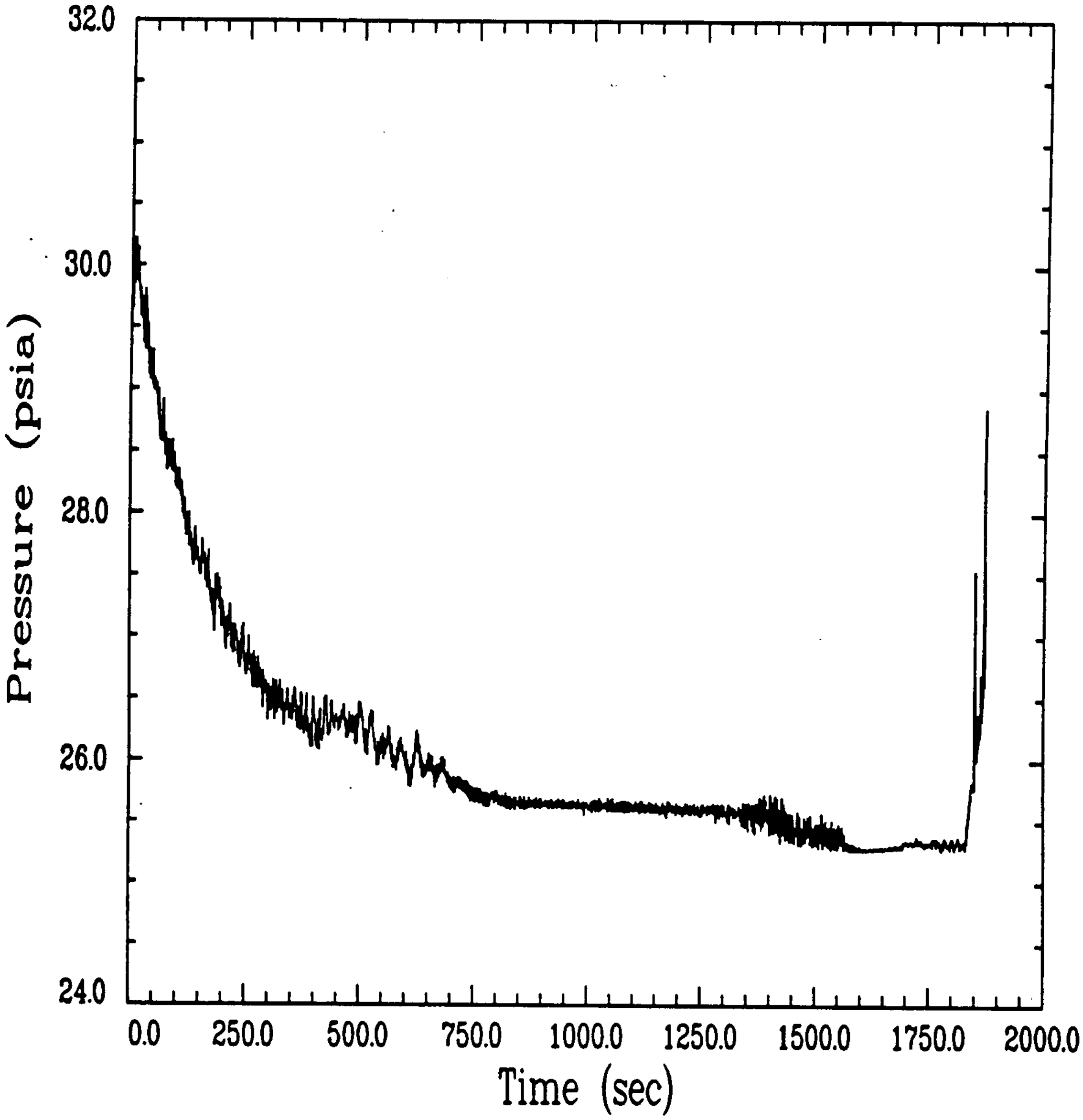

Figure 3.3 Primary System Pressure during Transfer of SI following LBLOCA (MOC)

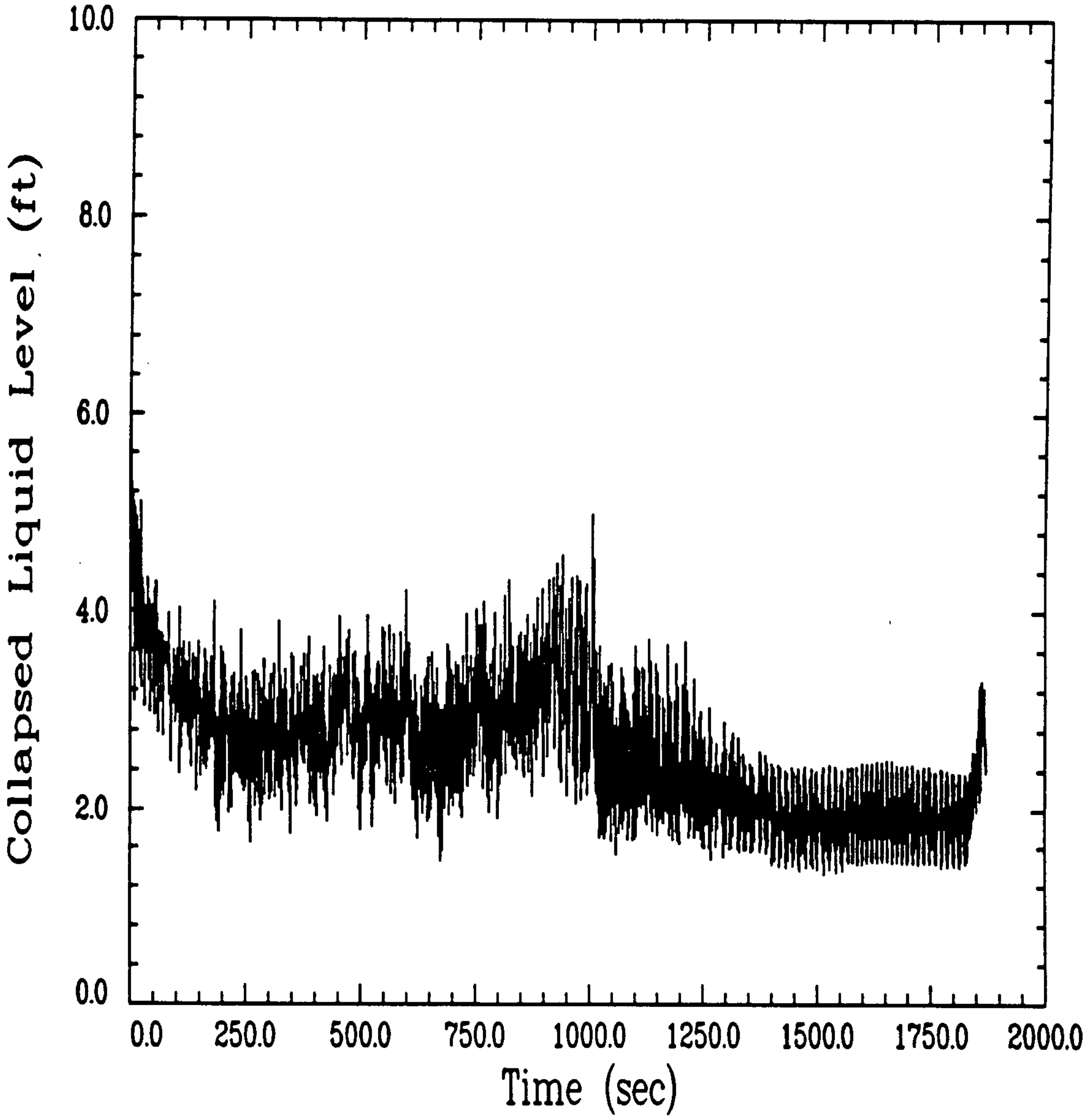

Figure 3.4 Collapsed Liquid Level during Transfer of SI following LBLOCA (MOC)

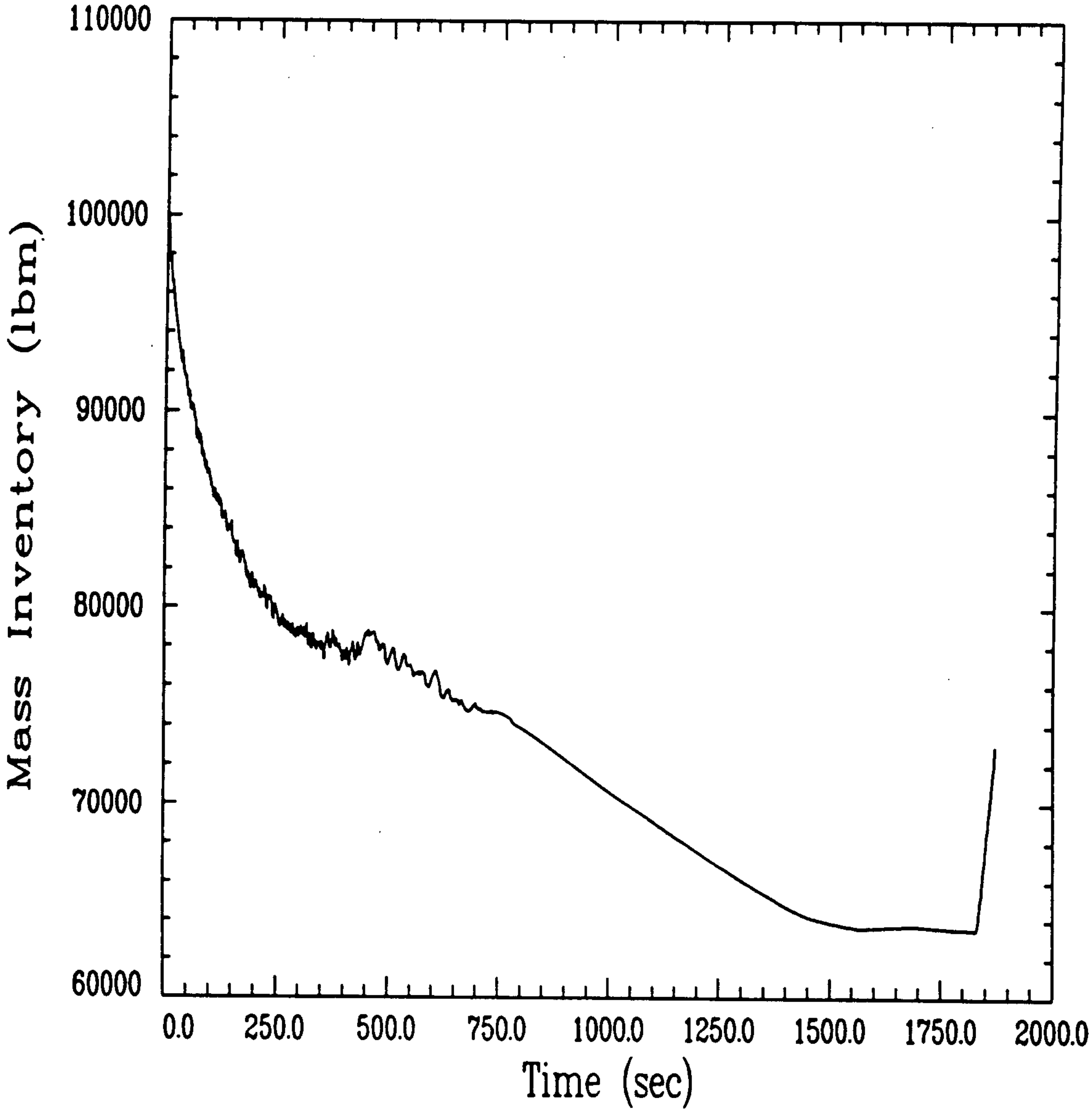

Figure 3.5 Total Reactor Vessel Inventory during Transfer of SI following LBLOCA (MOC)

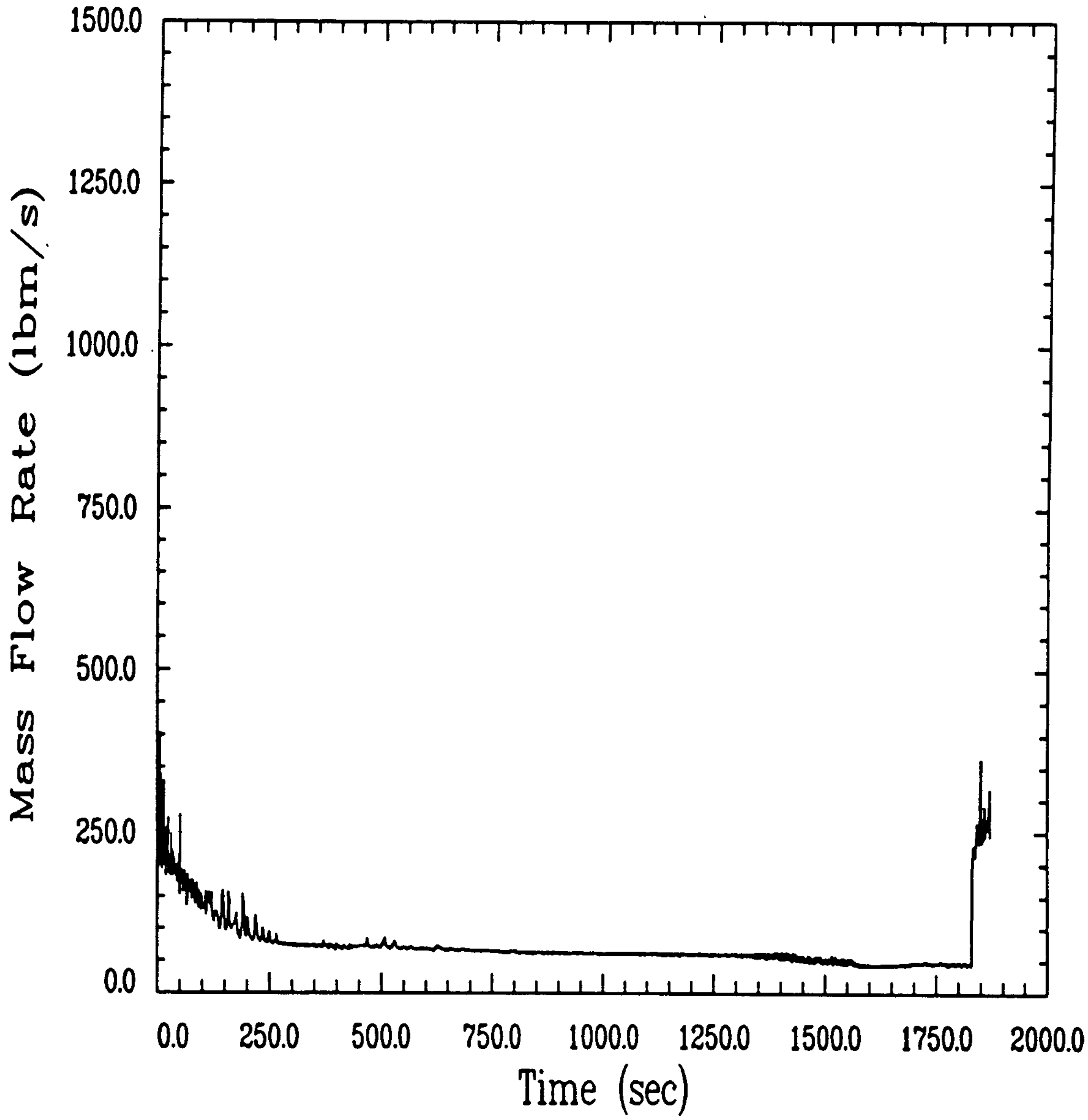

Figure 3.6 Total Break Flow during Transfer of SI following LBLOCA (MOC)

Figure 3.7 Vapor Fraction at Hot Rod Peak Power Node during Transfer of SI following LBLOCA (MOC)

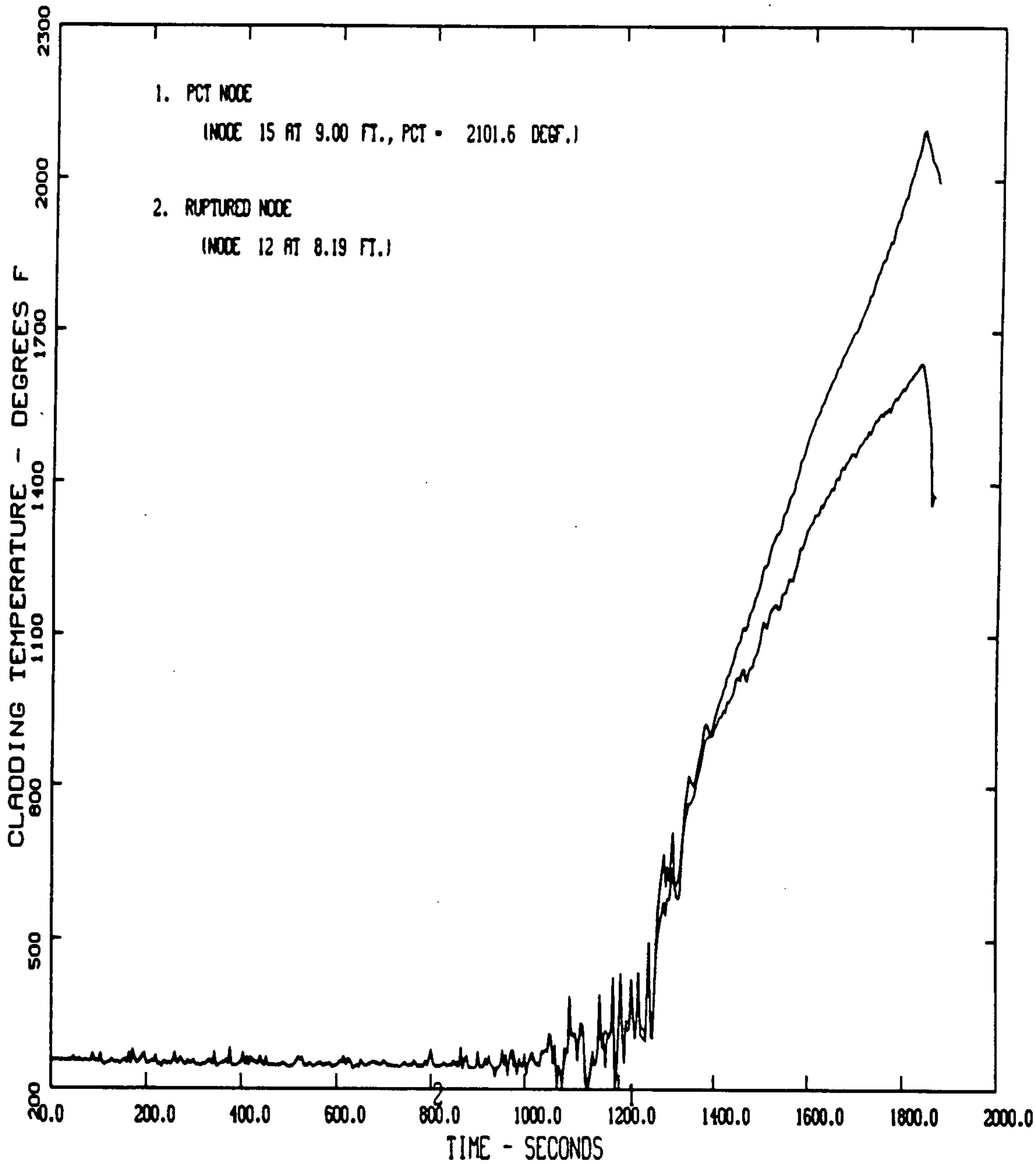

Figure 3.8 TOODEE2 Calculated Second Fuel Rod PCT during Transfer of SI following LBLOCA (MOC)

Figure 3.9 Vapor Fraction at Core Outlet during Transfer of SI following LBLOCA (EOC)

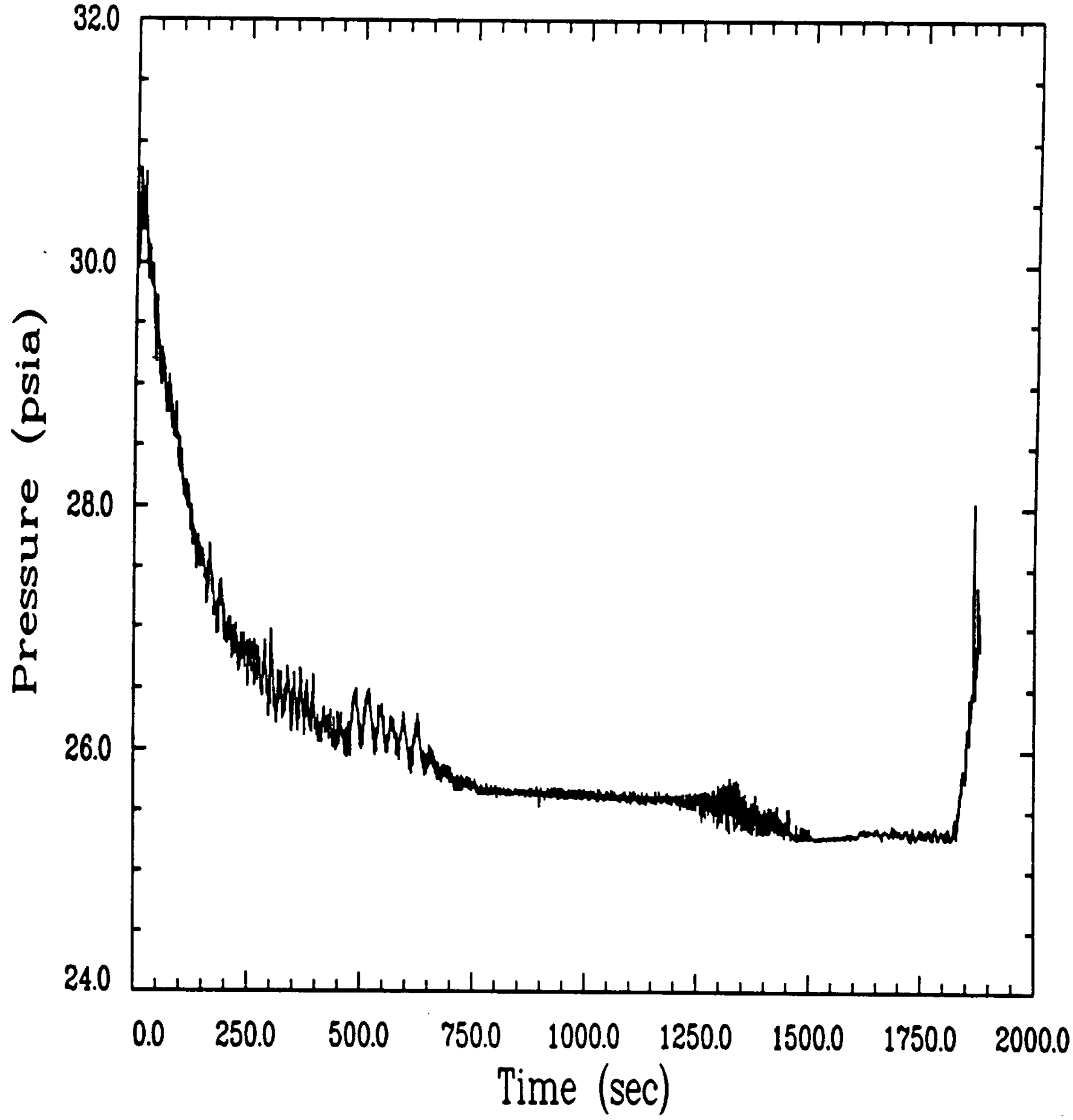

Figure 3.10 Primary System Pressure during Transfer of SI following LBLOCA (EOC)

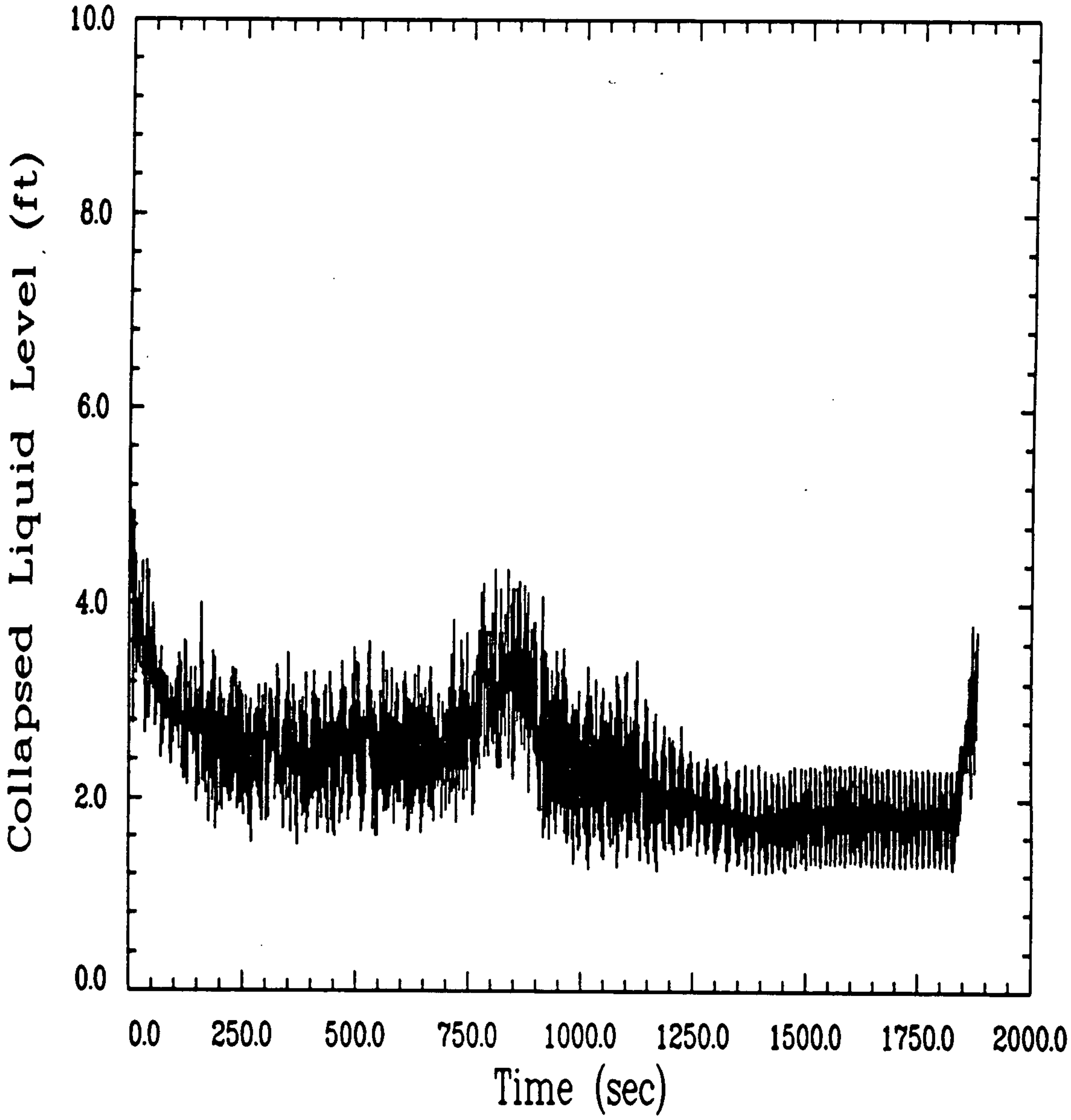

Figure 3.11 Collapsed Liquid Level during Transfer of SI following LBLOCA (EOC)

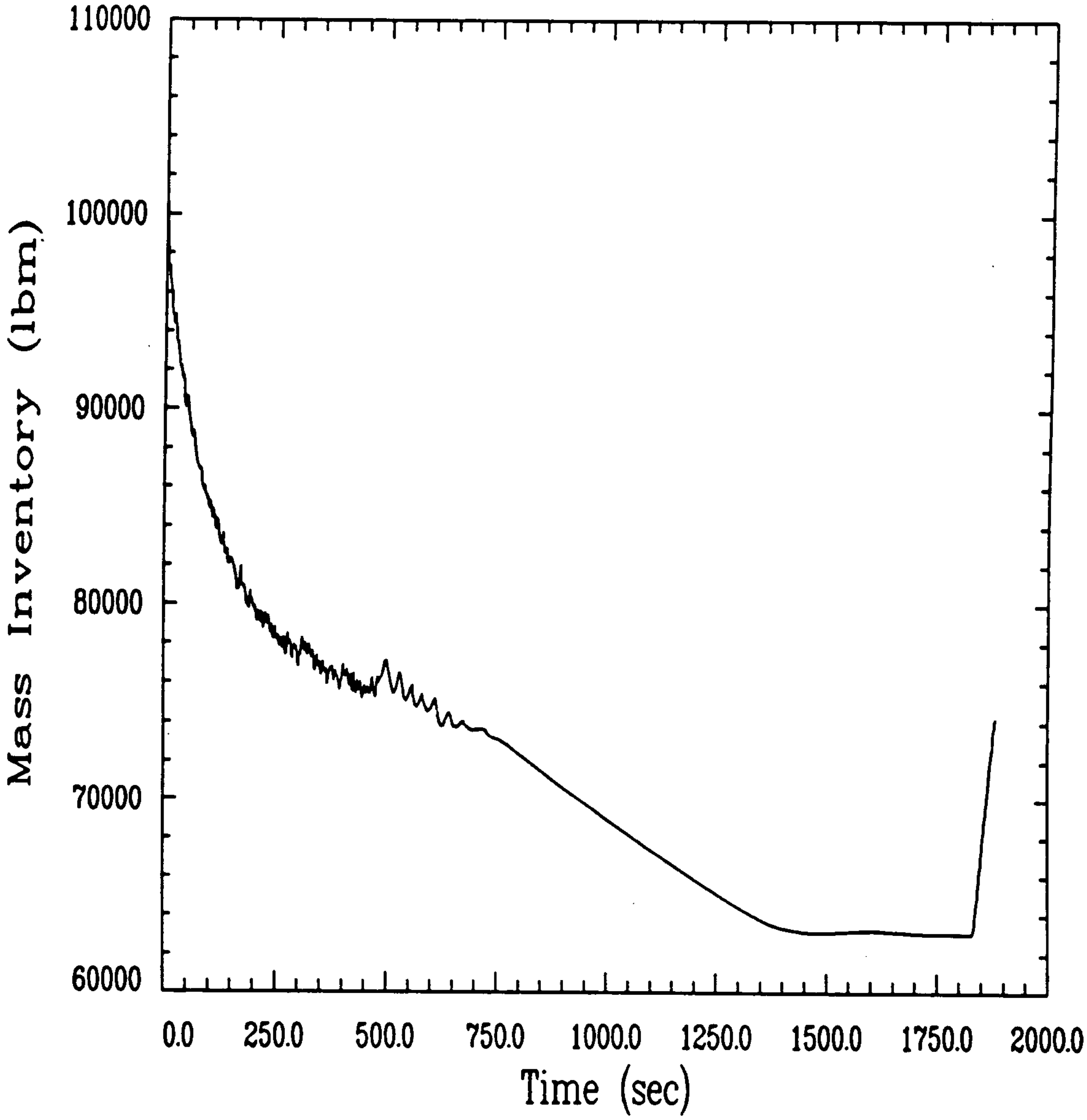

Figure 3.12 Total Reactor Vessel Inventory during Transfer of SI following LBLOCA (EOC)

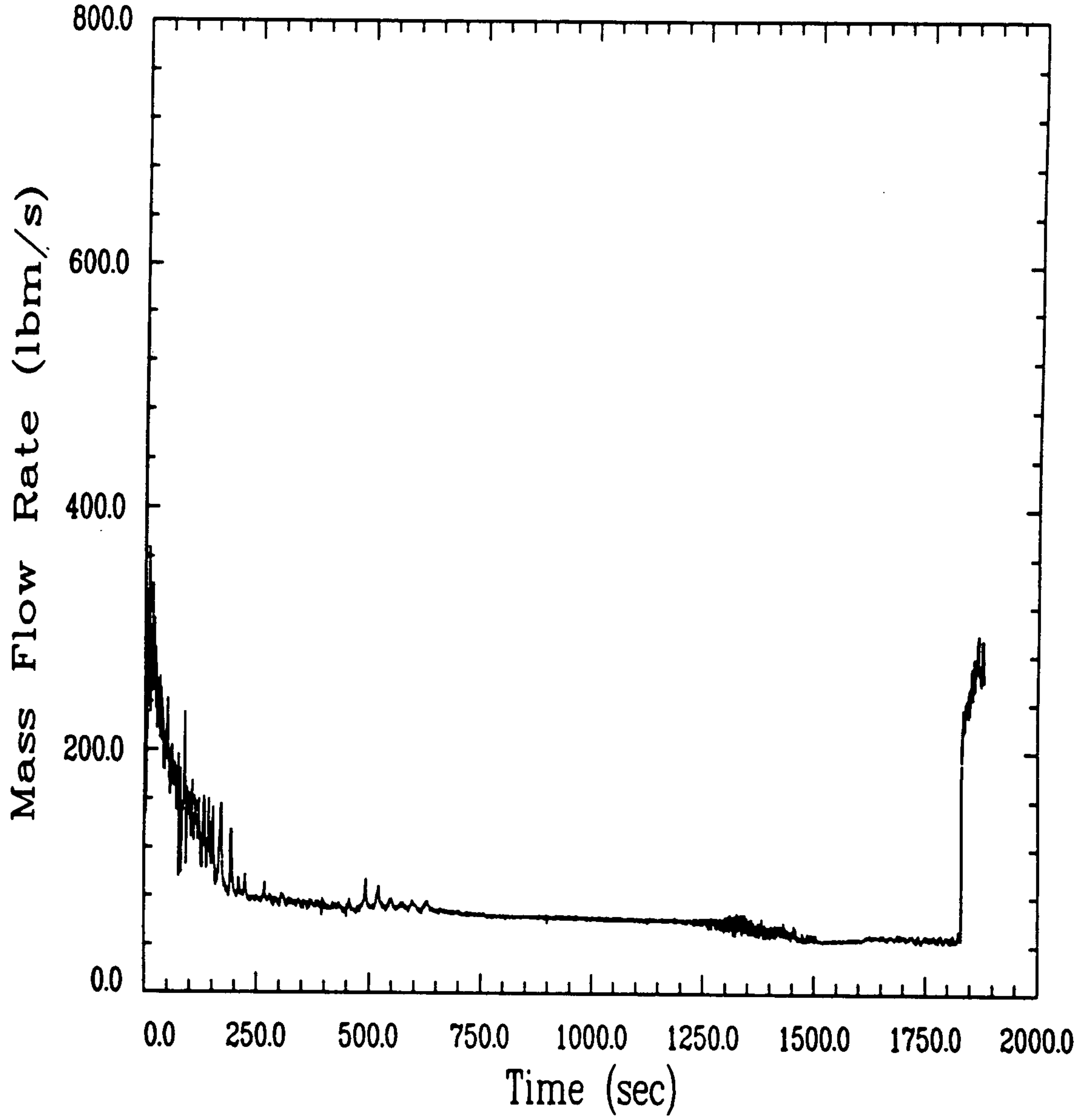

Figure 3.13 Total Break Flow during Transfer of SI following LBLOCA (EOC)

Figure 3.14 Vapor Fraction at Hot Rod Peak Power Node during Transfer of SI following LBLOCA (EOC)

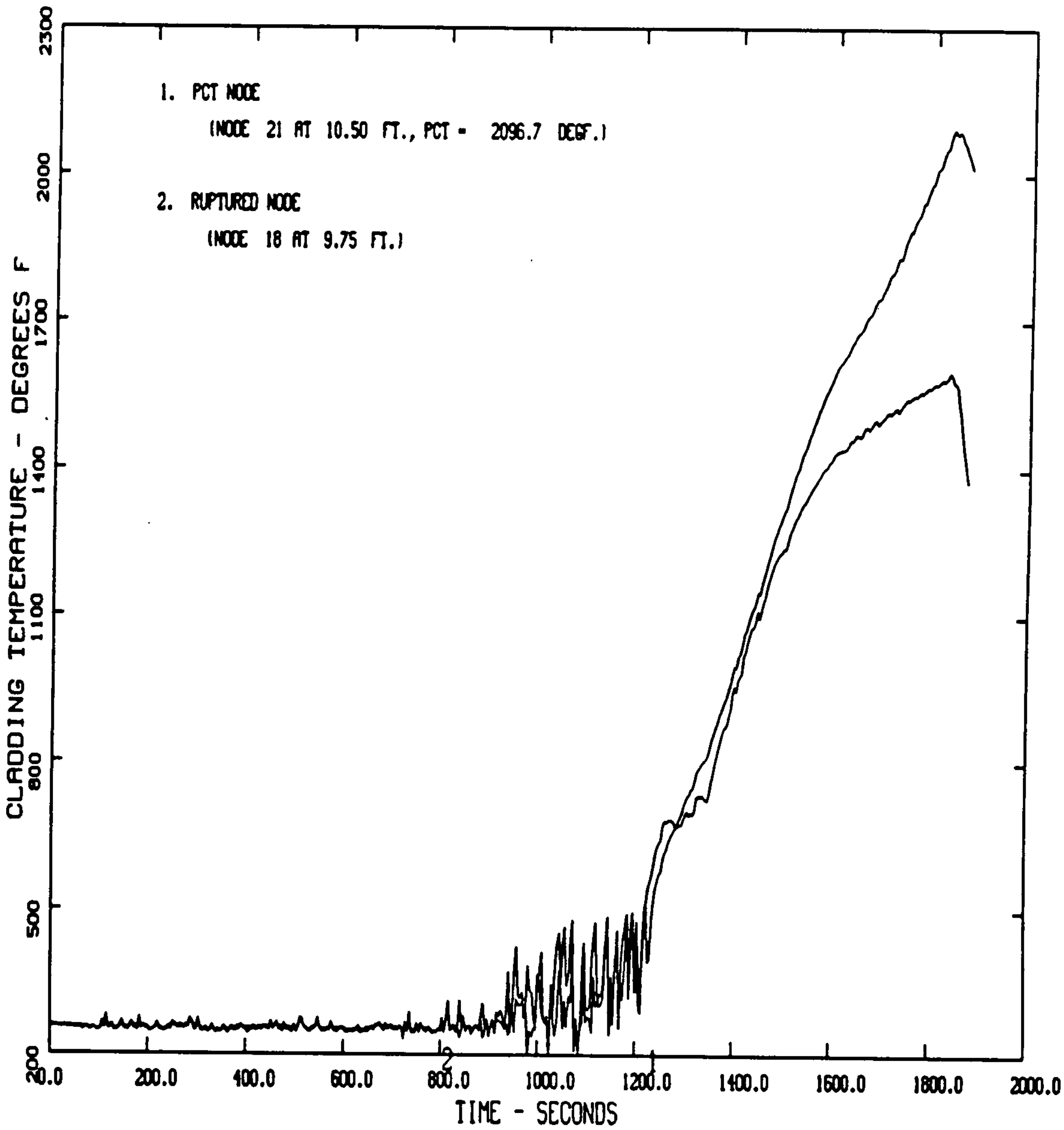

Figure 3.15 TOODEE2 Calculated Second Fuel Rod PCT during Transfer of SI following LBLOCA (EOC)

4.0 CONCLUSIONS

The evaluation of the extended transfer of the SI to cold leg recirculation using the appropriate plant procedure for Robinson meets the Acceptance Criteria as specified in 10 CFR 50.46 (b), with an $F_{\Delta H}$ of 1.80, an F_Q^T of 2.5, and with the axially-dependent power peaking limit [K(z) curve] shown in Figure 2.1.

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6. "RODEX2: Fuel Rod Thermal Mechanical Response Evaluation Model," XN-NF-81-58(P)(A), Revision 1, and Supplements 1-4, Exxon Nuclear Company, February 1983.