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LOSS-OF-FEEDWATER TRANSIENTS IN PWRs

Robert D. Burns III

The TMI-2 accident demonstrated that the nuclear industry must be prepared for events involving multiple equipment failures[1] The purpose of the LWR severe accident sequence analysis (SASA) research at the Los Alamos Scientific Laboratory (LASL) is to provide the NRC with a technical basis for judging the adequacy of plant operating procedures for dealing with such events. The LASL approach is to (1) identify potential types of multiple equipment failures at specific US commercial nuclear power plants[2], (2) perform computer simulations of postulated accident initiators including anticipated equipment malfunctions and operator actions throughout the event, and (3) determine key primary system responses, timing, and significance of events.

Recent SASA work in LASL's Multifault Accident Analysis Section has focused on loss-of-feedwater (LOFW) transients at a 4-loop Westinghouse nuclear power reactor[3]. This class of accidents was selected because of NRC concern over auxiliary feedwater (AFW) system reliability and because of concern over the capability of plants to "feed and bleed" in total LOFW situations.

In all transients studied, the initiator was loss of main feedwater and reactor coolant pump (RCP) trip, caused by temporary loss of off-site power. Subsequent automatic actions included reactor scram, closure of the main steam isolation valves, and initiation of AFW flow. TRAC-PD2 calculations were designed to study the consequences of AFW delivery rates below the minimum specified in the emergency operating procedures (EOPs) for the reference 4-loop plant.

Six types of LOFW scenarios have been studied, including (1) zero AFW availability (nominal case), (2) initially zero AFW but full recovery after 2 h, (3) zero AFW with steam generator (SG) atmospheric relief valve (ARV) malfunction, (4) zero AFW with high pressure charging flow initiated after 2 h, and (5) zero AFW with delay in reactor scram. Additional cases were considered to study the effects of uncertainties in pressurizer heater/spray operation, operator manual initiation of high pressure charging flow, reactor initial conditions, and RCP and power coastdown characteristics. Nominal case results, rationale for selections of other cases, and lessons learned are summarized below.

(1) Nominal case results indicate three phases of the LOFW transient with zero AFW, in which the behavior of the primary system is significantly different. The first phase (quasi-equilibrium) lasts until the SG inventory boils dry (approximately 70 min.). Natural circulation permits subcooling of the cold leg to the saturation conditions in the SG. Restoration of AFW delivery to at least one SG before the SGs dry out will result in continuation of the first phase and ultimately either normal progression to cold shutdown or return to power.

The second phase (subcooled expansion) begins when heat removal capacity is lost as the SGs boil dry. To accommodate primary water expansion in the vessel, system pressures increase within minutes to the setpoint of the power-operated relief-valves (PORVs), relieving the primary system in subcooled, isobaric expansion at approximately 80 cfm (0.04 m^3/s). The PORVs relieve steam at this rate for approximately 20 min., then water relief continues at the same rate for approximately another 20 min. Natural circulation continues during this phase.

System saturation at the start of the third phase (saturated expansion) drives natural circulation to zero after approximately 10 min. System pressures rise to the pressurizer safety valve setpoint to accommodate approximately 600 cfm (0.3 m^3/s) two phase flow out the pressurizer valves. Vapor forms in the primary system and clad temperatures begin to rise sharply after approximately 45 min of boiling in the primary system.

(2) A case involving recovery of AFW availability minutes before natural circulation was completely lost in the third phase was selected because operators would likely attempt to restore AFW as soon as possible, and recovery at that time is a bounding case for AFW recovery at any earlier time. Results showed that (a) AFW initiation caused rapid primary depressurization and subsequent refilling of the primary system by pressurizer water and (b) primary subcooling and natural circulation were re-established after 20-30 min. Operator initiation of increased charging flow in response to low pressurizer level (called for in the EOPs) would result in return to hot shutdown conditions.

(3) A case involving opening of one ARV to its full open position and subsequent failure to close was added as a complication in the LOFW scenarios because reactor operating experience shows that ARVs have malfunctioned in the past and because primary conditions during the first phase of a LOFW transient depend on secondary saturation conditions. Results showed that primary temperatures and pressures fall during the 10 min. required to blowdown the affected SG, but subcooled conditions are maintained even in the absence of pressurizer heaters. The impact on the duration of the first phase is small.

(4) A case involving operator initiation of full charging flow after primary system pressure reached the safety setpoint was selected as a bounding case for scenarios with feed and bleed initiation up to that time. When charging flow was initiated, the vapor-fraction in top quarter of the core was approximately 10 percent. After reaching a maximum of 30 percent about 10 min. later, a slow refill of the core began and completed approximately 2 h later. Results also showed that the primary system eventually returned to subcooled expansion. The circumstances of this are not yet fully understood and remain under study.

(5) A case involving delay in reactor scram was selected to determine the impact of opening the PORVs early in the transient as occurred during the TMI accident. Results indicated that following RCP trip without immediate reactor scram (1) PORVs open after approximately 4 s, safeties after 8 s, and all valves begin to close within seconds of scram initiation and (2) steam relief is accommodated through pressurizer valves up to about 20 s of scram delay, then water relief begins. Scram delay remains under study to include the effects of fuel and water temperature reactivity feedback. (For scram delays requiring pressurizer valve water relief, small breaks in the primary system will probably be forced to accommodate system saturated expansion.)

Work is continuing in the LASL SASA effort to fully document these results and to investigate other LOFW scenarios. Our continuing activities will focus on preparedness for multiple equipment failure events.

REFERENCES

1. R. D. Burns III, "Report of the Technical Assessment Task Force on WASH 1400 - Reactor Safety Study," Staff Report to the President's Commission on the Accident at Three Mile Island, Washington, DC (October 1979).

2. R. D. Burns III, "A Preliminary Review of Beyond-DBA PWR Accident Sequences," Proc. ANS Thermal Reactor Safety Meeting, Knoxville, TN (April 1980).

3. R. D. Burns III and N. S. DeMuth, "Computer Simulations of Postulated Nuclear Reactor Accidents," Proc. CUBE Conf., Livermore, CA (October 1980).

MULTIFAULT ACCIDENT ANALYSIS SECTION
REACTOR SAFETY ANALYSIS GROUP, Q-7
ENERGY DIVISION
LOS ALAMOS SCIENTIFIC LABORATORY

LOSS OF FEEDWATER TRANSIENTS IN PWRs

EIGHTH WATER REACTOR SAFETY
RESEARCH INFORMATION MEETING
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C.
OCTOBER 28, 1980

GENERIC CATEGORIES OF MFAs DEVELOPED EARLY IN LASL SASA EFFORT

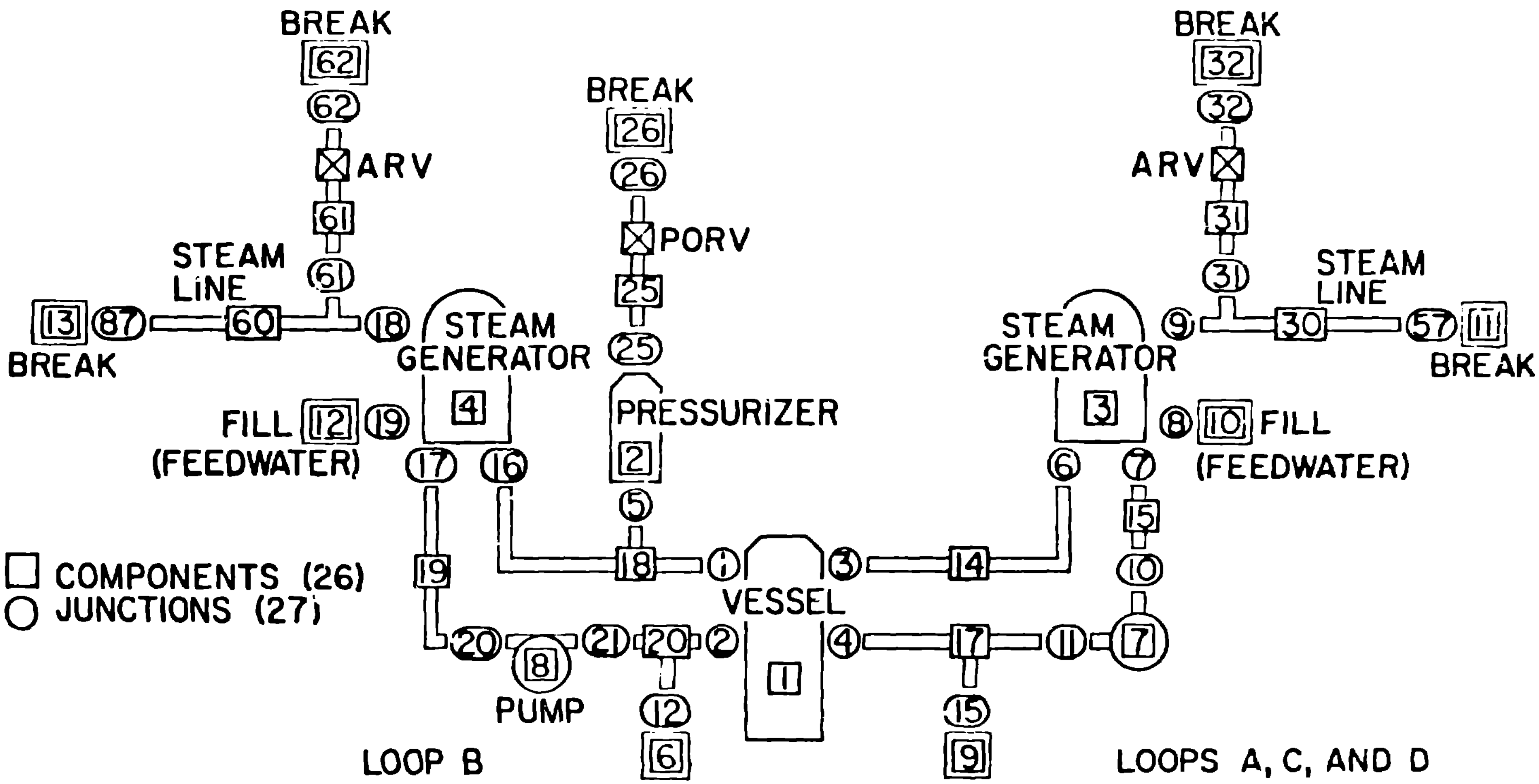
ALL AVAILABLE INFORMATION STUDIED TO IDENTIFY GENERAL, INCLUSIVE CATEGORIES

SOURCES:

- WASH-1400
- REACTOR EXPERIENCE(LERs,...)
- FSARs
- ENGINEERING EVALUATIONS OF PLANTS
- VITAL AREA STUDY(FAULT TREES)

CATEGORIES INCLUDE MULTIPLE EQUIPMENT FAILURE SCENARIOS

1. LOSS OF FEEDWATER (LOFW).
2. STATION BLACKOUT (SB).
3. LOSS OF RESIDUAL HEAT REMOVAL (LORHR).
4. SMALL-BREAK LOCA (S-LOCA).
5. INTERFACING-SYSTEM LOCA (IS-LOCA).
6. PRESSURIZER-VALVE LOCA (PV-LOCA).



ZION-I PWR
TRAC NODING DIAGRAM

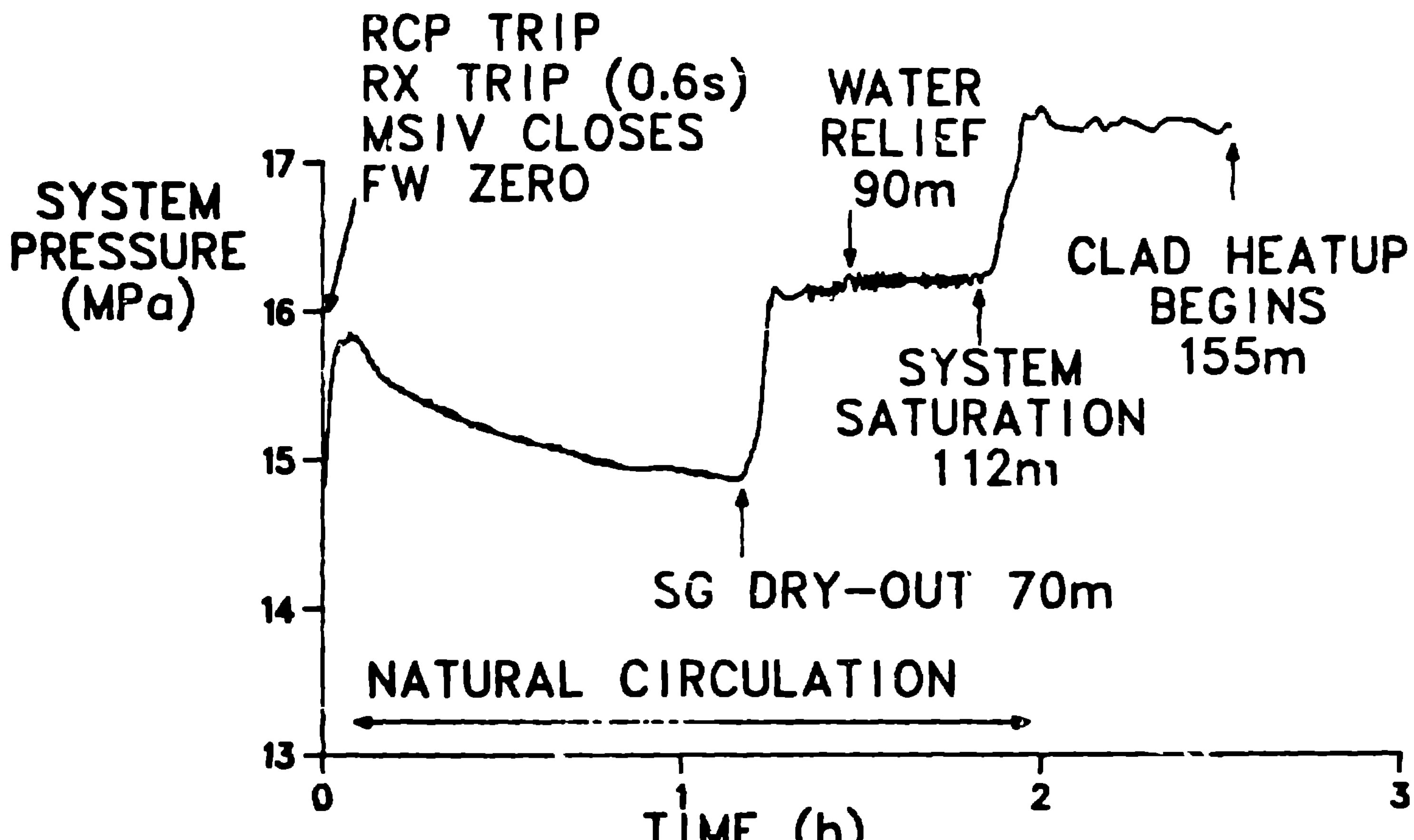
TRAC APPLIED TO SIMULATION OF ZION LOSS OF FEEDWATER SCENARIOS

LOFW CASES PRESENTED HERE:

1. NOMINAL SCENARIO (0–3h)
2. DELAYED/DEGRADED AFW (0–10h)
3. STUCK–OPEN ARV (0–1h)
4. FEED/BLEED (0–4h)
5. ATWS (0–1h)

...USE ANALYSES TO FIND AND RESOLVE SPECIFIC SAFETY–RELATED CONCERNS.

NOMINAL SEQUENCE IS TOTAL LOFW
INITIATED BY LOSS OF OFFSITE POWER



...CONSISTENT WITH SEMISCALE

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ANALYSIS OF STEAM GENERATOR DRY-OUT TIME VERIFIES TRAC RESULT

SG INVENTORY:

160,000 kg * 1.8 MJ/kg = 90 FPS

CORE ENERGY, 0–4200s:

APPROX. 80 FPS (MAINLY DECAY POWER)

FUEL ENERGY, 1350K–550K:

800K * 500 J/kgK * 200,000 kg = 8 FPS

ANNALYSIS OF PORV RELIEF BASED ON CALCULATED SYSTEM EXPANSION RATES

SUBCOOLED EXPANSION (80–112m)

$$(.003\ m^3/m^3K * 50\ MW)/(.005\ MJ/kgK * 700\ kg/\ m^3)$$

$$= 0.04\ m^3/s \quad (5\ kg/s\ STEAM\ OR\ 25\ kg/s\ WATER)$$

SATURATED EXPANSION (112m+)

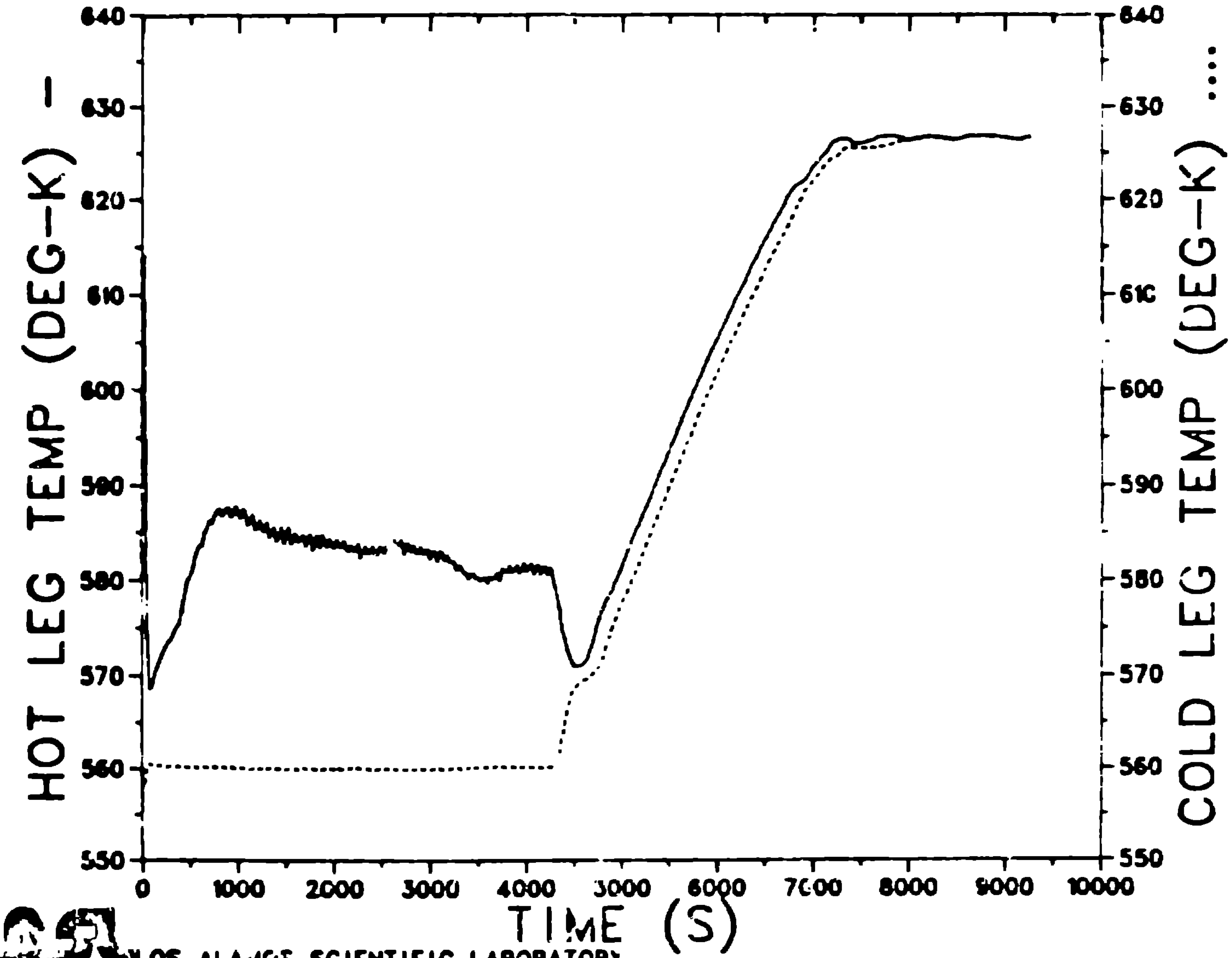
$$h_v - h_l = 0.9\ MJ/kg \qquad (AT\ \ 16.1\ MPa)$$

$$v_v - v_l = 0.0075\ m^3/kg$$

$$(0.0075 * 40\ MW)/0.9 = 0.33\ m^3/s$$

(40 kg/s STEAM OR 200 kg/s WATER)

COLD LEG TEMPERATURE EQUALS
SECONDARY SATURATION CONDITIONS



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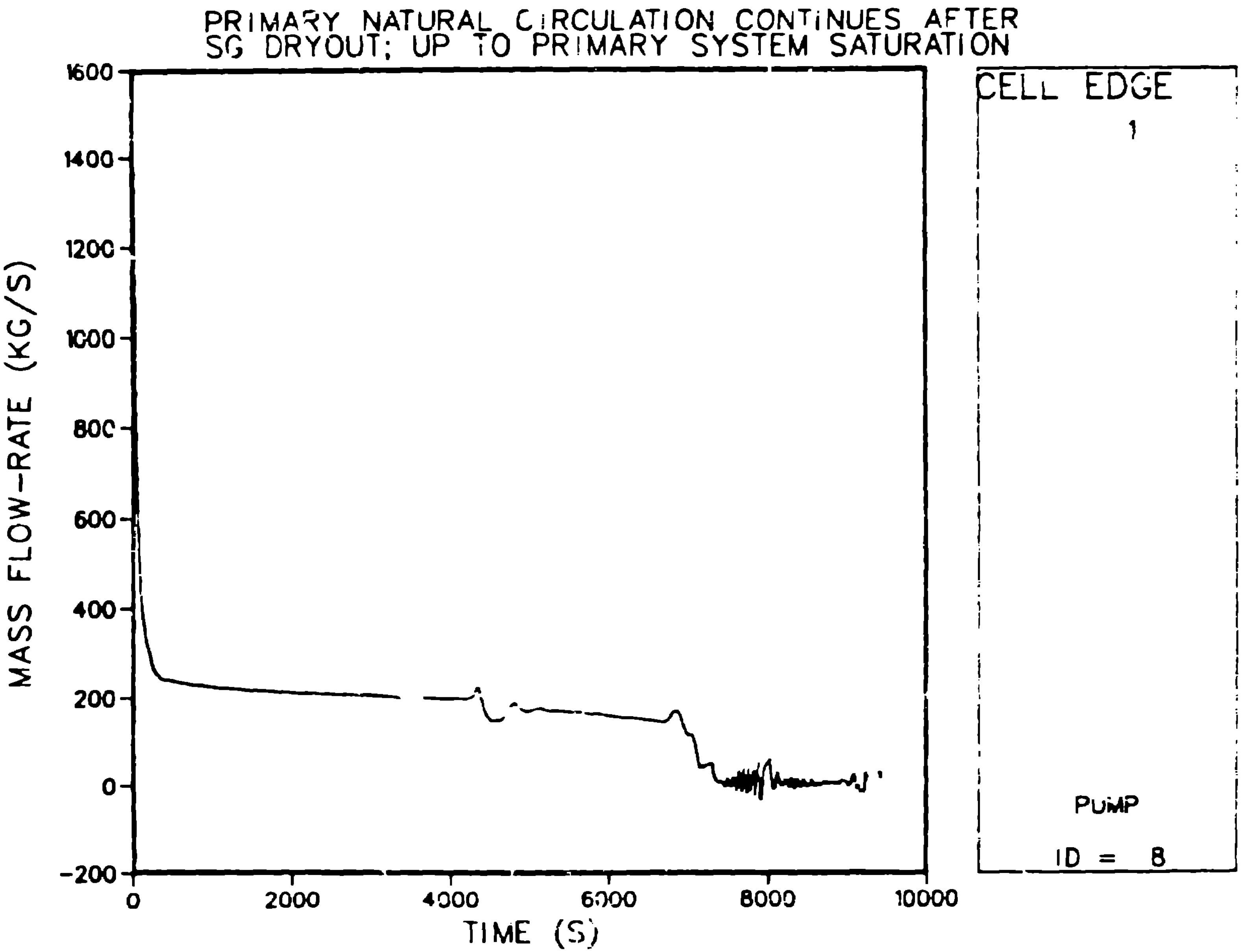
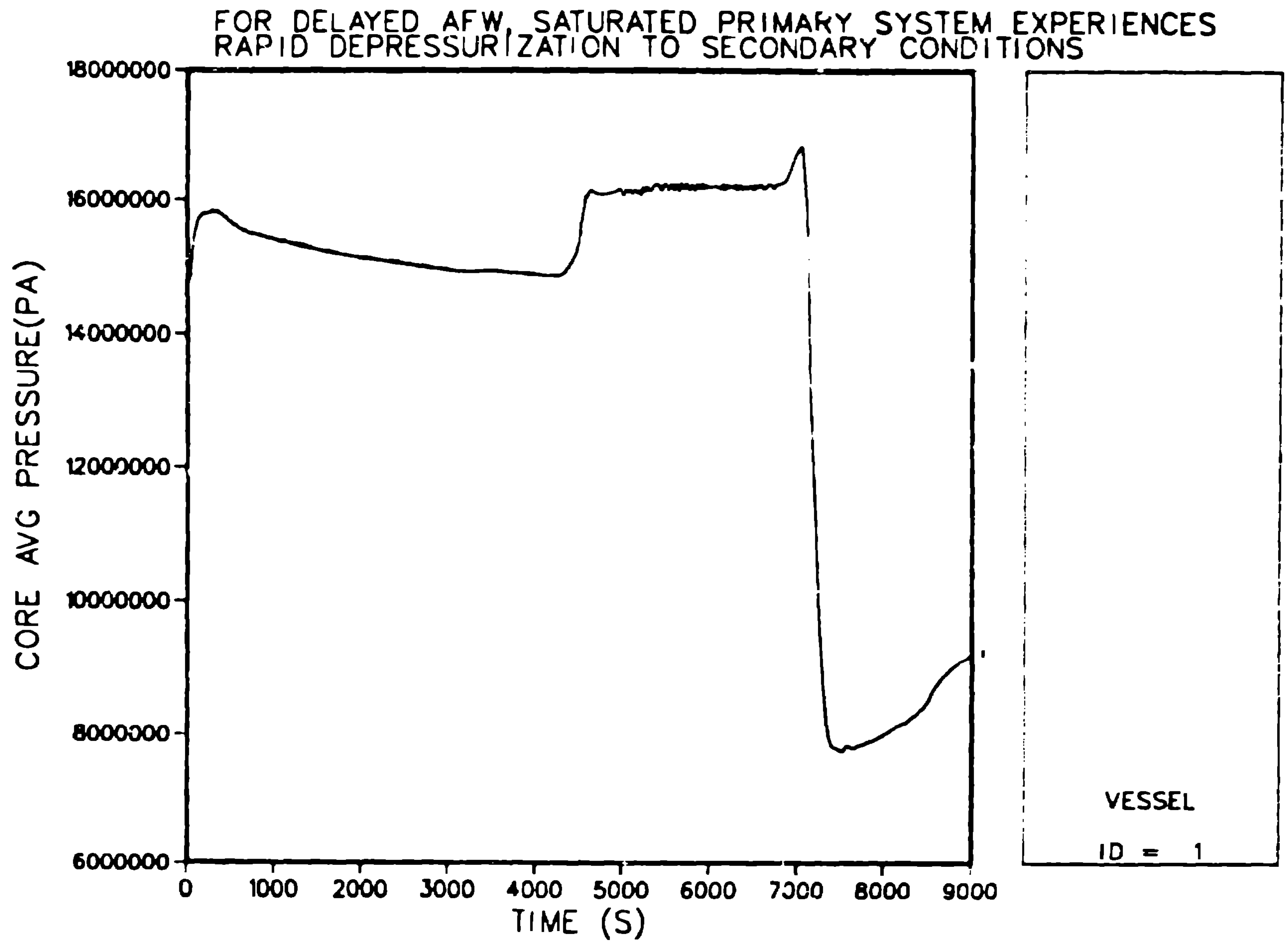

PRIMARY NATURAL CIRCULATION CONTINUES AFTER
SG DRYOUT; UP TO PRIMARY SYSTEM SATURATION
MASS FLOW-RATE (KG/S)
1600
1400
1200
1000
800
600
400
200
0
-200
0
2000
4000
6000
8000
10000
TIME (S)
CELL EDGE
1
PUMP
ID = 8

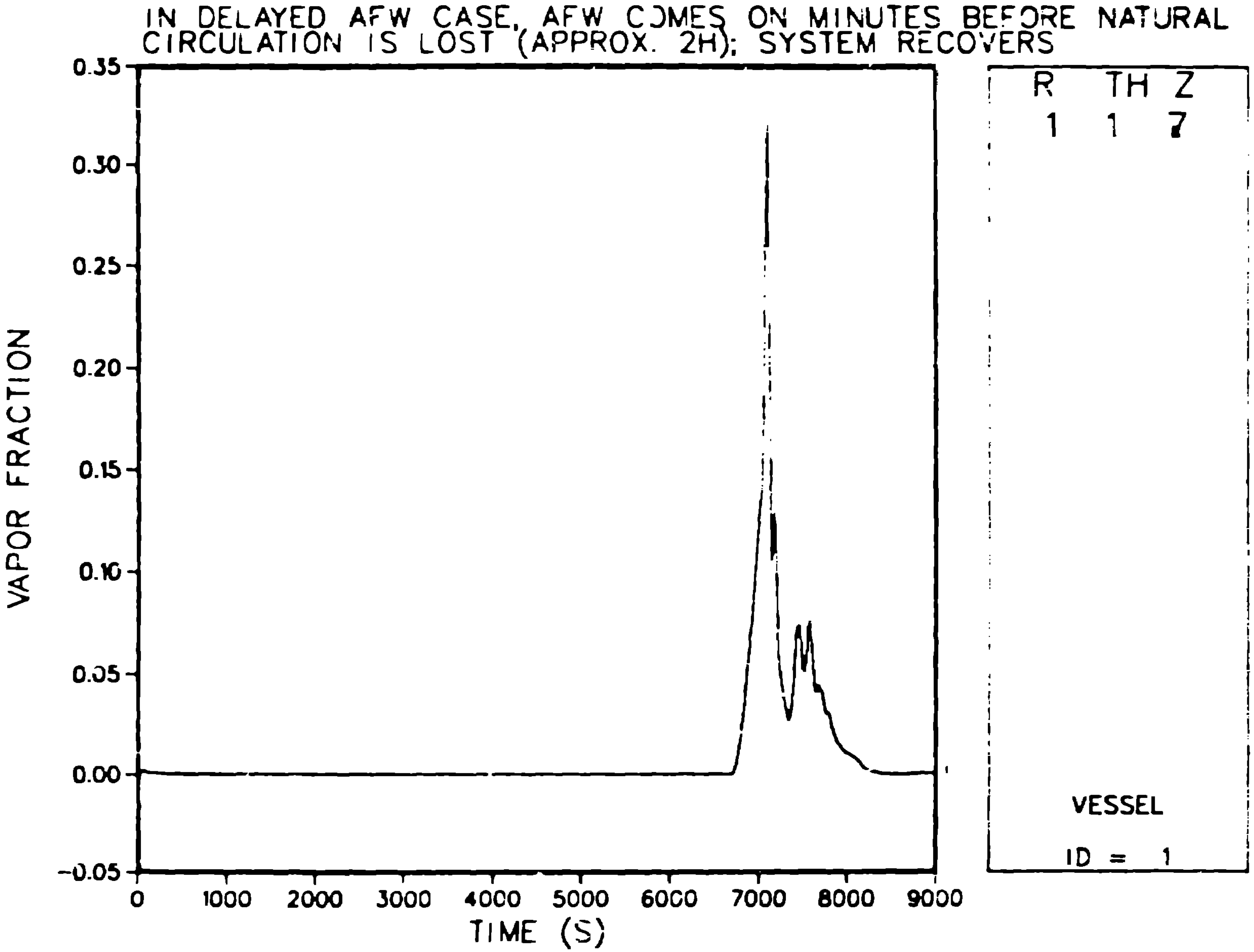
TRAC APPLIED TO SIMULATION OF ZION LOSS OF FEEDWATER SCENARIOS

LOFW CASES PRESENTED HERE:

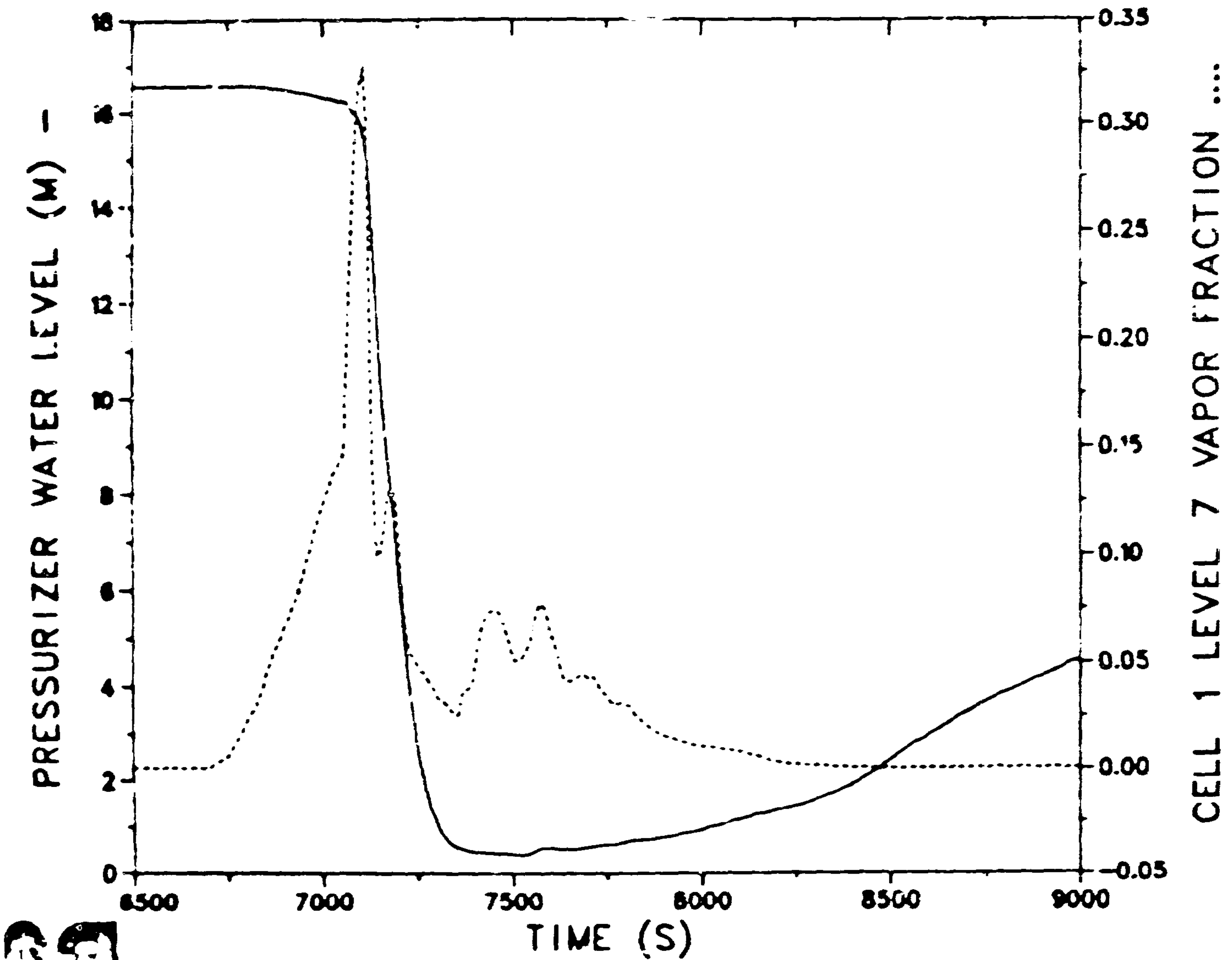
1. NOMINAL SCENARIO (0–3h)
2. DELAYED/DEGRADED AFW (0–10h)
3. STUCK-OPEN ARV (0–1h)
4. FEED/BLEED (0–4h)
5. ATWS (0–1h)

...USE ANALYSES TO FIND AND RESOLVE SPECIFIC SAFETY-RELATED CONCERNS.


FOR DELAYED AFW, SATURATED PRIMARY SYSTEM EXPERIENCES
RAPID DEPRESSURIZATION TO SECONDARY CONDITIONS
CORE AVG PRESSURE(PA)
18000000
16000000
14000000
12000000
10000000
8000000
6000000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
TIME (S)
VESSEL
ID = 1


IN DELAYED AFW CASE, AFW COMES ON MINUTES BEFORE NATURAL CIRCULATION IS LOST (APPROX. 2H); SYSTEM RECOVERS
VAPOR FRACTION
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
TIME (S)
R TH Z
1 1 7
VESSEL
ID = 1

RAPID SYSTEM DEPRESSURIZATION CAUSES PRESSURIZER WATER TO FALL INTO PRIMARY SYSTEM AND REFILL UPPER PLENUM



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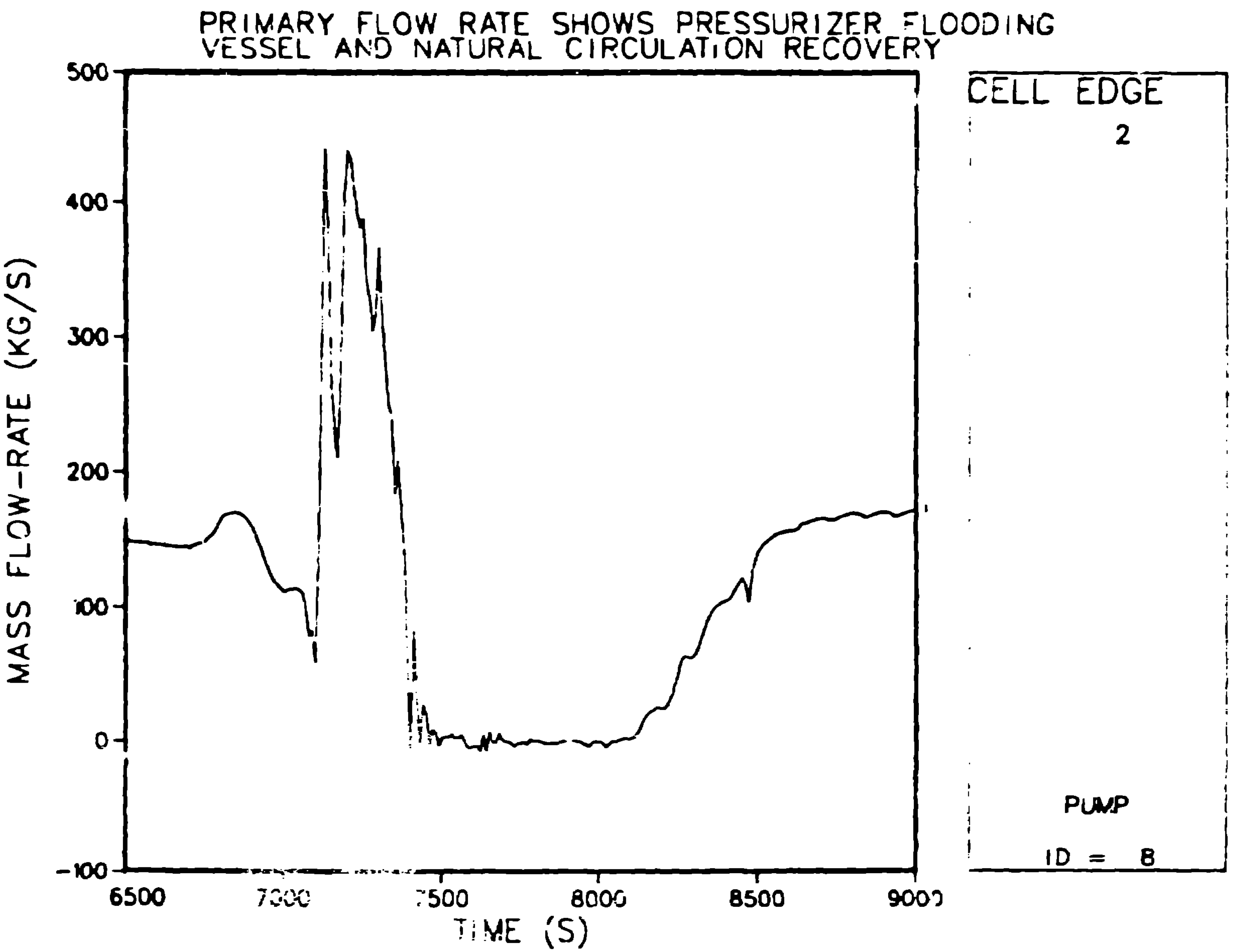


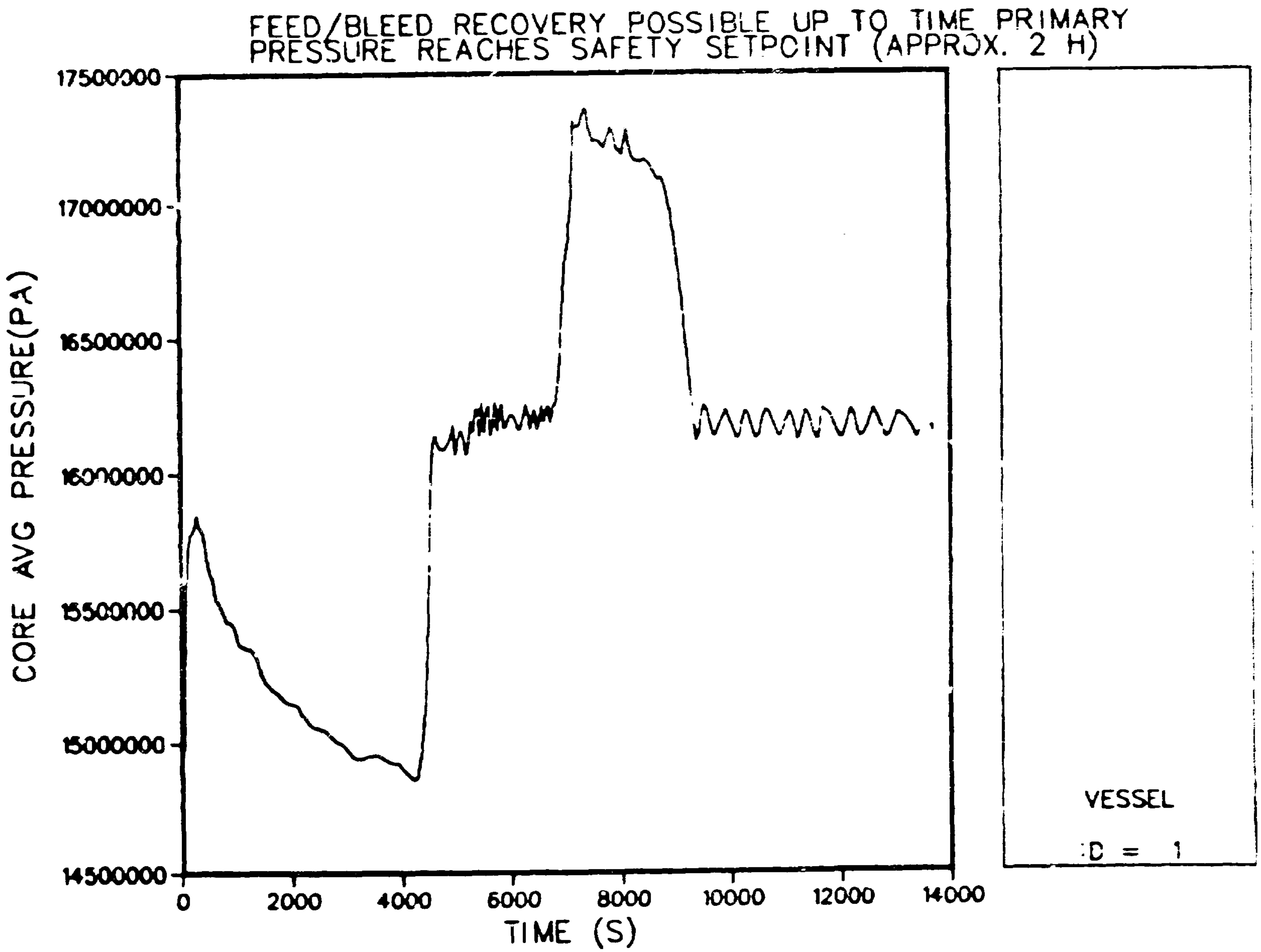
PRIMARY FLOW RATE SHOWS PRESSURIZER FLOODING
VESSEL AND NATURAL CIRCULATION RECOVERY
MASS FLOW-RATE (KG/S)
500
400
300
200
100
0
-100
6500
7000
7500
8000
8500
9000
TIME (S)
CELL EDGE
2
PUMP
ID = 8

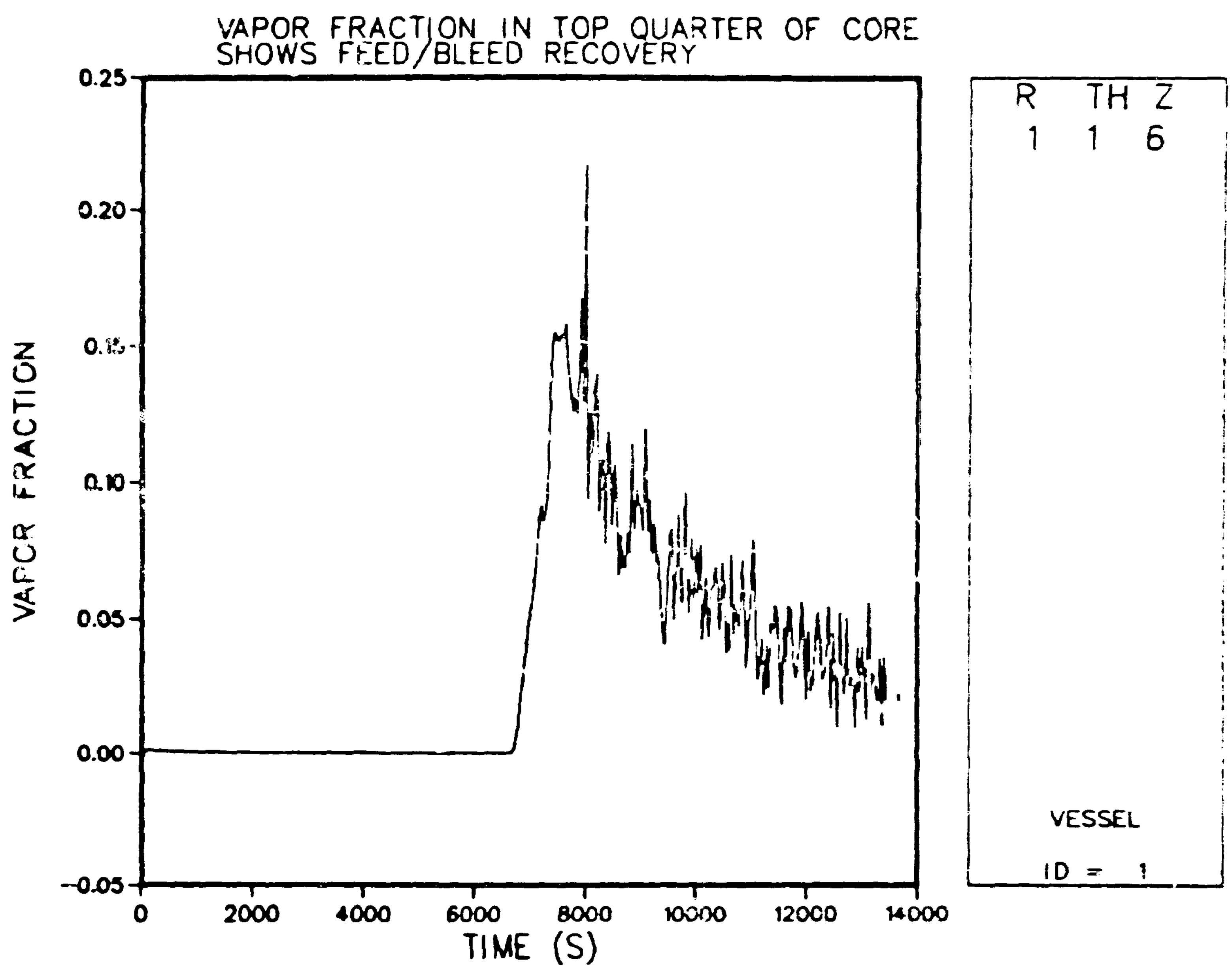
TRAC APPLIED TO SIMULATION OF ZION LOSS OF FEEDWATER SCENARIOS

LOFW CASES PRESENTED HERE:

1. NOMINAL SCENARIO (0–3h)
2. DELAYED/DEGRADED AFW (0–10h)
3. STUCK-OPEN ARV (0–1h)
4. FEED/BLEED (0–4h)
5. ATWS (0–1h)

...USE ANALYSES TO FIND AND RESOLVE SPECIFIC SAFETY-RELATED CONCERNS.


FEED/BLEED RECOVERY POSSIBLE UP TO TIME PRIMARY PRESSURE REACHES SAFETY SETPOINT (APPROX. 2 H)
CORE AVG PRESSURE(PA)
17500000
17000000
16500000
16000000
15500000
15000000
14500000
0
2000
4000
6000
8000
10000
12000
14000
TIME (S)
VESSEL
ID = 1


VAPOR FRACTION IN TOP QUARTER OF CORE
SHOWS FEED/BLEED RECOVERY
VAPOR FRACTION
TIME (S)
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
0
2000
4000
6000
8000
10000
12000
14000
R TH Z
1 1 6
VESSEL
ID = 1

FURTHER LOFW/ATWS CONSIDERATIONS FOUND IN ANALYSES

1. AFTER 80s AT FULL POWER, SGs DRY-OUT.
2. PORV/SAFETY WATER RELIEF STARTS AFTER ABOUT 20s AT FULL POWER.
3. AT ZION, STEAM RELIEF CAPACITY ADEQUATE IN ATWS - BUT WATER RELIEF MAY NOT BE.
4. REACTIVITY FEEDBACK MUST BE CONSIDERED.

∴ REQUIRES FURTHER STUDY.

LESSONS LEARNED IN BASE CASE TRAC SIMULATIONS OF ZION LOFW

1. APPROX. 1 h AVAILABLE FOR INITIATION OF NORMAL AFW RECOVERY.

2. APPROX. 2.5 h NEEDED BEFORE CLAD HEAT-UP BEGINS.

3. INITIATION OF AFW BEFORE NATURAL CIRCULATION LOSS LEADS TO RECOVERY.

4. 30 PERCENT OPERATION OF TURBINE AFW PUMP ADEQUATE FOR RECOVERY.

5. STEAM SIDE DEPRESSURIZATION MAY HAVE SIGNIFICANT REACTIVITY EFFECT.

6. FEED/BLEED RECOVERY POSSIBLE UP TO APPROX. 2 h INTO ACCIDENT.

7. SCRAM DELAY CAN CAUSE EARLY PORV/SAFETY OPENING, EARLIER SG DRY-OUT.

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