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TRAC ANALYSES OF POTENTIAL OVERCOOLING TRANSIENTS AT CALVERT CLIFFS-1 FOR PTS RISK ASSESSMENT*

Preliminary Summary

by

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Update 1

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ABBREVIATIONS

ADV	Atmospheric Dump Valve
AFAS	Auxiliary Feedwater Actuation Signal
AFW	Auxiliary Feedwater Flow
BG&E	Baltimore Gas & Electric Co.
CC	Calvert Cliffs
CE	Combustion Engineering Inc.
HFP	Hot, Full Power steady-state conditions
HPI	High-Pressure Injection
HZP	Hot, Zero Power steady-state conditions
LOFW	Loss of Feedwater
MFIV	Main Feedwater Isolation Valve
MFRV	Main Feedwater Regulating Valve
MSIV	Main Steam Isolation Valve
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PORV	Power-Operated Relief Valve
PTS	Pressurized thermal shock
RCP	Reactor Coolant Pump
SG	Steam Generator
SGIS	Steam Generator Isolation Signal
SIAS	Safety-injection Actuation Signal
TBV	Turbine-bypass Valve
TSV	Turbine-stop Valve

1. Introduction

Reactor vessels in older plants have a risk of cracking if subjected to a thermal shock with a subsequent system repressurization (referred to as pressurized thermal shock). After years of radiation exposure from the reactor core, the vessel wall and welds become embrittled and their reference temperature for nil-ductility transition (RT_{NDT}) increases. This means that as the fluence to the vessel wall and welds increases, the temperature at which it will crack increases. Overcooling transients that may bring the vessel wall temperature rapidly below its RT_{NDT} followed by a primary repressurization have been postulated to lead to PTS. For this reason, the NRC has identified this problem as Unresolved Safety Issue A-49 (USI A-49). A major effort among several organizations (BG&E, CE, NRC, ORNL, and Los Alamos) has been established to resolve the PTS issue.

Intense cooperation of BG&E, CE, NRC, ORNL, and Los Alamos has been required to adequately address USI A-49. BG&E and CE have put extensive effort into supplying information about the plant and its operation. Los Alamos has taken this information and prepared a TRAC-PF1 model to calculate the thermal-hydraulic events of several postulated overcooling transients. TRAC-PF1 is a three-dimensional transient computer code for thermal-hydraulic predictions. ORNL's job is both to specify the overcooling transients to be calculated by Los Alamos and to extend these calculations by predicting other postulated accidents. Also, ORNL will receive these data from Los Alamos so that fracture-mechanics analysis may be performed for transients that may be a PTS risk. The NRC oversees the entire project.

Calvert Cliffs is a CE-vendored pressurized water reactor located on the Chesapeake Bay in Maryland. It is owned by the Baltimore Gas & Electric Co. Unit 1 of the Calvert Cliffs Nuclear Power Plant began operation in January 1975. Unit 1 has a 2 x 4 loop arrangement: two hot legs and two steam generators with four cold legs and four reactor coolant pumps. It presently operates at 2700 MW_{th}.

The following pages briefly describe the TRAC-PF1 model, the steady-state conditions, and the transients calculated by Los Alamos.

2. TRAC-PF1 Model and Steady-state Calculations

Figures 2.1-2.3 depict the basic TRAC noding of the Calvert Cliffs-1 power plant. Extensive technical information about the plant and its operation was received from both BG&E and CE. Using measured plant data for both steady-state and transient operations, the TRAC model was normalized to match these data. Slight variations in the basic noding are required to simulate each specific transient. A brief summary of the basic TRAC model of Calvert Cliffs follows. (A more detailed description of the TRAC noding and applicable references are documented in an audit report to be issued at a later date.)

On the primary side, the three-dimensional vessel is divided into 12 axial levels, 2 radial rings, and 6 theta segments. The first level represents the lower plenum. The inner ring of the second level is the lower core support assembly with levels 3-7 modeling the core region. The upper plenum is modeled with three levels. Two levels are used for the upper head to more accurately predict liquid draining from this region. The core barrel is the basis for the radial division in the vessel. The six theta segments allow for the six piping penetrations in the vessel. Bypass flow paths including keyway, control-element-assembly shrouds and hot-leg connections, are modeled. Fictitious pipe components have been placed in the lower plenum to produce the correct net effect for loop-to-loop fluid mixing.

All four cold legs are modeled separately. Because of some calculational difficulties, the steam generator is noded more finely for some of the calculations. (Figure 2.1 represents the more finely noded SG model.) Single-phase head and torque curves for the RCPs are provided by CE. The pressurizer model includes a lower "heating" section to simulate the region in which the backup and proportional heaters are located. The control of these heaters is modeled with the control system of the plant model.

The TRAC model also contains the pertinent parts of the Calvert Cliffs control system. The three-mode and single-mode control on the feedwater regulating valves is modeled. Also, the main-feedwater-pump speed controller based on the pressure difference across the feedwater regulating valves is modeled. Valve control for the ADVs, TSVs, TBVs, SRVs, and PORVs is also modeled.

Two separate steady-state models are necessary to allow for the variations in plant conditions between hot, zero power and hot, full power. Tables 2.1 and 2.2 give the steady-state calculational results for the initial seven transients presented at the September 20-21, 1983 meeting in Baltimore. These numbers reflect the information updates received from BG&E and CE following the TRAC model review meeting held at Los Alamos on June 27-28, 1983. The steam generator was renoded somewhat for the final six transients so that the steady-state calculations had to be rerun; the results did not vary significantly.

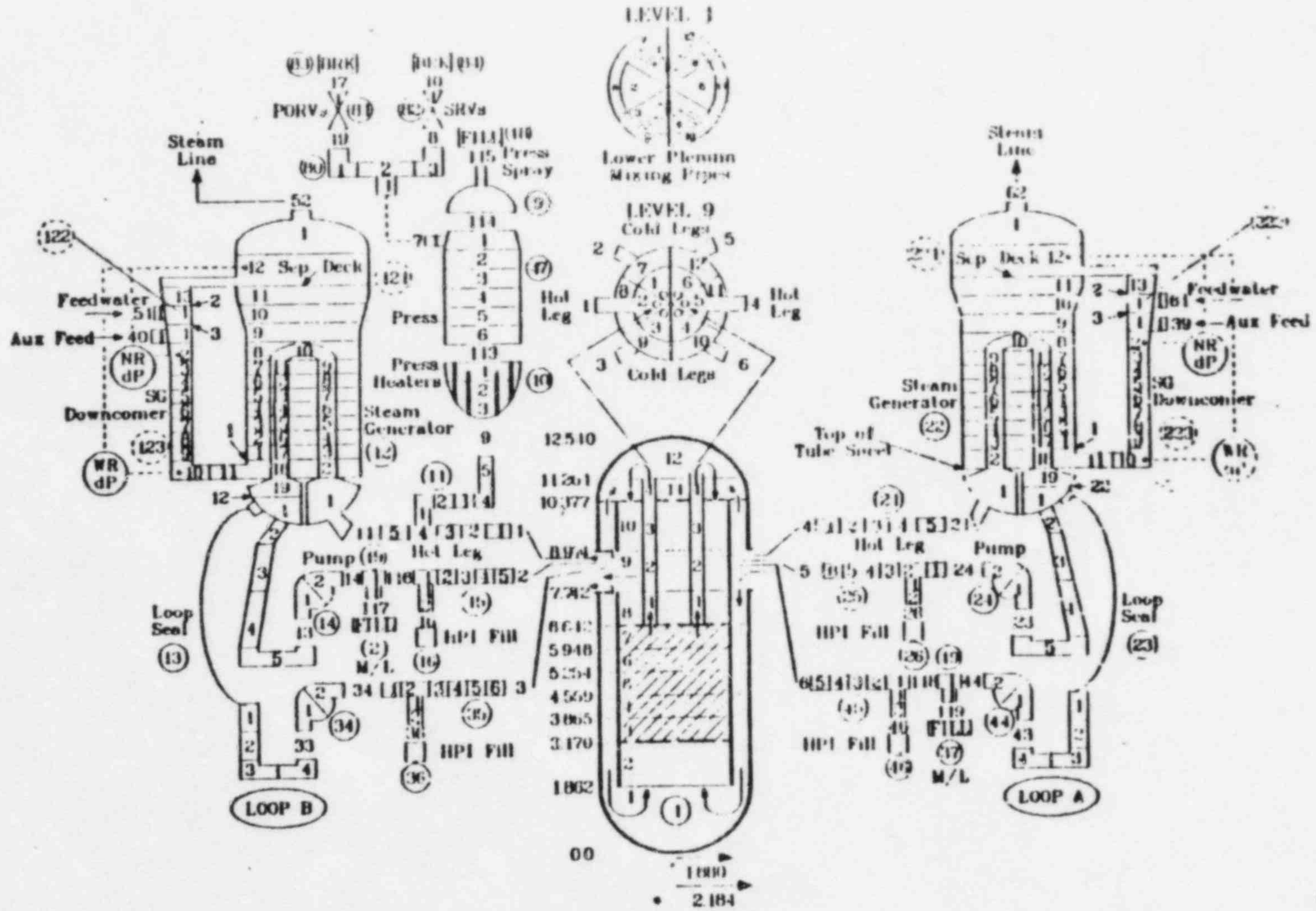

Fig. 2.1. TRAC noding for CC primary side.

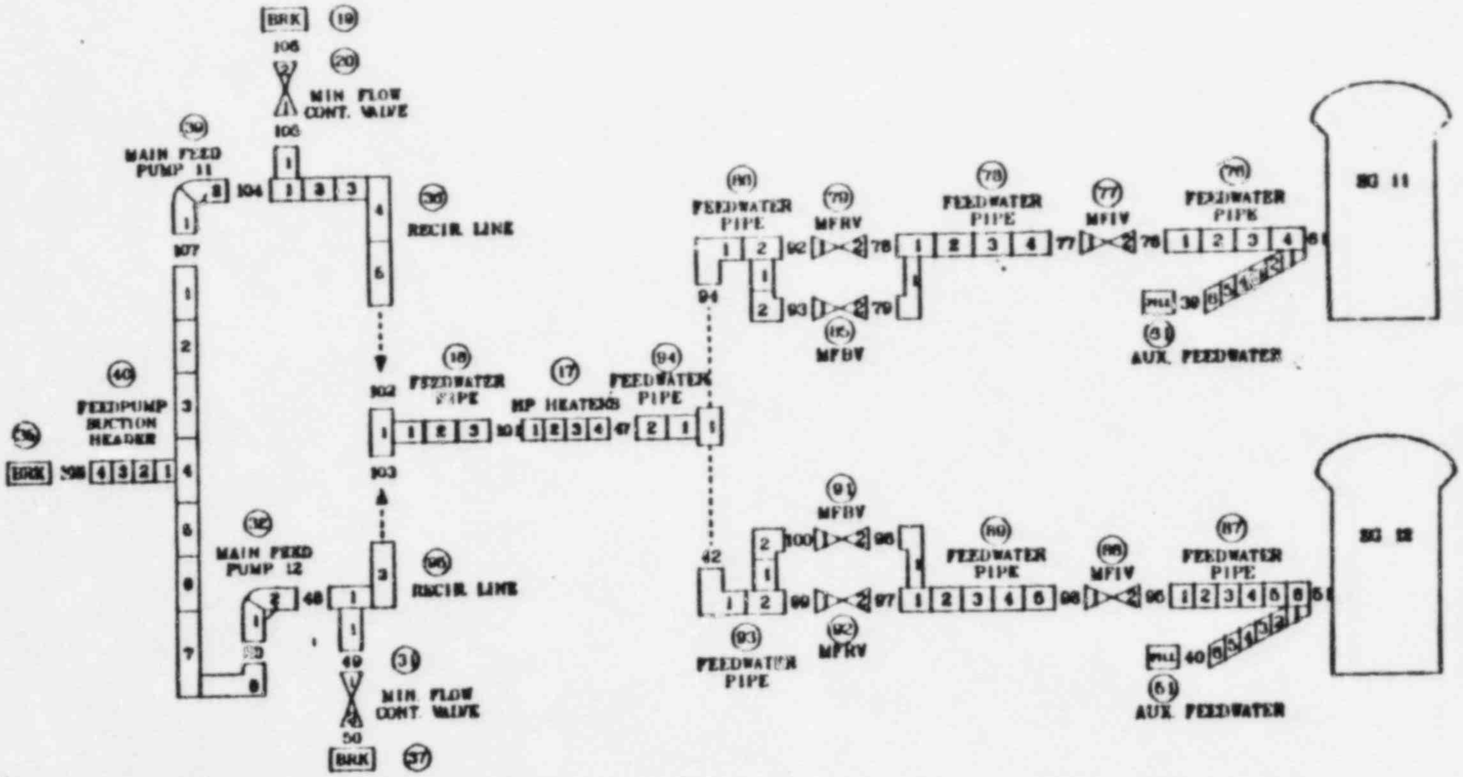

Fig. 2.2. TRAC noding for CC steamlines.

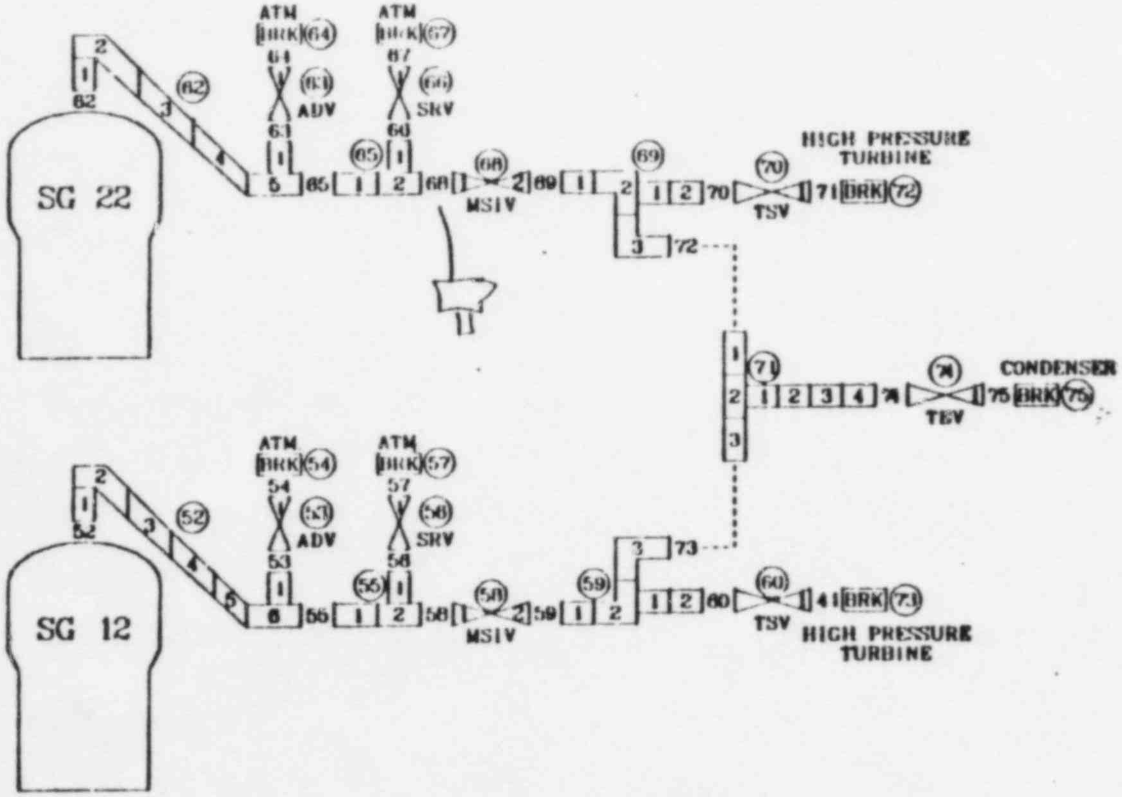

Fig. 2.3. TRAC noding for CC Feedwater/Condensate train.

TABLE 2.1
Comparison Between TRAC and Design/Plant at Hot, Zero Power Conditions.

	Design/Plant Data	TRAC Predictions
PRIMARY SIDE		
Power 100 hours after shutdown		
Decay heat	-	9.38 MW
Pump power	-	17.38 MW
Pressure	15.52 MPa (2250 psia)	15.52 MPa (2250 psia)
Mass Flow	19300 kg/s (42,549 lb/s)	19700 kg/s (43,431 lb/s)
Average Temperature	550.9 K (532 °F)	551.8 K 533.6 °F)
Pressurizer Level	3.68 m (144.0 inches)	3.68 m (144.0 inches)
SECONDARY SIDE		
Feedwater flow per SG	10.1 kg/s (22.3 lb/s)	11.8 kg/s (26.0 lb/s)
SG Dome Pressure		
SG 11 (TRAC component 22)	6.20 MPa (900 psia)	6.17 MPa (895.5 psia)
SG 12	6.20 MPa (900 psia)	6.17 MPa (895.5 psia)
Feedwater Temperature	299.8 °F (80.0 °F)	299.8 °F (80.0 °F)
TBV % open	-	5.0
SG Liquid Mass	102058 kg (225,000 lb)	102058 kg (225,000 lb)

TABLE 2.2
Comparison Between TRAC and Design/Plant at Full Power Conditions.

	Design/Plant Data	TRAC Predictions
PRIMARY SIDE		
Core power	2694 MW	2700 MW
Vessel flow	25.27 m^3/s (401,121 gpm)	25.28 m^3/s (401,324 gpm)
ΔP_{vessel}	-	0.28 MPa (40.65 psid)
ΔP_{sg}	0.19 MPa (28.15 psid)	0.24 MPa (34.60 psid)
ΔP_{loop}	0.54 MPa (78.73 psid)	0.538 MPa (76.28 psid)
T_{hot}	585.7 K (594.6 ^oF)	585.6 K (595.1 ^oF)
T_{cold}	559.3 K (547.0 ^oF)	559.6 K (547.6 ^oF)
ΔT_{vessel}	26.4 K (47.6 ^oF)	26.4 K (47.5 ^oF)
SECONDARY SIDE		
Feedwater flow per SG	749 kg/s (5.95 Mlb/hr)	737 kg/s (5.85 Mlb/hr)
SG Dome Pressure		
SG 11	5.90 MPa (856 psia)	5.90 MPa (852.9 psia)
SG 12	5.86 MPa (850 psia)	5.89 MPa (853.7 psia)
MFW Pump Discharge Pressure		
MFW 11	7.8 MPa (1130.7 psia)	7.67 MPa (1112.6 psia)
MFW 12	7.63 MPa (1106.7 psia)	7.57 MPa (1097.4 psia)

Feedwater Temperature	494.8 K (431.0 °F)	496.2 K (433.5 °F)
MFRV % open	~90	88.9
SG liquid mass	62,350 kg (137,458 lb)	64,600 kg (142,419 lb)

3. Transients

Table 3.1 summarizes the thirteen transients specified by ORNL. Four of the transients are steamline breaks from hot, zero power conditions. The remaining nine transients are from hot full power and include three steamline break/valve failures, two primary breaks, one PORV/ADV failure, and two runaway-feedwater cases.

Common to all of these transients (except in Transient 10) is the assumption that following SIAS the operator will manually trip all the RCPs. In addition, it is further assumed that no other operator intervention is allowed (except in Transient 11). Hence, once the HPI and charging flow are initiated, they are allowed to run unthrottled. During transients in which mass is not being lost from the primary system, the pressurizer will completely refill and repressurize to the PORV setpoint. If AFW is initiated, it is assumed that the operator will not turn off the AFW system when the steam generators regain level. Therefore, it is possible during some of these transients to fill the SGs and start to fill the steamlines with cold liquid.

The following sections summarize the results of these thirteen transients. Table 3.2 indicates the minimum downcomer liquid temperature and pressure and if the system repressurizes and if the flow stagnates in either one of the cold legs.

TABLE 3.1

CALVERT CLIFFS-1 INITIAL PTS TRANSIENT SPECIFICATIONS (AS SUPPLIED BY ORNL)

No.	Descriptive Title	Initial Plant State	Initiating Event	Equipment Failures on Demand	Operation Actions
1	1-ft^2 steam line break at standby	Hot 0% Power	1.0-ft^2 hole in steam line A	None	None
2	Full double-ended guillotine steam line break	Hot 0% Power	Full steam-line break	Auxiliary feed-water (AFW) is not isolated	None
3	1-ft^2 steam line break at full power	100% Power	1.0-ft^2 hole in steam line	None	None
4	Turbine-trip with turbine-bypass valve (TBV) stuck open	100% Power	Turbine trip	TBV sticks wide open	None
4a	Turbine trip with one TBV and one MSIV stuck open	"	"	TBV & MSIV stick open	
5	Primary power-operated and atmospheric-dump valve (ADV) stuck open	100% Power	PORV transfers to wide open	1 ADV opens on demand and sticks open	None
6	AFW overfeed after AFW response failure	100% Power	MFW system trips off	AFW delay for 8 minutes	AFW valves opened fully at 8 minutes
7	Small break loss-of-coolant accident with blocked natural circulation	100% Power	An 0.02-ft^2 hole appears in the hot leg	None	None
7a	Small break LOCA with no artificial flow blockage	100% Power	"	None	None
8	Main feedwater overfeed	100% Power	Turbine trip	2 MFRVs stick open	None

No.	Descriptive Title	Initial Plant State	Initiating Event	Equipment Failures on Demand	Operation Actions
9	Main feedwater overfeed to one SG	100% Power	Turbine trip	1 MFRV sticks open	None
10	1 ft^2 steamline break with 2 RCPs left operating	Hot 0% Power	1.0 ft^2 hole in steam line	None	None
11	Full double-ended guillotine steam line	Hot 0% Power	Full steam line break	MSIVS fail to close	AFW turned off at 8 min.

TABLE 3.2

Summary of Minimum Temperatures and Pressures

Transient	Minimum T (K)	Minimum P (MPa)	Repressurization	Flow Stagnation
1 1.0 ft^2 MSLB from HZP	395	4.8	yes	yes
2 Double-ended MSLB from HZP	377	3.7	yes	yes
3 1.0 ft^2 MSLB from HFP	450	6.0	yes	yes
3a Transient 3 rerun	468	6.6	yes	yes
4 Stuck-open TBV from HFP	530	10.8	yes	no
4a Transient 4 with one MSIV stuck open	500	11.4	yes	no
5 Stuck-open PORV & ADV from HFP	407	6.0	no	yes
6 Runaway AFW Following LOFW from HFP	375	6.5	yes	yes
7 Hot-leg break from HFP with forced flow blockage	342	2.6	no	specified-yes
7a Transient 7 with no blockage	440	3.8	no	yes
8 Runaway-feedwater with 2 MFRVS stuck open	480	7.0	yes	no
9 Transient 8 with 1 MFRV stuck open	490	6.4	yes	yes
10 Transient 1 with 2 RCP running	446	3.9	yes	specified-no
11 Transient 2 with 2 MSIV stuck open and no AFW after 8 min.	376	4.5	yes	no

4. Transient 1

1.0 ft^2 Main Steamline Break From HZP

This transient is initiated by a 0.0929 m^2 (1.0 ft^2) break in steamline A while the plant is at hot, zero power conditions. The break is downstream of the flow restricter and upstream of the MSIV. Timing for the major events is summarized in Table 4.1. In this transient, the ADVs never open and the TBVs close immediately. Until SGIS is reached on low SG pressure of 4.6 MPa at 18.4 s, both SGs blow down. After SGIS, SG B is isolated from the break by the closure of the MSIV. On the primary side, overcooling because of the blowdown of both SGs depressurizes the system below the SIAS setpoint of 12.1 MPa at 54.1 s. Thirty seconds later, the RCPs trip, an operator action specified by ORNL. No voiding occurs on the primary during the 7200 s transient.

SG A continues to depressurize after SGIS and reaches 1.0 MPa at about 200 s. AFW flow to SG A has been valved out based on a SG pressure differential greater than 0.8 MPa. The SG-A secondary drives a natural circulation flow of 500 kg/s in loop-A primary after the RCPs coast down around 200 s. This circulation continues until SG A dries out at 1325 s. After this, a circulation flow of 250 kg/s continues, driven by the gravity head between the downcomer and upper plenum that is induced by the decay heat and the charging flow. This flow continues until 4100 s when natural circulation begins in loop B.

SG B isolates at 18.4 s with a pressure of 4.6 MPa. A large mass inventory still remains and additionally, an AFW flow of 20 kg/s begins at 90.1 s. AFW is injected at 277.4 K (40°F). SG B secondary-side liquid becomes hotter than the primary side of loop B because of the cooling from SG A; reverse heat transfer opposes any natural circulation on loop B for the first 4100 s of the transient. At 3250 s, the SG-B secondary side fills completely with liquid and a natural circulation flow of 300 kg/s begins on the secondary side of the SG. This mixes the colder liquid in the SG downcomer with the liquid in the tube region. This flow on the secondary removes energy from the stagnant fluid on the primary side. By 4100 s, the energy removal from loop-B primary is enough to drive a natural circulation flow of about 350 kg/s in loop B. This flow reduces the circulation in loop A from 250 kg/s to 50 kg/s.

Figures 4.1-4.4 give the primary pressure, downcomer liquid temperature, heat-transfer coefficient at the vessel wall, and the downcomer liquid velocity. The HPI flow begins at about 50 s and ends at 1000 s. After this, flow from the charging pumps repressurizes the system, reaching the PORV setpoint at 3120 s. After this, the PORVs cycle to maintain a system pressure of about 16.1 MPa. The downcomer liquid temperature decreases to 395 K as a result of SG-A and SG-B secondary blowdown and from the HPI injection and charging flow. As the system pressure increases, the HPI flow terminates and the primary temperature levels off. After SG A dries out at 1325 s, primary temperature increases slightly. At 4100 s when natural circulation begins in loop B primary, the primary temperature decreases to 420 K. The calculation is terminated at 7200 s, as specified by ORNL.

TABLE 4.1
Transient 1
1.0 ft^2 Main Steamline Break Fom HZP

Sequence of Events

Time (s)	Event	Setpoint
0.0	0.0929 m^2 (1.0 ft^2) MSLB in loop A TBVs close	
9.1	Pressurizer heaters trip off following low pressurizer level	2.56 m (101 inches)
18.4	SGIS on low secondary pressure	4.61 MPa (653 psig)
28.4	Asymmetric SG pressure	0.80 MPa (115 psia)
54.1	SIAS on low primary pressure	12.1 MPa (1740 psig)
70.0	HPI flow begins	8.87 MPa (1270 psig)
84.1	RCPs trip; high natural circulation in loop A begins	
90.9	AFW to SG B begins	-4.3 m (-170 in)
632.4	Pressurizer proportional heaters tripped back on because of level recovery	2.56 (101 inches)
700.0	Minimum pressure of 4.8 MPa is reached	
1000.0	HPI flow ends (charging flow continues)	8.87 MPa (1270 psig)
1225.0	SG A dries out (natural circulation in loop A drops from 500 to 250 kg/s)	
2800.0	Pressurizer heaters trip because of high system pressure	15.7 MPa (2275 psia)
3120.0	System repressurizes to PORV setpoint	16.5 MPa (2400 psia)
3250.0	SG B fills with liquid and natural circulation on secondary side begins	
4100.0	Natural circulation of 350 kg/s on loop B begins	
7200.0	Calculation terminated	

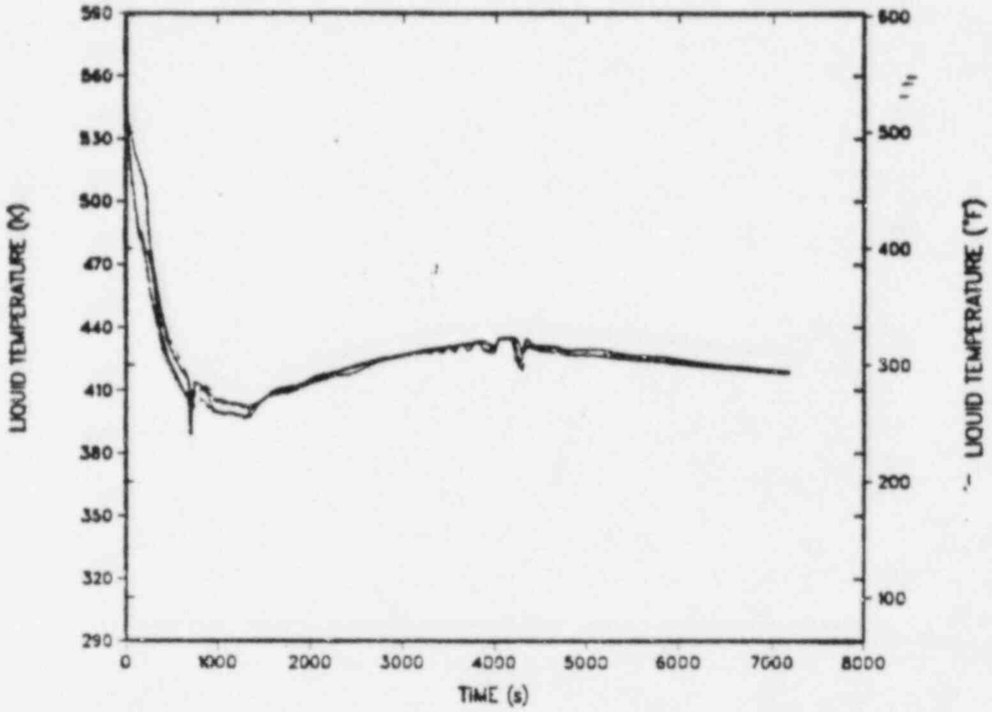

Fig. 4.1. Downcomer liquid temperature during Transient 1.

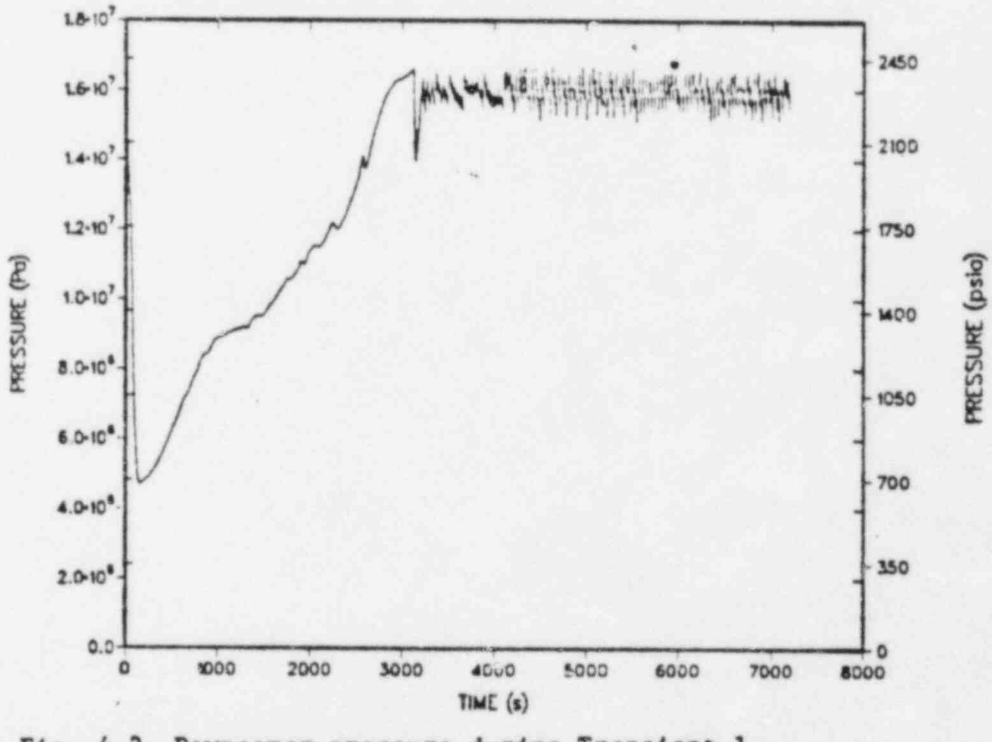

Fig. 4.2. Downcomer pressure during Transient 1.

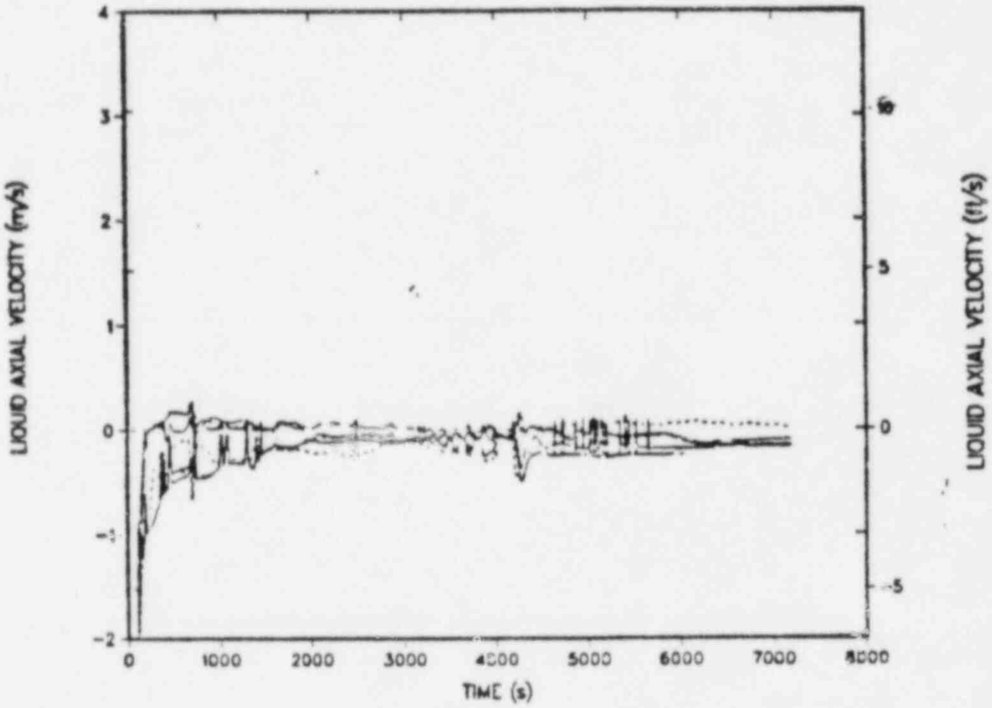

Fig. 4.3. Downcomer liquid velocity in z-direction during Transient 1.

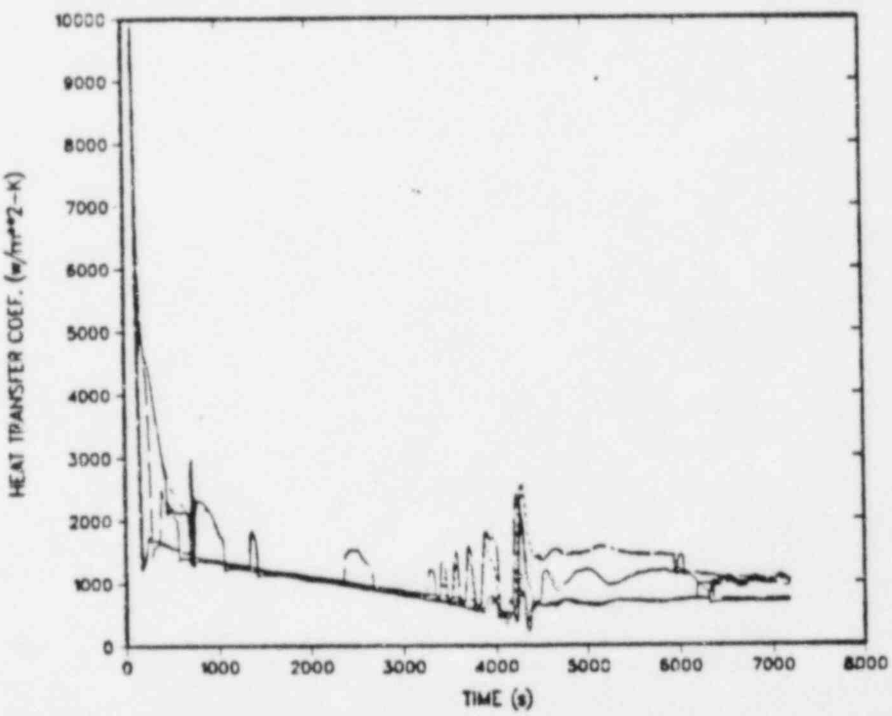

Fig. 4.4. Downcomer heat transfer coefficient during Transient 1.

5. Transient 2

Double-ended Main Steamline Break From HZP

This transient results from a double-ended guillotine break in steamline A between the flow restictor and MSIV. Before the transient, the reactor is assumed to be off-line in an HZP condition and steam is being bled through the TBV to maintain secondary pressure at 6.20 MPa. Further, it is assumed that the operator fails to isolate AFW to SG A when the asymmetric SG pressure signal is received.

The transient event sequence is summarized in Table 5.1 and the system pressure, downcomer liquid temperature, heat-transfer coefficient, and liquid velocity are given in Figures 5.1-5.4. Basically, this transient generates severe conditions because continuous charging flow causes repressurization and AFW flow to a ruptured SG results in a very cold heat sink. Initially, depressurization of the secondary side following the break results in flashing and rapid cooling of the primary. The resulting primary contraction causes SIAS on low pressure and the RCPs are tripped shortly after. Thereafter, natural circulation to the ruptured SG continues to cool the primary towards the atmospheric boiling point, while HPI and charging flow reverse the primary voiding that occurred in the upper head and eventually refill the pressurizer and repressurize the system.

The calculation was terminated at 3275 s because of time step limitations that resulted from liquid discharge through the pressurizer PORVs and safety valves. However, at this point the pressure is maintained between 15.7 and 16.5 MPa by PORV cycling, and the downcomer temperature is steady at 380 K with the SG-A heat sink at 373 K (boiling in SG A at atmospheric pressure). These conditions are expected to remain stable until at least 7200 s because the charging flow will continue to maintain the pressure at the PORV setpoint, and decay power is sufficient to heat the AFW to the atmospheric boiling temperature.

TABLE 5.1
Transient 2
DOUBLE-ENDED STEAMLINE BREAK FROM
HOT, ZERO POWER

Sequence of Events

Time (s)	Event	Setpoint
0.0	Double-ended break in loop A	
1.8	AFAS on low wide-range level in SG A a) MFIVs close (due to model error; effect negligible) b) AFW delivered to both SGs	-4.3 m (-170 inches)
2.4	Pressurizer heaters trip off following low pressurizer level	2.56 m (101 inches)
9.1	SGIS isolates SG B	4.61 MPa (653 psig)
18.7	Asymmetric SG pressure fails to isolate AFW to SG A	0.8 MPa (115 psid)
41.2	SIAS	12.1 MPa (1740 psig)
65.0	HPI flow begins	8.8 MPa (1270 psig)
71.2	Operator trips all RCPs	
90.0	Upper head begins voiding	
350.0	Upper head refilled; repressurization begins	
2980.0	PORVs open; pressure levels off	16.5 MPa (2400 psia)
3270.0	Calculation terminated; HPI flow continues; Conditions stable	

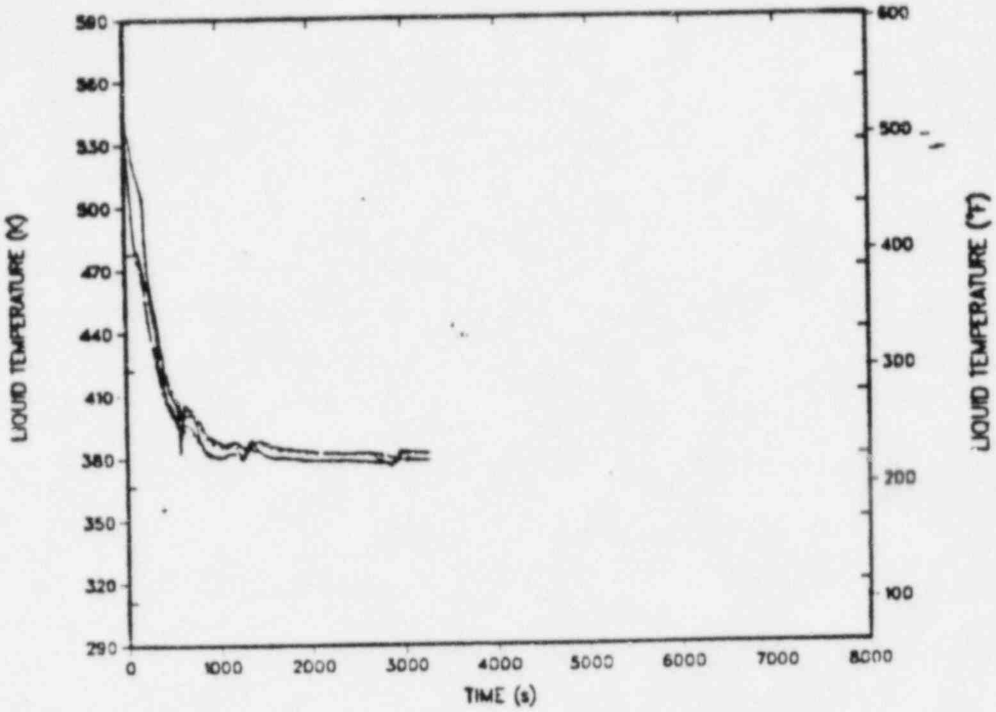

Fig. 5.1. Downcomer liquid temperature during Transient 2.

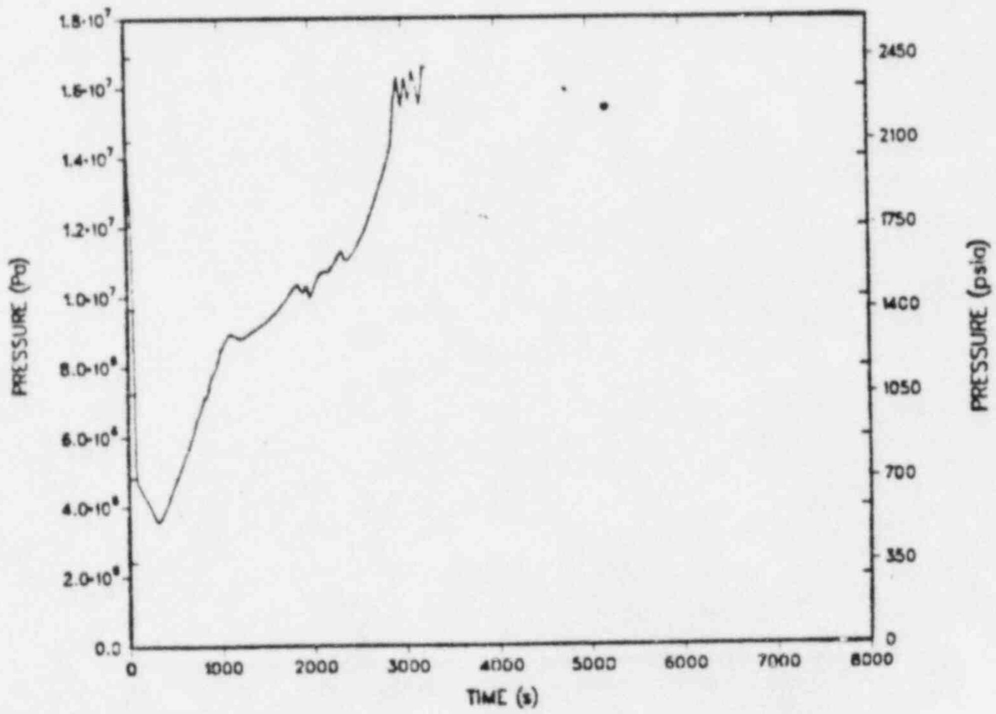

Fig. 5.2. Downcomer pressure during Transient 2.

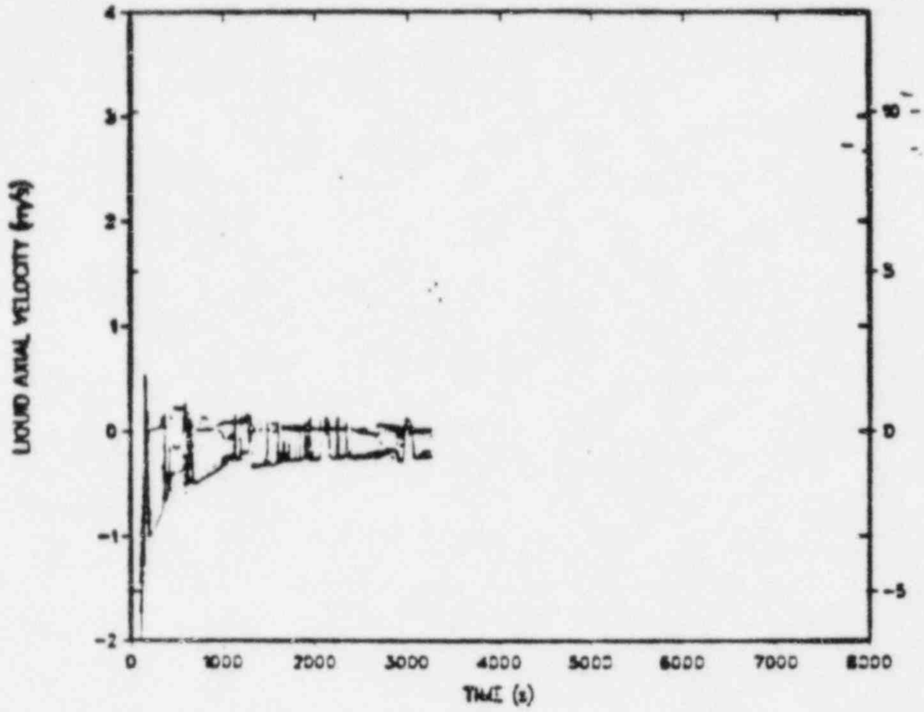

Fig. 5.3. Downcomer liquid velocity in z-direction during Transient 2.

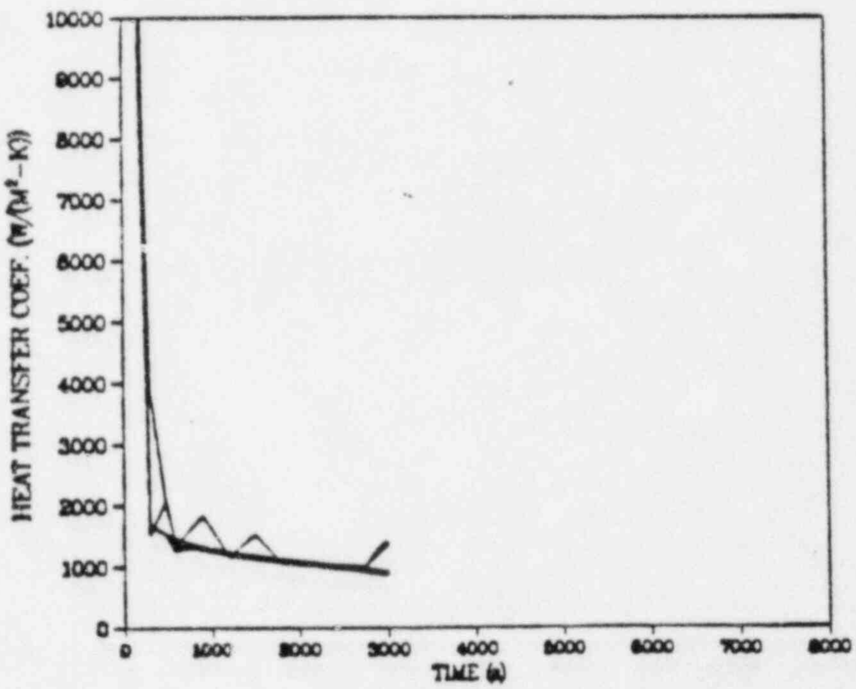

Fig. 5.4. Downcomer heat transfer coefficient during Transient 2.

6. Transient 3*

1.0 ft^2 Main Steamline Break from Full Power

This transient is initiated by a 0.0929 m^2 (1.0 ft^2) break in steamline A while the plant is operating at full power. Table 6.1 tabulates the sequence of events that occurred during this transient and Figs. 6.1 - 6.4 give the parameters of interest. As seen in Figure 6.1, the primary fluid temperature reaches a minimum at the point in time in which the broken steam generator dries out. All heat losses from the primary to the broken steam generator cease at this point. The primary fluid temperature begins to increase at this point because of the decay heat from the reactor core, and the energy transferred from the system structural material back into the fluid as the system seeks a new thermal equilibrium.

A small amount of energy is continually being transferred with the intact-steam generator throughout the transient. Before 600 seconds, the primary temperature drops below the temperature of the secondary side of the intact SG resulting in heat being transferred from the secondary side to the primary. This creates a gravity head in the steam-generator tubes that opposes the gravity head created in the vessel, causing the intact steam generator loop to stagnate for the time period between 100 seconds and 600 seconds. As cold AFW continues to be supplied to the intact steam generator, the average temperature in the secondary side of the intact steam generator drops below the primary temperature, and heat transfer from the primary to the secondary side is reestablished. This now creates an additional gravity head in the intact-steam-generator tubes that acts in parallel to the gravity head created in the vessel between the downcomer and the core region. A natural circulation flow in the intact loop is established that is approximately twice the natural circulation flow in the broken loop. The natural circulation in the broken loop is driven only by the gravity head in the vessel. At 1400 seconds, the primary system repressurizes because of the continued injection of charging flow.

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*This calculation was rerun in order to access the impact of an error in the initial liquid temperature in the pressurizer which lead to a primary depressurization that was much too rapid. (This error was present in the steady-state full-power deck used during transients #3, #4, #5, and #8.) The initial 2500 s were recalculated. A revised sequence of events is shown Table 6.2. The original run section is retained to provide a means of extrapolating the Transient-3-rerun to 7200 s.

TABLE 6.1
Transient 3
1.0 ft^2 MAIN STEAMLINE BREAK FROM FULL POWER

Sequence of Events

Time (s)	Event	Setpoint
0.0	0.0929 m^2 (1.0 ft^2) steamline break on loop A a) Turbine/reactor assumed to be tripped b) ADVs and TBVs open on "quick-open" logic	-
2.6	Pressurizer backup heater trip on because of low primary pressure	15.16 MPa (2200 psia)
15.5	SIAS on low primary pressure	12.1 MPa (1740 psig)
20.6	Pressurizer heaters tripped off following low pressurizer level	2.56 m (101 inches)
29.0	TBVs and ADVs close on low primary temperature	552 K (534 °F)
41.2	SGIS a) Feedwater pumps tripped off b) MFIVs and MSIVs begin to close	4.6 MPa (668 psia)
45.5	Reactor coolant pumps assumed to be manually tripped	
49.2	Asymmetric SG pressure obtained	0.8 MPa (115 psi)
64.0	HPI begins	
197.9	AFAS initiated to intact SG because of low SG level	-4.3 m (-170 inches)
400.0	SG A dries out	
545.5	Pressurizer proportional heaters tripped back on because of recovery of pressurizer level	2.56 m (101 inches)
610.0	HPI ends - charging flow continues	
1397.0	PORVs open because of high primary pressure	16.55 MPa (2400 psia)
5000.0	SG B completely full (because of SG model error which underestimated SG volume by 37 m^3)	
6300.0	Secondary SRVs on loop-B open on high steamline pressure	6.9 MPa (1000 psia)
7200.0	Calculation terminated	

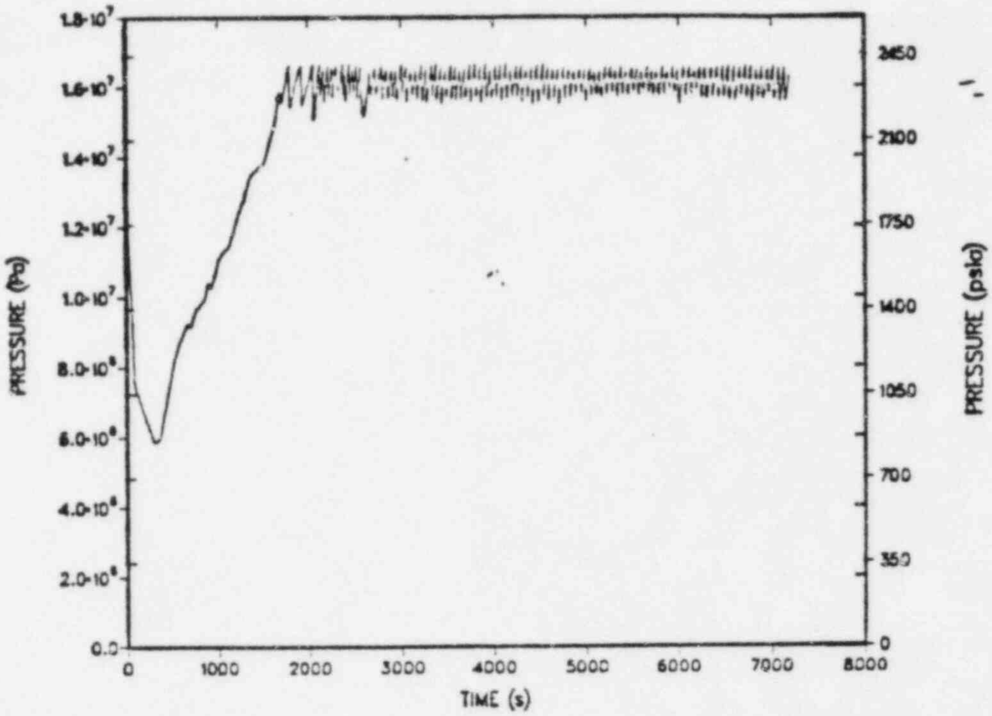

Fig. 6.1. Downcomer liquid temperature during Transient 3.

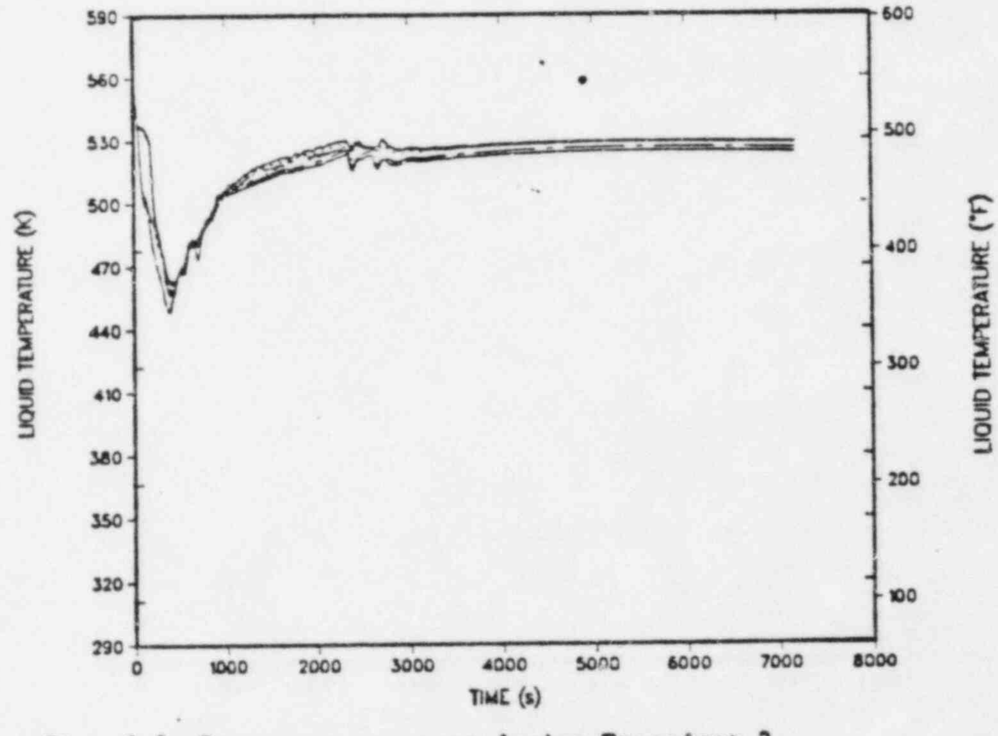

Fig. 6.2. Downcomer pressure during Transient 3.

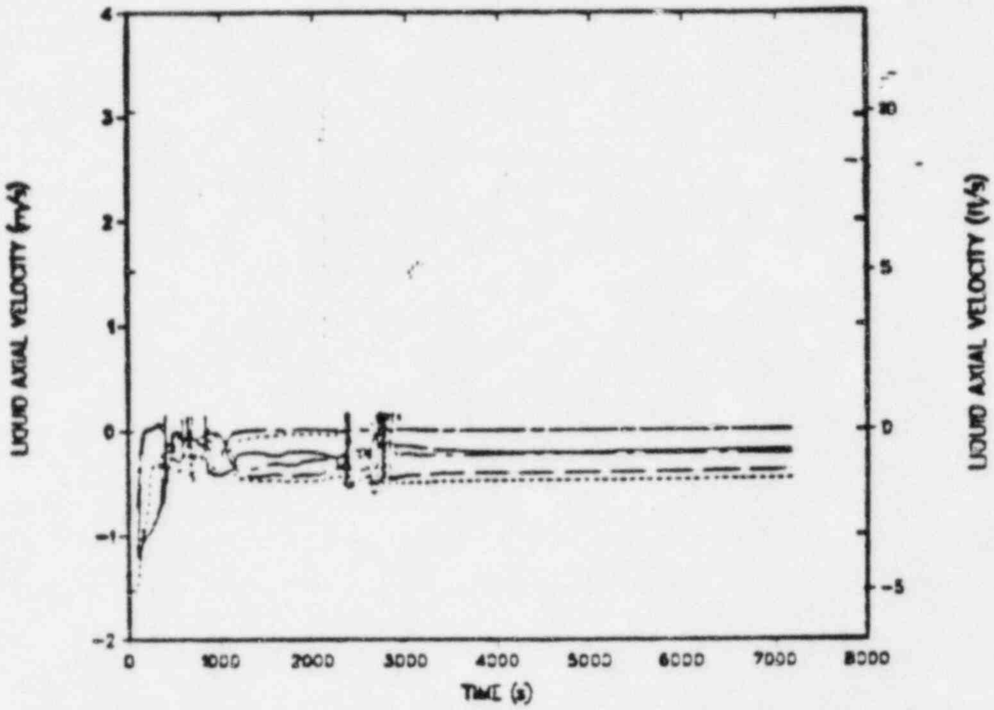

Fig. 6.3. Downcomer liquid velocity in z-direction during Transient 3.

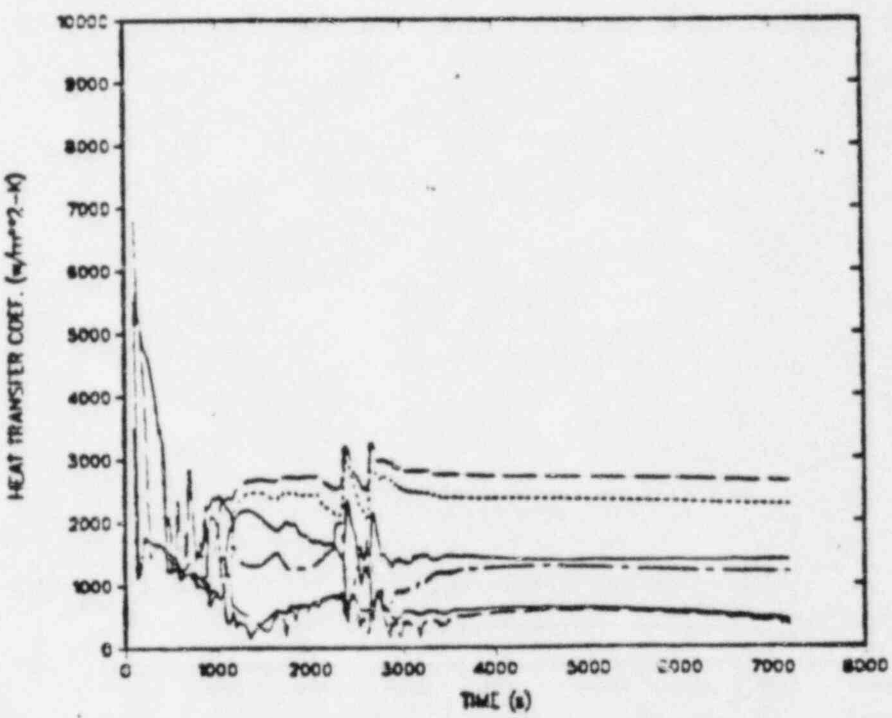

Fig. 6.4. Downcomer heat transfer coefficient during Transient 3.

TABLE 6.2
Transient 3 - Rerun
1.0 ft^2 MAIN STEAMLINE BREAK FROM FULL POWER

Sequence of Events

Time (s)	Event	Setpoint
0.0	0.0929 m^2 (1.0 ft^2) steamline break on loop A a) Turbine/reactor assumed to be tripped b) ADVs and TBVs open on "quick-open" logic	-
4.3	Pressurizer backup heater trip on because of low primary pressure	15.16 MPa (2200 psia)
20.1	Pressurizer heaters tripped off following low pressurizer level	2.56 m (101 inches)
29.0	TBVs and ADVs close on low primary temperature	552 K (534 °F)
32.2	SIAS on low primary pressure	12.1 MPa (1740 psig)
44.3	SGIS a) Feedwater pumps tripped off b) MFIVs and MSIVs begin to close	4.6 MPa (668 psia)
62.2	Reactor coolant pumps assumed to be manually tripped	
52.5	Asymmetric SG pressure obtained	0.8 MPa (115 psi)
70.0	HPI begins	
58.4	AFAS initiated to intact SG because of low SG level	-4.3 m (-170 inches)
300.0	SG A dries out	
595.4	Pressurizer proportional heaters tripped back on because of recovery of pressurizer level	2.56 m (101 inches)
495.0	HPI ends - charging flow continues	
1975.7	PORVs open because of high primary pressure	16.55 MPa (2400 psia)
2500.0	Calculation terminated	

7.a. Transient 4*

Stuck-open TBV from HFP

This transient is a simple loss-of-load from full power with the complication that one TBV fails to reseat. A summary of the major events is given in Table 7.1. The first 50 s are no different from a standard loss-of-load. With the TBV-failure, both SGs depressurize until SGIS based on low SG pressure of 4.6 MPa is reached at 509.1 s. For this transient the thermal-hydraulic behavior, both primary and secondary, is symmetric. On SGIS, the stuck-open TBV is isolated from the SG secondary and no longer plays a part in the transient.

Initially on the primary side, the turbine trip causes a reactor trip. Low primary pressure produces an SIAS at 28.4 s. The RCPs trip 30 s later at 58.4 s. The pressure is never low enough for HPI flow; only charging flow is injected. No voiding occurs on the primary side in this transient.

After SGIS, both SGs begin repressurizing from 4.6 MPa until the ADVs open on high primary temperature (greater than 552 K) at 1050 s. SG secondary side pressure is maintained at about 6.3 MPa until AFW begins at 4200 s. AFW is initiated based on low-low level in the SGs. The AFW injection gradually lowers the SG secondary side pressure.

Figures 7.1-7.4 show the primary pressure, downcomer liquid temperature, downcomer heat-transfer coefficient, and downcomer liquid velocities for the transient. The primary pressure decreases initially because of the turbine-trip. The depressurization and cooling between 50 s and 509 s is a result of the TBV failure. After this, the primary side heats and pressurizes because of the SG secondary side isolation and charging flow. The PORV setpoint is reached at 1269.9 s. The primary initially cools because of the stuck-open TBV. After SGIS, the primary temperature becomes so high that the operation of the ADVs is necessary to prevent further primary heating. Because main feedwater has been valved out, the SG mass inventory eventually is low enough (because of flow out the ADVs) for AFW actuation at 4200 s. This injection cools the primary to 530 K by 5800 s. The calculation ended at 5800 s because of a code/model problem and will be continued if necessary. However, the downcomer temperature and pressure for the next 1400 s are predictable; it is expected that the downcomer temperature would reach a minimum of 510 K.

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*The initial portion of this transient was rerun to determine the timing for the major events because of an error in the liquid temperature in the pressurizer. (The same error addressed for Transient 3 in Section 6.) The initial portion corresponds to 0-570 s in Transient 4a.

TABLE 7.1
Transient 4
STUCK-OPEN TBV FROM HFP

Sequence of Events

Time (s)	Event	Setpoint
0.0	Reactor/Turbine trip ADVs and TBVs receive quick-open signal	-
28.4	SIAS on low primary pressure	12.1 MPa (1740 psig)
38.2	Pressurizer heaters tripped off due to low pressurizer level	2.57 m (101 inches)
50.0	All four TBVs should have reseated but one failed; ADVs close	552.4 K (534.6 ^{0}F) (900 psig)
58.4	RCPs trip	
509.1	SGIS; Minimum pressure of 10.8 MPa is reached	4.61 MPa (653 psig)
1050.0	ADVs open on high primary temperature	552.4 K (534.6^{0}F)
835.5	Pressurizer proportional heaters tripped back on following level recovery	2.56 m (101 inches)
1100.0	Pressurizer proportional heaters tripped off because of high system pressure	15.6 MPa (2275 psia)
1269.9	PORV setpoint is reached	16.5 MPa (2400 psia)
4200.0	AFAS	-4.3 m (-170 inches)
4300.0	ADVs close on low primary temperature	552.4 K (534.6 ^{0}F)
5800.0	Minimum temperature of 530 K is reached (calculation ended-cooldown very slow)	

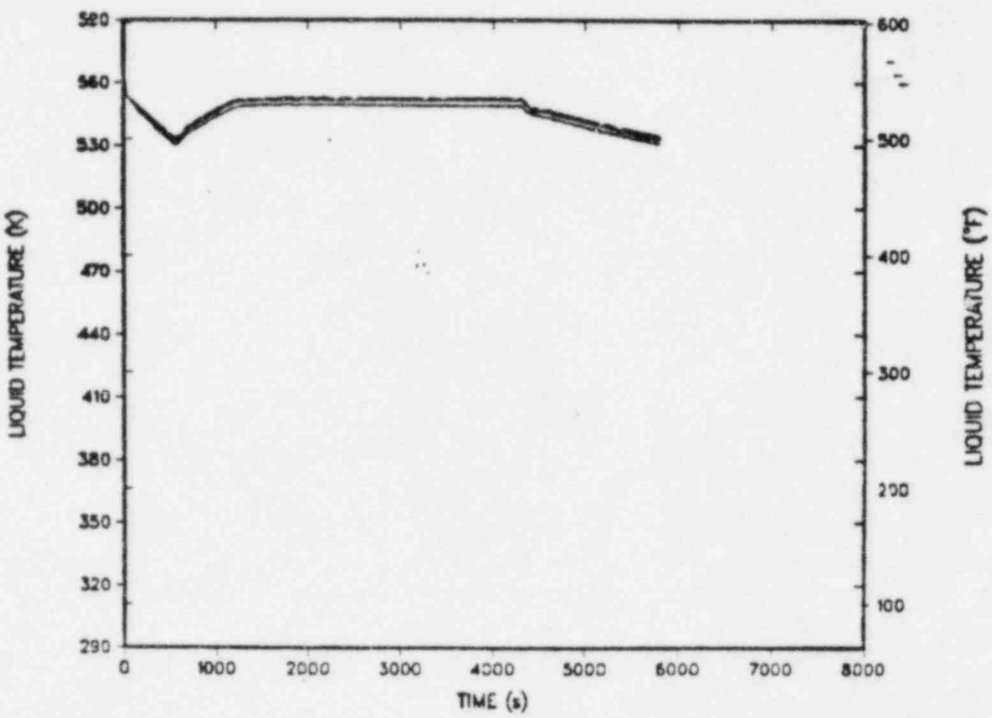

Fig. 7.1. Downcomer liquid temperature during Transient 4.

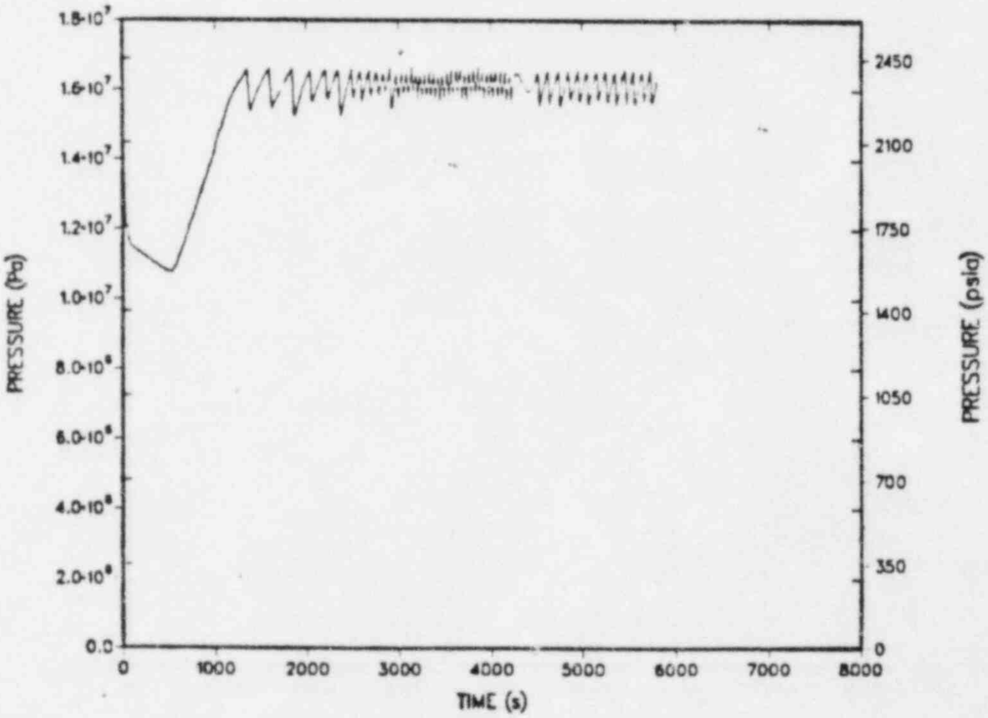

Fig. 7.2. Downcomer pressure during Transient 4.

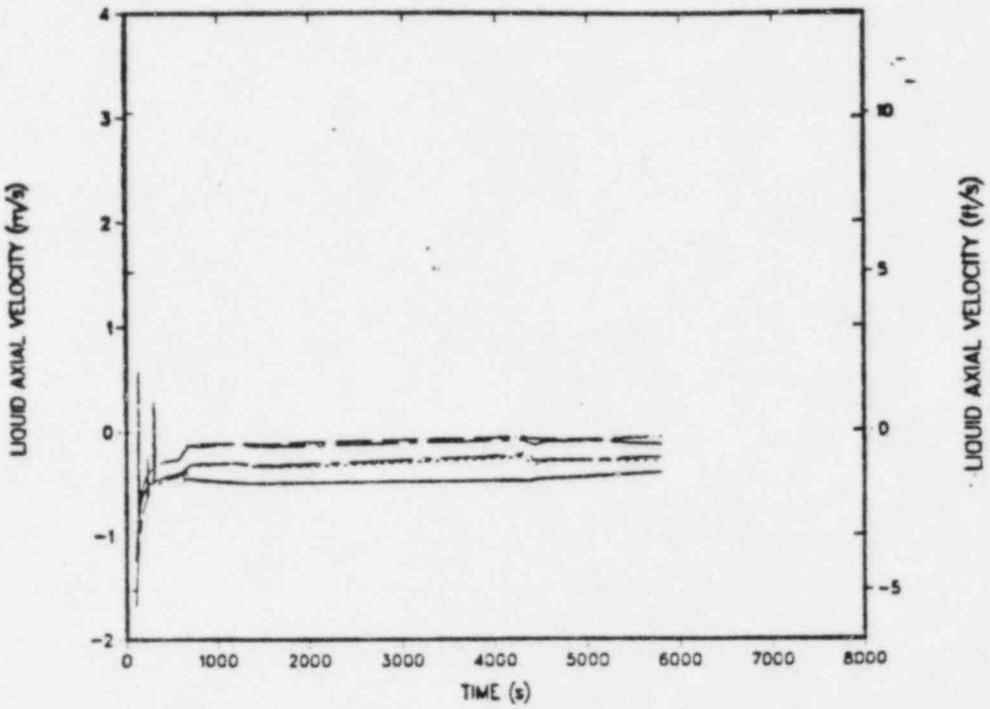

Fig. 7.3. Downcomer liquid velocity in z-direction during Transient 4.

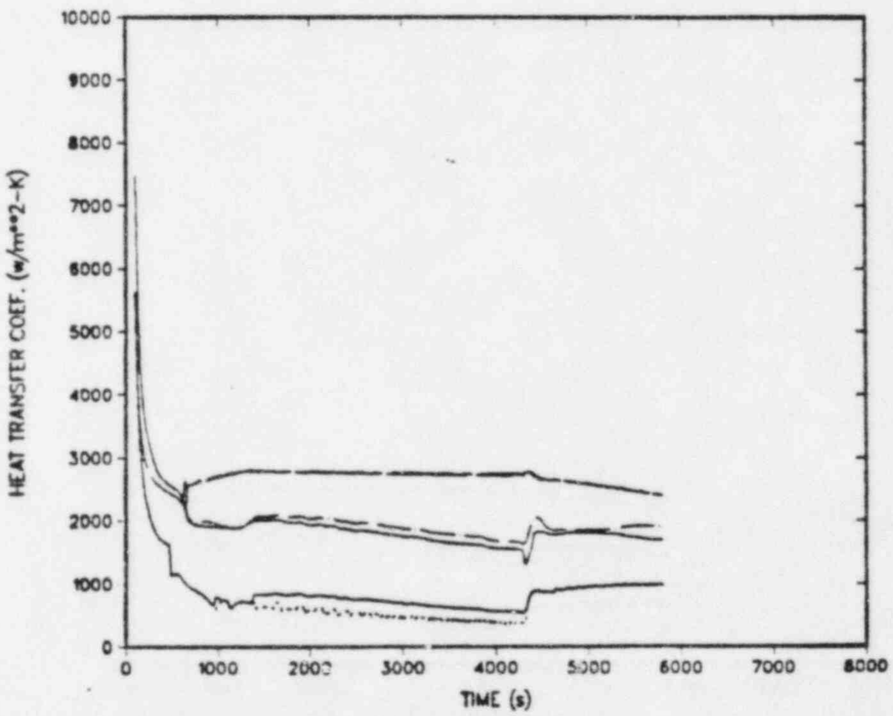

Fig. 7.4. Downcomer heat transfer coefficient during Transient 4.

7.b. Transient 4A

One TBV and MSIV Stuck Open from HFP

Transient 4A is initiated by a turbine trip from full power conditions. A sequence of events is given in Table 7.2 and Figs. 4.5-4.8 give a few key system parameters. The first 85 s of the transient are no different from a normal loss-of-load transient. The TBVs and ADVs open because the primary temperature is above 552 K (539^{0}F). By 85 s, the TBVs begin closing but one fails to reseat, initiating a small steamline "break". The ADVs close normally.

The small "break" slowly begins cooling and depressurizing the primary. The conditions on each loop are identical before SGIS. Removal of the energy from the core and system metal depletes the liquid inventory on the secondary side of both SGs; AFAS is reached at 422 s. AFW is then delivered to both SGs. By 470 s, the system pressure is low enough for SIAS, with the RCPs tripping 30 s later. The system presure is never low enough for the initiation of HPI flow, however. Heat removal by the steam generators slows with the loss of forced convection from the RCPs.

SGIS occurs at 570 s with MSIV-A failing to close (the variation from Transient 4). The small main feedwater flow through the MFBVs ends at this time. The failed-valve induces asymmetries on the primary side with loop A having a higher natural circulation flow than loop B. At 639 s, AFW is valved out to SG A based on an asymmetric pressure signal. Most of the energy is removed through SG A until it dries out at about 1750 s. Loop B flows then increases as SG B becomes the heat sink. The system repressurizes to the PORV setpoint by about 2500 s. The calculation was terminated at this point because the request by ORNL had been satisfied.

This transient helps to address the effect of the error in Transient 4. Because some of the liquid in the pressurizer was erroneously subcooled initially, the primary side depressurized much too rapidly. A more accurate timing for the events during 0-570 s is given in Table 4.2. The time for AFAS cannot be compared because in Transient 4 both SGs were bottled up after SGIS and mass was lost only after the ADVs opened on high primary temperature. The effect of SGIS occurring before or after AFAS would have some significance on the outcome of Transient 4. However, because of uncertainties in the behavior of instrumentation under transient conditions, the sequence of SGIS and AFAS may be absolutely determined.

TABLE 7.2
TRANSIENT 4A
ONE TBV AND MSIV STUCK OPEN (FROM HFP)

Sequence of Events

Time (s)	Event	Setpoint
0	Turbine trip/reactor trip; TBVs/ADVs "quick-open"	
39	Pressurizer heaters trip on low-low level	2.56 m (101 inches)
85	One TBV sticks while closing on low primary temperature	522 K (534^0F)
135	ADVs close on low primary temperature	552 K (534^0F)
422	AFAS on low SG liquid level (AFW to both SG)	45,000 kg (99,200 lbm)
470	SIAS on low primary pressure	12.1 MPa (1740 psig)
500	RCPs trip	SIAS + 30 s
570	SGIS on low secondary pressure; MSIV-A sticks open	4.6 MPa (653 psig)
639	Asymmetric SG pressure (AFW to SG-B only)	0.8 MPa (115 psid)
1750	SG-A dries out	
2092	Pressurizer proportional heaters trip back on because of level recovery	2.56 m (101 in)
2400	Pressurizer proportional heaters trip off because of high system pressure	15.7 MPa (2275 psia)
2500	PORV setpoint reached	16.5 MPa (2400 psia)
2500	Calculation terminated	

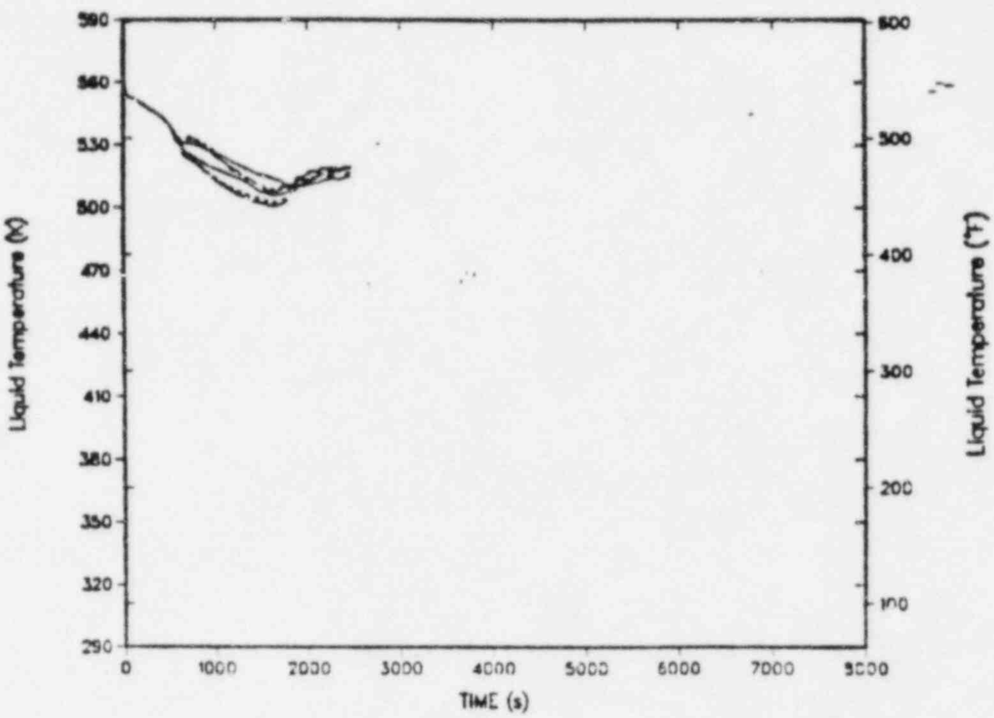

Fig. 7.5. Downcomer liquid temperature during Transient 4A.

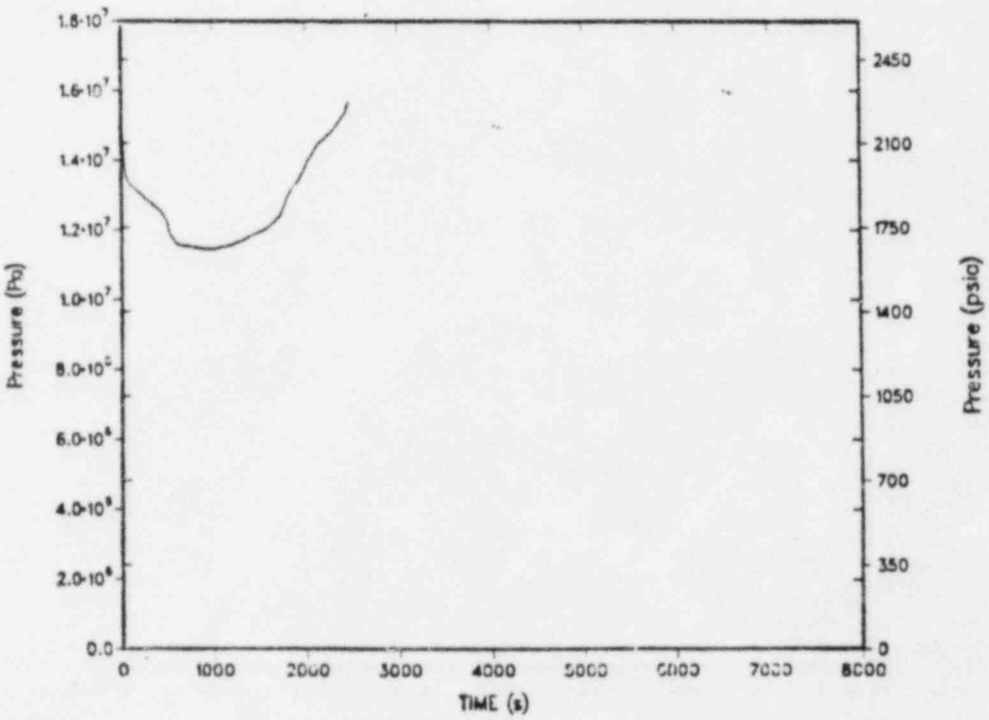

Fig. 7.6. Downcomer pressure during Transient 4A.

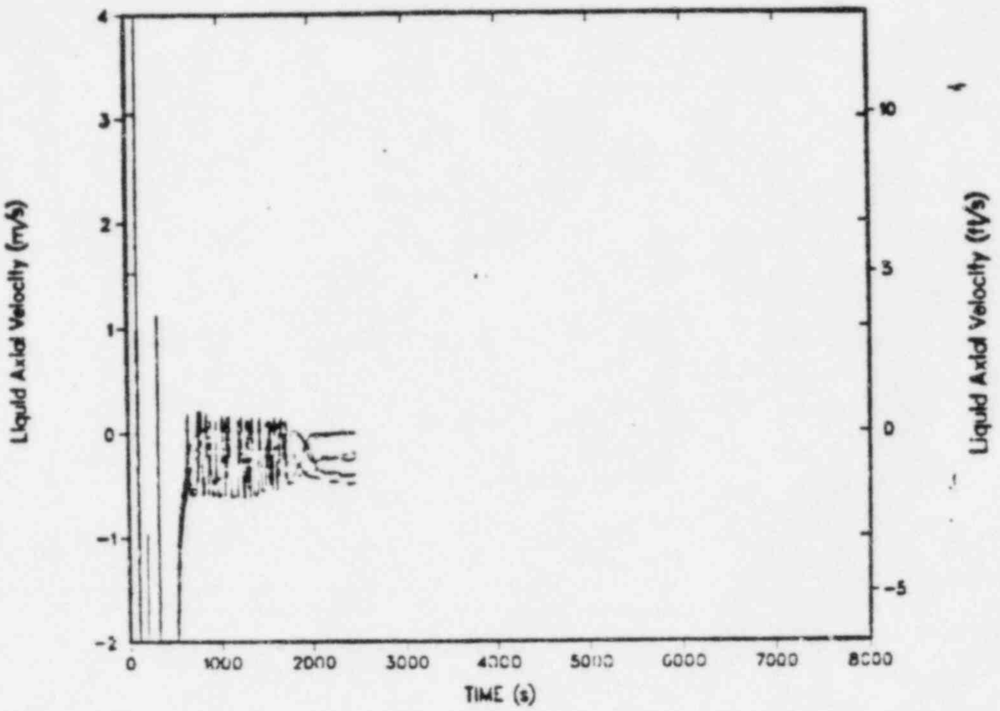

Fig. 7.7 Downcomer liquid velocity during Transient 4A.

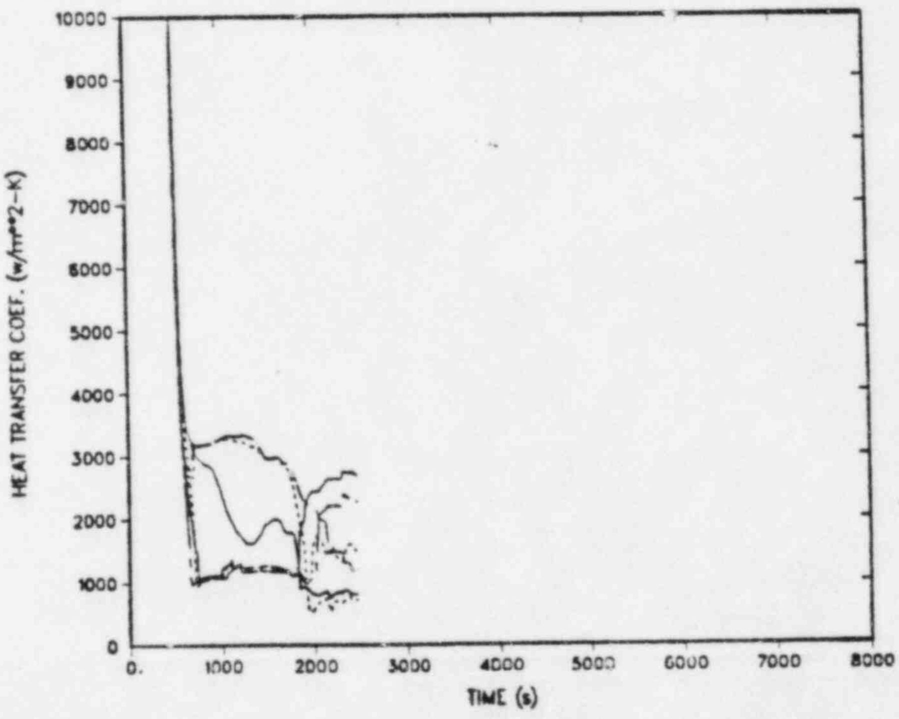

Fig. 7.8 Downcomer heat-transfer coefficient during Transient 4A.

8. Transient 5*

Stuck-open PORV and ADV From HFP

The transient was initiated from the steady-state run by opening one of the two PORVS completely. A summary of the transient events is given in Table 8.1. Figures 8.1-8.4 show the primary pressure, downcomer liquid temperatures, downcomer heat-transfer coefficient and downcomer liquid velocities for the transient.

From the beginning of the transient, the system rapidly depressurizes to about 6 MPa. The reactor power trips on low pressure at 14.6 seconds and follows the decay-heat curve. The HPI is initiated as the pressure falls below 12.1 MPa. The RCPs trip at 61.2 seconds and then follow the coast-down curve. The upper head begins to void at about 210 seconds and is completely vapor by 328 seconds; this is because of the residual heat stored in the vessel heat slabs. For the first 61 seconds, the mass flow rate through the core is essentially constant until the pumps trip. After the pump trip, the core mass flow rate drops with the pump speed.

Following reactor trip at 15 seconds, the MFW pumps for loops A and B begin to run back, the ADVs open, the TBVs open, and TSVs close. SGIS occurs at 836 s resulting in the closure of both the MFIVs and MSIVs. The AFW activates at 3279 seconds into the transient when the level in SG A drops too low. However, due to asymmetric SG pressure exceeding 0.8 MPa, the AFW flow is directed only to SG B which has the higher pressure.

The pressure curve for the balance of the 7200 s transient is fairly smooth except for the dip at 2600 s that results from a rapid condensation of all of the vapor in the upper head. At about 7000 seconds, a pressure dip also occurs when the vapor condenses in the pressurizer dome. These pressure dips are probably physically unrealistic. The calculation was terminated at 7200 s.

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*The authors wish to acknowledge Clay Booker of Los Alamos National Laboratory for performing this calculation.

TABLE 8.1
Transient 5
STUCK-OPEN PORV AND ADV FROM HFP

Sequence of Events

Time (s)	Event	Setpoint
0.0	PORV fails full open	-
14.6	Reactor/turbine trip TBVs/ADVs "quick open"	14.5 MPa (2100 psia)
31.2	SIAS	12.1 MPa (1740 psig)
61.2	RCPs are manually tripped	-
62.1	Pressurizer heater are tripped off based on low level	2.56 m (101 inches)
165.0	HPI flow begins	8.8 MPa (1270 psig)
210.0	Upper head in vessel voids	-
227.0	Loop-B ADV closes while loop-A ADV sticks full open; TBVs close	
846.0	SGIS a) Feedwater pumps tripped b) MFIVs and MSIVs begin to close	4.61 MPa (653 psig)
1032.4	Asymmetric SG pressure signal is received	0.8 MPa (115 psid)
2637.0	Upper head refills	
3279.0	AFAS (AFW to SG B)	-4.3 m (-170 inches)
7200.0	Calculation terminated	
114.7	Pessurizer proportional heaters trip on because of level recovery	2.56 m (101 inches)

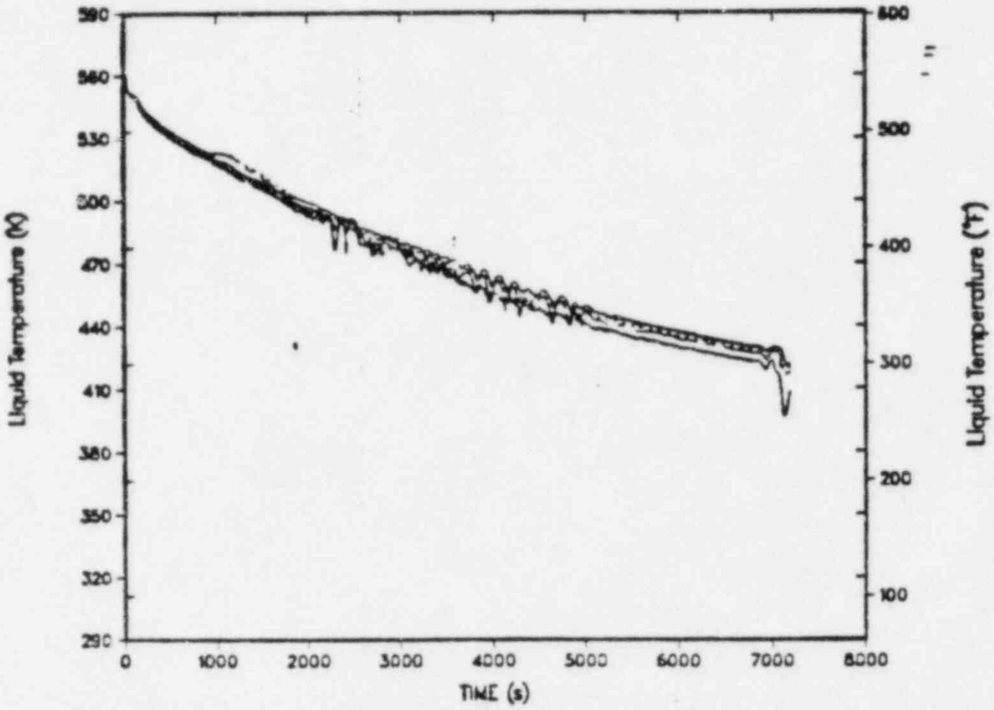

Fig. 8.1. Downcomer liquid temperature during Transient 5.

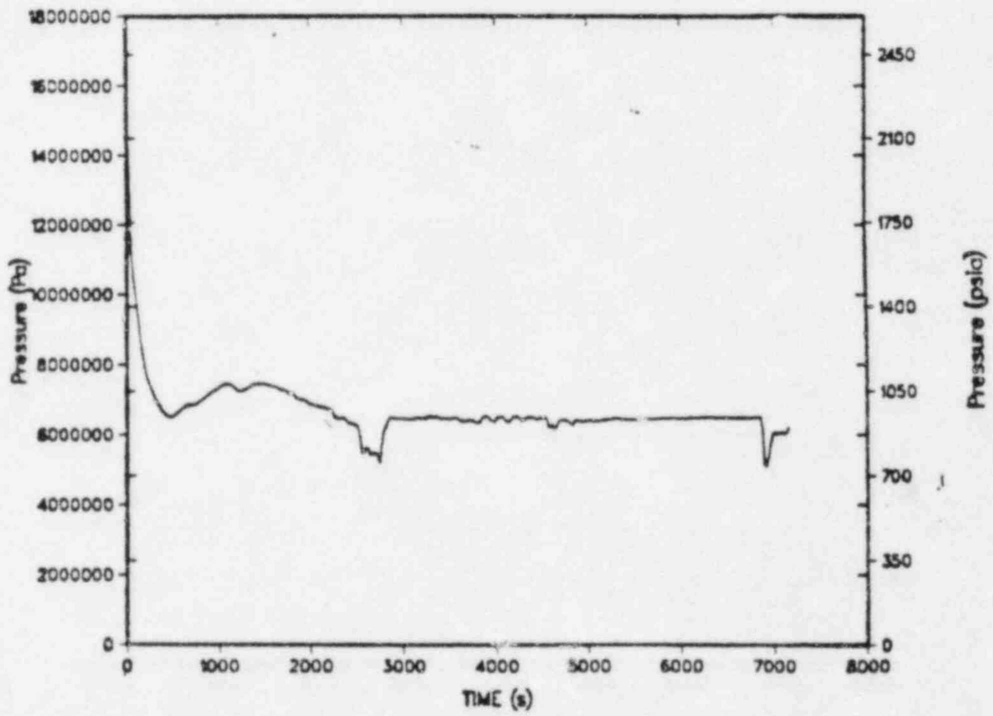

Fig. 8.2. Downcomer pressure during Transient 5.

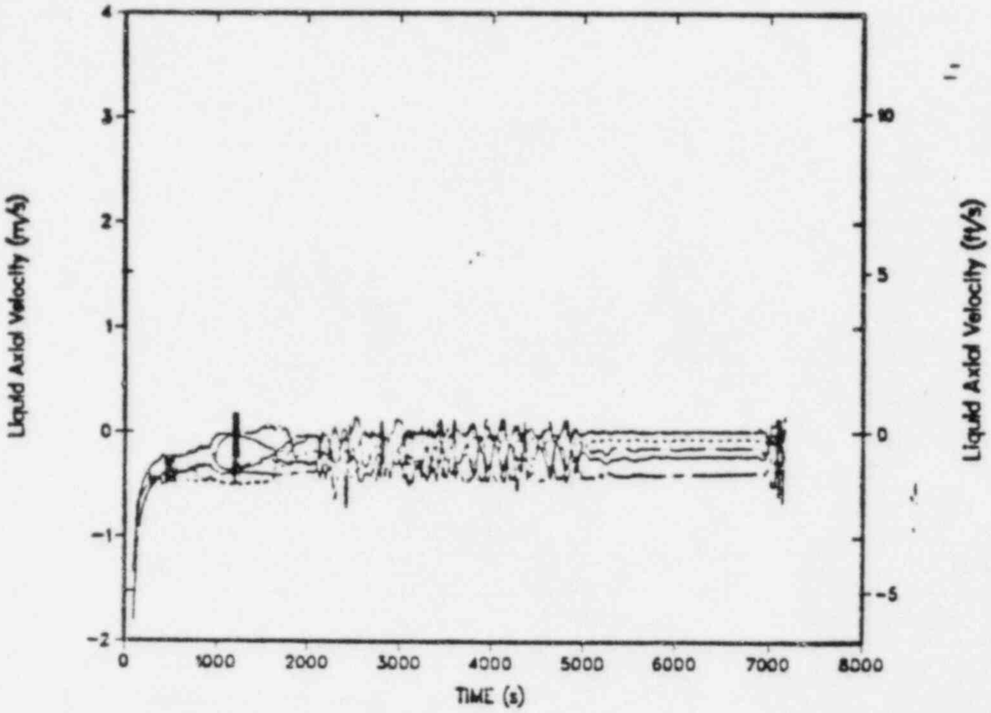

Fig. 8.3. Downcomer liquid velocity in z-direction during Transient 5.

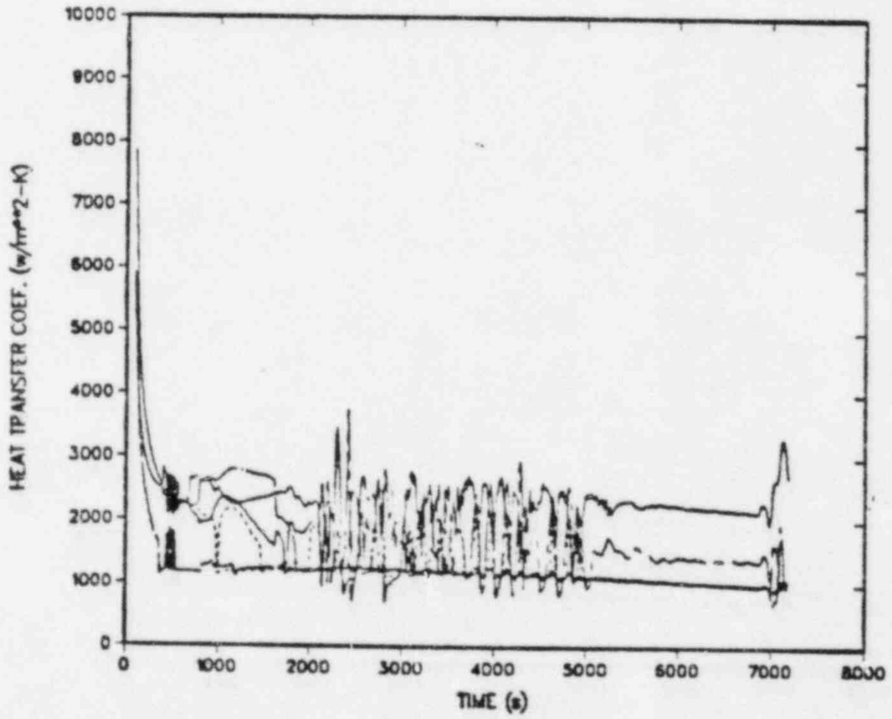

Fig. 8.4. Downcomer heat transfer coefficient during Transient 5.

9. Transient 6

Runaway AFW Following LOFW from HFP

This transient is assumed to result from a LOFW initiated by a MFW pump trip and followed by a 20-minute delay in AFW delivery. Furthermore, it is assumed that the operator deliberately maximizes AFW flow to the SGs by fully opening all of the AFW valves. A sequence-of-events summary is given in Table 9.1. Figures 9.1-9.4 give the system pressure, downcomer temperature, heat-transfer coefficients, and downcomer velocities for the transient.

The LOFW causes rapid depletion of the SG inventories and by 36 s the reactor and turbine trip on a low-level signal from the SGs. The ADVs and TBVs "quick open" as a result, and the transient proceeds as a total LOFW for the next 1200 s. SGIS occurs at 837 s which isolates the SGs. Dryout occurs at 898 s, at which time the PORVs open on high pressure. Although the primary begins to heat following SG dryout, it does not saturate before AFW flow begins.

When the operator finally succeeds in activating the AFW system at 1200 s, the AFW preferentially flows to SG B. This occurs because initial AFW flow into each SG causes more condensation in SG B, and the resulting vacuum provides suction to divert essentially all of the AFW to SG B causing even more condensation to sustain the vacuum. However, by ~2300 s SG B and its steamline are water-solid, and the subsequent pressurization diverts AFW to SG A. By ~2500 s, however, SG A and its secondary are also water-solid, and the secondary SRVs begin to lift to relieve the pressure. Because the steamlines are slightly asymmetric and a slight pressure difference is sufficient to open an SRV enough to relieve the AFW flow, the relief occurs primarily through the SRV on the SG A steamline.

Between ~1900 s and ~2300 s when the AFW is filling and cooling SG B, the flow in loop A of the primary stagnates. When this stagnation occurs SG B cools the primary enough to establish reverse heat transfer in SG A which opposes natural ciculation. Similarly, after ~3000 s the flow in loop B stagnates because SG A receives almost all of the AFW and cools the primary below the SG-B temperature. If AFW flow was delivered equally to both SGs (with AFW valve control), this stagnation would not occur.

By ~3200 s the HPI and charging flow refill the primary enough to repessurize the system to the HPI dead-head pressure, and thereafter charging flow alone continues to pressurize the system. By 5836 s the PORVs lift and begin cycling to relieve charging flow to the water-solid system. The calculation was terminated at 6152 s with the primary pressure cycling between the PORV setpoints, 15.7-16.5 MPa (2280-2400 psia). The downcomer liquid temperature is gradually decreasing from 370 K (200^{0}F) and AFW is flowing to SG A with stagnate conditions in both SG B and loop B.

TABLE 9.1
Transient 6
RUNAWAY AFW FOLLOWING LOFW FROM HFP

Sequence of Events

Time (s)	Event	Setpoint
0.0	Loss-of-feedwater to both SGs because of MFW pump trip	
36.0	Reactor and turbine trip on low narrow-range SG level; ADVs and TBVs "quick open"	-1.27 m (-50 inches)
42.6	Pressurizer back-up heaters activate on low pressure	15.2 MPa (2200 psia)
76.9	Pressurizer heaters trip off on low level in pressurizer	2.56 m (101 inches)
537	Pressurizer proportional heater activate when low-level trip clears	2.56 m (101 inches)
~815	Pressurizer proportional heaters turn off at the setpoint	15.5 MPa (2250 psia)
837	SGIS on low SG pressure; TBVs are isolated	4.61 MPa (653 psig)
898	PORVs open on high pressure because both SGs dry out	16.5 MPa (2400 psia)
1200	Operator activates all AFW pumps and fully opens all valves to both SGs	
~1200	PORVs close as secondary cooling is quickly recovered	15.7 MPa (2280 psia)
	Pressurizer proportional heaters activate as pressure falls	15.5 MPa (2240 psia)
1229	SIAS occurs on low pressure	12.1 MPa (1740 psig)
1258	ADVs close on low reactor temperature	552 K (535 F)
1259	Operator trips all RCPs	
1279	Pressurizer proportional heaters trip off on low level in pressurizer	2.56 m (101 inches)
~1800	HPI flow resumes	

~1900	Loop A stagnates	
~2300	Loop A flow resumes	
2824	Pressurizer proportional heaters activate when low-level trip clears	2.56 m (101 inches)
2912	Pressurizer proportional heaters trip off on low level in pressurizer	2.56 m (101 inches)
~3000	Loop B stagnates	
3070	Pressurizer proportional heaters activate when low-level trip clears	2.56 m (101 inches)
~3200	HPI pumps dead-head	8.89 MPa (1275 psia)
5836	PORVs open because primary is water-solid from charging flow	16.5 MPa (2400 psia)
6152	Calculation terminated with future conditions predictable	

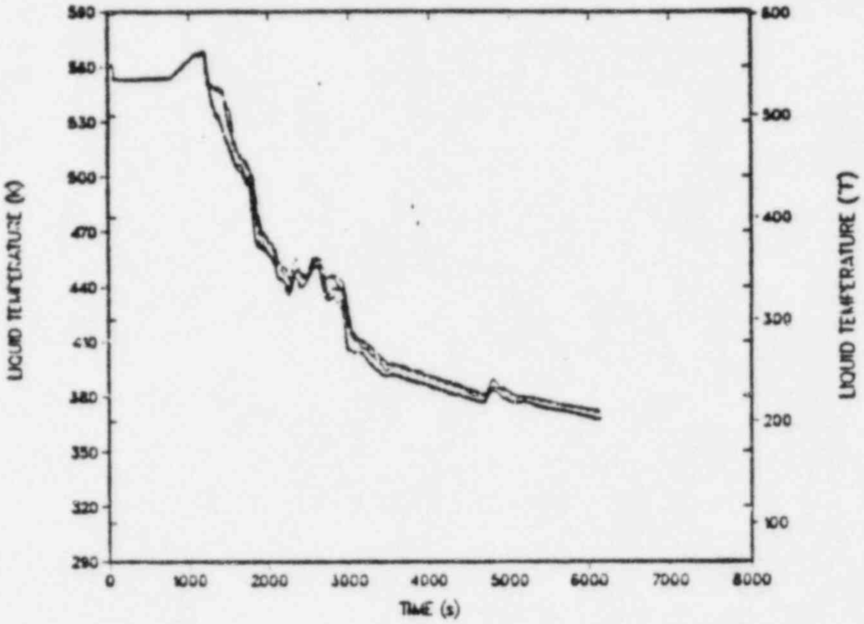

Fig. 9.1. Downcomer liquid temperature during Transient 6.

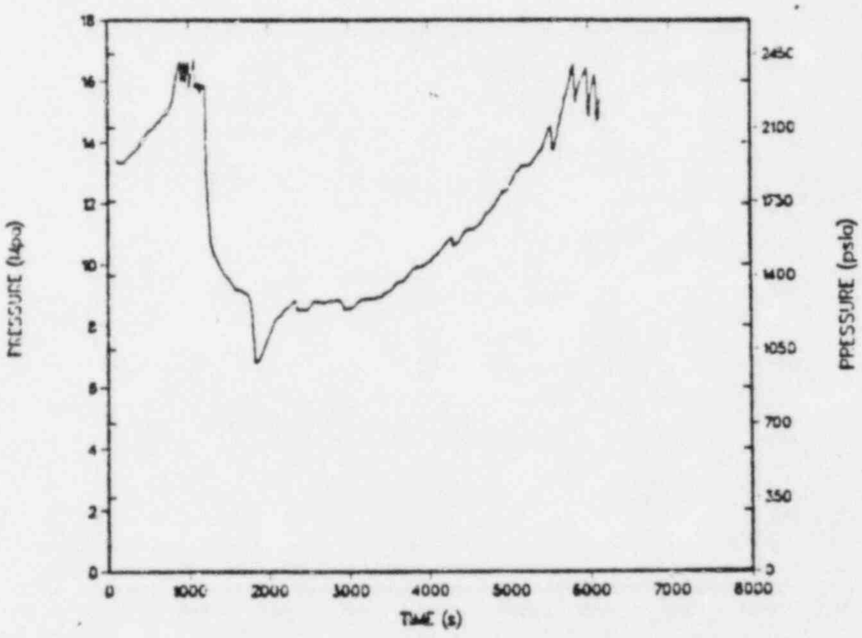

Fig. 9.2. Downcomer pressure during Transient 6.

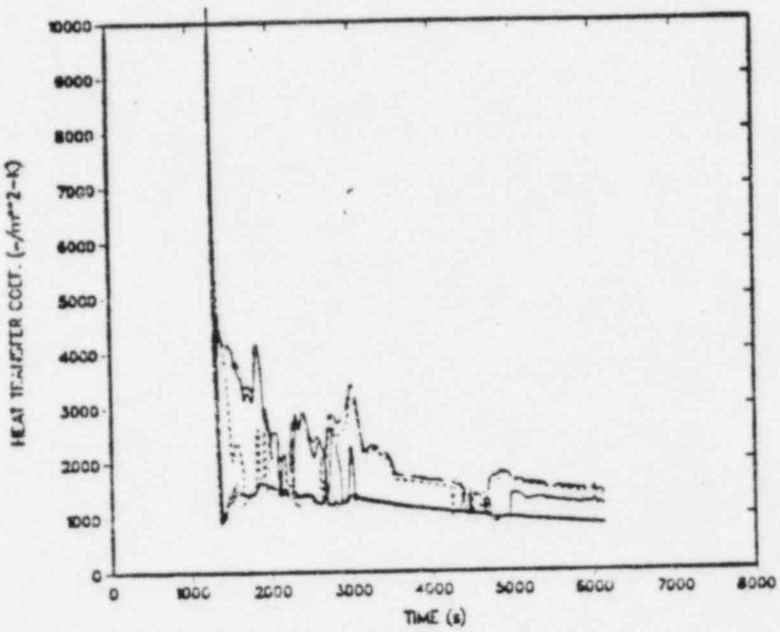

Fig. 9.3. Downcomer liquid velocity in z-direction during Transient 6.

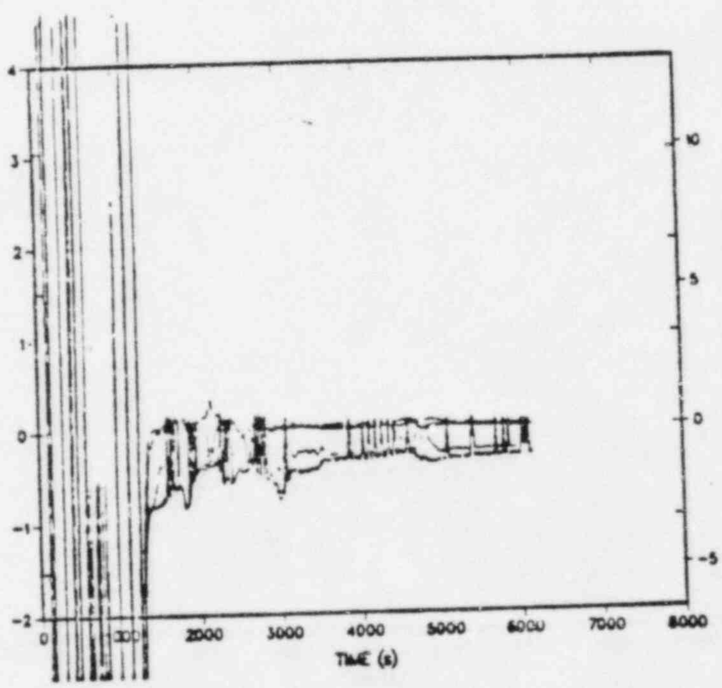

Fig. 9.4. Downcomer heat transfer coefficient during Transient 6.

10.a. Transient 7

Hot-leg Break with Blocked Natural Circulation from HFP

This transient is assumed to result from a .00186 m^2 (0.02 ft^2) break in hot-leg A during HFP and is aggravated by an assumed loss of all natural circulation when the primary pressure falls below 7.93 MPa (1150 psig). A sequence-of-events summary is given in Table 10.1. Figures 10.1-10.4 give the system pressure, downcomer liquid temperatures, heat-transfer coefficient, and downcomer velocity for the transient.

The hot-leg break causes the primary to depressurize, and the reactor trips on low pressure in about 16 s. SIAS occurs at 34 s as the pressure continues to fall, and the RCPs are tripped 30 s later. By 110 s the primary pressure reaches 7.93 MPa (1150 psig), and natural circulation is terminated by completely blocking the primary inlets and outlets of both SGs. The sudden loss of heat sink and flow stagnation result in rapid core heatup, and bulk boiling commences within 60 s. The primary temperature and pressure rise abruptly and peak at ~615 K (640 °F) and ~14.7 MPa (2130 psia), respectively, at ~600 s. Thereafter, both temperature and pressure decrease as cold charging flow and HPI slowly refill the system and displace the relatively hot fluid being discharged at the hot-leg break. Nevertheless, bulk boiling persists until roughly 4500-5000 s when subcooling is finally regained. By 7200 s the primary pressure has fallen to ~2.8 MPa (400 psia), the downcomer temperature is ~340 K (150 °F) but the upper head is still voided.

TABLE 10.1
Transient 7
0.02 ft^2 HOT-LEG BREAK FROM HFP

Sequence of Events

Time (s)	Event	Setpoint
0.0	0.02 ft^2 break appears in hot leg A	
4.8	Pressurizer back-up heaters activate on low pressure	15.2 MPa (2200 psia)
15.7	Reactor trips on low pressure (thermal margin/low-pressure); turbine trips simultaneously	14.5 MPa (2100 psia)
15.8	ADVs and TBVs "quick-open" on turbine trip	
34.0	SIAS on low pressure	12.1 MPa (1740 psig)
34.5	Pressurizer heaters trip off on low level	2.56 m (101 in.)
64.0	Operator trips all RCPs	
~110	Bulk boiling in the core begins	
~200	Upper head begins voiding	
~4500	Subcooling in core returns	
7200	Calculation ended	

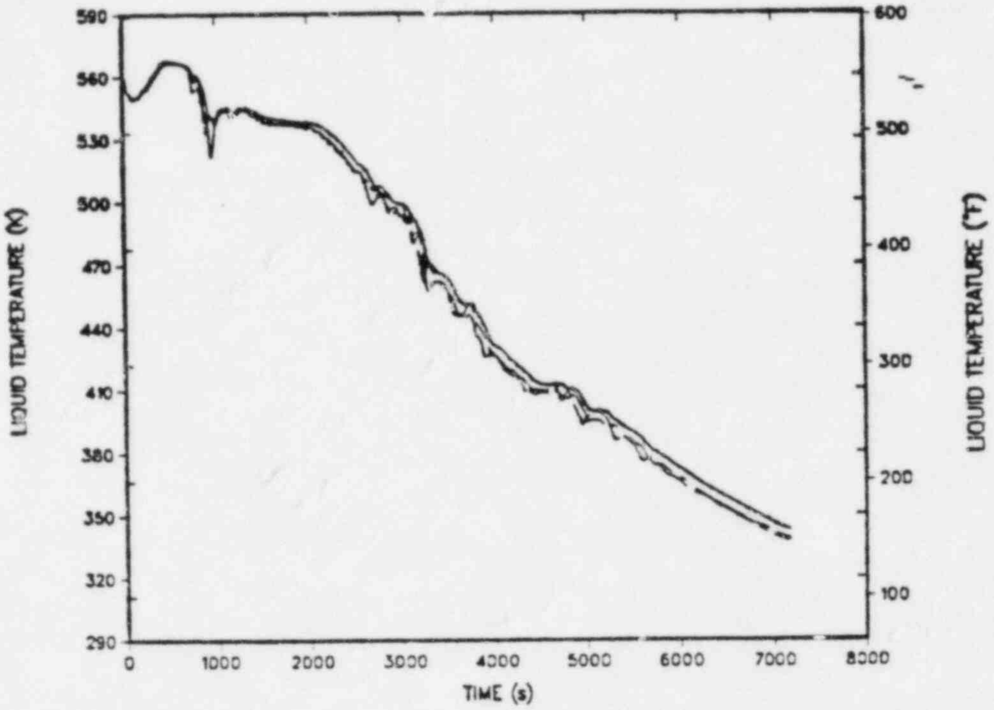

Fig. 10.1. Downcomer liquid temperature during Transient 7.

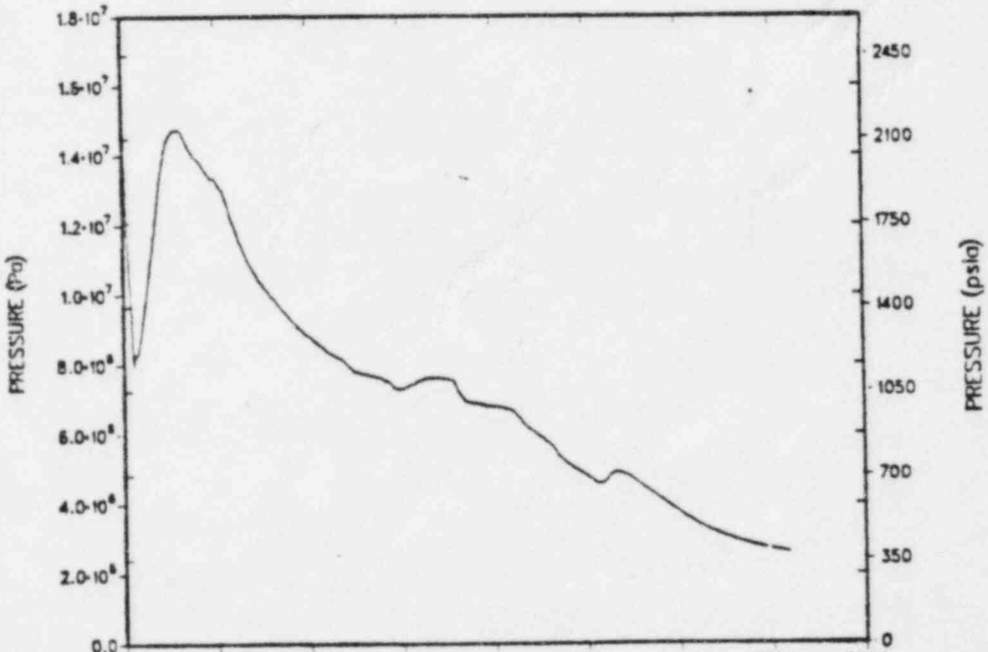

Fig. 10.2. Downcomer pressure during Transient 7.

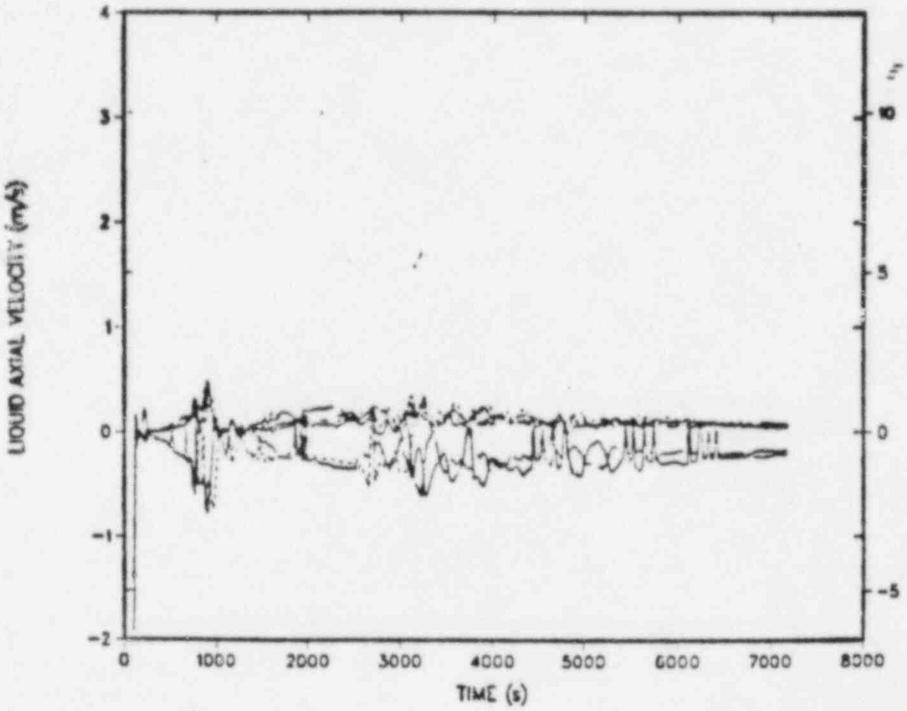

Fig. 10.3. Downcomer liquid velocity in z-direction during Transient 7.

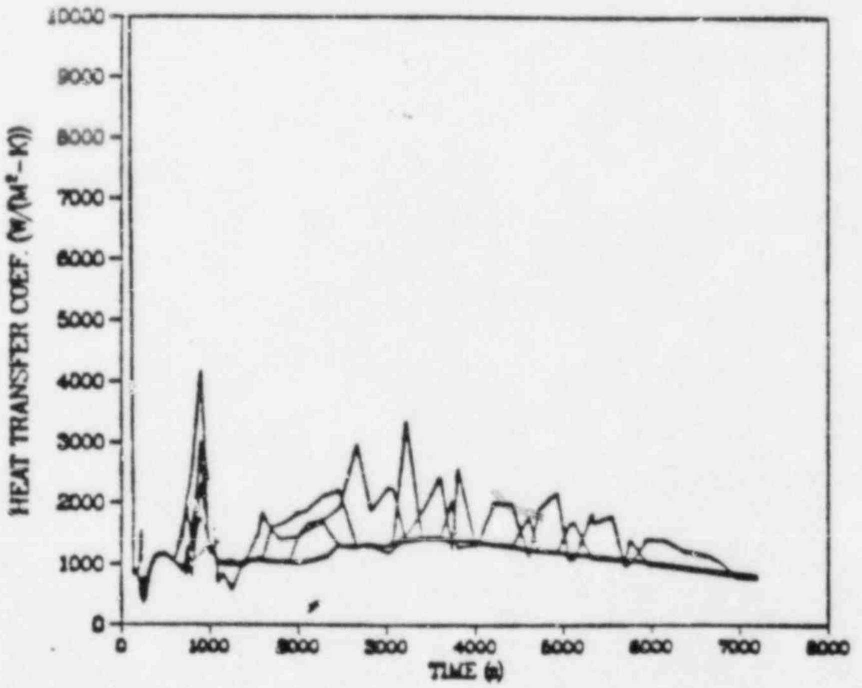

Fig. 10.4. Downcomer heat transfer coefficient during Transient 7.

10.b. Transient 7A

Hot-leg Break (0.02 ft^2) Without Flow Blockage from HFP

This transient is assumed to result from a .00186 m^2 (0.02 ft^2) break in hot-leg A during HFP. This transient differs from Transient 7 in that natural circulation is not artificially blocked. A sequence of events summary is given in Table 10.2. Figures 10.5 - 10.8 give the system pressure, downcomer liquid temperatures, heat transfer coefficient, and downcomer velocity for the transient.

The hot-leg break causes the primary to depressurize, and the reactor trips on low pressure in about 16 s. SIAS occurs at 24 s as the pressure continues to fall, and the RCPs are tripped 30 s later. As the RCPs coastdown the pressure falls below the HPI pump dead-head and HPI flow rapidly begins to surpass the limited flow available from the positive-displacement charging pumps.

By 502 s, the hot fluid discharged through the hot-leg break pressurizes the containment to 4 psig, causing SGIS. SGIS isolates the TBVs, but the effect is minimal because the primary and secondary are essentially in thermal equilibrium. In fact, by 529 s the ADVs close as the primary temperature falls below 552 K (535 F). However, without the additional cooling from the open ADVs, the cooling provided by the HPI and hot-leg break is insufficient to prevent the primary from gradually reheating to the ADVs' setpoint. The ADVs reopen slightly at 664 s but close permanently at 968 s.

After the ADVs close the secondary sides of both SGs are bottled-up, and the HPI flow causes the primary temperature to fall below the secondary. The resulting reverse heat transfer tends to retard natural circulation in the loops. By ~6500 s the reverse heat transfer in conjunction with flow escaping through the break in hot leg A causes the flow to stagnate in loop A downstream of the break.

The calculation was terminated at 6636 s with the primary pressure and downcomer temperatures gradually decreasing from ~3.5 MPa (500 psia) and ~440 K (330 F), espectively. The stagnate condition in loop A causes the cold-leg temperatures to fall below 350 K (170^{0}F).

TABLE 10.2
Transient 7A
0.02 ft^2 HOT-LEG BREAK WITHOUT
FLOW BLOCKAGE FROM HFP

Sequence of Events

Time (s)	Event	Setpoint
0.0	0.02 ft^2 break appears in hot leg A	
4.8	Pressurizer back-up heaters activate on low pressure	15.2 MPa (2200 psia)
15.7	Reactor trips on low pressure (thermal margin/low-pressure); turbine trips simultaneously	14.5 MPa (2100 psia)
15.8	ADVs and TBVs "quick-open" on turbine trip	
34.0	SIAS on low pressure; maximum charging flow begins	12.1 MPa (1740 psig)
34.5	Pressurizer heaters trip off on low level	2.56 m (101 in.)
64.0	Operator trips all RCPs; HPI flow begins	8.8 MPa (1270 psig)
502	SGIS on high containment pressure; TBVs are isolated	0.129 MPa (4 psig)
529	ADVs close on low reactor temperature	552 K (535 F)
664	ADVs open on high reactor temperature	552 K (535 F)
968	ADVs close on low reactor temperature	552 K (535 F)
~6500	Flow stagnates in loop A	
6636	Calculation terminated	

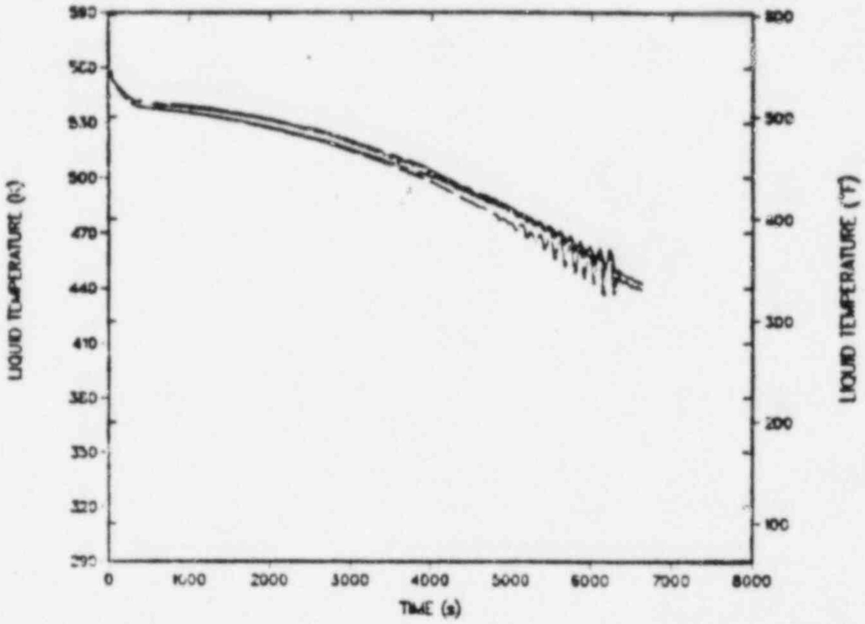

Fig. 10.5 Downcomer liquid temperature during Transient 7A.

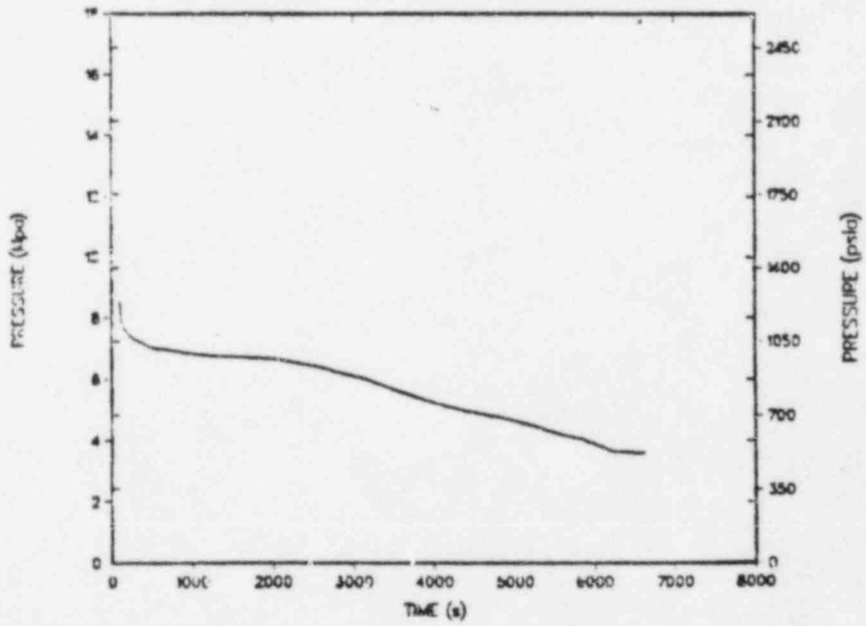

Fig. 10.6 Downcomer pressure during Transient 7A.

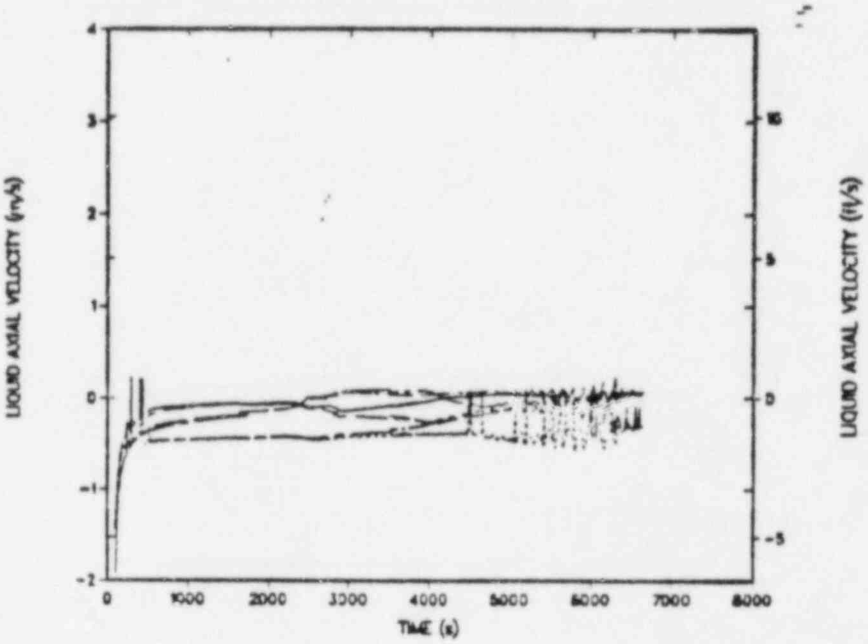

Fig. 10.7 Downcomer liquid velocity in z-direction during Transient 7A.

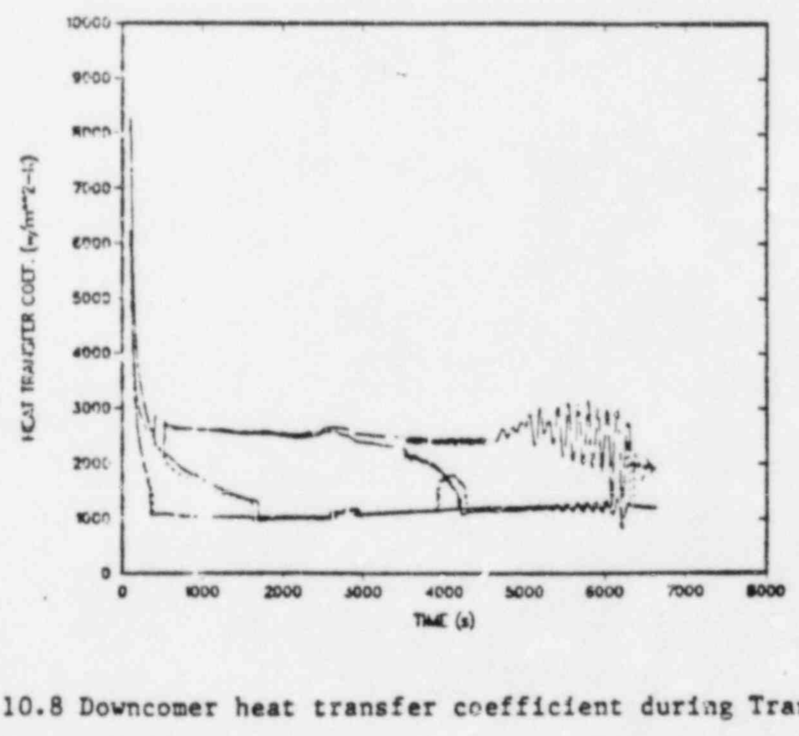

Fig. 10.8 Downcomer heat transfer coefficient during Transient 7A.

11. Transient 8

Two Stuck-Open MFRVs from HFP

This transient is initiated by a failure of both main feedwater regulating valves to close following a turbine trip. Table 11.1 tabulates the sequence of events that occurred during this transient, and Figures 11.1-11.4 show the time history of the requested parameters.

As seen in Figure 11.1, the primary fluid temperature reaches a minimum and the MFW pumps trip on low suction pressure following loss of liquid inventory in the condenser/hotwells. The steam lines are partially filled at this time; however, the void fraction downstream of the MSIVs remained so large during this interim that adequate high-quality steam was continuously delivered to the MFW pump turbines prior to the low suction pressure trip.

Following the MFW pump trip, decay heat and energy transferred from the system structural material back into the primary fluid exceeds the heat being transferred into the relatively colder SGs, resulting in primary fluid heating. The primary system repressurizes to the PORV setpoint because of the heatup and the charging flow refilling the primary system.

TABLE 11.1
Transient 8
Two Stuck-Open MFRVs from HFP

Sequence of Events

Time (s)	Event	Setpoint
0.0	Turbine/Reactor trip; main feedwater regulating valves fail to close; ADVs and TBV open on "quick-open" logic	-
3.4	Pressurizer backup heaters trip on following low primary pressure	15.2 MPa (2200 psia)
26.4	SIAS	12.1 MPa (1740 psig)
33.5	Pressurizer heaters trip off following low level in pressurizer	2.56 m (101 inches)
51.7	High level in SGs	1.27 m (50 inches)
56.4	Reactor coolant pumps assumed to be manually tripped off 30 s after SIAS	-
60.0	ADVs close	
120.0	SGs completely liquid full	$.18x10^6$ kg ($.397x10^6$ lb)
156.0	HPI begins	
217.9	MFW pumps trip off following loss of liquid inventory in condenser/hotwells	$.291x10^6$ kg ($.642x10^6$ lb)
490.0	HPI ends	
629.9	Pressurizer proportional heaters trip on following level recovery in Pressurizer	2.56 m (101 inches)
2131.2	Pressurizer proportional heaters trip off following high primary pressure	15.34 MPa (2275 psia)
2310.1	PORVs open following high primary pressure	16.55 MPa (2400 psia)
7200.0	Calculation terminated	-

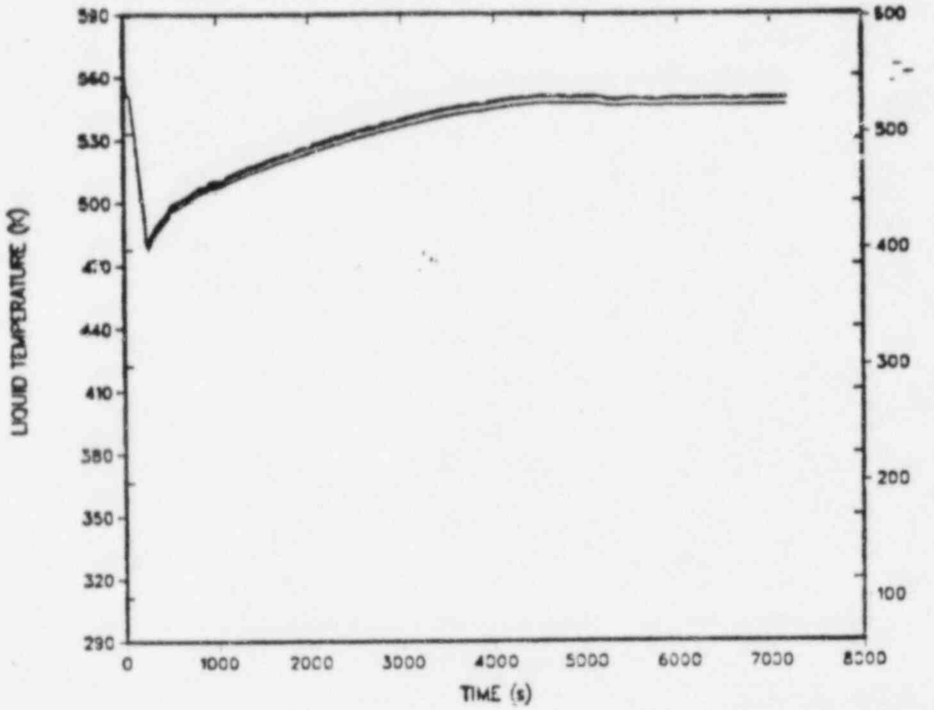

Fig. 11.1. Downcomer liquid temperature during Transient 8.

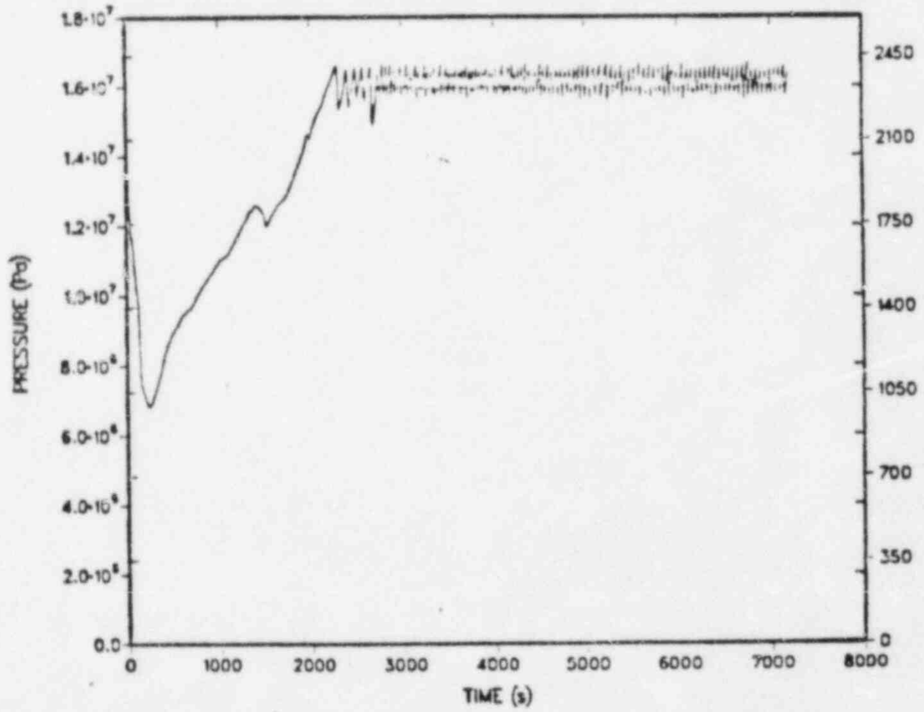

Fig. 11.2. Downcomer pressure during Transient 8.

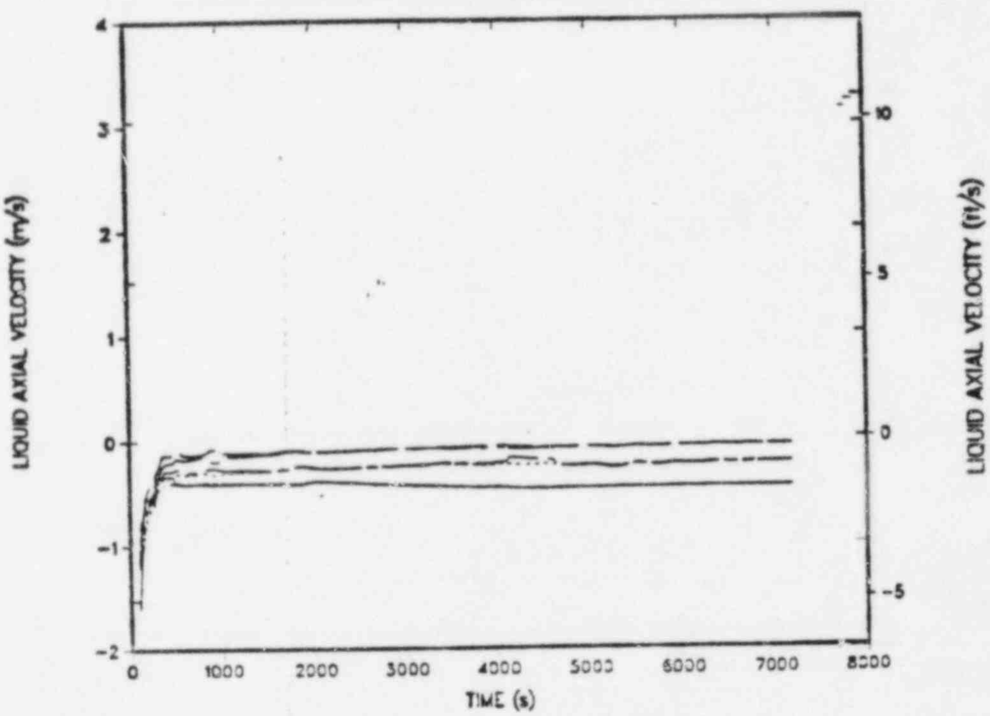

Fig. 11.3. Downcomer liquid velocity in z-di·ection during Transient 8.

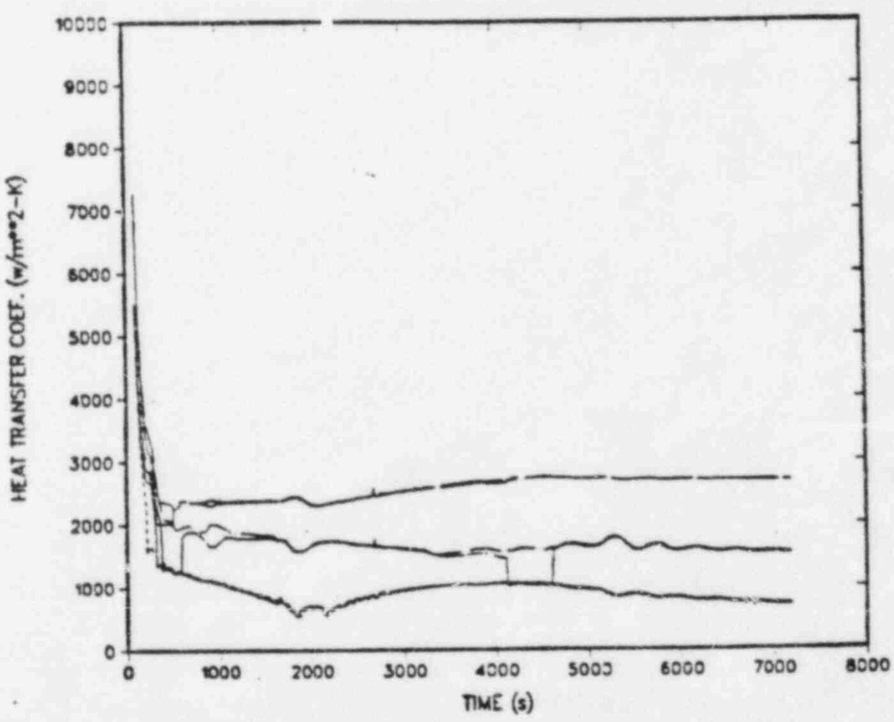

Fig. 11.4. Downcomer heat transfer coefficient during Transient 8.

12. Transient 9

One Stuck-Open MFRV from HFP

Transient 9 is initiated when the turbine trips from hot, full power conditions. Normally, both MFRVs would close in 20 s and both MFBVs would open to allow 5% steady-state MFW flow. However, in this transient, the MFRV in loop A fails to close allowing full feedwater flow until the MFW pumps trip. This trip could occur on low condenser/hotwell inventory or a low void fraction in the steamlines that drive the turbines of the MFW pumps. This transient was performed to determine if flow stagnation occurs in the intact primary loop, a situation in which PTS to the reactor vessel can be of concern.

The primary pressure, liquid temperature, velocity, and heat-transfer coefficient in the vessel flows are given in Figs. 12.1 - 12.4. The turbine trip causes the reactor to trip and a quick-open signal to be sent to the ADVs and TBVs. MFRV-B closes in 20 s as required but MFRV-A remains open delivering the full feedwater flow of 740 kg/s (5.85 Mlb/hr) or more to SG A. Because the turbine has tripped and no steam is available to heat the feedwater the feedwater temperature continually decreases. The "runaway" feedwater overcools the primary until the MFW pumps trip at 303 s on low condenser/hotwell inventory.

On the primary in loop A, high heat transfer drives a natural circulation flow of about 400 kg/s after the RCPs trip at 153 s. On loop B, the SG secondary liquid is hotter than the primary liquid and flow stagnation does occur between 500 and 1000 s. The system pressure is low enough for HPI injection flow between 250 and 600 s so that the period of flow stagnation overlaps somewhat with HPI flow. These conditions can be of interest in the PTS analysis.

The primary fluid cooling ends when the MFW flow ends and heating begins as the HPI flow stops. Charging flow repessurizes the system to the PORV setpoint at 1850 s. The fluid heating (from core decay heat and the system metal) creates a driving force in SG B which causes a natural circulation flow in loop B also. Both loops have natural circulation flows of about 400 kg/s. AFAS occurs on low liquid inventory in SG B at 4800 s; this provides a small amount of additional cooling. The calculation was terminated at 5800 s; the primary pressure and temperature can be extrapolated to be 16.1 MPa and 520 K by 7200 s.

TABLE 12.1
Transient 9
One Stuck-Open MFRV from HFP

Sequence of Events

Time (s)	Event	Setpoint
0	Turbine trip/reactor trip TBVs/ADVs receive quick-open signal	
34	Pressurizer heaters trip off based on low-low level	2.56 m (101 in)
75	ADVs close on low primary temperature	552 K (534 F)
123	SIAS on low primary pressure	12.1 MPa (1740 psig)
126	Feedwater-heater-drain tank flow trips off on low level	
153	RCPs trip	30 s after SIAS
250	HPI flow begins	8.87 MPa (1270 psig)
303	MFW pumps trip on low condenser/hotwell inventory	$.291 \times 10^6$ Kg ($.642 \times 10^6$ lb)
303	TBV closes on low secondary pressure	6.17 MPa (895.5 psia)
600	HPI flow ends as system pressure recovers	8.87 MPa (1270 psig)
665	Pressurizer proportional heaters tripped back on because of level recovery	2.57 m (101 in)
1700	Pressurizer proportional heaters tripped off because of high system pressure	15.7 MPa (2275 psia)
1850	PORV setpoint reached	16.5 MPa 2400 psia)
2650	ADV/TBV reopen on high primary temperature	552 K (534 F)
4800	AFAS on low liquid inventory	45,000 kg (99,200 lbm)
5800	Calculation terminated	

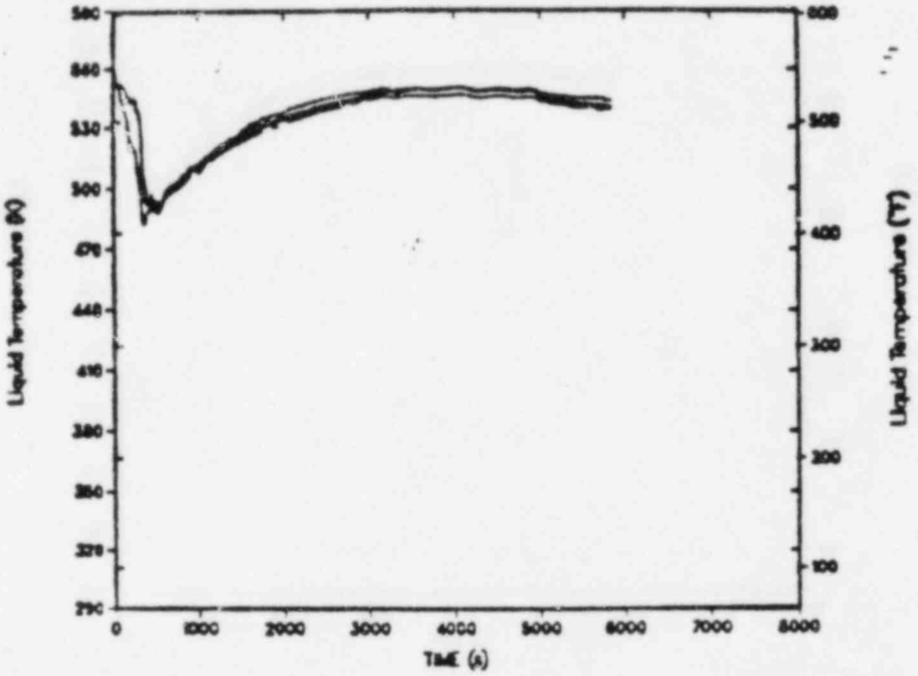

Fig. 12.1. Downcomer liquid temperature during Transient 9.

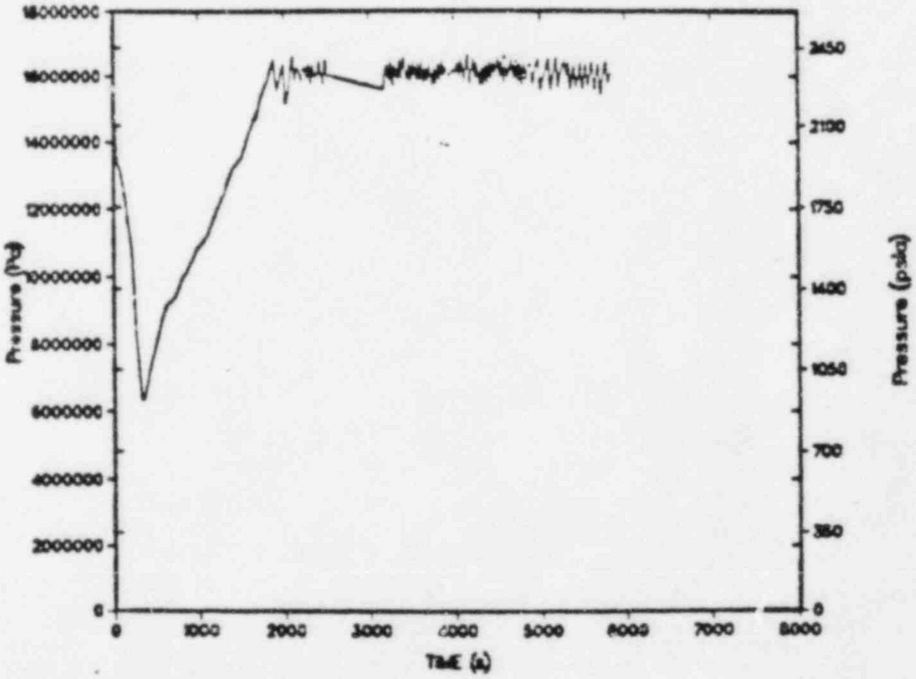

Fig. 12.2. Downcomer pressure during Transient 9.

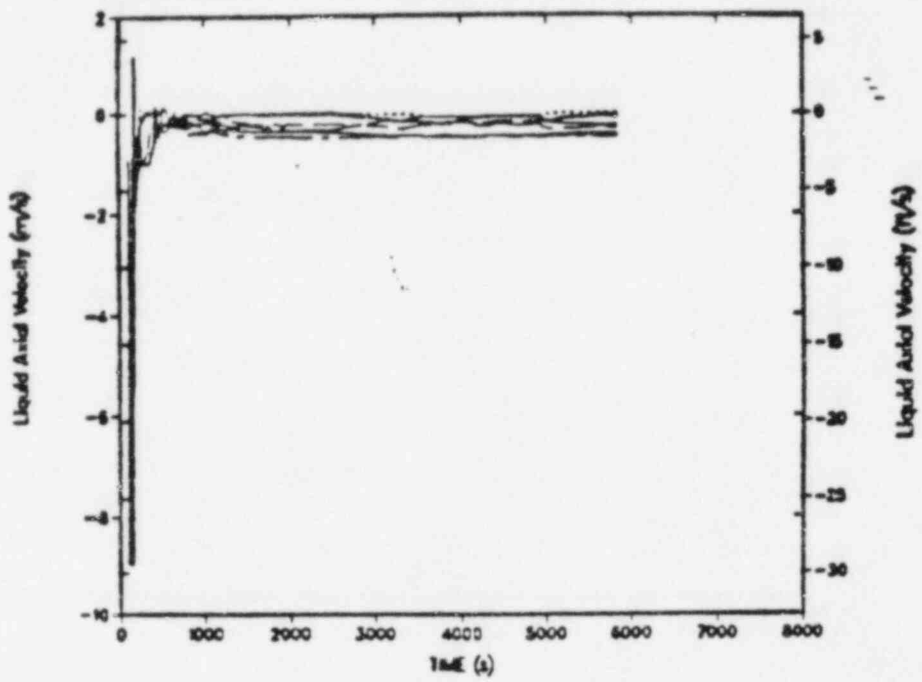

Fig. 12.3. Downcomer liquid velocity in z-direction during Transient 9.

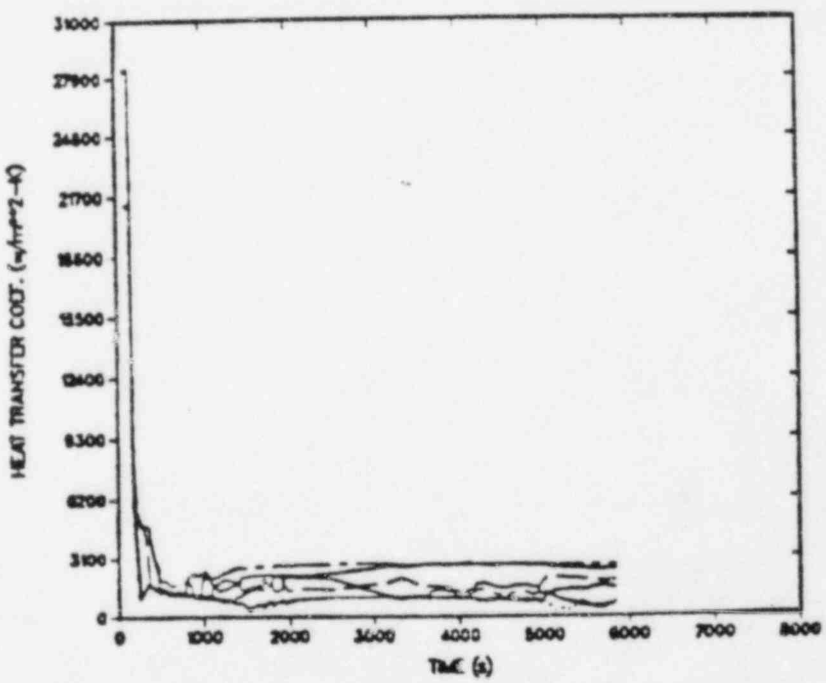

Fig. 12.4. Downcomer heat transfer coefficient during Transient 9.

13. Transient 10

1.0 ft^2 MSLB with 2 RCP from HZP

This transient is the same as Transient 1 except that only two of the four RCPs are tripped 30 s after SIAS. This, of course, changes the nature of the entire transient. Flow stagnation is not of PTS concern in this transient; only a low bulk fluid temperature would be of PTS interest. Table 13.1 lists the sequence of events for the transient and Figs. 13.1-13.4 give a few system parameters.

Transient 1 and Transient 10 should be identical until the RCPs trip at 112 s. However, because of model changes to the steam generator and pressurizer, the timing of the two transients are not the same. The discrepancies in timing give an indication of the sensitivities involved in the calculations.

Following the break in steamline A, both SG rapidly blow down. SGIS occurs at 34 s, isolating SG B. By 45 s, the pressure differential between the SGs causes the AFW-valves to SG A to close (although AFW has not initiated).

The SIAS setpoint is reached at 82 s with 2 diagonally-opposite RCPs tripping 30 s later. The forced-convection flow drops to about 50% steady-state flow in the hot legs. In the cold legs, the two operating RCPs pump about 70% steady-state flow with 20% reverse flow in the cold legs with tripped RCPs. With two pumps in operation, much higher heat-transfer rates occur in both SGs. While SG A removes energy more rapidly than in Transient 1, SG B adds considerably more energy to the primary during 80-500 s. The net result is that the minimum primary temperature is 50 K higher in Transient 10 than in Transient 1.

HPI flow initiates at 115 s. AFAS is based on a collapsed-liquid level in Transient 10 as opposed to a Δp-measurement in Transient 1. AFW is delivered to SG B only at 222 s based on a low liquid inventory in SG A. SG A dries out by 500 s, at which time the primary temperature begins increasing slightly. HPI and charging flow repressurize the system until the shutoff head of the HPI pumps is reached at 930 s; charging flow then brings the system pressure to the PORV setpoint at 2406 s.

Because 2 RCPs are operating and velocities are relatively high, the Courant limit keeps the time step fairly low. This limit resulted in a slow-running problem and so the calculation was terminated at 5300 s. The system pressure is at the PORV setpoint and the primary temperature will probably remain around 450 K for the rest of the transient.

TABLE 13.1
Transient 10
1.0 ft^2 MSLB WITH 2 RCP FROM HZP

Sequence of Events

Time (s)	Event	Setpoint
0	0.0929 m^2 (1.0 ft^2) MSLB in loop A, TBVs close	
22	Pressurizer heaters trip off on low-low level	2.56 m (101 inches)
34	SGIS	4.6 MPa (653 psig)
45	Asymmetric SG pressure	0.8 MPa (115 psid)
82	SIAS	12.1 MPa (1740 psig)
112	Two of the four RCPs are tripped	SIAS+30 s
115	HPI flow begins	8.8 MPa (1270 psig)
222	AFAS	-4.3 m (-170 inches)
500	SG A dries out	
579	Pressurizer proportional heaters tripped back on because of level recovery	2.56 m (101 inches)
930	Pressurizer heaters tripped of on high pressure; HPI flow ends	15.6 MPa (2275 psia)
2406	PORV setpoint reached	16.5 MPa (2400 psia)
5300	Calculation terminated; conditions stable	

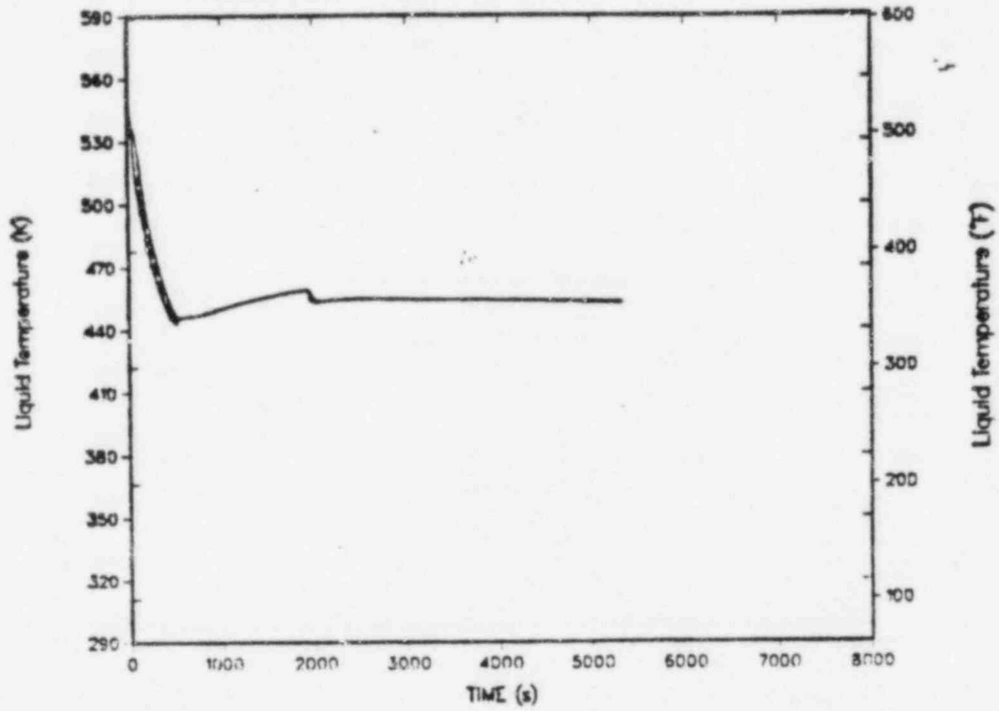

Fig. 13.1. Downcomer liquid temperature during Transient 10.

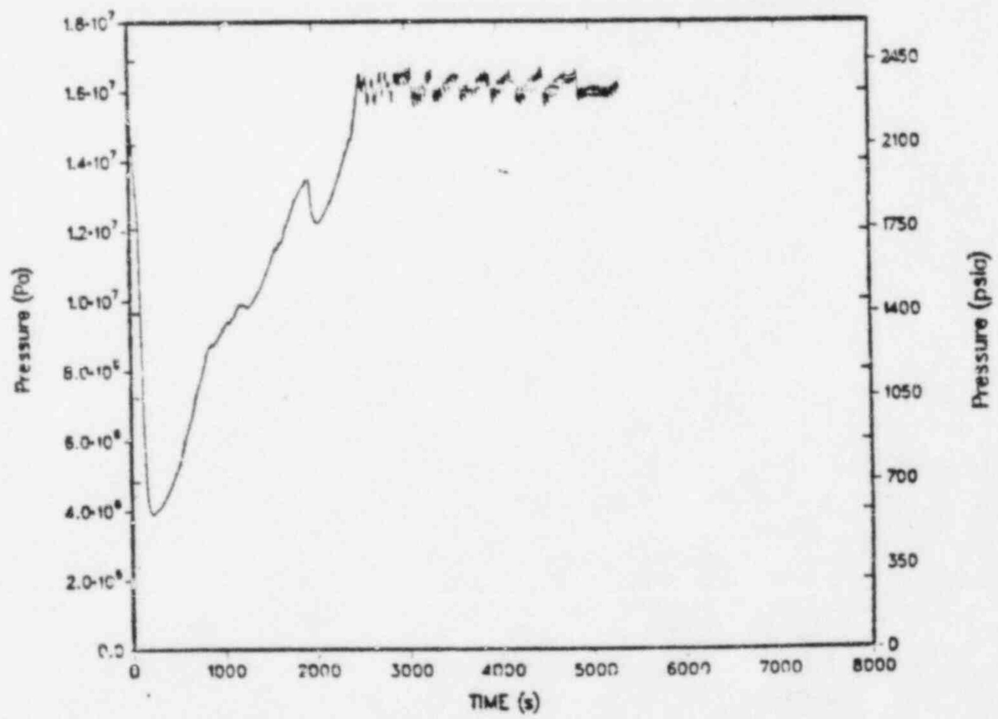

Fig. 13.2. Downcomer pressure during Transient 10.

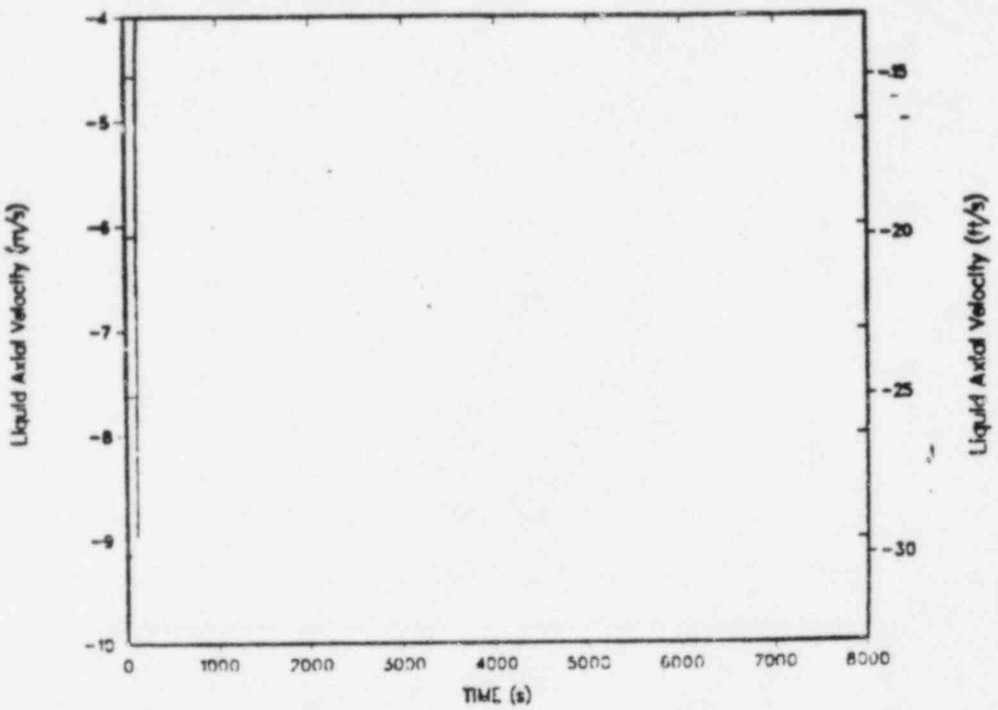

Fig. 13.3. Downcomer liquid velocity in z-direction during Transient 10.

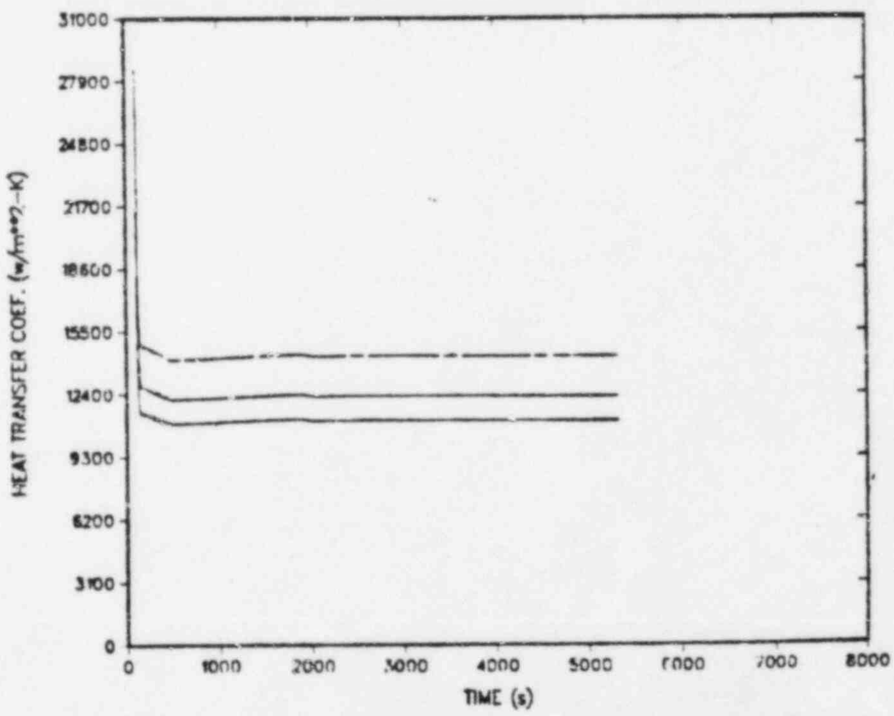

Fig. 13.4. Downcomer heat transfer coefficient during Transient 10.

14. Transient 11

Double-ended Steam Line Break from HZP with Stuck Open MSIVs

This transient is initiated by a double-ended guillotine break in steamline A between the flow restrictor and the MSIV. It is assumed that when SGIS is obtained due to low SG pressure that the MSIVs fail to close. Hence, both SGs continue to blowdown. It was farther specified that the operator would turn off the auxiliary feedwater system eight minutes into the transient. Table 14.1 tabulates the sequence of events that occurred during this transient, and Figures 14.1-14.4 show the time history of requested parameters.

As seen in Figure 14.1, the primary fluid temperature reaches a minimum temperature of 376 K and levels off at that value. This temperature corresponds to a few degrees above the temperature of the water remaining in the bottom of each SG following the blowdown to .1 MPA (1 atm.) of the secondary side. Because of the decay heat from the core and the energy transferred from the structural material to the primary fluid, each SG is operating at approximately 9 Mw. This power continues to slowly boil off the water remaining in each SG at a rate of approximately 4 kg/s per SG. The power produced by the decay of the heat slabs is expected to decay to zero as the slab temperatures come into thermal equilibrium with the primary fluid. The power to each SG from the core decay heat will eventually approach 4.65 Mw and the boiling rate will decrease to approximately 2 kg/s per SG. Based upon an extrapolation procedure, it is estimated that each SG will dry out at approximately 6350 seconds.

The primary system repressurizes to the PORV setpoint because of the charging flow refilling the primary system liquid solid.

TABLE 14-1
Transient 11
Double-Ended Steam Line Break with Stuck Open MSI'/s

Sequence of Events

Time	Event	Setpoint
0.0	Double-Ended steam line break on loop A	-
6.0	Pressurizer backup heaters trip on due to low primary pressure	2200 psia
11.2	SGIS	4.6 MPa (668 psia)
12.8	Pressurizer heater tripped off following low pressurizer level	2.56 m (101 inches)
32.2	SIAS	12.1 MPa (1740 psig)
37.5	HPI begins	8.65 MPa (1240 psig)
62.2	RCPs assumed to be manually tripped	-
91.9	AFAS (based upon collapsed liquid level)	-4.3 m (-170 inches)
480.0	Operator assumed to turn off aux feed to both SGs	-
654.8	Pressurizer proportional heaters tripped on following pressurizer level recovery	-
1250.0	HPI ends	8.65 MPa (1240 psig)
2444.3	PORVs open due to high primary pressure	16.55 MPa
3300.0	calculation terminated	(2400 psia)
6350.0	SGs dry out (based upon extrapolation)	

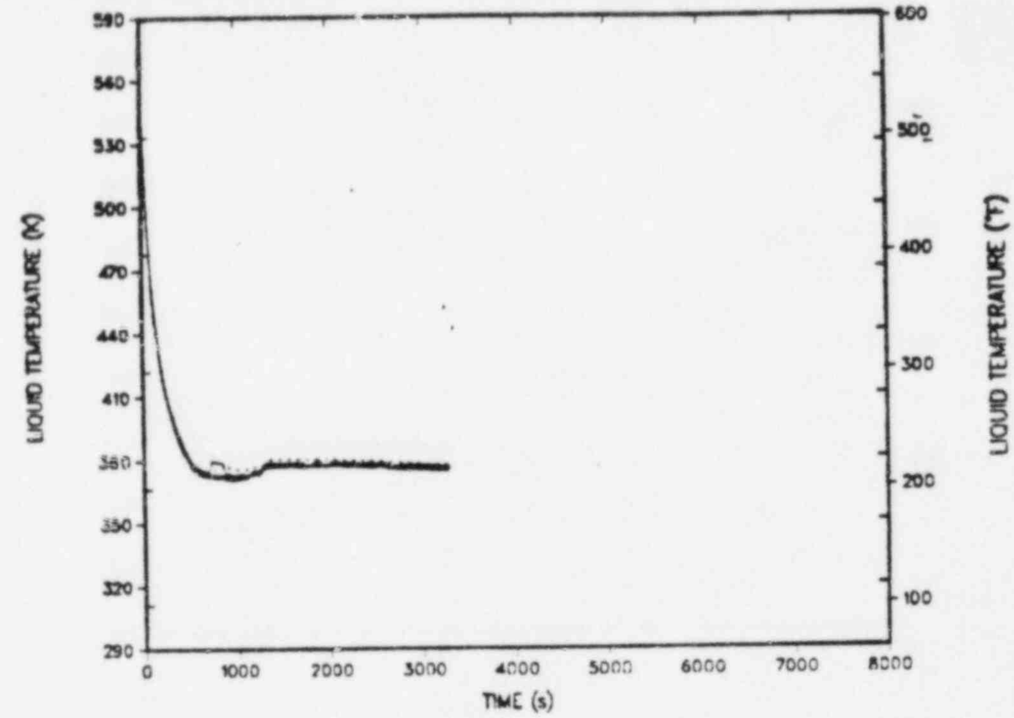

Fig. 14.1. Downcomer liquid temperature during Transient 11.

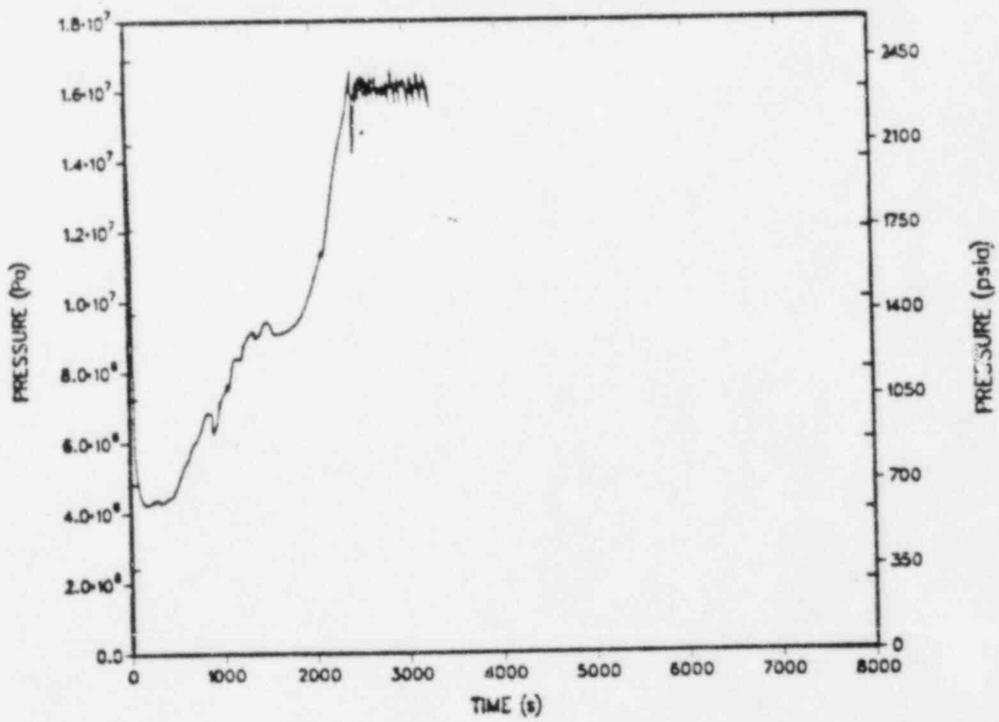

Fig. 14.2. Downcomer pressure during Transient 11.

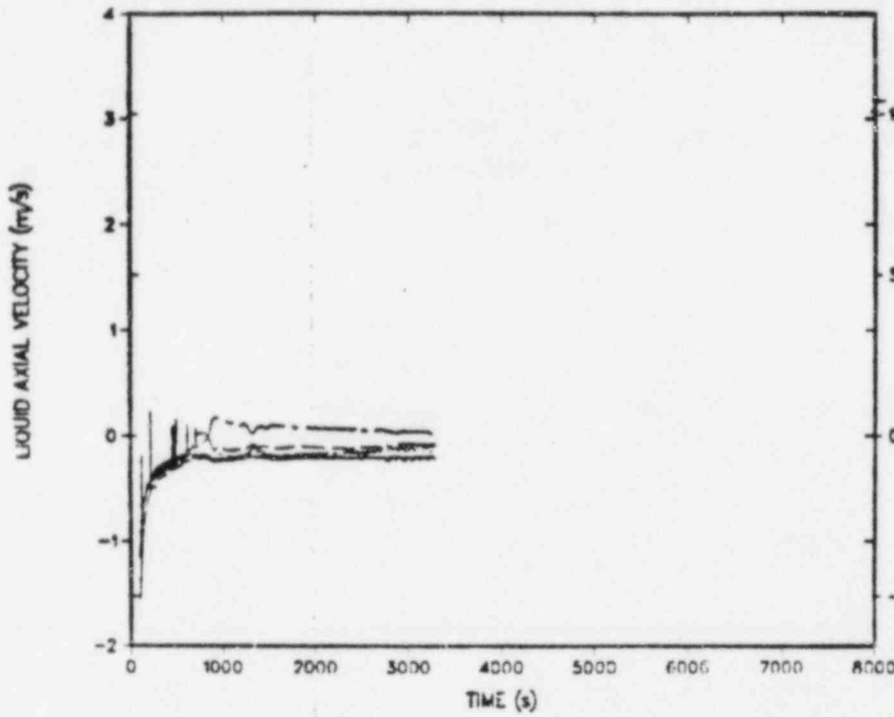

Fig. 14.3. Downcomer liquid velocity in z-direction during Transient 11.

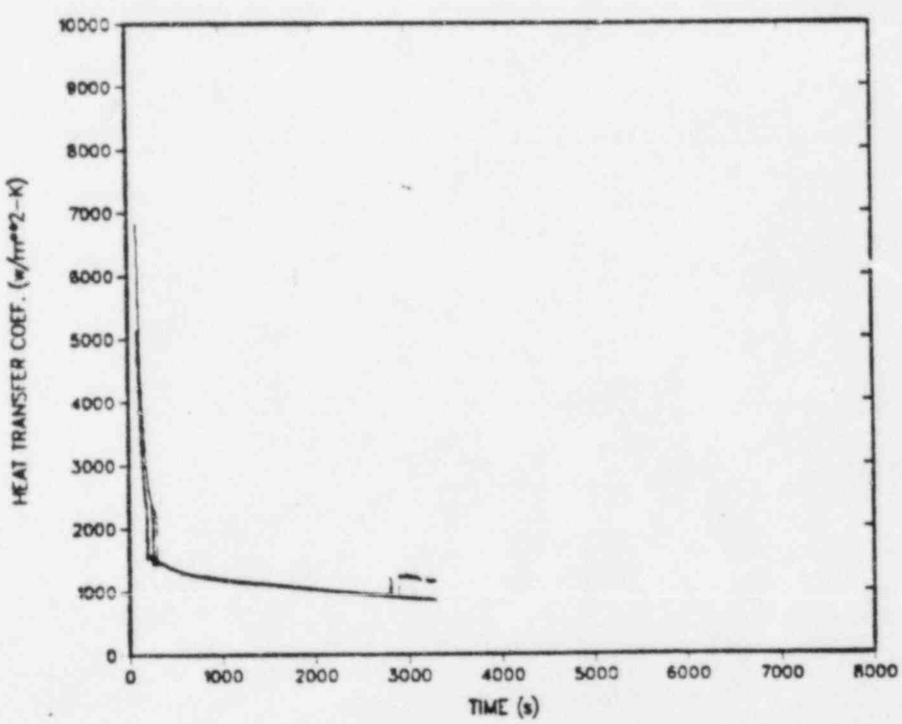

Fig. 14.4. Downcomer heat transfer coefficient during Transient 11.