PDR

DRAFT

ANL/LWR/NRC 83-6
July 1983

Decay Heat Removal During a Total Loss of Feedwater Event for a C-E System 80 Plant

H. Komoriya
P. B. Abramson

Light Water Reactor Systems Analysis Section
Reactor Analysis & Safety Division
ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

Prepared for:
Division of Systems Integration
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

NOTICE: This informal document contains preliminary information prepared primarily for interim use by the Office of Nuclear Reactor Regulation, Nuclear Regulatory Commission (NRC). Since it does not constitute a final report, it should be cited as a reference only in special circumstances, such as requirements for regulatory needs.

ARGONNE NATIONAL LABORATORY

1.0 INTRODUCTION

This report presents the results of a series of RELAP5/MOD1.5 calculations to examine the ability of a C-E System 80 plant to avoid core uncovery during a total loss of feedwater (TLOFW) event. The study included parametrics with and without concurrent Loss of Offsite Power (LOOP), considered the use of the C-E Auxiliary Pressurizer Spray (APS) for rapid depressurization, and examined the potential value of installation of a Pilot Operated Relief Valve (PORV) as a direct manual method of depressurization and feed and bleed decay heat removal. There are two C-E plants in operation without PORVs: San Onofre-2 and ANO-2, and C-E System 80 plants under construction are Palo Verde-1, -2, and -3 and Waterford-3.

The three major areas of transient analysis addressed in this study are:

1. Study the impact of TLOFW (with and without LOOP) with and without operator recovery actions as stated in the C-E Recovery Guidelines

2. Perform feed and bleed sensitivity studies with respect to PORV sizes and PORV opening time.

3. Identify the latest time when AFW can be actuated to avoid core uncovery.

Detailed RELAP5/MOD1.5 modeling descriptions and initial plant conditions are presented in Chapter 2 of this report. Chapter 3 contains the transient analysis assumptions and scenarios. The results and discussions are contained in Chapter 4, and the summary and conclusions are presented in Chapter 5. Also included in Chapter 5 is a brief discussion of modeling uncertainties and their impact upon the conclusions.

DRAFT

2.0 PLANT DESCRIPTIONS AND INITIAL CONDITIONS

ANL initial plant conditions for the TLOFW transient analysis are compared with C-E data in Table 2.1. These represent 100% full power steady state conditions for a C-E system 80 plant obtained with RELAP5/MOD1.5 cycle 29 with updates. (All calculations were performed on the INEL computers.)

During preliminary calculations, the results with RELAP5/MOD1.5 Cy=29 exhibited significant mass error accumulations in the regions where saturation conditions existed. Code updates provided by the RELAP5 code developers were incorporated into Cycle 29 which resulted in a dramatic reduction in mass errors. Calculations reported in this study were performed with Cycle 29 with these updates.

The plant nodal diagram is shown in Fig. 2.1. The system-80 plant is designed with two cold legs per loop and thus also contains four reactor coolant pumps. In the analysis the cold legs were combined in pairs and each cold leg and RCP delivers a combined flow of two plant size cold legs.

Pressurizer safety valves were similary combined such that one valve had an equivalent flow area to yield a combined steam flow of two valves at the rated pressure. Similarly, when two PORVs were assumed in the analysis, they were simulated with one valve sized to yield a combined rated steam flow at the rated pressure.

The safety engineering features modeled in the analysis are:

- Steam Generator Safety Valves

Actuation:	Steam line pressure > 1282 psia
Capacity:	20 valves
	4 valves 1270 psia
	4 valves 1305 psia
	12 valves 1333 psia
	Total capacity 19.0 x 10^6 lbm/hr

DRAFT

- Pressurizer Safety Valves

  Actuation: Pressurizer pressure > 2525 psia

  Capacity: 2 valves

  255.56 lbs/sec

- Charging Pump

  Actuation: started by the operated after TLOFW

  Capacity: 6.90 lbs/sec (1 pump), 120°F

- Auxiliary Spray System

  Actuation: Hot leg subcooling > 25°F; open.

  Hot leg subcooling < 20°F; close.

  Capacity: 6.90 lbs/sec (1 charging pump capacity), 120°F

- PORVs

  Actuation: Open by the operator

  Capacity: 2 valves

  119.71bs/sec (Calvert Cliff type)

  254.0 lbs/sec

- Accumulator Injection

  Actuation: Cold leg pressure < 624.7 psia

  Capacity: 1536.7 ft^3 of liquid volume (per tank)

- Auxiliary Feedwater Pump

  Actuation: Started by the operator

  Capacity: 121.27 lbs/sec, 100°F

DRAFT

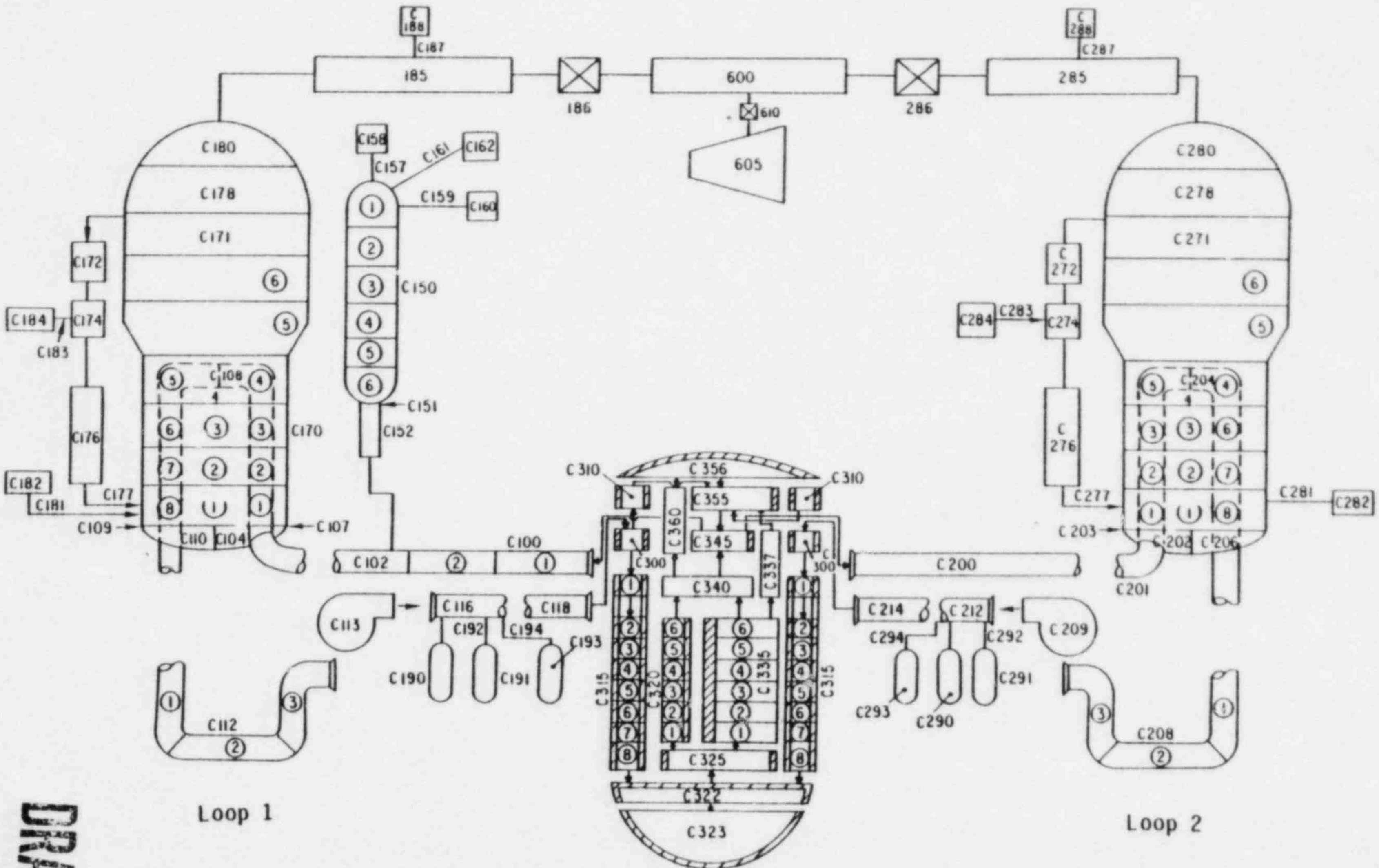


Fig. 2.1. RELAP5/MOD1.5 Nodal Diagram of C-E System 80 Plant.

DRAFT

Table 1. CESSAR NSSS Component Thermal and Hydraulic Parameters

Component	Plant Nominal Conditions	Steady State Initial Conditions
Reactor Vessel		
Rated core thermal power, MWt	3,800	3,800
Operating pressure, $lb/in.^2a$	2,250	2,250
Coolant outlet temperature, °F	621.2	621.6
Coolant inlet temperature, °F	564.5	566.0
Coolant outlet state	Subcooled	Subcooled
Total coolant flow, 10^6 lb/hr	164	164
Core average coolant enthalpy		
Inlet, Btu/lb	565	565
Outlet, Btu/lb	645	645
Average coolant density		
Inlet, lb/ft^3	45.9	45.8
Outlet, lb/ft^3	41.2	41.1
Upper head recirc. path flowrate, lb/s	319.4	320
Steam Generators		
Number of units	2	2
Primary Side (tube side)		
Operating pressure, psia	2,250	2,215
Inlet temperature, °F	621.2	621.9
Outlet temperature, °F	564.5	565.7
Secondary (shell side)		
Steam pressure/temperature, psia/°F	1070/552.86	1070/552.86
Steam flow per gen., lb/hr	8.59×10^6	8.59×10^6
Exit steam quality, %	99.75	99.75
Feedwater temperature, °F	450	450 (at 1070 psia)
Recirc. Ratio	3.25	3.27

DRAFT

3.0 TRANSIENT ASSUMPTIONS

The transient was initiated following 100 seconds of steady state calculation in the analysis. The figures presented in the next section also include these 100 seconds, however, the time discussed in the text of this report refers to the transient time rather than the computer run time.

Two sets of transient conditions are introduced in the calculations:

1. Total Loss of Feedwater (TLOFW) with concurrent Loss of Offsite Power (LOOP) at t = 0.0 s.

2. TLOFW without LOOP at t = 0.0 s.

Under each set of transients, the following scenarios are studied:

1. a) TLOFW with operator recovery action based on the C-E Recovery Guidelines.
   b) without

2. TLOFW with initiation of feed and bleed.

3. TLOFW with actuation of auxiliary feedwater flow.

The general transient assumptions are:

- One charging pump (6.09 lbs/s) was started at 10 minutes after TLOFW.

- APS (6.09 lbs/s) initiation by the operator based on the Recovery Guidelines.

- Only one HPSI pump was available.

DRAFT

- HPSI actuation on SIS (1600 psia) when no operator recovery action is assumed, otherwise by the operator at 10 minutes after TLOFW.

- Two PORVs were modeled in the feed and bleed sensitivity study with PORV size and the PORV opening times as variables. Two PORV sizes were simulated:

  Nominal size: 119.7 lbs/s (113.4 lbm/hr/MWt)

  Giant size: 268.1 lbs/s (254.6 lbm/hr/MWt) of steam at 2400 psia.

- AFW initiation by the operator

Trip setpoints and the associated delay times are summarized in Table 3.1. There are four operator actions simulated in the RELAP5 calculations

Table 3.1 Reactor Protection System Trips Used in the Analyses

Trip	Setpoint	Delay time, s
High pressurizer pressure, psia	2475	0.55
Low pressurizer pressure, psia	1600	---
Pressurizer safety valves, psia	2525	---
Steam generator safety relief valves, psia	1282 to open 1218 to close	--- ---
RCP trip	on signal	0.55
Turbine trip	on signal	0.55

based on the C-E Loss of Feedwater Recovery Guidelines; CEN-152 Rev. 01 and are the following:

1. Auxiliary Pressurizer Spray
   - on if the hot leg subcooling > 25°F
   - off if the hot leg subcooling < 20°F, or the pressurizer level > 90%

DRAFT

2. HPSI

- on if the pressurizer level < 100 inches, or the hot leg subcooling < 20°F
- off if the pressurizer level > 100 inches and the subcooling > 20°F

During the time the operator takes control of the HPSI system, the injection is actuated only based on the above criteria, and not by the automatic actuation on a low primary pressure setpoint at 1600 psia.

3. PORVs

- opened by the operator and left open throughout the transient.

4. Auxiliary Feedwater

- actuated by the operator and left on throughout the transient.

Cases analyzed are summarized in Table 3.2. For the TLOFW with LOOP transient, the reactor trip, turbine trip, and RCP trip occur at 0.0 second due to LOOP, and the feedwater is lost at the same time. Whereas, for the TLOFW without LOOP transient, the loss of feedwater occurs at t= 0.0 s and a short time later, the reactor trips on either high RC system pressure or low steam generator level. At that time the turbine is isolated but the coolant pumps are still operated until they are tripped by the operator as soon as the TLOFW is detected to minimize heat input into the RCS. In the analysis RCPs were tripped at 10 minutes into the transient.

In the feed and bleed sensitivity study, the only operator action simulated was opening of the PORVs and leaving them open for the remainder of the transient. Sensitivity to PORV sizes and the initiation time was examined. Attempts were made in both transients to estimate the latest time at which the operator could open PORVs without resulting in core uncovery. Similary the sensitivity to the AFW flow was studied by determining the latest time for the actuation of flow.

AFT

DRAFT

Table 3.2. Summary of TLOFW Transient Cases

TLOFW WITH LOOP Transient Description	TLOFW WITHOUT LOOP Transient Description
Case 1 -- Base Case No operator actions HPSI on at 1600 psia No APS	Case 2 -- Base case No operator actions HPSI on at 1600 psia No APS RCPs tripped at t=10 min
Case 3 Operator Action at t=10 min APS, HPSI	Case 4 Operator actions at t=10 min APS, HPSI RCP tripped at t=10 min
Case 3ai -- Small PORVs No APS HPSI on low RCS pressure on at t=10 min PORV opened at t=20 min	Case 4ai -- Small PORVs No operator actions RCP tripped at t=10 min PORVs opened at t=10 min
Case 3bi -- Giant PORVs No APS HPSI on low RCS pressure on at t=10 min PORV opened at t=20 min	Case 4bi -- Giant PORVs No operator action RCP tripped at t=10 min PORVs opened at t=20 min
Case 3aii -- Small PORVs Find the latest PORV opening time	Case 4aii -- Small PORVs 1) PORV opened at t=10 min Find the latest PORV opening time
Case 3bii -- Giant PORVs	Case 4bii -- Giant PORVs
Case 1i -- AFW Find the latest AFW initiation time	Case 2i -- AFW Find the latest AFW initiation time

DRAFT

4.0 CALCULATIONAL RESULTS AND ANALYSIS

In this section we present the detailed results and discussions on four cases related to the ability of the APS to depressurize the system (cases 1, 2, 3, and 4) and eight cases related to the feed and bleed mode of depressurizing the system (cases 3ai, 3bi, 4ai, 4bi, 3aii, 3bii, 4aii, and 4bii). Also discussed in this section are two cases investigating the latest effective time for restoration of auxiliary feedwater (AFW) flow (cases 1i and 2i). These cases cover three areas of the transient:

1) Total loss of feedwater (TLOFW) flow with and without operator recovery actions.

2) TLOFW with initiation of feed and bleed.

3) Restoration of AFW.

Analysis is focused upon determination of the effectiveness of CE's operator recovery guidelines and analysis of the relative capabilities of auxiliary pressurizer spray (APS), the Pilot Operated Relief Valve (PORV) and AFW as methods of rapid system depressurization.

Results are presented in the following order; first, cases on TLOFW with concurrent Loss of Offsite Power (LOOP) are discussed, followed by those for TLOFW without LOOP. In the next section, cases where the PORVs are utilized are discussed, and finally we examine the sensitivities to PORV opening time and to AFW initiation time. Results are summarized at the end of this section.

DRAFT

4.1 Total Loss of Feedwater Flow Concurrent with Loss of Offsite Power

4.1.1 Case 1

Normal feedwater flow is assumed to be lost as an initiator of the transient, and at the same time, the offsite power is also assumed lost ("A" in Fig. 4.1). A signal is generated to actuate the reactor trip, turbine trip and the reactor coolant pump (RCP) trip, which initiates RCP coast-down. Throughout this first transient, we assume that no operator recovery actions are taken to mitigate severe consequences; eventual core uncovery is indicated by the presence of both of the following conditions: 1) complete voiding of the upper node in the core; 2) high cladding (and also coolant) temperatures.

Figures 4.1 and 4.2 show that the RCS pressure increases rapidly due to the secondary side temperature increase and concomitant pressure buildup due to the loss of cold feedwater into the steam generators, aggravated by the turbine trip. This caused degraded primary-to-secondary heat transfer. The steam generator relief valves opened immediately following the onset of the transient and remained open as the steam generators boiled away their inventory. Following the delay time associated with the reactor trip, the RCS pressure dropped instantly to 2130 psia then rose immediately to 2220 psia due to power-to-flow mismatch. The RCS pressure gradually dropped to 2150 psia and remained at this level until the steam generators dried out at 2400 seconds into the transient (Fig. 4.3). At this time, the primary-to-secondary heat transfer was completely lost and the primary pressure rose to the pressurizer safety setpoint (2525 psia) and permitted the RCS inventory to be discharged through the pressurizer safety valves. Small fluctuations in the primary pressure between points B and C on the curve in Fig. 4.4 corresponded directly to the times when the liquid level in the steam generator crossed the computational node boundary, hence to the change of heat transfer regimes (Fig. 4.4). With the loss of energy removal capability, the RCS temperature rose and the coolant expanded, increasing pressurizer level as shown in Fig. 4.5. We note that around 3100 seconds after the transient initiation the pressurizer became solid (in Fig. 4.5). The pressurizer safety valves opened around 2630 seconds into the transient and, when the pressurizer

DRAFT

went solid, the discharge from the pressurizer safety valves became single phase liquid (Fig. 4.6). Since the primary pressure was greater than the maximum HPSI pump head (~ 1790 psia), without operator actions to depressurize to enable ECCS delivery the primary temperature rose until it reached the saturation temperature corresponding to the pressurizer safety setpoint (Fig. 4.7). From that time on, the primary temperature stayed constant while void was generated in the primary system (Fig. 4.8). Core uncovery began at 5800 seconds into the transient (Fig. 4.9), when the RCS inventory became so low that the void fractions in the top three nodes of the core reached 1.0. At that time, the collapsed water level in the core began to decrease rapidly (Fig. 4.10) and the cladding and core outlet flow temperatures began to rise (Fig. 4.11 and 4.7).

DRAFT

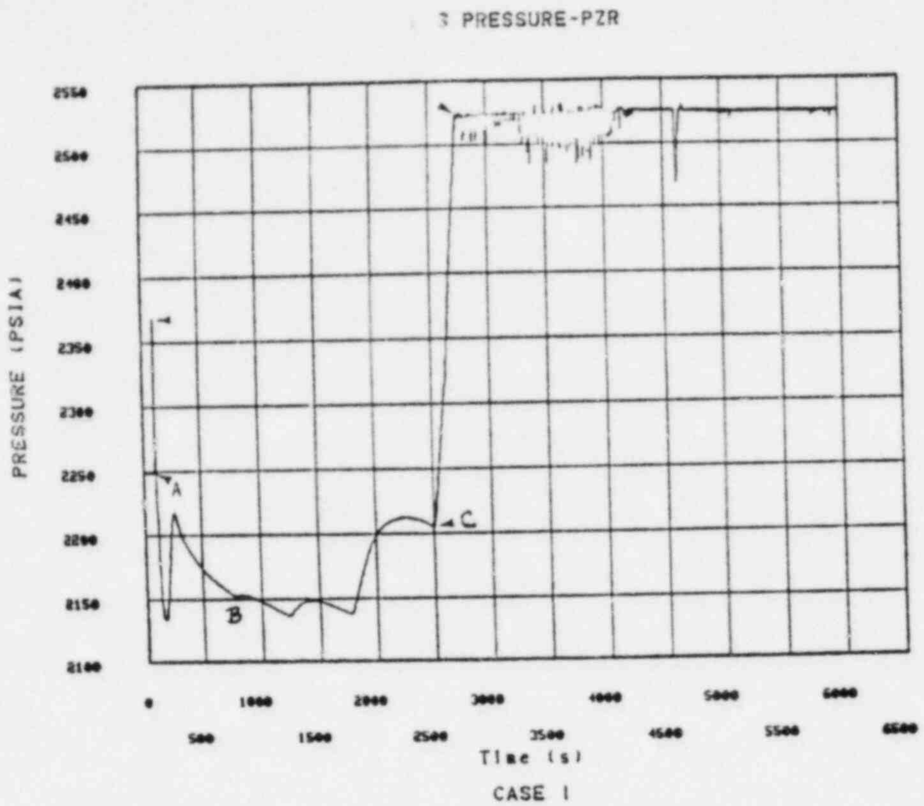


Fig. 4.1

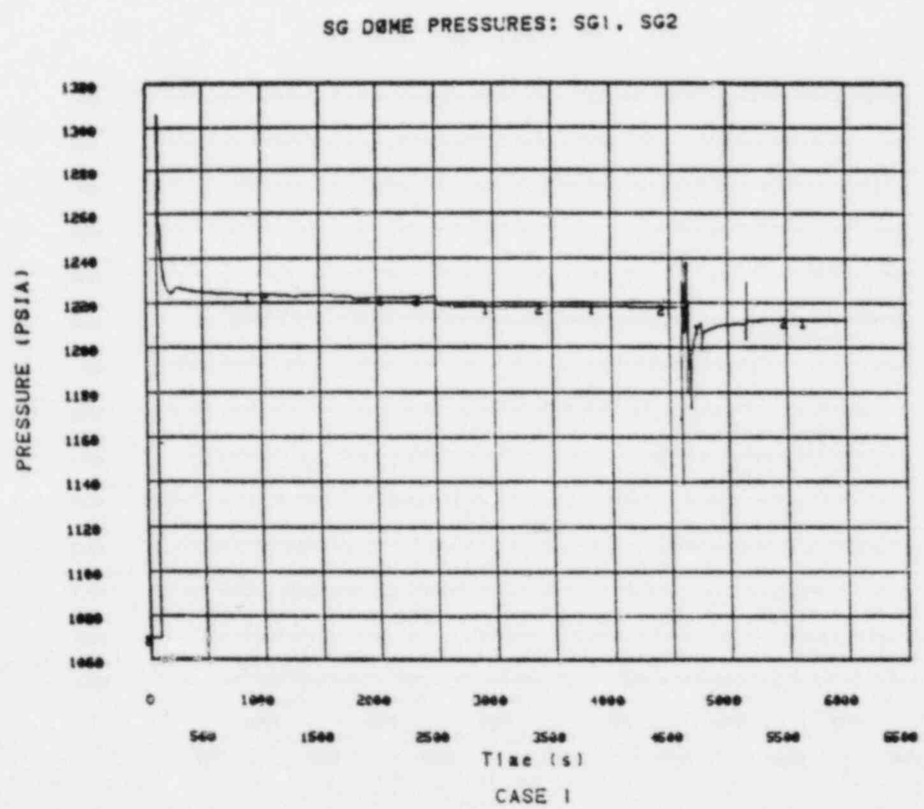


Fig. 4.2

AFT

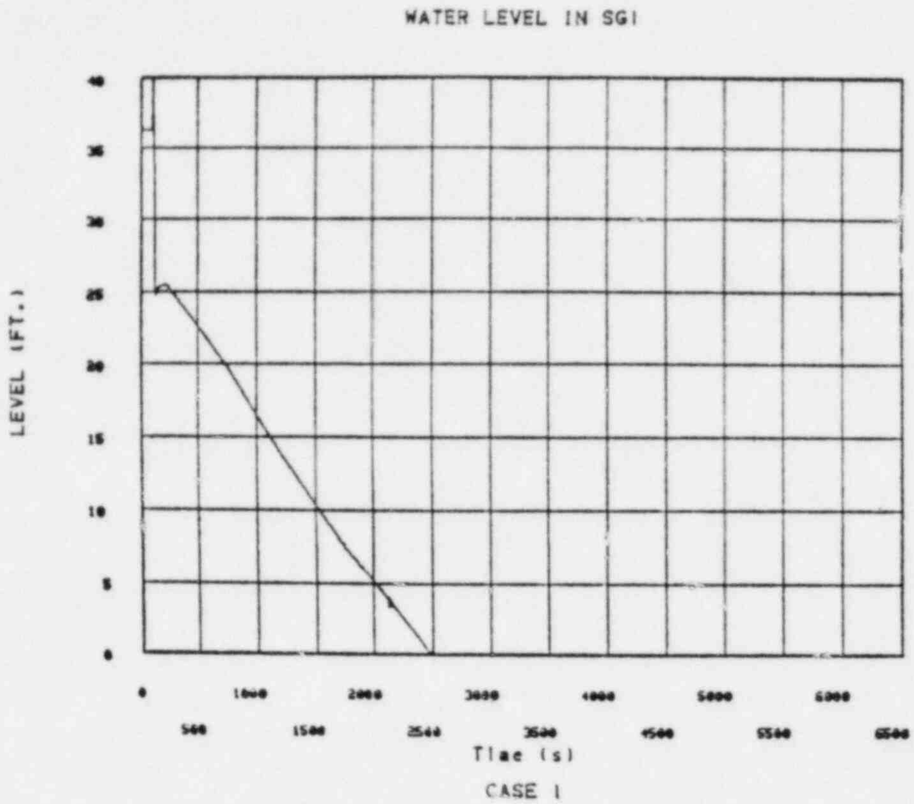


Fig. 4.3

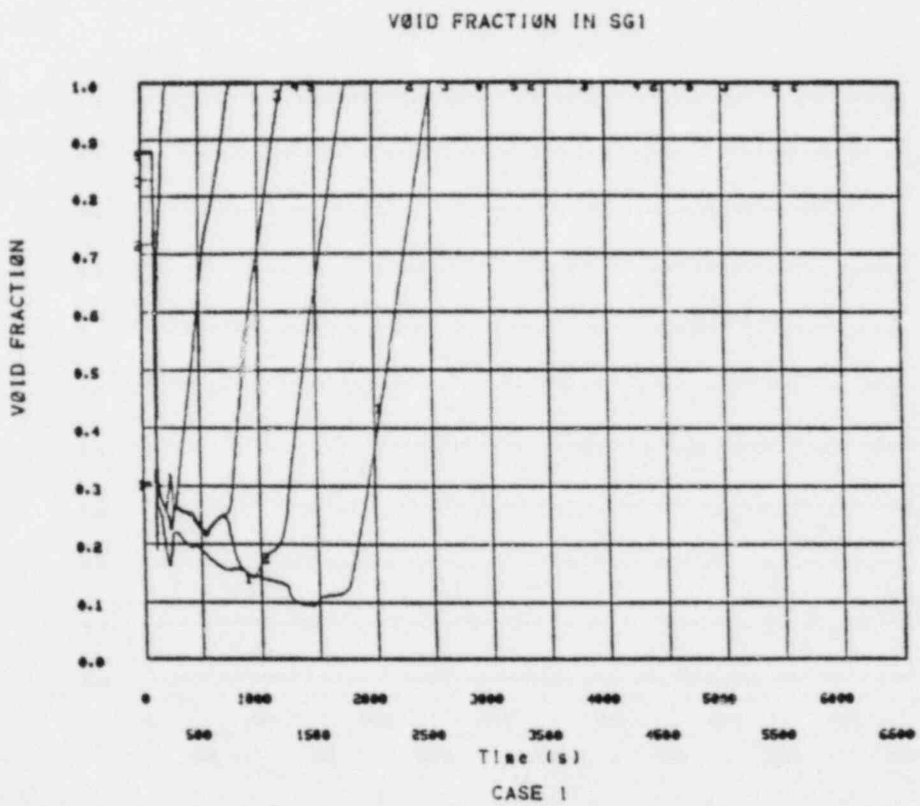
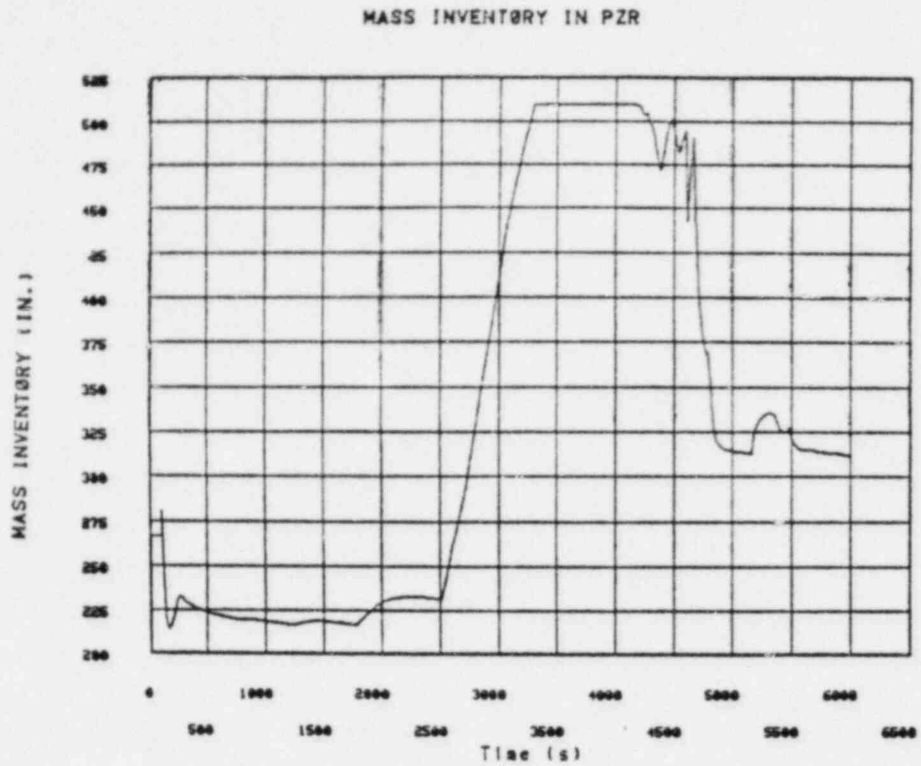


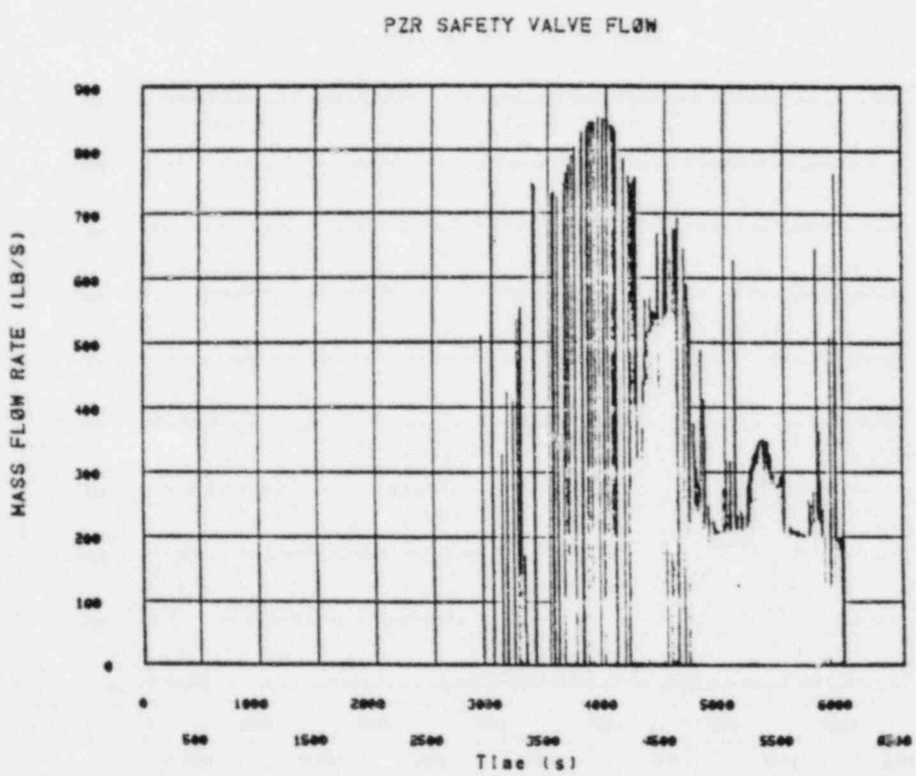
Fig. 4.4

DRAFT



CASE I

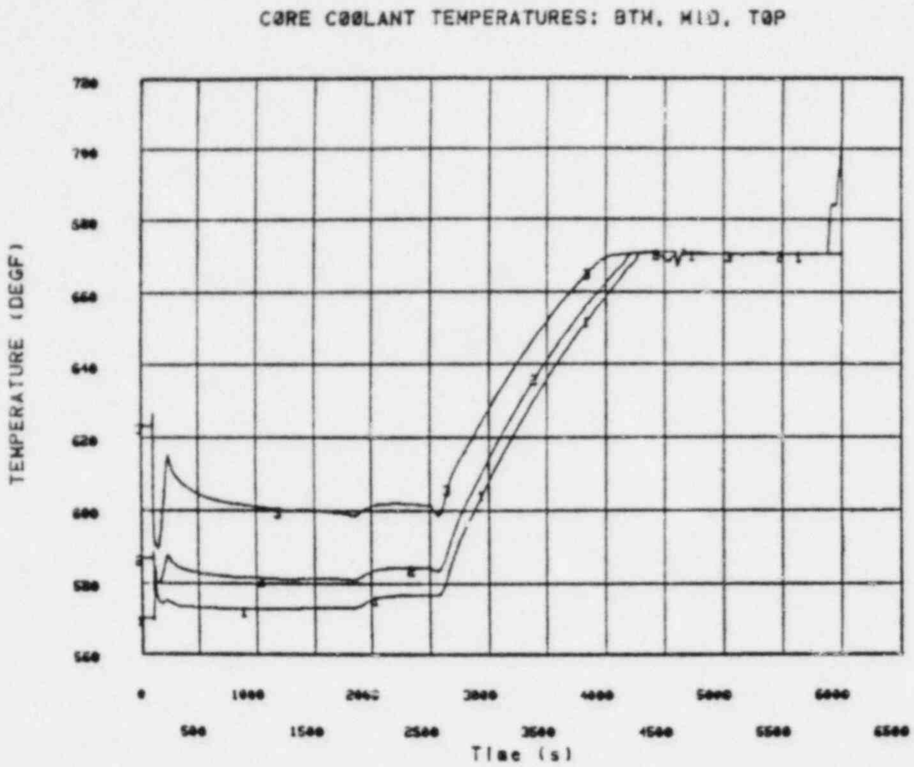
Fig. 4.5



CASE I

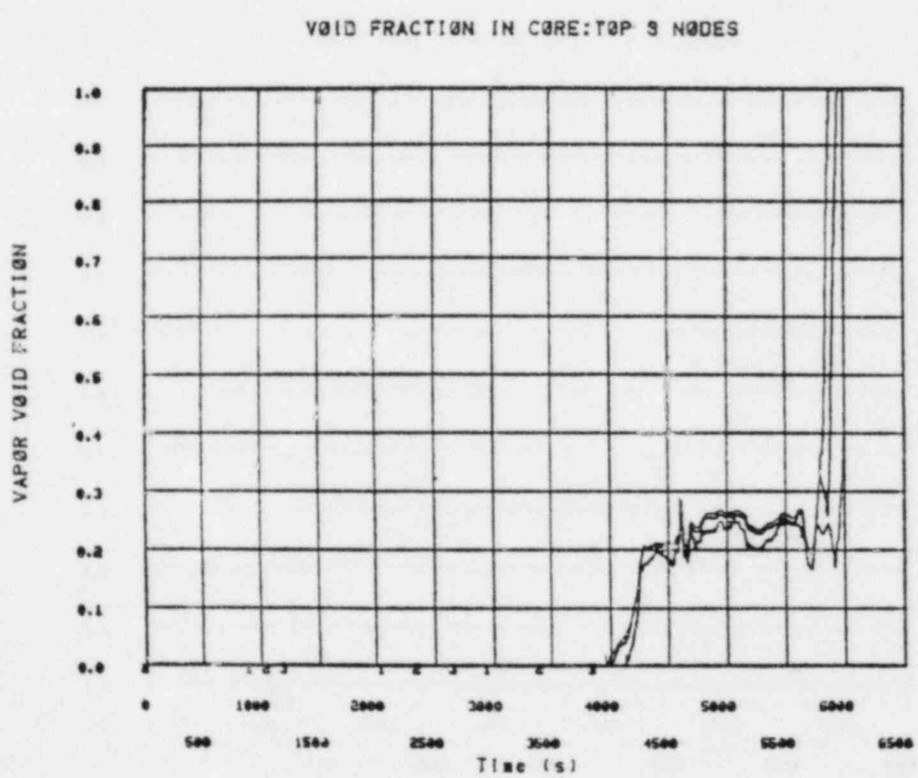
Fig. 4.6

DRAFT



CASE I

Fig. 4.7



CASE I

Fig. 4.8

DRAFT

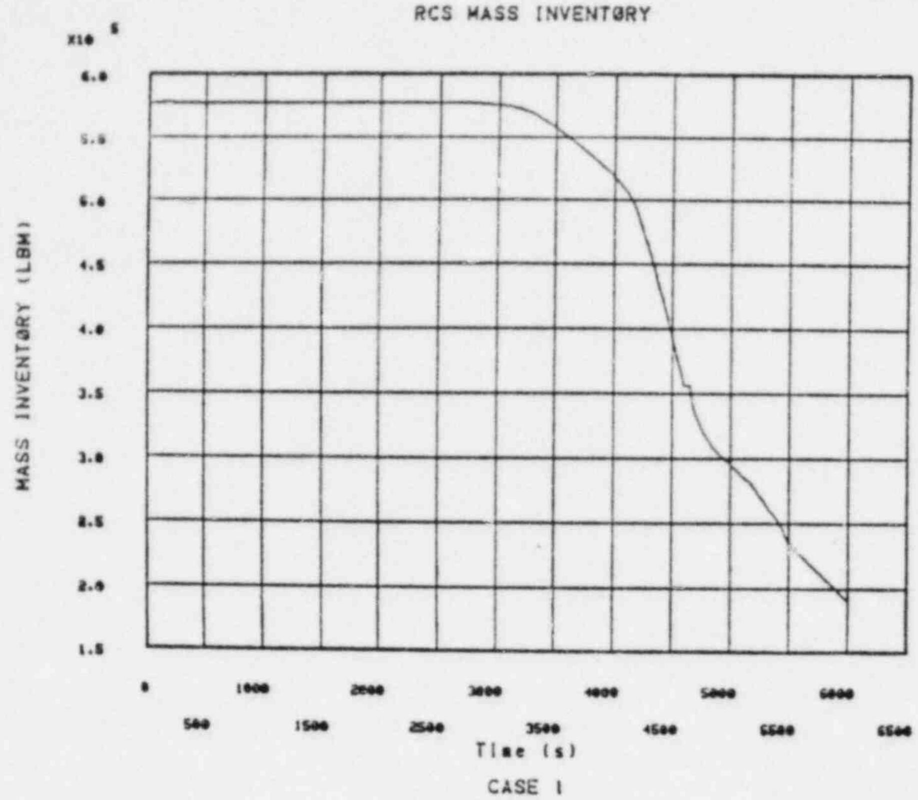


Fig. 4.9

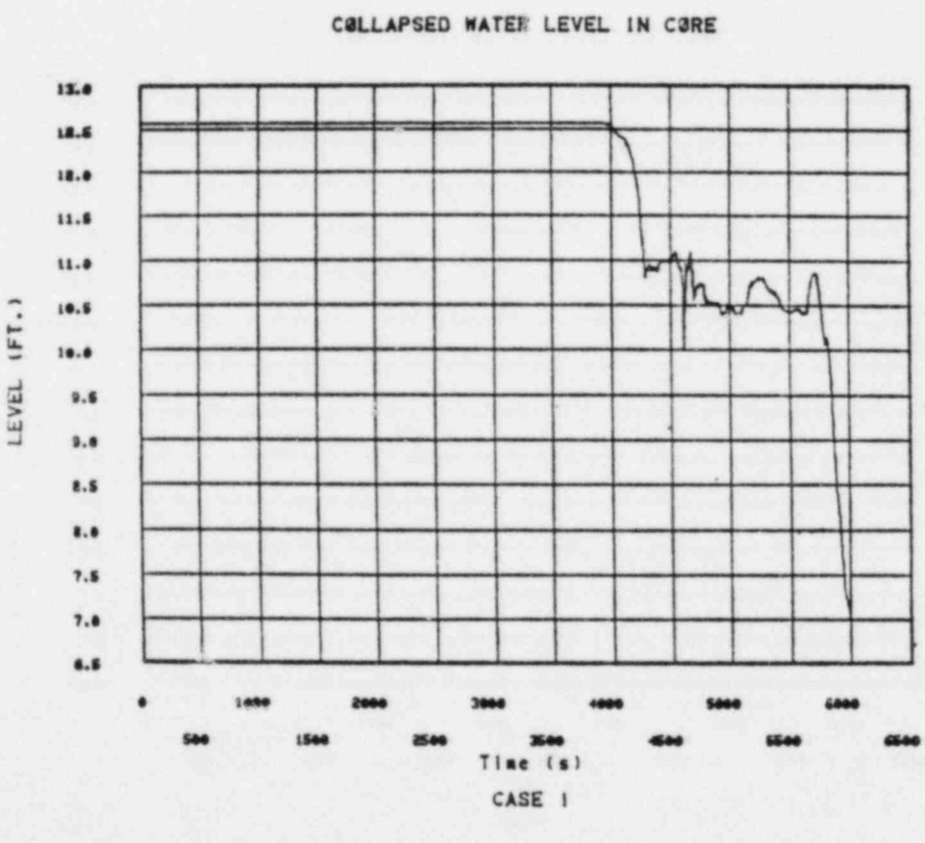
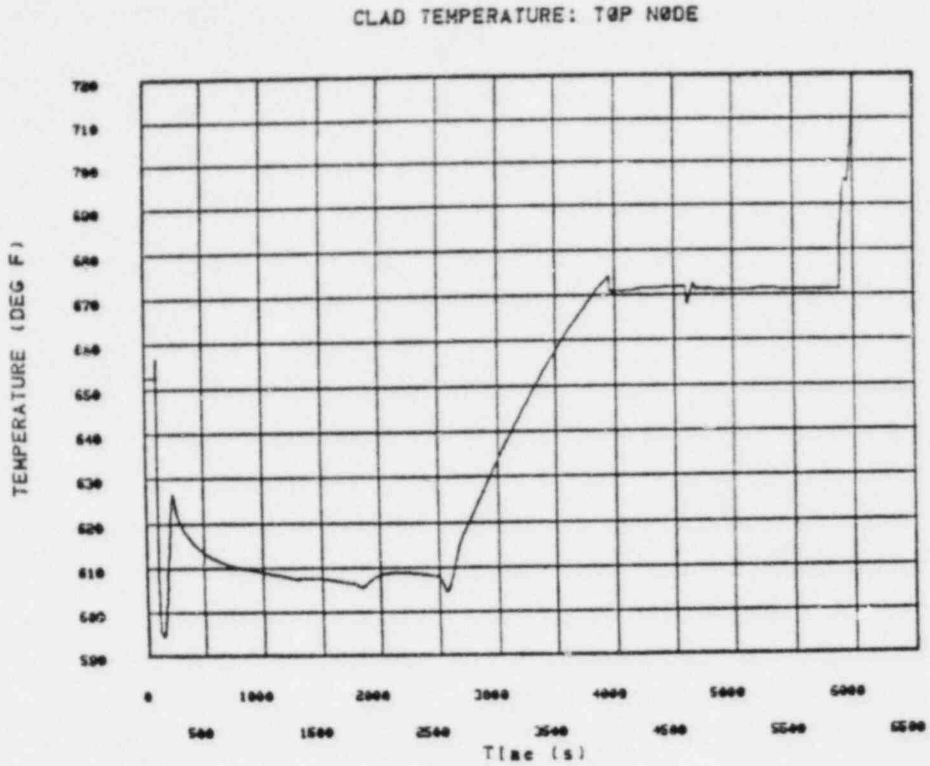


Fig. 4.10

DRAFT



CASE 1

Fig. 4.11

DRAFT

4.1.2 Case 3

This transient differs from Case 1 after 600 seconds into the transient, after which time operator actions based on the CE Recovery Guidelines were simulated in this case. The purpose of these actions is to provide alternate means of cooling by activating the APS and HPSI to attempt to maintain decay heat removal capability.

The following operator actions were modeled:

1. Actuation of the APS using one charging pump (6.09 lbm/s) with an objective to maintain a range of 20-25°F subcooling in the hot leg. However, the APS was turned off when the pressurizer level reached 90% (or more) of the total pressurizer height because beyond that it would merely aggravate pressurizer refilling and would flow out of the safeties directly.

2. Actuation of the high pressure safety injection (HPSI) system, using one pump, when the pressurizer level was less than 100 inches or the hot leg subcooling became less than 20°F. The HPSI was turned off when the pressurizer level rose above 100 inches and the degree of subcooling in the hot leg was more than 20°F. *(However, it is important to note that HPSI maximum head is ~ 1800 psi and that for most of this transient the primary pressure is well above that value. Thus the HPSIs produced no substantial flow.)*

At 10 minutes into the transient, the APS was actuated (with the 120°F water) because the subcooling in the hot leg at this point (see Figs. 4.12 through 4.14) was 44.5°F. The primary pressure had decreased from 2157 psia to 1760 psia by roughly 1240 seconds into the transient, at which point the subcooling fell below 20°F and the APS flow terminated. The APS was actuated on and off four more times in the ensuing 2400 seconds as the hot leg subcooling fluctuated. Each time it actuated, the RCS pressure dipped a little, but the flow had less and less impact as the transient progressed, since by 2400 seconds into the transient, the steam generators were dry and had therefore lost energy removal capability. The steam generators represent

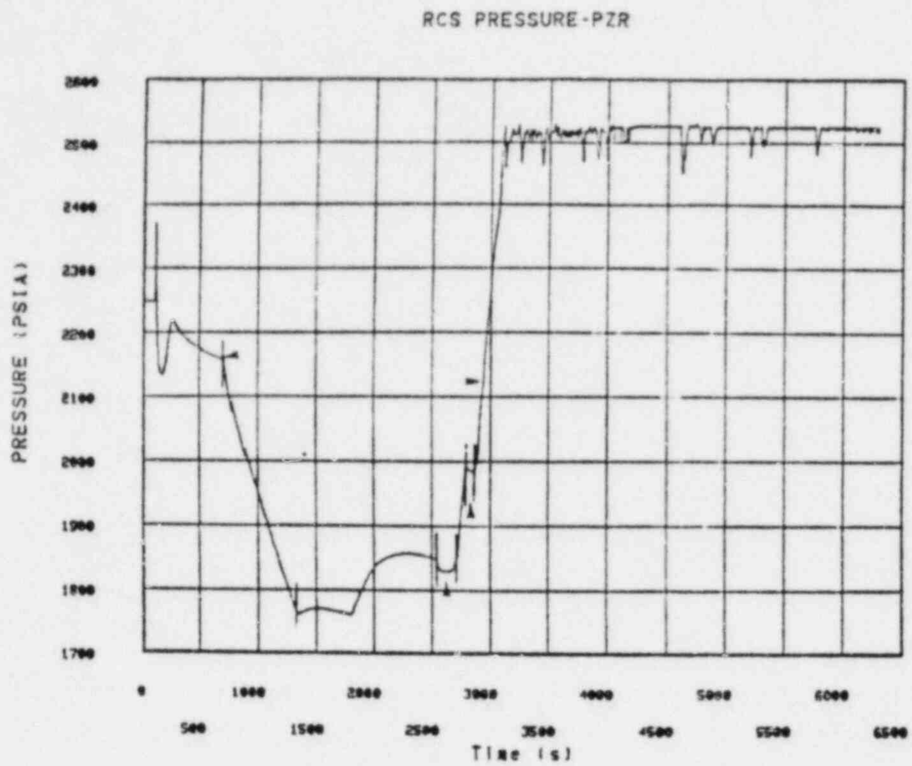
DRAFT

the major heat removal mechanism, so once they are lost the primary saturation pressure no longer decreases. Thus, since APS activation is keyed on the saturation temperature, the APS is not effective. The APS was actuated for the last time around 2830 seconds into the transient and was shut off due to the high level in the pressurizer (Fig. 4.15). As discussed with Case 1, the humps in the primary pressure curve between 1300 and 2400 seconds after the onset of the transient are numerical effects, caused by RELAP5, due to the water level crossing the code node boundaries in the steam generators. As in Case 1, as the steam generators dried out, primary pressure increased to the pressurizer safety valve setpoint. This occurred about 3015 seconds after transient initation. We note that this is approximately 400 seconds later than for Case 1 due to the actuation of the APS flow which depressurized the system roughly 400 psia more than Case 1 (which had no APS flow).

Roughly 1237 seconds into the transient, the HPSI flow was initiated at the rate of a few pounds per seconds when the hot leg subcooling fell below 20°F. The flow was insignificant however because the RCS pressure was too high for the HPSI pump head to deliver more flow. For the remainder of this transient, the system pressure remained above the HPSI maximum head, and the results became very similar to those from Case 1.

As soon as the steam generators boiled dry, the primary temperature rose (Fig. 4.16) resulting in insurge into the pressurizer with the expanding primary liquid. The pressurizer went solid at about 2950 seconds into the transient at which point the flow out of the pressurizer safety valves became single-phase liquid (Fig. 4.17). The RCS inventory was rapidly lost through the safeties (Fig. 4.18), void formation in the core started at about 3880 seconds after transient initation, and by 6030 seconds the core began to uncover. See Figs. 4.19 through 4.21.

DRAFT

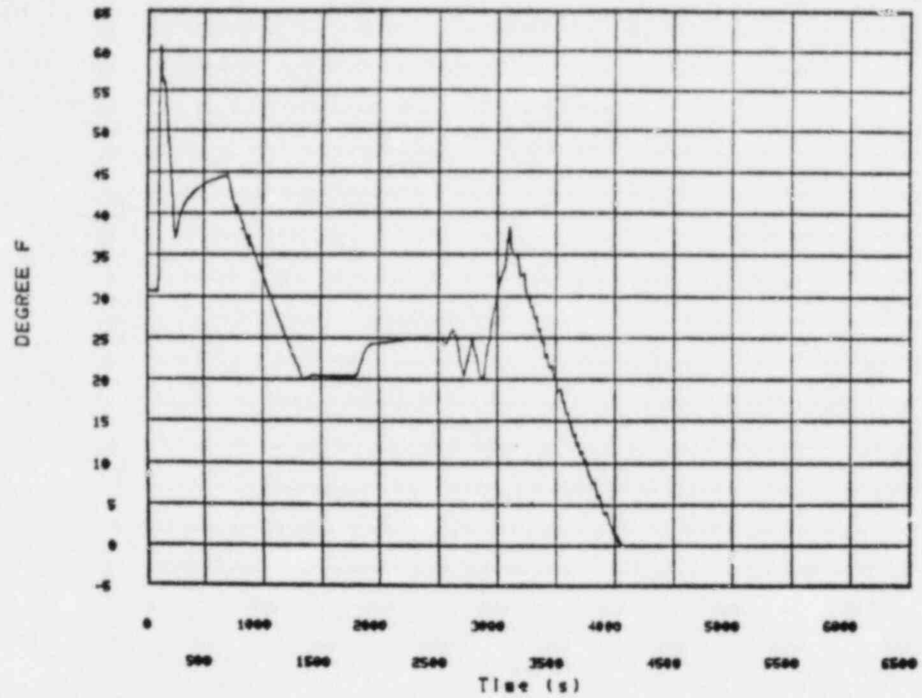


CASE 3

Fig. 4.12

DRAFT

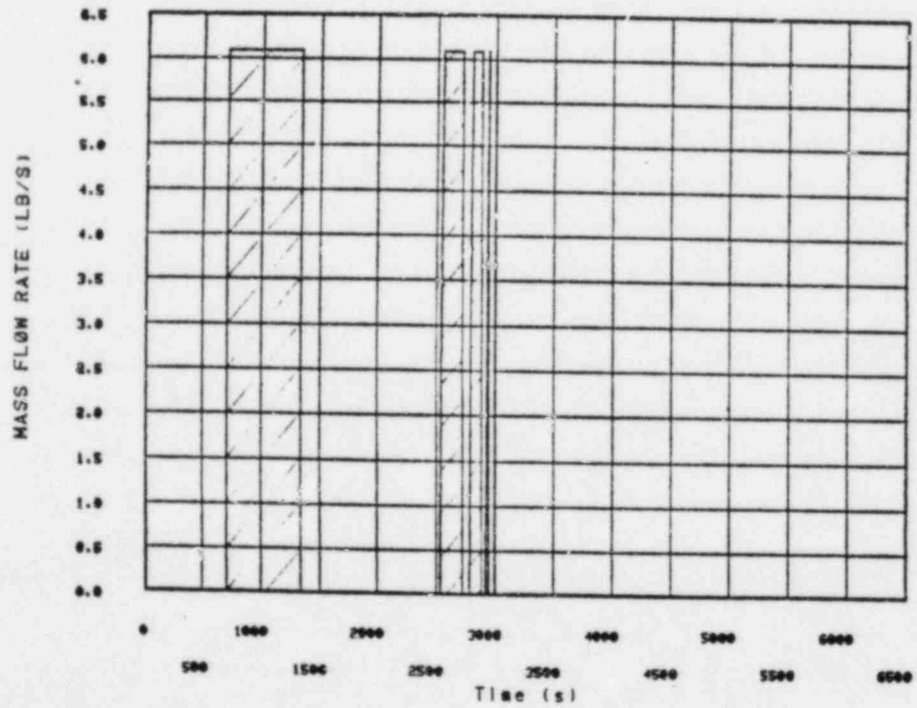
HØT LEG SUBCØØLING



CASE 3

Fig. 4.13

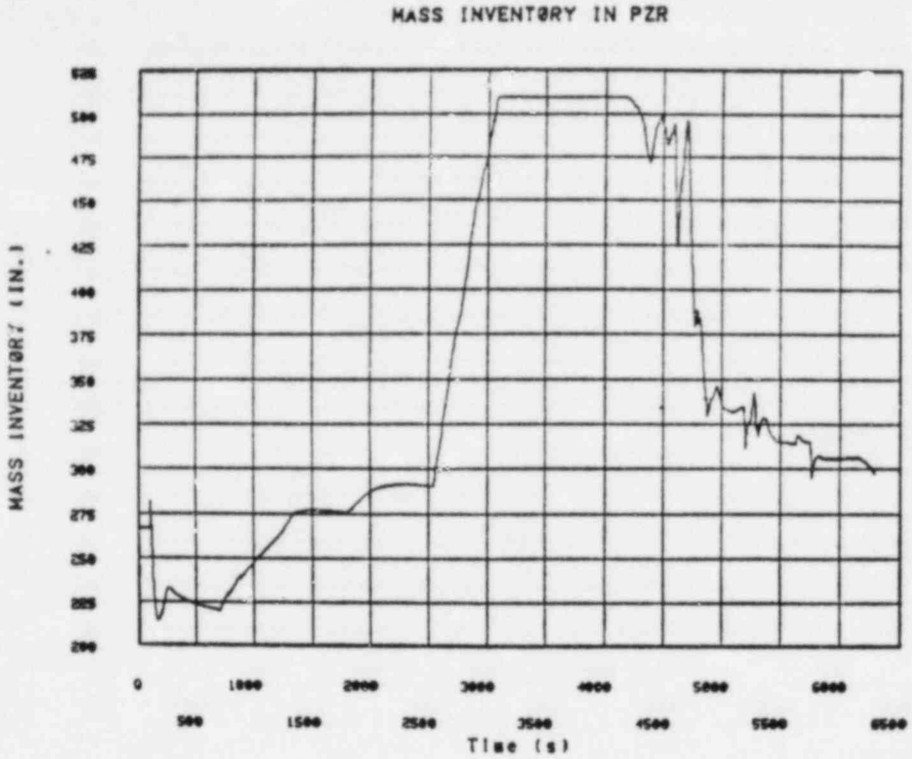
AUX PZR SPRAY FLØW



CASE 3

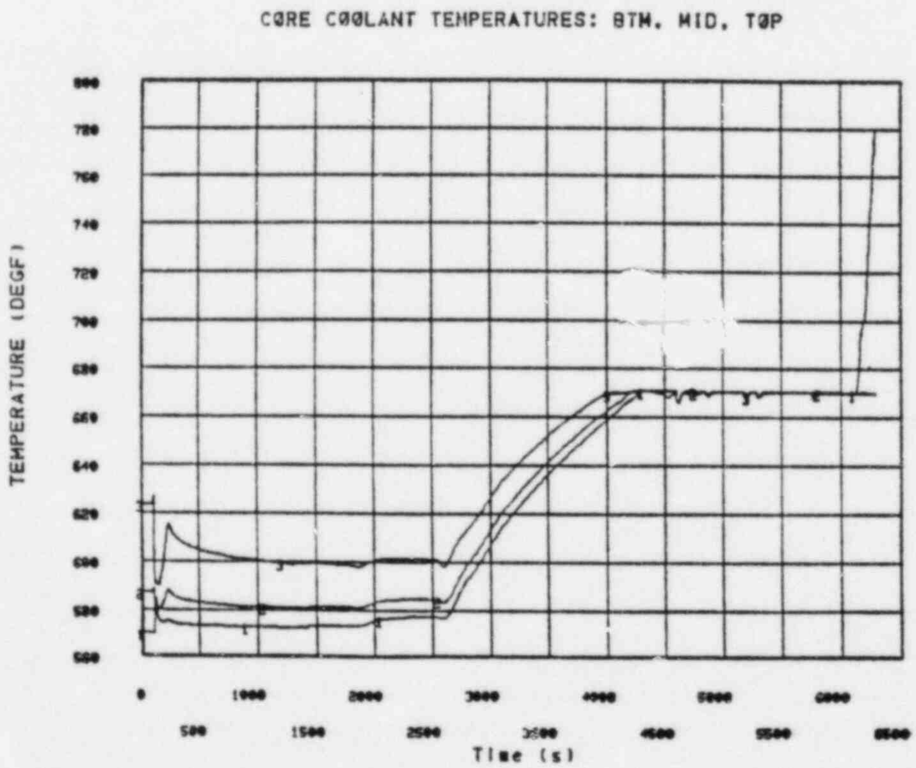
Fig. 4.14

DRAFT



CASE 3

Fig. 4.15



CASE 3

Fig. 4.16

DRAFT

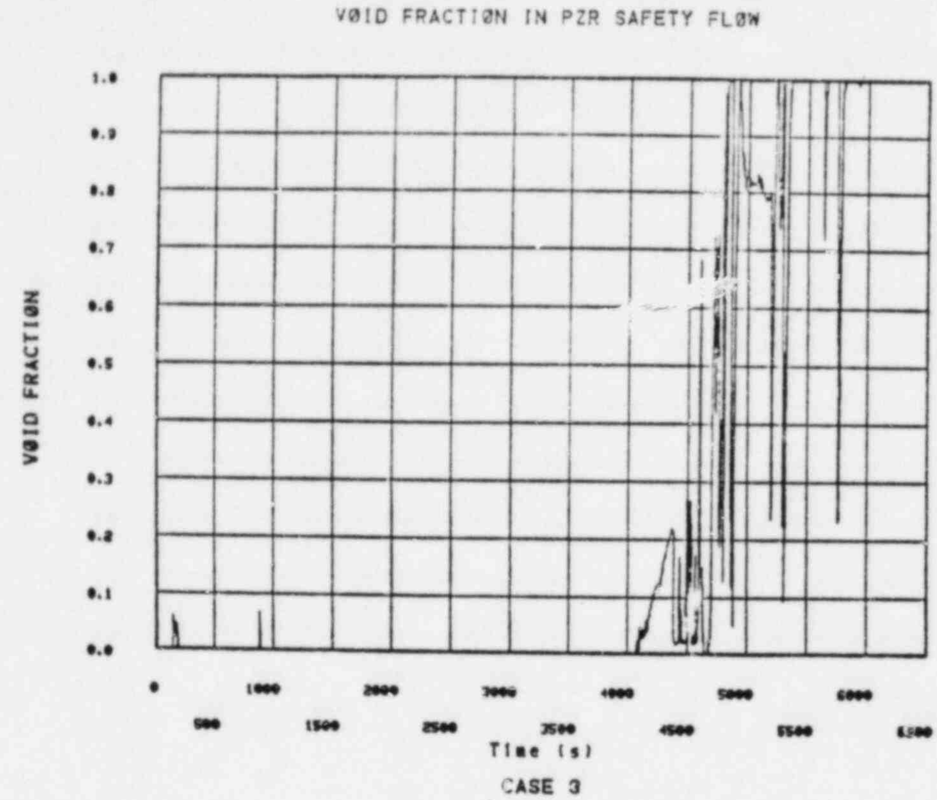


Fig. 4.17

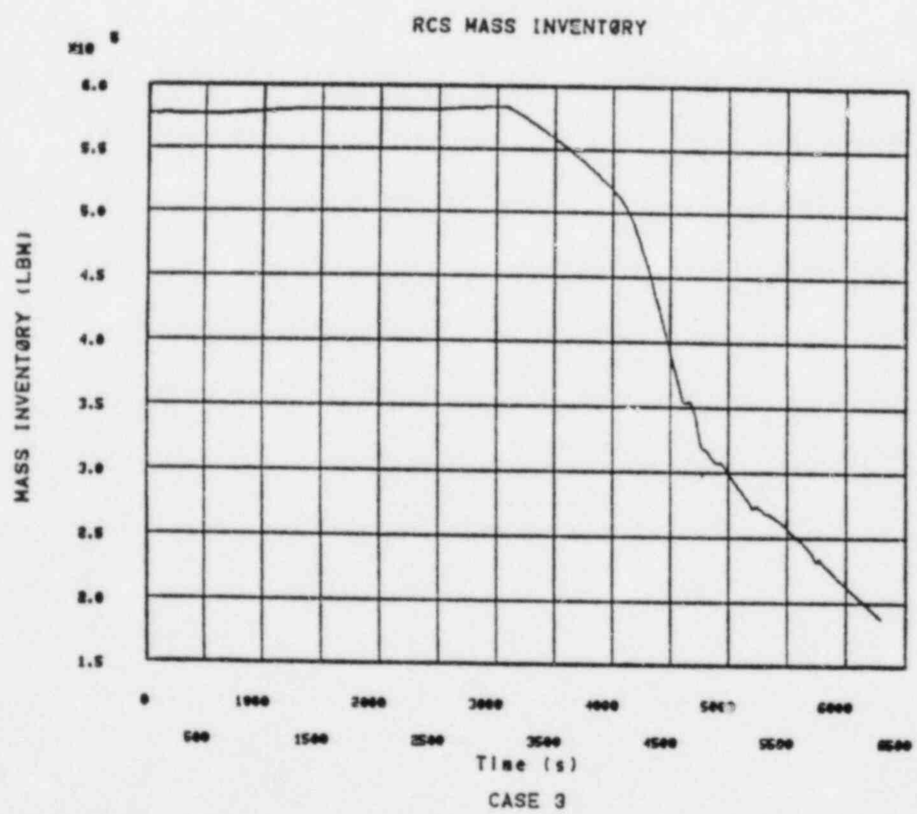
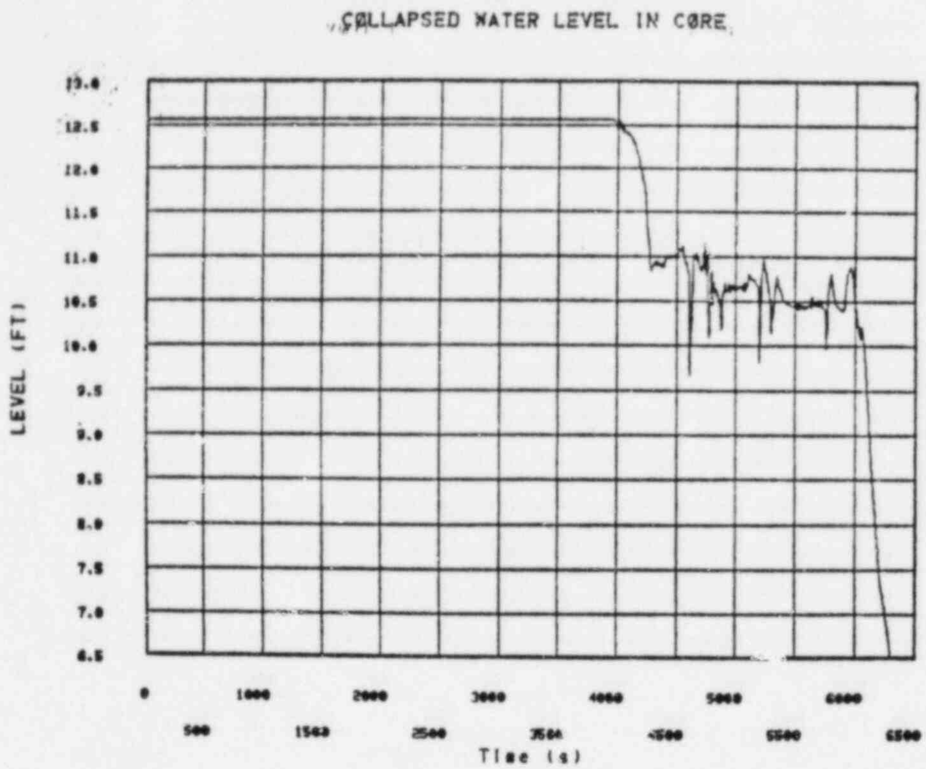


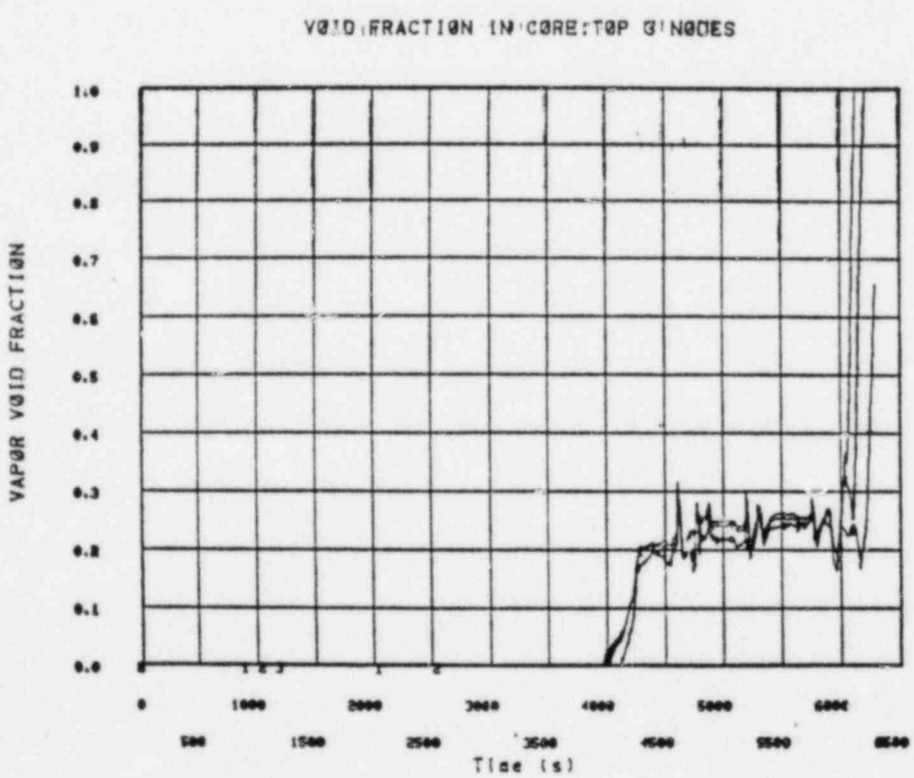
Fig. 4.18

DRAFT



CASE 3

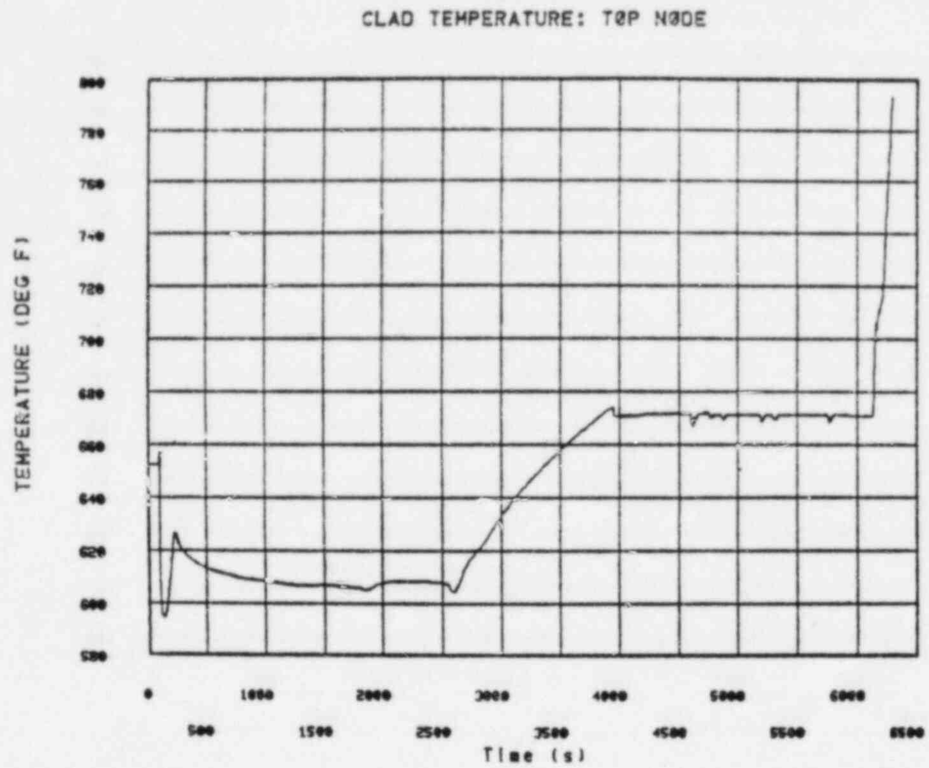
Fig. 4.19



CASE 3

Fig. 4.20

DRAFT



CASE 3

Fig. 4.21

DRAFT

4.2 TLOFW with Power Remaining Available

4.2.1 Case 2

In this case, although normal feedwater flow was assumed to be lost, power was assumed to remain available to the RCPs and the reactor was not tripped concurrent with loss of feedwater. Ten minutes after the loss of feedwater, we assumed that the operator manually tripped the reactor coolant pumps and started pump coast-down (Fig. 4.22).

Without the cold feedwater flow into the steam generators, the secondary side temperature rose (Fig. 4.23) and steam pressure increased while the turbine was maintaining constant 100% load (constant steam flow) (Fig. 4.24). The primary-to-secondary heat transfer degraded and the primary pressure rose (Fig. 4.25) to the reactor trip setpoint on high primary pressure (2475 psia) at 29.8 seconds after loss of feedwater. The reactor trip was assumed to actuate a turbine trip signal. The RCS pressure continued to increase rapidly and reached the pressurizer safety valve setpoint, but by that time the control rods were fully inserted into the core and the pressure decreased immediately (spike roughly 30 seconds after loss of feedwater). The secondary side inventory boiled dry much more rapidly in this case (Fig. 4.26) primarily because there was an additional 30 seconds of full power operation after the loss of feedwater and additionally in part because the reactor coolant pumps were still forcing flow through the RCS so that more heat was transferred from the core to the secondary side. Thirty seconds of full power operation generates enough heat to completely dry out the mass inventory of one steam generator; the balance of energy which caused early dryout came from decay heat and pump power. Thus in this case the steam generators dried out less than ten minutes into the transient, in sharp contrast to the situation with LOOP (Case 1) where the heat removed was due solely to decay heat. Compare Fig. 4.26 to Fig. 4.3.

The loss of primary inventory out of the safeties began much earlier in this case (Fig. 4.27) and the primary inventory began to deplete correspondingly (Fig. 4.28). It is useful here to compare the RCS inventory history in this case to that of Case 1 (Fig. 4.8 and Fig. 4.28). We note that

DRAFT

the slope of inventory decay is nearly identical but that in this case it occurs more than thirty minutes earlier due in large part to failure to trip the RCPs.

As we saw before, once the steam generators dried out, the primary inventory began to thermally expand and the pressurizer filled (Fig. 4.29). Because the loss of mass in the steam generators was so rapid in this case, however, the numerical "humps" in the primary pressure (which were also visible as a secondary effect in the pressurizer inventory level) which were so marked in Cases 1 and 3 were not particularly noticeable here.

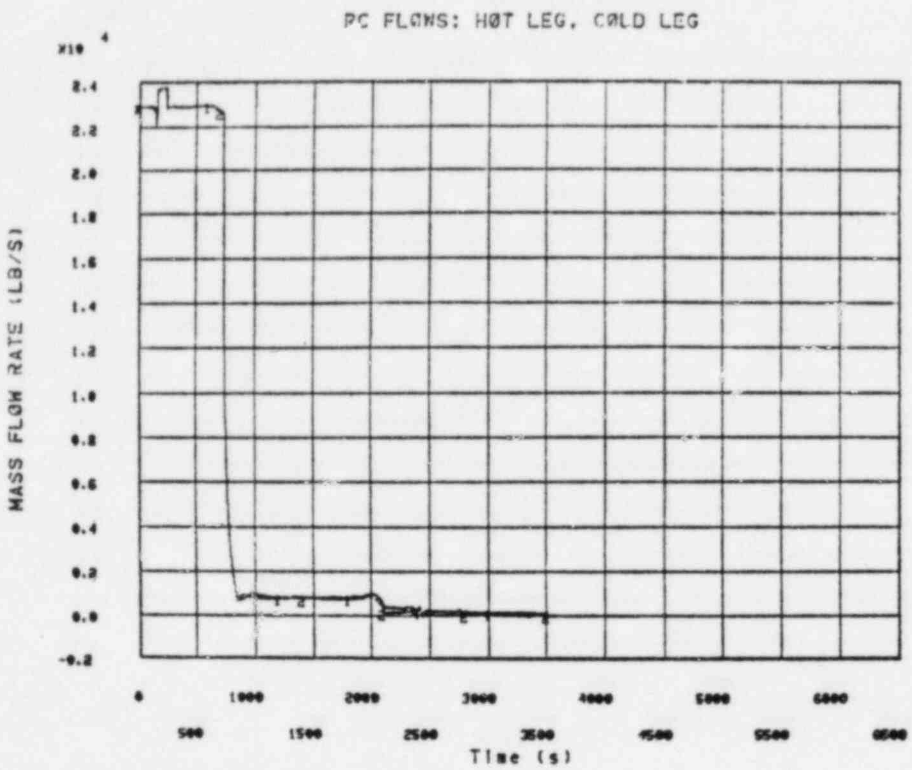
As the hot leg vapor fraction reached 100% in the junction to the surge line (Fig. 4.30), the surge line began to draw vapor (Fig. 4.31). (We note that the junction is on the bottom of the pipe and the RELAP5 flow regime map forces the surge line to draw only liquid from the stratified flow until no liquid remains.) Once the surge line begins to draw vapor, the net inventory in the pressurizer drops rapidly because low quality mixture was still flowing out of the safeties (Fig. 4.32 and 4.29).

Since the primary inventory was rapidly depleting (Fig. 4.28), the void generation in the hot leg (Fig. 4.30) causing voids in the surge line (Fig. 4.31) was nearly co-incident with onset of voids in the core (Fig. 4.33) and a decrease of collapsed water level in the core which occurred at about 2100 seconds after the loss of feedwater (Fig. 4.34). We observe, as before, that rate of the loss of inventory from the primary decreased as the pressurizer safety flow returned to high quality flow at around 2500 seconds in this transient (see Figs. 4.27 and 4.28), permitting the core water level to temporarily level off (Fig. 4.34) (although inventory is still being lost from the system). Since this transient was proceeding much faster than Case 1, the inventory in the core leveled off for a somewhat shorter period. (This is a compound result of the inventory loss rate through the safeties, somewhat higher decay heat, and lower primary inventory at the onset of uncovery.) (Compare Figs. 4.34 to 4.10). As before, this results eventually in core uncovery (Fig. 4.34) and coolant and cladding heatup (Fig. 4.35 and 4.36).

DRAFT

In summary, we observe the marked negative impact of failure to trip the RCPs at loss of feedwater, and that it results in onset of core uncovery more than 40 minutes earlier!

DRAFT



CASE 2

Fig. 4.22

DRAFT

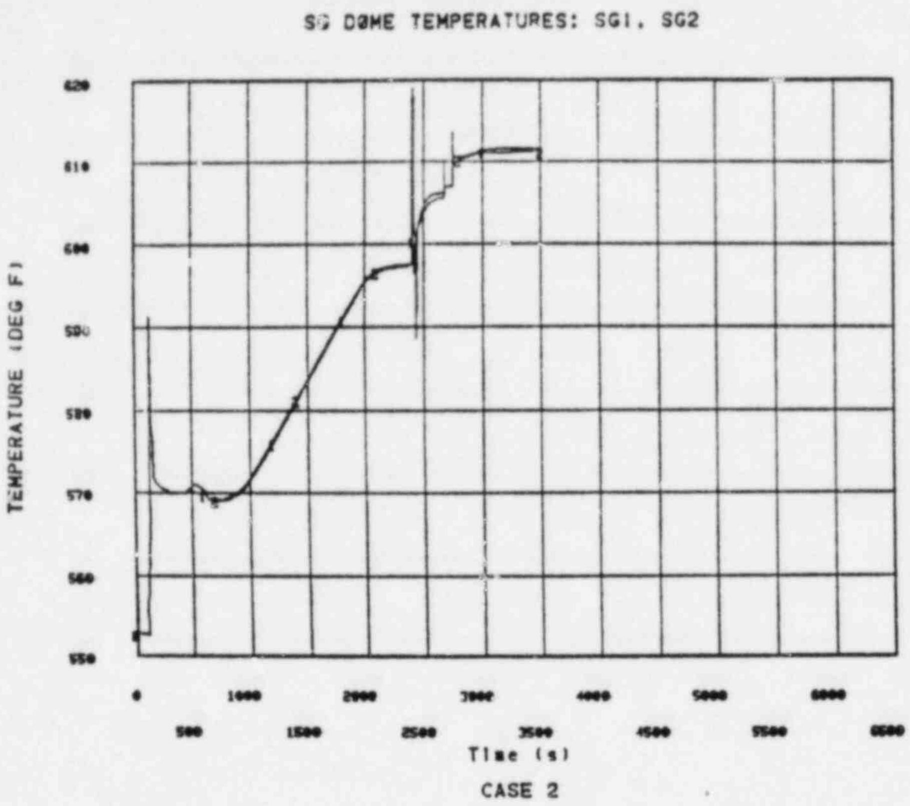


Fig. 4.23

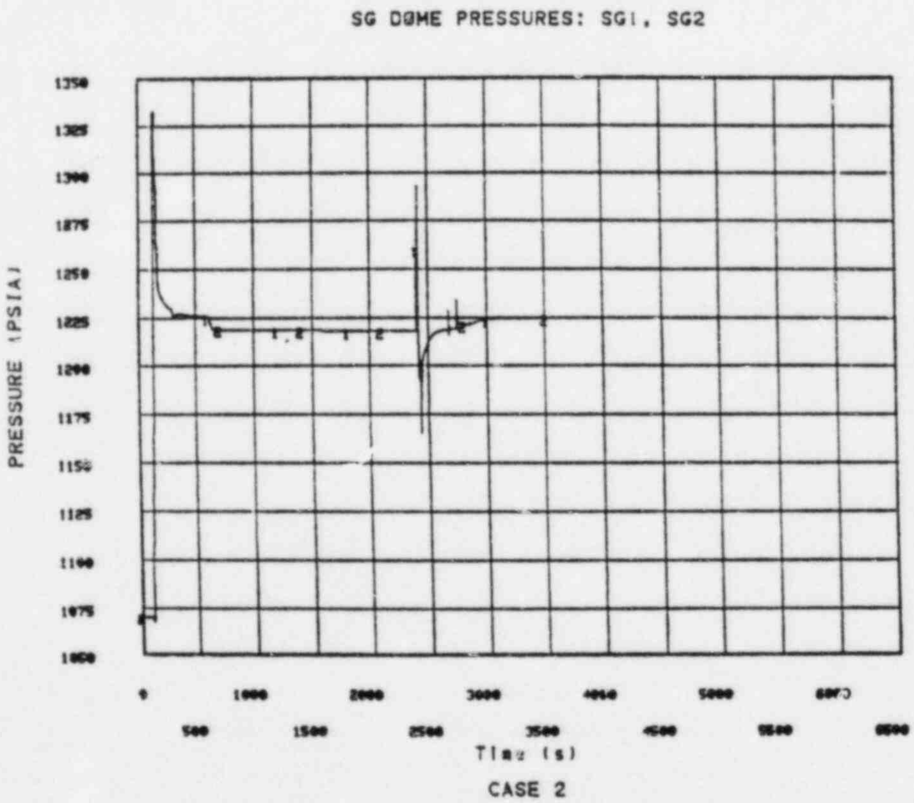
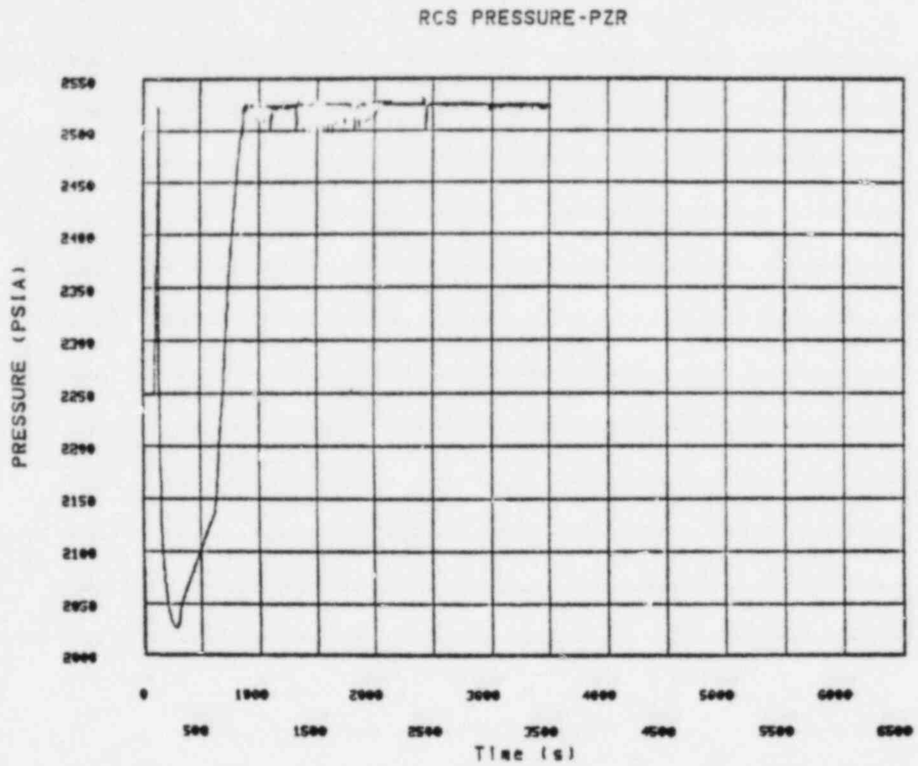


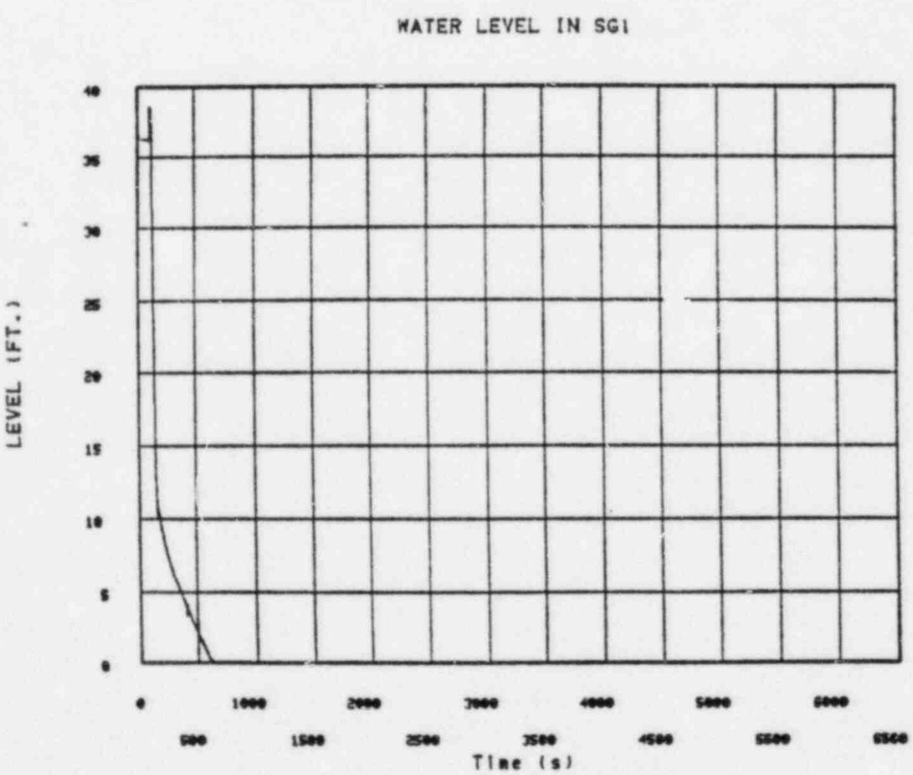
Fig. 4.24

DRAFT



CASE 2

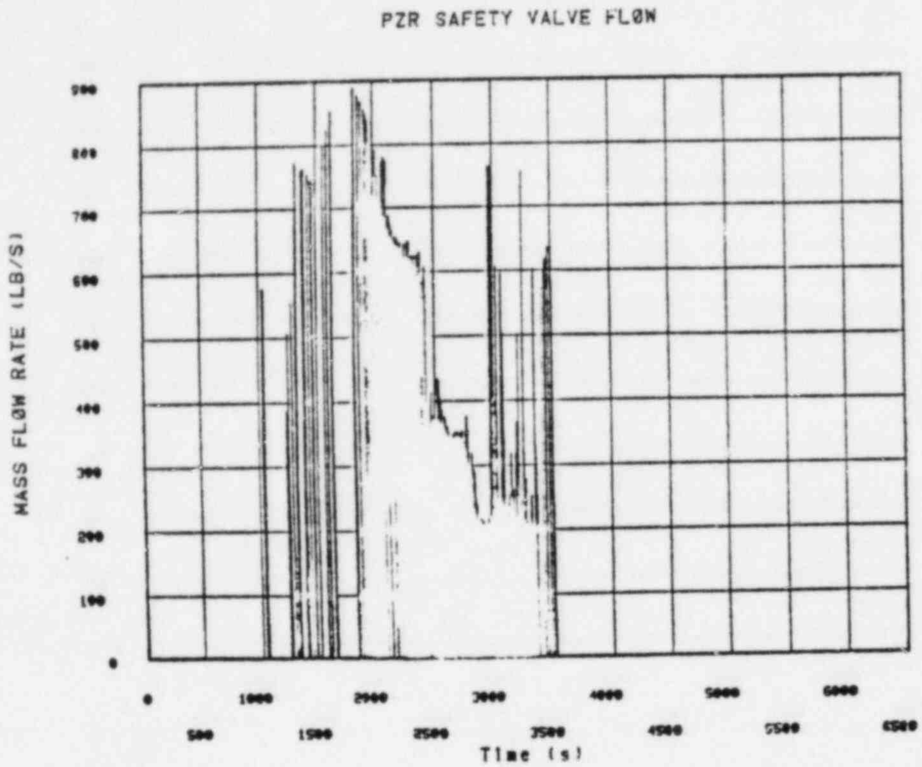
Fig. 4.25



CASE 2

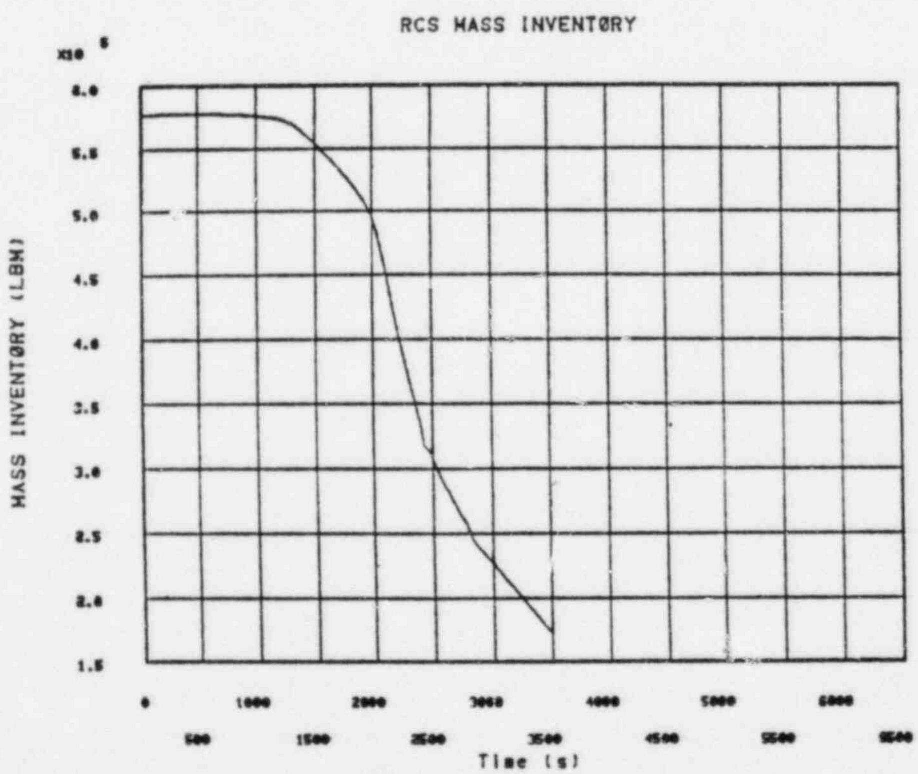
DRAFT

Fig. 4.26



CASE 2

Fig. 4.27



CASE 2

Fig. 4.28

DRAFT

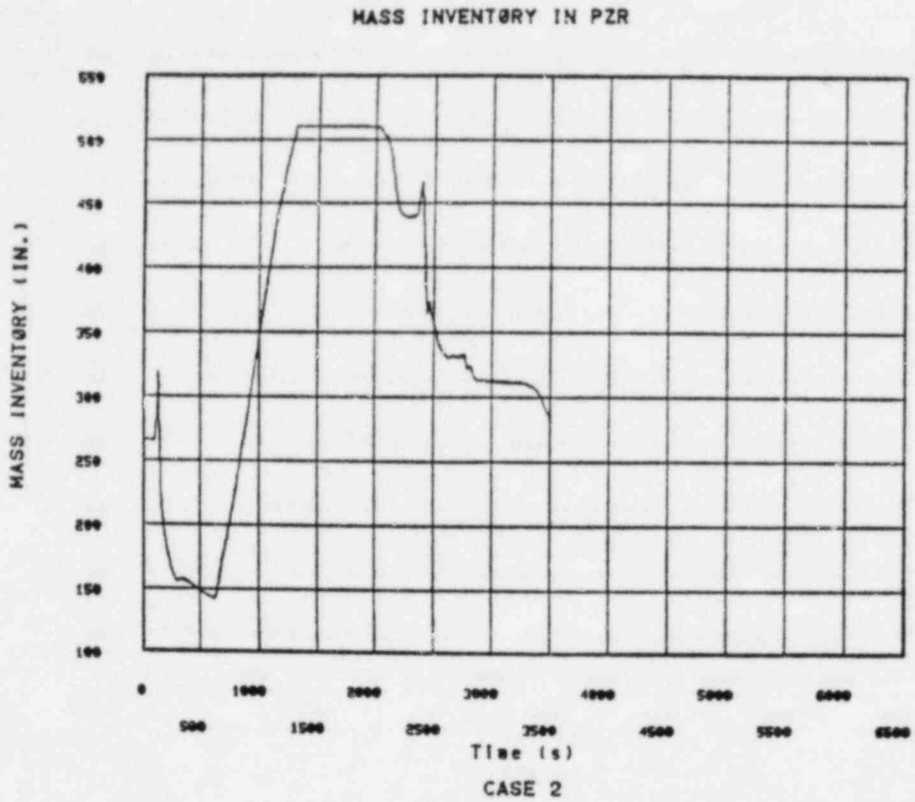


Fig. 4.29

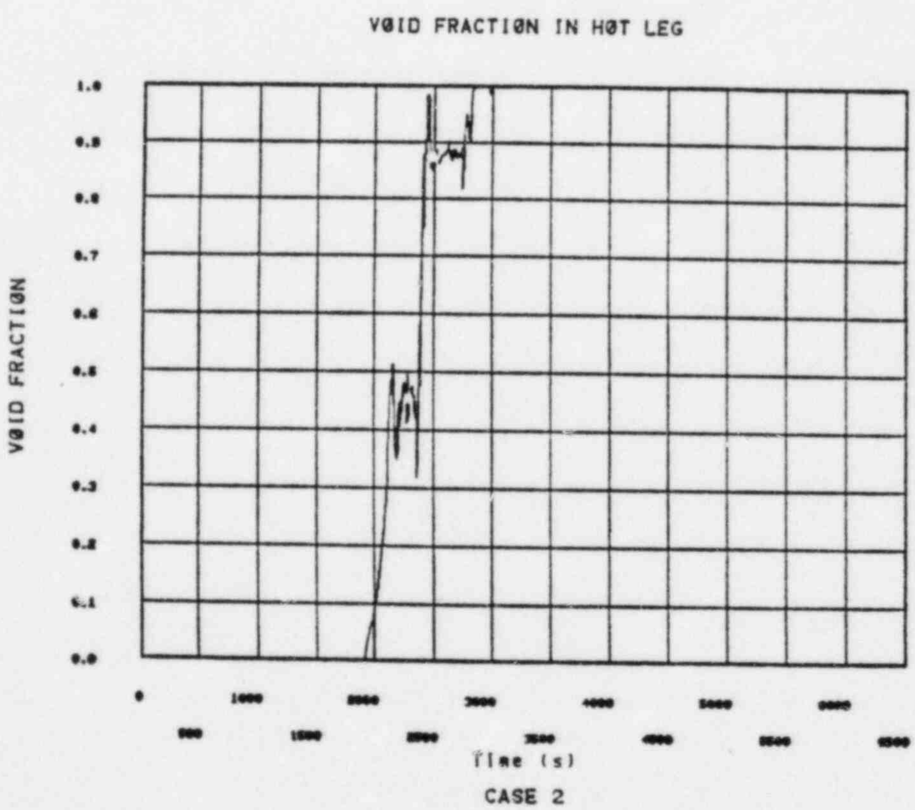
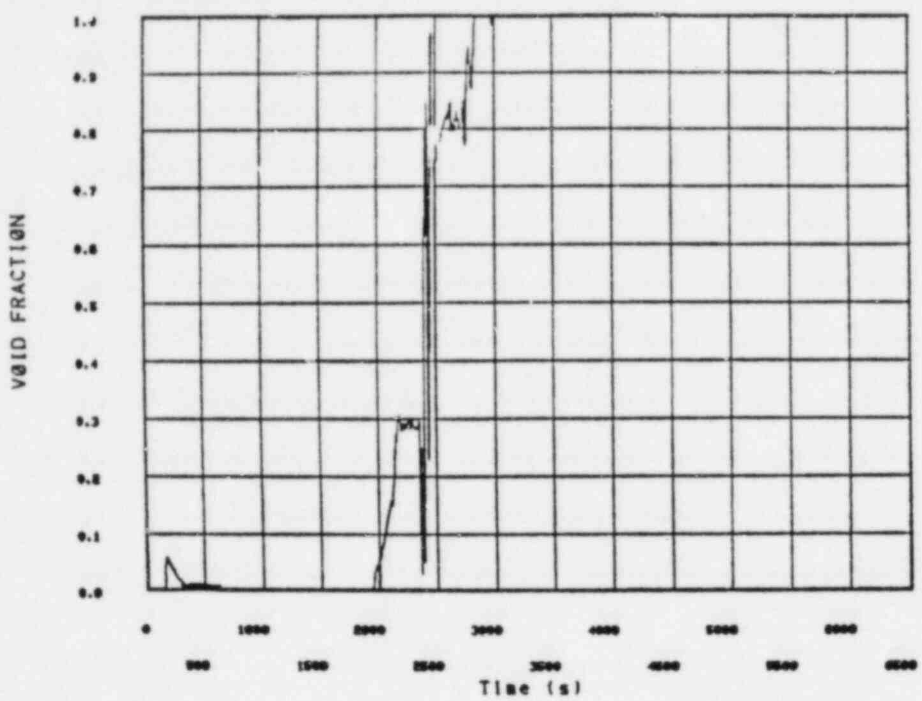


Fig. 4.30

DRAFT

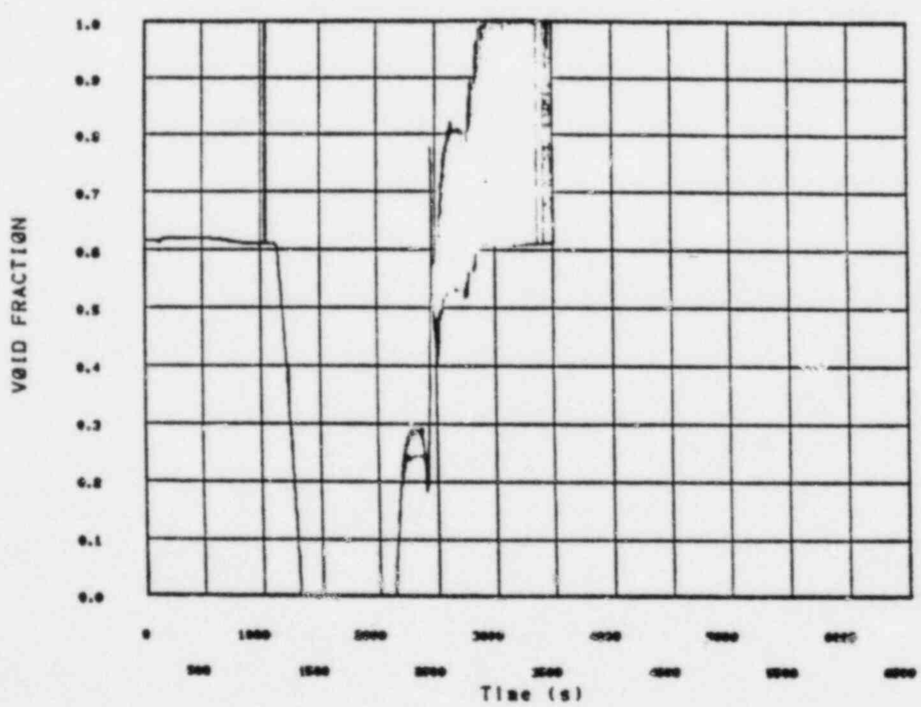
VØID FRACTIØN IN SURGE LINE



CASE 2

Fig. 4.31

VØID FRACTIØN IN PZR SAFETY FLØW

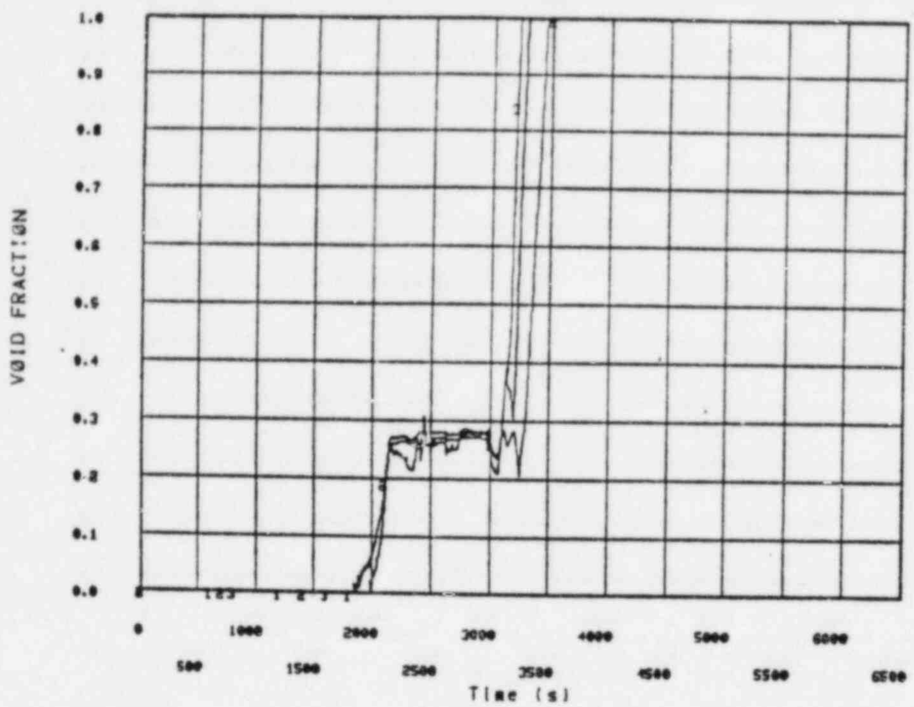


CASE 2

DRAFT

Fig. 4.32

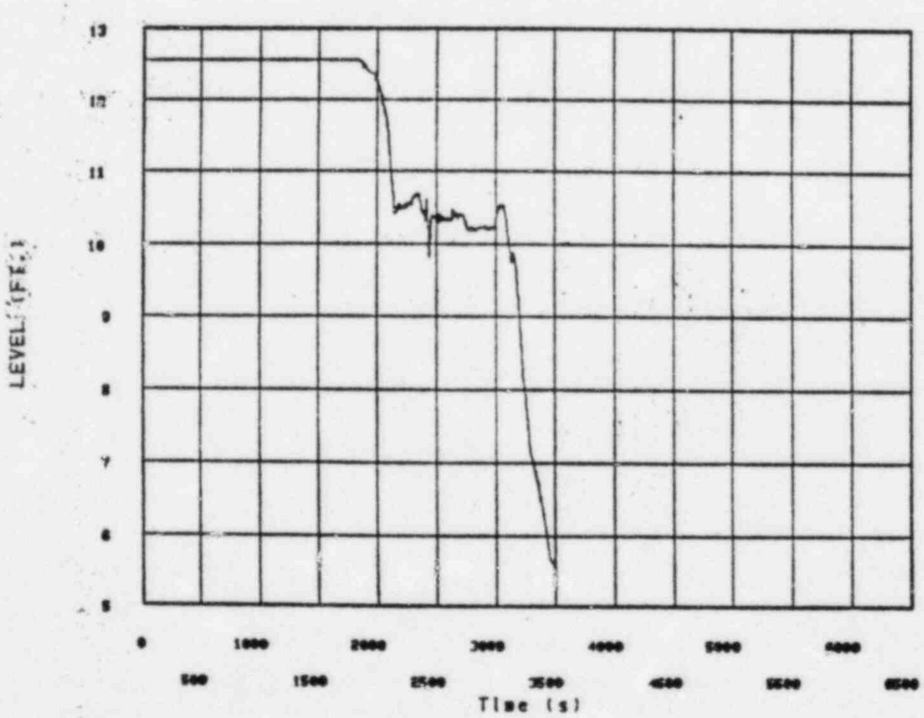
VØID FRACTIØN IN CØRE:TØP 3 NØDES



CASE 2

Fig. 4.33

CØLLAPSED WATER LEVEL IN CØRE

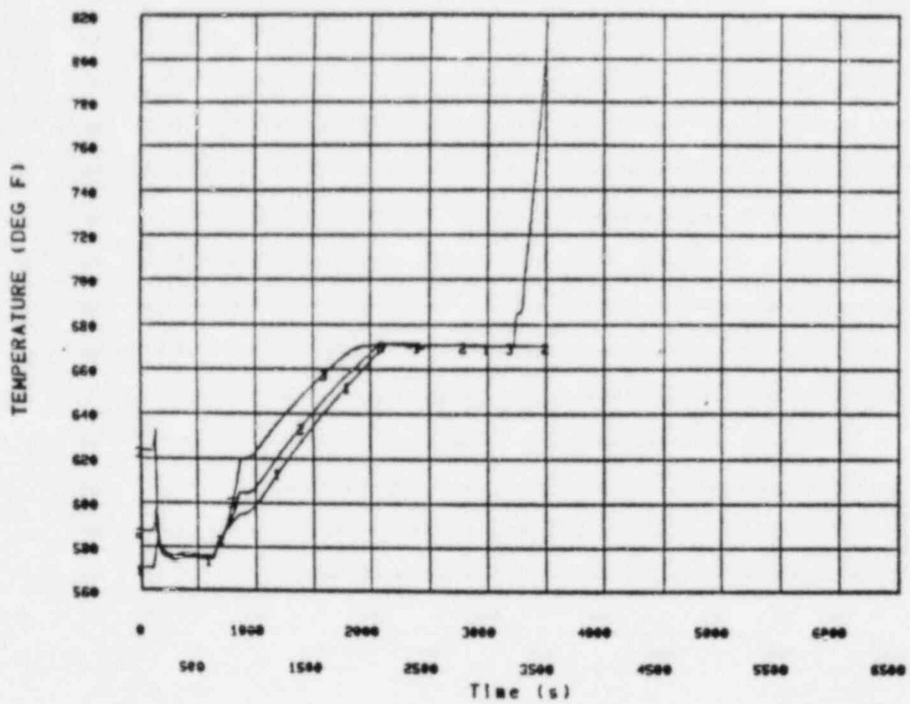


CASE 2

DRAFT

Fig. 4.34

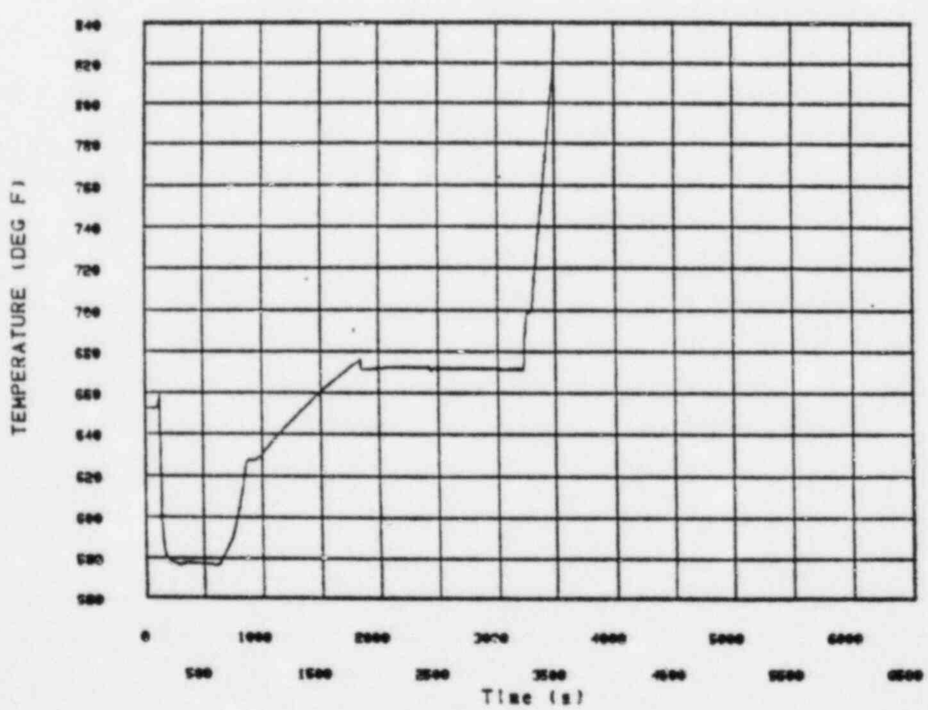
CØRE CØØLANT TEMPERATURES: BTM, MID, TØP



CASE 2

Fig. 4.35

CLAD TEMPERATURE: TØP NØDE



CASE 2

Fig. 4.36

DRAFT

4.2.2 Case 4

This case was identical to Case 2 for the first 10 minutes of the transient, at which point the RCPs were tripped and operator actions were initiated. However in this case, as in Case 3, the operator actions were assumed to include APS and HPSI actuation according to operator guidelines. We recall from Case 2 that by about 510 seconds into the transient both steam generators were dry and had totally lost primary-to-secondary heat transfer capability. In this case, as with case 2, within 100 seconds after dryout the RCS pressure was on a sharp rise (Fig. 4.37). Thus, when the APS flow was initiated (Fig. 4.38) because of high hot leg subcooling margins (Fig. 4.39), the APS flow had little impact in lowering the RCS pressure because, in contrast to Case 3, there was NO heat sink available here. The APS was eventually turned off when the pressurizer inventory level reached the high level setpoint (90% level) roughly 1015 seconds into the transient (Fig. 4.40). Nevertheless, the APS did slow down the primary pressure increase to the pressurizer safety valve setpoint by about three minutes. As in all cases discussed thus far, the primary pressure leveled off at the pressurizer safety setpoint, and the RCS inventory was rapidly discharged out of these safeties (Fig. 4.41). HPSI produced no flow because the primary pressure was too high, and core uncovery began about 3240 seconds after the transient initiation (Figs. 4.42 and 4.43). As before, the code computed cladding and core coolant temperatures rose sharply (Figs. 4.44 or 4.45) when the void fraction in the upper node finally reached 1.0.

Thus we observe that, as in the immediately preceding case, the impact of continued operation of the reactor and RCPs dominated the transient. Although operator actuation of APS and HPSI was assumed here, the single impact from roughly ten minutes of APS flow (initiated immediately when the operator first acted -- at the same time of RCP trip) was a roughly ten minute delay in actual core uncovery.

Only one charging pump was assumed available for APS in this study. Since APS logic will turn off APS when there is less than 20°F subcooling, the use of all three charging pumps would alter only the timing not the substance of this result.

DRAFT

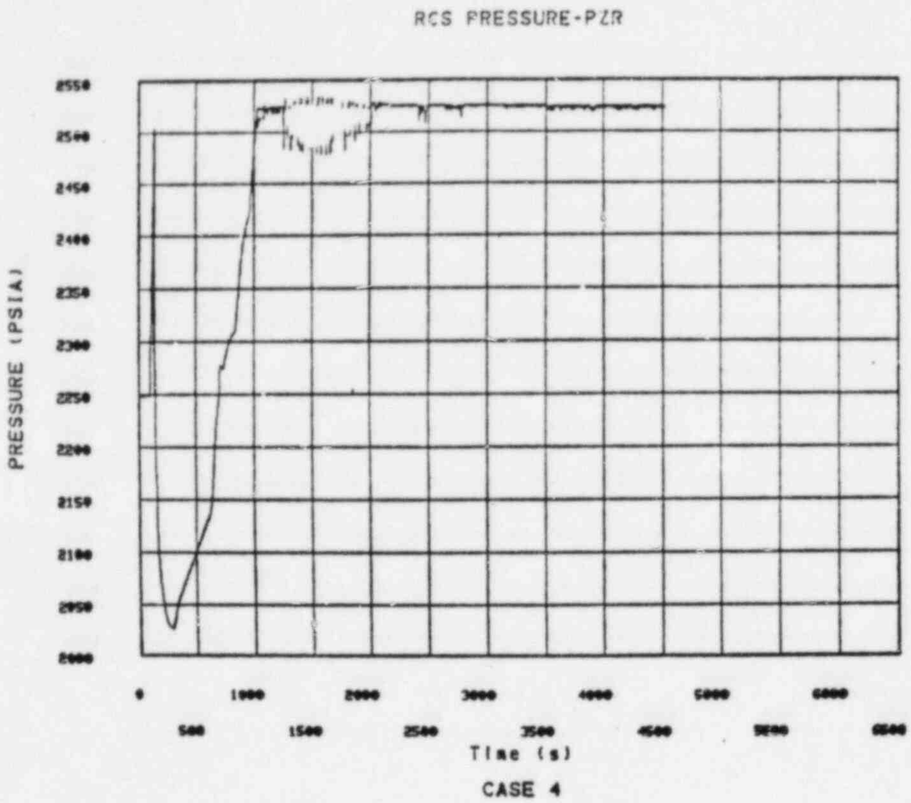


Fig. 4.37

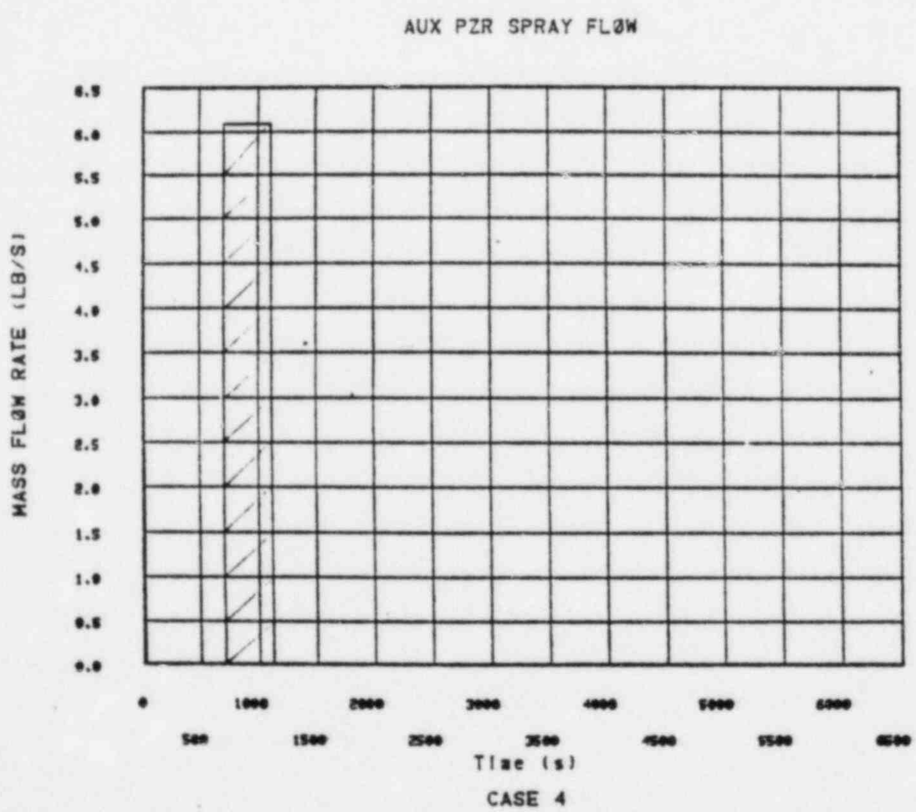


Fig. 4.38

DRAFT

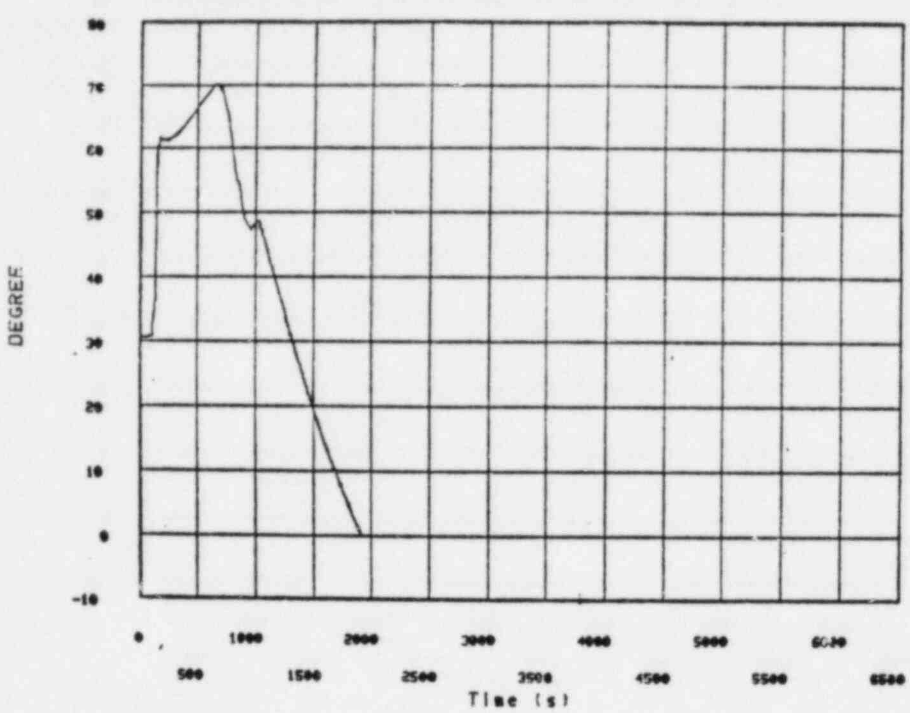


Fig. 4.39

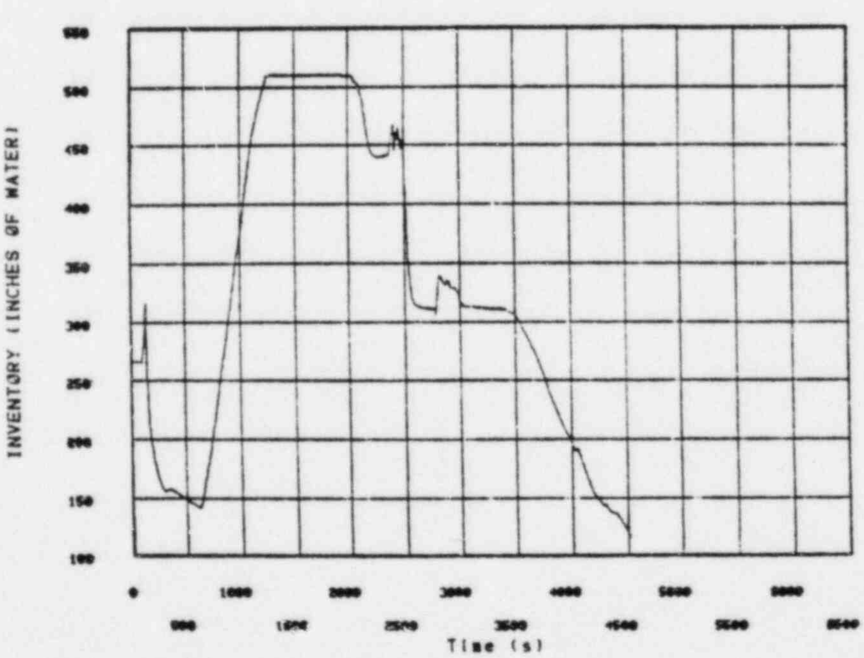
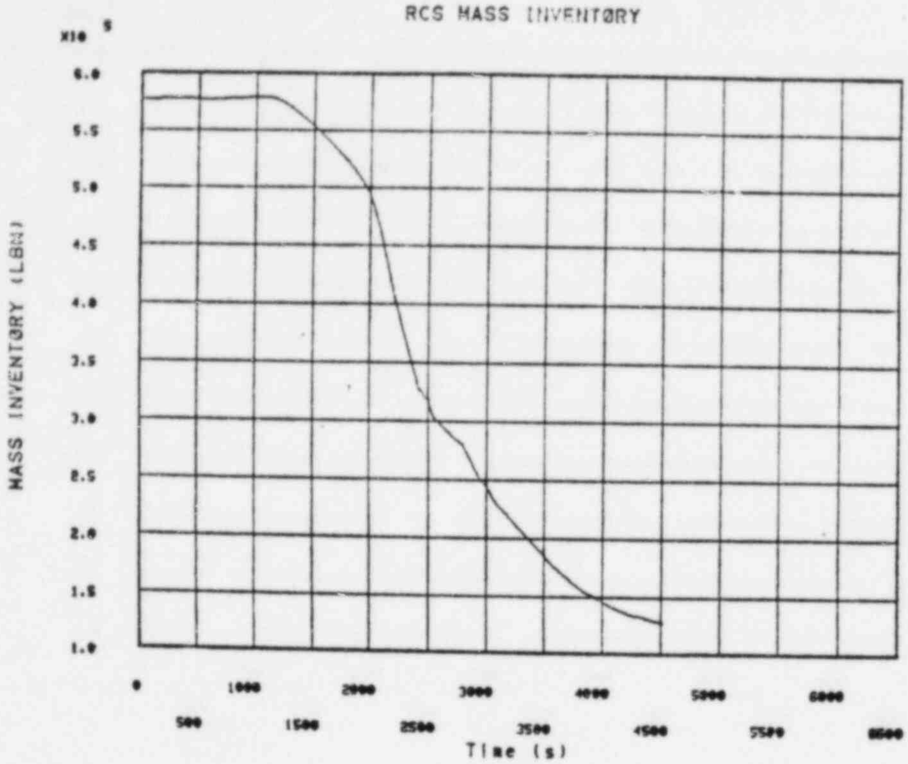


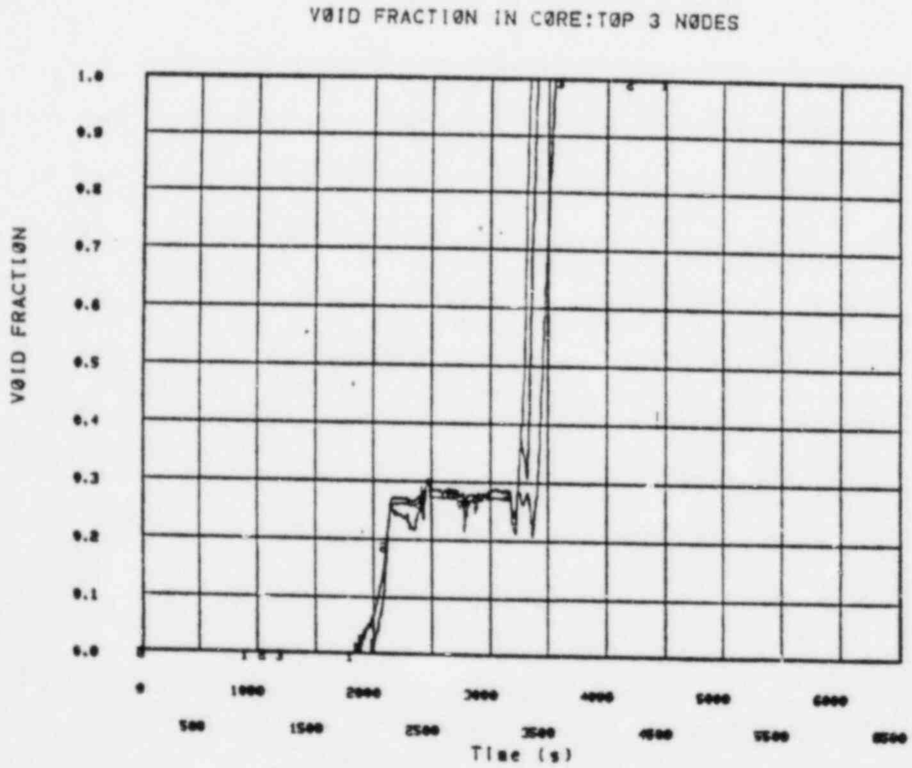
Fig. 4.40

DRAFT



CASE 4.

Fig. 4.41



CASE 4

Fig. 4.42

DRAFT

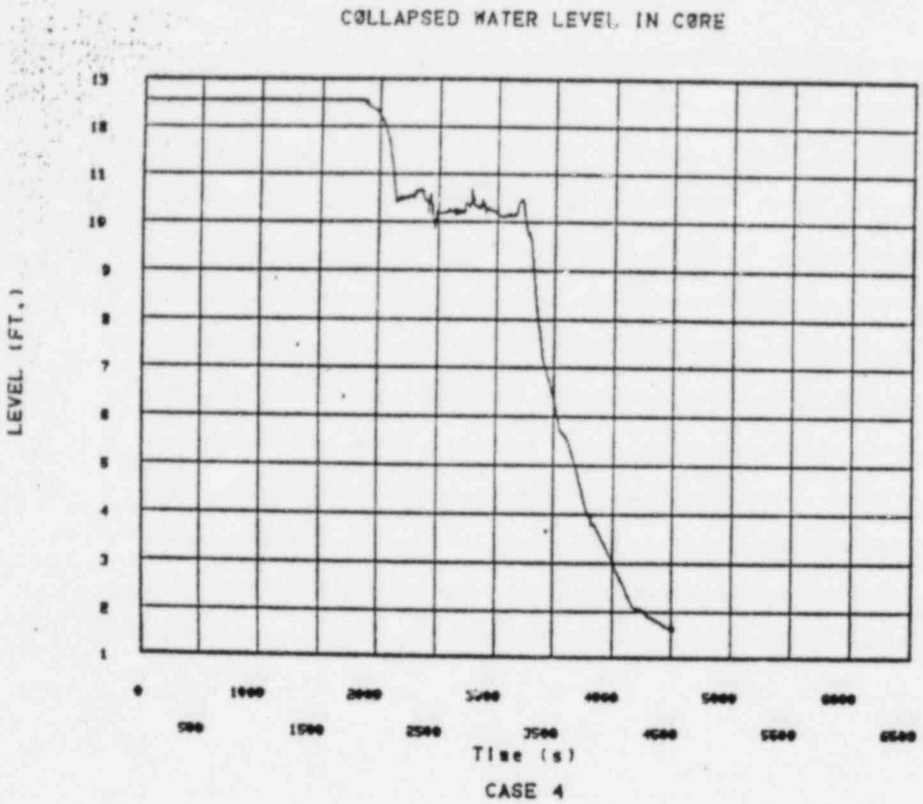


Fig. 4.43

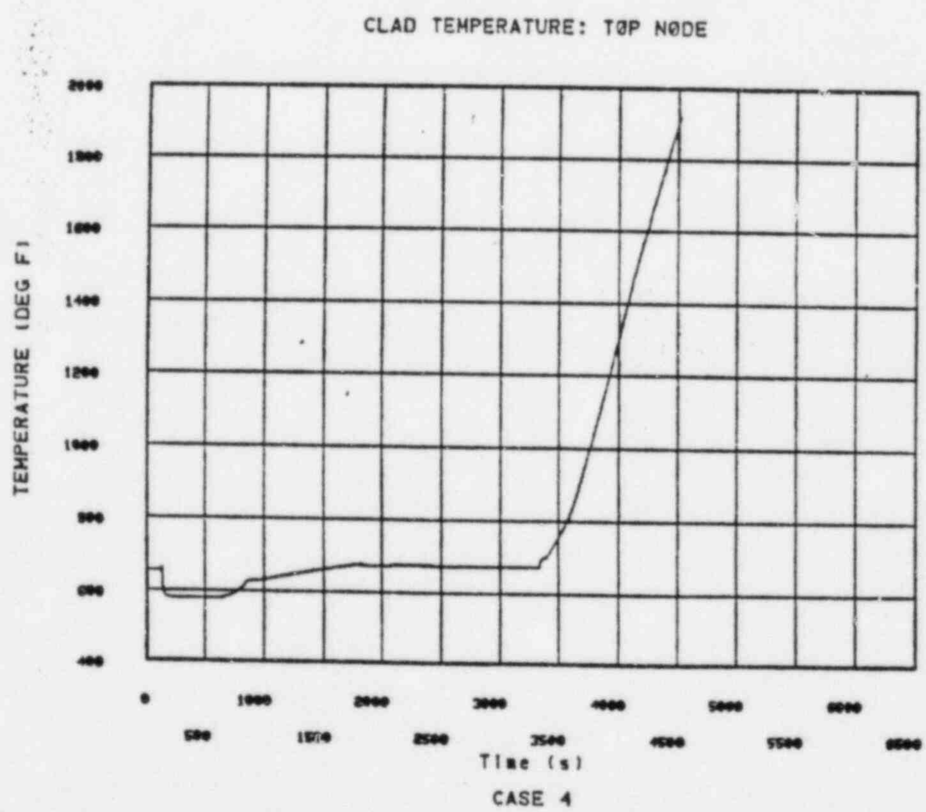
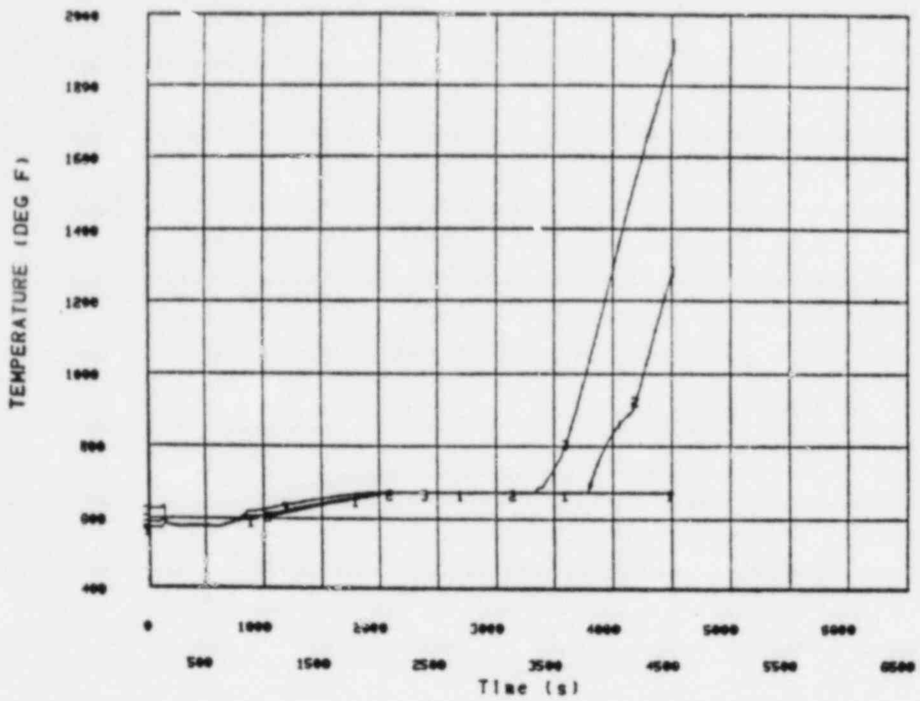


Fig. 4.44

DRAFT

CØRE CØØLANT TEMPERATURES: BTM, MID, TØP



CASE 4

Fig. 4.45

DRAFT

4.3 Feed and Bleed Operation

In this section we present results from four cases where "core flushing" (feed and bleed) was utilized to attempt to cool the core by opening a PORV and aligning the SIS for cold leg injection. "Core flushing" takes place when the cold fluid enters from the cold legs passes through the core and out the PORV.

Assumptions in this transient are:

1) Two PORVs were simulated in each analysis and

2) Two different sizes were examined with the following combined (total) flowrates
   a) 119.7 lbm/s (113.4 lbm/hr/MWt) (nominal)
   b) 268.1 lbm/s (254.0 lbm/hr MWt) (giant)

3) The PORVs were assumed to be manually opened after 20 minutes into the transient and to remain open.

4) One train of SIS was assumed to be available (i.e., one HPSI pump).

Other than to open the PORVs and to shut off the RCPs in those cases based on Case 2, no further operator actions were assumed required.

The PORVs were sized in the code to deliver the rated VAPOR mass flowrate at 2400 psia. However it is important for the reader to recognize that the two-phase flowrate is substantially greater and is not well known. Thus these (and any other) analyses should be taken to be only representative of the general behavior to be expected and the fine details of the analysis, while interesting, have substantial uncertainties.

DRAFT

4.3.1 Case 3ai

This case and the next case (3bi) are both identical to Case 1 up to 20 minutes into the transient when the PORVs were manually opened. In ths case we assumed the small PORVs while the next uses large PORVs. A significant amount of energy was removed through the PORVs when the flow out of these valves was a single-phase vapor; however as the flow leaving the PORVs became two-phased, the energy removal slowed down, hence the primary pressure decrease also slowed down (Fig. 4.46, 4.47, and 4.48) and briefly began to repressurize when the quality in the PORV flow reached 0.0 (single-phase liquid). At that point the pressurizer was solid. This slight upturn in the primary pressure was aggravated by the steam generator relief valve closure until the secondary side pressure built up enough to open relief valves again.

The HPSI was actuated at about 1255 seconds into the transient when the primary pressure fell below 1600 psia shortly after the PORVs were opened (Fig. 4.49). As the RCS depressurized, HPSI flowrate into the cold leg increased and because the injected fluid was at 120°F, the HPSI flow also contributed to further reduction of the RCS pressure. This depressurization in turn permitted higher HPSI flow, so that the symbiotic effects resulted in a relatively monotonic increase of HPSI flowrate.

The combination of opening the PORVs, which resulted in loss of RCS inventory, and the HPSI injection of cold fluid, which lowered the RCS average temperature and therefore led to contraction of RCS fluid, eventually caused voiding in the RC system (Figs. 4.50, 4.51, and 4.52). Void formation was evident in the core as early as 1500 seconds into the transient. From that time onward, the primary inventory decreased monotonically and the void in the surge line finally reached 1.0 at slightly after 3000 seconds (Fig. 4.53). As we saw in case 2, a drop in the pressurizer inventory accompanied voiding in RCS and finally reached the pressurizer through the surge line (Fig. 4.54). As discussed earlier, the delay is due to the fact that the surge line is connected to the bottom of the hot leg pipe, and until 3100 seconds into the transient the flow in the horizontal hot leg was stratified so that the insurge into the pressurizer was extracting only the liquid portion of the flow from the hot leg until the flow in the hot leg became pure steam.

DRAFT

The temporary drop in the void fraction in the core at roughly 4000 seconds after transient initiation (Fig. 4.52) was due to a clearance of one of the loop-seals which forced cold fluid to flow into the core (Fig. 4.55).

During the period for which the PORV flow was two-phase mixture the RCS pressure had leveled off, but when the flow momentarily became pure vapor at ~ 4200 seconds (Fig. 4.48) the pressure dropped again and the HPSI flow increased. The system pressure continued to decrease, eventually reaching the accumulator injection setpoint (640 psia) about 5325 seconds into the transient. *By 5000 seconds, the system had depressurized enough for the HPSI flow to turn over the RCS inventory. With the accumulator flow, the net flow into RCS was positive (Fig. 4.56). Core uncovery was not computed to occur in this case (Figs. 4.52, 4.57 and 4.58).*

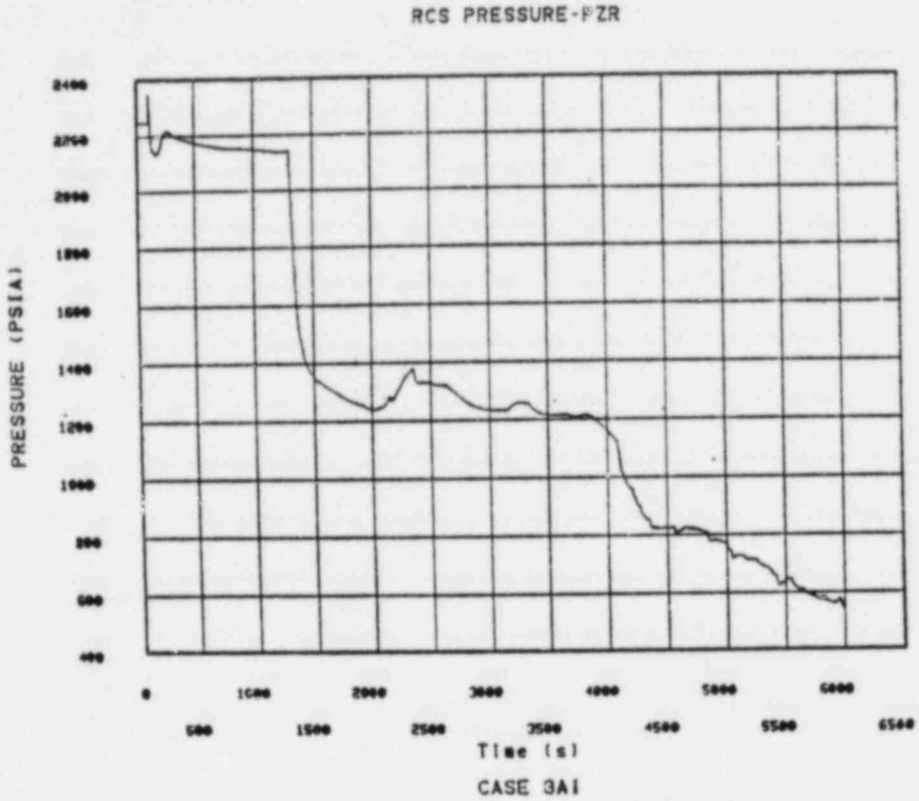


Fig. 4.46

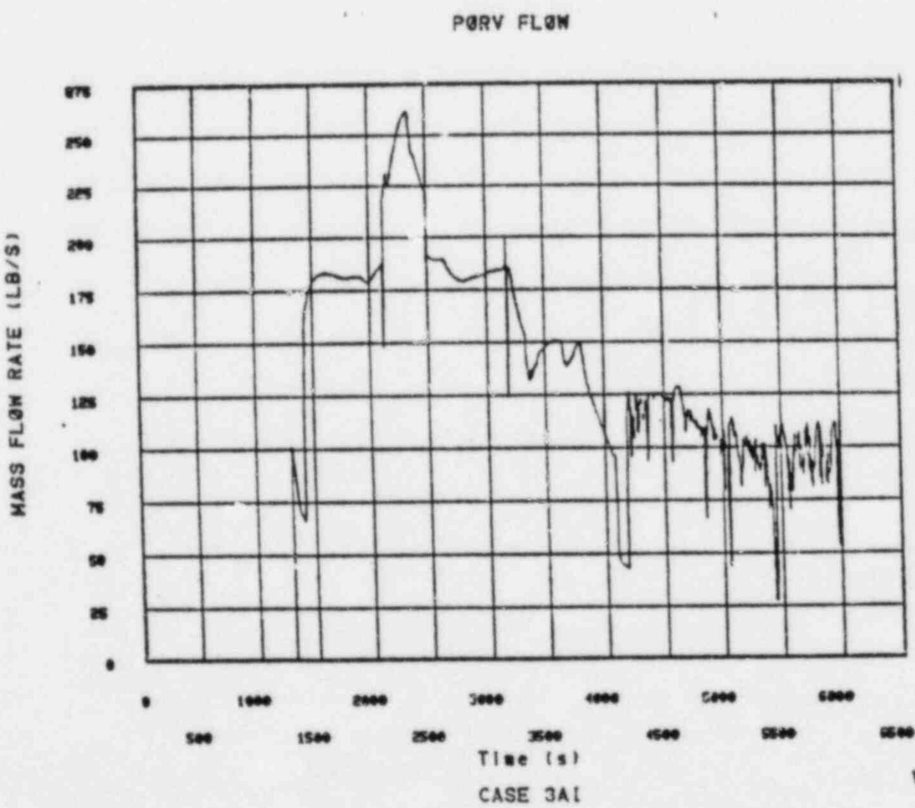


Fig. 4.47

DRAFT

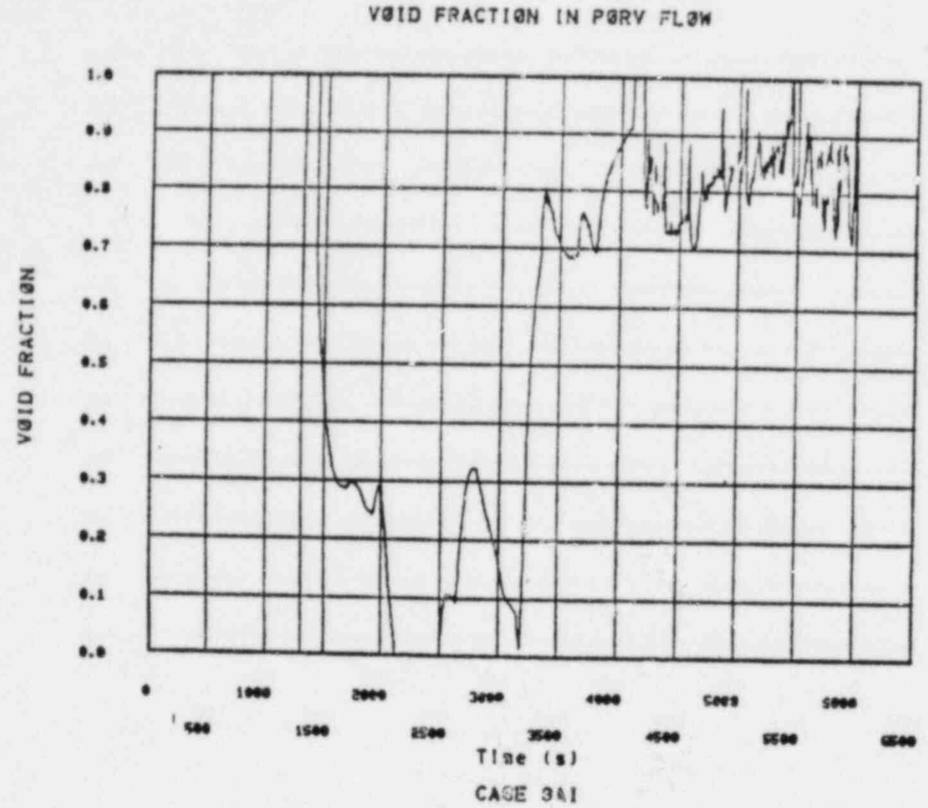


Fig. 4.48

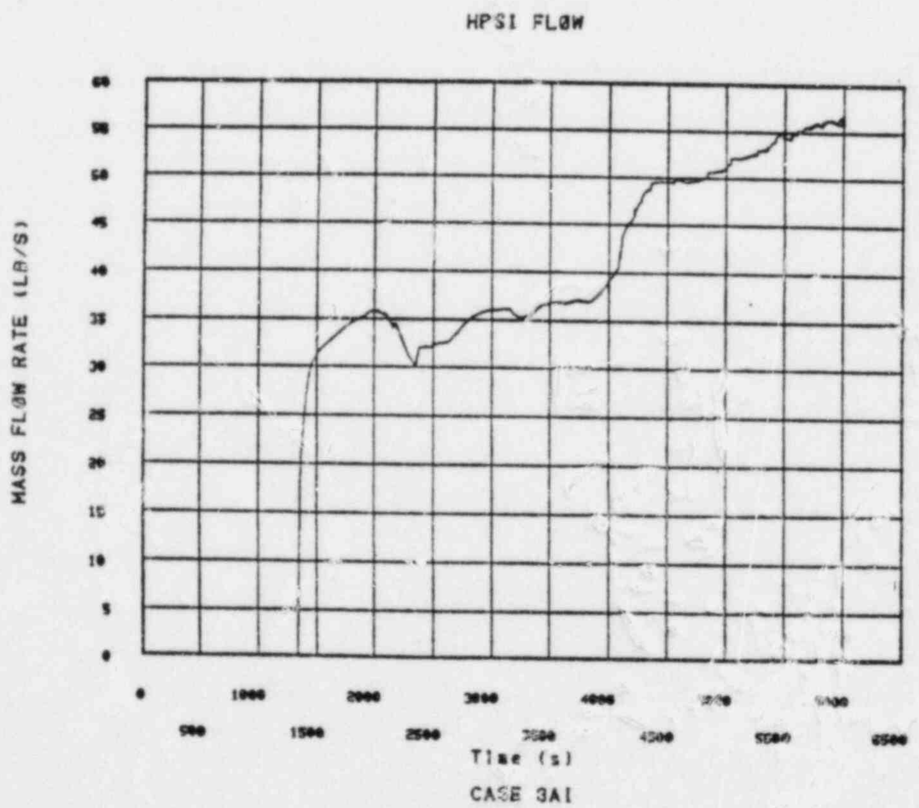


Fig. 4.49

DRAFT

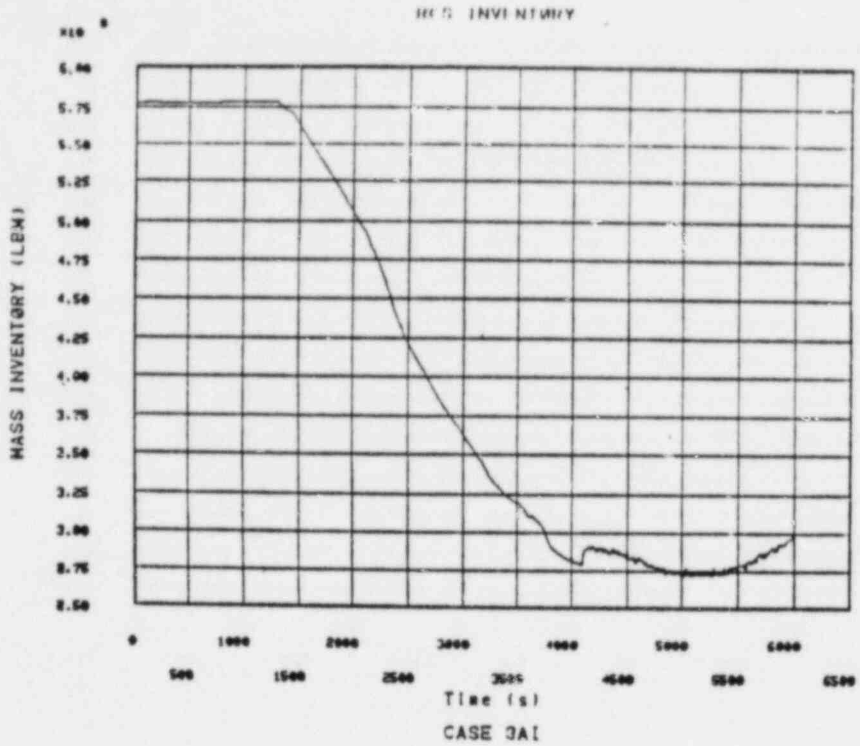


Fig. 4.50

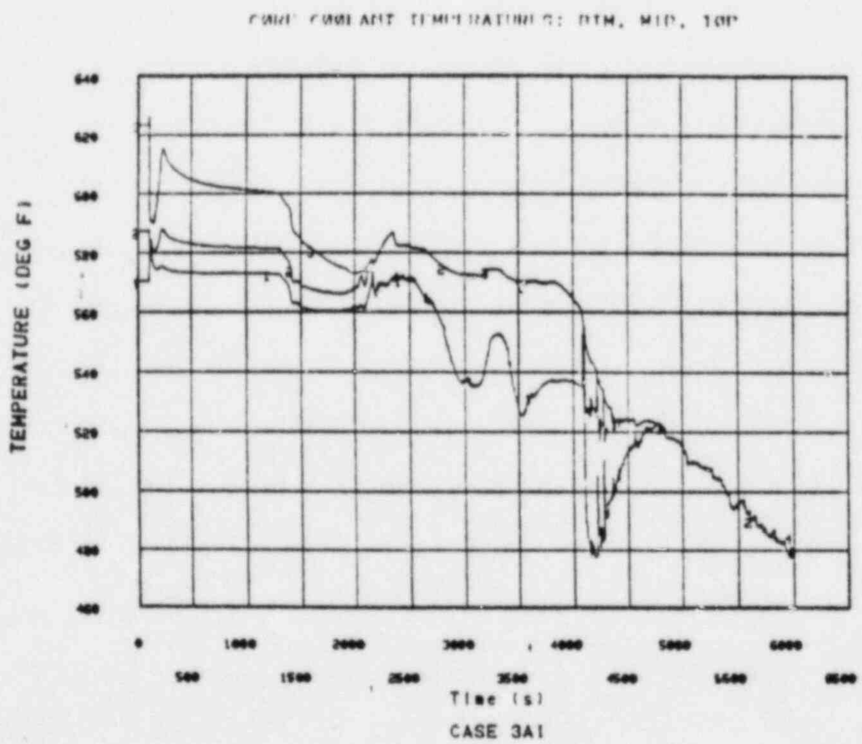
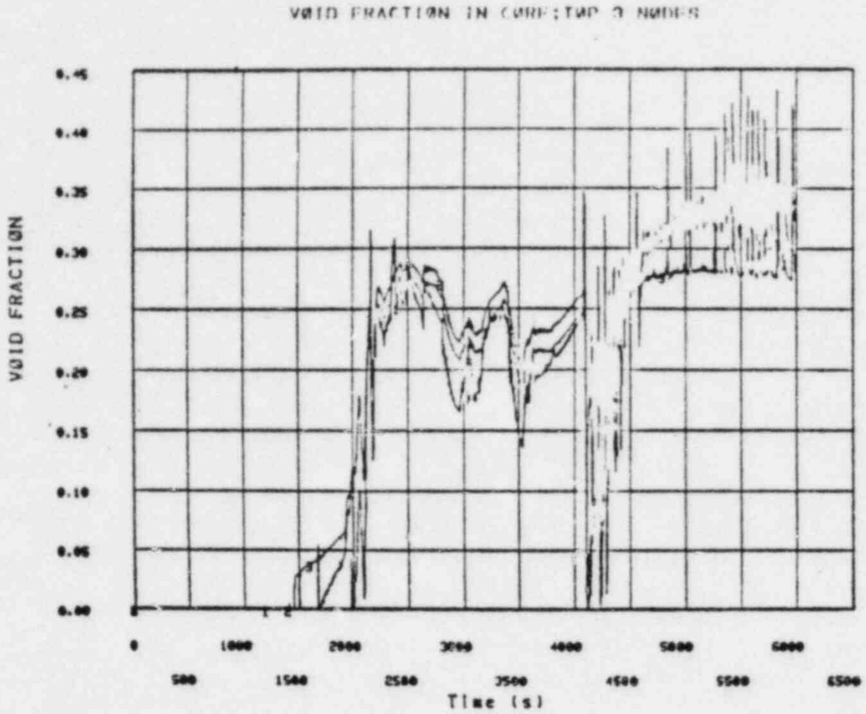


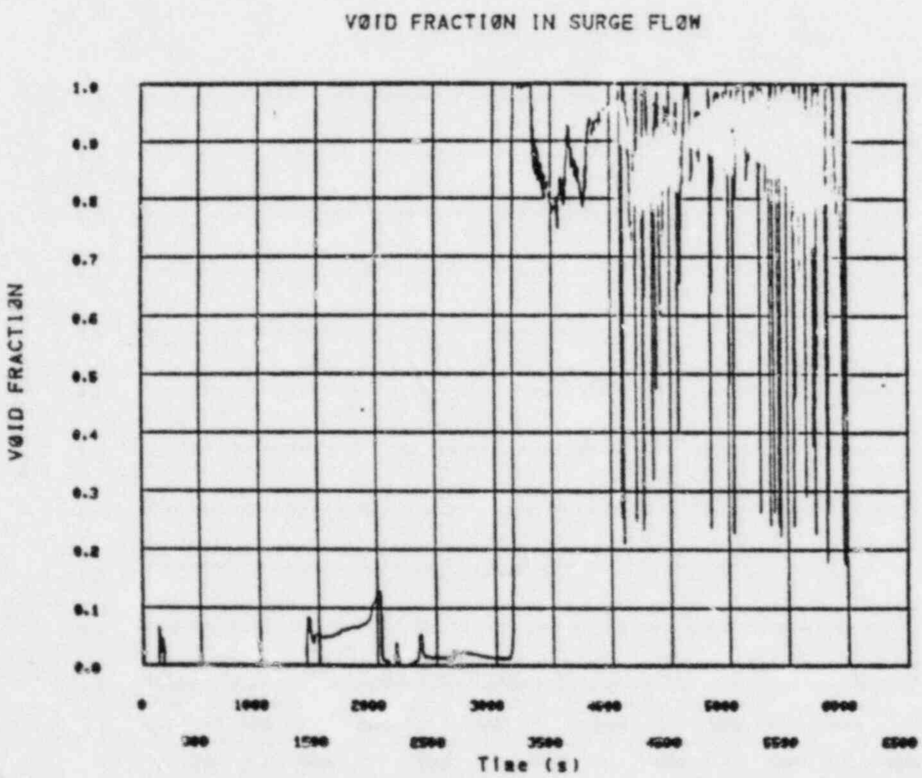
Fig. 4.51

DRAFT



CASE 3AI

Fig. 4.52



CASE 3AI

Fig. 4.53

DRAFT

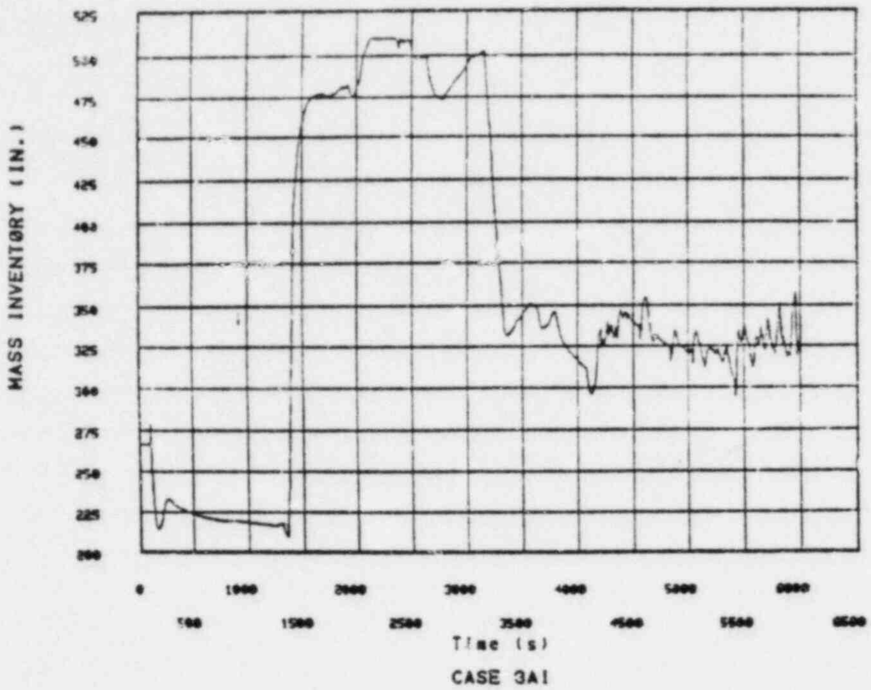


Fig. 4.54

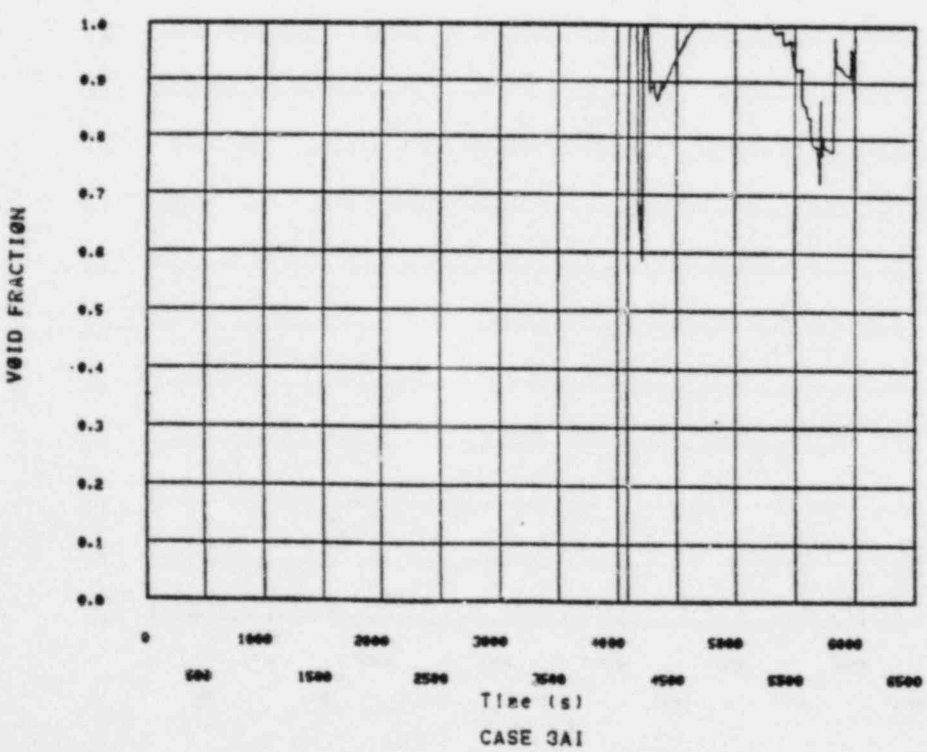


Fig. 4.55

DRAFT

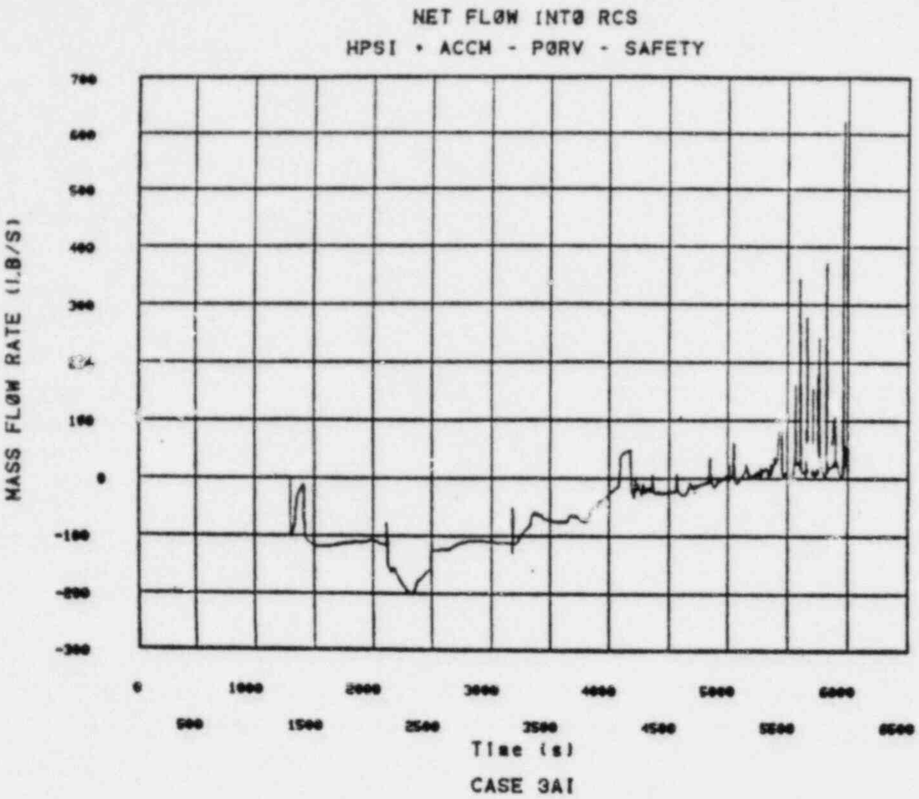


Fig. 4.56

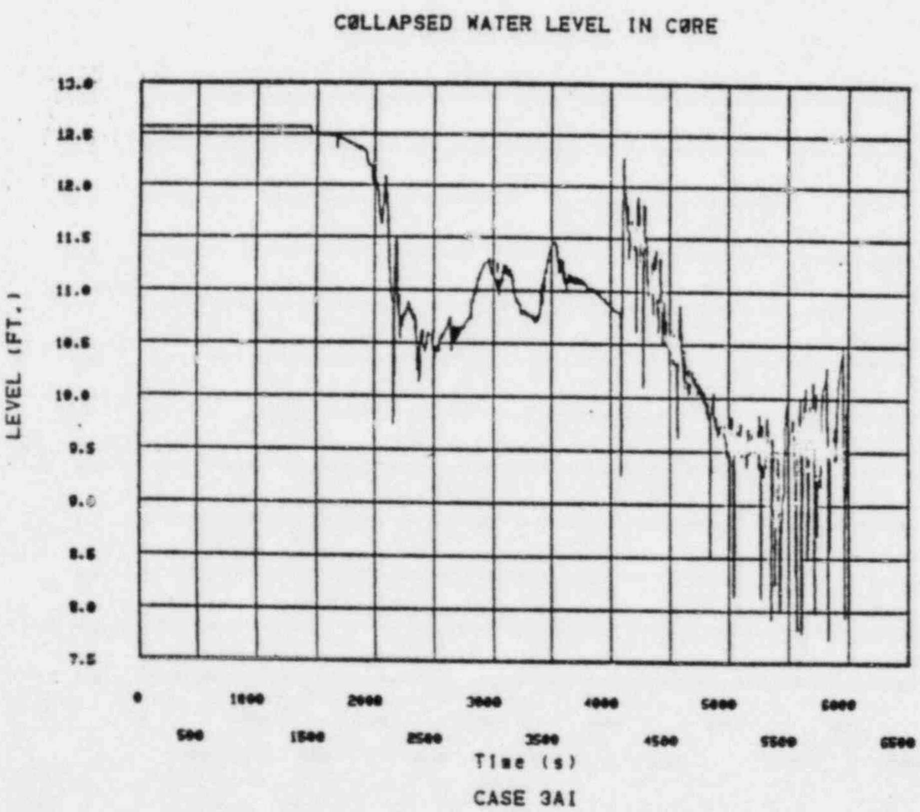


Fig. 4.57

DRAFT

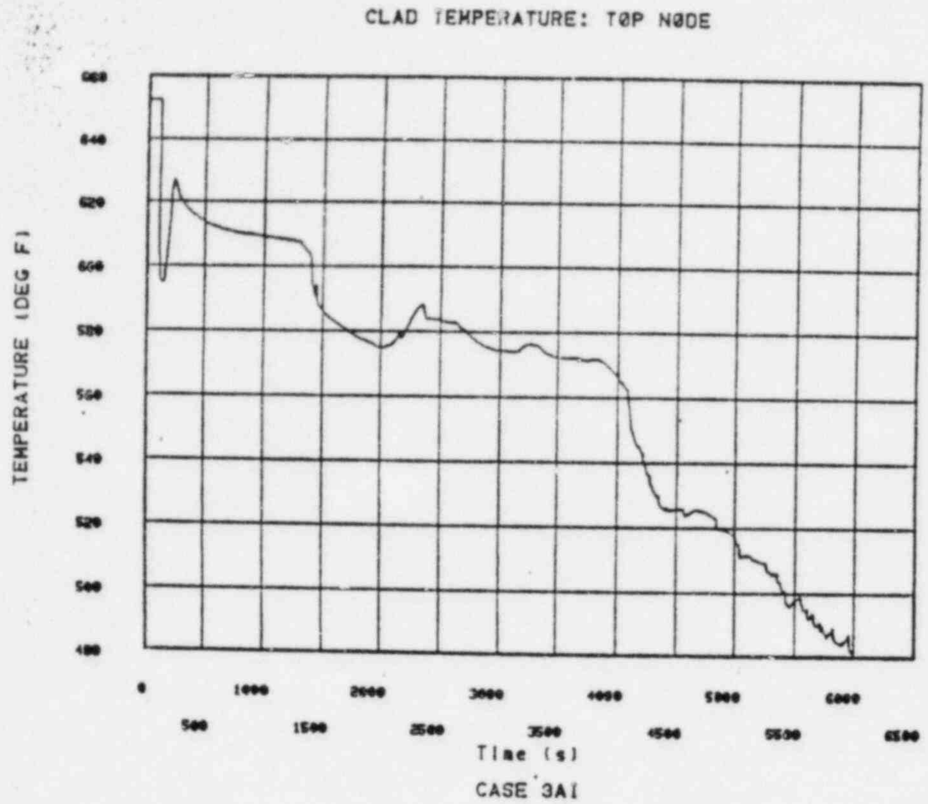


Fig. 4.58

DRAFT

4.3.2 Case 3bi

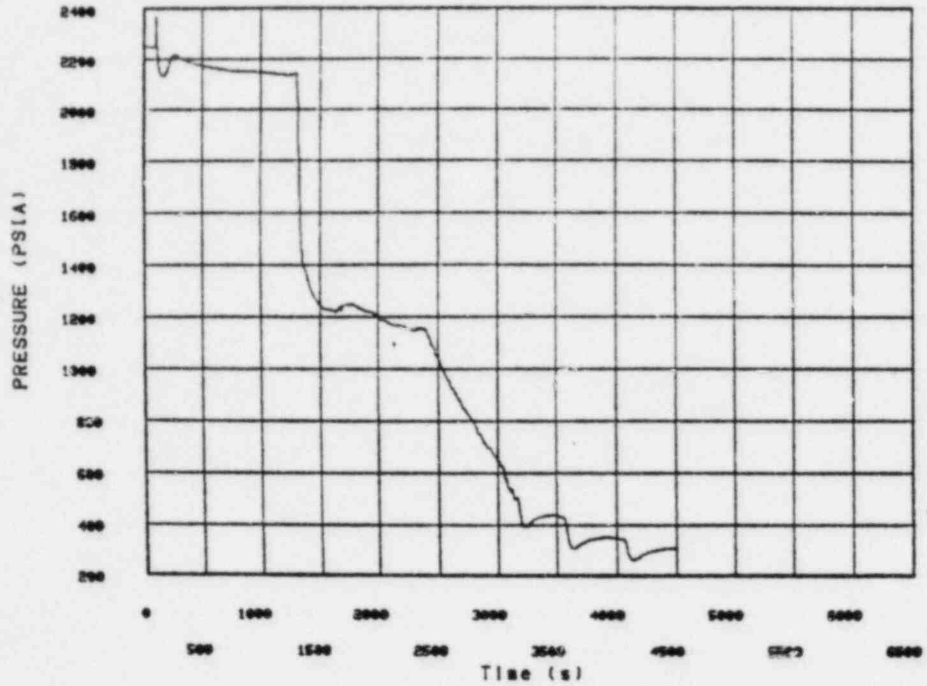
This case is identical to case 3ai, except that we used the larger PORV size through which more energy can be removed. The RCS pressure dropped to approximately 1200 psia compared to 1350 psia with smaller PORVs (Figs. 4.59, 4.60, and 4.61). The HPSI was actuated immediately following the opening of the PORVs (Fig. 4.62), and the flow continued to increase as long as the RCS pressure continued to drop (as expected). In that case the system depressurized and cooled down so rapidly that the steam generators did not dryout (Fig. 4.63). More liquid was discharged from the PORVs permitting generation of void in the RCS system to take place earlier (Fig. 4.64). The dip in the void fractions in the core at 1900 seconds into the transient was, as in the prior case, due to loop-seal clearance (Fig. 4.65). The void fractions in the core increased when the accumulator injection was on because the cold accumulator flow condensed the vapor and cooled the core inlet temperature causing mixture collapse (compare Figs. 4.64, 4.66, 4.67 and 4.68).

The RCS inventory appeared to bottom out by 3500 seconds after the onset of transient, and although it was fluctuating, tne trend seems to be up (Fig. 4.69). The collapsed water level in the core also stabilized, with occasional dips also due to accumulator injection. No core uncovery was computed to occur in this case.

Although none of the other cases analyzed encountered mass error problems with RELAP5, this case originally had significant problems. With assistance from the RELAP5 code developers who prepared code modifications to cure these errors, we were able to complete the study without any further code problems. Hence, this particular transient was run with these code updates, while the remainder were not. For completeness, selected parameters were compared for this transient using the original code and the updated version. These results are pesented briefly in Appendix 1. We point out here only that the differences in major plant transient parameters are negligible.

DRAFT

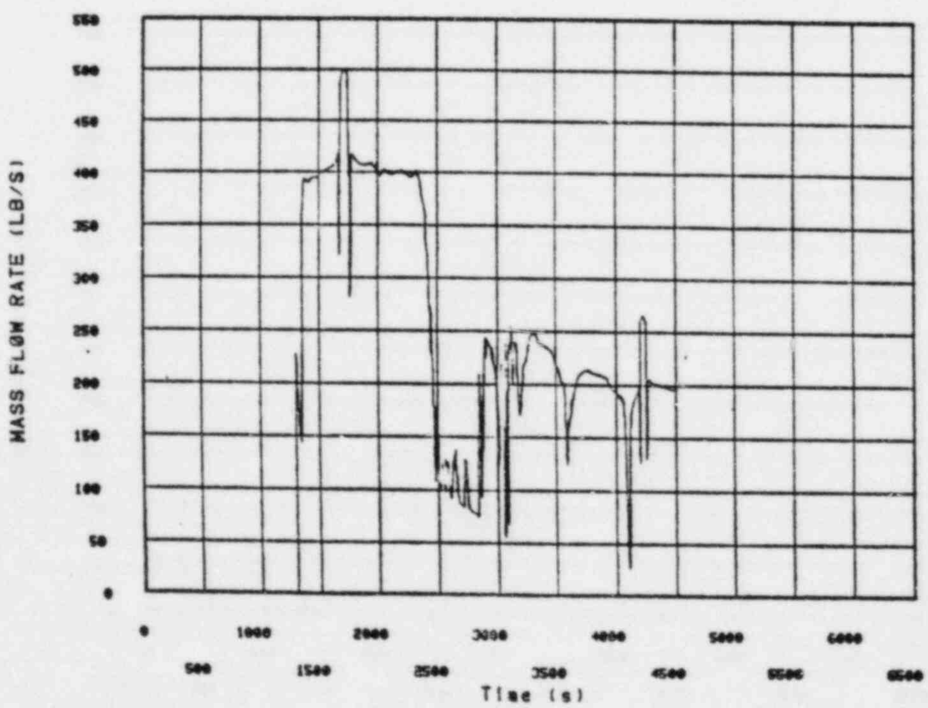
RCS PRESSURE-PZR



CASE 3BI

Fig. 4.59

PØRV FLØW



CASE 3BI

Fig. 4.60

DRAFT

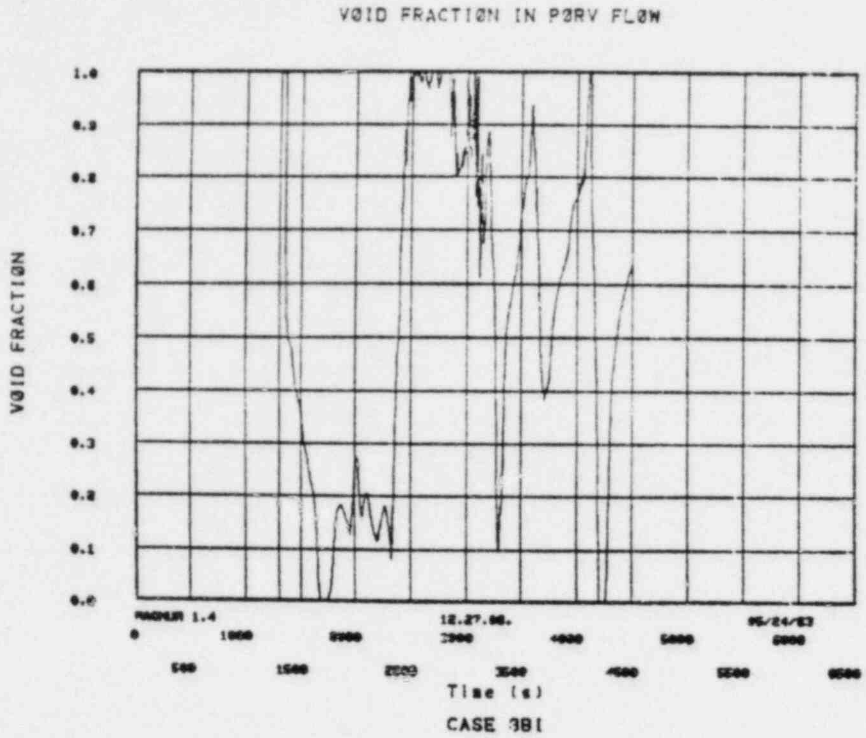


Fig. 4.61

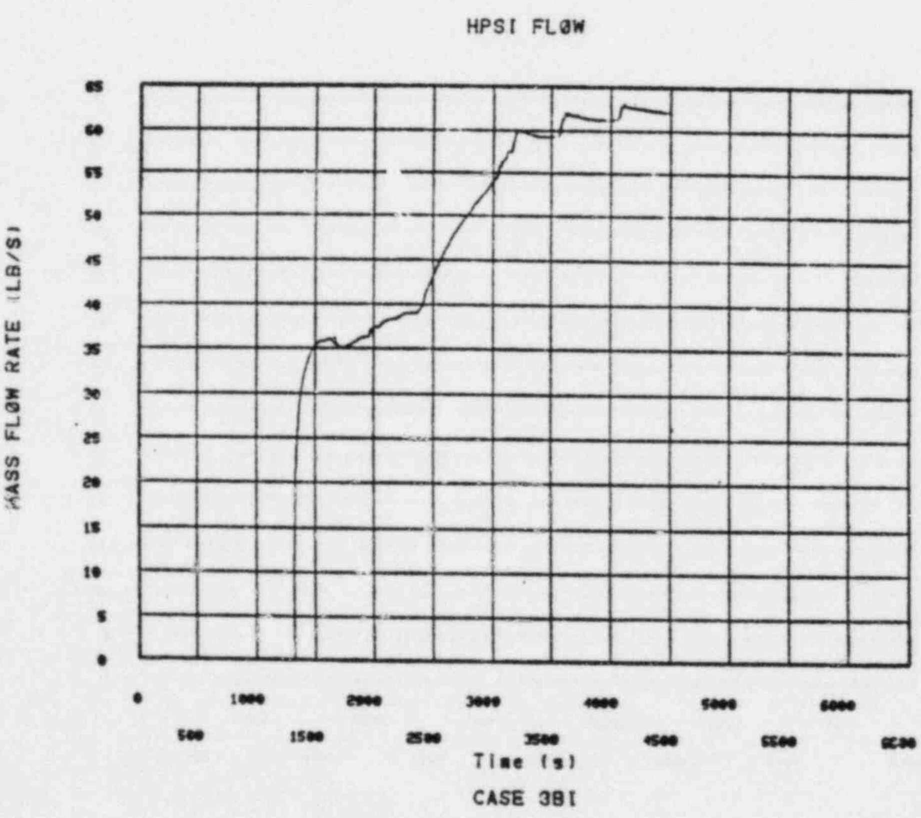
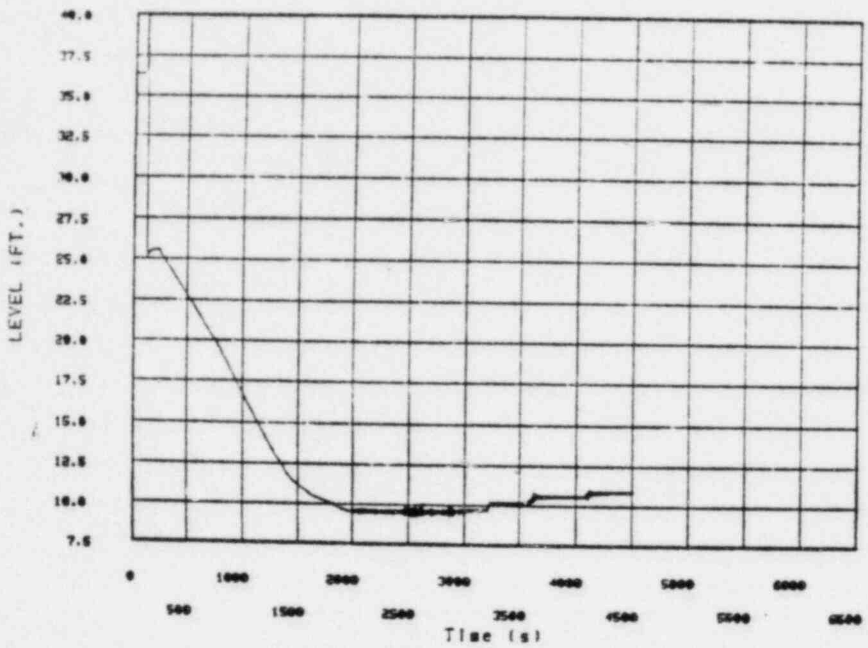


Fig. 4.62

DRAFT

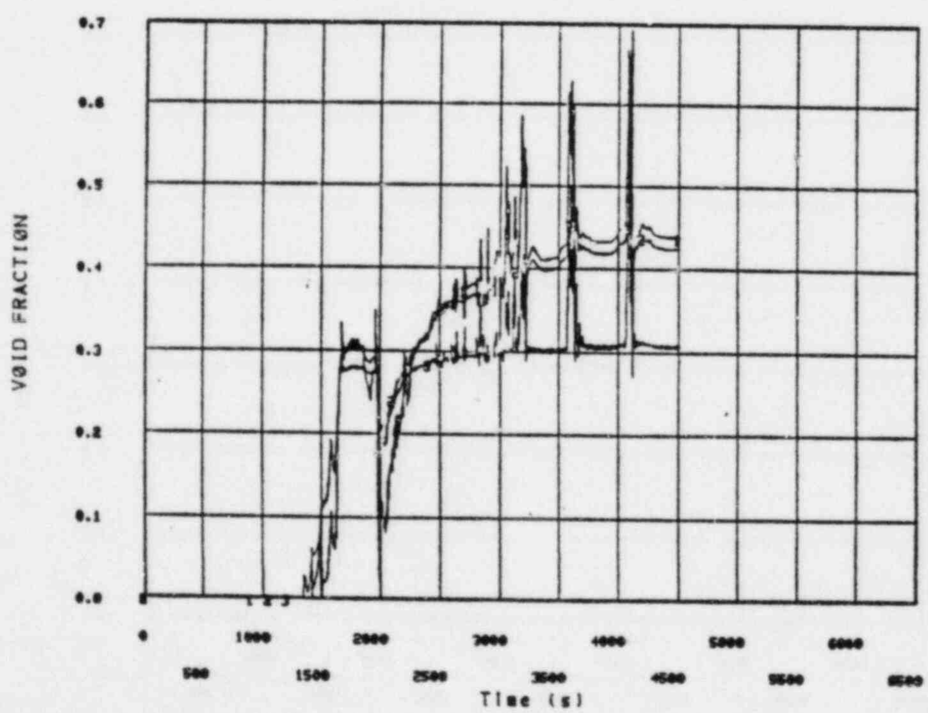
STEAM GENERATØR WATER LEVEL IN SG1



CASE 3B1

Fig. 4.63

VØID FRACTIØN IN CØRE: TØP 3 NØDES



CASE 3B1

Fig. 4.64

DRAFT

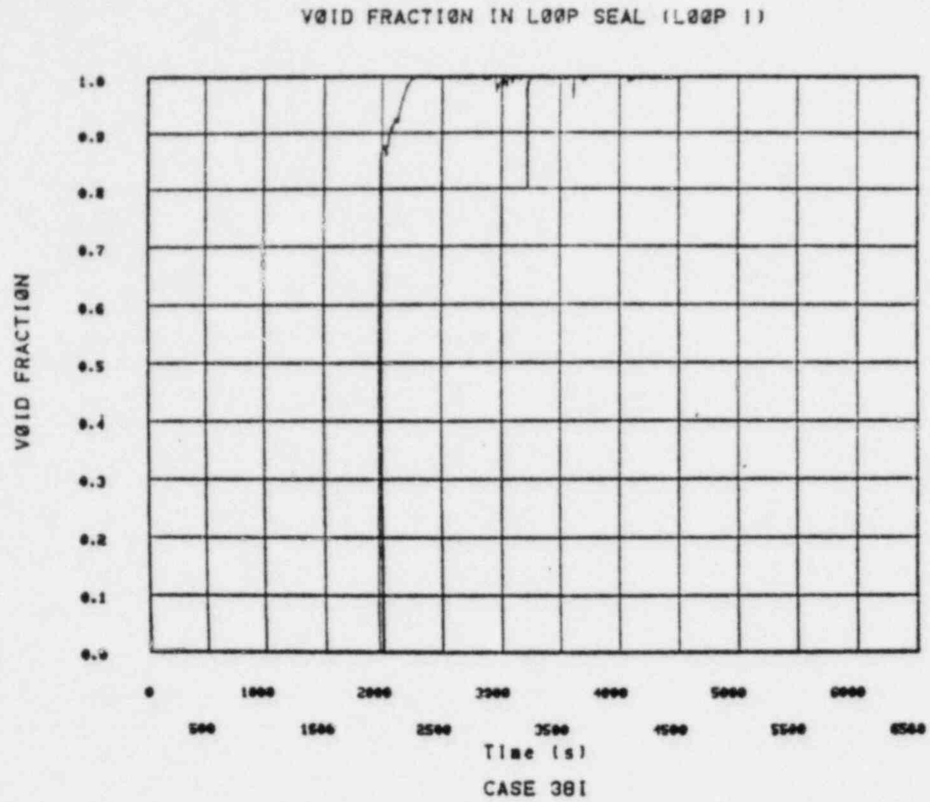


Fig. 4.65

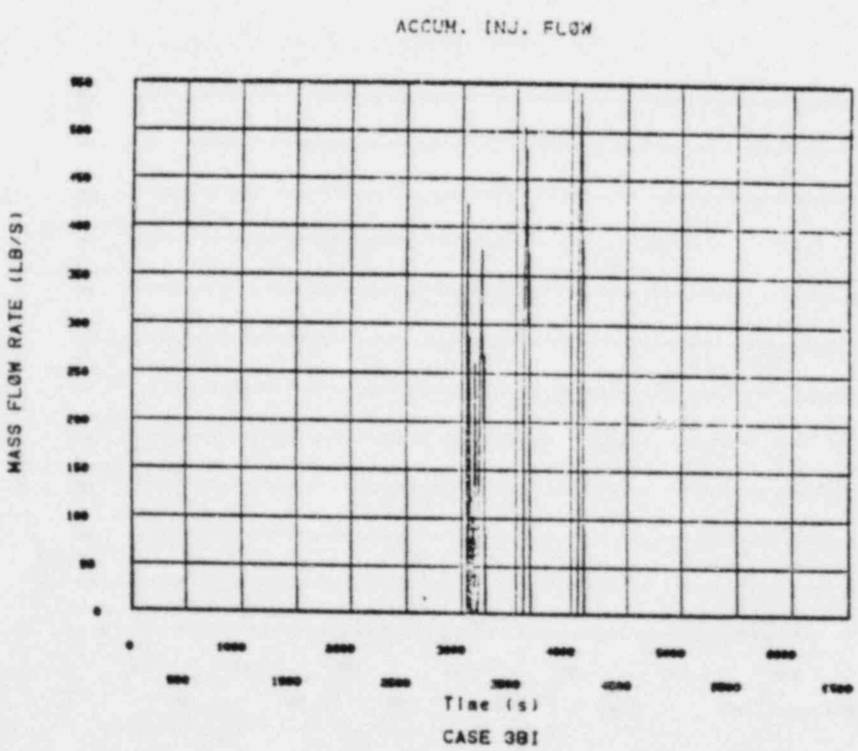
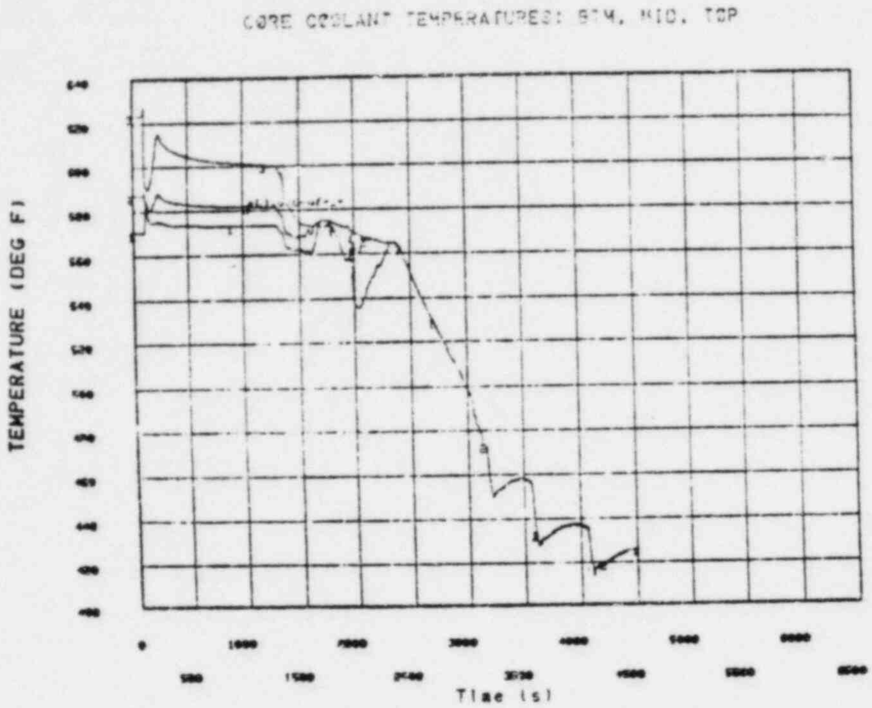


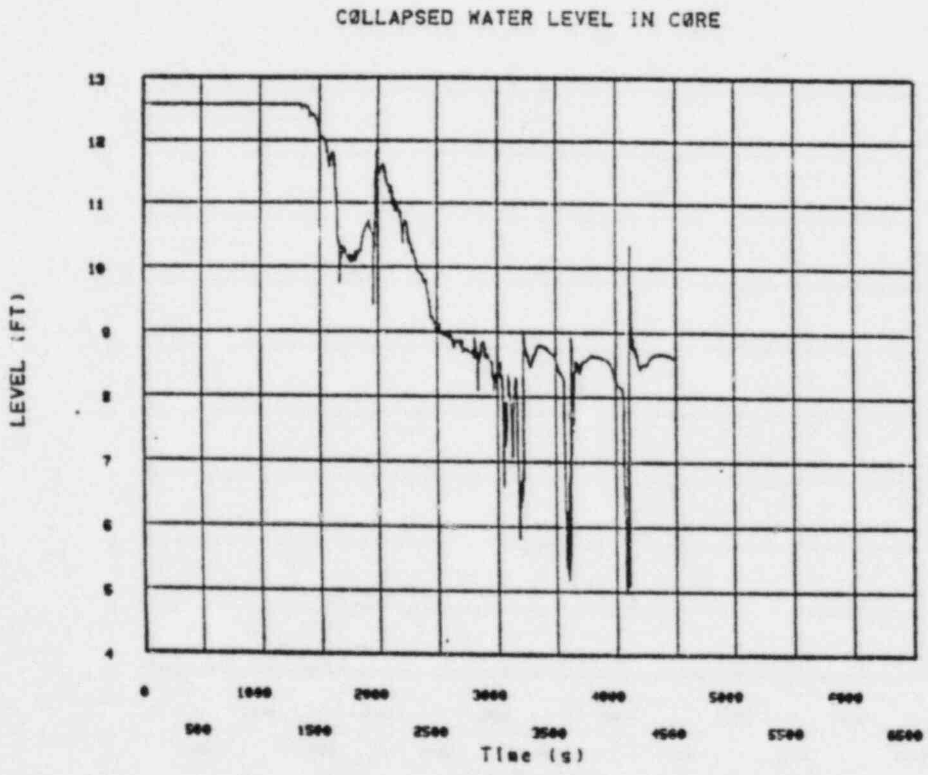
Fig. 4.66

DRAFT



CASE 3BI

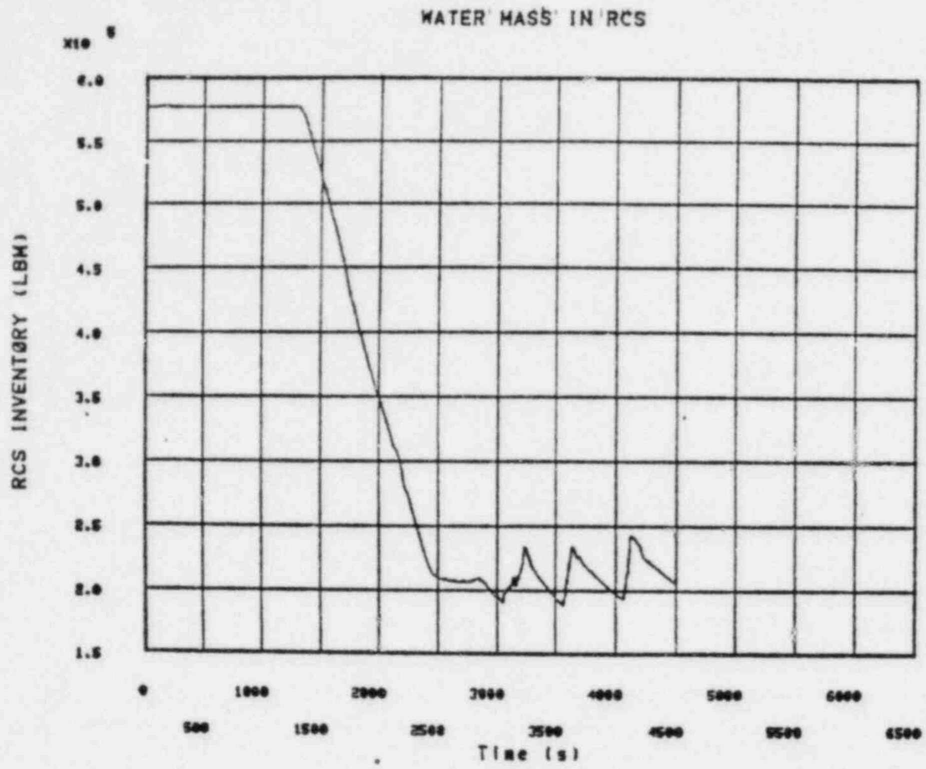
Fig. 4.67



CASE 3BI

Fig. 4.68

DRAFT



CASE 3BI

Fig. 4.69

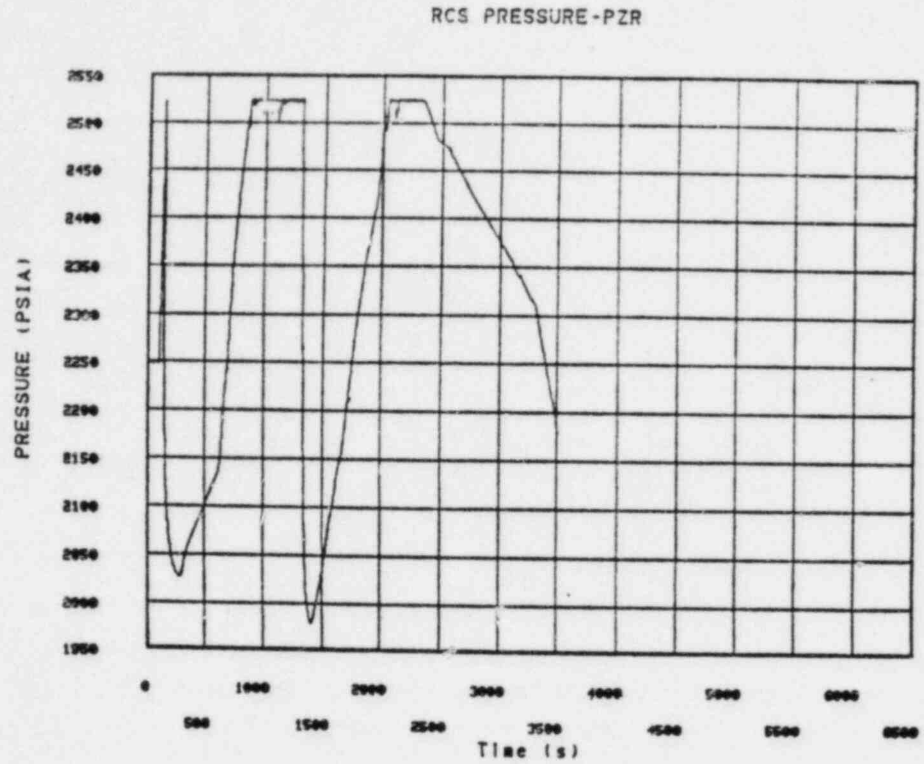
DRAFT

4.3.3 Case 4ai

This case and the following case (4bi) are identical to Case 2 (ten minutes of RCP operation) up to 1200 seconds (20 minutes into the transient) when the PORVs were opened. As with the previous two cases, in 4ai we study the effect of the small PORVs while in 4bi we study the effect of the lare PORVs. We note that by the time the PORVs were opened the RCPs had been tripped (at 10 minutes after transient initiation) and both steam generators (this plant is nearly symmetric) were dried out (Fig. 4.26). Figure 4.70 shows that the RCS pressure was already at the pressurize safety valve setpoint and the RCS inventory was being discharged (Fig. 4.71). The pressurizer was nearly solid with water at this point (Fig. 4.72). When the PORVs were opened, the void fraction in the PORV flow indicated that the flow was single-phase liquid, which degraded the energy removal capability and the RCS pressure began to rise to the safety setpoint (Figs. 4.73 and 4.74). RCS pressure was, nevertheless, momentarily reduced by 450 psia due to opening the PORVs.

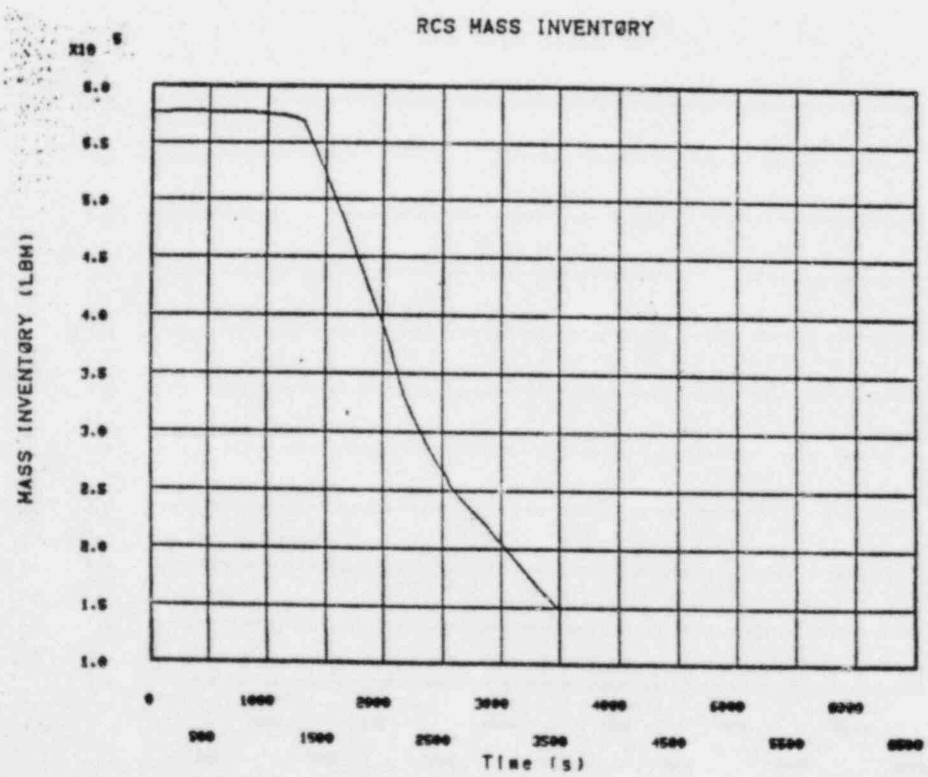
Void formation began as soon as the PORVs were opened and quickly propagated through the RCS up to the surge line and into the pressurizer. The inventory in the pressurizer dropped as the flow into the pressurizer became two-phased and finally pure steam (Figs. 4.75, 4.76 and 4.70). When the discharge out of the PORVs finally became two phased. and therefore began to remove energy at a greater rate, the RCS pressure began falling (about 2100 seconds into the transient). However, by 3050 seconds into the transient, the system had lost enough inventory that core uncovery was indicated by the core coolant temperatures, the liquid level in the core, and the cladding temperature (Figs. 4.77, 4.78 and 4.79).

This case indicates that the small PORVs were unable to depressurizer the plant enough to enable HPSI delivery to prevent core uncovery. As for Cases 2 and 4, 30 seconds of full power operation exacerbated the transient.



CASE 4AI

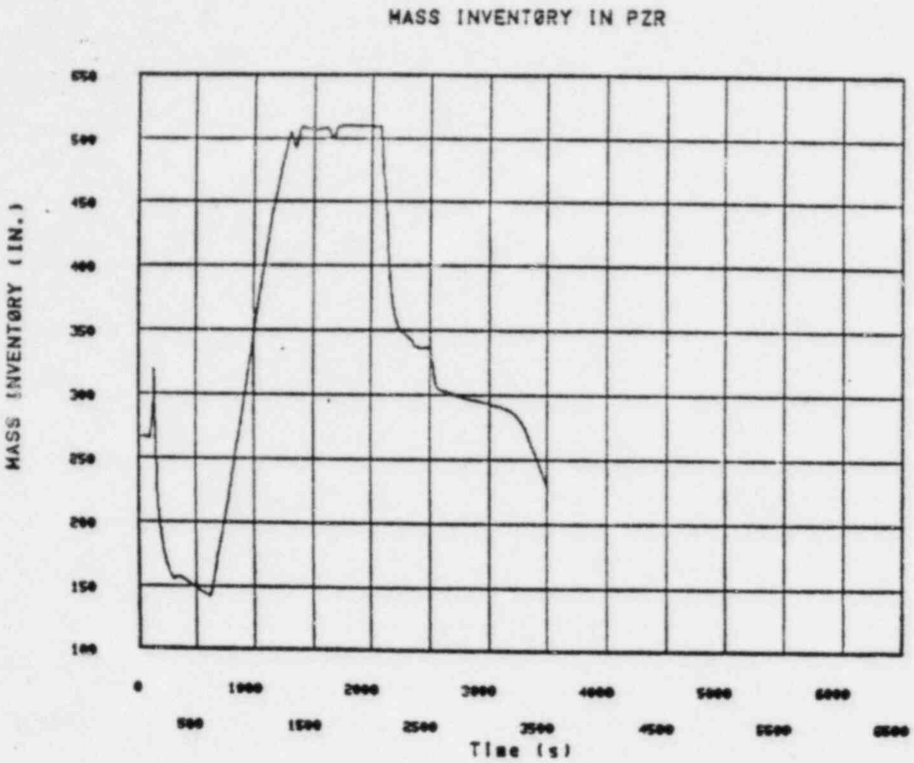
Fig. 4.70



CASE 4AI

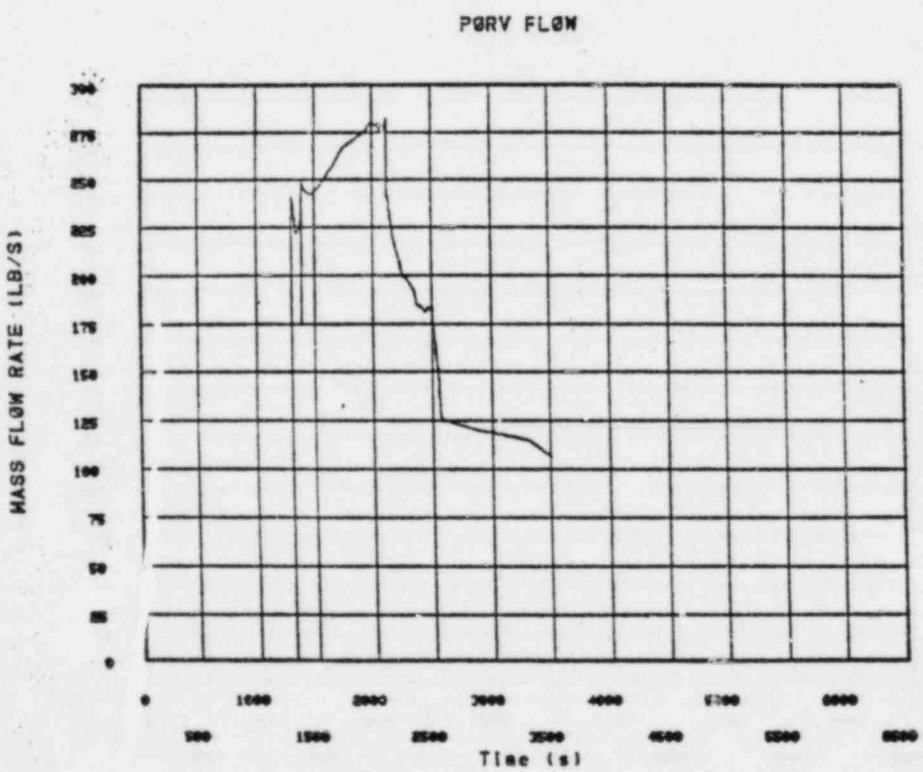
Fig. 4.71

DRAFT



CASE 4AI

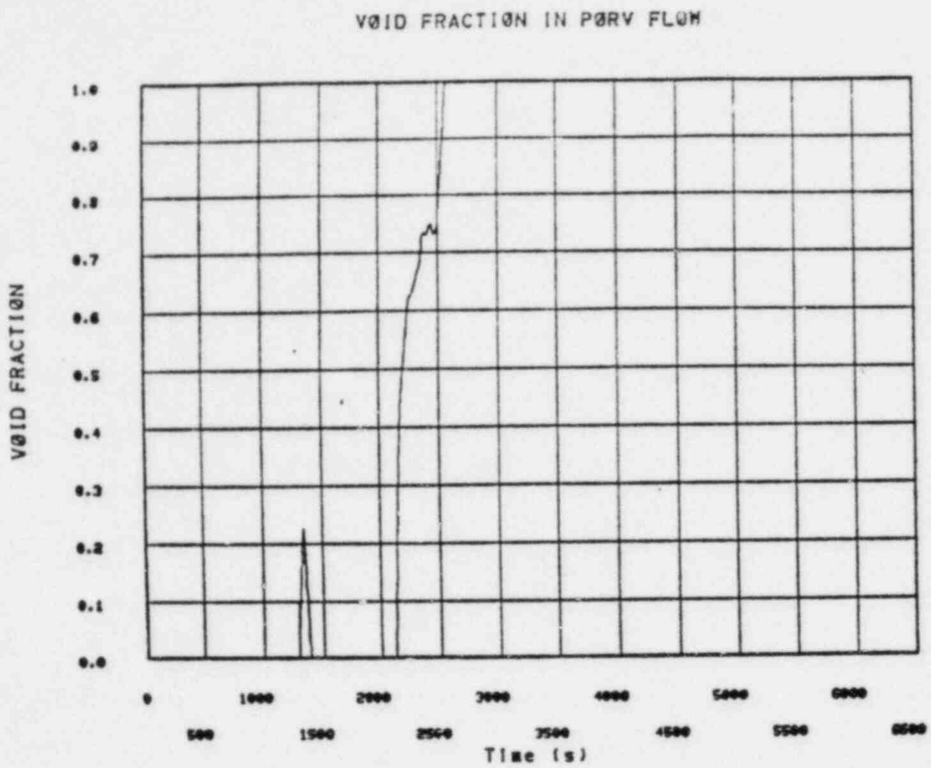
Fig. 4.72



CASE 4AI

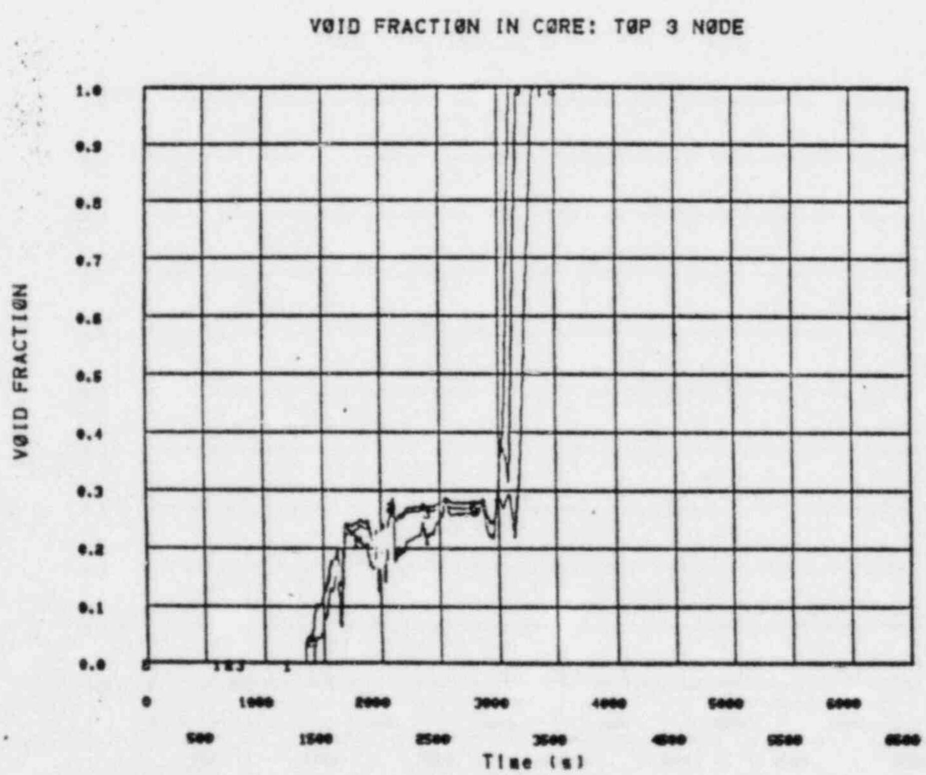
DRAFT

Fig. 4.73



CASE 4AI

Fig. 4.74



CASE 4AI

Fig. 4.75

DRAFT

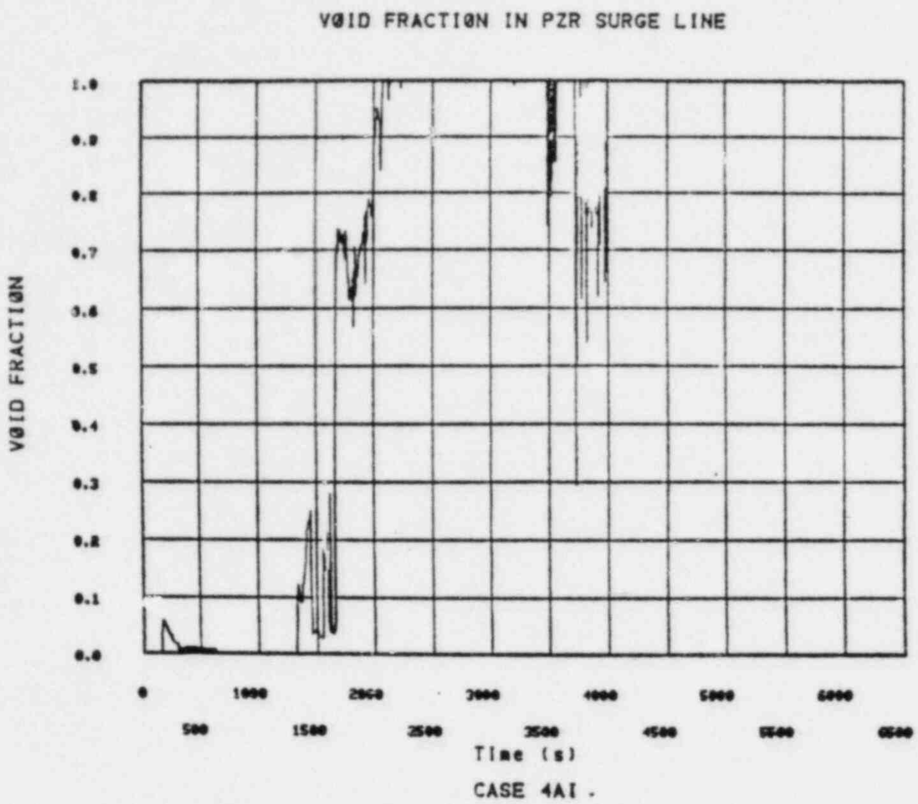


Fig. 4.76

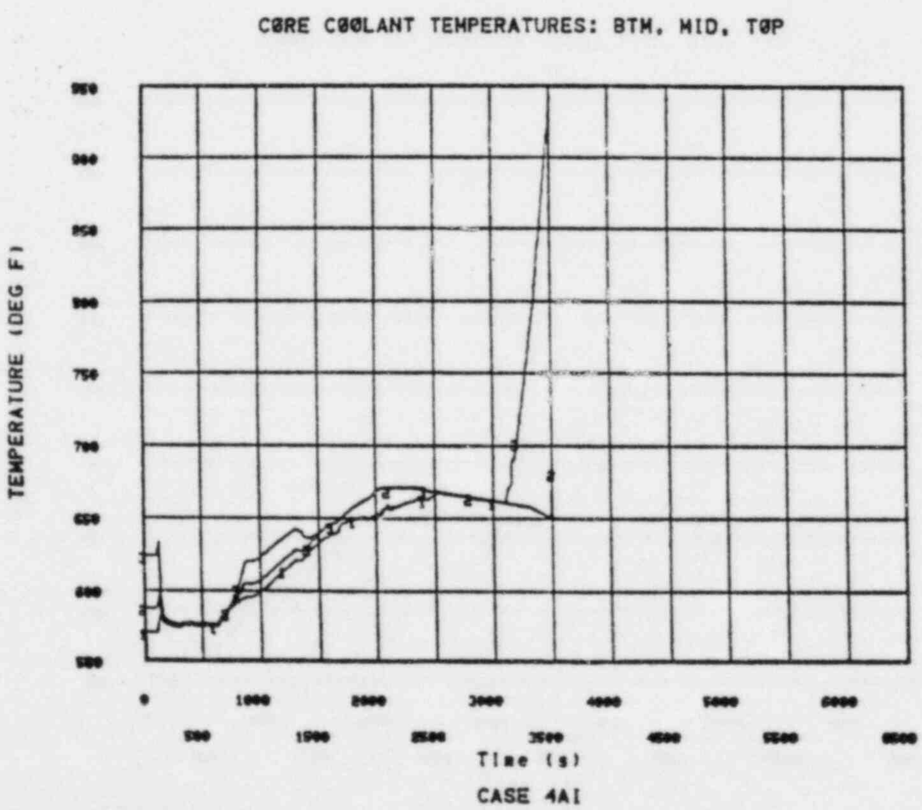


Fig. 4.77

DRAFT

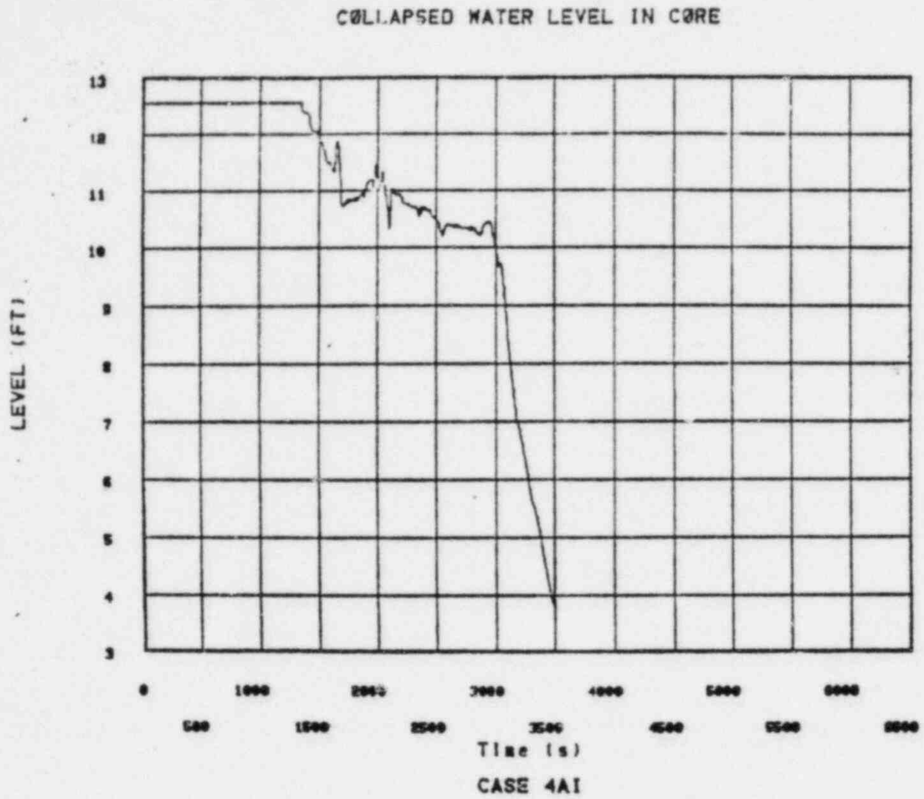


Fig. 4.78

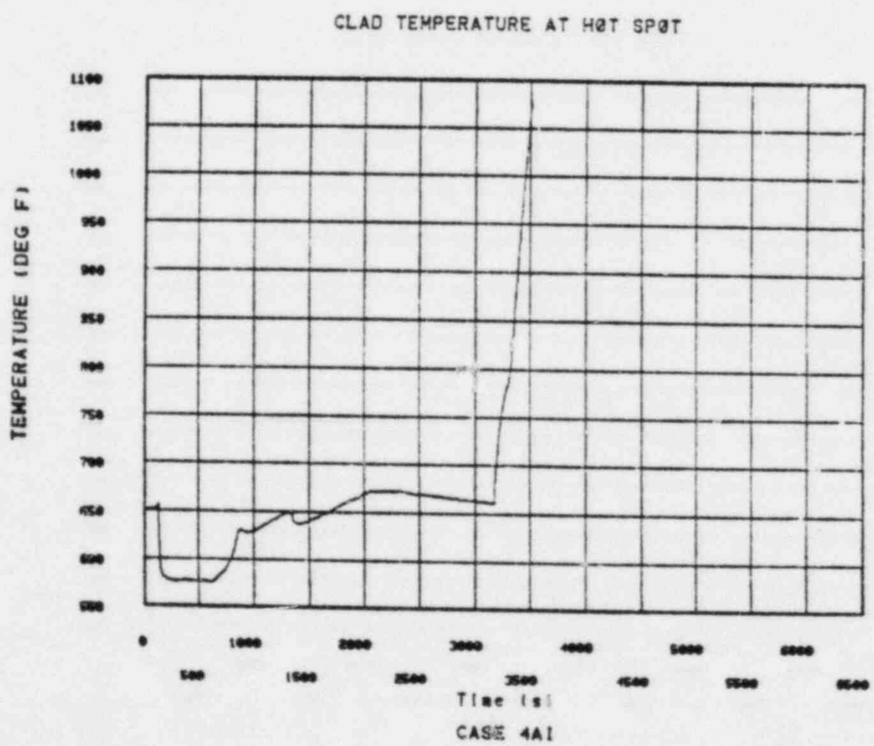


Fig. 4.79

DRAFT

4.3.4 Case 4bi

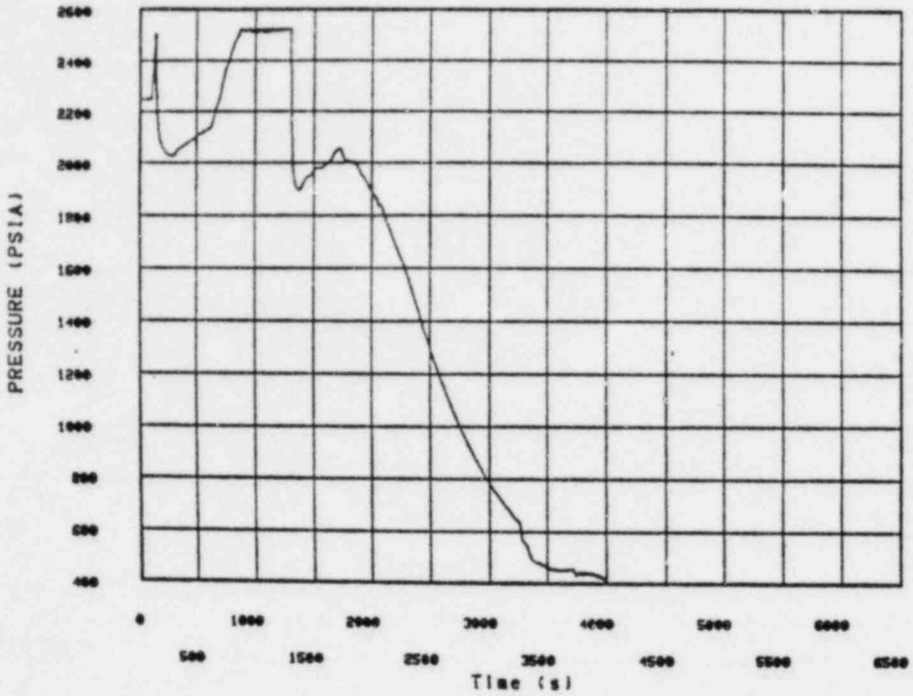
This case differs from 4ai only in that here the larger PORV size was utilized. All other conditions of the plant at the time of PORV opening were identical to Case 4ai. The flowrate through these larger PORVs was so great that even though the initial flow was nearly all liquid, it was able to pull the voids generated in the core immediately after the PORV opening through the surge line into the pressurizer. By 2000 seconds into the transient the PORV flow was pure steam (occurring about 500 seconds sooner than Case 4ai with smaller PORVs) and the RCS pressure fell rapidly.

In this case, the RCS pressure fell below 1600 psia and HPSI was actuated at 2150 seconds into the transient (Fig. 4.80 and 4.81). *Depressurization of the RCS continued and at 3120 seconds, the pressure became low enough (below 640 psia) for accumulator injection (Fig. 4.82). The RCS mass inventory (Fig. 4.83), however, turned around before the accumulator actuation because of rapid primary pressure reduction allowing HPSI flow to reach a near maximum flowrate 300 seconds sooner than for Case 3bi (compare Figs. 4.81 to 4.62).*

Figures 4.84 shows that the top node in the core nearly voided at about 2300 seconds into the transient but core uncovery was not indicated by the core coolant temperature or the water level in the core (Figs. 4.85 and 4.86).

DRAFT

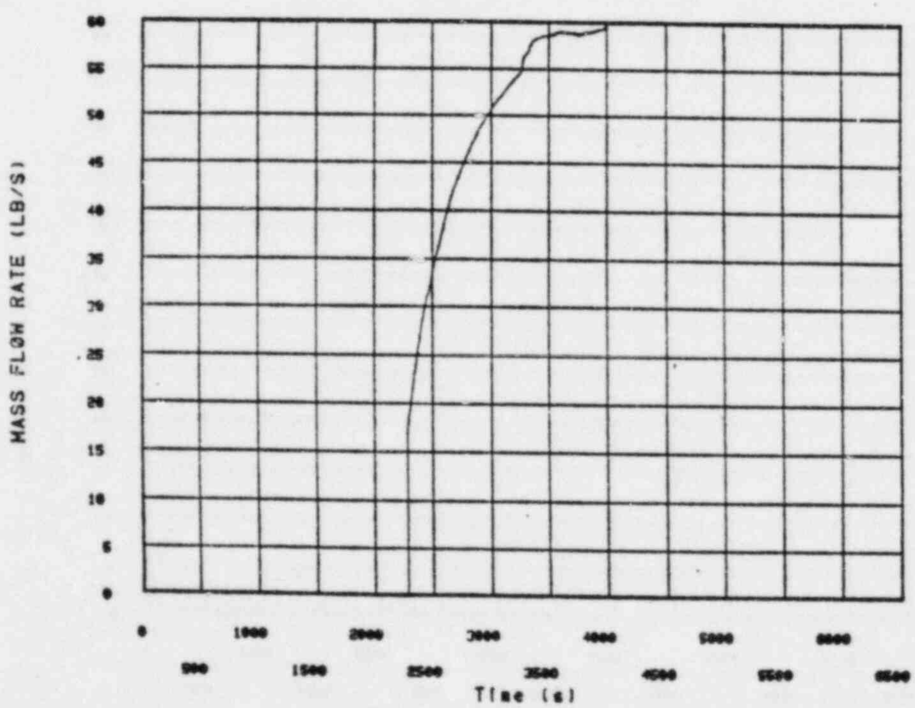
RCS PRESSURE-PZR



CASE 4BI

Fig. 4.80

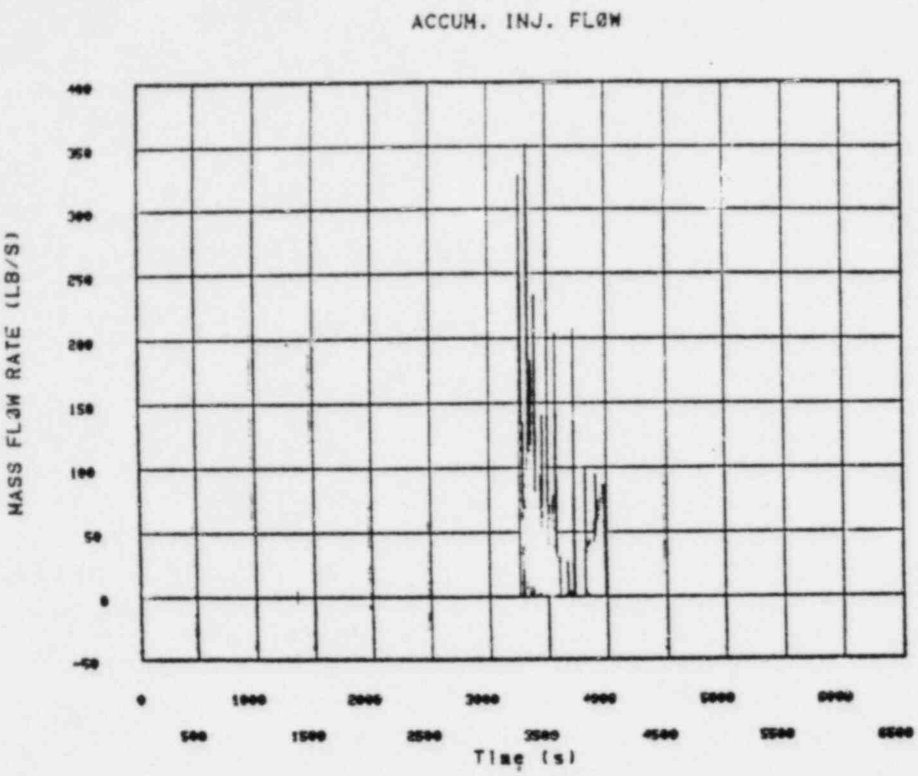
HPSI FLØW



CASE 4BI

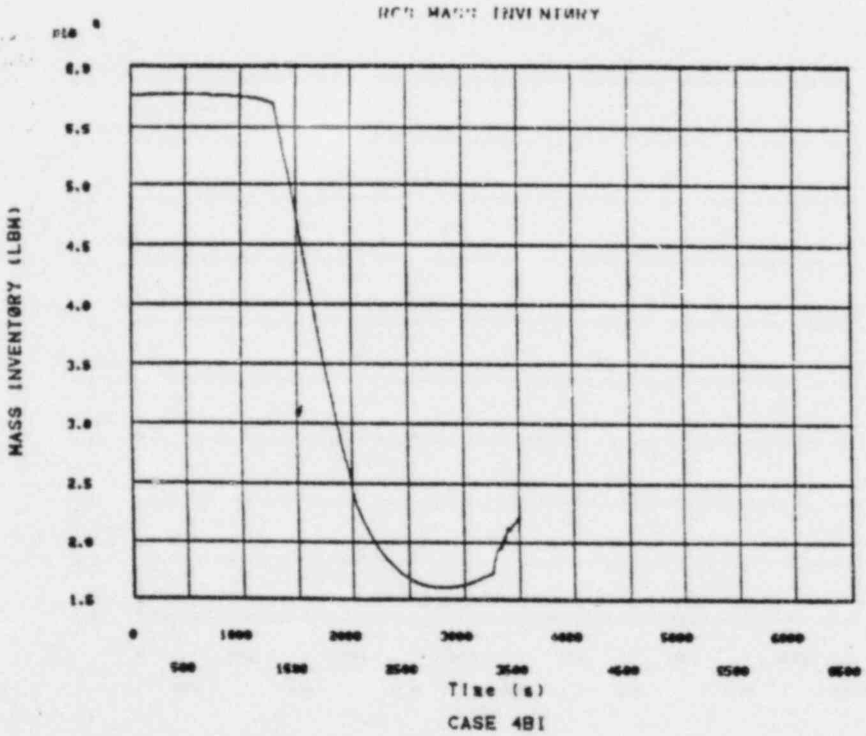
Fig. 4.81

DRAFT



CASE 4BI

Fig. 4.82



CASE 4BI

Fig. 4.83

DRAFT

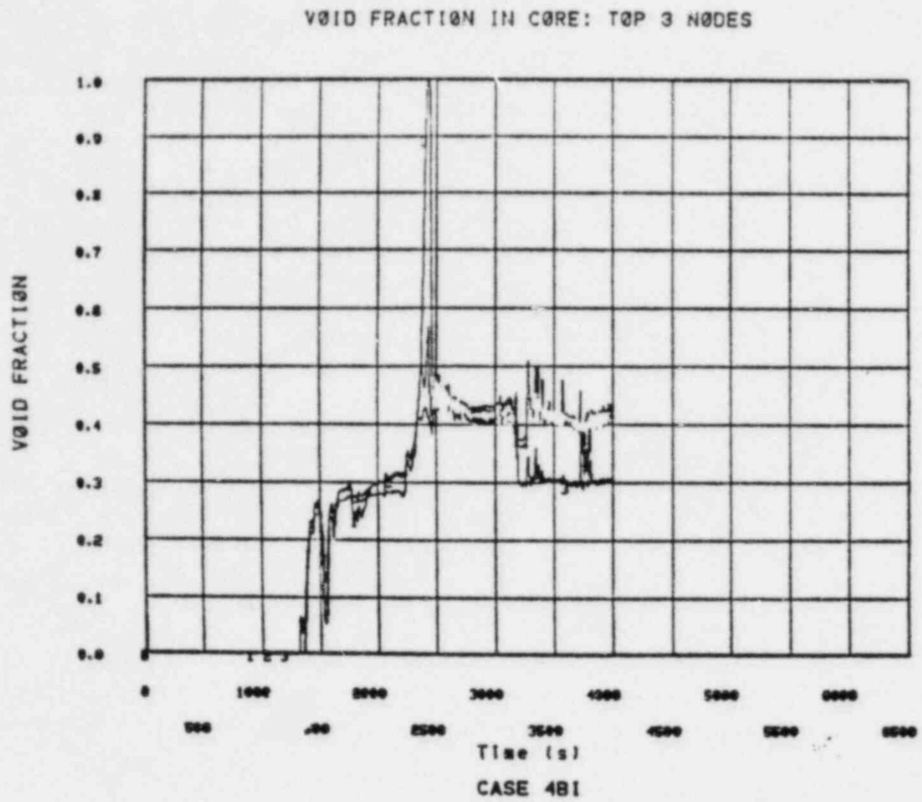


Fig. 4.84

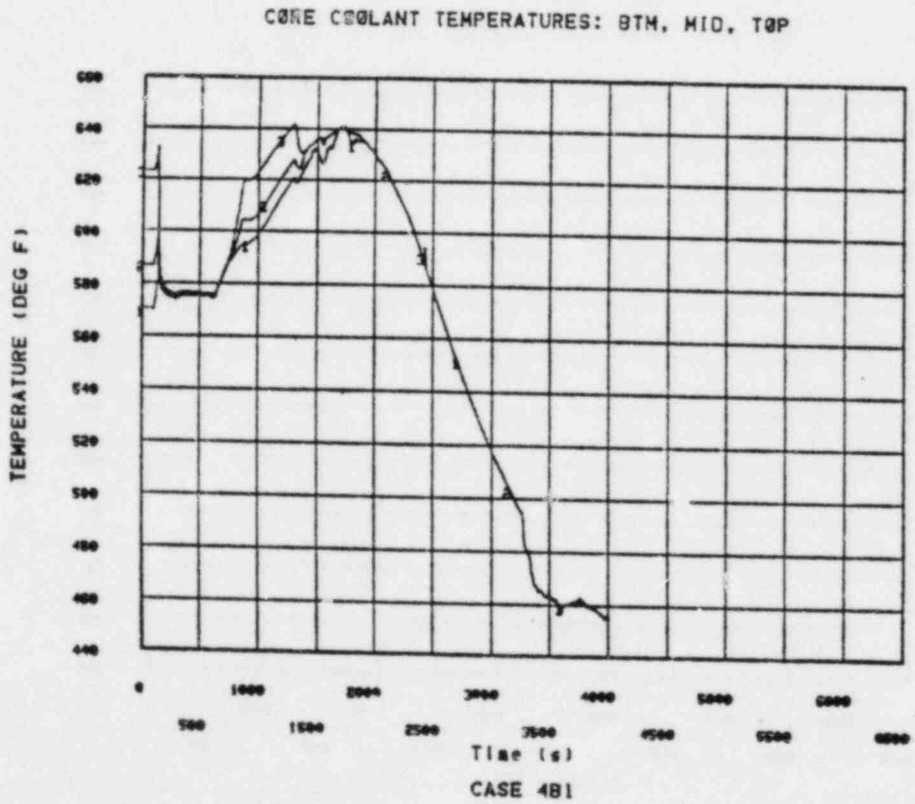


Fig. 4.85

DRAFT

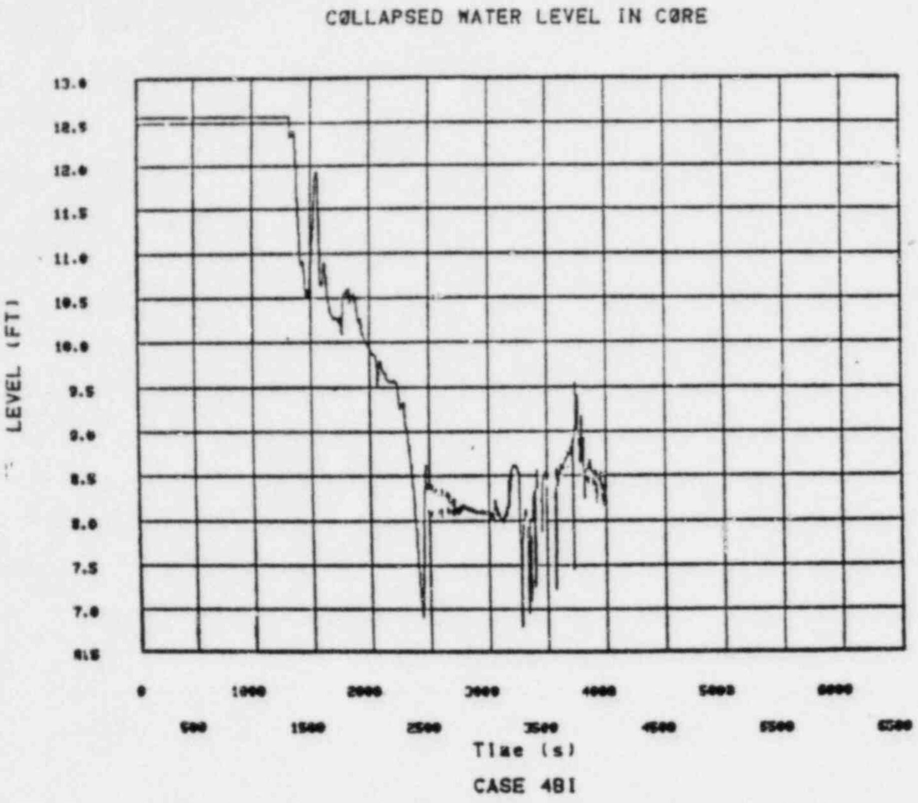


Fig. 4.86

DRAFT

4.4 Sensitivity to PORV Opening Time and AFW Restoration Time

In this section, sensitivities to PORV opening time and to AFW restoration time were investigated. In all cases analyzed here, we attempted to determine the approximate time of core uncovery by presenting, whenever possible, results from two RELAP5 calculations. The only assumption changed from those discussed earlier is the time of PORV opening. As before, once opened the PORVs stayed open for the duration of the transient. Since plant responses to use of PORVs were similar to the earlier cases, only those parameters affected by the timing of PORV opening are presented here.

DRAFT

4.4.1 Cases 3aii and 3bii

In Case 3aii, smaller PORVs were opened at 30 minutes after the transient initiation in one calculation (curve 1 in figure) and at 40 minutes in another (curve 2). We recall that in the original Case 1 the pressurizer water level rose rapidly between 2400 and 3200 seconds into the transient and the pressurizer became solid at 3200 seconds (Fig. 4.5). When the PORVs were opened early, the system had a greater period of time during which the PORV flow was two phased than the later opening (~ 700 seconds for early opening and 250 seconds for late opening (Figs. 4.87 and 4.88) because with later opening the primary fluid continued to swell and fill the pressurizer (Fig. 4.89). *Thus, more energy was removed by earlier PORV opening, depressurizing the system and permitting continuous HPSI delivery (Figs. 4.90 and 4.91). When the PORVs were opened late, the system repressurized after PORV opening (Fig. 4.90) terminating the HPSI flow for approximately 2800 seconds. During this period, there was not cold liquid coming into the RCS in this case and, the RCS inventory was reduced to a lower level than when the PORVs were opened early (Fig. 4.92).*

By 4900 seconds into the transient, the collapsed water level in the core had dropped substantially for the late opening case (curve 2 Fig. 4.93), the core uncovered (Fig. 4.94), and the coolant temperature suddenly rose (curve 2, Fig. 4.95) whereas curve 1 shows that this was not the case in Figs. 4.93 through 4.95 because of continuous HPSI flow. When the HPSI flow was actuated again in the late opening case by eventual RCS pressure reduction, the transient turned over.

Thus we conclude that with the small PORVs, the operator has at most 40 minutes after TLOFW and LOOP initiation to open PORVs without risking core uncovery.

In Case 3bii, we performed a similar parametric analysis using the larger PORV size. In this study the PORVS were opened at 3000 sec into the transient (curve 1) and at 3600 seconds into the transient (curve 2) to bracket the time when the pressurizer went solid (~ 3200 + seconds into the transient) (Fig. 4.96). Thus with 50 minute opening the initial PORV flow was

DRAFT

two phased (at least for a brief interval) while for the 60 minute case the PORV initial flow was single phase liquid (Figs. 4.97, 4.98). *Because these PORVs have such large capabity, the pressure dropped far enough in both cases to permit HPSI flow (Figs. 4.99, 4.100).* the slight repressurization in both cases began coincident with the PORV flow being single phase liquid and turned over as the flow void fraction increased. Compare Figs. 4.98 with 4.99.) Although there were indications that the 60 minute case was closer to core uncovery (Fig. 4.101), neither case reached cladding heatup conditions (Figs. 4.102, 4.103).

In both cases the inventory turned around about the time that accumulator injection began (Fig. 4.104).

From this study one observed that the operator would have on the order of 60 minutes after TLOFW and LOOP to open the large PORVs -- compared with roughly 40 minutes for the smaller ones.

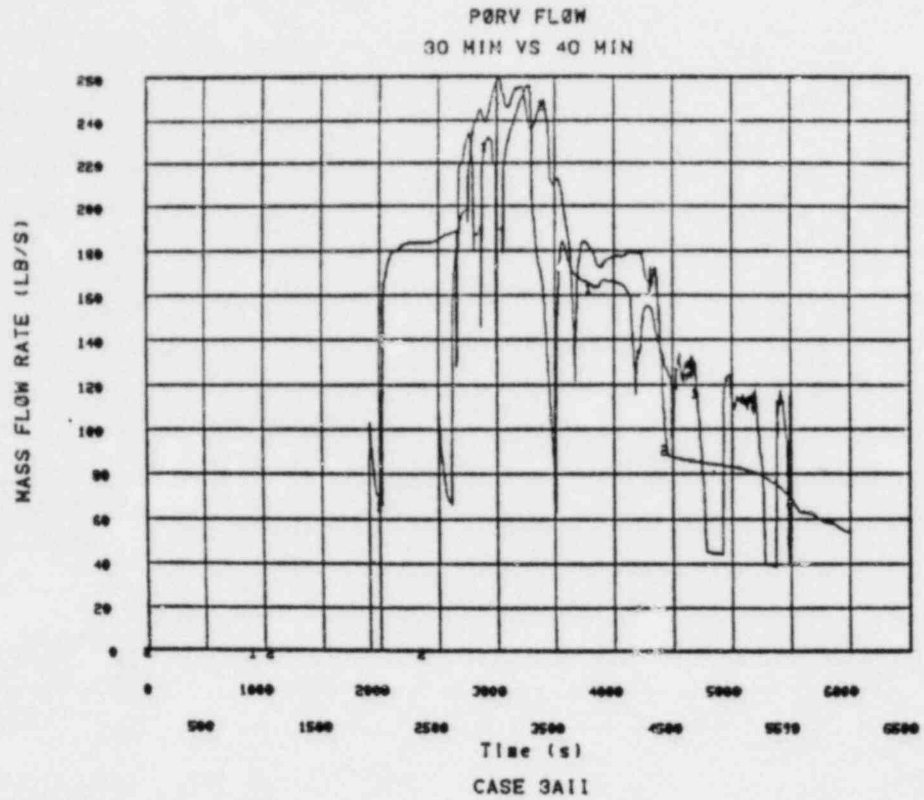
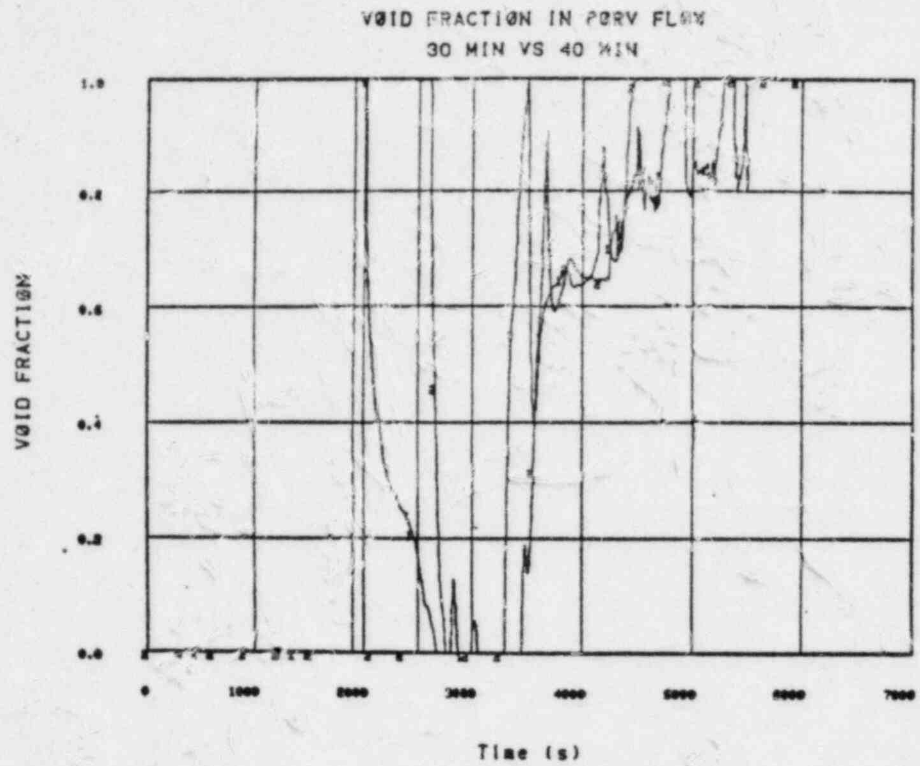


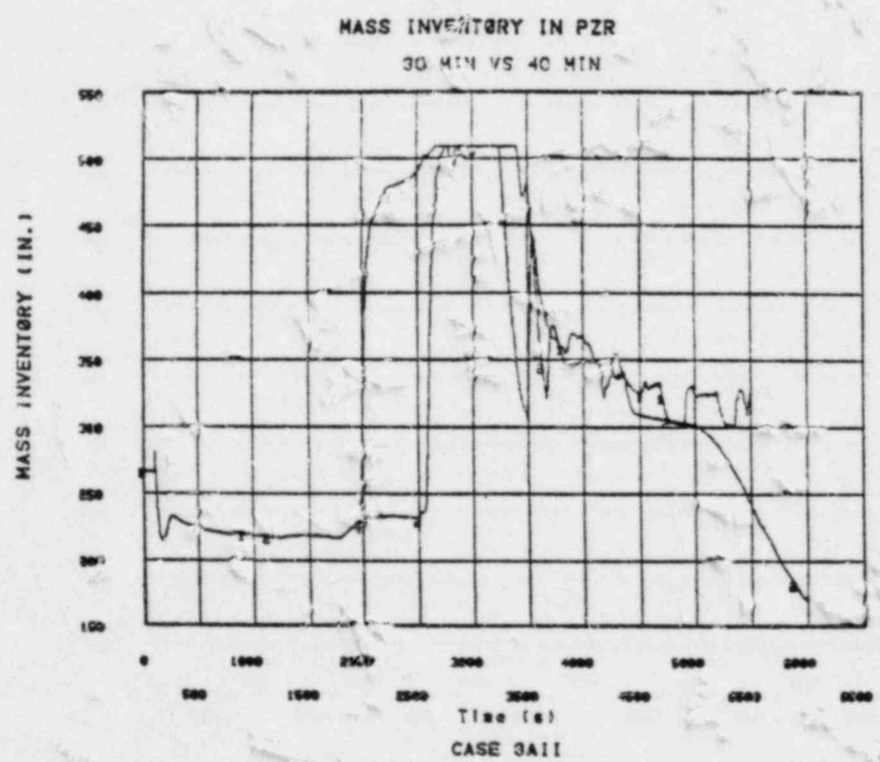
Fig. 4.87

DRAFT



CASE 3AII

Fig. 4.88



CASE 3AII

Fig. 4.89

DRAFT

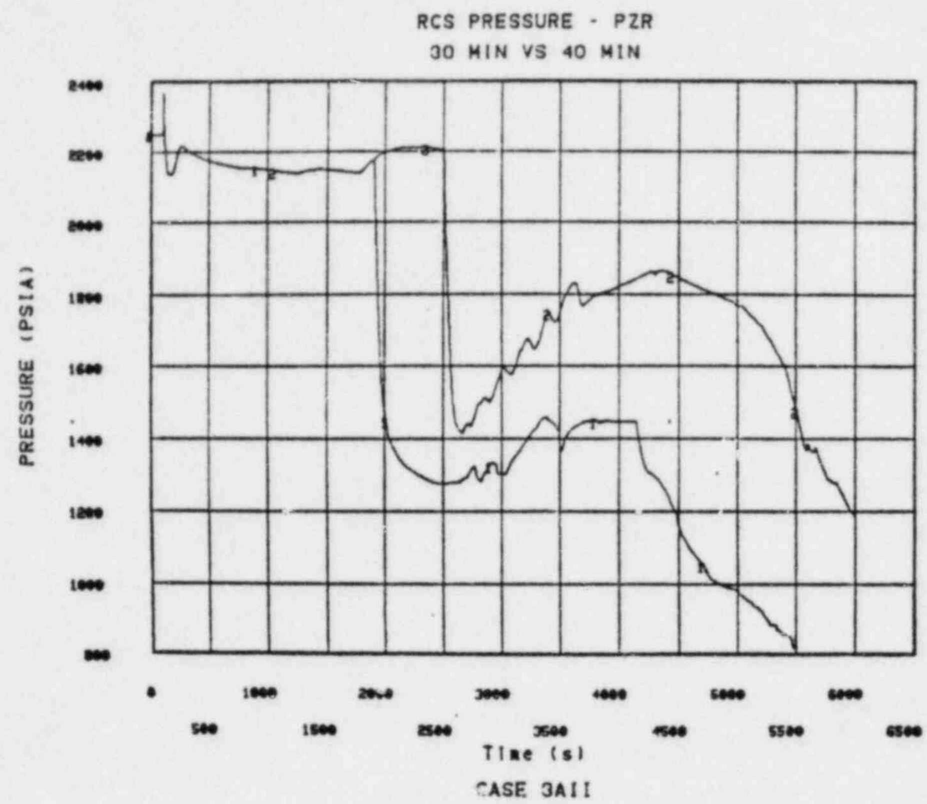


Fig. 4.90

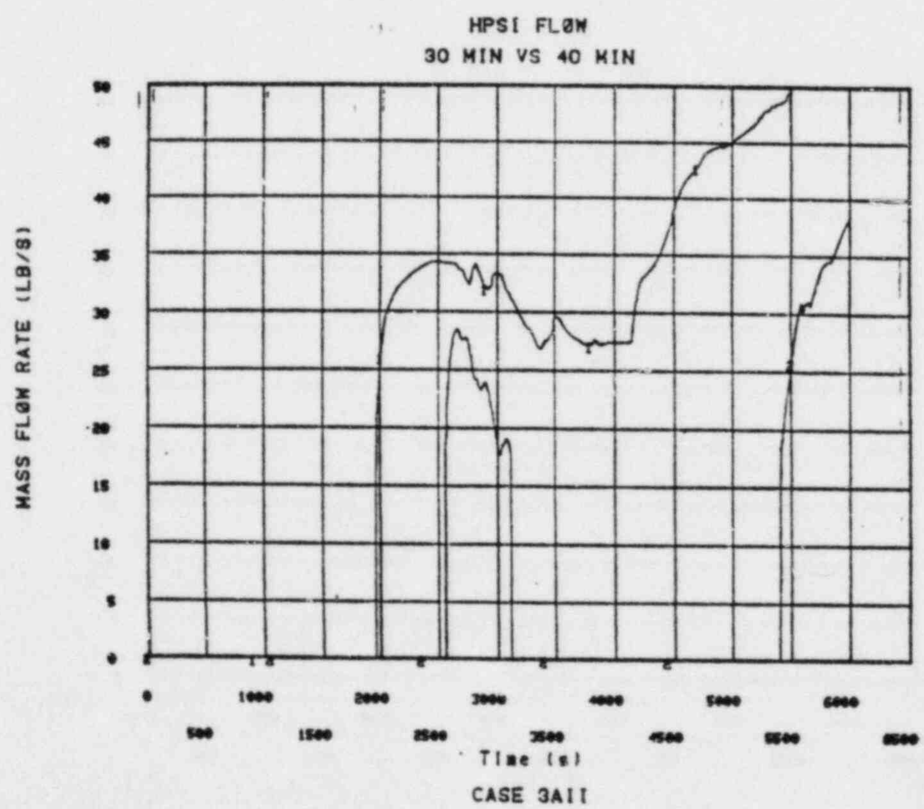
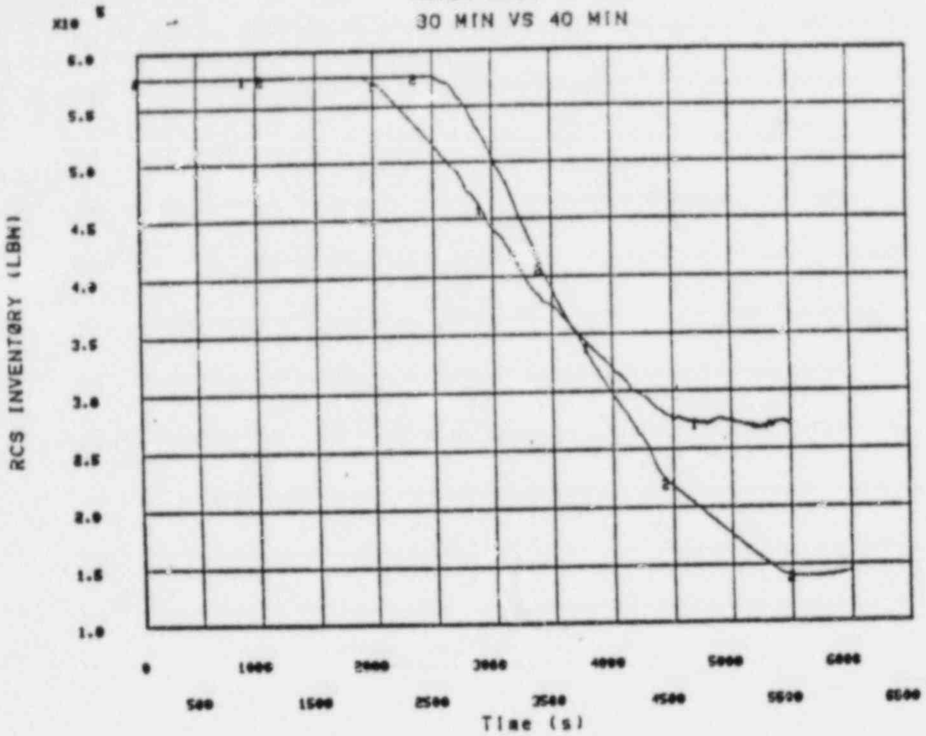


Fig. 4.91

DRAFT

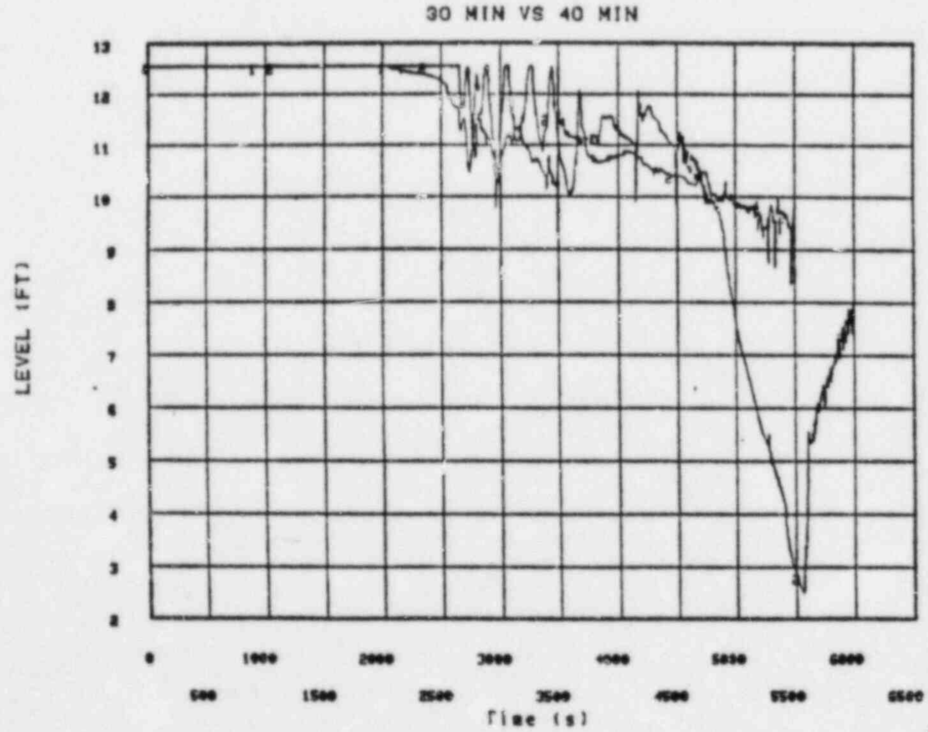
WATER MASS IN RCS
30 MIN VS 40 MIN



CASE 3AII

Fig. 4.92

COLLAPSED WATER LEVELS IN CORE
30 MIN VS 40 MIN



CASE 3AII

Fig. 4.93

DRAFT

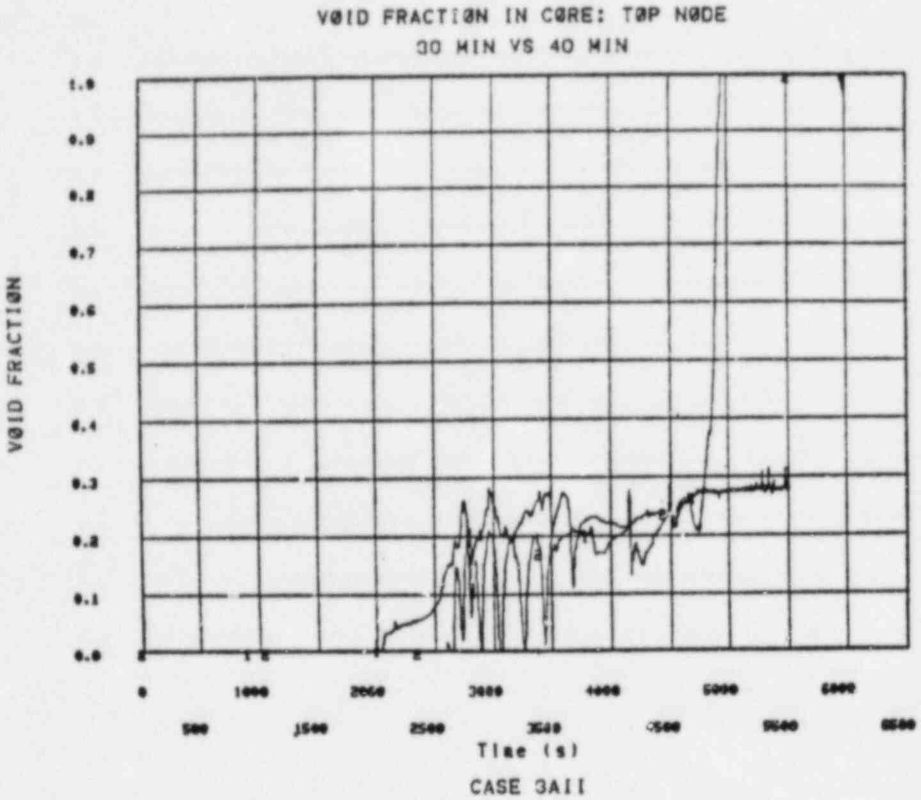


Fig. 4.94

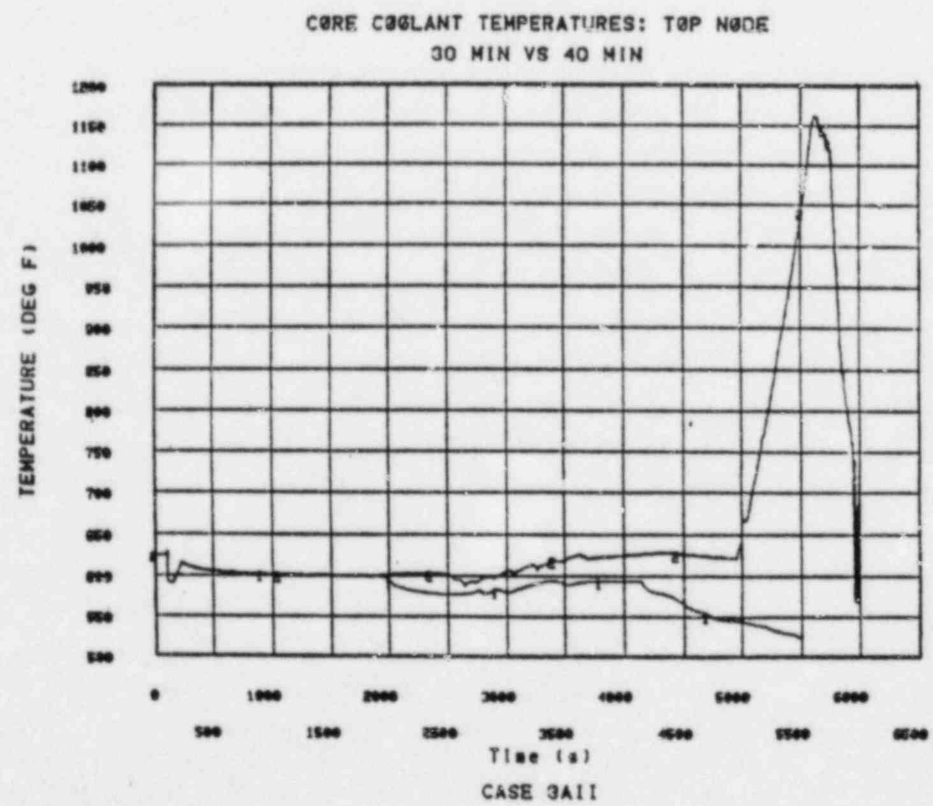
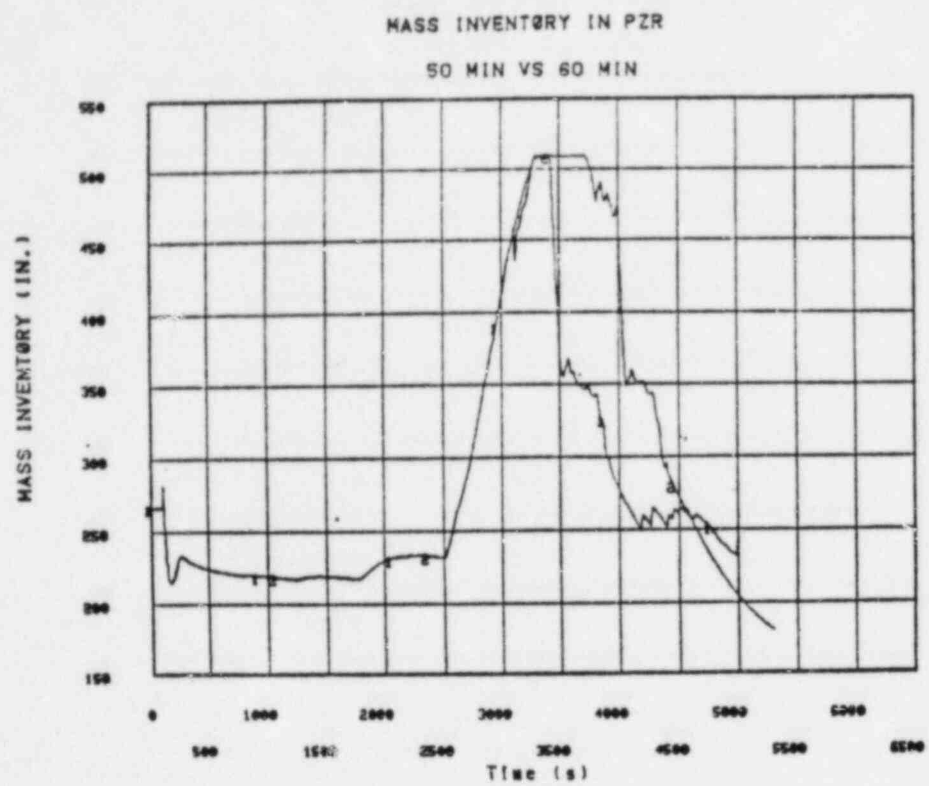


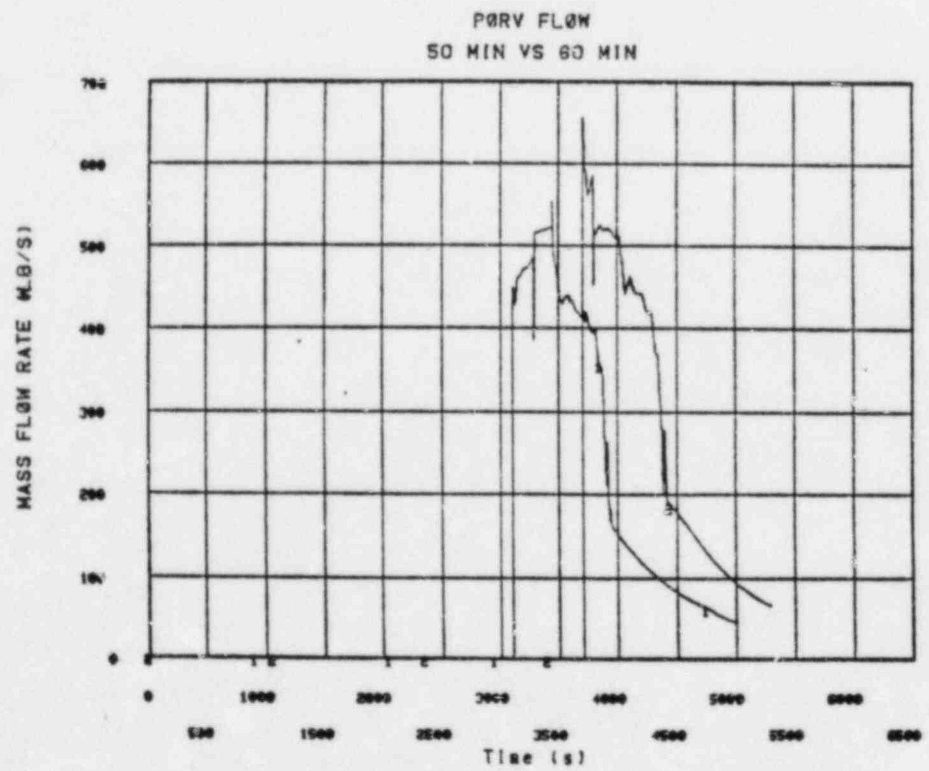
Fig. 4.95

DRAFT



CASE 38II

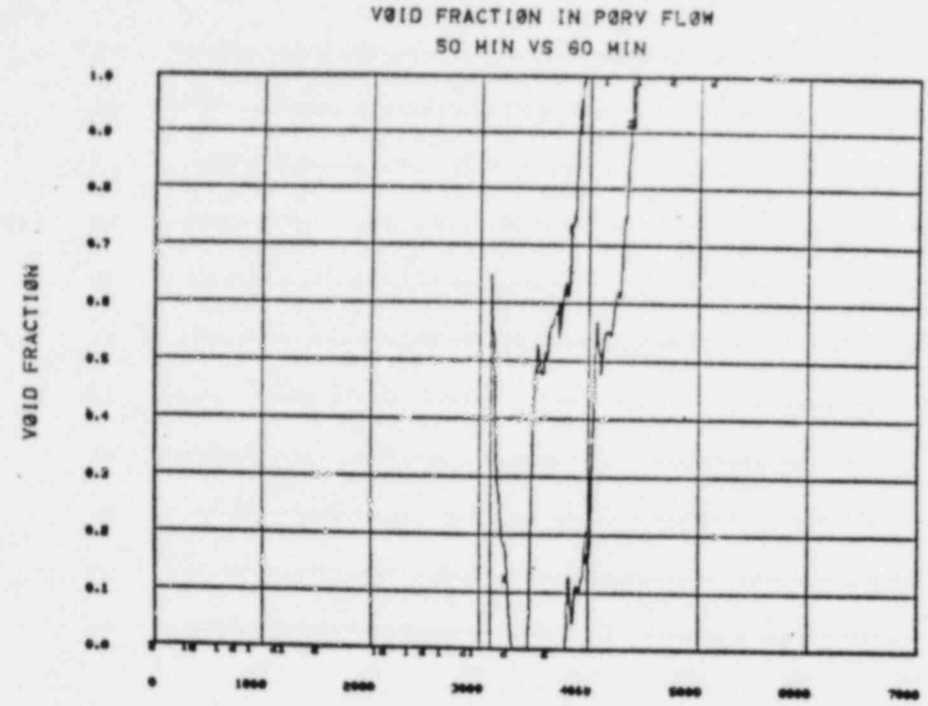
Fig. 4.96



CASE 38II

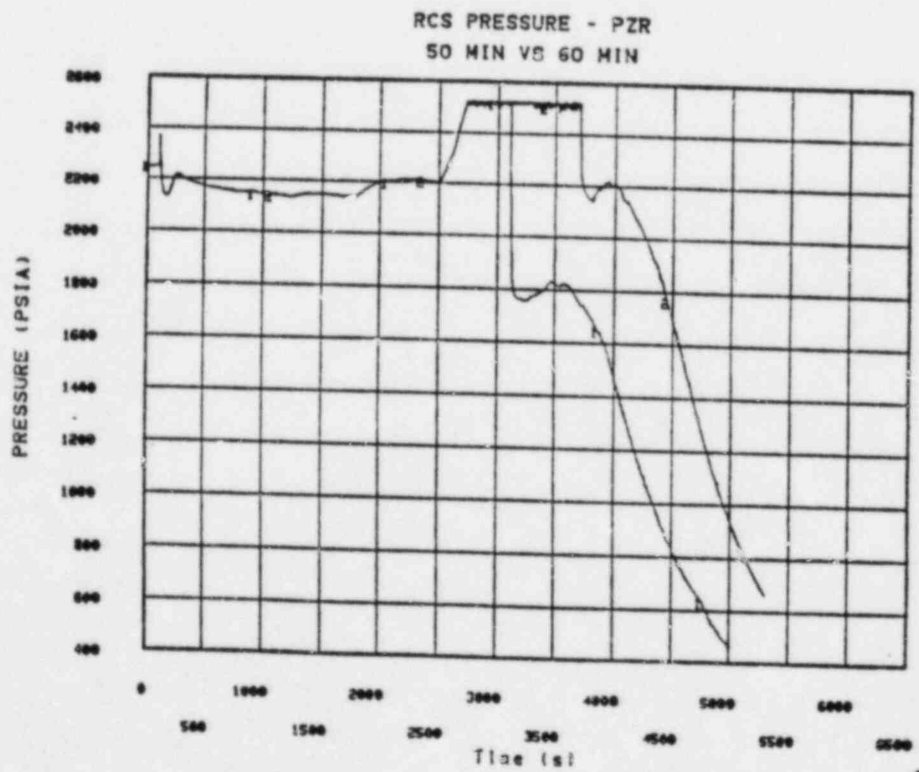
Fig. 4.97

DRAFT



CASE 3BII

Fig. 4.98



CASE 3BII

Fig. 4.99

DRAFT

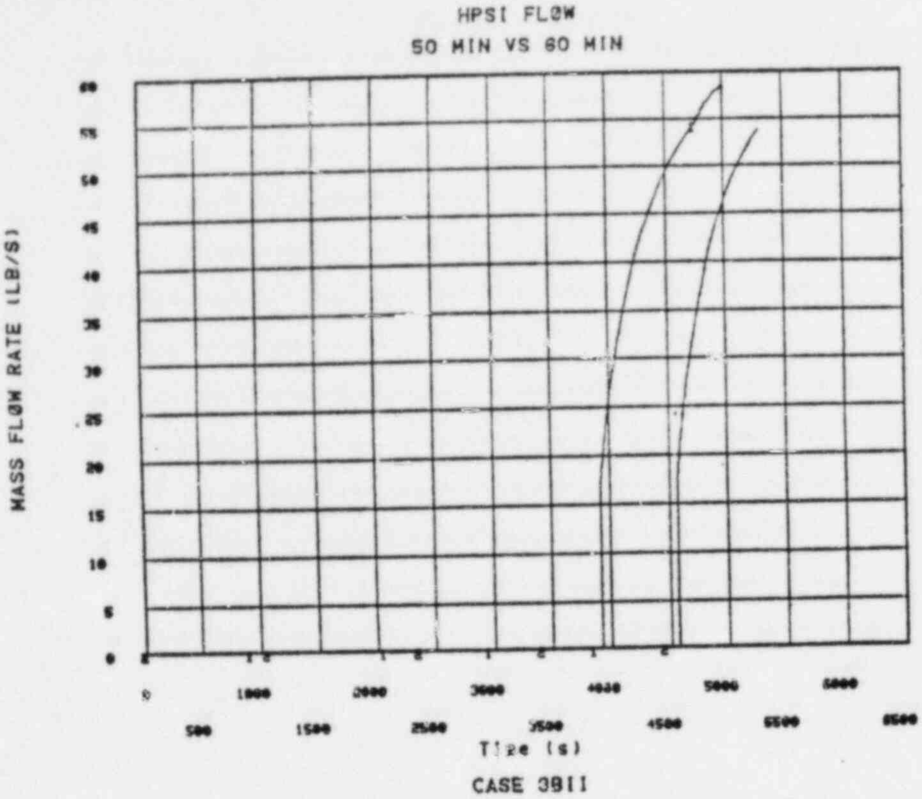


Fig. 4.100

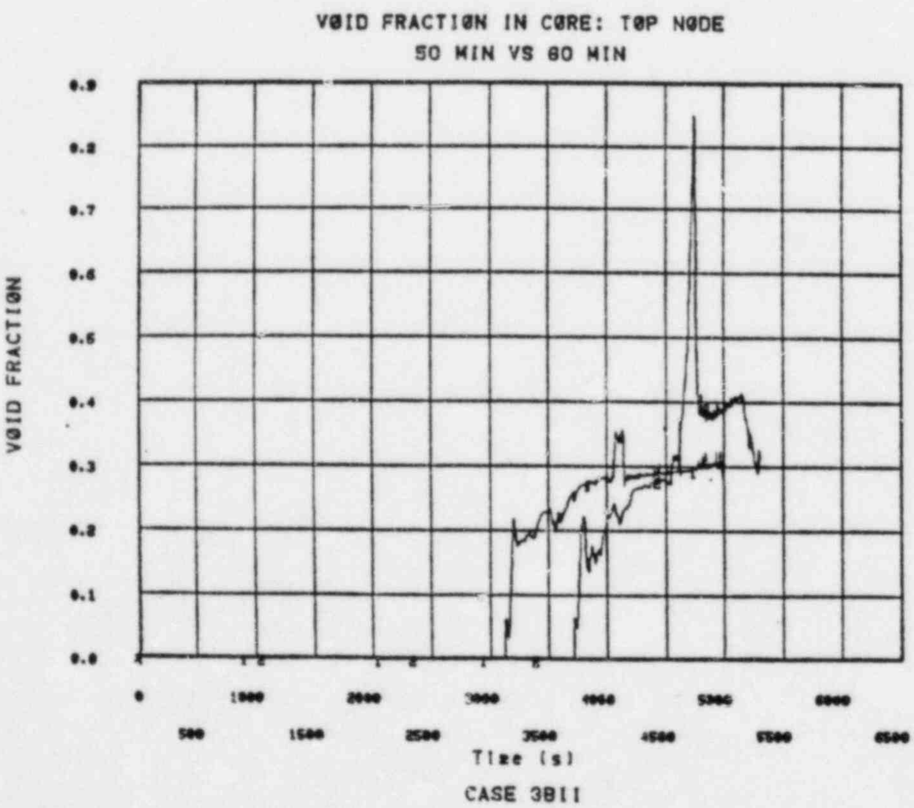
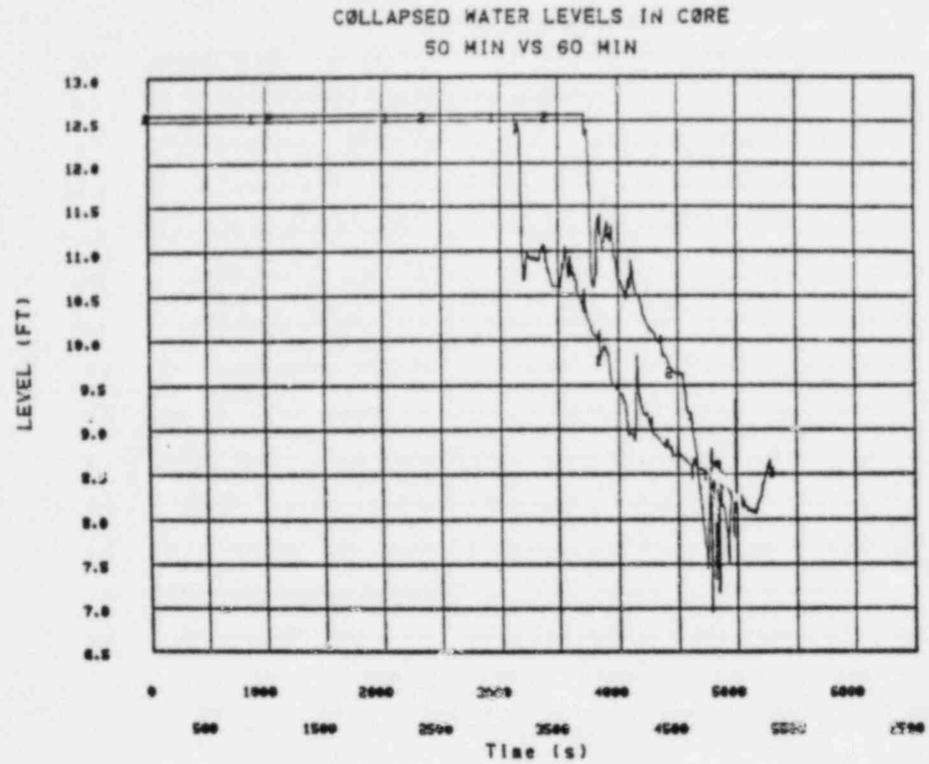
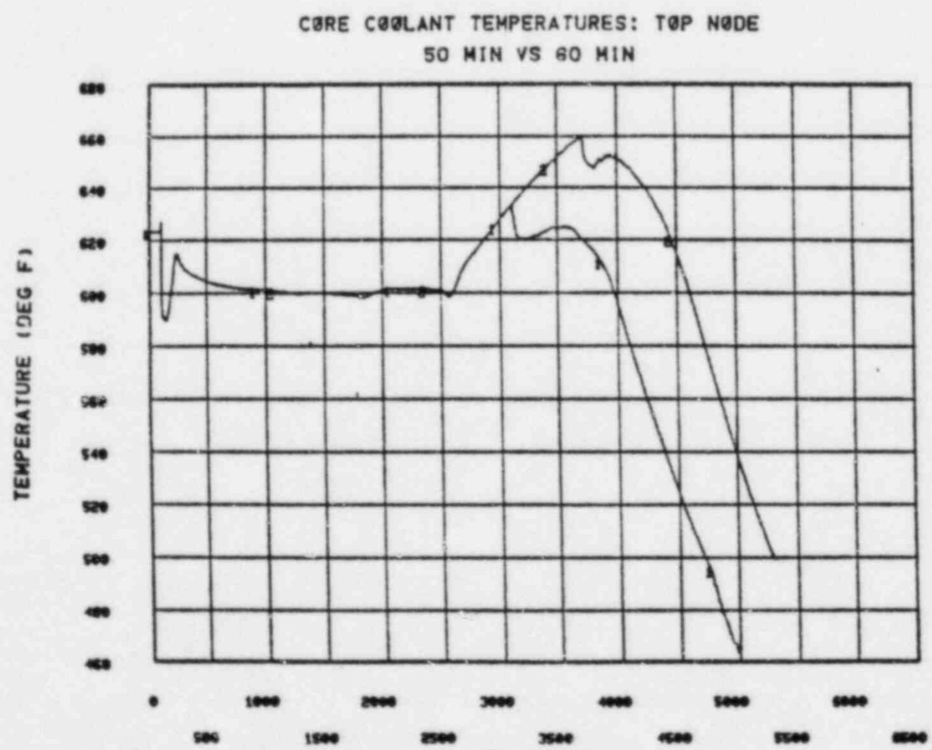


Fig. 4.101



CASE 38II

Fig. 4.102



CASE 38II

Fig. 4.103

DRAFT

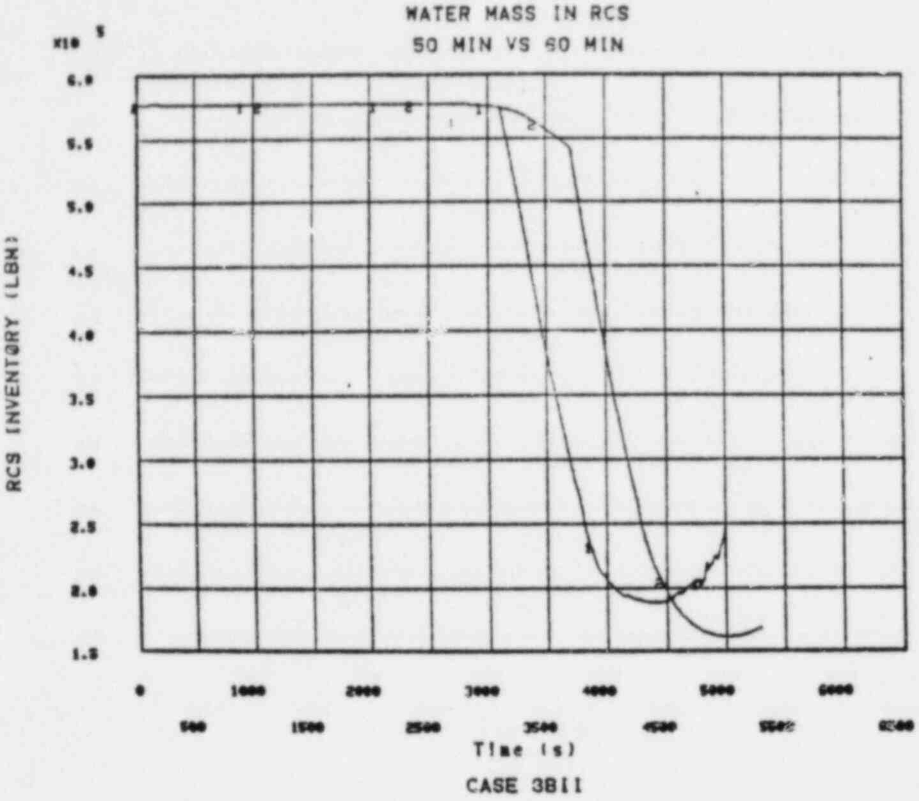


Fig. 4.104

DRAFT

4.4.2 Cases 4aii and 4bii

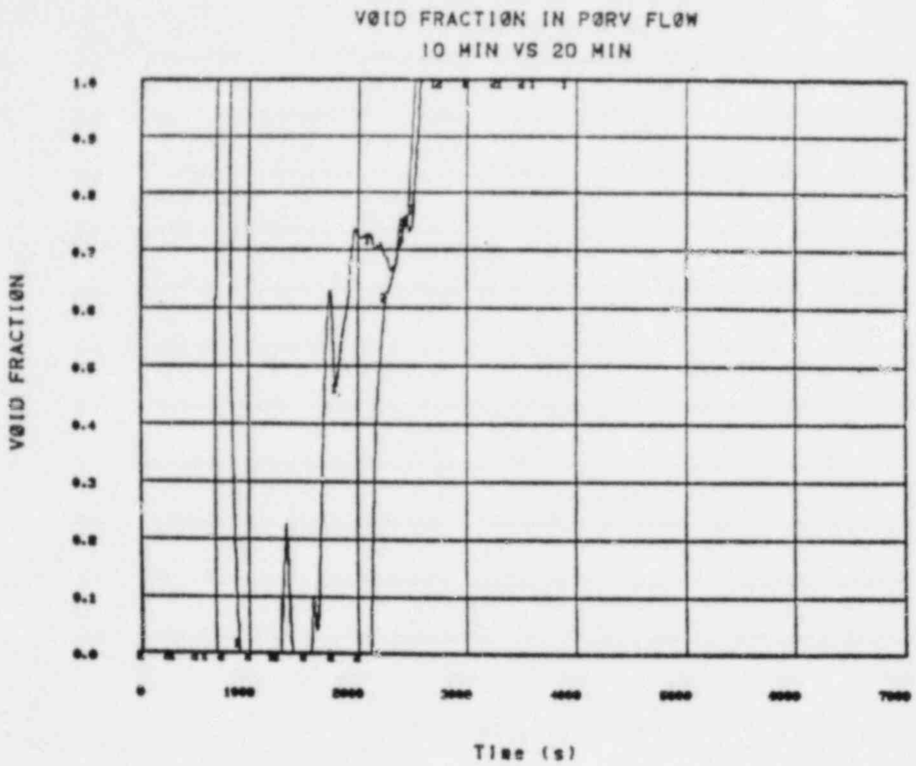
In these two cases we investigated PORV opening time in a manner similar to that discussed in §4.3.1 using case 2 as the base case (i.e., 10 minutes of RCPs).

Case 4ai had resulted in core uncovery (when the PORVs were opened at 20 minutes), so in this parametric the valves were opened at 10 minutes into the transient (Case 4aii is the small PORVs). We recall that in Case 2, by 10 minutes into the transient the steam generators dried out since the RCPs were not tripped until 10 minutes after loss of feedwater. In previous cases, we saw that the smaller sized valves were unable to depressurize enough to mitigate core uncovery under the combination of TLOFW and LOOP conditions. Here again, as in all cases, the ability of the PORVs to depressurize was governed by the quality of the flow through them (Figs. 4.105, 4.106).

Opening at 10 minutes permitted the RCS pressure to fall enough for HPSI injection, however the pressure quickly turned over terminating the flow into the cold legs (Fig. 4.107 and 4.108). The sequence of events was very similar to Case 4ai throughout the transient (although taking place about 250 seconds earlier instead of 600 seconds due to HPSI injection) and similarly ended with core uncovery (Figs. 4.109 through 4.112).

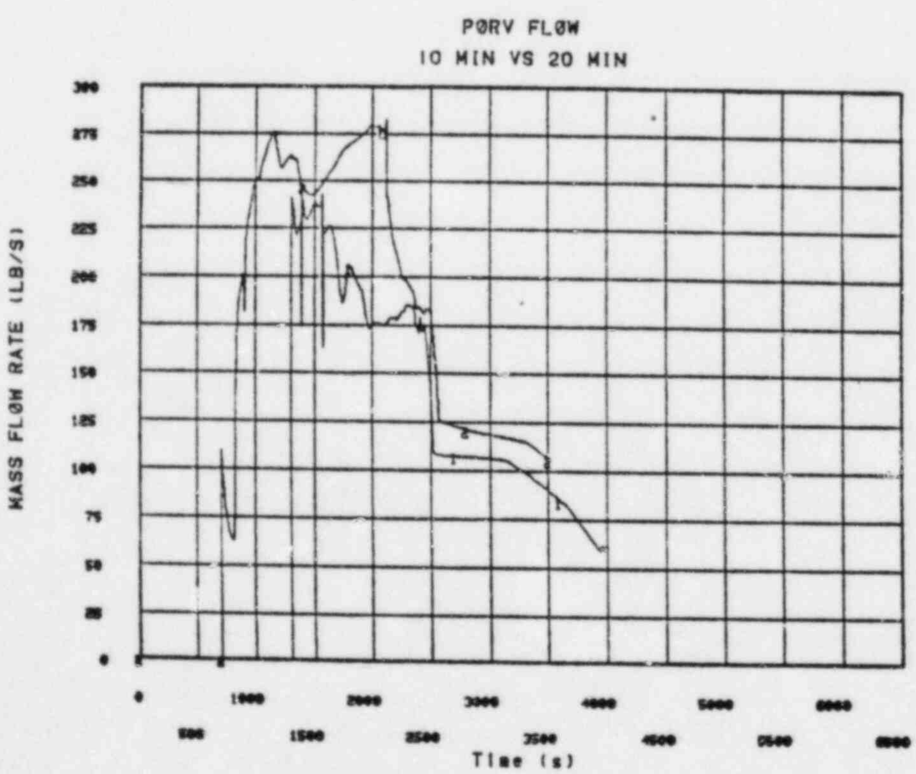
In Case 4bii, the larger PORVs were opened at 1800 seconds into the transient (curve 1) and at 2400 seconds (curve 2) of Fig. 4.113.

The larger PORVs, as before, were able to take the primary pressure down enough for continuous HPSI injection (Figs. 4.113 and 4.114). Voids formed in the core following PORV opening were pulled through the system rapidly to force the PORV flow to turn to pure steam from the two-phased mixture (Figs. 4.115, 4.116 and 4.117). The RCS inventory leveled off and started refilling on HPSI flow (Fig. 4.118). However in the 40 minute case, complete core uncovery was encountered (Fig. 4.119) and clad heatup was computed to occur (Fig. 4.120). *Thus, we conclude that the operator has roughly 30 minutes to open the larger PORVs to cool down the plant and still avoid core uncovery.*



CASE 4AII

Fig. 4.105



CASE 4AII

Fig. 4.106

DRAF

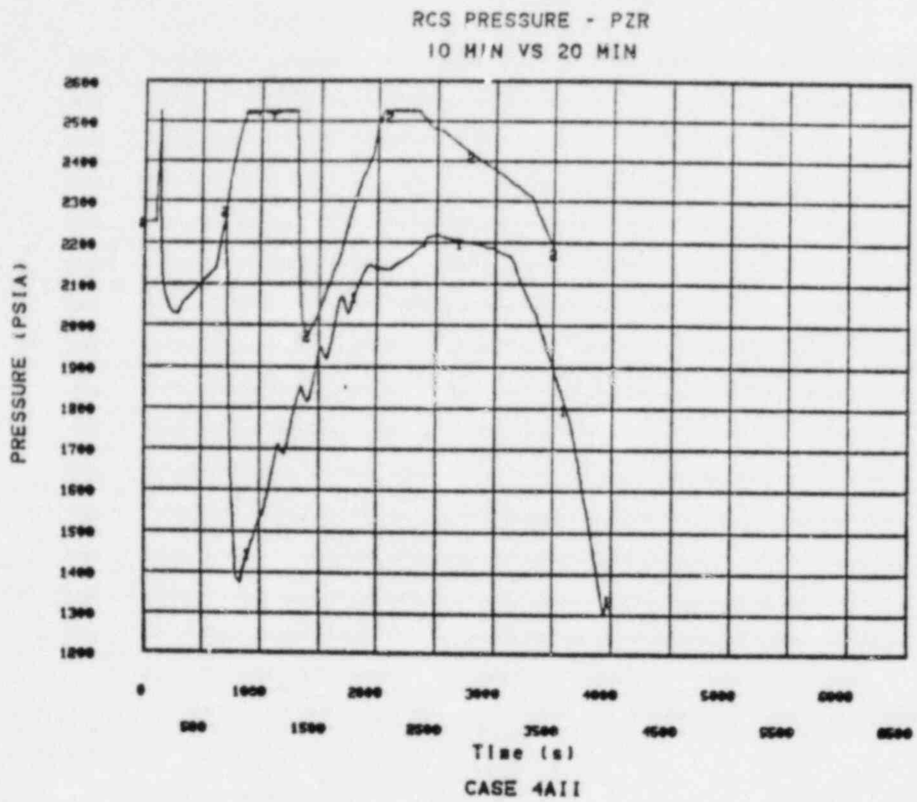


Fig. 4.107

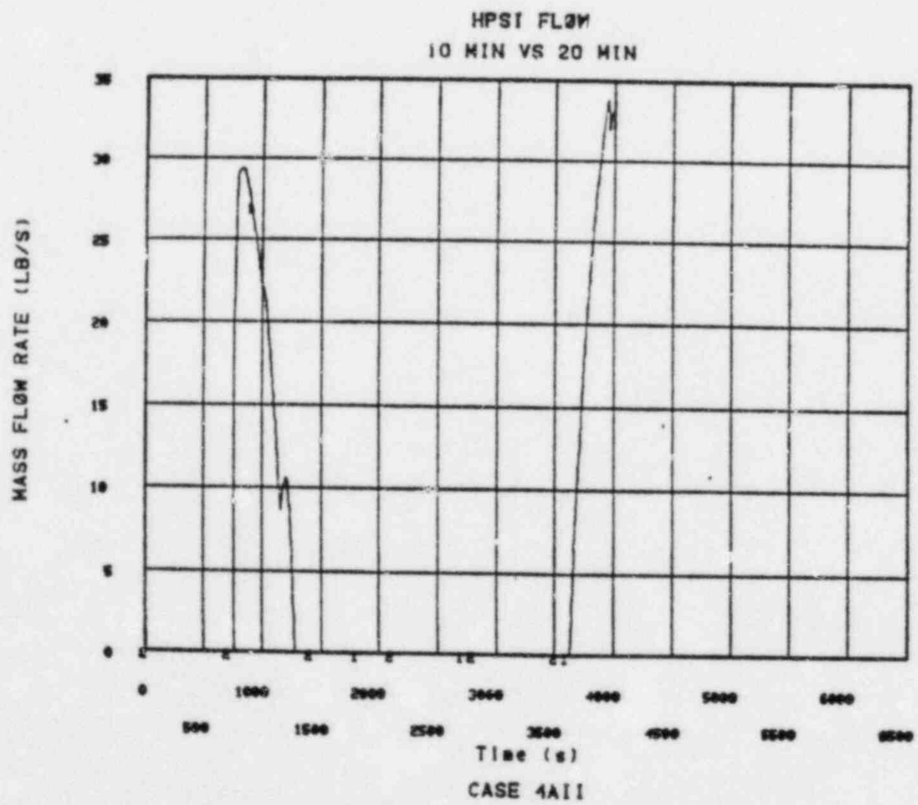


Fig. 4.108

DRAFT

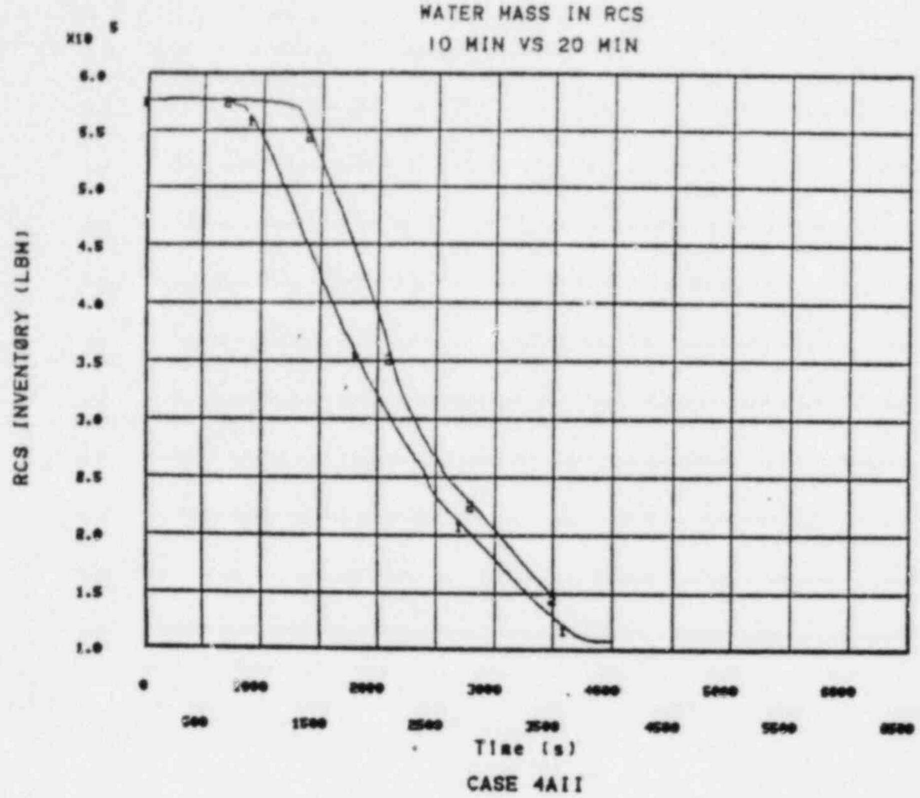


Fig. 4.109

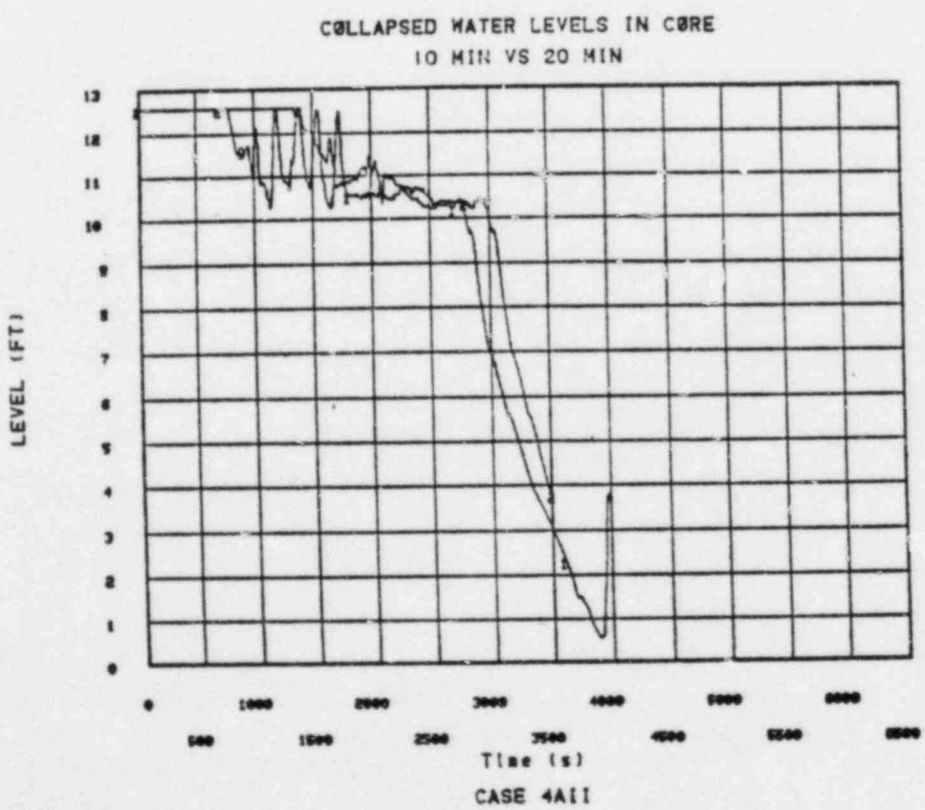
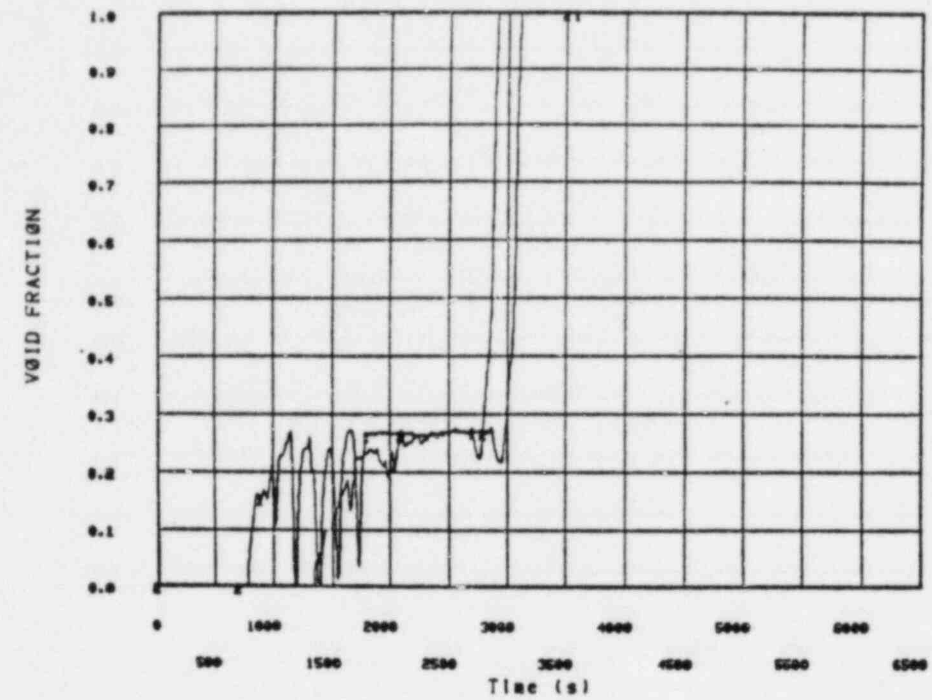


Fig. 4.110

DRAFT

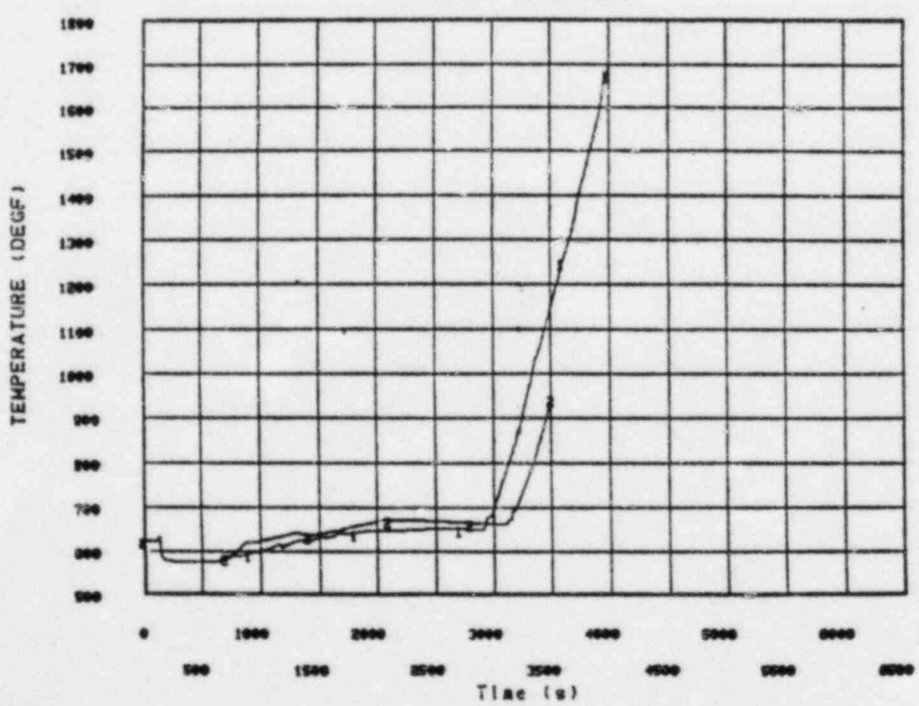
VØID FRACTIØN IN CØRE: TØP NØDE
10 MIN VS 20 MIN



CASE 4AII

Fig. 4.111

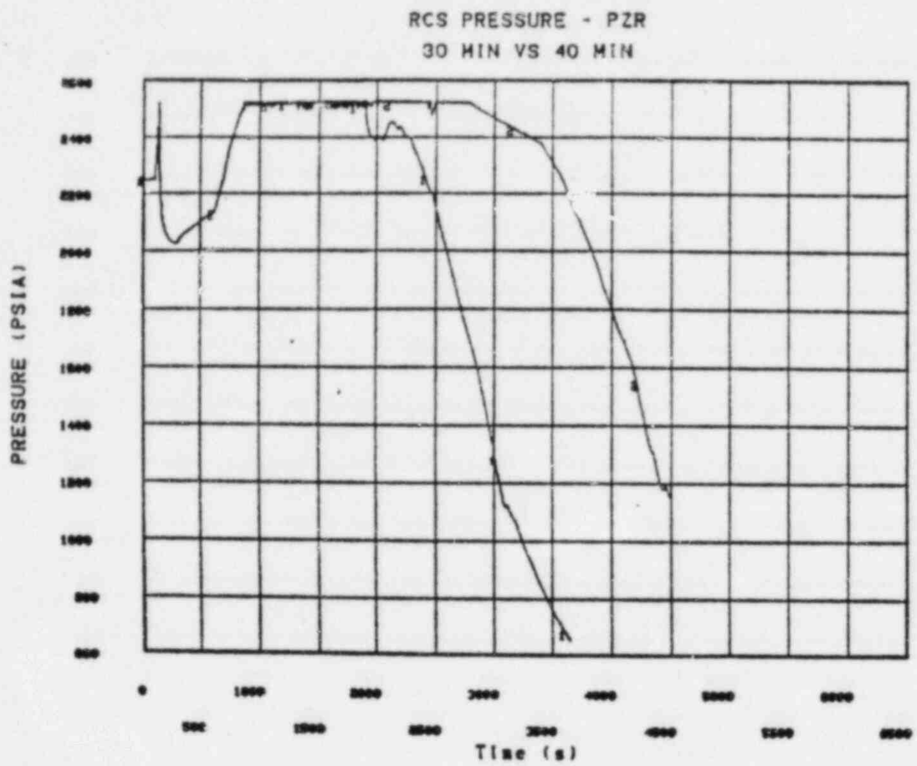
CØRE CØØLANT TEMPERATURES: TØP NØDE
10 MIN VS 20 MIN



CASE 4AII

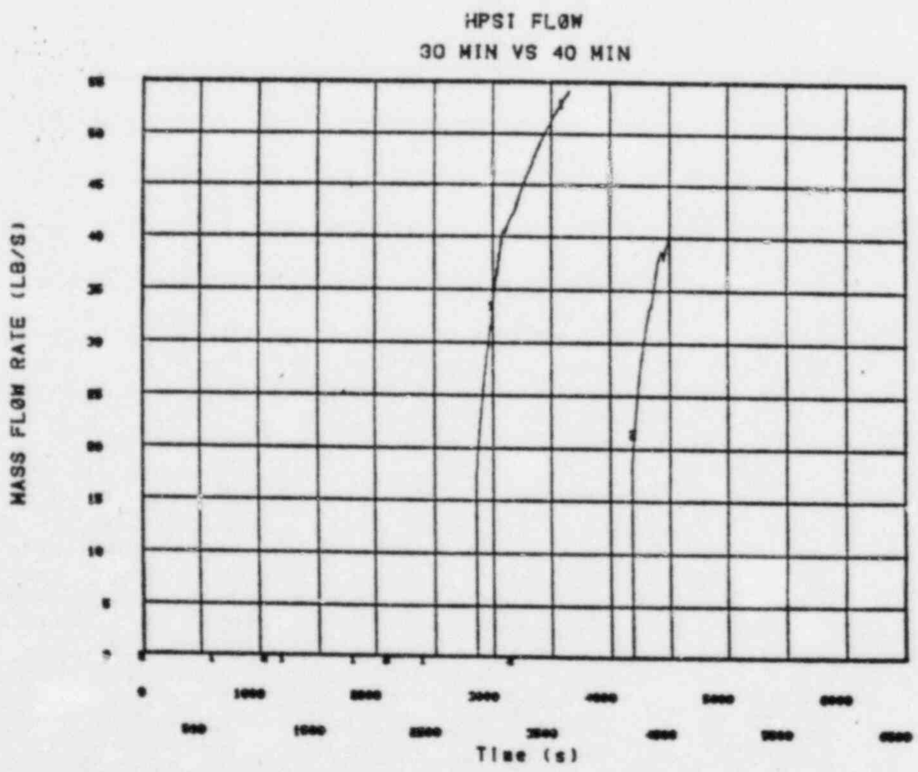
Fig. 4.112

DRAFT



CASE 4BII

Fig. 4.113

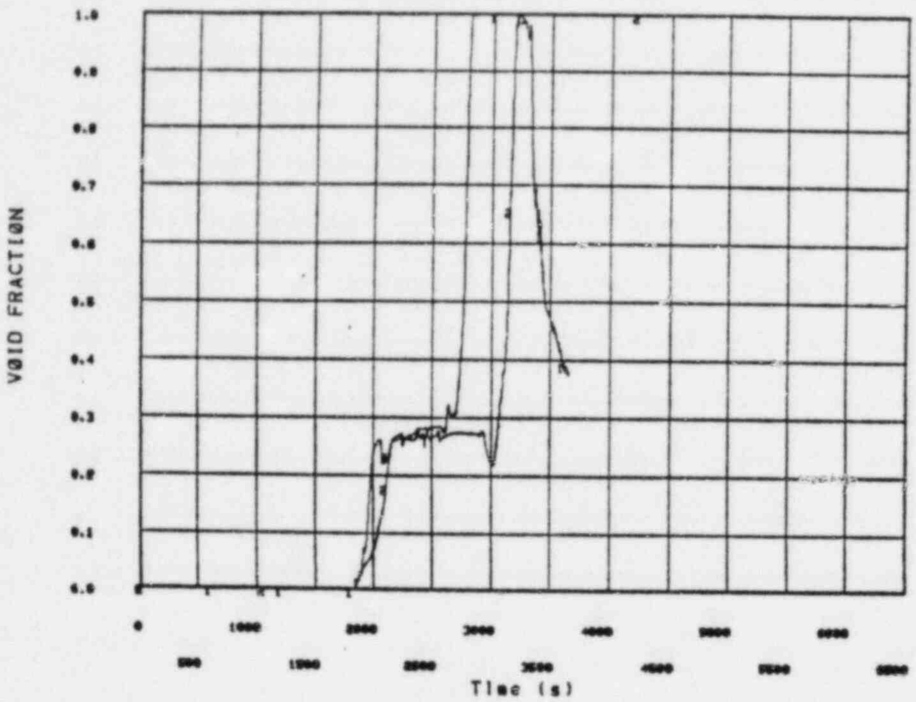


CASE 4BII

Fig. 4.114

DRAFT

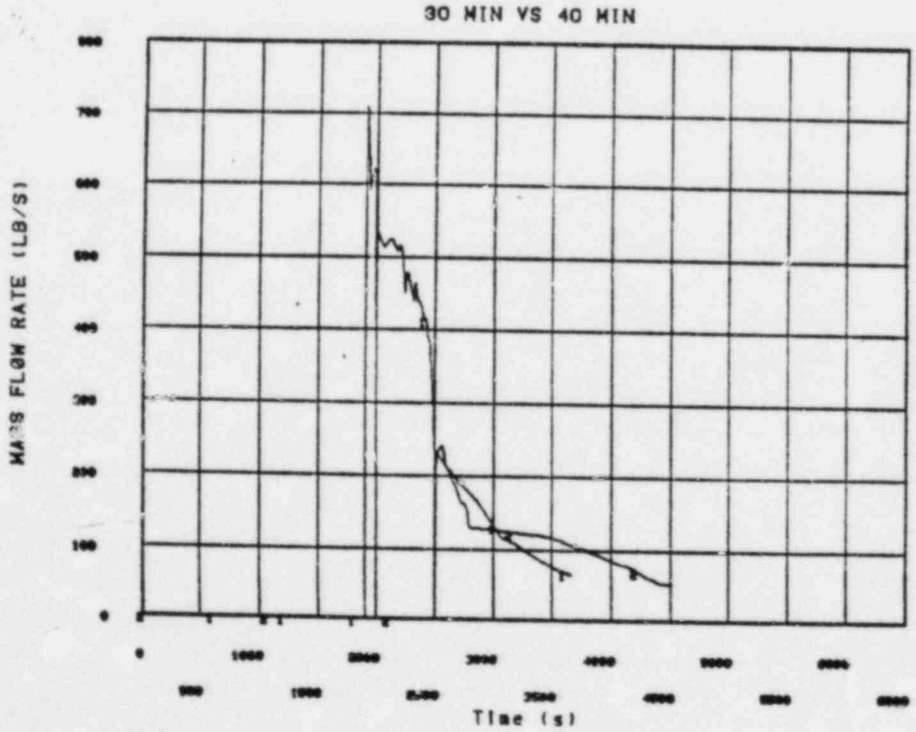
VØID FRACTIØN IN CØRE: TØP NØDE
30 MIN VS 40 MIN



CASE 4BII

Fig. 4.115

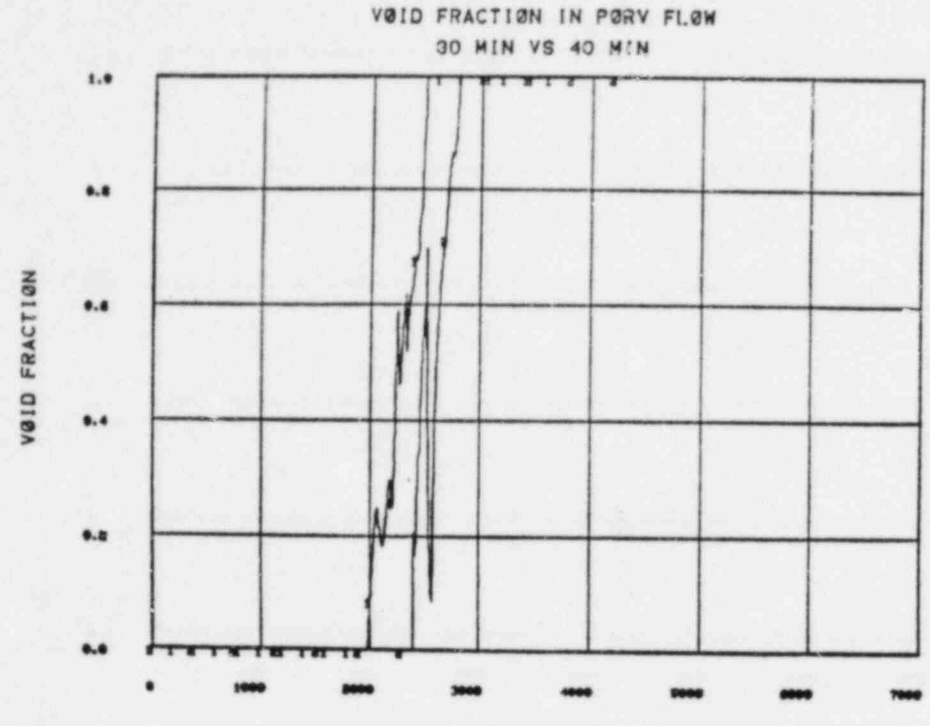
PØRV FLØW
30 MIN VS 40 MIN



CASE 4BII

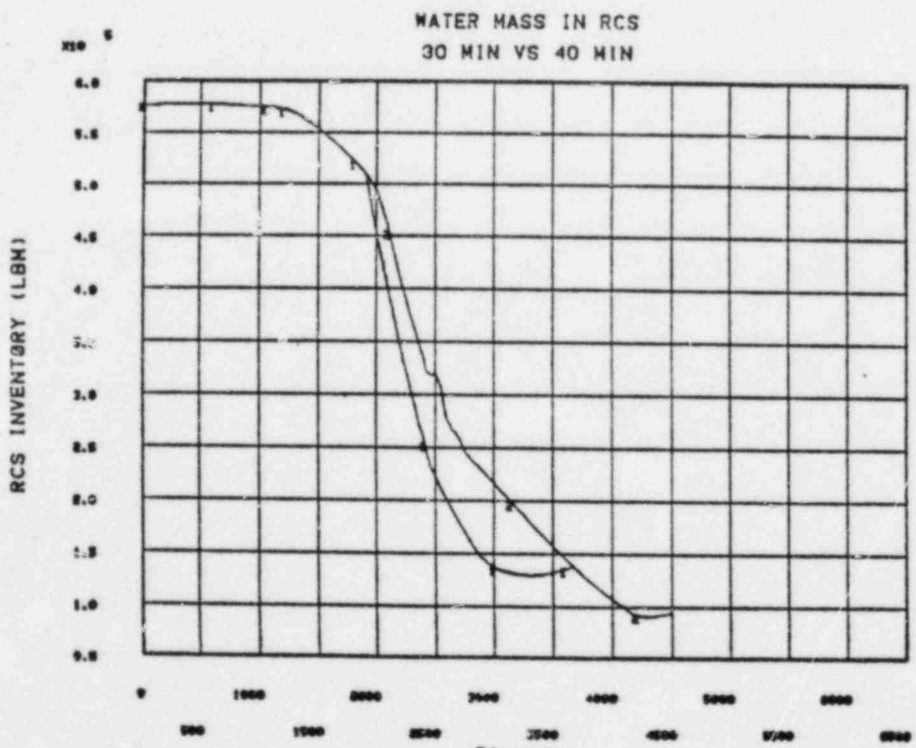
Fig. 4.116

DRAFT



CASE 4BII

Fig. 4.117



CASE 4BII

Fig. 4.118

DRAFT

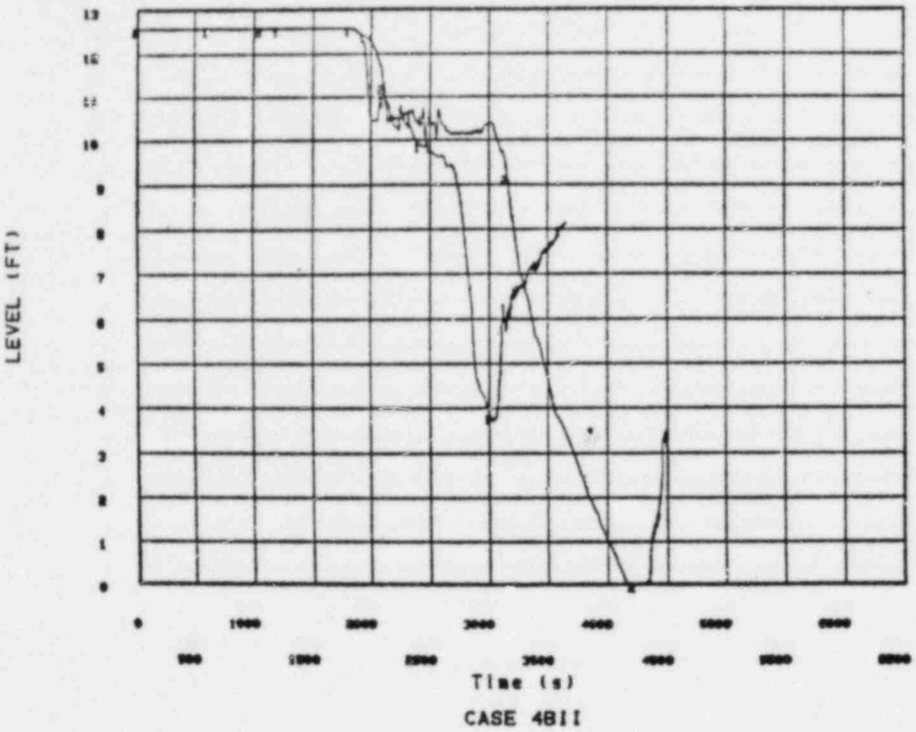


Fig. 4.119

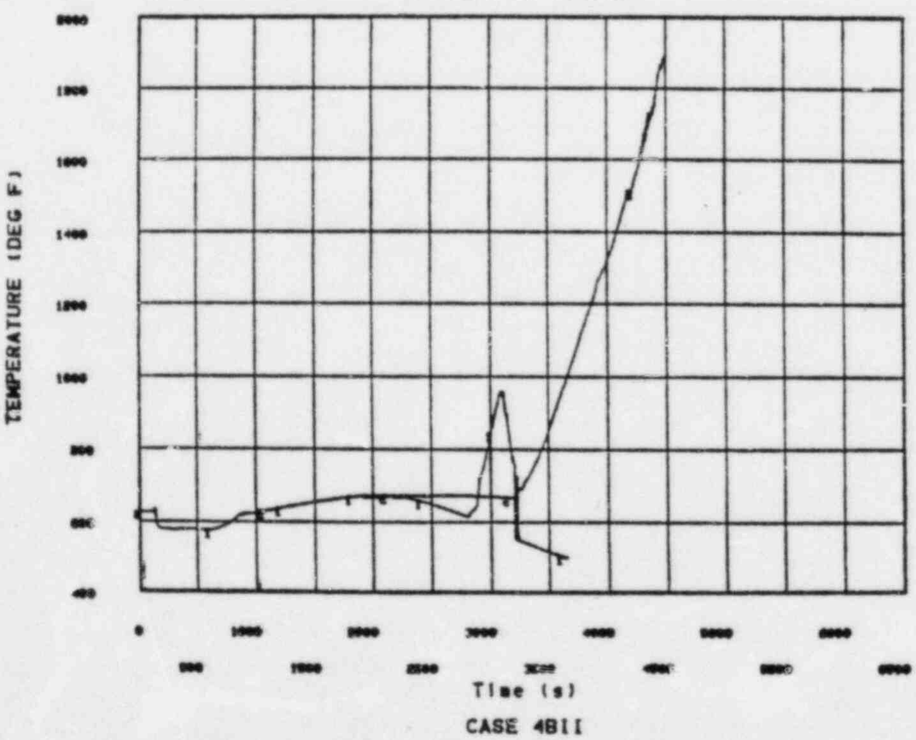


Fig. 4.120

DRAFT

4.4.3 Case 1i and Case 2i (Restoration of AFW)

In these cases, instead of opening PORVs, the AFW was assumed to be restored to regain primary-to-secondary heat transfer capabilities, providing cold (100°F) feedwater flow into both steam generators. This portion of the study was directed at identifying the latest possible moment for restoration of AFW which would prevent core uncovery.

As soon as the AFW began flowing into the SGs at 75 min into the transient in one case and 90 min in the other case (Fig. 4.121), heat removal began from the primary loop, the coolant temperature dropped, and the system depressurized rapidly (Figs. 4.122 and 4.23). When the RCS pressure decreased below the pressurizer safety valve setpoint, the RCS inventory loss was terminated (Fig. 4.124). As depressurization continued due to feedwater flow, the HPSI came on line (Fig. 4.125) and the RCS inventory began refilling.

However, as the reactor coolant temperature dropped, liquid contraction took place. Hence, even after the loss of primary inventory was terminated, some risk of core uncovery still existed since HPSI flowrate could not keep up with the contraction rate, although that uncovery should be brief. In Case 1i, onset of significant core voiding occurred when the AFW was restored at t = 90 min into the transient (Figs. 4.126, 4.127). Howver the voiding was not significant enough to result in core uncovery (as indicated by the coolant temperature continuing to fall (Fig. 4.122).

We recall that in Case 2, core uncovery began at roughly 3140 seconds into the transient. Commencing AFW flow as late as 3000 seconds would cool down the RCS enough to avoid that core uncovery in Case 2i (Figs. 4.128 through 4.133).

In summary, use of AFW is more effective for rapid system depressurization than the APS or PORVs in that the operator has at least 1 1/2 hours before taking action to initiate AFW under the TLOFW and LOOP conditions. Even when power is available and RCPs are permitted to operate for 10 minutes after the feedwater is lost, there is still almost one hour after the

DRAFT

transient initiation for the operator to actuate AFW without resulting in core uncovery.

DRAFT

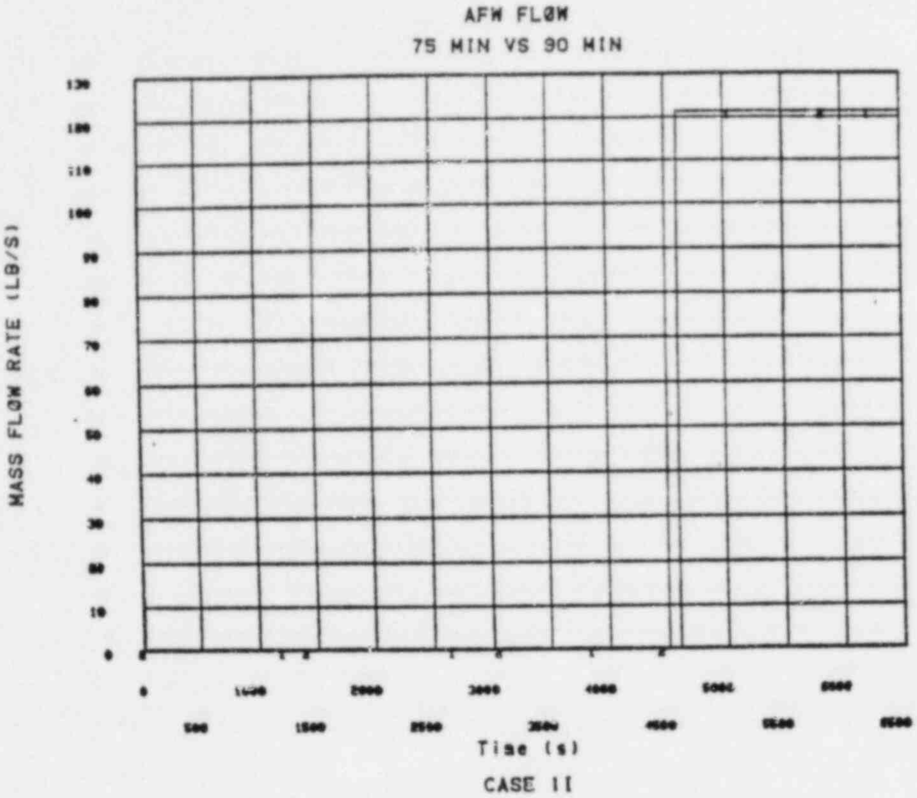


Fig. 4.121

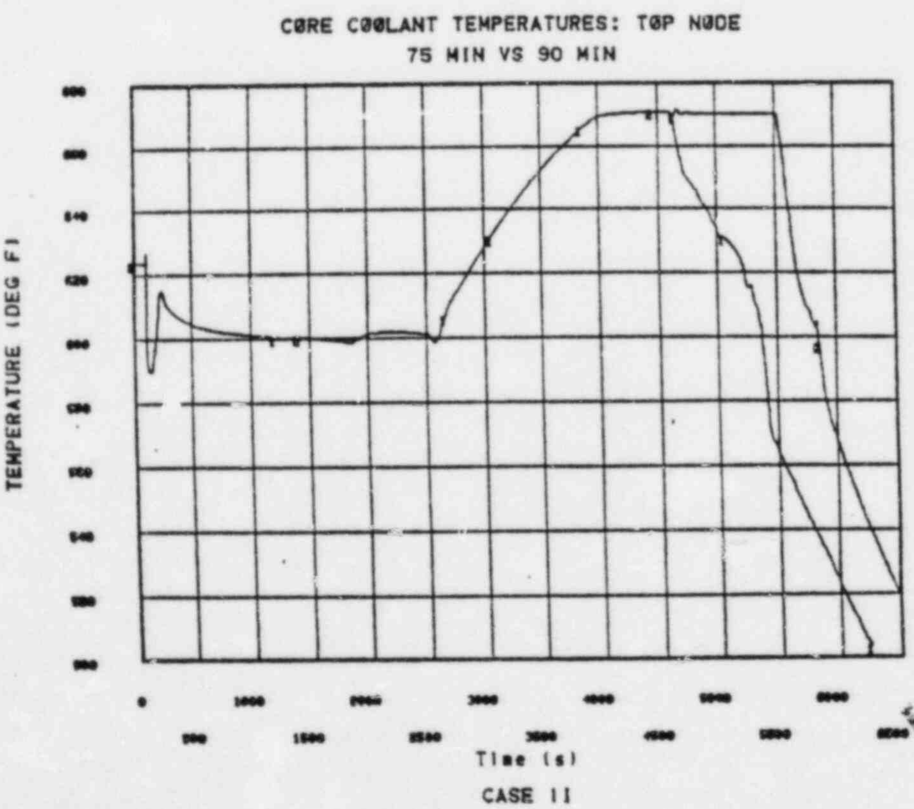


Fig. 4.122

DRAFT

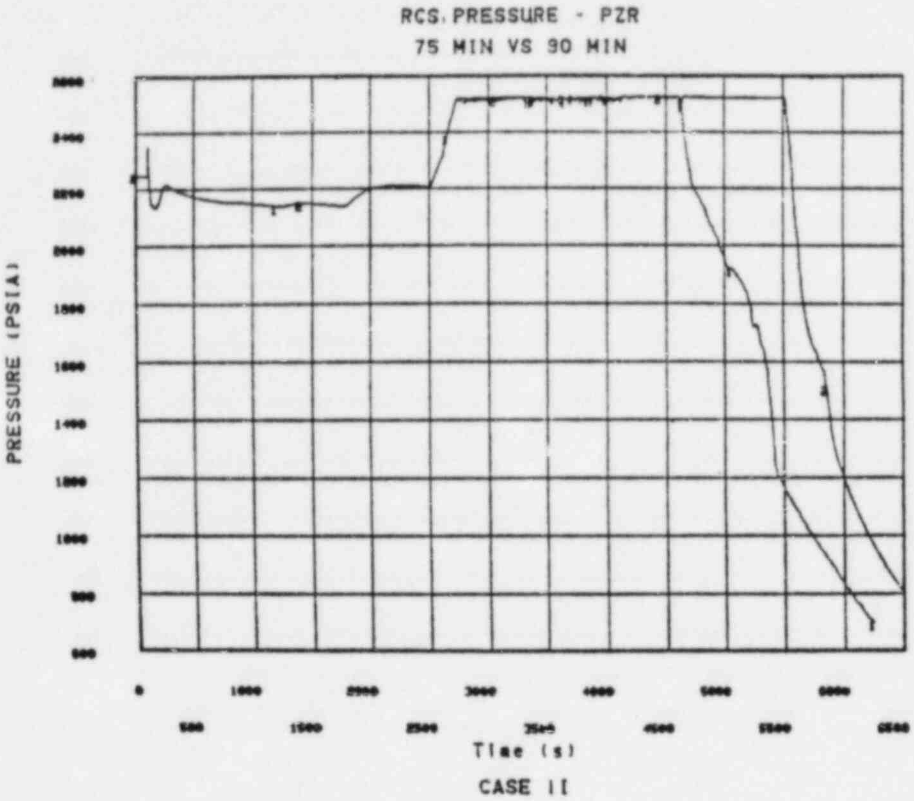


Fig. 4.123

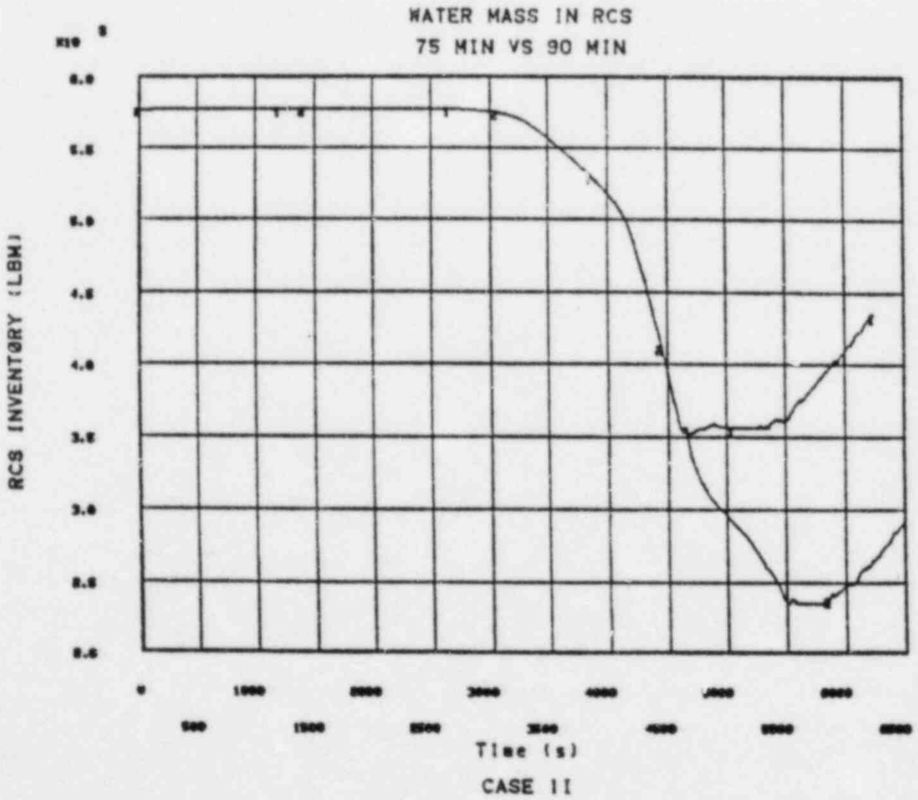
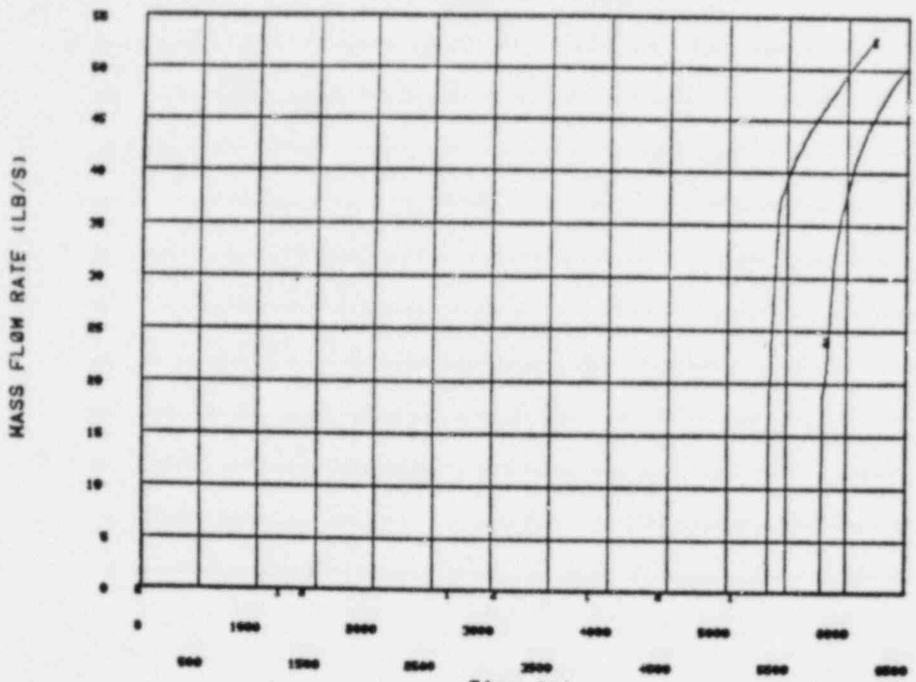


Fig. 4.124

DRAFT

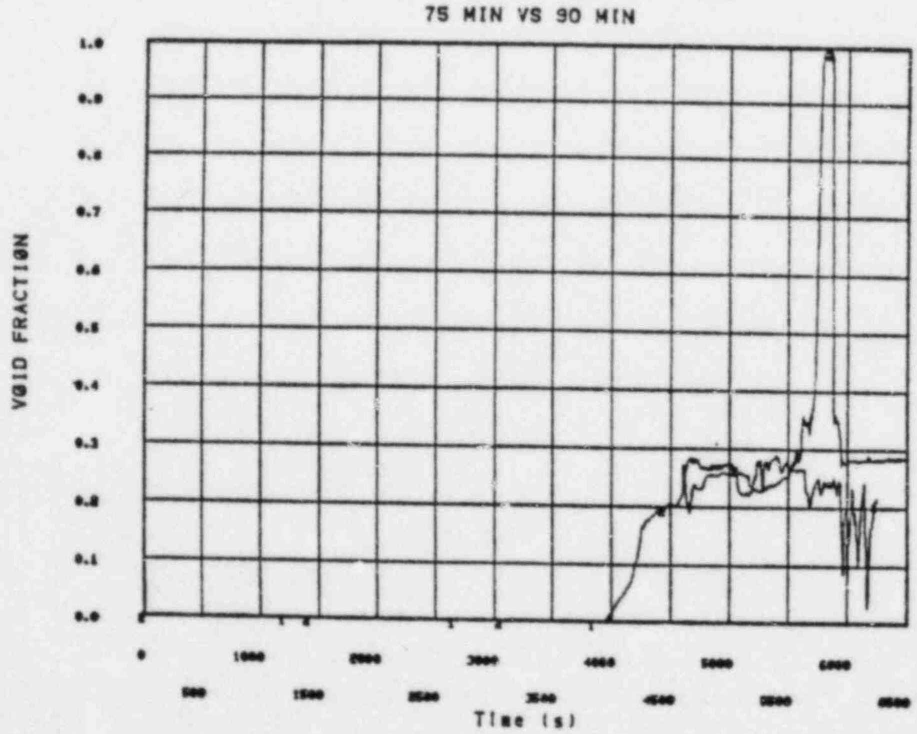
HPSI FLØW
75 MIN VS 90 MIN



CASE II

Fig. 4.125

VØID FRACTIØN IN CØRE: TØP NØDE
75 MIN VS 90 MIN

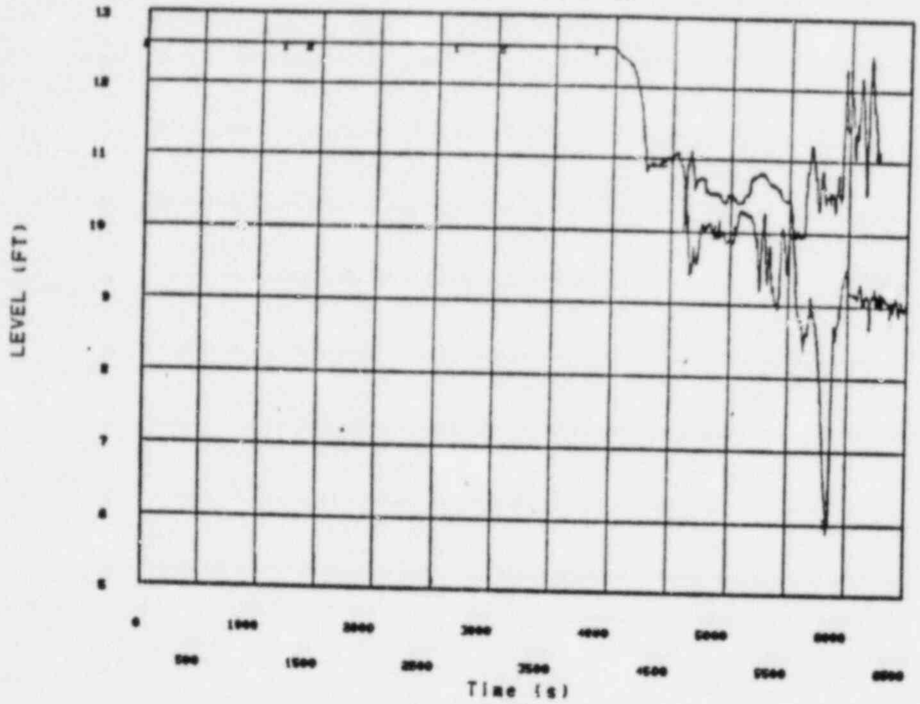


CASE II

Fig. 4.126

DRAFT

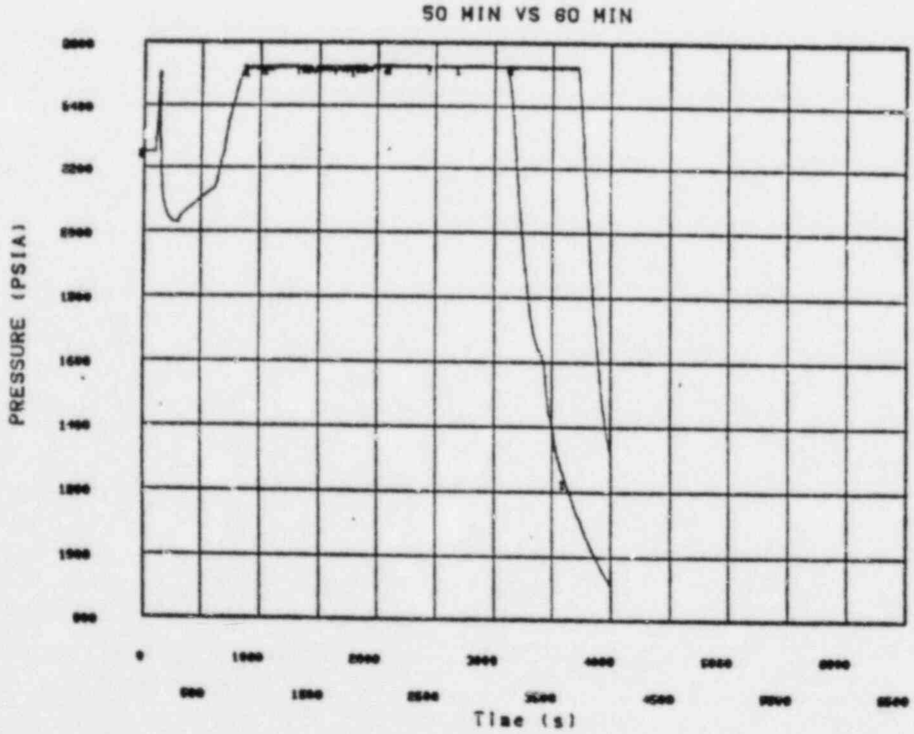
CØLLAPSED WATER LEVELS IN CØRE
71 MIN VS 90 MIN



CASE II

Fig. 4.127

RCS PRESSURE - PZR
50 MIN VS 60 MIN



CASE 2I

DRAFT

Fig. 4.128

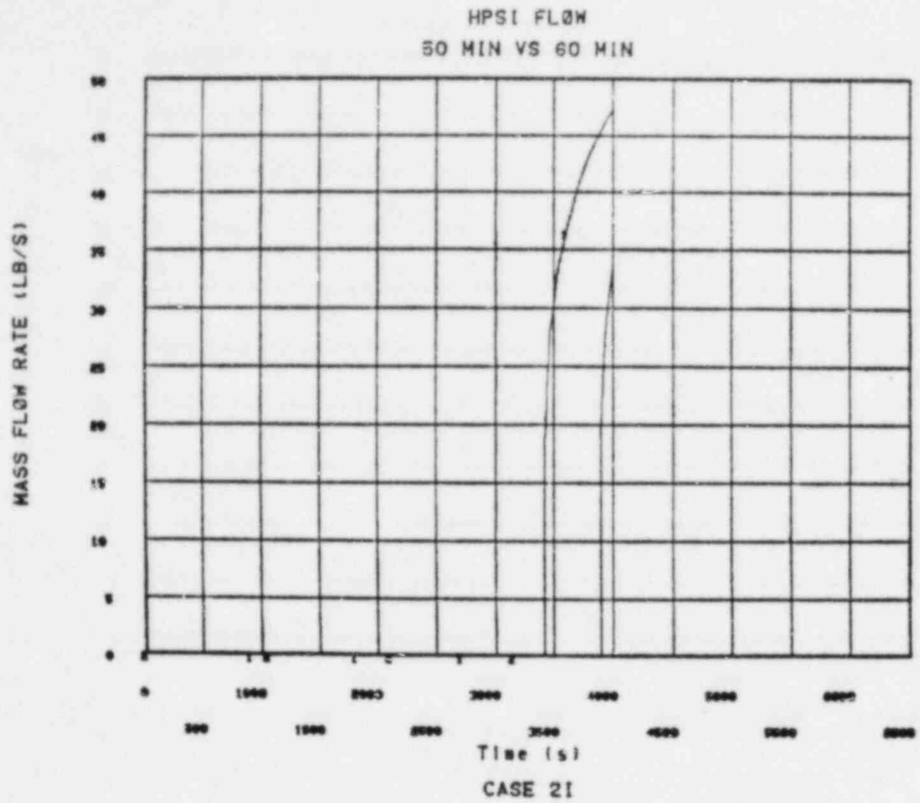


Fig. 4.129

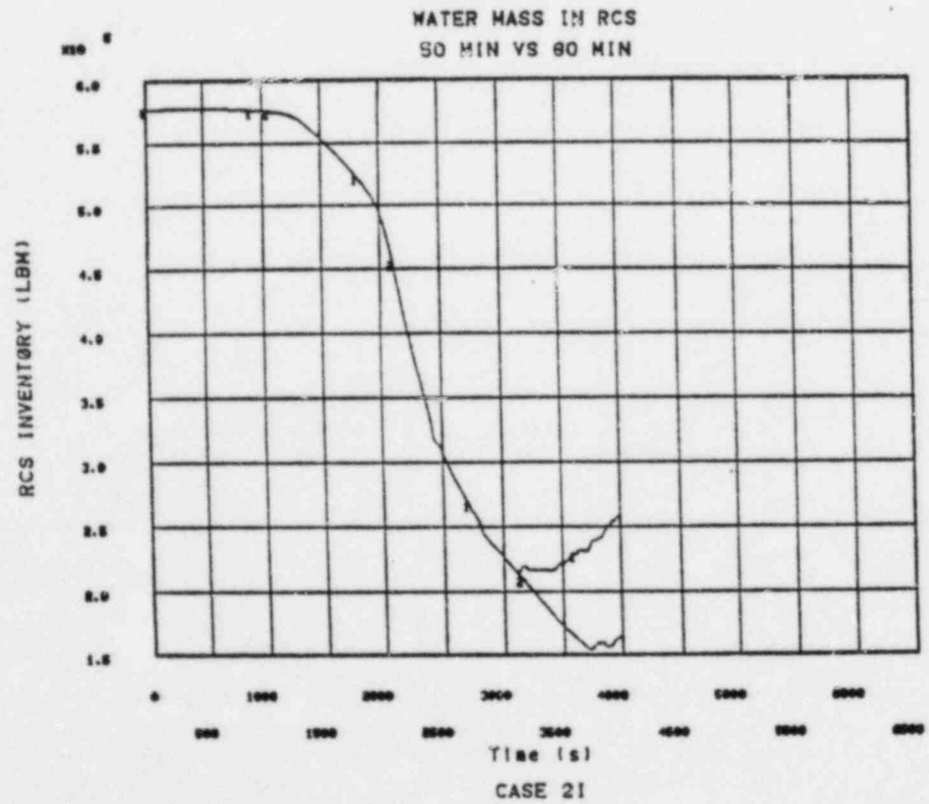


Fig. 4.130

DRAFT

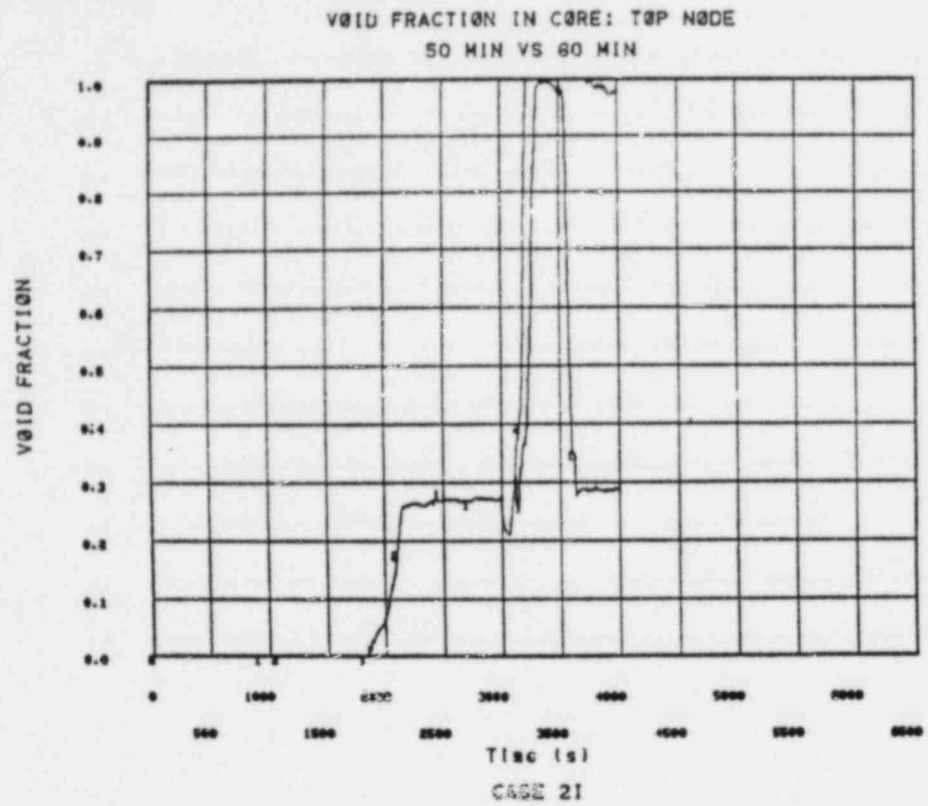


Fig. 4.131

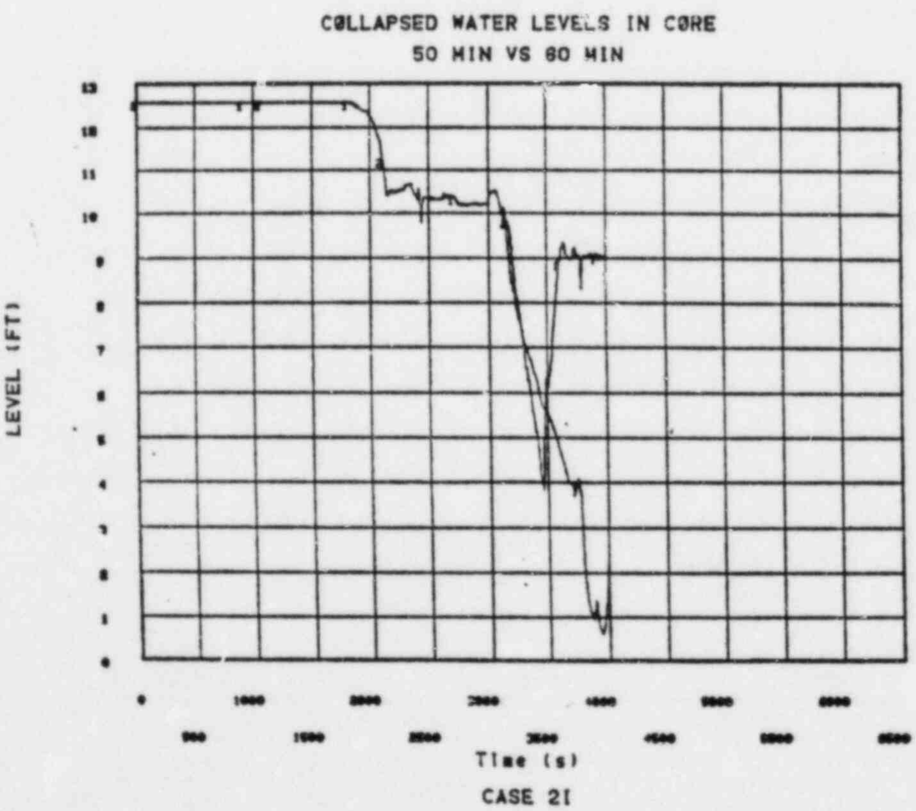
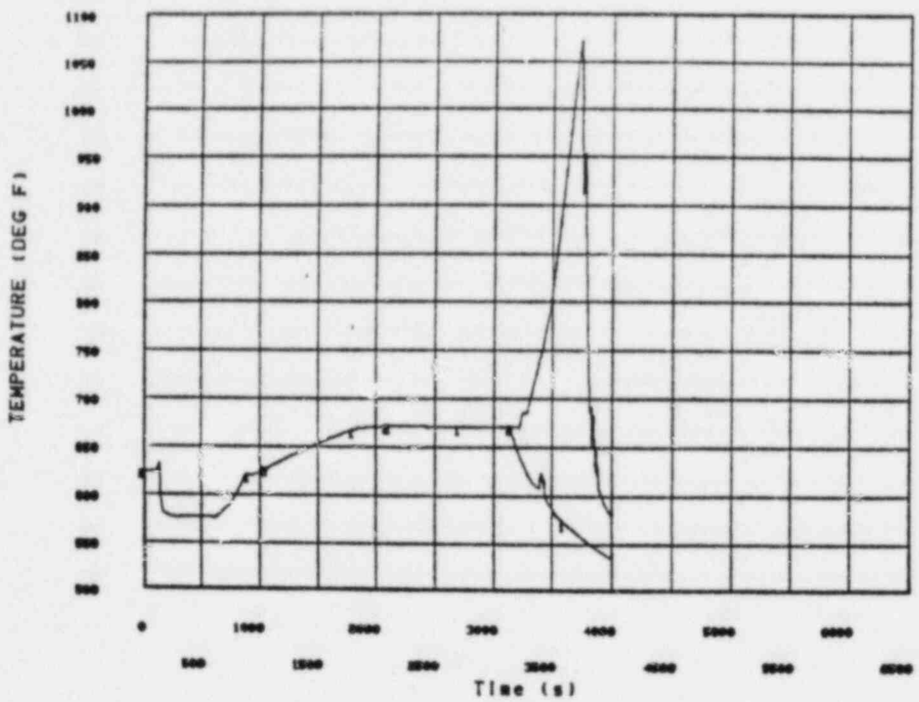


Fig. 4.132

DRAFT

CØRE CØØLANT TEMPERATURES: TØP NØDE
50 MIN VS 60 MIN



CASE 2I

Fig. 4.133

DRAFT

5.0 SUMMARY AND CONCLUSIONS

5.1 Modeling Uncertainties

Like all computer codes, RELAP5 is limited by the phenomenological models built into the code by the code developers. In addition, however, RELAP5 permits the user to vary the nodalization (an option not present in CESEC and some other codes) and to utilize the "control functions" to override certain built in RELAP5 models. This latter option was not invoked in this analysis, however there are important effects of the built in modeling which definitely affected the absolute values of numbers computed during these transients. Thus, in interpreting this analysis, the following modeling uncertainties and variabilities must be considered.

- PORV flow modeling

  The PORV flow was initialized at the rated steam flow for those valves. As the pressurizer fills up, the flow becomes two phase and the computed mass flow rate changes markedly from the rated value. This is phenomenologically expected to happen, but there are definite uncertainties in the flow rate. No experimental data is currently available, and the RELAP5 model is probably no worse than any other model, nor can we say with confidence that it is significantly better.

  This uncertainty in actual mass discharge rate causes a concomitant uncertainty in the primary inventory and therefore in the depletion of coolant from the core region. However, we do not believe this uncertainty negates the trends computed as differences between cases. Thus the trend conclusions of the study are not affected by this uncertainty.

- Flow regime modeling

  RELAP5 has a family of flow regime "maps" in which the drag between liquid and vapor flow is computed. The state of the art of

DRAFT

modeling flow regimes is weak, and the RELAP5 maps reflect this weakness. When RELAP5 indicates that flow changes from bubbly flow (bubbles rising due to density differences) in which the drag is very high and the slip between phases small, to a high slip flow regime (such as annular flow), the flow pattern changes markedly. Similarly, the stratified flow in horizontal pipes changes rather sharply as a function of local vapor fraction and vapor and liquid mass fluxes.

In the primary loop

These maps strongly influence the computed distribution of mass around the primary loop (for example because of potential countercurrent flow in the hot legs) and the flow into the surge line (because the stratified flow map couples with the fact that the surge line joins to the bottom of the hot leg) and therefore the PORV flow.

In the core

More importantly, however, the maps dominate the computed behavior in the core. As we observed in the main body of this report, the vapor fractions in the core region tend to hang up in the 25-30% range for the entire axial extend of the core for extended periods of time. When core uncovery is computed to occur, it frequently takes place in such a manner that the local vapor fraction jumps from ~.3 to 1.0 over a very brief time interval. This is purely a result of the flow regime maps in RELAP5.

That is not to say that other codes do this part of the computation with more accuracy. In fact, there is very little data on vapor distributions in core bundles during the quasi-static boiloff conditions characteristic of a small break LOCA -- which is the situation during the transients computed here. Every computer code has some model for its vapor/liquid drag and that model almost singularly

governs the mixture level in the core during core uncovery. Most of these models are based upon data gathered at relatively high flux rates characteristic of conditions on the secondary side of steam generators, since that is of major importance and is relevant to most transients of interest. Another large body of data exists for Large Break LOCA conditions of extremely rapid core draining and reflooding because of extensive concern over that accident in the past. Unfortunately prior to the accident at TMI-2, virtually no data existed for the quasi-static boiloff conditions -- and very little new data has been generated since that accident. Furthermore, in general, systems code developers have not paid particularly strong attention to the low mass flux conditions.

Thus significant uncetainty exists in the prediction of core mixture level, and therefore in the prediction of the specific time of onset of core uncovery. For computations which border on uncovery or uncover only slightly, it is not possible to state with any confidence that those situations would or would not cause core uncovery.

However, as with the other uncertainties, we believe that the general trends computed are believable. Thus we believe that overall conclusions regarding the general effect of size of PORV or of the efficacy of APS are valid.

The caution that we put forth here goes toward the validity of any specific time of core uncovery and toward interpretation of borderline cases. If the code predicts extensive core uncovery, it is our judgment that the conclusion that core uncovery would occur is warranted. Similarly if the code predicts that the core never uncovers and the vapor fraction never even get near 30%, we feel that a conclusion that core uncovery would not occur is warranted.

Taken in combination, these can be used to examine the predicted time of onset of core uncovery. When the onset of core uncovery is predicted under two different situations to differ by a

DRAFT

thousand seconds, the trend is very credible. When the onset only differs by one hundred seconds, we would question whether the models are adequate to accurately make the distinction.

5.2 Analysis Summary and Conclusions

In this section we summarize the results of calculations performed to examine the ability of a CE System 80 plant to avoid core uncovery during a total loss of feedwater event accompanying Loss of Offsite Power (LOOP) considering the use of the CE Auxiliary Pressurizer Spray (APS) to lower the system pressure to enable High Pressure Safety Injection (HPSI) flow to cool the primary. We also examine the use of the Auxiliary Feedwater (AFW) system and the potential effect of installation of Pilot Operated Relief Valves (PORVs). In addition, we investigated the impact of LOOP by examination of what would happen without LOOP. A summary of the results are presented in Table 5.1.

Continued full power operation in cases 2 and 4 generated more primary heat to be transferred to the steam generators and therefore more rapidly depleted the secondary side inventories. (These cases were accompanied by an additional roughly 30 s of full power operation because the reactor did not trip concurrently with TLOFW, but tripped later on high primary pressure.) The steam generators dried out by roughly 500 seconds into the transient, after which time the pressure in the primary rapidly rose to the pressurizer safety valve setpoint where it remained. By contrast, if the reactor is tripped (which accompanies LOOP), the loss of inventory from the steam generators is much more gradual and they do not dry out until ~2400 seconds in Case 1 (and even longer in some cases with PORVs depending upon the PORV sizes and the timing of PORV opening). Once the steam generators dried out and the primary pressure rose to the safety setpoint, the safeties opened and primary inventory began to be lost. HPSI flow could not enter the primary because the pump head was insufficient to overcome the high system pressure. Thus, once the safeties (and later the PORVs) opened, the inventory depleted at a rate which was dominated by the valve flow, since the primary pressure was constant. (The valves represent the only energy removal mechanism after SG dryout.) Thus inventory decay once the safeties opened was essentially the

DRAFT

same between cases 1 and 2, with 30 minutes extra time available in case 1 because of LOOP at the onset of the transient.

The APS system was not useful either with or without offsite power, since it was unable to depressurize the primary pressure to a low enough value to permit significant HPSI flow. (We note that in this study we assumed that only one charging pump was available for APS; however, since APS logic will turn off APS when there is less than 20°F subcooling, the use of all three charging pumps would alter only the timing but not the substance of this result.) Although use of the APS did permit depressurization to slightly below 1800 psia, since the HPSI maximum head was only 1775 psig only a trickle of HPSI flow entered the system. The use of APS did delay opening of the pressurizer safeties by roughly 300 to 400 seconds. However, that made virtually no difference in primary inventory and therefore had no impact upon core uncovery.

If the steam generators are not available as a heat removal mechanism use of a PORV appears to be necessary to depressurize the system to a low enough value to permit HPSI and eventually accumulator injection to get into the primary and to cool down in a feed and bleed mode. In this study, we assumed two PORVs were opened by the operator at some point during the transient and were left in the full open position thereafter. Both the nominal sized PORVs (yielding a combined flow of 120 lb/sec at pure steam) and the large PORVs (270 lb/sec) permitted operation in a feed and bleed mode. Naturally the larger PORV permits more rapid depressurization and is accompanied by more rapid primary inventory depletion.

After TLOFW and LOOP, the operator would have roughly 60 minutes to open the large PORVs, compared with roughly 40 minutes for the smaller valves. When the offsite power is available, the operator has on the order of 30 minutes to open the large PORVs and still avoid core uncovery compared with less than even 10 minutes for the smaller ones. Throughout this study we assumed that only one HPSI pump was available, however, we examined the effect of utilizing two HPSI pumps by performing a calculation similar to case 4aii. The results indicate that increasing the HPSI flowrate instead of HPSI pump head does not alter the transient scenario enough to avoid core uncovery,

because with smaller PORVs the RCS pressure does not drop enough to permit a singificant HPSI flow.

These RELAP5 calculations indicate that to be effective the installation of two small PORVs should be accompanied by installation of higher head HPSI pumps, whereas the larger PORVs would suffice without the higher head HPSIs. With the larger PORVs, the operator has at least a 30 minute window in which he can make a decision to open them and to attempt to restore his AFW. However with smaller PORVs for some transients the window is less than 10 minutes. Thus, it would appear preferable to utilize two large PORVs instead of two small ones.

Restoration of AFW is effective in rapidly causing system depressurization and preventing core uncovery. After TLOFW and LOOP, the operator can wait at least 90 minutes before actuating the AFW flow, and even when the power is available if the operator can restore the AFW flow within 50 minutes he can avoid core uncovery. It should be stated and emphasized in the Recovery Guidelines that the operator should utilize the time available to make all possible attempts to restore main or auxiliary feedwater systems in order to provide a primary decay heat sink for a controlled reactor cooldown before resorting to PORVs. Use of PORVs is a good backup measure when he is unable to restore feedwater.

DRAFT

Table 5.1. TLOF Summary

Case ID	Description	LOF	Reactor Trip	PORV	AFW	RCPCD	SG Relief	SG Dryout	PZR Safety	APS	HPSI	ACCUM	Core Uncovery
						Initiation Time, s							
Case 1	Base Case No op. act.	0.	0.	--	--	0.	5.3	2400.	~2630	--	--	--	5800
Case 3	Op. guidelines HPSI and APS	0.	0.	--	--	0.	5.3	2400.	~3000	600 2400 2690 2830	1237	--	6030
Case 3ai	PORV -- 20 min	0.	0.	1200	--	0.	5.3	3090.	--	--	1255.3	5325.0	--
Case 3aii	PORV -- 30 min	0.	0.	1800	--	0.	5.3	2950.	--	--	1855.	--	
3aii	PORV -- 40 min	0.	0.	2400	--	0.	5.3	2440.	--	--	2450. 5300.	--	4900
Case 3bi	PORV -- 20 min	0.	0.	1200	--	0.	5.3	--	--	--	1220.	2900	--
Case 3bii	PORV -- 50 min	0.	0.	3000	--	0.	5.3	2400.	~2630	--	3820.	4650	--
3bii	PORV -- 60 min	0.	0.	3600	--	0.	5.3	2400.	~2630	--	4460.	5250	--
Case 1i	AFW -- 75 min	0.	0.	--	4500	0.	5.3	2400.	~2630	--	5240.	--	--
1i	AFW -- 90 min	0.	0.	--	5400	0.	5.3	2400.	~2630	--	5700.	--	--
Case 2	Base Case No op. act.	0.	29.8	--	--	600.	33.0	~500.0	772	--	--	--	~3140
Case 4	Op. guidelines HPSI and APS	0.	29.8	--	--	600.	33.0	~500.0	950	600	--	--	~3240
Case 4ai	PORV -- 20 min	0.	29.8	1200	--	600.	33.0	~500.0	772	--	--	--	~3050
Case 4aii	PORV -- 10 min	0.	29.8	600	--	600.	33.0	~500.0	--	--	650.	--	~3100
Case 4bi	PORV -- 20 min	0.	29.8	1200	--	600.	33.0	~500.0	772	--	2150.	3120	--
Case 4bii	PORV -- 30 min	0.	29.8	1800	--	600.	33.0	~500.0	772	--	2250.	3570	--
4bii	PORV -- 40 min	0.	29.8	2400	--	600.	33.0	~500.0	772	--	4075.	--	3100
Case 2i	AFW -- 50 min	0.	29.8	--	3000	600.	33.0	~500.0	772	--	3320.	--	--
2i	AFW -- 60 min	0.	29.8	--	3600	600.	33.0	~500.0	772	--	3790.	--	3140

DRAFT

Acknowledgments

This report was prepared by ANL staff in partial fulfillment of a project under the direction of the U.S. NRC Division of Systems Integration, R. J. Mattson, Director; B. Sheron, Branch Chief for Reactor Systems; N. Lauben, Section Leader; J. Guttmann, Project Manager. L. B. Marsh of the NRC Reactor Systems Branch provided direct technical guidance during the performance of this task.

ANL staff who provided input to this report were H. Komoriya and P. B. Abramson, authors; K. Rank and J. Bracken, report preparation; and R. D. Wright, Jr., drafting services.

DRAFT