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WCAP-11916

OG-88-41

November 21, 1988

Mr. Marvin W. Hodges, Reactor Systems Branch Chief
Division of Engineering & System Technology
U.S. Nuclear Regulatory Commission
Mail Station PI-137
Washington, D.C. 20555

Subject: Westinghouse Owners Group
Information Transmittal of WCAP-11916,
"Loss of RHRS Cooling While the RCS is Partially Filled"

Dear Mr. Hodges:

Enclosed for your information and use are three copies of WCAP-11916, Rev. 0, "Loss of RHRS Cooling While the RCS is Partially Filled", dated July 1988. This report is the result of the Westinghouse Owners Group effort originally to provide each member utility with information which they could use in responding to the NRC Generic Letter 87-12, "Loss of Residual Heat Removal (RHR) While the Reactor Coolant System (RCS) is Partially Filled". The report specifically addressed Item 5 of GL-87-12. It will also be useful in responding to the more recent NRC Generic Letter 88-17, "Loss of Decay Heat Removal", which superceded GL-87-12.

The report describes the results of fluid systems evaluations performed to provide analytical information concerning the phenomena of air ingestion into the Residual Heat Removal System (RHRS) during mid-loop operations. In addition, thermal-hydraulic computer analyses were performed to predict Reactor Coolant System behavior following loss of RHR Cooling during mid-loop operations.

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This report provided the basis for a significant portion of the technical information that was presented at the Mid-Loop Operations Guidance Workshop held on September 21 and 22, 1988 in Pittsburgh. I wish to personally thank you and Warren Lyon for participating and helping in making it a successful workshop.

Very truly yours,

Roger A. Newton, Chairman
Westinghouse Owners Group

RAN/dac

enclosure

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0490G

WCAP-11916

LOSS OF RHRS COOLING WHILE THE RCS IS PARTIALLY FILLED

Revision 0

July 1988

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ABSTRACT

A fluid system evaluation was performed, to provide analytical information concerning the phenomena of air ingestion into the Residual Heat Removal System (RHRS) during mid-loop operations. In addition, thermal-hydraulic computer analyses were performed to predict reactor coolant system behavior following the loss of RHRS cooling during mid-loop operations.

Scale model testing was performed to obtain data relative to air ingestion and vortex formation at the RHRS inlet nozzle. This data was used along with plant operational data, to develop correlations for RCS level and RHR flow rate which will avoid air binding of the RHRS.

Thermal-hydraulic computer analyses were performed to predict the time to boiling, the RCS pressurization rate, and time to core uncovery following the loss of RHRS cooling during mid-loop operations. Various RCS configurations and conditions were modelled to cover the range expected for various maintenance and surveillance activities.

ACKNOWLEDGEMENTS

The co-operation of Consolidated Edison and Public Service of New Hamshire is acknowledged. These utilities shared results of mid-loop testing performed at Indian Point Unit 2 and Seabrook, to aid in industry understanding of this generic concern. In addition, several utilities provided operating data in response to the Owner's Group survey; this data was used to define model geometry and test conditions.

LOSS OF RHRS COOLING WHILE THE RCS IS PARTIALLY FILLED

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EXECUTIVE SUMMARY

Various maintenance and inspection activities performed on the reactor coolant system (e.g., steam generator tube inspections, RCS check valve inspections, RTD replacements) require the coolant level in the RCS to be lowered into the loop piping. The Residual Heat Removal System (RHRS), which is used to cool the reactor during this "mid-loop" operation, is susceptible to air ingestion/air binding if the level in the RCS drops too low. A number of loss of decay heat removal events have occurred as a result of air binding during mid-loop operations. One such event occurred at Diablo Canyon in April 1987 which prompted the NRC to issue Generic Letter 87-12, "Loss of Residual Heat Removal (RHR) while the Reactor Coolant System (RCS) is Partially Filled". The Generic Letter requested information from utilities in several areas related to mid-loop operation.

This report was written under the direction of the WOG Analysis Subcommittee, with additional guidance from the WOG Operations Subcommittee. Its purpose is to provide utilities with analytical information concerning the phenomena of air ingestion into the RHRS during mid-loop operations and analysis of RCS behavior following the loss of RHRS during mid-loop operations for utility use in responding to GL 87-12, Item 5.

In order to provide analytical data concerning the phenomena of air ingestion into the RCS, a fluid systems evaluation was performed utilizing scale model test data and plant operational data. In order to provide data relative to RCS behavior following the loss of RHR during mid-loop operations, thermal-hydraulic analyses were performed for various plant conditions and configurations.

Fluid Systems Evaluation

Scale model testing was performed to obtain data relative to air ingestion and vortex formation at the RHRS inlet nozzle. This data was used along with plant operational data, to develop correlations for RCS level and RHRS flow rate which will avoid air binding of the RHRS. The results of the fluid system evaluation are discussed in Section 1.2.1. In general the results indicate:

- o A specific relationship exists between air ingestion into the RHR system and Hot Leg level. The minimum conservative Hot Leg level that avoids air binding is identified for all WOG plants' RHR suction line configurations and sizes, as a function of RHRS flow rates.

- o The Hot Leg level is not accurately represented by level indications at other points within the RCS.

- o Once the suction line vortex is formed and significant air is ingested into the RHR piping, level must be increased and the RHR system must then be vented prior to RHR pump restart in order to restore sufficient RHR system performance.

These results and correlations can be used as input for plant operating procedures for mid-loop operations.

<u>Thermal-hydraulic Analyses</u>

Thermal-hydraulic analyses were performed to predict RCS behavior following the loss of RHRS cooling during mid-loop operations. The analyses predict the time to core boiling, the RCS pressurization rate, and the time to core uncovery for various RCS configurations. These configurations were chosen to model a range of RCS conditions that may exist for various maintenance and inspection activities. In addition to heatup and pressurization calculations, analyses were performed to investigate a number of recovery techniques. The analyses will help define RCS configuration constraints, minimum equipment availability, and other operational considerations to ensure a coolable core geometry. The results of the thermal-hydraulic analyses are described in Section 1.2.2. In general the results indicate:

- o For mid-loop operation prior to a typical refueling, the RCS would be expected to reach saturation in about 20 to 30 minutes. For more limiting conditions (shorter times after shutdown and higher initial RCS temperatures) the RCS could start to boil in less than 10 minutes.

- Once the core starts to boil, RCS behavior depends on the RCS configuration, i.e., the size and location of RCS openings, secondary side inventory, and status of nozzle dams and loop isolation valves (LIVs).

- If there are no RCS openings or the openings are small, the RCS will pressurize after boiling starts. RCS pressures can reach 400 psia in about one hour or more.

- If the RCS is open and the loops are not obstructed with SG nozzle dams or closed LIVs, air and boil-off steam can be vented. Following a possible initial spill of liquid or two-phase mixture, the water will boil-off, eventually leading to core uncovery if no actions are taken to restore inventory. The time to prolonged core uncovery following loss of RHR cooling exceeds 30 minutes for large cold side openings and typically exceeds one hour for hot side openings.

- Certain plant configurations, however, can lead to core uncovery several minutes after boiling starts. For these configurations where there is a large cold leg opening but the hot leg is isolated, hot leg or upper plenum injection is required to mitigate prolonged core uncovery.

- For each configuration studied, methods to restore RCS level and provide interim decay heat removal were identified.

The results of these thermal hydraulic analyses can be used as input to recovery procedures following the loss of RHRS cooling during mid-loop operations. Results can also be used in outage planning to define equipment requirements for different RCS configurations.

1.0 DESCRIPTION OF PLANT OPERATION WITH THE RCS LOOPS PARTIALLY FILLED

This section states the purpose of this report and provides guidance for its intended use by participating utilities. Program conclusions and recommendations are then presented. It also presents, as background necessary for an understanding of the evaluations presented in Chapters 2 and 3, a description of a typical newer vintage Residual Heat Removal System, the Standard Westinghouse Maintenance Instruction for Draining the Reactor Coolant System, and the Technical Specifications, (Rev. 5) associated with RCS loops partially filled (mid-loop) operations.

1.1 Purpose

On July 9, 1987 the Office of Nuclear Reactor Regulation issued Generic Letter 87-12 (Reference 1). The letter deals with concerns that the NRC has with operation of Pressurized Water Reactors (PWR) when the Reactor Coolant System (RCS) water level is below the top of the reactor vessel. The principle concerns expressed in the letter are: 1) whether the RHR System meets the licensing basis of the plant in this condition, 2) whether there is a resultant unanalyzed event that may have an impact upon safety and 3) whether any threat to safety that warrants further NRC attention exists in this condition. In order for the NRC to address these concerns the letter requested, pursuant to 10 CFR 50.54(f), that all licensees of operating PWRs and holders of construction permits for PWRs provide to the NRC a description of the operation of their plant when the water level is below the top of the reactor vessel.

Specifically required was a description of the plant operation during the approach to a partially filled RCS condition and during operation with a partially filled RCS to ensure that the plant meets its licensing basis. The letter provided guidance in the form of nine items which each utility is to address in its response. These items include requests for detailed plant specific information in the following areas while in or approaching plant operations with the RCS partially filled: 1) the draindown process circumstances and conditions, 2) instrumentation and alarms available, 3) pumps available to control NSSS inventory, 4) containment closure requirements, 5) control room procedures and analytical basis for them,

6) operator training, 7) additional personnel assignment, 8) modified plant conditions specific to operations with the RCS partially filled and 9) current changes related to operations with the RCS partially filled.

Each plant was requested to respond within 60 days of receipt of the Generic Letter. Additionally, the NRC stated that it would be acceptable for the utilities to provide a portion of its response in association with their industry owners group.

This report was written with the support of the Westinghouse Owner's Group (WOG). It provides an owners group response to portions of item 5 as requested in Generic Letter 87-12. The report provides generic information applicable to the fluid systems performance when the RCS is partially filled and thermal hydraulic analysis of the RCS following the loss of RHR during operations with the RCS loops partially filled. This information is presented based on categorization of plants by RHRS nozzle size and orientation for the fluid system performance and by the number of loops and rated thermal power to RCS volume ratio for the thermal hydraulic response. It is intended that the WOG plants participating in this program will be able to utilize the results of this report based on the categorization applicable to their particular plant.

1.2 Program Conclusions and Recommendations

This program included both a fluid system evaluation of the phenomena of air ingestion into the RHRS during partial loop operations as well as a thermal-hydraulic analysis of the RCS behavior following the loss of RHR cooling during partial loop operations. The conclusions and recommendations resulting from both of these efforts follow.

1.2.1 Fluid System Evaluation

A fluid system evaluation was performed to provide analytical information related to air ingestion into the RHRS resulting from vertex formation. The primary input was from scale model testing. This information was supplemented by previous testing and evaluations, plant operating experience, and in-plant testing. The evaluation resulted in the development of correlations for RCS hot leg levels and RHR flow rates to be used as guidelines for operations with the RCS partially filled. These correlations are based on limiting air entrainment to maintain acceptable RHR pump operation. The fluid systems evaluation is described in detail in Section 2.0 with the correlations applicable to all WOG plant's RHR suction configurations presented in Section 2.4.3. The conclusions and recommendations resulting from the fluid systems evaluation are as follows:

1. A specific relationship between air ingestion into the RHR System and hot leg level exists. The relationship is a function of RHR flowrate, with higher flowrates requiring higher hot leg levels to limit air ingestion. The relationship can be defined by a correlation of critical submergence depth (S_c) relative to the Froude number (F_r).

2. Plant operating and test data show that the correlations developed and presented in this report are both reasonable and conservative. However, the recommended operating limits are not intended to replace operating experience.

3. Operating at low RHRS intake flowrates during partial loop operations greatly reduces the risk of entraining air.

4. Once the suction line vortex is formed and significant air is ingested into the RHR, RCS level must be increased and the RHR system must be vented in order to restore sufficient RHR system performance. The best way to vent the system is to recover level and sweep entrained air from the system by operating the system at a relatively high flow rate.

5. Plant test data suggest that the first symptom of air entrainment is noise at the RHR pump. This is followed by a drop in suction pressure and finally by oscillations in suction pressure, flow rate or motor current. It is recommended, therefore, that RHR noise be monitored when entering into a level/flow combination with which the operating staff has limited experience.

6. Differences exist in RCS levels between active cold legs, inactive cold legs, active hot legs, and in inactive hot legs during partial loop operations. An active leg is defined as a loop in which a RHR pump either takes suction or discharges. The magnitude of the level differences is significant (on the order of 1-2 inches depending on flow rate).

1.2.2 Thermal-Hydraulic Analyses

Thermal-hydraulic computer analyses were performed to predict RCS behavior following the loss of RHRS cooling during mid-loop operations. The analyses predict the time to core boiling, the RCS pressurization rate, and the time to core uncovery for various RCS configurations. These configurations were chosen to model a range of RCS conditions that may exist for various maintenance and inspection activities. In addition to heatup and pressurization calculations, analyses were performed to investigate a number of recovery techniques. The analyses will help define RCS configuration constraints, minimum equipment availability, and other operational considerations to ensure a coolable core geometry. The thermal-hydraulic analyses are described in Section 3.0. The results and conclusions are discussed in detail in Section 3.11.

In general, the results indicate that for mid-loop operation prior to a typical refueling (5 days after reactor shutdown, RCS initial temperature less than 100°F), the RCS would be expected to reach saturation in about 20 to 30 minutes following the loss of RHR cooling. However, at more limiting conditions for mid-loop operation (e.g., 48 hours after shutdown, 140°F initial RCS temperature) the RCS could start to boil in less than 10 minutes. Once the core starts to boil, the RCS behavior depends on the number of parameters such as the time after shutdown and the RCS configuration.

Typical RCS configurations during mid-loop operations include: (1) An intact RCS, with no water in the secondary side of the SGs, (2) An intact RCS with water in the secondary side of the SGs, (3) A large opening or vent path on the hot leg side of the RCS, (4) A large opening on the cold leg side, with no loop obstructions (SG nozzle dams, loop isolation valves), (5) A large opening on the cold leg side, with loop obstructions. Section 3.11 describes these five configurations in more detail.

The RCS response for the different configurations varies:

1. If the RCS is intact and there is no water in the secondary side of the SGs, the RCS will pressurize after boiling starts and reach 400 psia in about 1 hour or more after loss of RHR cooling. Providing water to the secondary side for cooling can slow the pressurization rate significantly due to steam condensation in the SG tubes. For these configurations, interim cooling can be provided by bleed and feed with one high-pressure SI pump and one pressurizer PORV or by a secondary heat sink using half or more of the SGs.

2. If the RCS is open and the loops are not obstructed with SG nozzle dams or closed Loop Isolation Valves (LIVs), air and boil-off steam can be vented. Following a possible initial spill of liquid or two-phase mixture, the water will boil-off, eventually leading to a prolonged core uncovery if no action is taken to restore inventory. The time to reach core uncovery generally exceeds one hour if the opening is on the hot leg or upper plenum side of the RCS. For large cold leg openings, a prolonged core uncovery could start about 30 minutes following the loss of RHRS cooling.

3. The case of primary concern involves loss of RHR cooling when there is a large cold side opening and the loop with the opening is isolated. Under this postulated condition, the RCS will pressurize faster at the core exit than at the cold leg, once boiling starts. RCS inventory will then be forced out of the cold side opening at a rapid rate. Typically, the core will become uncovered within several minutes after the onset of boiling, i.e., as early as ten minutes following loss of RHR cooling. Because the SG nozzle dams (or closed loop isolation valves) do not allow a vent path to the opening, the core will remain uncovered for a prolonged period of

time unless actions are taken to restore RCS inventory in a timely manner. To avoid prolonged core uncovery for this scenario, it was found that hot leg injection using one or two high-pressure SI pumps would be effective in suppressing boiling and refilling the RCS.

If the cold side opening is an open SG manway, the scenario described above would be made less severe if the cold side nozzle dams are installed first and removed last. After the cold side dams are in place, however, there is still a potential for a rapid core uncovery if the RCS pressurizes and one of the cold side SG nozzle dams fails before a hot side dam fails. It is therefore recommended that the RCS level be raised above mid-loop after the nozzle dams are installed to minimize the potential for loss of RHR cooling under this configuration.

For each of the RCS configurations, the report identifies one or more methods for increasing RCS inventory following the loss of RHR cooling. Recovery actions include gravity feed from the RWST, normal charging, cold leg injection or hot leg injection. The recovery methods recommended depend to some extent on the RCS configuration. The five configurations described are not always mutually exclusive, so some evaluation may be required to determine which description best applies to a given situation. In the event RHR cooling cannot be easily restablished, at least one alternate mode of decay heat removal has also been identified to provide interim cooling until RHR cooling can be restablished.

1.3 Residual Heat Removal System Description

Figure 1-1 is a simplified flow diagram showing a typical newer RHR System design. The system consists of two parallel flow paths. Each path takes suction from a separate RCS hot leg. Each flow path contains a residual heat removal pump, a residual heat exchanger and associated piping, valves and instrumentation required for operational control.

During system operation, reactor coolant flows from the RCS to a residual heat removal pump, through the tube side of a residual heat exchanger, and back to the Reactor Coolant System through the Safety Injection (SIS) cold leg injection header. Heat is transferred from the reactor coolant to the component cooling water, which is circulating through the shell side of the residual heat exchangers.

A brief description of the operation of the RHR system during the different plant modes of operation is provided below.

Plant Startup

At the beginning of the plant startup, at least one residual heat removal pump is operating. The number of pumps and heat exchangers in service depends upon the residual heat load at the time. A portion of the RHR discharge may be directed to the Volume Control Tank (VCT) in the Chemical and Volume Control System (CVCS) for purification and/or letdown. The RCS has been completely filled (water-solid) at this time and the pressurizer heaters are energized. After a steam bubble is formed in the pressurizer the reactor coolant pressure and temperature are increased by utilizing Reactor Coolant Pump (RCP) heat. After the RCPs are started, the RHR pump is stopped and the RHRS is isolated from the RCS.

Normal Plant Operation

Normal operation includes the power generation and hot standby operation phases of plant operation when the RCS is at normal operating temperature and pressure. During normal operation the RHRS is not in service, but for most plants is aligned and ready for operation as part of the Emergency Core Cooling System (ECCS).

Plant Cooldown/Shutdown

When the reactor coolant temperature and pressure are reduced to approximately 350°F and 380 psig, following reactor shutdown, the RHRS is typically placed in operation.

Startup of the RHRS includes a warm-up period during which time reactor coolant flow through the heat exchangers is limited to minimize thermal shock to the heat exchangers. The rate of heat removal from the reactor coolant is controlled manually by regulating the reactor coolant flow through the residual heat exchangers. The total flow in the RHRS is regulated automatically by the heat exchanger bypass valves so as to maintain a constant return flow.

After the reactor coolant pressure has been reduced and the temperature is 140°F or lower, the RCS may be opened for refueling or maintenance. Depending upon the residual heat load, which decreases with time, one pump and its associated heat exchanger may be taken out of service.

Refueling

During refueling, the residual heat removal loop is maintained in service with the number of pumps and heat exchangers in operation as required by the heat load and fuel movement.

1.4 Partial RCS Loop Operation and FSAR Commitments

Many plants discuss operation with the reactor coolant loops partially filled. An abridged description of the type of information provided in the FSAR (Reference 2) for a plant having a typical, newer, RHR System design is presented below.

During partial drain operations of the RCS, adequate RCS inventory, level control, and Net Positive Suction Head (NPSH) must be maintained. If it is required that the RCS water level be lowered to drain the steam generator tubes, the residual heat removal flow rate through each of the RHRS loops should be throttled back to prevent vortexing and possible air entrainment of the pumps. Draining is to the point where the indicated level is stable and maintained above a predetermined point (usually at the elevation of the center of the reactor vessel nozzles). At this point, reactor coolant level is monitored continuously to assure that the RHRS inlet lines do not become uncovered. Inventory makeup, if required, is accomplished via the CVCS centrifugal charging pumps.

Should a RHRS inlet line become uncovered, air may be drawn into the suction piping and entrained in the fluid. Factors which minimize the effects of air entrainment on pump performance are as follows:

1. The location of the residual heat removal pumps provides positive head on the pump inlet, and

2. The circulation flow rate is kept low and unnecessary circulation of fluid is avoided (i.e., minimum flow required for core decay heat removal and boron mixing is maintained).

Provisions have been made to minimize the effects of air entrainment. However, should such an event preclude the continued use of the operating train, actions need to be taken to permit the utilization of the alternate train by providing sufficient refill/makeup from the CVCS/charging pumps.

Provisions are incorporated to ensure rapid restoration of the RHRS to service in the event that the RHRS pumps become air bound. On identifying this situation, the affected train would be isolated, the reason for the loss of RHR would be identified and corrected, and heat removal accomplished by the redundant train.

Procedures have been developed to address the provision of alternate sources of cooling should loss of RHR cooling occur during shutdown maintenance evolutions. These provisions consider maintenance evolutions during which more than one cooling system may be unavailable, such as loss of steam generators when the RCS has been partially drained for steam generator inspection or maintenance.

1.5 Draining the Reactor Coolant System

Westinghouse provides General Operating Instructions for Nuclear Steam Supply Systems. Included is an instruction for "Draining the Reactor Coolant System." This instruction generally forms the basis for the plant's operating instruction. An abridged description of the Westinghouse provided General Operating Instruction (Reference 3) for a plant having a typical newer RHR System design is presented below.

1.5.1 Westinghouse Maintenance Instruction: DRAINING THE REACTOR COOLANT SYSTEM

Purpose

This instruction describes the lowering of the reactor coolant level in the RCS for maintenance prior to removing the reactor vessel head for refueling.

Initial Conditions

1. The RCS is in cold shutdown conditions, the temperature of the coolant is set at or below 140°F and the pressurizer is completely filled with coolant. Degassing and purification have been completed.

2. The RHRS is in operation.

3. The Waste Gas Handling System is in operation.

4. A plastic hose has been connected between the pressurizer and the pressurizer relief line vent connections.

5. A 5 to 8 psig nitrogen blanket is being maintained on the pressurizer from the Pressurizer Relief Tank (PRT) through the pressurizer relief vent line.

6. The steam generators are in wet layup.

7. The charging pumps are stopped, letdown orifice isolation valves are closed and the RCP No. 1 seal leakoff valves are closed.

8. The Safety Injection pumps are locked out and the accumulator isolation valves are closed with power removed.

Instructions

1. A nitrogen gas cylinder is attached to the reactor vessel head vent connection.

2. Open both pressurizer spray valves to the full open position.

3. Set the pressurizer relief tank nitrogen regulator to makeup at pressure of 0.5 psig or less.

4. Line up the Reactor Coolant Drain Tank (RCDT) pumps to transfer coolant to the Recycle Holdup Tanks (RHT).

5. Begin draining the reactor coolant to the drain pumps by opening the manual valves in the drain line from one of the reactor coolant loops.

6. Attach a tygon hose to the connection on the drain line of reactor coolant loop 2. Extend the hose at least two feet above the top of the pressurizer.

7. Before the indicated pressurizer water level reaches the bottom of the instrument range, stop draining and place the tygon hose indicator in service by opening the manual isolation valves.

8. If the RCS is to be opened, close the pressurizer relief line vent valve and remove the tygon hose from the pressurizer to open the pressurizer vent to the containment atmosphere.

9. Re-establish the drain operation and drain slowly until the tygon level indicator shows the water level to be at about the top of the reactor vessel head. Then stop the drain operation.

NOTE: If draining is from the loop connected to the tygon hose level indicator, the draining operation should be stopped when it is desired to obtain an accurate level reading. If draining is from the reactor coolant loop not connected to the tygon hose, proper communication should be established to coordinate the draining operation with the level indication.

10. Close the loop drain valve and open the reactor vessel head vent to slowly admit nitrogen, verify that the water level is indicated to have been forced back into the pressurizer by the nitrogen added to the vessel head.

11. Close the reactor vessel head vent valve and remove the nitrogen cylinder.

12. Re-establish the drain operation and continue to drain slowly until the indicated level on the tygon hose indicator is again at about the top of the reactor vessel head. Then slowly open the reactor vessel head vent valve.

NOTE: Only after the reactor vessel has been vented to the atmosphere will the tygon hose level indicator show the true water level in the reactor vessel.

13. Continue to drain slowly with the head vent open to admit air until the water level is about four inches below the reactor vessel flange.

14. Stop the draining and close the reactor coolant loop drain valves.

NOTE: If maintenance requires that the water level be lowered to the point where gas could enter the reactor coolant piping from the pressurizer surge line, close the regulator and the manual isolation valve in the nitrogen supply line to the PRT, close the vent valve on the relief line and replace the blank flange and open the pressurizer vent to the containment atmosphere.

15. If it is required that the water level be lowered to drain the steam generator tubes, throttle the residual heat removal flow rate, including manual control of the bypass flow, to about [1000 gpm] through each of the residual heat removal loops.

16. Re-establish the drain operation and begin to lower the water level in the reactor vessel. As the level reaches the reactor vessel nozzles, coolant will begin to drain from the steam generator tubes in slugs causing erratic level indication. Stop the draining periodically to allow the water level in the system to stabilize.

17. Continue to drain until the indicated level is stable and at the elevation of the center of the reactor vessel nozzles.

18. Stop the drain operation and close the drain valves.

CAUTION: Monitor the water level continuously to assure the RHR System inlet lines do not become uncovered and gas bind the RHR pumps or that the reactor coolant pipes do not become refilled back into the steam generators.

1.6 Technical Specifications Associated with RCS Loops Partially Filled Operations

The "Standard Technical Specifications for Westinghouse Pressurized Water Reactors", NUREG-0452, Draft Revision 5, is the basis for the plant specific technical specifications for the typical, newer RHR System design. A brief description of the technical specifications found in the NUREG, Draft Revision 5, associated with RCS loops partially filled operations is presented below.

The following specifications are considered to be germaine and each will be commented on.

3/4.1.2.3	CHARGING PUMP - SHUTDOWN
3/4.1.2.5	BORATED WATER SOURCE - SHUTDOWN
3/4.3.2	ENGINEERED SAFETY FEATURES ACTUATION SYSTEM INSTRUMENTATION
3/4.4.1.4.2	COLD SHUTDOWN - LOOPS NOT FILLED
3/4.9.8.2	REFUELING OPERATIONS - LOW WATER LEVEL

Two specifications, 3/4.4.1.4.2 (Figure 1-2) and 3/4.9.8.2 (Figure 1-3), specifically address RCS operations with the loops not filled and place limitations on RHRS flow.

Specification 3/4.4.1.4.2, REACTOR COOLANT SYSTEM - COLD SHUTDOWN - LOOPS NOT FILLED, requires as a Limiting Condition for Operation (LCO) that "Two residual heat removal (RHR) loops shall be OPERABLE* and at least one RHR loop shall be in operation** when in Mode 5 with the reactor coolant loops not filled. The operation of the RHR loop is demonstrated by Surveillance Requirement 4.1.4.2 which states "At least one RHR loop shall be determined to be in operation and circulating reactor coolant at least once per 12 hours." It should be noted that there is no minimum flow requirement stated for this surveillance requirement. Plants generally use the minimum flow specified in surveillance requirement 4.9.8.2 which is applicable in Mode 6 or the FSAR stated values for midloop operation.

Specification 3/4.9.8.2, REFUELING OPERATIONS - LOW WATER LEVEL, requires as a LCO that "Two independent residual heat removal (RHR) loops shall be OPERABLE, and at least one RHR loop shall be in operation *" when in MODE 6, when the water level above the top of the reactor vessel flange is less than 23 feet. The operation of the RHR loop is demonstrated by Surveillance Requirement 4.9.8.2 which states "At least one RHR loop shall be verified in operation and circulating reactor coolant at a flow rate of greater than or equal to [2800] gpm at least once per 12 hours." It should be noted that this particular Surveillance requirement as written does not allow reduced flow rates in Mode 6 to prevent vortexing and possible air entrainment.

The required RHR flow is a function of many factors including the time after shutdown, boron dilution and stratification concerns, level in the refueling cavity, RCS pressure and temperature, and the level of the reactor coolant in the loops when the RCS is partially drained. No one flow requirement applies to all the possible RHR configurations. Chapter 2 of this report provides specific guidance on minimum RHR flows to prevent vortexing and possible air entrainment while still providing adequate decay heat removal.

Both specifications require OPERABILITY to be determined consistent with the definition supplied in Section 1.18. Additionally, both specifications allow for removal of RHR loops from operation for short periods of time for performance of CORE ALTERATIONS or surveillance testing provided no operations are permitted that would cause dilution of the RCS boron concentration and core outlet temperature is maintained at least 10°F below saturation temperature.

Several specifications place Limiting Conditions for Operation on equipment which could be used to mitigate the consequences of a loss of RHRS cooling while the RCS is partially filled. These specifications deal with charging pumps, borated water sources, and Engineered Safety Features Actuation Systems (ESFAS).

Specification 3/4.1.2.3 (Figure 1-4), REACTIVITY CONTROL SYSTEMS - CHARGING PUMPS - SHUTDOWN, requires as a LCO that "One charging pump in the boron injection flow path required by specification 3.1.2.1 shall be OPERABLE and capable of being powered from an OPERABLE emergency power source" when in Modes 5 and 6. This specification and Specification 3.5.3 (Figure 1-5), Emergency Core Cooling Systems, which requires locking out all but one charging and safety injection pump limits the available ECCS pumps to mitigate or recover from a loss of RHRS cooling.

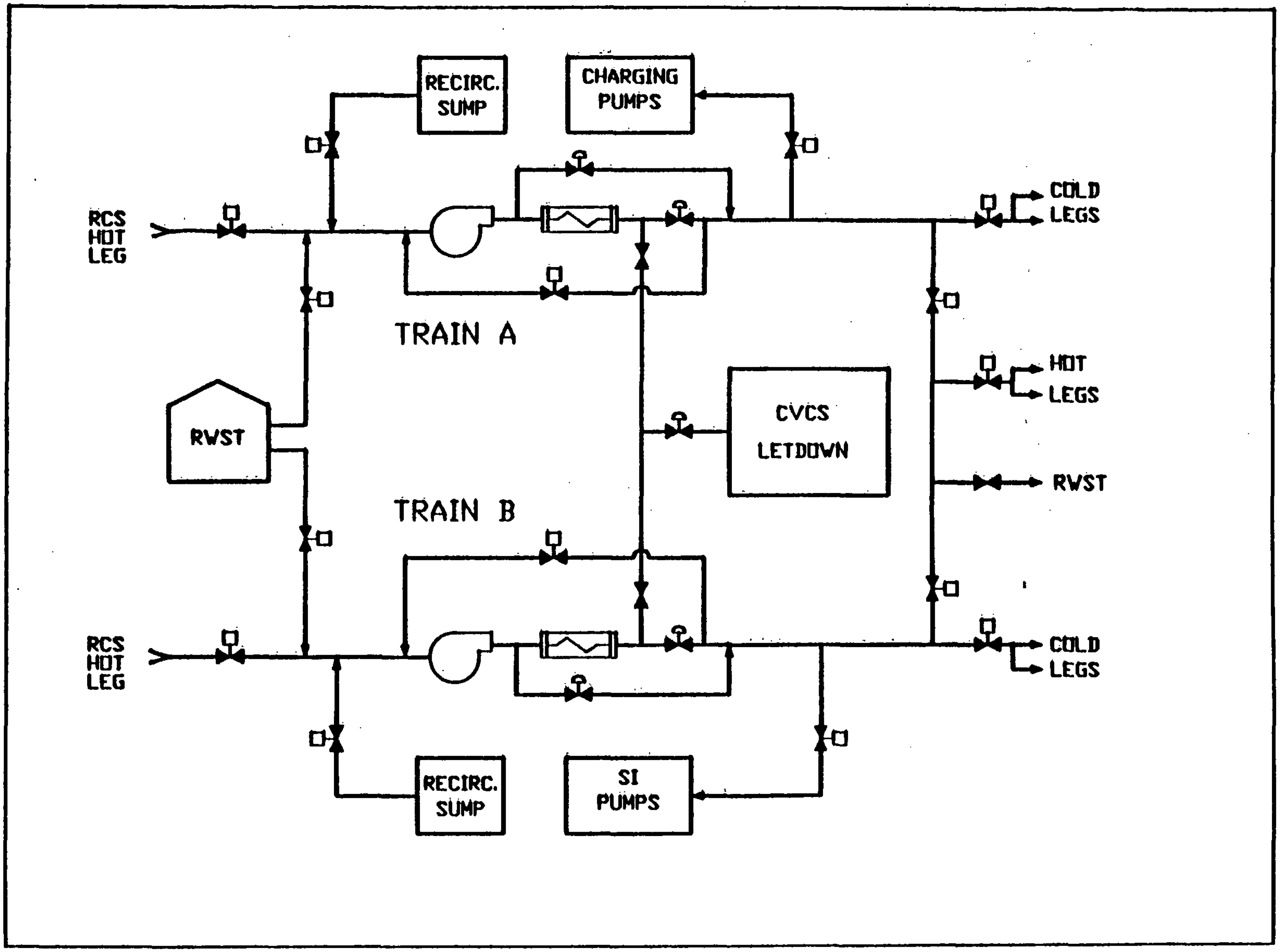

Figure 1-1. Simplified Typical Residual Heat Removal System

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REACTOR COOLANT SYSTEM

COLD SHUTDOWN - LOOPS NOT FILLED

LIMITING CONDITION FOR OPERATION

3.4.1.4.2 Two residual heat removal (RHR) loops shall be OPERABLE* and at least one RHR loop shall be in operation.**

APPLICABILITY: MODE 5 with reactor coolant loops not filled.

ACTION:

a. With less than the above required RHR loops OPERABLE, immediately initiate corrective action to return the required RHR loops to OPERABLE status as soon as possible.

b. With no RHR loop in operation, suspend all operations involving a reduction in boron concentration of the Reactor Coolant System and immediately initiate corrective action to return the required RHR loop to operation.

SURVEILLANCE REQUIREMENTS

4.4.1.4.2 At least one RHR loop shall be determined to be in operation and circulating reactor coolant at least once per 12 hours.

*One RHR loop may be inoperable for up to 2 hours for surveillance testing provided the other RHR loop is OPERABLE and in operation.

**The RHR pump may be deenergized for up to 1 hour provided: (1) no operations are permitted that would cause dilution of the Reactor Coolant System boron concentration, and (2) core outlet temperature is maintained at least 10°F below saturation temperature.

W-STS 3/4 4-6

Figure 1-2. Technical Specification 3/4.4.1.4.2

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LOW WATER LEVEL

LIMITING CONDITION FOR OPERATION

3.9.8.2 Two independent residual heat removal (RHR) loops shall be OPERABLE, and at least one RHR loop shall be in operation.*

APPLICABILITY: MODE 6, when the water level above the top of the reactor vessel flange is less than 23 feet.

ACTION:

a. With less than the required RHR loops OPERABLE, immediately initiate corrective action to return the required RHR loops to OPERABLE status, or to establish greater than or equal to 23 feet of water above the reactor vessel flange, as soon as possible.

b. With no RHR loop in operation, suspend all operations involving a reduction in boron concentration of the Reactor Coolant System and immediately initiate corrective action to return the required RHR loop to operation. Close all containment penetrations providing direct access from the containment atmosphere to the outside atmosphere within 4 hours.

SURVEILLANCE REQUIREMENTS

4.9.8.2 At least one RHR loop shall be verified in operation and circulating reactor coolant at a flow rate of greater than or equal to [2800] gpm at least once per 12 hours.

*Prior to initial criticality, the RHR loop may be removed from operation for up to 1 hour per 8-hour period during the performance of CORE ALTERATIONS in the vicinity of the reactor vessel hot legs.

Figure 1-3. Technical Specification 3/4.9.8.2

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REACTIVITY CONTROL SYSTEMS

CHARGING PUMP - SHUTDOWN

LIMITING CONDITION FOR OPERATION

3.1.2.3 One charging pump in the boron injection flow path required by Specification [3.1.2.1] shall be OPERABLE and capable of being powered from an OPERABLE emergency power source.

APPLICABILITY: MODES 5 and 6.

ACTION:

With no charging pump OPERABLE or capable of being powered from an OPERABLE emergency power source, suspend all operations involving CORE ALTERATIONS or positive reactivity changes.

SURVEILLANCE REQUIREMENTS

4.1.2.3.1 The above required charging pump shall be demonstrated OPERABLE by verifying, on recirculation flow, that a differential pressure across the pump of greater than or equal to ____ psid is developed when tested pursuant to Specification 4.0.5.

4.1.2.3.2 All charging pumps, excluding the above required OPERABLE pump, shall be demonstrated inoperable at least once per 31 days, except when the reactor vessel head is removed, by verifying that the motor circuit breakers are secured in the open position.

Figure 1-4. Technical Specification 3/4.1.2.3

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3/4.5.3 ECCS SUBSYSTEMS - T_{avg} LESS THAN 350°F

LIMITING CONDITION FOR OPERATION

3.5.3 As a minimum, one ECCS subsystem comprised of the following shall be OPERABLE:

a. One OPERABLE centrifugal charging pump,*

b. One OPERABLE RHR heat exchanger,

c. One OPERABLE RHR pump, and

d. An OPERABLE flow path capable of taking suction from the refueling water storage tank upon being manually realigned and transferring suction to the containment sump during the recirculation phase of operation.

APPLICABILITY: MODE 4.

ACTION:

a. With no ECCS subsystem OPERABLE because of the inoperability of either the centrifugal charging pump or the flow path from the refueling water storage tank, restore at least one ECCS subsystem to OPERABLE status within 1 hour or be in COLD SHUTDOWN within the next 20 hours.

b. With no ECCS subsystem OPERABLE because of the inoperability of either the residual heat removal heat exchanger or RHR pump, restore at least one ECCS subsystem to OPERABLE status or maintain the Reactor Coolant System T_{avg} less than 350°F by use of alternate heat removal methods.

c. In the event the ECCS is actuated and injects water into the Reactor Coolant System, a Special Report shall be prepared and submitted to the Commission pursuant to Specification 6.9.2 within 90 days describing the circumstances of the actuation and the total accumulated actuation cycles to date. The current value of the usage factor for each affected Safety Injection nozzle shall be provided in this Special Report whenever its value exceeds 0.70.

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* A maximum of one centrifugal charging pump and one Safety Injection pump shall be OPERABLE whenever the temperature of one or more of the RCS cold legs is less than or equal to [275]°F.

Figure 1-5. Technical Specification 3/4.5.3 (Sheet 1 of 2)

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EMERGENCY CORE COOLING SYSTEMS

SURVEILLANCE REQUIREMENTS

4.5.3.1 The ECCS subsystem shall be demonstrated OPERABLE per the applicable requirements of Specification 4.5.2.

4.5.3.2 All charging pumps and Safety Injection pumps, except the above allowed OPERABLE pumps, shall be demonstrated inoperable by verifying that the motor circuit breakers are secured in the open position at least once per 12 hours whenever the temperature of one or more of the RCS cold legs is less than or equal to [275]°F.

Figure 1-5. Technical Specification 3/4.5.3 (Sheet 2 of 2)

2.0 EVALUATION OF AIR ENTRAINMENT POTENTIAL AT VARIOUS RCS LEVELS AND RHRS FLOW RATES

2.1 Introduction

This Section contains the results of various tests and investigations related to air entrainment into the RHRS resulting from vortex formation. The primary input was obtained from scale model testing conducted in December 1987. This information was supplemented by previous testing and evaluations, plant operating experience, and in-plant tests.

Originally, the design of the RCS and RHRS on Westinghouse plants assumed that the RCS water level would always be at or above the reactor vessel flange. In addition, loop isolation valves were supplied to allow draining of part of the RCS while keeping higher water level in the reactor vessel. Subsequently, inspection and maintenance requirements became more stringent. This required that the entire RCS water level be lowered into the loop piping at certain times. The RCS/RHRS interface considers this requirement in establishing preferred RHRS inlet nozzle orientation. Reference operating instructions were also developed to provide guidance for drained-down operation.

Most plants have the RHRS inlet nozzle located at 45° below the horizontal (see Section 2.3 for a detailed listing of all plants' nozzle orientation). The bases for this location are:

a) The amount of crud that collects and is transported through the RHRS is reduced, as opposed to a bottom mounted nozzle.

b) If an unisolable leak occurred in the RHRS inlet pipe, some water would be retained in the loops, even without makeup.

c) It was judged that vortex formation and consequential air entrainment would be less likely with an offset orientation.

These reasons were based on engineering judgement. The results contained herein now provide quantitative information for each plants' configuration regarding item c.

2.2 Background

The sensitivity of air entrainment on RHR pumps to RCS level and pump flow has long been recognized. References 4) through 6) contain examples and discussions of various past events related to loss of RHR capability, including inadequate RCS level. Based on operating experience, many plants have developed guidelines regarding required level for various RHR flows. These limits were typically established from existing plant instrumentation (e.g., RHR pump motor current fluctuations) and operating experience.

The temporary loss of RHR at Diablo Canyon in April, 1987 intensified regulatory and industry attention on various aspects of RHRS operation, including RCS level and RHR flow effects with respect to air entrainment. Recent NRC concerns have been addressed in References 7) through 9).

Prior to initiation of this WOG program, several studies of RCS level and RHR flow were performed. Westinghouse performed a scale model test for one RHR nozzle size/orientation (equivalent to 12" and 45°). While the relation of RCS level versus RHR flow was based on qualitative observations of vortex formation and air-entrainment, this test served as a guideline in providing input to a number of utilities, and in establishing the WOG test program.

In addition, a Westinghouse Licensee (Mitsubishi Heavy Industries) performed scale model tests for one configuration (equivalent to 8" and 45°). This test was initiated in response to a RHR pump failure at Genkai Unit 1, which was believed to be related to air entrainment. Their results are contained in Reference 10), and are included in the generation of conclusions and operating limits contained in Section 2.5 of this report.

b. Radial Reynolds Number (R): The radial Reynolds number accounts for viscosity effects and is defined

$$R = \frac{\pi}{2} \times \frac{V\, d}{\nu}$$

Where ν is the liquid kinematic viscosity and V and d are as previously defined.

c. Weber Number (W_S): The Weber Number is the product of density (ρ), velocity squared and intake diameter divided by surface tension (σ).

$$W_S = \frac{\rho V^2 d}{\sigma}$$

The Weber Number models the effect of surface tension on vortex formation.

d. Relative Submergence: This is the ratio of submergence depth (s) to outlet nozzle diameter (d), and is used as a reference parameter to which the other dimensionless numbers are equalized. Submergence depth is the height of the fluid above the top of the intake nozzle. Refer to Figure 2-1.

References 11) and 12) contains a discussion on the importance of R and W_S in vortex modeling. It is concluded that for $R > 5 \times 10^4$, viscosity effects are negligible, and for $W_S > 120$, surface tension effects are negligible. The following lists the range of test values for R and W_S, and corresponding typical plant values.

	Test	Plant
R	$> 6 \times 10^4$	$> 32 \times 10^4$
W_S	200-2000	> 3400

As part of this program, a literature search was conducted. While a significant body of literature exists regarding vortex formation, almost all work is related to flow out of tanks, usually with bottom mounted connections. Some applicability was found in Reference 11), particularly with respect to horizontal nozzles. A complete list of all literature reviewed is contained in Appendix A.

The WOG test facility was constructed and tests were performed at OMNI Services, Inc. in East Pittsburgh, PA. A detailed description of the test facility is contained in Appendix B. Note that the bases for scaling the RCS/RHRS interface are contained in Section 2.3. The instrumentation used for these tests is also listed in Appendix B, and the calibration of this instrumentation is discussed in Appendix C. Note that a void fraction meter was used to measure air entrainment. A detailed description of this meter, its principle of operation, and the calibration is contained in Appendix D.

Note that this test specifically addresses the relation of level and flow to air entrainment. However, certain other related phenomena were observed during the course of testing (e.g., RCS level depression). These observations are included in Section 2.5.

2.3 Test Description

In order to accurately model the RCS to RHRS interface for vortex evaluation, dimensional analyses were reviewed to determine which dimensionless parameters were important. References 11) and 12) indicate that the following parameters are important when studying vortex formation:

a. Froude Number (F_R): The Froude Number equals the hotleg outlet pipe (RHR nozzle) velocity (V) divided by the square root of the gravitational constant (g) times pipe inside diameter (d).

$$F_R = V/(g \cdot d)^{1/2}$$

Both plant and test values of W_S and R are large enough to ensure that liquid surface tension and viscosity will not significantly effect vortex formation. Therefore, it is not necessary to account for the fact that test and plant values of W_S and R are different since the effect of these parameters is insignificant.

The test model size was then determined based on the capability of obtaining Froude Numbers corresponding to those which occur in plants. To determine the range of values to use, plant operating data (flow rate and level) and geometric data (nozzle size and orientation) were required. Table 2.1 contains the categorization of plant geometry. Table 2.2 contains a list of plant data, with F_R value included. From this table, a range of F_R from 0.4 to 4.1 exists when the RCS is drained down.

A categorization of plants by RHRS geometry was done to insure that all plants would be enveloped by the scaling, and to choose which categories would be scaled explicitly. (Note that it was decided not to prepare a test model for each plant, in order to limit test costs.) Table 2.3 contains this summary of information (combining Table 2.1 and 2.2). From the data contained in Tables 2.2 and 2.3, test configurations as listed in Table 2.4 were selected. Table 2.5 provides a comparison of plant categories and corresponding tests. For plants not explicitly modeled, their configuration (orientation and size) was bounded above and below by scaled data for other correlations. The test data was extrapolated to these plants.

The test was based on Froude scaling; i.e., test parameters were correlated with plant parameters such that the Froude numbers would be equal under corresponding operating conditions. As noted above, no corrections were made for differences between plant and the test values of W_S and R since these parameters do not play a significant role in vortex formation within the ranges of interest. This conclusion is valid as long as the geometric scale ratio between model and plant does not exceed a 1:4 ratio. On this basis, a 7" (ID) model hot leg was chosen. The model RHR suction line sizes were chosen to maintain a 7:29 geometric ratio between test and plant. It is noted that the length of RCS model hot leg pipe was selected to facilitate construction, and does not necessarily model plant layout. The remaining portions of the test loop were designed to obtain required test conditions. The test system design is described in Appendix B.

2.4 Test Results

2.4.1 Test Method

The RHR intake configurations which were tested are summarized in Table 2.3. Each configuration was tested over a range of intake flow rates which bounded expected plant operating conditions. For each intake flow rate, several runs were performed at different water levels. Test runs were typically 3 minutes to 5 minutes in duration during which time the following data were recorded:

a. Intake Flow Rate
b. Tank Water Level
c. Loop (Model Hot Leg) Water Level (3 Locations)
d. Water Temperature
e. Pump Suction Pressure
f. Pump Discharge Pressure
g. Intake Liquid Fraction was Continuously Recorded During the Test Run

2.4.2 Data Analysis

The dimensionless parameters: s/d (relative submergence), F_r (Froude Number), and α (intake air fraction) were calculated from the recorded data. Refer to Figure 2-1 for a schematic representation of geometric relations. Based on Reference 12, it was anticipated that the relation between dimensionless parameters would be of the form

$$\frac{S_c}{d} = a\,F_r^{\,b}$$

where S_c is the critical submergence level and a and b are parameters which depend on the intake geometry. Critical submergence is defined as the water level (relative to top of the intake) at which a vortex just tends to entrain air into the intake. A more precise definition of the term critical submergence, as used in this report, will be given shortly. Reynolds number and Weber number effects were assumed negligible and therefore were not factored into the functional relation (Refer to Section 2.3). Final validity of this assumption is based on how well the test data fit the equation.

The formation, growth and subsequent ingestion of a vortex air core was not a gradual, well-behaved phenomenon; vortices tended to form and dissipate in fairly rapid succession. Small gulps of air were sporadically ingested even at relatively high loop water levels. The following criteria were used to determine the critical or minimum allowable RCS hot leg water level for RHR operations. The more limiting of:

1. Level at which air is ingested on a continuous basis but not more than 2% by volume of intake flow rate, or

2. Level at which air is ingested in sporadic gulps which do not exceed 5% by volume of intake flow rate.

These criteria are based on the information provided in Reference 16. The first criteria (above) is a direct conclusion of Reference 16 which states:

> "Based on the data available, a limit of acceptable air ingestion is established at 2% by volume. All test data show that for ingestion levels up to 2%, negligible degradation occurs. At ingestion rates slightly above (>3%) degradation starts to become pump and operating point dependent. Because of the concern for air binding at very low flows, the 2% applies to pump flow rates at or near best efficiency point. It should be noted that for flow rates at less than 50% of rated flow, chances of air binding are substantial. However, at such low flow rates, sump suction pipe velocities would be half the values of rated conditions and the likelihood of air ingestion decreases."

The second criteria stems from the fact that instantaneous spikes in entrained air fraction are allowed to exceed 2% by volume but must be limited to a reasonable value. Figure 4-1 of Reference 16 shows that there is relatively minor degradation in performance beyond that due to the change in fluid density for air fraction of 5%. On this basis it is judged that an air fraction of 5% is acceptable as a limit for sporadic gulps of air. The volumetric air ingestion rates are referenced to atmospheric conditions. This is conservative as RHR pump suction pressure during partial loop operation is expected to exceed atmospheric pressure.

2.4.3 Results

Using the above definition, a critical submergence depth was determined for each intake flow rate. When the sets of data points (F_r, S_c/d) for each intake orientation were plotted on a log-log scale the fit was linear, implying a relation of the form $S_c/d = a\, F_r^{\,b}$ as expected. The relationships between S_c/d and F_r for the various intake geometries are shown on Figures 2-2 through 2-6. Numerical values for the parameters a and b of the above equation, and equations for calculating the level relating to centerline of the hot leg pipe, are provided in Table 2.6. This table also provides ranges of applicability for these correlations. With reference to Figure 2-6, it is observed that as a nozzle of given size is rotated from 0° (horizontal) to 90° (vertical) the required relative submergence (S_c/d) continuously increases. In terms of level above the bottom of the hot leg, a nozzle oriented at 0° requires the highest level followed in order by nozzles oriented at 90°, 60° and 45° (lowest required level).

Figure 2-6 also illustrates Harleman's relation (Reference 17) for required submergence as a function of Froude number. This is a popular equation for estimating the submergence ratio (S/d) to prevent gas entrainment for pump intakes at the bottom of a cylindrical tank. Due to lack of better information, this relation has often been used to predict the onset of air entrainment during RHR mid-loop operations. It is evident from Figure 2-6 that the Harleman equation bounds test data for 0° nozzles and 45° nozzles with $0.32 \leq d/D \leq 0.39$ (where D is the Hot Leg ID) over the range of operation considered. It is otherwise inappropriate for application to RHR mid-loop operations.

Figures 2.10 through 2.18 contain curves of RCS hot leg level vs. RHR flow rate for each category of plant. These curves were derived from the dimensionless curves (Figure 2-6).

2.4.4 Discussion of Mitsubishi Heavy Industries Test

Mitsubishi Heavy Industries (MHI) has also performed tests to model RHR partial-loop operations. The MHI tests were also based on Froude Scaling with a geometric similarity ratio between prototype and model of 3.2:1.

The model hot leg diameter was approximately 227 mm (approximately 9") and the intake nozzle diameter was 54 mm (2-1/8"). Tests were performed with nozzles oriented at both 45° and 90°. The purpose of this test was threefold:

1) Predict onset of air entrainment,

2) determine relationship between intake flow rate, water level and air entrainment, and

3) study movement of air through intake piping as a function at flowrate.

A significant conclusion of the MHI study is that entrained air is carried along with the water when $F_r \geq 1$. The MHI test loop incorporated a model of RHR pump suction piping in order to determine if air bubbles were held up in horizontal runs and how they behaved in descending runs. It was concluded that for Froude ($F_r \geq 1$):

a. In ascending sections, air bubbles traveled with the water due to buoyancy effects.

b. In horizontal sections, air bubbles followed the upper portions of the pipe and traveled with the water.

c. In descending sections, air bubbles travel with the water and are forced outward by the influence of a bend.

The conclusion that air bubbles are carried along with water when F_r is greater than or equal to 1 is supported by the Westinghouse test data. The data for nozzles oriented at 45°, 60° and 90° from the horizontal depict a discontinuity in the rate of change of critical submergence with respect to Froude number at F_r approximately 1. This discontinuity implies that buoyancy effects become significant for $F_r \leq 1$. In other words, the tendency for fluid velocity to pull air into intakes rotated below the horizontal plane is reduced when the $F_r \leq 1$; buoyancy effects are sufficiently strong to provide some degree of self-venting of the intake at this point.

It is noted that this discontinuity was not used in establishing operating limits for this report. As a result the limits provided in this report are conservative at low flow operations. One of the practical impacts of this effect is that once air is trapped in the RHR System, it is necessary to fill the loop and increase the system flow rate to move air out of the system.

2.4.5 Comparison with Operating Data

Figure 2-7 shows a comparison between the correlation for 45° nozzles ($0.32 \leq d/D \leq 0.39$) and the corresponding plant operating data from Table 2.2. The correlations provided herein are based on the height of water above the RHR suction nozzle in the hot leg. The operating data provided in Table 2.1 is based on water levels as measured in the cross-over leg.

Since the hot leg water level is expected to be lower than the cross-over leg water level during partial loop operations, Figure 2-7 can be used to reach the following conclusions:

1) The correlation is representative of conditions under which plants have operated, and

2) plants have successfully operated their RHR systems at submergence levels below that required by the correlation.

It is therefore concluded, that the criteria used in establishing the correlation is both reasonable and conservative.

2.4.6 Indian Point Unit 2 Tests

Consolidated Edison conducted tests at Indian Point Unit 2 in October and December 1987, in which maximum RHR flow at various RCS levels was determined. Indian Point Unit 2 draws RHRS flow from Loop 2. For this test, level was measured at Loop 1 hot leg (Tygon Tube), and Loop 1 crossover pipe (transmitter). Their test results referenced the Loop 1 hot leg level. The allowable operating curve derived from these tests is shown on Figure 2-8 which also contains the curve generated from the WOG scale model tests. A comparison of the curves indicates that Indian Point Unit 2 requires approximately 1 1/2 inches higher RCS level at the same RHRS flow than that predicted by the WOG tests. The possible reasons for this difference were reviewed with Consolidated Edison. While no definitive conclusions were reached, the following observations can be made.

1. Different criteria for determining the minimum allowable RCS hot leg level as a function of RHR flow was used in the tests. The Westinghouse Owner's Group test limited air volume intake to $\leq$ 2% on a continuous basis or 5% on a sporadic basis. Con Edison used a minimum RHR pump suction pressure of 10 psig as the criterion for their test. At this pump suction pressure, Con Edison did not expect air from the hot leg to be entrained into the RHR suction pipe.

2. The RCS level was measured on hot leg 1, while the RHR inlet was from hot leg 2. It is expected that the in-active hot legs will have elevation higher than the active hot leg. Therefore, the hot leg 2 (RHRS inlet) elevation would have been lower than that measured/referenced for Indian Point Unit 2.

3. Operating data from other plants with the same RHRS nozzle configuration indicate that higher flowrates (equal or greater than the WOG curve) can be achieved (Figure 2-7). A number of possible

reasons of why other plants achieve higher flows exist. It is expected that some small amount of air will entrain into the RHR flowstream. The tests at Indian Point Unit 2 and Seabrook (refer to Section 2.4.7) both concluded that a change in RHR pump sound was a precursor to other indications (suction pressure and motor current oscillations). As discussed in Section 2.4.2, a small amount of entrainment is expected. This acceptable amount of entrained air may cause the change in RHR pump sound, but still be acceptable. This would imply additional conservatism in the Indian Point Unit 2 tests; since when plants operate at mid-loop, the operators typically rely on motor current oscillation as the first indication of air entrainment.

4. The elevation from the hot leg pipe centerline to the first horizontal section of RHRS inlet piping is small (2-1/2 feet, centerline to centerline). The corresponding scale model elevation difference is about 3-2/3 feet, while many plants have elevation difference of five feet or more. In addition, the length of inclined 45° piping is short (about one foot). It is postulated that because of the small elevation/pipe length, it becomes easy to trap air in the horizontal section. Furthermore, as noted in Section 2.4.4, the air may not immediately be swept through the RHRS inlet pipe due to low velocities. Therefore, air may accumulate in the horizontal sections of pipe, and then be "gulped" into the RHR pump. It is believed that some air remained trapped in the horizontal piping from previous test runs, since the time between test runs was relatively short (about 15 minutes), and venting was not performed between runs.

The preceding items provide possible explanations of why the Indian Point Unit 2 tests resulted in more restrictive operating conditions than indicated by other sources. However, the Unit 2 tests also highlight the need for caution when operating with the RCS partially drained. Suggestions would include stationing an operator at the RHR pump when entering into a level/flow combination with which the operating staff has limited experience. (Note: Due consideration must be given to ALARA) This will allow advance warning to onset of air entrainment. Once air is entrained into the RHRS suction, special attention must be given to venting all air, since its presence may impose addition RHRS flow limits. The sensitivity to air trapped in the RHRS is believed to be a function of the elevation from the hot leg to the first horizontal RHRS pipe section, and the total length of horizontal pipe.

2.4.7 Seabrook Tests

Public Service of New Hampshire conducted tests at Seabrook in April 1988. With fuel in the vessel (but not irradiated - therefore no decay heat), maximum RHR flow at various RCS levels was determined. Seabrook has RHRS inlet connections on loops 1 (RHR Pump A) and 4 (RHR Pump B). During these tests, RHR Pump A returned flow to Loops 1 and 2, and Pump B to Loops 3 and 4. RCS level was measured by a transmitter on Loop 1 crossover pipe, and by tygon tubes on Loops 2 and 3 crossover pipe. For the test runs with only one RHR pump operating, the level in the loops without returning RHRS flow was up to two inches higher than the level in the loops with returning RHRS flow. In addition, it is expected that the level in the hot leg from which RHRS flow is drawn would be lower than either of the crossover pipe measurements.

Data selected from the test log are plotted on Figure 2-9, along with the appropriate WOG test curve. For the cases were one RHR pump was operating, both the high and low level are plotted. It is emphasized that the WOG curve is referenced to hot leg level, while the Seabrook test data is for the crossover pipe level, with the actual hot leg level expected to be lower than either level plotted. The Seabrook tests used change in RHR pump sound as the criteria for determining where air is entrained in the RHR loop. As discussed in Section 2.4.6, this results in conservative limits since a change in RHR pump sound is the first indication of air entrainment and may not be an indication of the limiting condition for operation. Comparison of the Seabrook test data indicates that the WOG tests are conservative, but reasonable.

A number of additional observations can be made based on the Seabrook tests.

1. As with the Indian Point Unit 2 tests, the first indication of air entrainment was a change in pump noise.

2. Level gradients exist in the RCS, and are dependent on RHRS flow rates.

3. Once air accumulates in the RHRS inlet piping, it is very time consuming to remove. (It took almost one hour to clear air after one test run.)

2.5 Conclusions and Recommendations

1. Correlations between RCS hot leg water level and RHR intake flow rate have been developed as guidelines for RHR operations with a partially filled system. These correlations are based on limiting air entrainment within the guidelines for RHR pump operation provided in Reference 16. The relationships between S_c and F_r are shown in Figure 2-1 and Table 2.6; this information has been converted into hot leg water level as a function of RHR intake flow rate in Figures 2-10 through 2-18.

2. Plant operating and test data show that the correlations developed herein are both reasonable and conservative. However, the recommended operating limits are not intended to replace operating experience.

3. The test data gathered during this program and data received from MHI indicate that air is carried along with water when F_r is greater than 1. Also, when F_r is less than 1 the ability to entrain air into the RHR intake is greatly reduced. This suggests in accordance with common sense that:

   a) Operating at a low RHR intake flow rate ($F_r \leq 1$) during partial loop operations greatly reduces the risk of entraining air, and

   b) If air is entrained in the RHR system during partial loop operations, the best way to vent the system is to recover level and sweep entrained air from the system by operating the system at a relatively high flow rate ($F_r \geq 1.5$).

4. Plant test data suggest that the first symptom of air entrainment is noise at the RHR pump. This is followed by a drop in suction pressure and finally by oscillations in suction pressure, flow rate or motor current. It is recommended that an operator be stationed at the RHR pump when entering into a level/flow combination with which the operating staff has limited experience.

5. Plant test data show that differences in levels exist between active cold legs, inactive cold legs, active hot legs, and inactive hot legs during partial loop operations. An active loop is defined as a loop which an RHR pump either takes suction or discharges. The magnitude of the level differences is significant (on the order of 1-2 inches depending on flow rate) for partial loop operations.

   The model tests indicated that the water level decreased across the tank exit nozzle; this decrease is presumed to be the result of velocity changes and form losses between the tank and loop. There was also a smaller level gradient along the length of the hot leg due to frictional effects. The same phenomenon will exist in the plant; however, the magnitude of the form and friction losses which exist in plant operations will differ from those which occurred in the model test.

6. It must be noted that when changes in RCS water level are made, sufficient time must be allowed for a level monitoring system (based on differential pressure) to stabilize and indicate the correct level; otherwise, the indicated level will lag the actual RCS water level.

TABLE 2.1

PLANT CATEGORIES

Category	Description*	Plants
A.1	0°/6"	Rowe
A.2	0°/10"	Haddam Neck
B.1	45°/8"	Prairie Island 1&2, Kewaunee, San Onofre 1
B.2	45°/10"	Point Beach 1&2
B.3	45°/12"	Farley 1&2, Byron 1&2, Braidwood 1&2, Catawba 1&2, Beaver Valley 2, Summer Harris, Vogtle 1&2, Callaway, Wolf Creek, Comanche Peak 1&2, South Texas 1&2, Seabrook
B.4	45°/14"	Cook 1&2, Zion 1&2, McGuire 1&2. Beaver Valley 1, Turkey Point 3&4, Indian Point 2&3, Trojan, Salem 1&2, Sequoyah 1&2 Watts Barr 1&2, Surry 1&2, North Anna 1&2, Diablo Canyon 1&2,
C	55°/12"	Millstone 3
D	60°/14"	Robinson 2
E	90°/10"	Ginna

* RHRS Nozzle Angle From Horizontal and Nominal Diameter

TABLE 2.2

OPERATING AND GEOMETRIC PLANT DATA

Nozzle Orientation(1)/Size(2)	Flow Rate (GPM)	Water Level(3)	F_R	H/D
45/14 (11.500)	800	9 1/2	.4	0.826
45/14 (11.188)	1500	0	.8	0
45/14 (11.500)	4000	2 1/4	2.2	0.196
45/14 (11.188)	2000	0	1.1	0
45/14 (11.188)	3000	4	1.7	0.358
45/14 (11.188)	3500	8	1.9	0.715
45/14 (11.762/11.498)	3000	9	1.7	0.776
45/14 (11.188)	3000	0	1.7	0
45/14 (11.500)	3500	8	1.9	0.727
45/14 (11.500)	2540	0	1.4	0
45/14 (11.188)	3200	10	1.8	0.894
45/14 (11.500)	3000	0	1.7	0
45/12 (10.500)	2000	11 1/2	1.4	1.095
45/12 (10.500)	1500	0	1.0	0
45/12 (10.500)	2800	4	2.0	0.381
45/12 (10.500)	3000	12	2.1	1.143
45/12 (10.500)	1000	0	.7	0
45/12 (10.500)	1600	0	1.1	0
45/12 (10.500)	3000	0	2.1	0
45/12 (10.500)	1500	0	1.0	0
45/10 (8.750)	1500	7	1.7	0.8
45/8 (6.817)	1000	4	2.0	0.587
45/8 (7.001)	2000	0	4.0	0
45/8 (7.001)	500	7	1.0	1
90/10 (8.500)	800	-1/2	.9	-0.059
90/10 (8.500)	500	-4 1/2	.6	-0.529
0/6 (5.187)	1000	14 1/2	4.1	2.795

(1) Degrees from horizontal
(2) Nominal diameter, inches & actual ID, inches
(3) Above centerline, reference specific plant level measurement location

TABLE 2.3

SUMMARY OF PLANT GEOMETRIC DATA

Haddam 27 1/2
San Onofre 1 27 1/2
Rowe 16 1/8
All others 29

Category	Number of Plants/Units	RHRS Nozzle Orientation(1)/Size(2)	F_R(3)	
A.1	1/1	0°/6"	4.1	Rowe
A.2	1/1	0°/10"	--	Haddam
B.1	3/4	45°/8"	1.0-4.0	Zion, Kewaunee, San Onofre 1
B.2	1/2	45°/10"	1.7	Point Beach
B.3	13/20	45°/12"	0.7-2.1	Many p. 2-16
B.4	14/24	45°/14"	0.4-2.2	″
C	1/1	55°/12"	--	Millstone 3
D	1/1	60°/14"	--	Robinson 2
E	1/1	90°/10"	0.6-0.9	Ginna

(1) Degrees from horizontal
(2) Nominal pipe size
(3) For plants reporting flow information

TABLE 2.4

TEST CONFIGURATIONS

Test Number	Orientation[1]/Size[2]	F_R
1.1	0°/1 1/4"	1.7-5.7
1.2	0°/2 1/4"	1.0-2.8
2.1	45°/1 1/4"	1.7-5.7
2.2	45°/2 1/4"	1.0-2.8
2.3	45°/2 3/4"	.3-1.7
3.1	60°/2 1/4"	1.0-2.8
3.2	60°/2 3/4"	.3-1.7
4.1	90°/1 1/4"	1.7-5.7
4.2	90°/2 1/4"	1.0-2.8
4.3	90°/2 3/4"	.3-1.7

(1) Degrees from horizontal

(2) Pipe inside diameter

TABLE 2.5

COMPARISON OF PLANT DATA AND TESTS

Plant Category	Corresponding Test(s)	Plant F_R (1)	Test F_R
A.1	1.2	4.1	1.7-5.7
A.2 (2)	1.1 and 1.2	--	1.0-5.7
B.1 (2)	2.1 and 2.2	1.0-4.0	1.0-5.7
B.2 (2)	2.1 and 2.2	1.7	1.0-5.7
B.3	2.2	0.7-2.1	1.0-2.8
B.4	2.3	0.4-2.2	0.3-1.7
C (2)	2.2 and 3.1	--	1.0-2.8
D	3.2	--	0.3-1.7
E (2)	4.1, 4.2 and 4.3	0.6-0.9	.3-5.7

(1) For plants reporting flow information

(2) The plants in these categories were not explicitly modeled, but are enveloped by the listed corresponding test runs.

TABLE 2.6

SUMMARY OF CORRELATION CONSTANTS

Angle(1)	d/D(2)	Constants(3) a	Constants(3) b	Range of Applicability
0°	0.18	0.31	0.69	$2 \leq F_R \leq 6$
	0.32	0.31	0.69	$1 \leq F_R \leq 3$
45°	0.18	1.6	0.12	$2 \leq F_R \leq 6$
	0.32	0.45	0.64	$1 \leq F_R \leq 3$
	0.39	0.45	0.64	$1 \leq F_R \leq 3$
60°	0.32	0.96	0.1	$1 \leq F_R \leq 3$
	0.39	0.68	0.17	$1 \leq F_R \leq 3$
90°	0.18	2.3	0.12	$2 \leq F_R \leq 6$
	0.32	1.5	0.14	$1 \leq F_R \leq 3$
	0.39	1.5	0.14	$1 \leq F_R \leq 3$

(1) Degrees from Horizontal

(2) d = RHR intake nozzle ID, D = RCS Hot Leg ID (29", except as follows: Yankee Rowe - 16 1/8" Haddem Neck - 27 1/2" San Onofre - 27 1/2")

(3) S_c = required submergence (level above top of nozzle)

$$S_c/d = a F_R^b$$

FIGURE 2-1

NOMENCLATURE

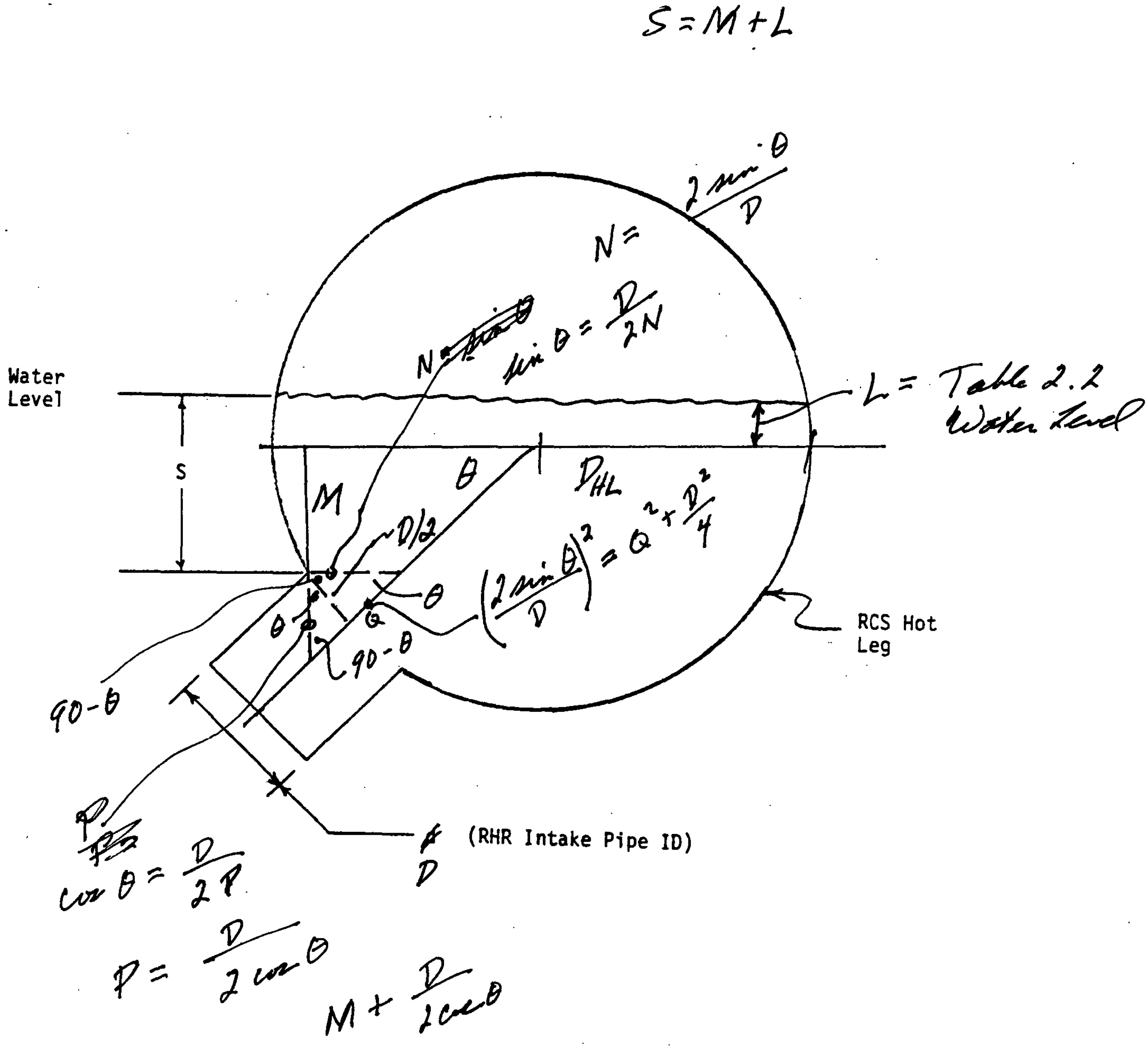


FIGURE 2-2

TEST RESULTS - 0° INTAKE NOZZLES

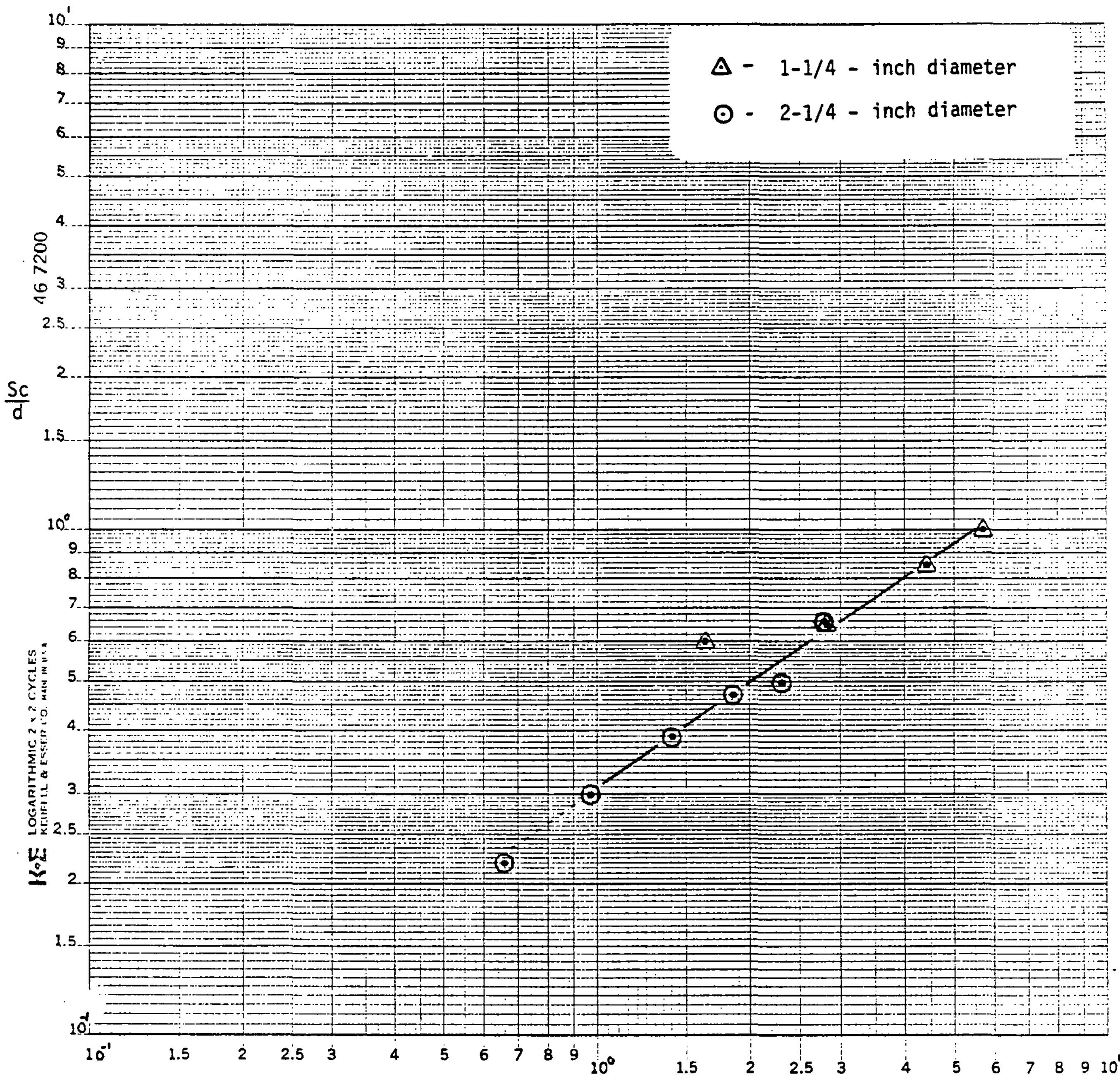


FIGURE 2-3

TEST RESULTS - 45° INTAKE NOZZLES

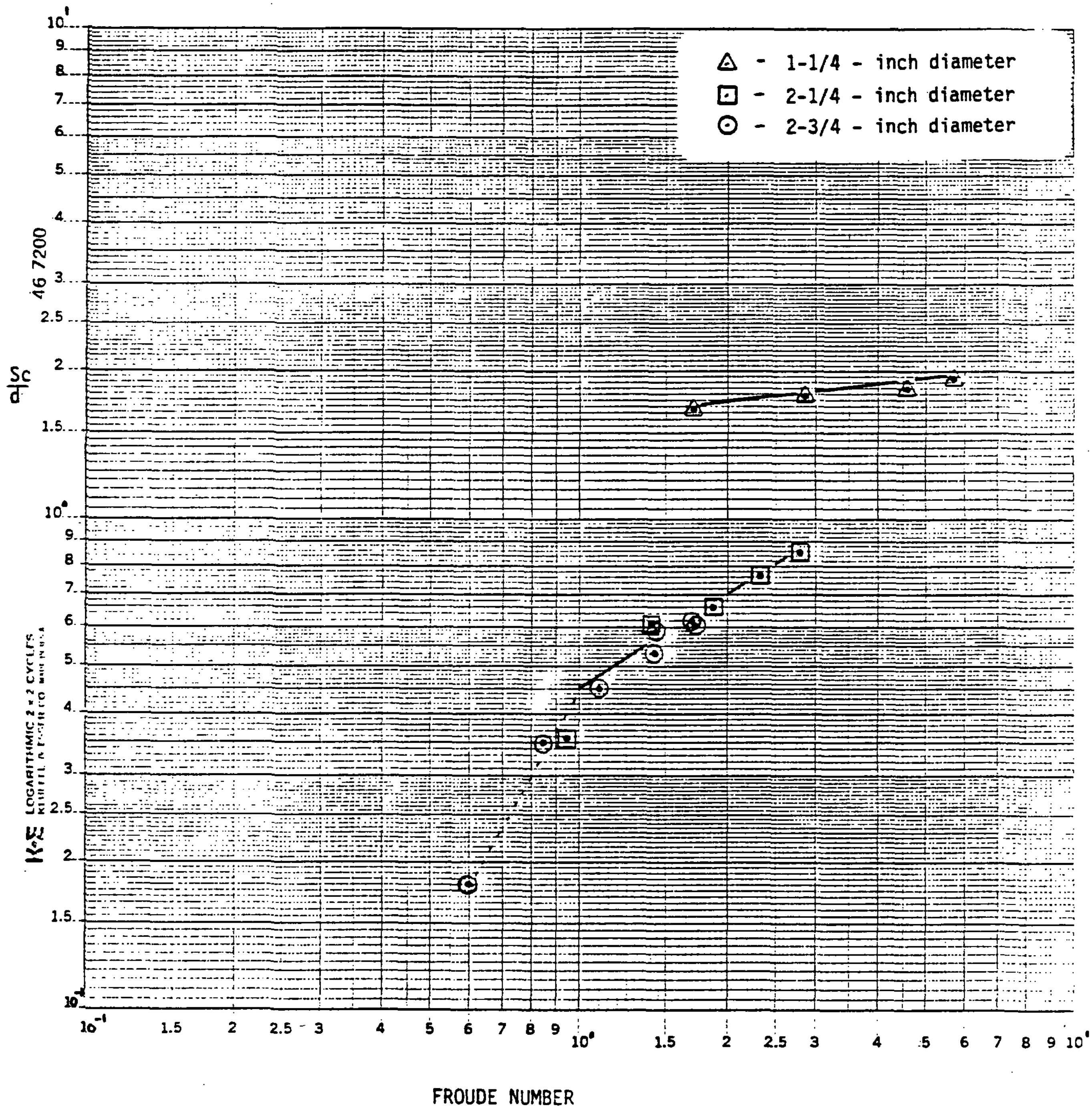


FIGURE 2-4
TEST RESULTS - 60° INTAKE NOZZLES

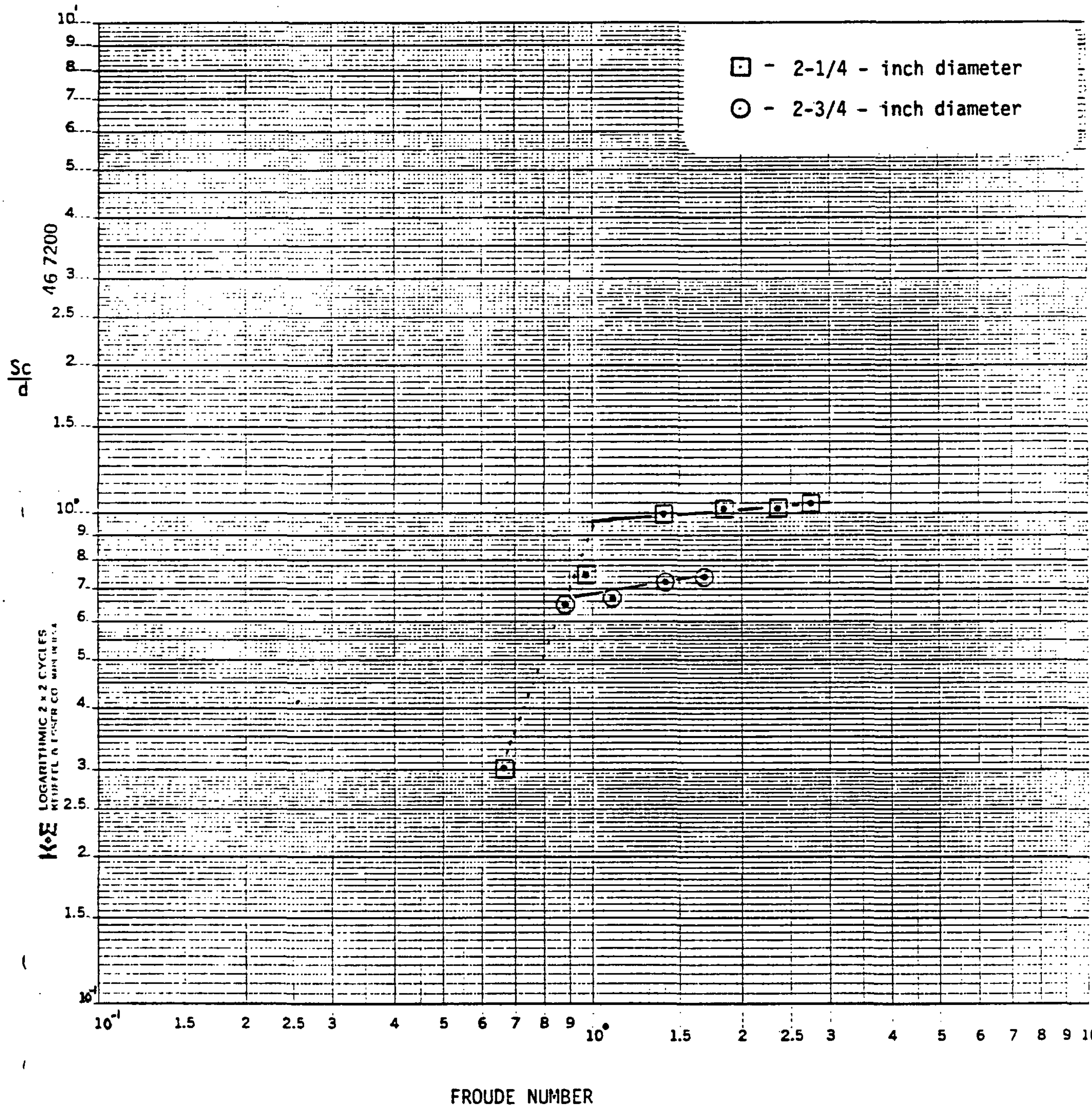


FIGURE 2-5

TEST RESULTS - 90° INTAKE NOZZLES

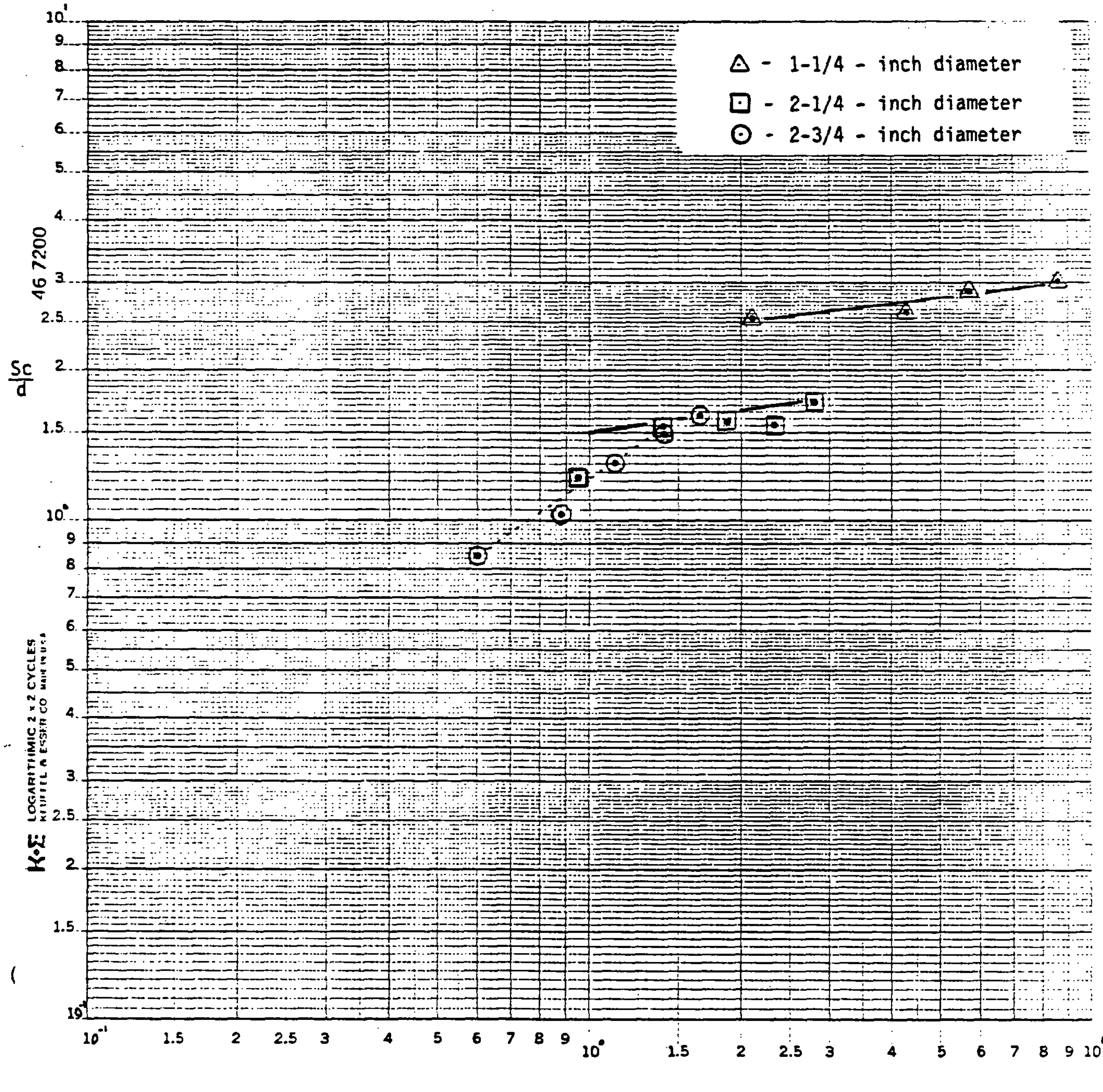


FIGURE 2-6

SUMMARY OF TEST RESULTS

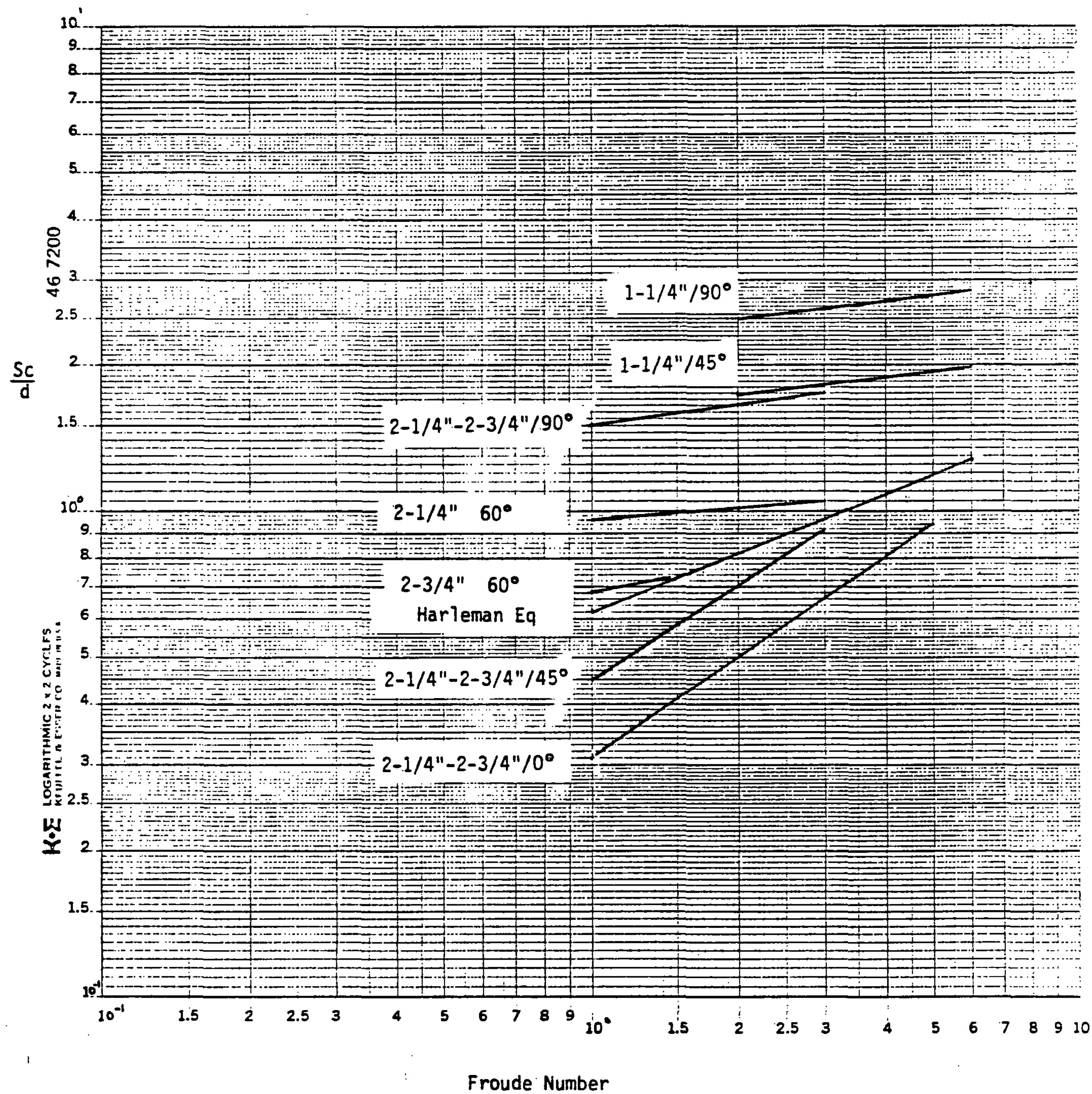


FIGURE 2-7

COMPARISON OF TEST DATA AND PLANT OPERATING DATA

45° INTAKE NOZZLES

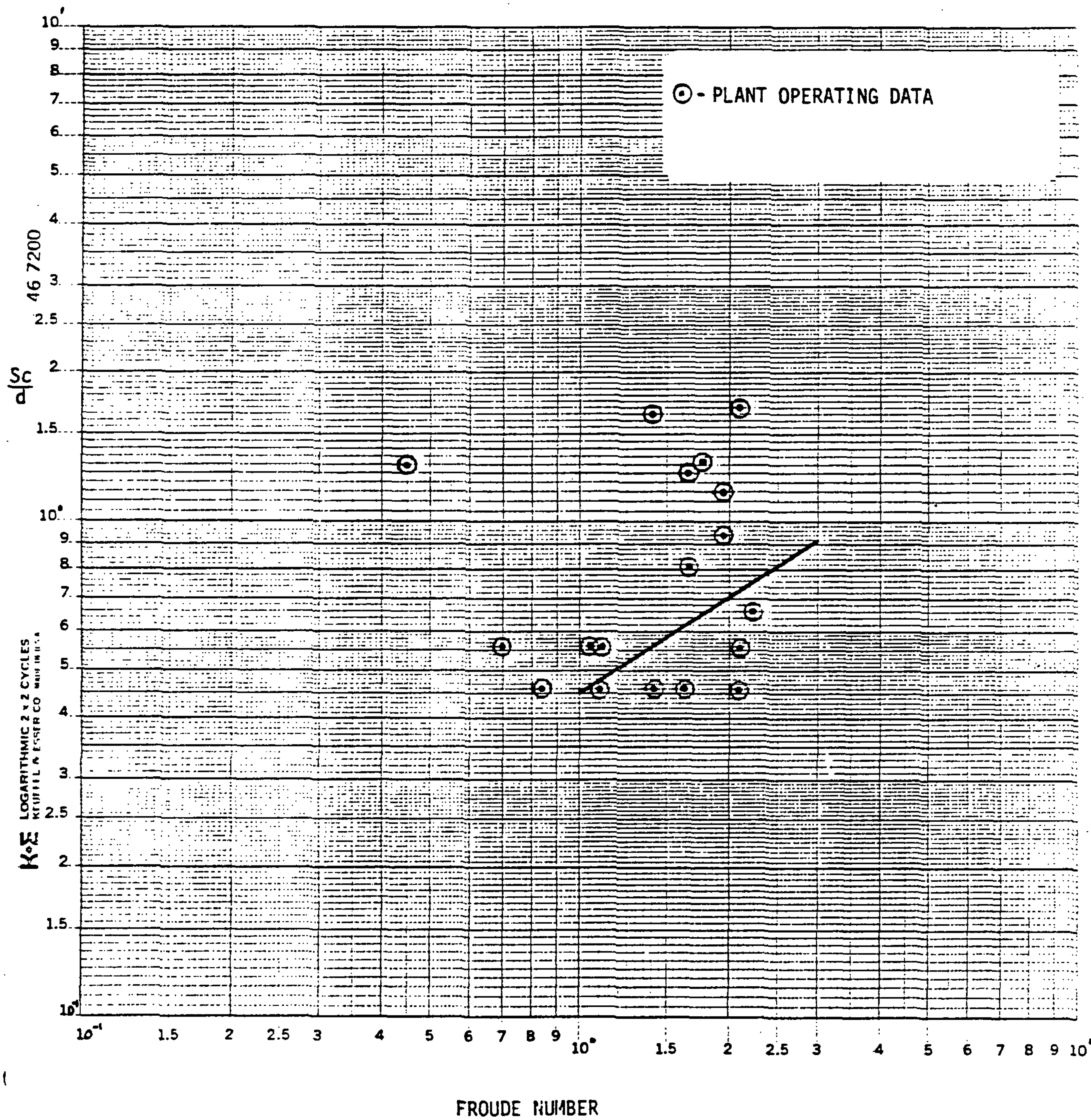


FIGURE 2-8

COMPARISON OF TEST DATA AND INDIAN POINT UNIT 2 DATA

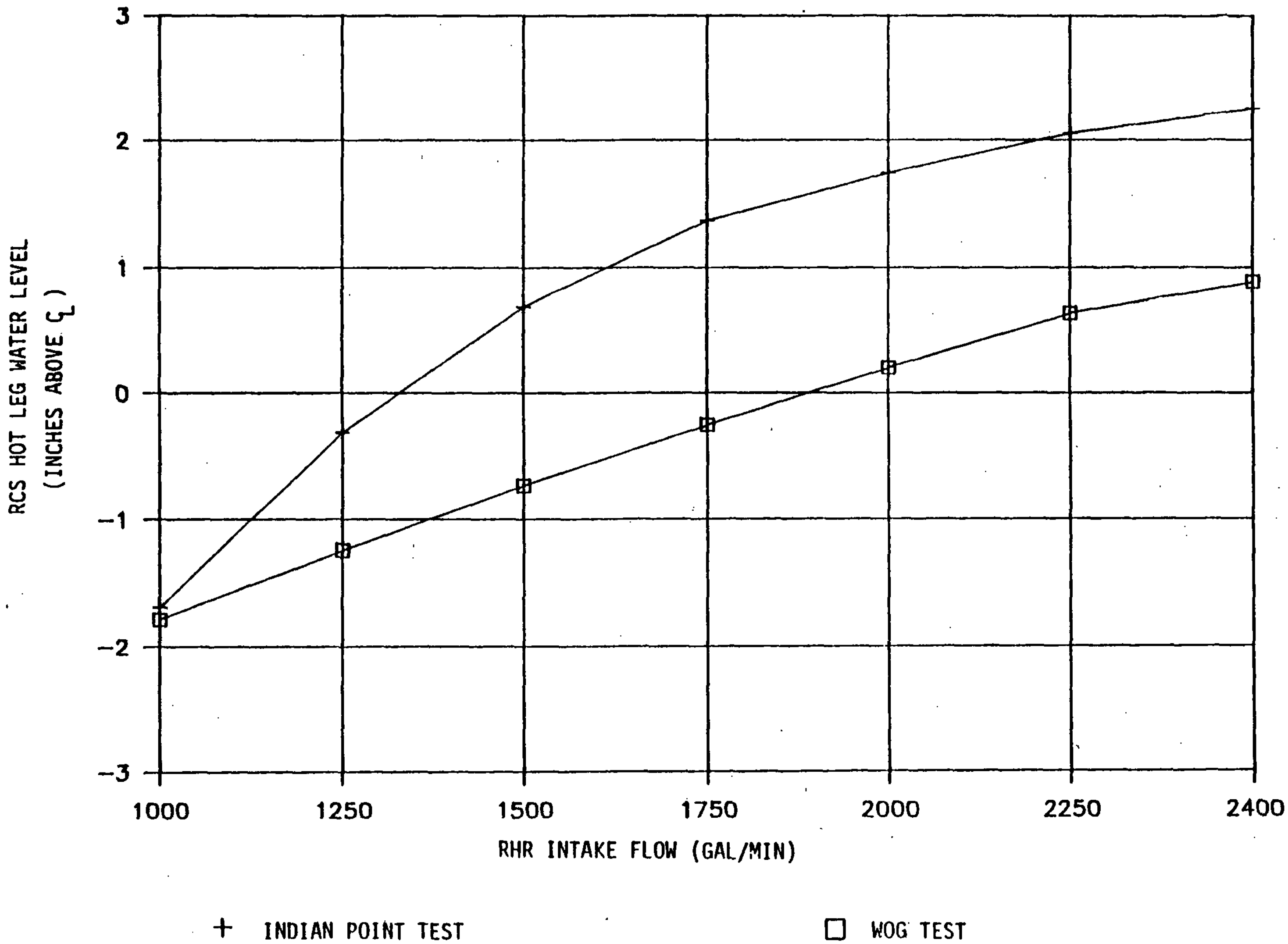


FIGURE 2-9

COMPARISON OF WESTINGHOUSE DATA AND SEABROOK DATA

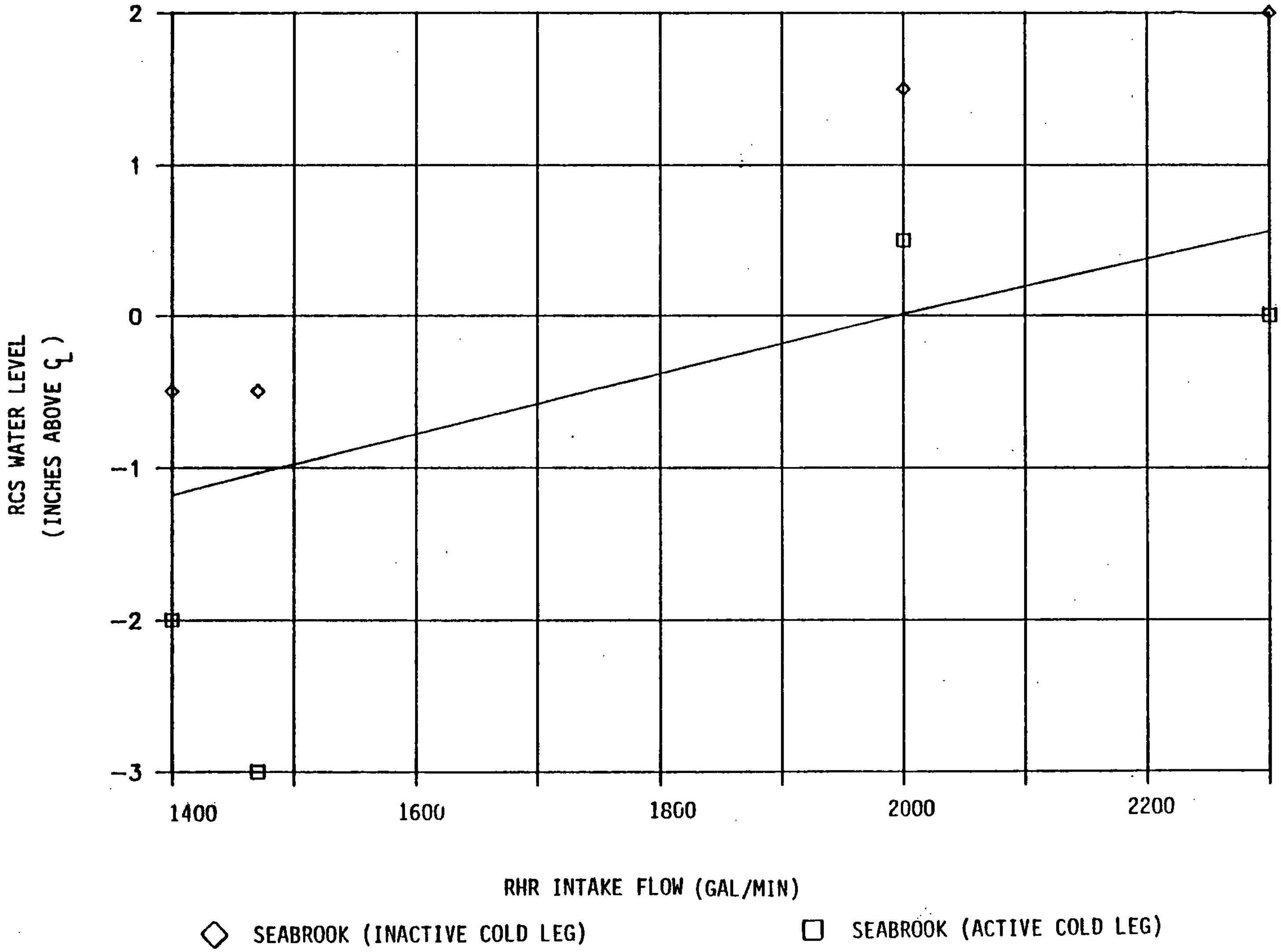


FIGURE 2-10

REQUIRED RCS WATER LEVEL

CATEGORY A.1 PLANTS (0°/6")

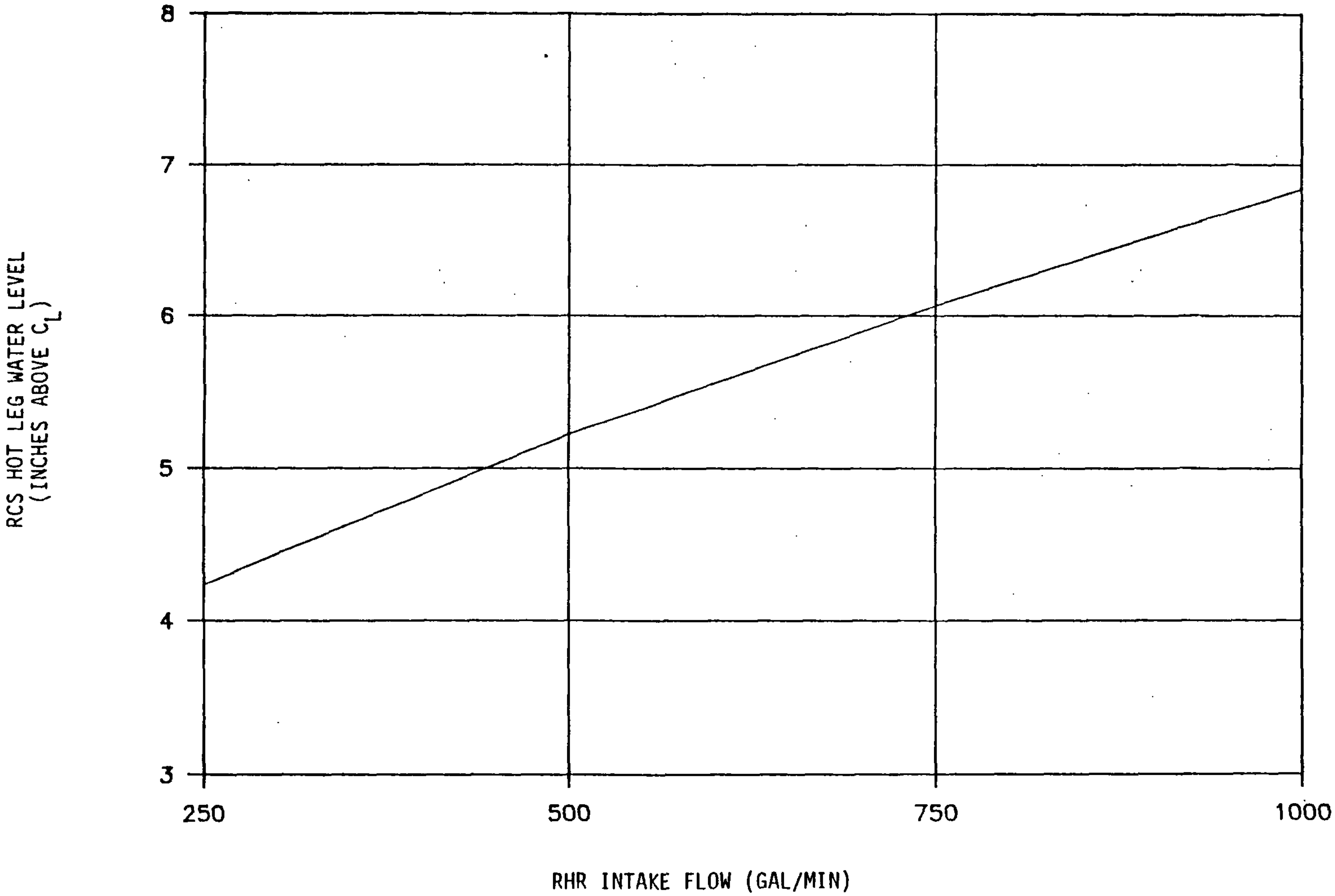


FIGURE 2-11

REQUIRED RCS WATER LEVEL

CATEGORY A.2 PLANTS (0°/10")

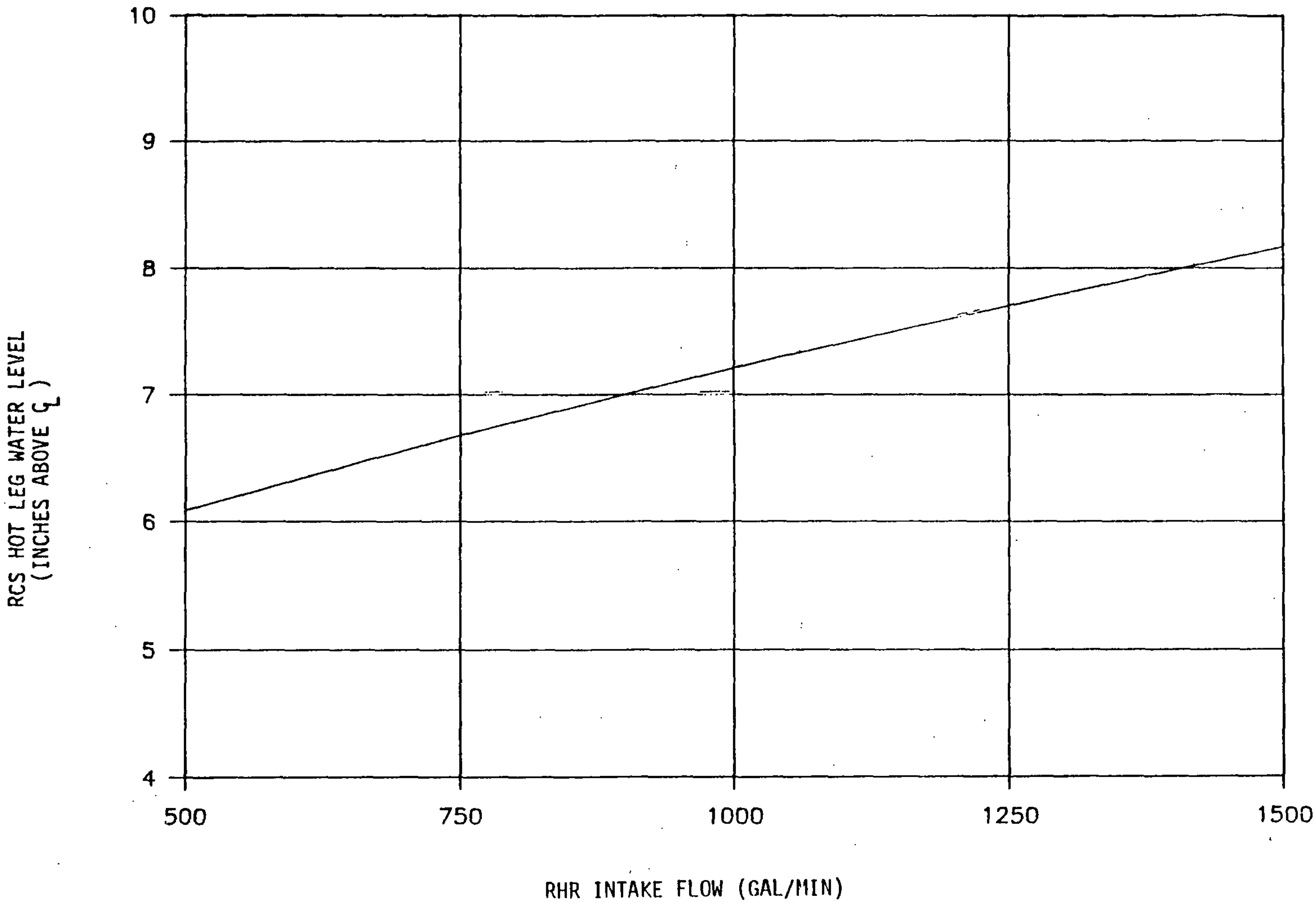


FIGURE 2-12

REQUIRED RCS WATER LEVEL

CATEGORY B.1 PLANTS (45°/8")

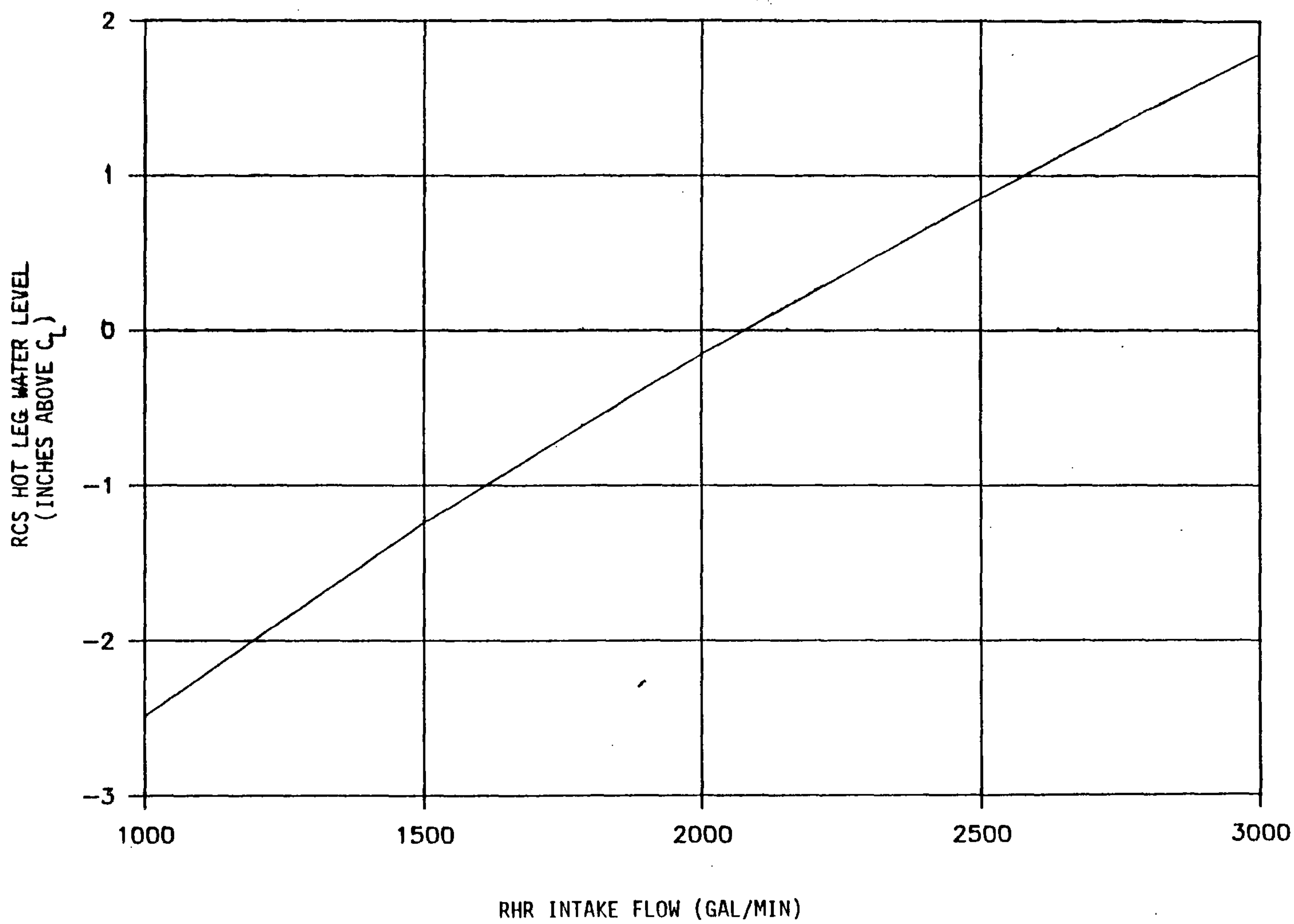


FIGURE 2-13
REQUIRED RCS WATER LEVEL
CATEGORY B.2 PLANTS (45°/10")

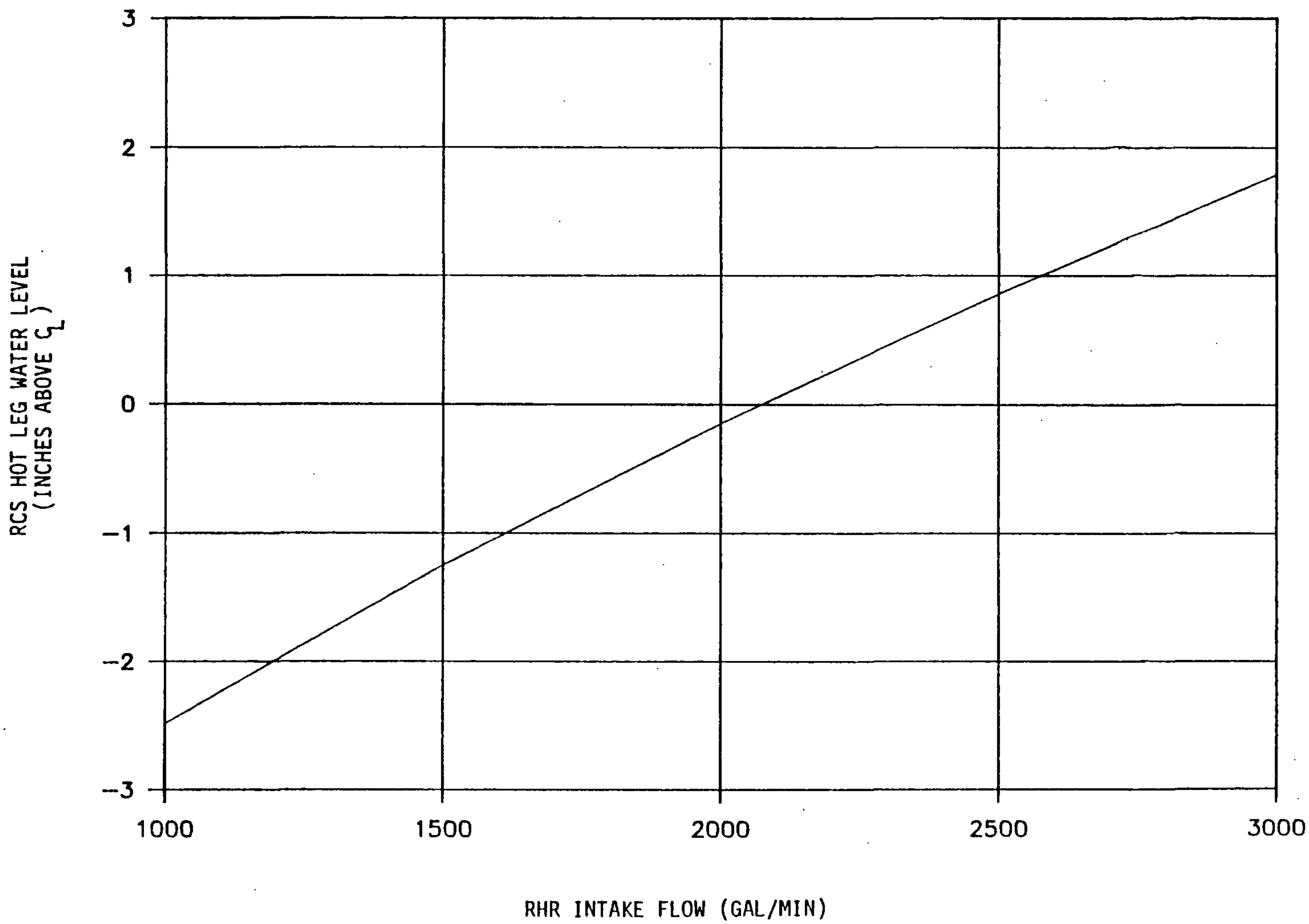


FIGURE 2-14

REQUIRED RCS WATER LEVEL

CATEGORY B.3 PLANTS (45°/12")

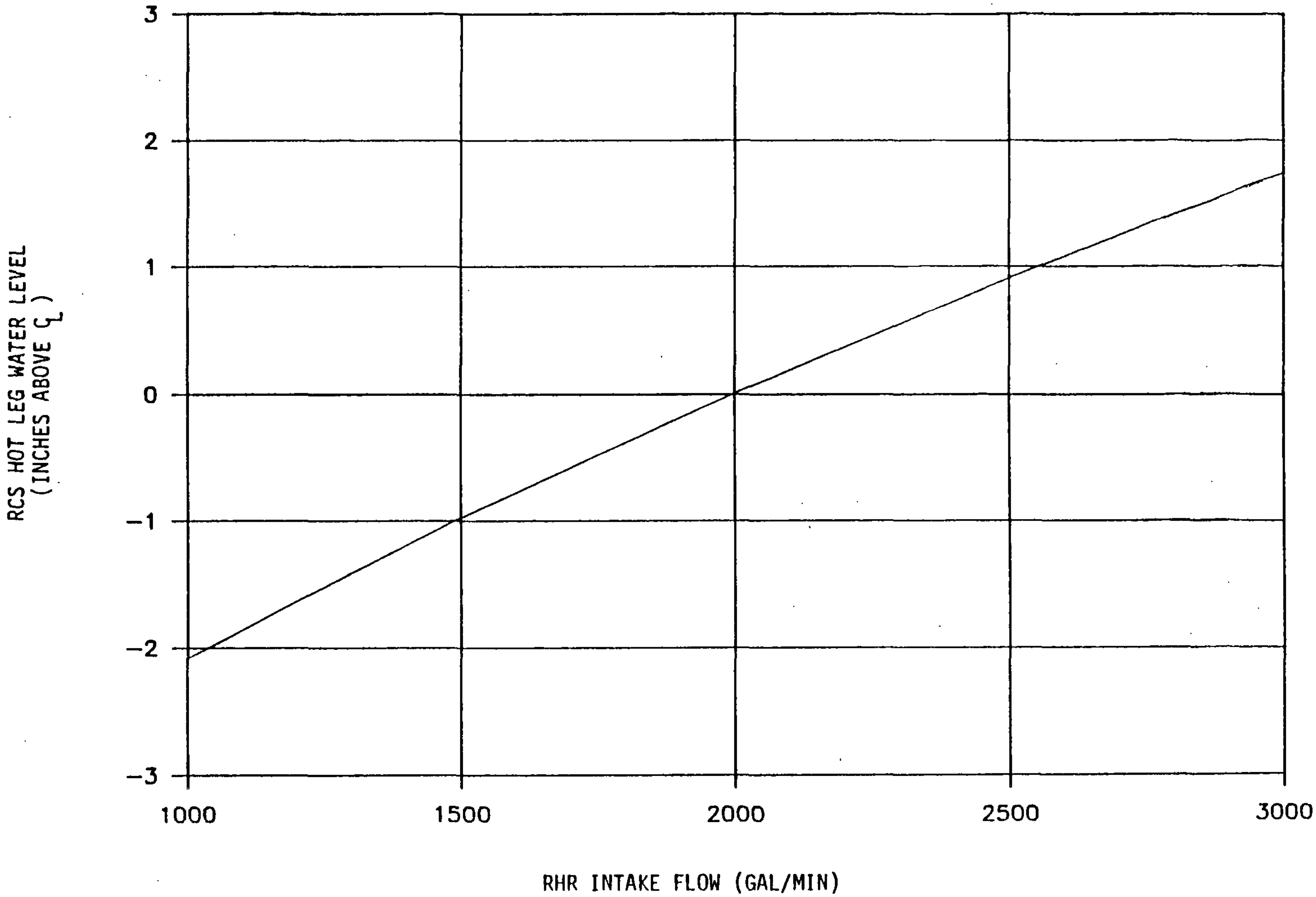


FIGURE 2-15

REQUIRED RCS WATER LEVEL

CATEGORY B.4 PLANTS (45°/14")

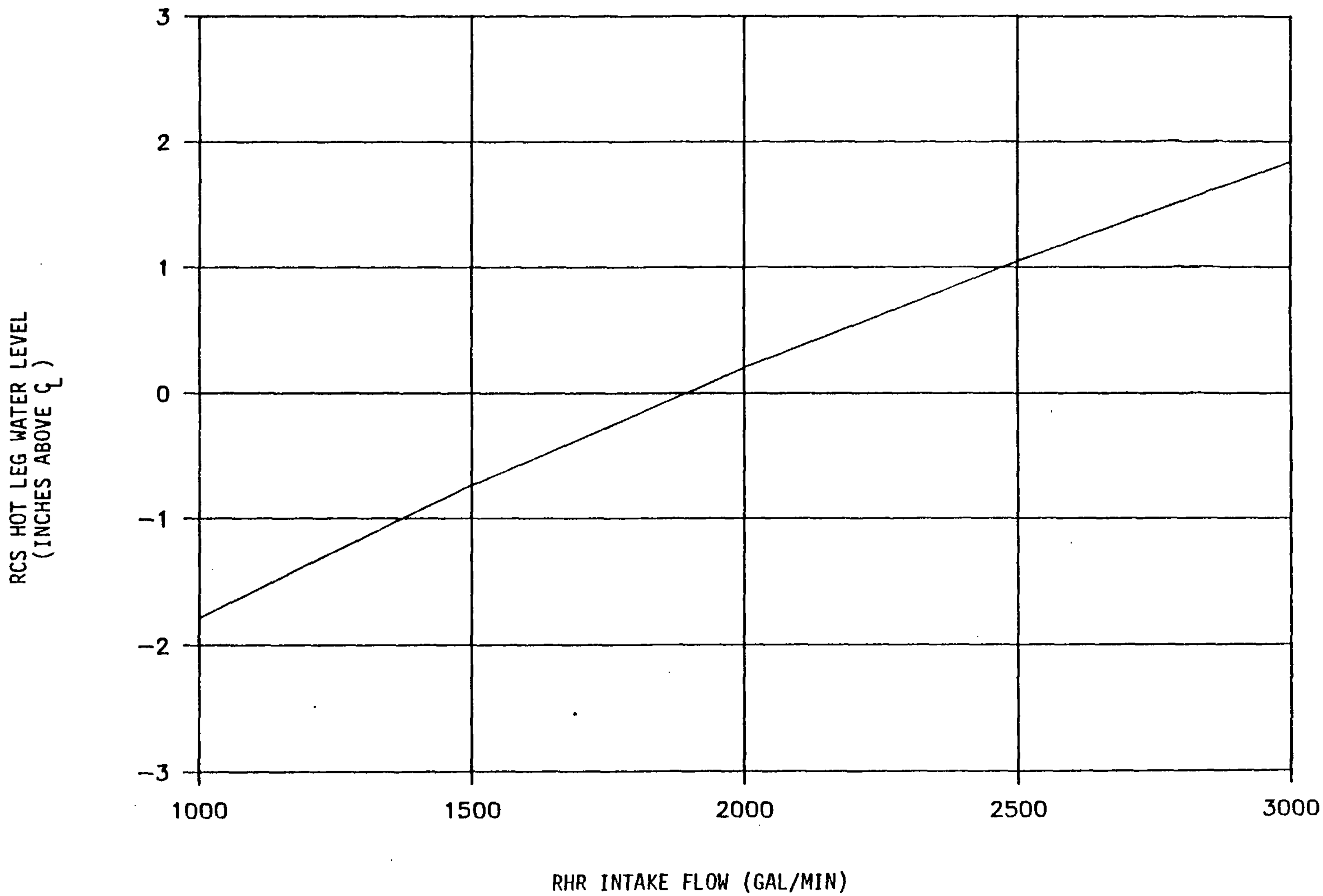


FIGURE 2-16

REQUIRED RCS WATER LEVEL

CATEGORY C PLANTS (55°/12")

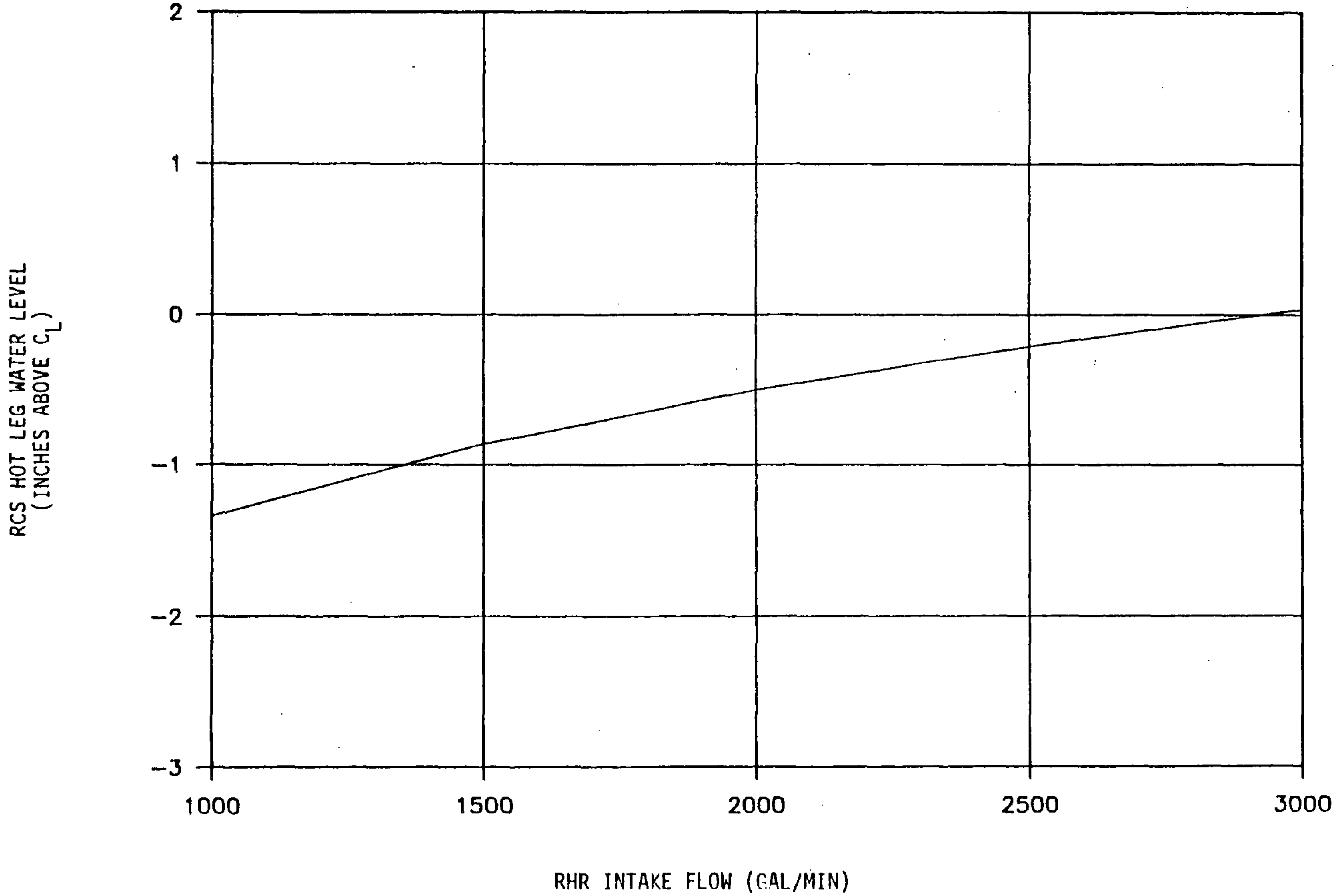


FIGURE 2-17

REQUIRED RCS WATER LEVEL

CATEGORY D PLANTS (60°/14")

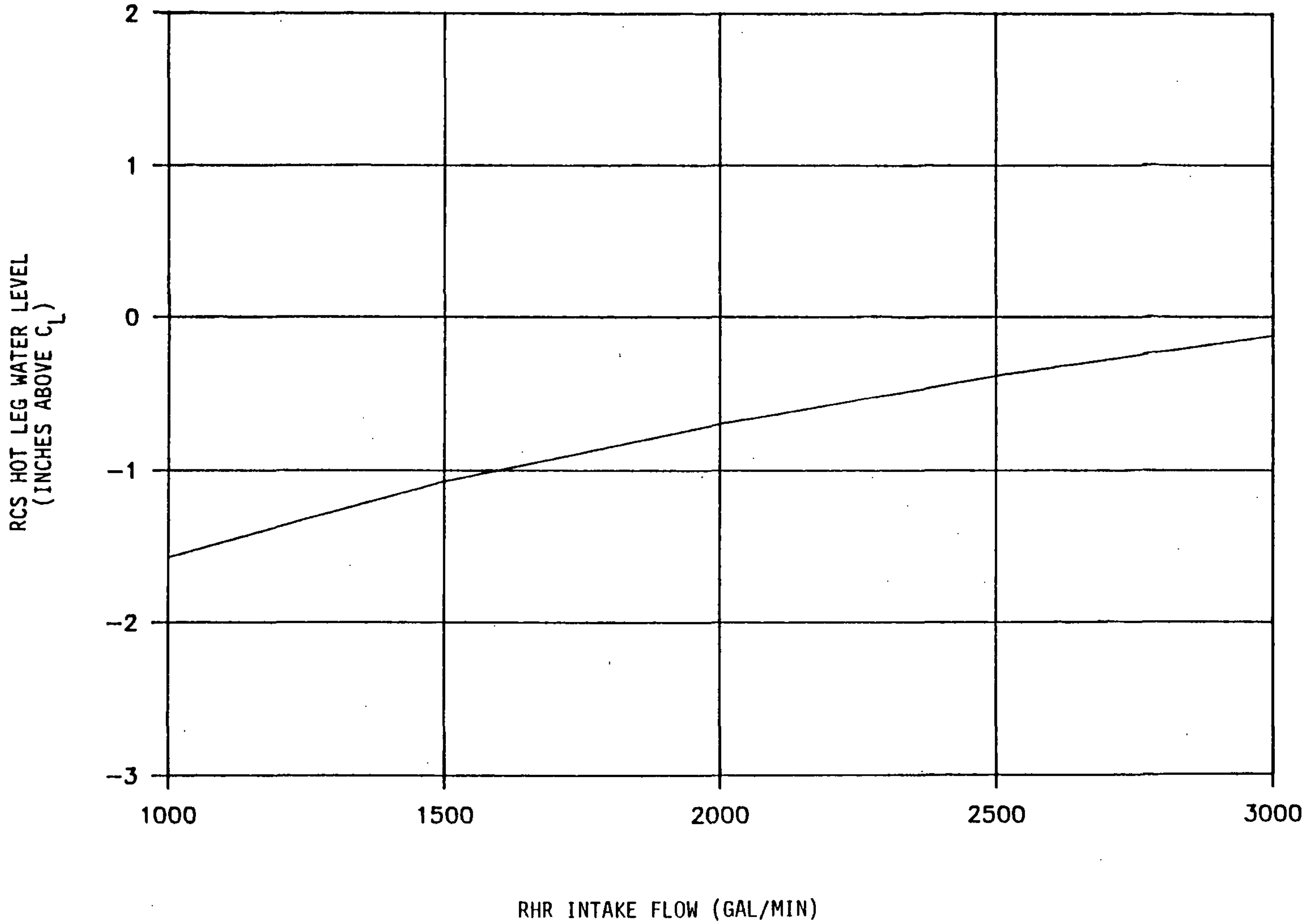
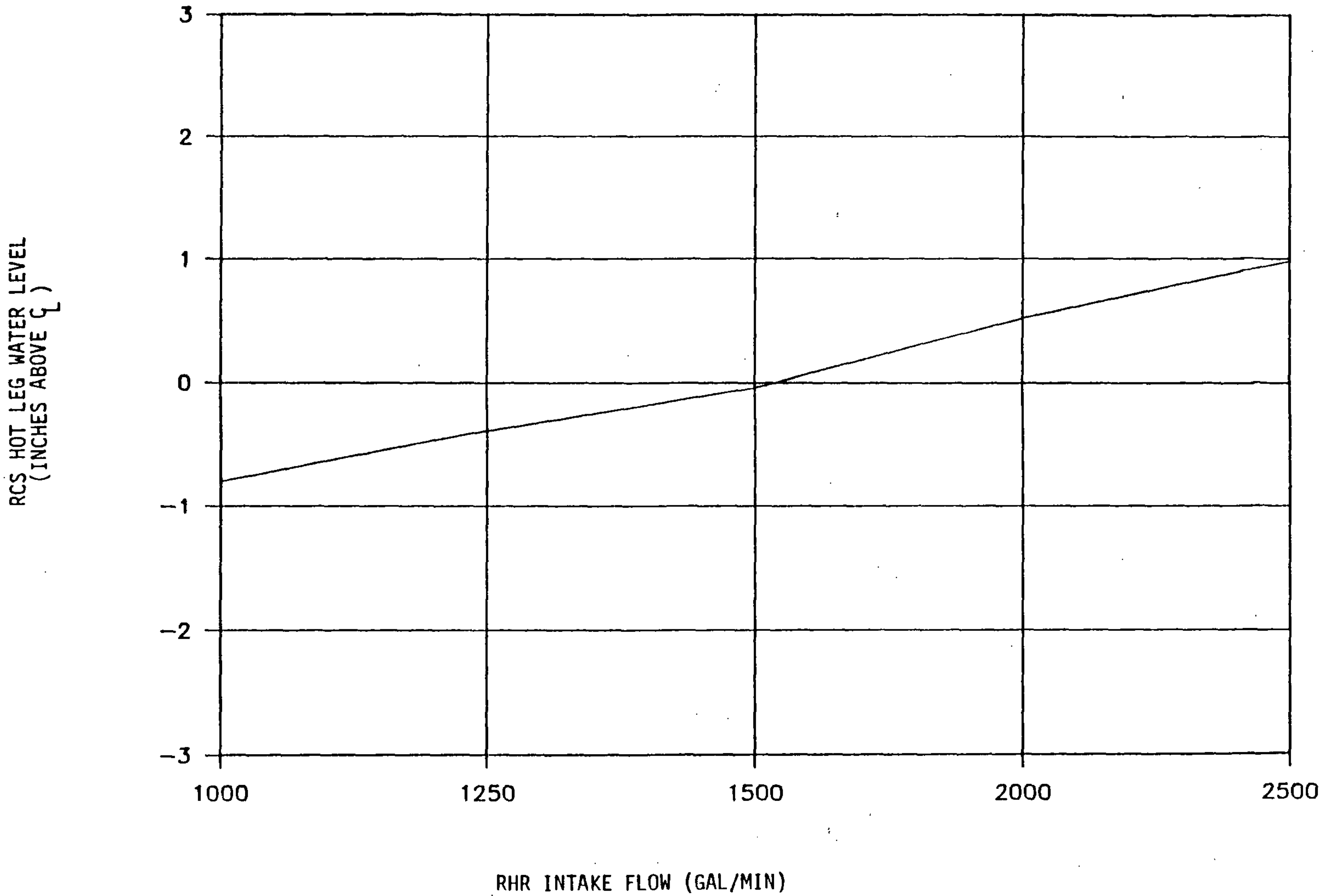


FIGURE 2-18
REQUIRED RCS WATER LEVEL
CATEGORY E PLANTS (90°/10")



3.0 THERMAL HYDRAULIC EVALUATION OF THE LOSS OF RHR WITH THE RCS LOOPS PARTIALLY FILLED

Following a loss of RHR during mid-loop operation, the core decay energy must be removed by some other means or the RCS will heatup, boil and pressurize to the cold overpressure setpoint. Steam generator condensation is one means of removing the core decay heat, however, the presence of air in the loops complicates that process. In addition, the RCS pressure boundary may not be intact during mid-loop operation because of various maintenance activities. Resulting RCS inventory losses from the openings after the RCS reaches saturation is another important consideration. This section will examine the thermal hydraulic response of the RCS following the loss of RHR during mid-loop operation.

3.1 Introduction and Purpose

The objective of the analyses presented in this section is to calculate the RCS thermal-hydraulic response to the loss of RHR during mid-loop operation for typical 2, 3 and 4 loop Westinghouse PWRs. The analyses were performed to determine the time to boiling, RCS pressurization rate and time to core uncovery for a number of postulated scenarios. For the current analyses, the times to core damage for the various scenarios were not determined. Instead, the times to core uncovery were conservatively used to determine the time available to mitigate the event.

These scenarios included sensitivities to study the effects of different vent opening sizes and locations, nozzle dam locations, and availability of steam generators for condensation. In addition, several possible high level recovery methods were analyzed.

These analyses can be used to specify the minimum constraints that will be needed to maintain a coolable geometry, i.e. prevent core uncovery. They can also be used as the basis for the writing of recovery procedures or guidelines.

3.2 Description of Analysis

This section discusses the operational concerns, case descriptions, analysis model, and input assumptions used for the mid-loop operation analysis.

3.2.1 Operational Considerations

The analysis presented in this report is intended to provide input to and support the procedures for draindown, mid-loop operation and loss of RHR during mid-loop operation. Several analysis concerns related to the loss of RHR cooling event during mid-loop operations have been identified and are summarized below.

First, during mid-loop operation, the core exit thermocouples may be disconnected in preparation for upper head removal. If the core exit thermocouples are not functional, a direct indication of RCS temperature would not be readily available if forced RHR flow is lost. A conservative estimate of the RCS heatup rate and time to saturation is therefore important to determine when core boiling will begin and for the timing of subsequent recovery actions.

Secondly, it is also important to know the RCS pressurization transient that follows the initial heatup to boiling. If pressure remains low for an extended period of time (e.g., less than approximately 40 psia), it would be possible to increase RCS inventory by gravity feed from the RWST (this mode of recovery was used at Diablo Canyon). If the pressure is higher but the makeup requirements are relatively low (on the order of 100 gpm or less), one charging pump could be used to increase RCS inventory. Additional high-pressure injection would be required for increased makeup requirements. If the heatup and pressurization transient is allowed to continue further, the RHR cut-in conditions (e.g. 350°F, 375 psig) and design conditions (e.g. 400°F, 600 psig) could be exceeded. It would then be necessary to use an alternate mode of cooling for interim or long term recovery prior to returning to the RHR cooling mode.

Thirdly, the RCS boil-off rate and time to core uncovery are important to know in order that core damage be prevented. Additional radiological concerns are introduced if core uncovery is allowed to occur for a prolonged period of time.

A fourth concern is maintenance activities and how they affect the safe operation of the plant. Openings in the RCS boundary can have a major impact on the RCS response after boiling starts. The RCS is often drained for the purpose of maintenance activities that introduce these openings. Typical examples include repair and/or inspection of valves, SG tubes, and RCP seals. The installation of SG nozzle dams is another activity that could potentially impact the system response. This analysis provides results related to these items that can be used for developing guidance to ensure safe operation during these maintenance activities.

A fifth area studied is the impact and timing considerations for various operator recovery actions taken in response to loss of RHR cooling. These results can then be used to develop operational guidance for the loss of RHR scenario.

3.2.2 Description of the Analysis Cases

The RCS heatup and pressurization rate following loss of RHR cooling during mid-loop operation is dependent upon several factors. For example, if the steam generators are in dry layup, steam produced by the boiling core will not be condensed significantly and pressure will increase rapidly. Core uncovery is also possible after RHR cooling is lost. For example, the steam produced by the core can vent to containment through a large steam vent path in the RCS. Without operator action to provide makeup water, the water above the core will eventually boil away leading to core uncovery. The presence of cold leg openings can also lead to faster RCS inventory losses if the RCS reaches saturation and starts to boil.

The WOG analyses for loss of RHR cooling during mid-loop operation have been divided into six catagories which will be described below. These six catagories cover various postulated conditions in the RCS during the loss of RHR cooling event.

In addition to these analyses, a set of typical recovery analyses has been included. These recovery analyses may be used in the development or improvement of plant specific procedures for recovery from a loss of RHR cooling during mid-loop operation.

The results of the analyses have been categorized by the power to heatup-volume ratio so they may be adjusted to produce plant specific results. This power to volume ratio (P/V) proves to be a convenient and meaningful parameter to use for determining the heatup rate and response to the loss of RHR cooling scenario. Based on a conservative application of NUREG-1269 (Reference 9), the heatup volume is comprised of the water volumes in the core and upper plenum plus 30% of the hot leg water. Since the hot leg water contribution is a small fraction of the heatup volume, the impact of loop isolation valves on the initial heatup transient is not significant. Section 3.10 provides guidance on using results based on this power to volume ratio and also presents more accurate methods for application of the thermal hydraulic analysis results.

Table 3.2.2-1 presents the P/V ratios for all of the domestic WOG member plants. The analyses were performed for typical 2, 3 and 4 loop plants. Table 3.2.2-2 presents the 3 plants used for the analyses. These plants were chosen to represent the 3 most common plant sizes. The P/V ratios were selected to cover typical ranges of this parameter.

Case A - Base Case Heatup and Pressurization Analyses

The purpose of this case is to determine the time to reach boiling in the core and the maximum RCS pressurization rate following the loss of RHR during mid-loop operation. The RCS is assumed to remain intact throughout the transient (i.e., no consequential failures were assumed such as the rupture of a tygon tube or failure of a nozzle dam), the steam generators are assumed to be dry so condensation is not possible, and no operator recovery actions are assumed.

A survey of utility members indicated that mid-loop operation could be established no earlier than 30 hours after shutdown. To provide some flexibility, the time after shutdown used in the analyses was varied between 20 and 200 hours to determine the effect on the heatup and pressurization rates.

An initial RCS temperature of 140°F was selected for these analyses. To determine the effect of the initial temperature on the heatup rate, sensitivity analyses were performed in which the initial temperature was varied between 100 and 160°F for the 4 loop plant.

In all, 13 separate analyses were performed to cover the various sensitivities for typical 2, 3 and 4 loop plants at different power levels. Table 3.2.2-3 provides a list of the assumptions for each of the analyses in this case. The results are tabulated as a function of the P/V ratio in Section 3.3.

Case B - Large Vent Analyses

The purpose of these analyses is to determine the time to core uncovery assuming a large (2.1 sq-ft modeled) steam vent path in the RCS. With a large steam vent path open to containment, the liquid inventory above the core will simply boil off after RHR cooling is lost and the RCS reaches saturation. In this case, the time for the upper plenum fluid level to reach the top of the core is a function of the initial fluid mass above the core and the decay heat.

The time after shutdown was varied in these analyses. Ten analyses were performed for this case to cover typical 2, 3 and 4 loop plants at various decay heat levels. Table 3.2.2-3 provides a list of the assumptions for each of the analyses in this case. The results are tabulated as a function of the P/V ratio in Section 3.4.

If the bottom of the opening is situated near the top of the hot legs (e.g., SG manway or LIV open on the hog leg side), an initial spill of two-phase mixture will occur prior to steady-state boil-off. Several analyses were performed to determine the corrections required to account for this initial spill.

Case C - SG Nozzle Dam Sensitivity Analyses

The purpose of these analyses is to determine the effect of SG nozzle dam placement and cold leg openings on core uncovery following the loss of RHR cooling during mid-loop operation. With a certain combination of SG nozzle dams in place and a cold leg opening, the RCS will pressurize and begin forcing fluid out of the opening soon after the core reaches saturation. This differential pressure between the hot and cold sides of the RCS will cause a rapid core uncovery.

The 2 loop plant model (at 48 hours after shutdown) was used for these limiting case study analyses. The placement of the nozzle dams and cold leg opening size and location were varied to determine the effect on the core uncovery rate. Spray line connections and all other steam relief paths were assumed shut, however, the gap between the hot leg nozzles and downcomer at cold conditions was modeled. This hot to cold side vent path has an area roughly comparable to that of an open pressurizer spray line.

Three separate analyses were performed for this case. Table 3.2.2-3 provides a list of the assumptions for each of the analyses in this case. The first scenario assumes that both hot leg nozzle dams are in place and one of the cold side SG manways is removed. This scenario was selected since it was felt that this situation could result in the fastest core uncovery. The second scenario assumes that the hot leg nozzle dams are in place and a 12" check valve in the cold leg (accumulator line) is open for repair or inspection. This scenario would also lead to a possible rapid core uncovery. The third scenario assumes a hot leg nozzle dam in one SG is in place and the cold side manway in the same SG is open. This scenario was selected to determine the effect of having the additional relief path through the other SG on the core uncovery rate predicted in the first scenario. The results are presented in Section 3.5.

Case D - Vapor Vent Sensitivity Analyses

The purpose of these analyses is to determine the effect of a small vapor vent opening on the RCS pressurization rate following a loss of RHR cooling during mid-loop operation. If a small vapor vent path is able to remove most of the steam generated by the core, the RCS pressurization may be limited so that gravity feed of RWST water would be able to recover the lost RCS inventory.

The 4-loop plant model (at 48 hours after shutdown) was used for these analyses. The size and location of the steam vent paths were varied to determine the affect on the pressurization rate.

Two analyses were performed for this case. Table 3.2.2-3 provides a list of the assumptions for each of the analyses in this case. In the first analysis, the head and pressurizer were vented through 3/4 inch lines. In the second analysis, the pressurizer PORVS were also assumed open to containment. The results of these analyses are presented in Section 3.6.

Case E - Cold Leg Opening Sensitivity Analyses

The purpose of these analyses is to determine the effect of various sized cold leg openings with no SG nozzle dams in place on the core uncovery rate and RCS pressurization rate following a loss of RHR cooling during mid-loop operation. The opening in the cold leg will remove liquid inventory and may result in a somewhat earlier core uncovery prediction than the large vapor vent path case.

The size of the liquid openings were varied to determine the affect on the core uncovery and RCS pressurization rate. Both 2 and 4 loop plant models (at 48 hours after shutdown) were used in these analyses.

Three types of analyses were performed for this case. Table 3.2.2-3 provides a list of the assumptions for each of the analyses in this case. The first analysis modeled a 100 gpm leak and was performed with the 4-loop plant model. This analysis bounds the results expected for a postulated rupture of tygon tube. In the cold leg opening study, five different cases were analyzed using the 2-loop and 4-loop models. The valve openings included 3", 6", and 12" cases. Condensation in the intact SG was also included in one of the cases. The last analysis modeled a 19" cold leg SG manway opening without nozzle dams in place and was performed with the 2-loop plant model. Results from these analyses are presented in Section 3.7.

Case F - SG Condensation Analyses

These analyses were performed to determine the effects of condensation on the RCS heatup and pressurization rates following the loss of RHR during mid-loop operation. With condensation, the RCS pressure will not rise as rapidly after the core begins to boil. This will allow the operator more time to realign flow paths to provide gravity feed from the RWST and recover RCS inventory.

Seven analyses were performed for this case. Table 3.2.2-3 provides a list of the assumptions for each of the analyses in this case. For each analysis, the RCS was assumed to remain intact throughout the transient. The fraction of steam generators with water in the secondary side was varied in the first five analyses, i.e., 1 of 2 SGs is 0.5, 1 of 3 SGs is 0.33, etc., to determine the effect on the RCS pressurization rate. The last two analyses were performed at an increased time after shutdown (120 versus 48 hours) to show the effect of reduced core decay heat. The results of these analyses are presented in Section 3.8.

Case G - Recovery Analyses

The recovery analyses were performed to present the RCS response to several possible high-level recovery actions following a loss of RHR during mid-loop operation. Operator recovery actions were intentionally not included in the previous analysis cases. The recovery analyses investigate various methods for increasing RCS inventory (e.g., RWST gravity feed, forced makeup) and alternate cooling modes (SG condensation, bleed and feed) that may be used until RHR cooling can be reestablished.

In all, 11 recovery analyses were performed in this study. Table 3.2.2-3 provides a list of the assumptions for each of the analyses.

The first 2 analyses were performed using the 2 loop plant, 48 hours after shutdown. In the first analysis, both steam generators were assumed to be empty so condensation was not available and the RCS would pressurize rapidly. In the second analysis, 1 SG was assumed to be at the 5% narrow range level. In both analyses, the RCS was assumed to remain intact throughout the transient.

The recovery method assumed in the first analysis was to initiate RWST gravity feed approximately 15 minutes after the loss of RHR cooling to determine if enough subcooled water could be injected at that time to significantly increase RCS inventory. The recovery method assumed in the second analysis was to initiate gravity feed at a later time (30 minutes) since SG condensation would help reduce the RCS pressurization rate.

The third analysis was performed using the 4 loop plant, 48 hours after shutdown. All 4 SGs were assumed to be empty. The recovery method assumed in this analysis was to initiate 120 gpm of charging (typical PD pump capacity for a 4 loop plant) 30 minutes after the loss of RHR cooling. The purpose of this analysis was to determine if that amount of charging flow was able to restore RCS inventory.

The fourth recovery analysis was performed using the 3-loop plant, 48 hours after shutdown. A large steam vent path was assumed and all SGs were empty. The recovery method used in this analysis was to initiate 90 gpm of charging (typical PD pump capacity for a 3-loop plant) just prior to core uncovery. The purpose of this analysis was to determine if that amount of charging flow this late in the transient would be able to restore RCS inventory and prevent core uncovery.

The fifth and sixth recovery analyses were performed using the 2 loop plant, 48 hours after shutdown. A 12" cold leg opening was assumed in both analyses. In the first, no hot leg nozzle dams were in place, and in the second both hot leg dams were in place.

The recovery method used in these analyses was to initiate 55 gpm of makeup flow (typical charging flow for a 2-loop plant) to the RCS. In the first analysis this flow was started 30 minutes after RHR was lost and was injected into one cold leg. In the second analysis, this flow was started at 11 minutes (just after the core started to boil) and injected into the hot leg. (Note: for most plants, hot leg injection can only be performed using SI pumps, so the flow rate expected would be much higher.) The purpose of these analyses was to determine if this small amount of makeup flow would be able to restore RCS inventory and prevent core uncovery.

The seventh, eighth and ninth recovery analyses were also performed with the 2 loop plant, 48 hours after shutdown. In the first 2 analyses, the cold side SG manway was assumed to be open and both hot leg nozzle dams installed. In the ninth analysis, a 12" valve was assumed to be open instead.

The recovery method used in these analyses was to initiate 360 gpm of safety injection flow (a conservatively low flowrate for a high-pressure SI pump) to the RCS 11 minutes (just after the core starts to boil) after the loss of RHR cooling. In the first analysis, this flow was injected into the cold legs. In the last two analyses, the flow was injected into the hot legs. The purpose of these analyses was to determine if the SI flow would be able to restore RCS inventory or instead pass out of the cold leg opening.

The tenth recovery analysis was also performed with the 2-loop plant, 48 hours after shutdown. Both steam generators were assumed to be dry at the time RHR cooling was lost. The recovery method used in this analysis was to begin refilling one of the steam generators at 15 minutes and allow RWST gravity feed to begin at 30 minutes. The purpose of this analysis was to determine if refilling the steam generator would significantly decrease the RCS pressurization rate and therefore increase the time available for the operator to align for RWST gravity feed.

The last recovery analysis was performed with the 4-loop plant, 48 hours after shutdown. The SGs were assumed to be empty and the RCS was assumed to remain intact throughout the transient. The recovery method used in this analysis was to open a pressurizer PORV (or equivalent vent path) and start 450 gpm of SI flow after the RCS had pressurized to approximately 400 psia. The purpose of this analysis was to determine if this "bleed and feed" recovery with one train could be used as a last resort for decay heat removal in the event other recovery actions are not successful.

3.2.3 Analysis Model Description

The thermal hydraulic analyses described in this report was performed using the interactive computer program TREAT-NC, the non-condensible gas version of TREAT (Transient Real-time Engineering Analysis Tool). A description of TREAT can be found in Reference 13. Appendix E describes TREAT-NC.

3.2.4 Description of Input and Assumptions

Conservative input assumptions have been made in the TREAT analysis which maximize the core heatup rate and pressurization and minimize the time to boiling and core uncovery. A number of these assumptions are explained below.

1. At the time of loss of RHR cooling, flow is assumed to be zero at all points in the system. In reality, RHR flow would coast down to zero from its initial rate when the RHR pumps are lost. The assumption neglects a small amount of core heat that would be transported to the hot leg(s) as the flow decays.

2. The decay heat power was determined using the ANSI/ANS-5.1-1979 decay heat standard (Reference 14) and includes 2-sigma uncertainty plus conservative estimates for heavy element decay and fission product absorption. A high average burnup was also assumed in these calculations (core average

irradiation time of 800 days or 30,000 MWD/MTU). As a cross-check on the results, the ANSI/ANS-5.1-1979 values were then compared to a Westinghouse 3-region core calculation and found to be within 2% over the range of decay times of interest. (For the 3-region core calculations, the irradiation times were 333, 667, and 1000 days.) The higher of the two decay heat powers was then used in the analysis. Figure 3.2.4-1 shows the decay heat power as a function of time after reactor shutdown. At 20, 48, 120, and 200 hours after shutdown, the decay heat power is .64, .48, .33, .26% of full power respectively.

3. No credit for operator action is taken except for the recovery (G) and SG condensation (F) cases. In the SG condensation cases, the SG PORVs are assumed to be opened (or previously opened) once secondary side boiling occurs.

4. The area of the flow link connecting the core and downcomer is given a smaller than actual flow area to minimize mixing of the cold downcomer water with the hot core water. This keeps the core isolated from the cold leg side, minimizes the time to boiling and maximizes the pressurization rate. The downcomer will still heat up a small amount due to heat transfer across the baffle-barrel wall. For cases where this input would be non-conservative (e.g., cold leg opening cases) the flow area is increased.

5. The plant models used in the analysis assume downflow in the barrel-baffle region and standard fuel in the core region. Both of these assumptions minimize the water allowed to heatup in the core region. Small bypass flows (e.g., in the annular gap between the hot leg nozzles and the core barrel) are also conservatively ignored.

6. Heat transfer to containment air and support structures is neglected.

In addition to these conservative assumptions and input, a number of other realistic or simplifying assumptions have been made. These are discussed below.

1. Except in a few cases where heat transfer to some of the metal heat sinks is reduced or neglected for conservatism or code stability reasons, the models assume heat transfer to most of the major structures in the RCS.

2. The RCS level is assumed to be at nozzle centerline when the loss of RHR cooling transient occurs. Additionally, the remainder of the RCS is assumed to be comprised entirely of air at the same temperature as the RCS. The metal heat sinks are also at RCS temperature.

3. The fluid volume of the core and the upper plenum is lumped into one 'core' node. Originally, this region was represented with two core nodes and one upper plenum node. Preliminary analysis indicated that the one node model was adequate since the temperatures in the three node model were the same (to within about 10°F) at the onset of boiling.

4. The annular gaps between the hot leg nozzles and the core barrel are indirectly modeled by adding half the area of the gap to an existing flow link connecting the upper head to the downcomer. This is an approximation to the actual geometry which would have a vapor flow path directly connecting the upper plenum to the downcomer. Note that this correction is only made for the vapor flow path. Circulation of mixture through these gaps is conservatively ignored.

5. The RCS model used neglects volumes for a number of small boundary regions. These include safety injection lines, loop bypass, and RTD manifold lines, etc.

6. For cases involving condensation in the SGs, a variation on this noding is used which combines the hot leg nodes with the core node as one 'supernode.' This modeling results in a slightly longer time to core boiling since the hot leg water must be heated to saturation before the

RCS pressurizes. The resulting delay in time to boiling is typically less than one minute. This has negligible impact on the SG condensation cases analyzed.

The general RCS and secondary noding can be summarized as follows:

1 pressurizer node (on loop 1)
3 crossover/cold leg nodes/loop
1 hot leg node/loop
4 SG tube nodes/loop
3 vessel nodes (core, downcomer, upper head)
4 SG nodes/loop (downcomer, tube region, steam dome, steamline)

7. For the 2 and 3 loop plants, all loops are modeled explicitly. For the 4 loop plant, loops 2,3 and 4 are lumped together as loop 2 in the TREAT model. All models assume the pressurizer is located in loop 1. The specific geometry of the TREAT input is based on the following plants:

2 loop - R. E. GINNA
3 loop - SURRY UNIT 1
4 loop - DIABLO CANYON UNIT 2

Table 3.2.2-1

Effective Heatup Volume and Core Power Data

WOG Analysis for Loss of RHR at Mid-Loop Conditions

Plant	Number of Loops	Core Power Po (MWt)	Heatup Volume Vo (cu-ft)	Ratio Po/Vo
Point Beach 1/2	2	1519	640	2.37
Ginna	2	1520	640	2.38
Prairie Island 1/2	2	1650	640	2.58
Kewaunee	2	1650	640	2.79
San Onofre 1	3	1347	890	1.51
Turkey Point 3/4	3	2200	945	2.33
H. B. Robinson 2	3	2300	945	2.43
Surry 1/2	3	2441	945	2.58
Farley 1/2	3	2652	945	2.80
Beaver Valley 1/2	3	2775	945	2.94
North Anna 1/2	3	2775	945	2.94
V. C. Summer	3	2775	945	2.94
Shearon Harris	3	2775	945	2.94
Yankee Rowe	4	600	230	2.61
Haddam Neck	4	1825	1050	1.74
Indian Point 2	4	2758	1260	2.19
Indian Point 3	4	3025	1260	2.40
Zion 1/2	4	3250	1260	2.58
Cook 1	4	3250	1260	2.58
Cook 2	4	3411	1260	2.71
Trojan	4	3411	1260	2.71
Salem 1/2	4	3411	1260	2.71
Diablo Canyon 1/2	4	3411	1260	2.71
Byron 1/2	4	3411	1260	2.71
Braidwood 1/2	4	3411	1260	2.71
Catawba 1/2	4	3411	1260	2.71
Comanche Peak 1/2	4	3411	1260	2.71
Millstone 3	4	3411	1260	2.71
McGuire 1/2	4	3411	1260	2.71
Seabrook	4	3411	1260	2.71
Sequoyah 1/2	4	3411	1260	2.71
Vogtle 1/2	4	3411	1260	2.71
Watts Bar 1/2	4	3411	1260	2.71
Wolf Creek	4	3411	1260	2.71
Callaway	4	3565	1260	2.83
South Texas 1/2	4	3800	1365	2.78

Notes: 1. In some cases, uprated core powers have been listed.
2. Heatup volumes have been calculated conservatively low using NUREG-1269 methodology. Volumes for the older non-standard plants were estimated based on core size.
3. Plants with 14x14 OFA may add 4% to the heatup volume. Plants with 17x17 OFA or Vantage-5 may add 2.7%.

Table 3.2.2-2

Analysis Model P/V Ratios

Plant Model	Power-to-Heatup Volume (MWt/ft^3)
2-Loop : R. E. Ginna	$\frac{1520}{640} = 2.38$
3-Loop : Surry	$\frac{2441}{945} = 2.58$
4-Loop : Diablo Canyon 2 (Uprated)	$\frac{3700}{1260} = 2.94$

Table 3.2.2-3

List of Analyses Assumptions for

Loss of RHR During Mid-Loop Operation

Case A - Base Case Analyses

RCS Intact
No SG Water

	Loops	Decay	Temp
1.	2-Loop	/20 hrs	/140°F
2.	2-Loop	/48 hrs	/140°F
3.	2-Loop	/120 hrs	/140°F
4.	3-Loop	/20 hrs	/140°F
5.	3-Loop	/48 hrs	/140°F
6.	3-Loop	/120 hrs	/140°F
7.	4-Loop	/20 hrs	/140°F
8.	4-Loop	/48 hrs	/140°F
9.	4-Loop	/120 hrs	/140°F
10.	4-Loop	/200 hrs	/140°F
11.	4-Loop	/48 hrs	/100°F
12.	4-Loop	/48 hrs	/160°F
13.	2-Loop	/48 hrs	/140°F/All Dams

Case B - Large Vent Analyses

Large Steam Vent Opening
No SG Water

	Loops	Decay	Temp
1.	2-Loop	/20 hrs	/140°F
2.	2-Loop	/48 hrs	/140°F
3.	2-Loop	/120 hrs	/140°F
4.	3-Loop	/20 hrs	/140°F
5.	3-Loop	/48 hrs	/140°F
6.	3-Loop	/120 hrs	/140°F
7.	4-Loop	/20 hrs	/140°F
8.	4-Loop	/48 hrs	/140°F
9.	4-Loop	/120 hrs	/140°F
10.	4-Loop	/200 hrs	/140°F

Case C - Nozzle Dam Analyses

2-Loop Plant
48 Hrs After Shutdown
All Vapor Vents Closed

1. Both Hot Leg Dams Installed, Cold Side Manway (19") Removed in One SG

2. Both Hot Leg Dams Installed, Large Check Valve (12") Open for Repair

3. Hot Leg Dam in Place, SG Manway Open on Cold Side of Same SG

Case D - Vapor Vent Analyses

4-Loop Plant
48 Hrs After Shutdown

1. Przr Vented to Cntmt - 3/4"
   Head Vented to Cntmt - 3/4"

2. 2 Przr PORVs vent to Cntmt (0.022 sq-ft vent area)

Table 3.2.2-3 (continued)

List of Analyses Assumptions for
Loss of RHR During Mid-Loop Operation

Case E - Liquid Vent Analyses

48 Hrs After Shutdown
Cold Leg Opening

1. 4-Loop, 100 gpm leak
   (Ruptured Tygon Hose)
2. 2-Loop, 12" Check Valve Open
2a. 2-Loop, 6" Check Valve Open
2b. 2-Loop, 6" Check Valve Open
   Water in Intact Loop SG
2c. 4-Loop, 6" Check Valve Open
2d. 4-Loop, 3" Check Valve Open
3. 2-Loop, 19" SG Manway Open

Case F - SG Condensation

	Loops	SGs with Water	Decay
1.	2-Loop,	1 SG,	48 Hrs
2.	3-Loop,	1 SG,	48 Hrs
3.	3-Loop,	2 SG,	48 Hrs
4.	4-Loop,	1 SG,	48 Hrs
5.	4-Loop,	4 SG,	48 Hrs
6.	4-Loop,	1 SG,	120 Hrs
7.	4-Loop,	4 SG,	120 Hrs

Case G - Recovery Analyses

1. 2 Loop, 48 hr decay, both SGs empty, RCS intact
   - Initiate gravity feed after 15 minutes

2. 2 Loop, 48 hr decay, 1 SG empty, 1 full, RCS intact
   - Initiate gravity feed after 20 minutes

3. 4 Loop, 48 hr decay, all SGs empty, RCS intact
   - Initiate 120 gpm charging after 30 minutes

4. 3 Loop, 48 hr decay, all SGs empty, large steam vent
   - Initiate 90 gpm charging just prior to core uncovery

5. 2 Loop, 48 hr decay, all SGs empty, 12" valve open, no nozzle dams in place
   - Initiate 55 gpm makeup to cold leg after 30 minutes

5a. 2 Loop, 48 hr decay, all SGs empty, 12" valve open, both hot leg nozzle dams in place
   - Initiate 55 gpm makeup to hot leg just after core boils

6. 2 Loop, 48 hr decay, all SGs empty, cold side manway open, both hot leg nozzle dams in place
   - Initiate 360 gpm SI flow to cold legs just after core boils

6a. 2 Loop, 48 hr decay, all SGs empty, cold side manway open, both hot leg nozzle dams in place
   - Initiate 360 gpm SI flow to hot legs just after core boils

Table 3.2.2-3 (continued)

List of Analyses Assumptions for

Loss of RHR During Mid-Loop Operation

Case G - Recovery Analyses (continued)

6b. 2 Loop, 48 hr decay, all SGs empty, 12" valve open, both hot leg nozzle dams in place
- Initiate 360 gpm SI flow to hot legs just after core boils

7. 2 Loop, 48 hr decay, both SGs empty
- Begin refilling one SG at 15 minutes, begin gravity feed at 30 minutes

8. 4 Loop, 48 hr decay, all SGs empty
- Open a PRZR PORV, start 450 gpm of SI after RCS reaches 400 psia (bleed and feed recovery)

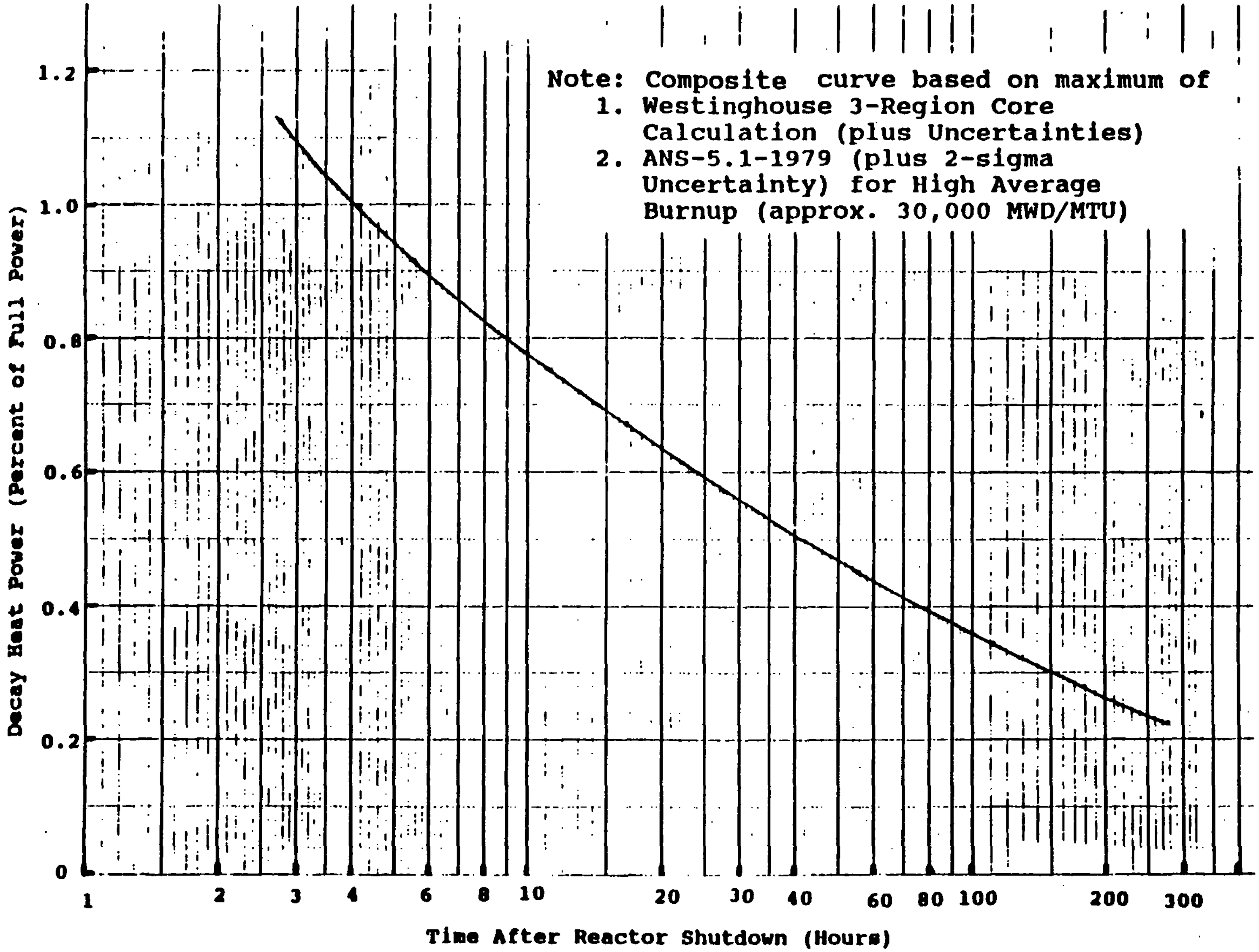


Figure 3.2.4-1 Decay Heat Power Versus Time After Reactor Shutdown

3.3 Base Case Analysis

The base case analysis was performed to determine time to saturation and maximum RCS pressurization transients for loss of RHR cooling while at mid-loop conditions. For these analyses, the RCS was considered to be intact (no vent paths or openings) and all steam generators were assumed to be in dry layup. Representative transients for the 2, 3, and 4-loop plants are described in the following sections.

3.3.1 Two-Loop Case A.2, 48 Hours after Shutdown

In the scenario described here, the reactor is assumed to have been shutdown for 48 hours following an extended period of full power operation at 1520 MWt. Based on the decay heat curve of Section 3.2, the core power is 0.48% of full power or 7.3 MWt. The RCS initial temperature is 140°F. At t=0, the time RHR cooling is assumed to be lost.

The RCS pressure transient is shown in Figure 3.3.1-1. Pressure remains nearly constant at 15 psia until the core reaches saturation (213°F) at about 570 seconds (Figure 3.3.1-2). After boiling starts, the pressure starts to rapidly increase as part of the decay energy goes to steam production. At the end of the 4800 second transient, approximately 3000 lbm of steam plus the original 250 lbm of air exists in the RCS; the corresponding pressure is approximately 420 psia.

The initial core heatup to boiling occurs at a nearly uniform rate (Figure 3.3.1-2). The heatup rate then decreases as steam is produced and energy losses to the metal heat sinks become more important. The core temperature is at saturation for the remainder of the transient and eventually reaches 450°F at 4800 seconds. The downcomer warms from 140°F to 160°F due to heat transfer through the barrel-baffle region; additional heatup due to bypass flow paths (e.g., between the hot leg nozzles and the downcomer) has been neglected to maximize the pressurization.

During the initial heatup to saturation, the hot leg temperatures remain less than 150°F (Figure 3.3.1-3). After boiling starts, the hot legs approach saturation and the temperatures continue to increase as the core temperature increases. Note that by 600 seconds, the hot leg temperatures have increased to 200°F; after this time, RCS pressure increases at an accelerated rate.

The core and downcomer levels are shown in Figure 3.3.1-4. During the initial heatup, the core level swells several inches and the downcomer level drops a similar amount. The core level increases to 26 ft after boiling starts (the top of the hot leg is at 26.6 ft), and remains near this level for the duration of the transient. In response, the downcomer level decreases until 1000 seconds; after this time, the core void fraction stabilizes at about 10 % and a hydraulic balance between the core and the downcomer is established.

As RCS pressure continues to increase, the water level at the outlet of the steam generators is depressed forcing water into the pump suction and cold leg piping. An insurge of this water from the cold legs eventually causes a downcomer and core level increase at 1800 seconds. The downcomer level then gradually drops (until 2400 seconds) to reestablish the hydraulic balance with the core. After this time, the core and downcomer level response is strongly influenced by the response of the pressurizer and corresponding hot leg levels (Figure 3.3.1-5).

Since the pressurizer has flow communication with the RCS through the surge line, some water would be drawn up into the (lower pressure) pressurizer region as soon as the hot leg level swells sufficiently to cover the bottom of the surge line. The first such insurge occurs at approximately 800 seconds, i.e., soon after boiling starts and the core and hot leg levels swell. Between 1800 and 2400 seconds, the core and hot leg levels again swell and a more significant volume of water is predicted to move into the pressurizer starting at 2400 seconds. This insurge continues until about 3700 seconds. In response, the core, downcomer, and hot leg levels gradually decrease. Thus, after 3700 seconds, the liquid insurge stops and levels in the RCS stabilize.

Since upper plenum level has stabilized to a level higher than the initial level, the transient described here would not produce the most conservative and limiting uncovery and core damage results. The time to boiling and RCS pressurization data, however, will be used in the subsequent evaluation given in Section 3.3.6.

3.3.2 Three-Loop Case A.5, 48 Hours After Shutdown

The 3-loop plant response to the loss of RHR during mid-loop operation 48 hours after shutdown with the RCS intact and the steam generators in dry layup is similar to the 2-loop plant transient response presented above. The typical transient response for a 3 loop plant is presented in Figures 3.3.2-1 through 3.3.2-5.

Since the 3 loop P/V ratio is slightly higher than the 2 loop plant, the core reaches saturation a little earlier (at 520 seconds) as shown in Figure 3.3.2-2.

After boiling begins, the 3-loop plant pressurizes slightly slower than either the 2 or 4 loop plants as shown in Figure 3.3.2-1. The reason for this is that the 3-loop plant has more total volume per megawatt than the 2 and 4-loop plants so an equivalent amount of steam production will result in a slower pressurization rate.

The core and downcomer mixture level response shown in Figure 3.3.2-3 is similar to that of the 2-loop plant. The core mixture level initially increases soon after boiling begins, then slowly decreases. The decrease in core mixture level occurs as water is forced into the pressurizer through the surge line. The pressurizer and hot leg mixture levels are shown in Figure 3.3.2-4. Approximately 5000 lbm of water has been converted to steam by the end of the transient as shown in Figure 3.3.2-5.

3.3.3 Four-Loop Case A.8, 48 Hours After Shutdown

The reactor is assumed to have been shutdown 48 hours following an extended run at full power of 3700 MWt. Decay heat is therefore 17.76 MWt (16840 BTU/sec). Initial RCS temperature is 140°F and at time t=0 RHR flow is lost (and assumed isolated).

Figure 3.3.3-1 shows RCS pressure. Pressure begins to rise from 15 psia once the core reaches saturation at approximately 480 seconds (see Figure 3.3.3-2). The pressurization rate is dominated by the rate of steam production (boil-off) and pressure continuously rises at an increasing rate as steam production rate increases with time. There is a small slope change at about 2800 sec which corresponds to cold water flowing from the downcomer into the core after water in the loop seal piping is forced into the cold leg and downcomer. At the end of the 4000 second transient, RCS pressure has increased to 431 psia and a net of 7100 lbm of liquid has been boiled-off to steam.

Figure 3.3.3-2 shows a linear rise in core temperature with time until saturation at 480 seconds, followed by a continuous temperature rise at system saturation temperature to 450°F at 4000 seconds. The hot leg temperatures start to increase at the onset of boiling (480 sec) and reach T_{sat} at about 800-1000 sec.

Figure 3.3.3-3 shows core level swelling as it is heated to saturation, followed by a steady decrease as mass is boiled off and also as the pressurizer absorbs a steady insurge of mixture mass. Downcomer level decreases also to maintain a hydraulic balance with the core. At 2200 sec, the loop 1 loop seal clears and the downcomer level increases. This causes a delayed increase in core level. At 2800 sec, the same event occurs more dramatically when the lumped loop (representing plant loops 2,3 and 4) loop seal clears. After this event, the core and downcomer levels return to their earlier balance trends.

Figure 3.3.3-4 shows pressurizer level increasing as it absorbs an influx of mixture mass from the hot leg and core until the hot leg has emptied to below the surge line elevation (1000 sec). The pressurizer mixture level then increases at a slow rate which corresponds to the condensation of most of the steam entering it.

The system total vapor mass, which strongly correlates to system pressure, is shown on Figure 3.3.3-5. The system initially has 566 lbm of air. An additional net 7100 lbm of steam exists at 4000 sec. The curve shows a slightly increasing accumulation rate which is attributable to a smaller heat of vaporization at elevated pressures.

The heat transfer rate to the core water is shown on Figure 3.3.3-6. This heat rate never quite equals the decay heat rate as a portion of the decay heat added to the water is transferred to the adjacent metal nodes, namely the baffle-barrel. Also part of the decay heat is stored in the core metal itself. The net heat addition is plotted. At the end of the run, the net heat to the water is constant at 14600 BTU/sec. Decay heat is 16800 BTU/sec, so heatup of the core metal accounts for 13% of decay heat.

3.3.4 Four-Loop Case A.11, 48 Hours after Shutdown, 100°F Initial Condition

For this case, all conditions are assumed identical to case A.8 with the exception that RCS and metal temperatures are set to 100°F initially.

By comparing the pressurization plots for this case and case A.8, two benefits of a lower initial temperature can be observed. Figure 3.3.4-1 shows an overlay of the two pressure plots. The first benefit is a 285 second delay in the time to core boiling. The second is an initial slower pressurization rate once the low temperature case does start boiling. This can be observed in Figure 3.3.4-2, where both cases A.8 and A.11 have been time shifted so that t=0 corresponds to the onset of boiling. The decrease in the pressurization rate is due to the impact of the metal heat sinks and water in the rest of the system, which are colder at a given RCS temperature for this case than for case A.8. After a period of time, this difference in the pressurization rate becomes diminished and the slopes of the pressure plots become equal (at the same normalized time of Figure 3.3.4-2). The final constant value of this second lag is approximately 350 sec, so the time to reach any pressure greater than about 100 psia is increased 635 sec.

3.3.5 Two-Loop Pressurization with SG Nozzle Dams Installed (Case A.13)

If nozzle dams are installed in both steam generators of the two-loop plant used in these analyses, the RCS vapor volume above mid-loop changes from 3806 cu-ft to 1973 cu-ft, i.e., 52% of the original volume. Thus, it would be expected that the RCS would pressurize about twice as fast as in the base case without dams after boiling starts, provided the nozzle dams remain intact.

To accurately determine the pressure transient for the configuration with all nozzle dams in place requires considerable renoding and geometry changes to the TREAT two-loop model. An approximate solution, however, was obtained by restricting the flow areas at the SG inlet and outlet and removing the remainder of the required volume from the pressurizer and upper head regions. Because of global compressibility, the flow area reduction technique did not completely shut off the SGs from the RCS. This is because the steam plus air partial pressures in each node must add up to the total RCS pressure. However, the net steam in the RCS (core production minus droplet and heat sink wall condensation) is expected to be predicted reasonably well. Knowing the total amount of steam present and using the ideal gas law, it is possible to correct the results and obtain an approximate solution for the RCS system.

The results of this analysis for the 48 hours after shutdown case is shown in Figure 3.3.5-1. The dashed line represents the corrected value of the RCS pressure. Note that RCS pressure reaches 200 psia at about 1950 seconds. This is 1380 seconds after the core reaches saturation. For Case A.2 without dams (see Section 3.3.1), the RCS pressure does not reach 200 psia until 3280 seconds, 2710 seconds after the start of boiling. The two time differentials (1380 versus 2710 seconds) are, to a close approximation, inversely proportional to the initial vapor volumes. This shows that simple scaling can be used to estimate the pressure transient for other scenarios of interest.

It is expected that the 3-loop and 4-loop plants will also pressurize at approximately double the rates of the previous base cases since the vapor volumes above mid-loop are in similar proportion. For the 3-loop plant, the volumes that apply are 6258 cu-ft without and 2950 cu-ft with SG nozzle dams (a ratio of 47%). For the 4-loop plant, the volumes that apply are 8403 cu-ft without and 3987 cu-ft with SG nozzle dams (also a ratio of 47%).

The SG nozzle dams have limited strength capability, so the transient described here for the case of all SG nozzle dams in place will be valid only up to a certain RCS pressure. A typical design pressure for the SG nozzle dams is 13 psig (28 psia). However, they are normally tested to 28 psig without failure, begin to yield at 47 psig, and have been tested to an ultimate strength of 56.5 psig (71 psia). At this ultimate limit, the dams would be expected to leak; it is not likely that they would catastrophically fail until pressure increases to a higher value. Since higher strength dams are also available, it may be possible for RCS pressure to increase to 100 psia or higher before nozzle dam failure occurs. Based on the study presented here, RCS pressure reaches 100 psia before 1500 seconds (25 minutes), i.e., approximately 15 minutes after the RCS starts to boil. Thus, even assuming high strength dams with a capability of 100 psia, the time to potential failure after the onset of boiling is comparatively short.

The nature of the previous pressurization transient changes altogether if one of the SG nozzle dams does fail. If a dam on the hot leg side fails first, the RCS would depressurize and the SG manway opening near the failed dam would provide a vent path for the air and boil-off steam to escape. The scenario for this case would be similar to that described in the next section (3.4) for the large vent analysis.

A more severe situation would occur if a cold side dam fails first. For this scenario, water would be forced out of the cold side manway at a rapid rate. The core would uncover within minutes (possibly seconds) after the dam fails and remain uncovered for a prolonged period of time unless action is taken to increase RCS inventory. This transient resembles Case C.1 (cold side SG manway opening, hot side isolated) described in Section 3.5 except the uncovery transient could be even faster if the dam fails at a high pressure. Recovery guidance for Case C.1 presented in Section 3.9.4 describes actions that can also be followed for this cold side SG nozzle dam failure case.

3.3.6 Summary of Base Case Analyses

The power-to-heatup volume ratio is used to try to make the heatup results independent of the type of plant being modeled. For example, the 2-loop plant, which has the smallest power to heatup-volume ratio, reaches saturation latest for a given time after shutdown.

Table 3.3.6-1 presents as comparison of the 2, 3 and 4-loop base case transient pressurization rates and times to saturation as a function of the time after shutdown. Times to pressurize to 30 psia (typical limit for RWST gravity feed) through 400 psia (typical RHR cut-in pressure) are indicated. Figures 3.3.6-1 through 3.3.6-3 present a comparison of the pressurization rate curves at various times after shutdown for the 2, 3 and 4 loop plants respectively. Figure 3.3.6-4 presents the time to reach boiling as a function of the time after shutdown for 3 power to heatup-volume ratios. Figure 3.3.6-5 presents the heatup rate (°F/min) as a function of the time after shutdown for the 3 power to heatup-volume ratios. Section 3.10 describes how the results of these analyses may be modified using the power to heatup-volume ratios to produce plant specific information.

TABLE 3.3.6-1

BASE CASE SUMMARY
RCS INTACT, 140°F, NO SG CONDENSATION

Case	Plant Type	Time After Shutdown	Decay Heat (MWt)	T_{sat}	Time in Seconds to Reach 30 psia	200 psia	400 psia
A.1	2-Loop	20 Hrs	9.73	415	700	2570	3600
A.2	2-Loop	48 Hrs	7.30	560	980	3280	4800
A.3	2-Loop	120 Hrs	5.02	830	1560	5230	8000
A.4	3-Loop	20 Hrs	15.62	380	645	2720	3800
A.5	3-Loop	48 Hrs	11.72	520	910	3701	5245
A.6	3-Loop	120 Hrs	8.06	770	1430	5600	8000*
A.7	4-Loop	20 Hrs	23.7	350	650	1800	2700
A.8	4-Loop	48 Hrs	17.8	475	875	2600	3875
A.9	4-Loop	120 Hrs	12.2	725	1400	4250	7250*
A.10	4-Loop	200 Hrs	9.62	900	1750	5550	8125*
A.11	4-Loop (100°F)	48 Hrs	17.8	750	1300	3300	4500*
A.12	4-Loop (160°F)	48 Hrs	17.8	350	600	2300	3600
A.13 (All SG Nozzle Dams in Place)	2-Loop	48 Hrs	7.3	560	770	1950	—

* - Extrapolated Result

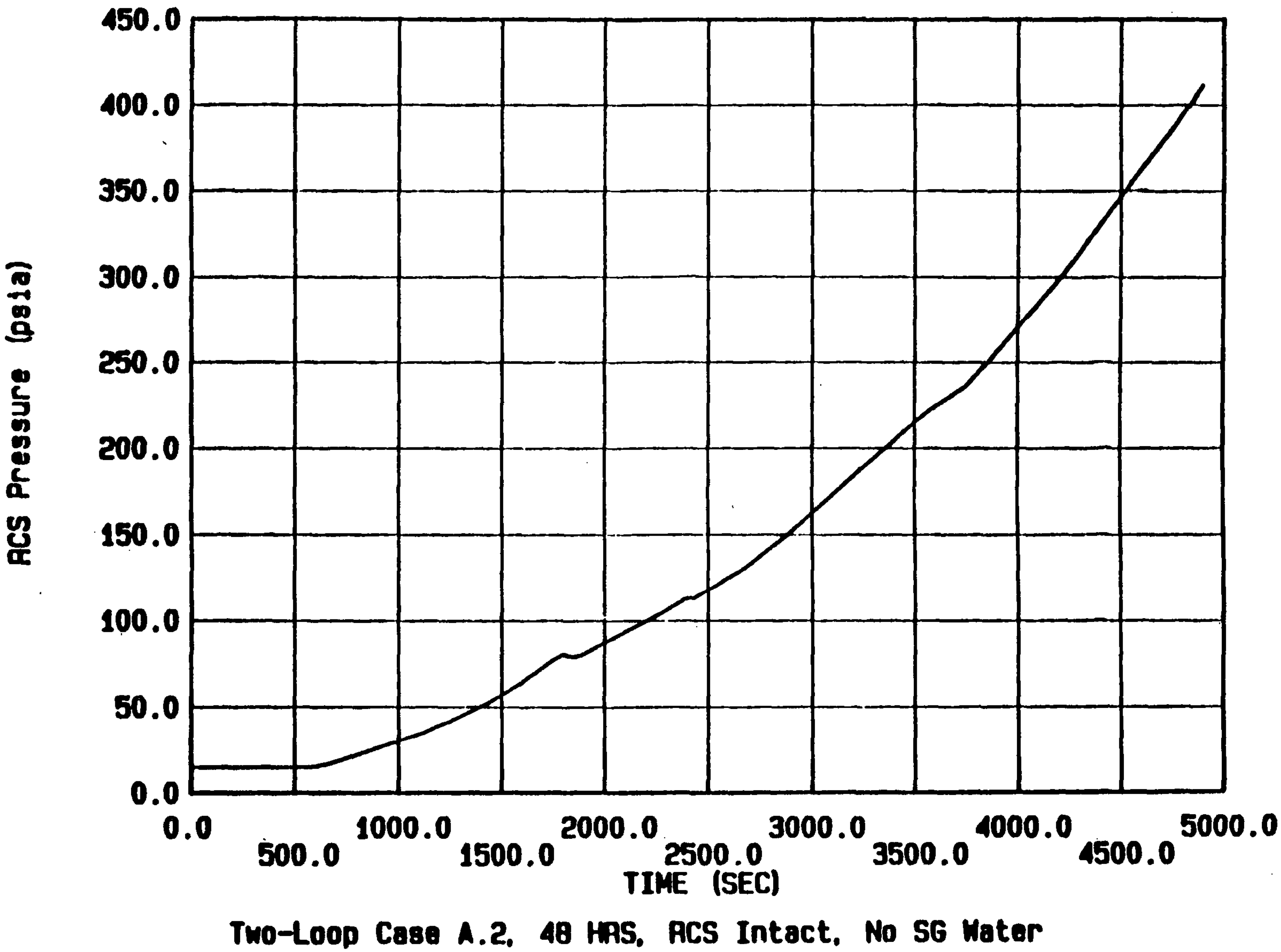


Figure 3.3.1-1 Two-Loop Case A.2, RCS Pressure

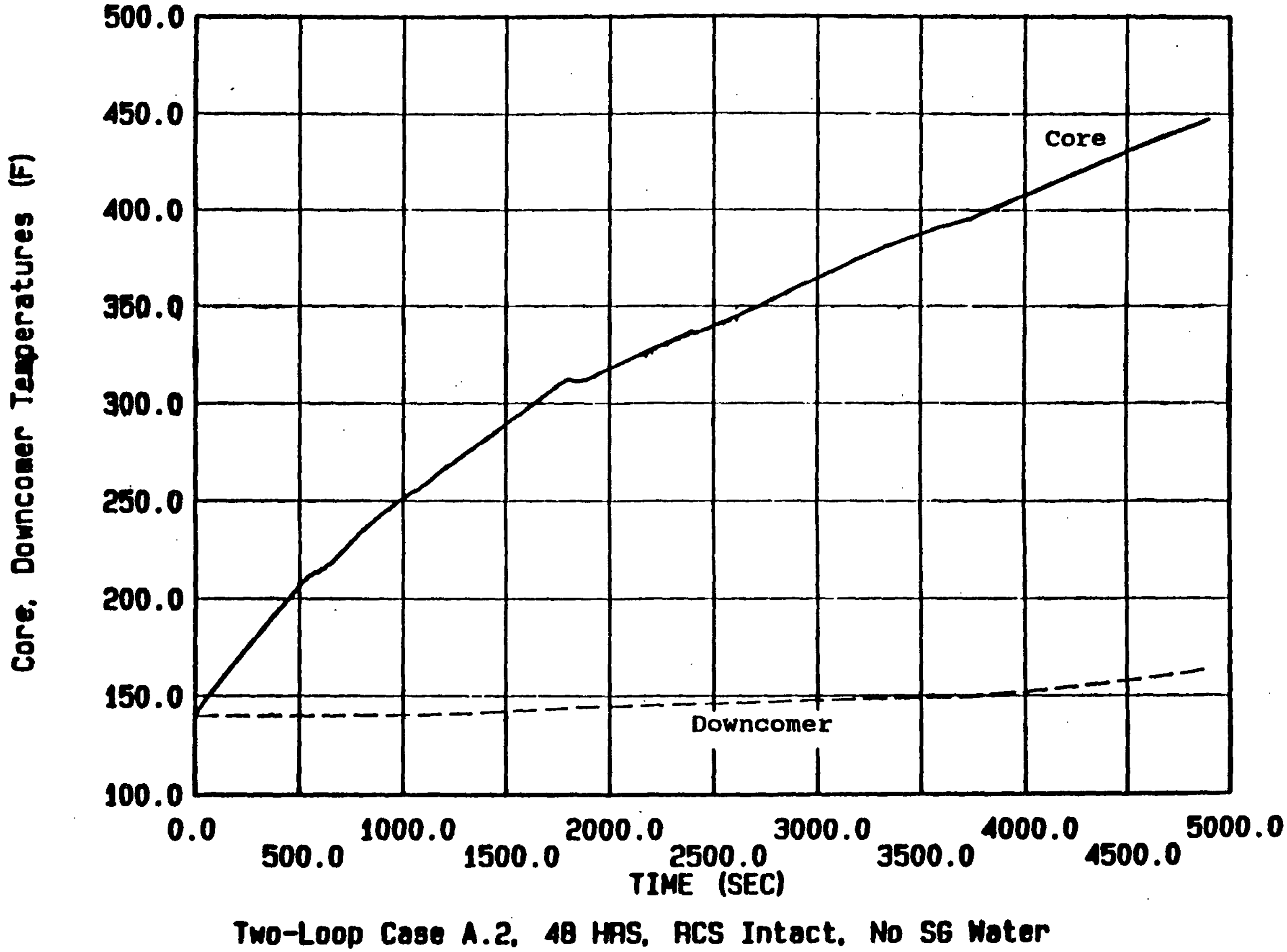


Figure 3.3.1-2 Two-Loop Case A.2, Core and Downcomer Temperatures

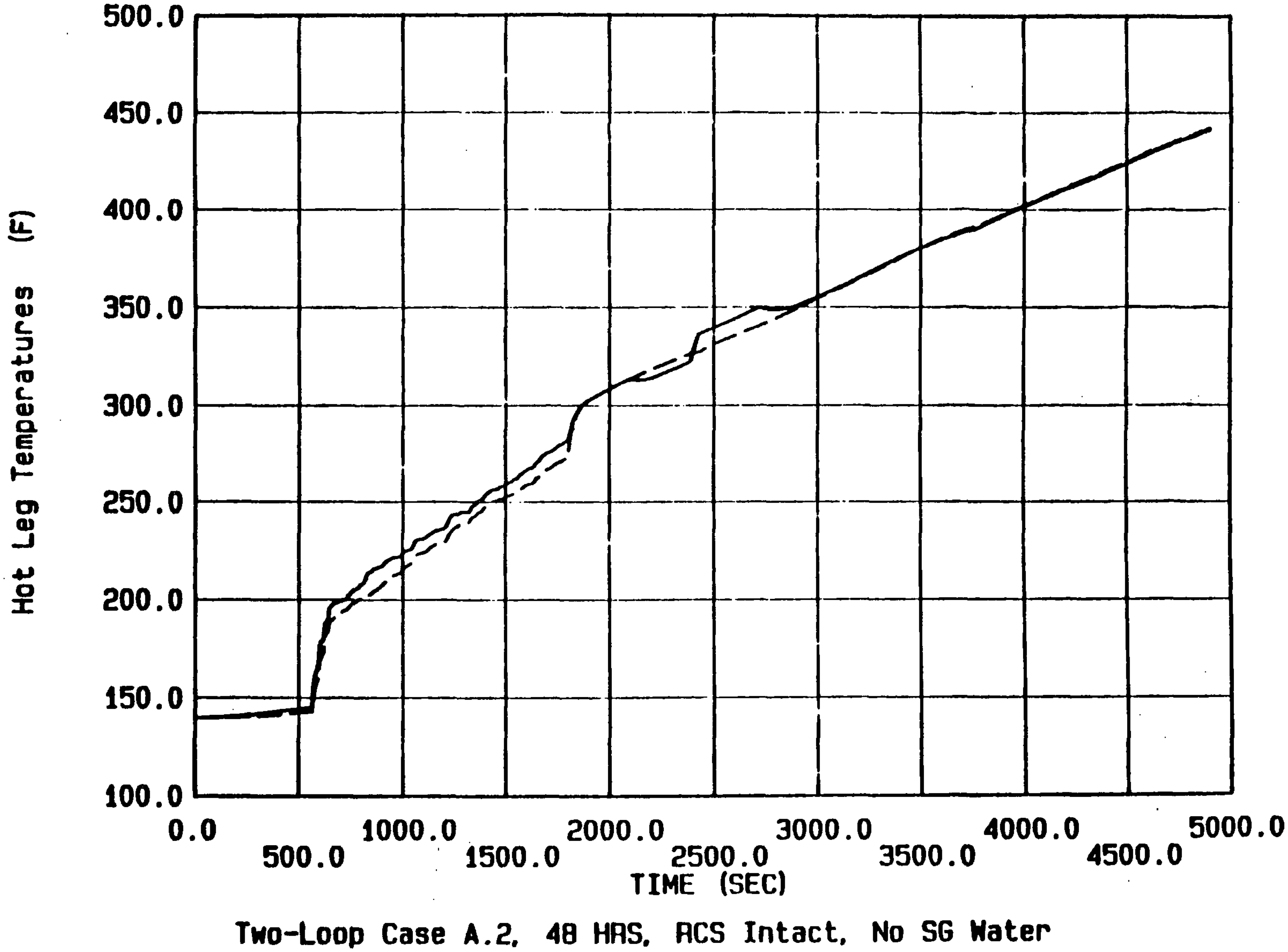


Figure 3.3.1-3 Two-Loop Case A.2, Hot Leg Temperatures

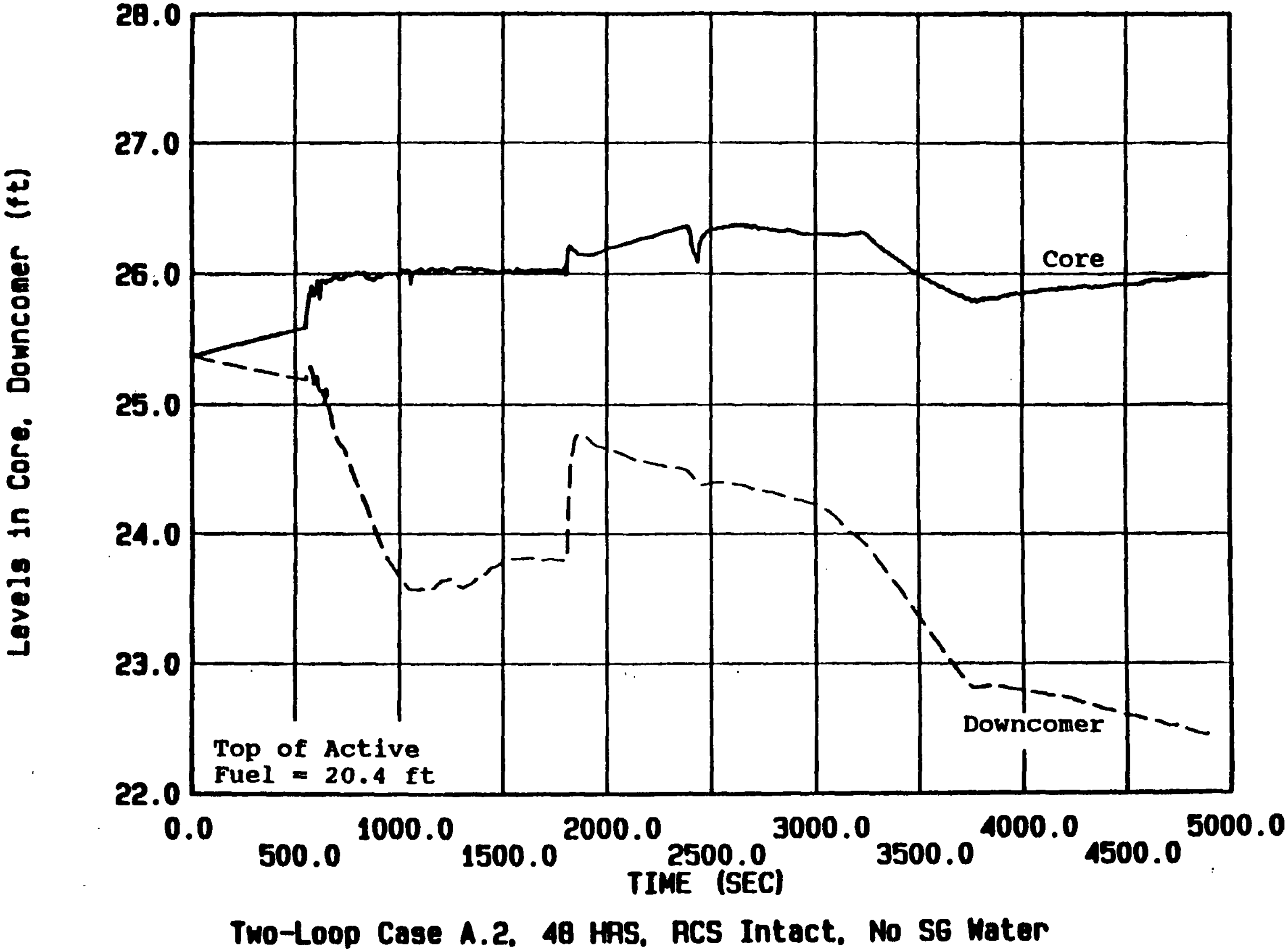


Figure 3.3.1-4 Two-Loop Case A.2, Core and Downcomer Mixture Levels

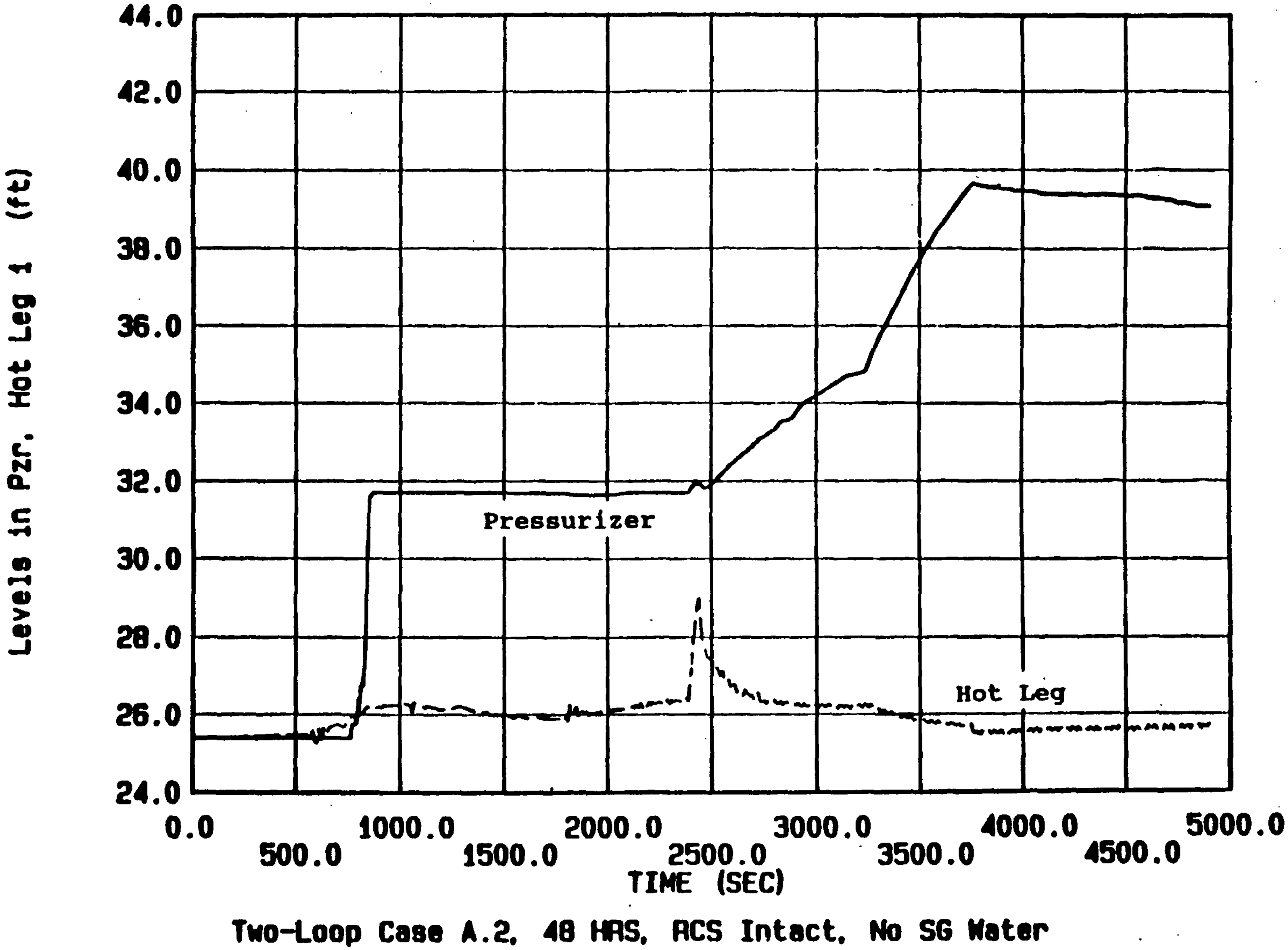
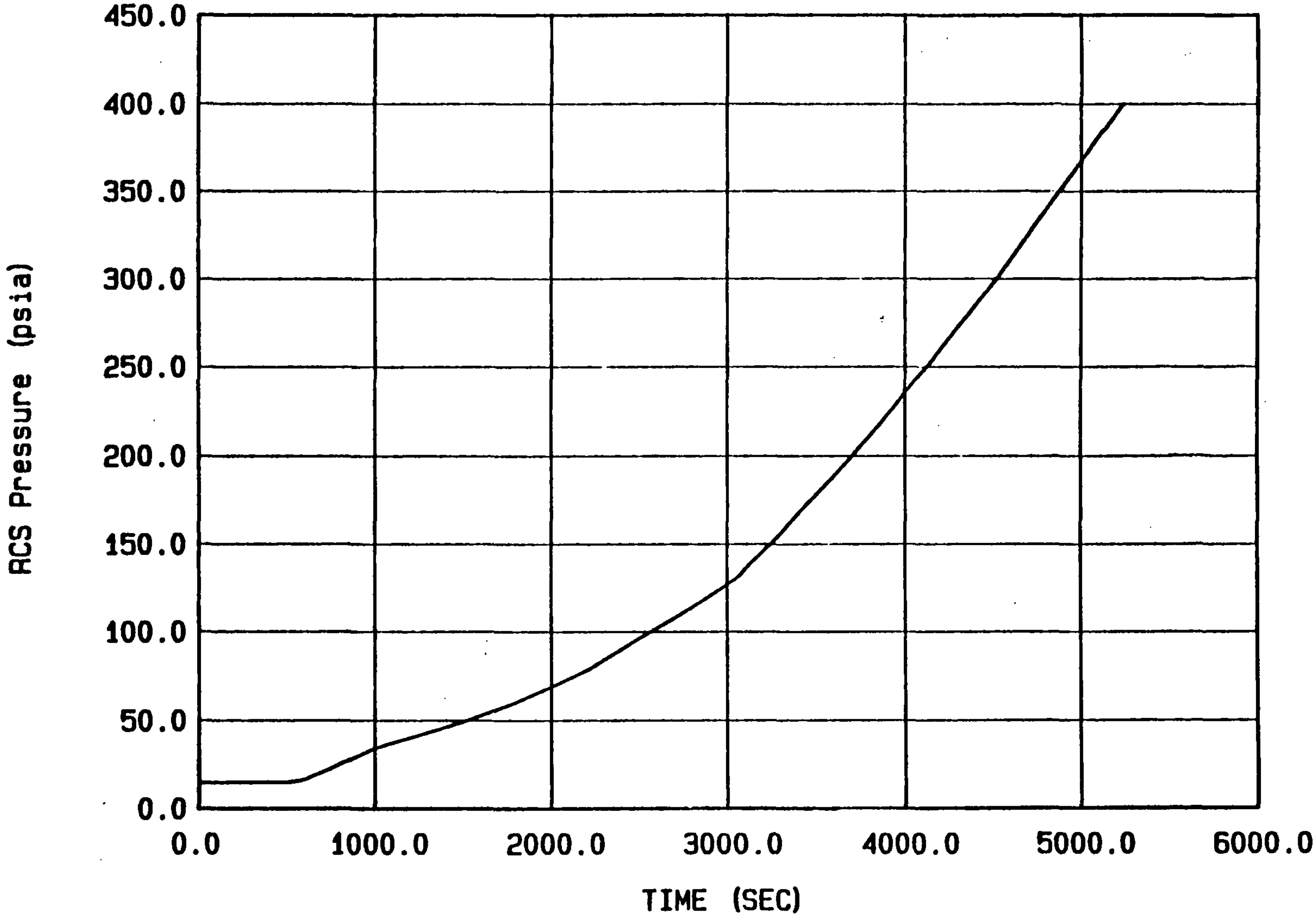
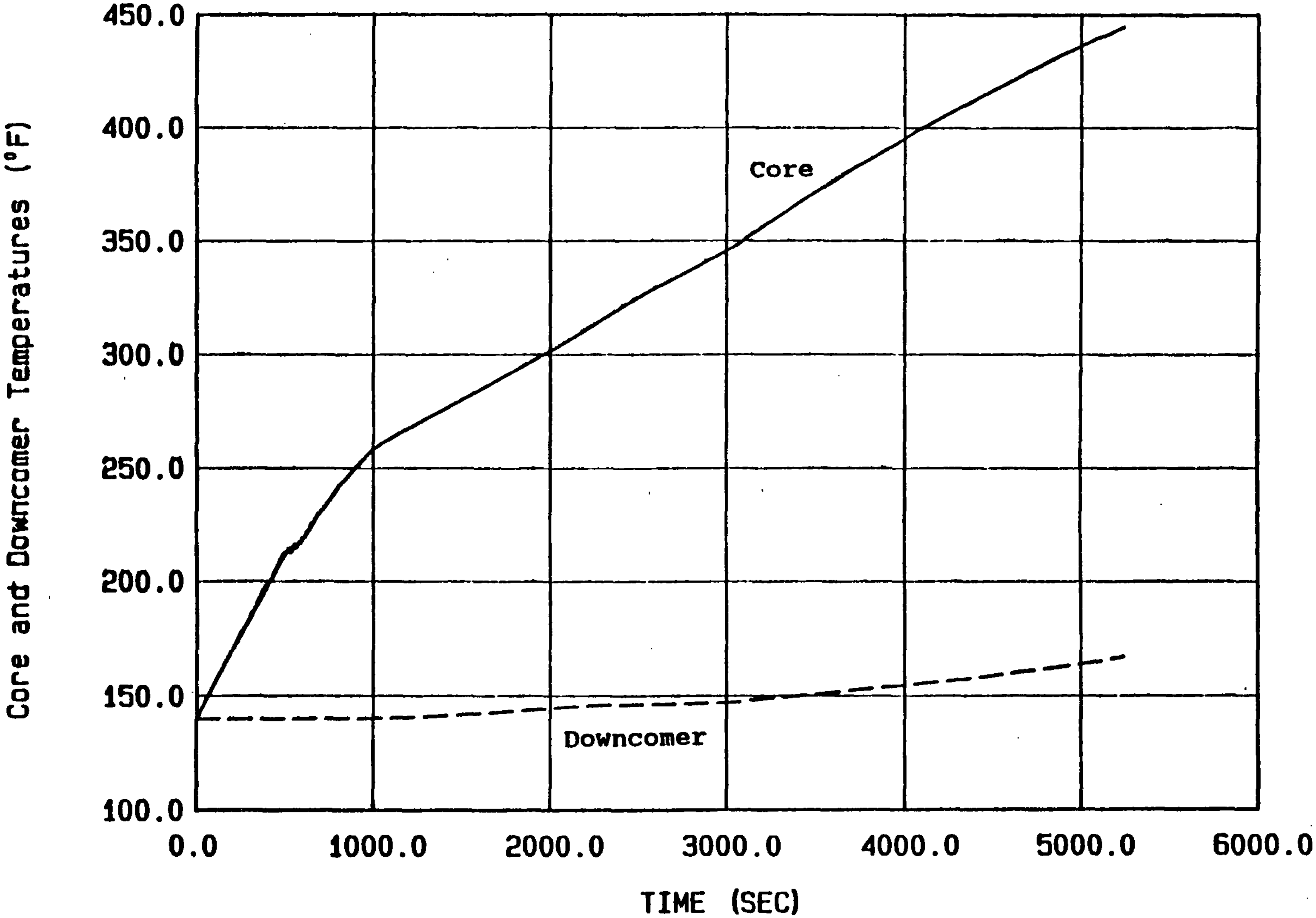


Figure 3.3.1-5 Two-Loop Case A.2, Hot Leg and Pressurizer Levels



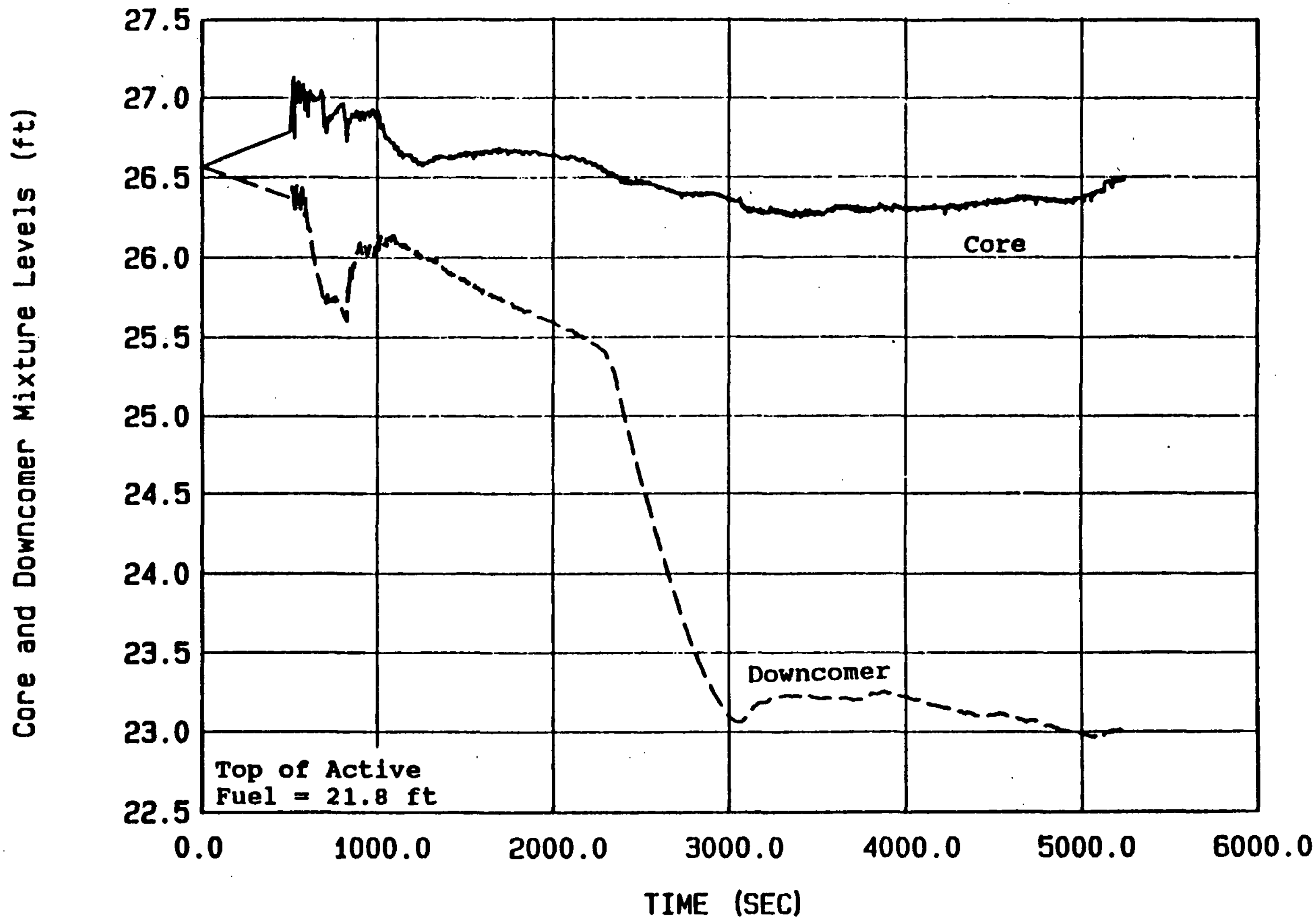
Three-Loop Case A.5, 48 HRS, Intact RCS, No SG Water

Figure 3.3.2-1 Three-Loop Case A.5, RCS Pressure



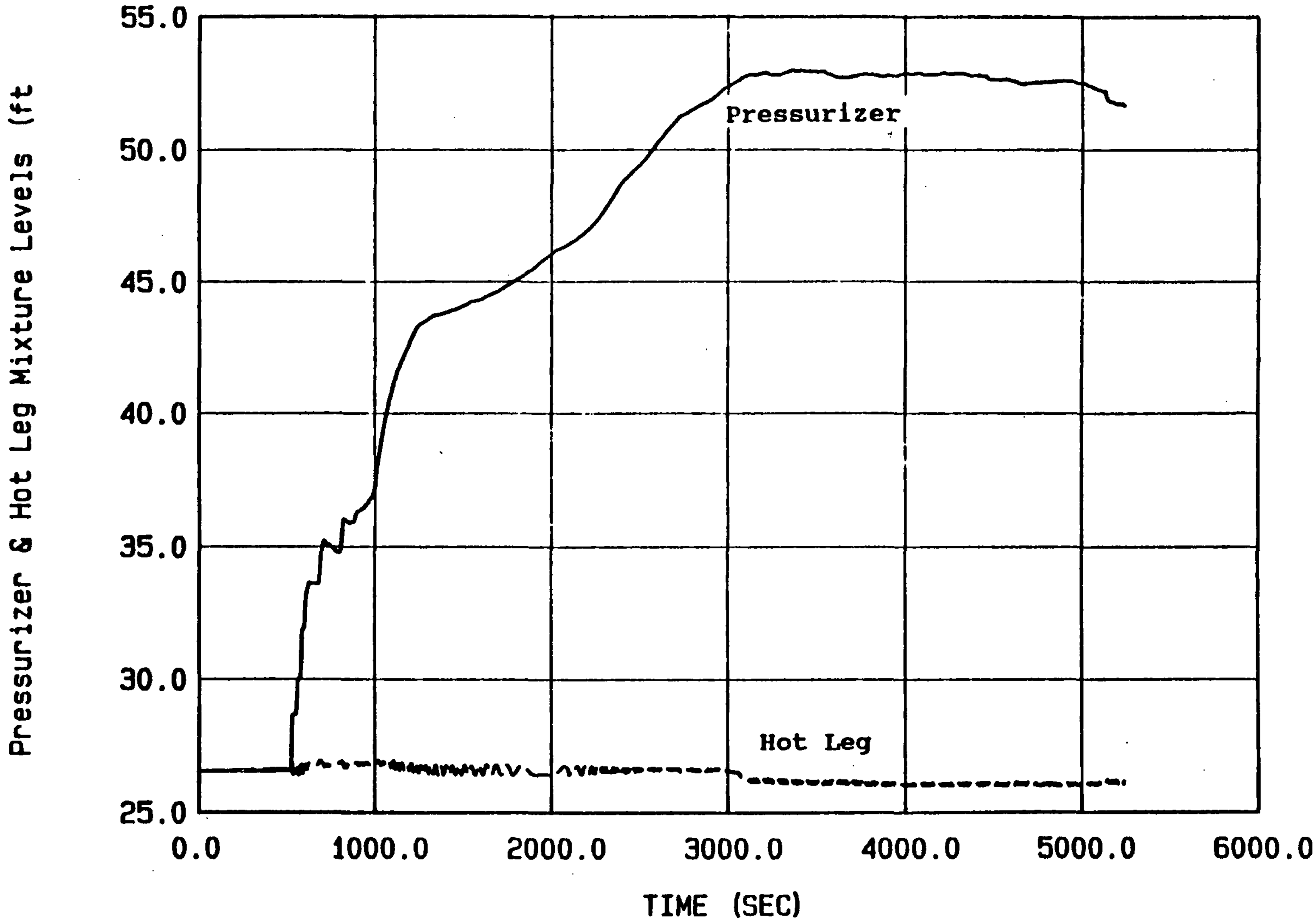
Three-Loop Case A.5, 48 HRS, Intact RCS, No SG Water

Figure 3.3.2-2 Three-Loop Case A.5, Core and Downcomer Temperatures



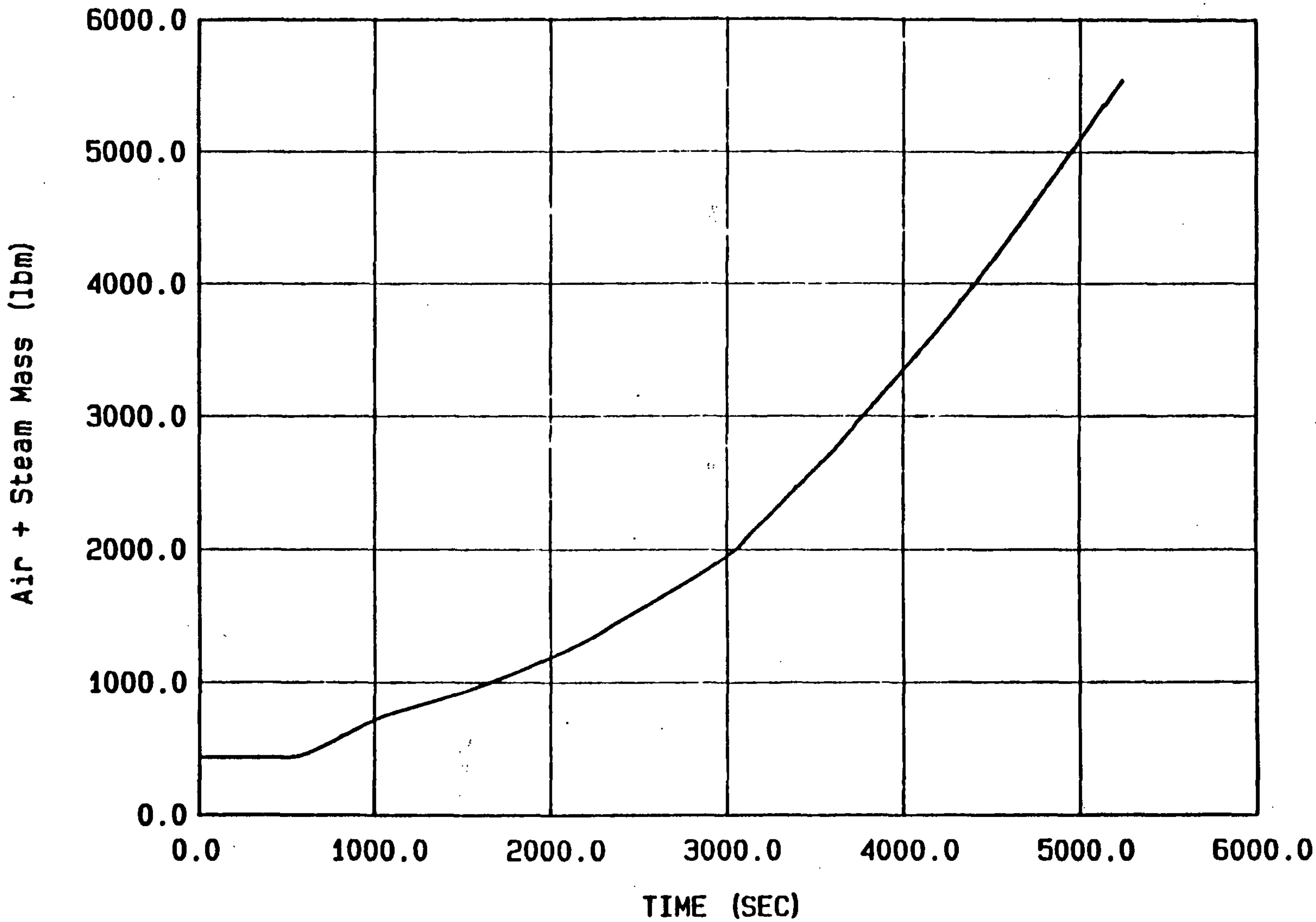
Three-Loop Case A.5, 48 HRS, Intact RCS, No SG Water

Figure 3.3.2-3 Three-Loop Case A.5, Core and Downcomer Mixture Levels



Three-Loop Case A.5, 48 HRS, Intact RCS, No SG Water

Figure 3.3.2-4 Three-Loop Case A.5, Pressurizer and Hot Leg Mixture Levels



Three-Loop Case A.5, 48 HRS, Intact RCS, No SG Water

Figure 3.3.2-5 Three-Loop Case A.5, Air + Steam Mass

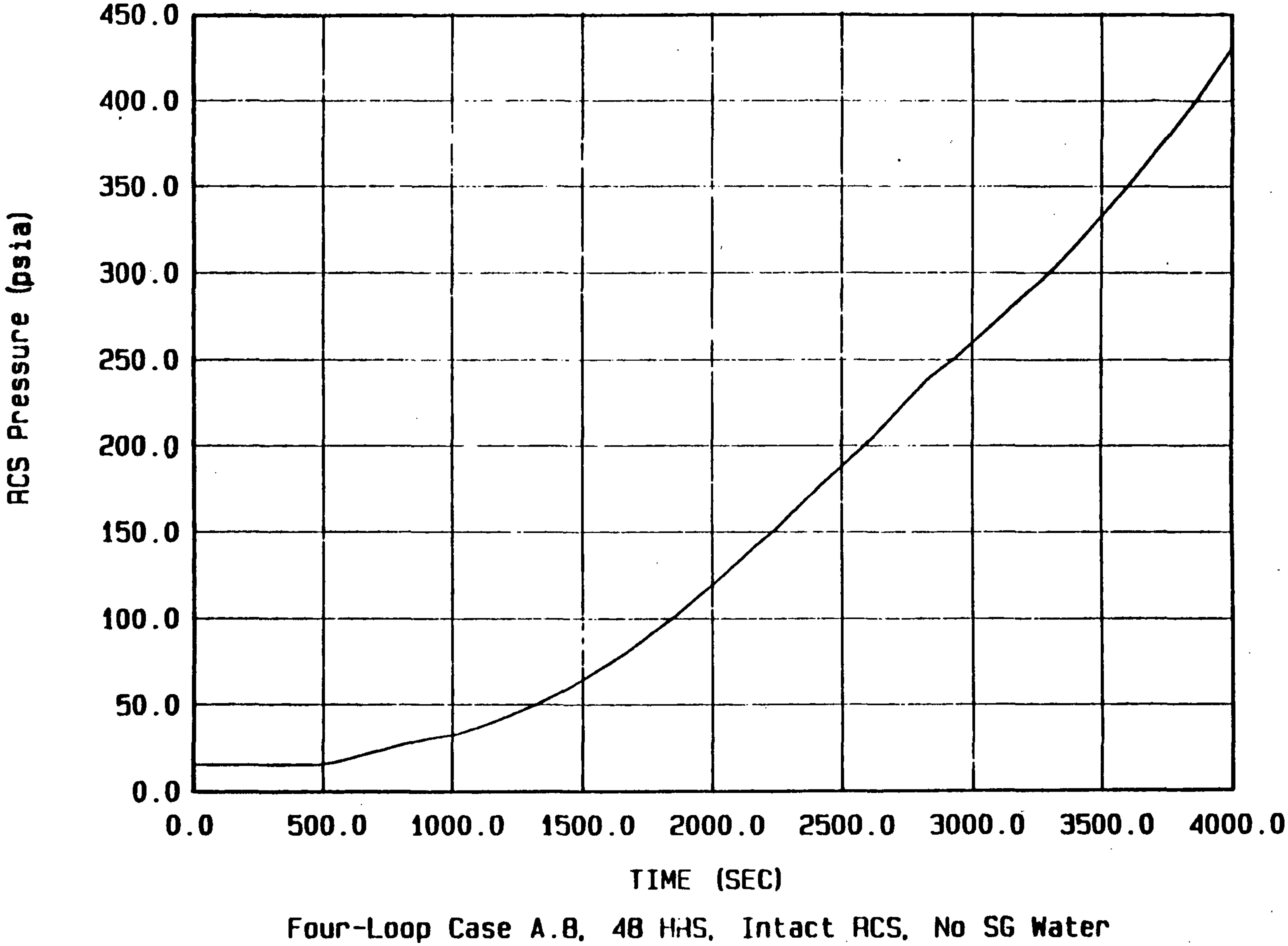


Figure 3.3.3-1 Four Loop Case A.8, RCS Pressure

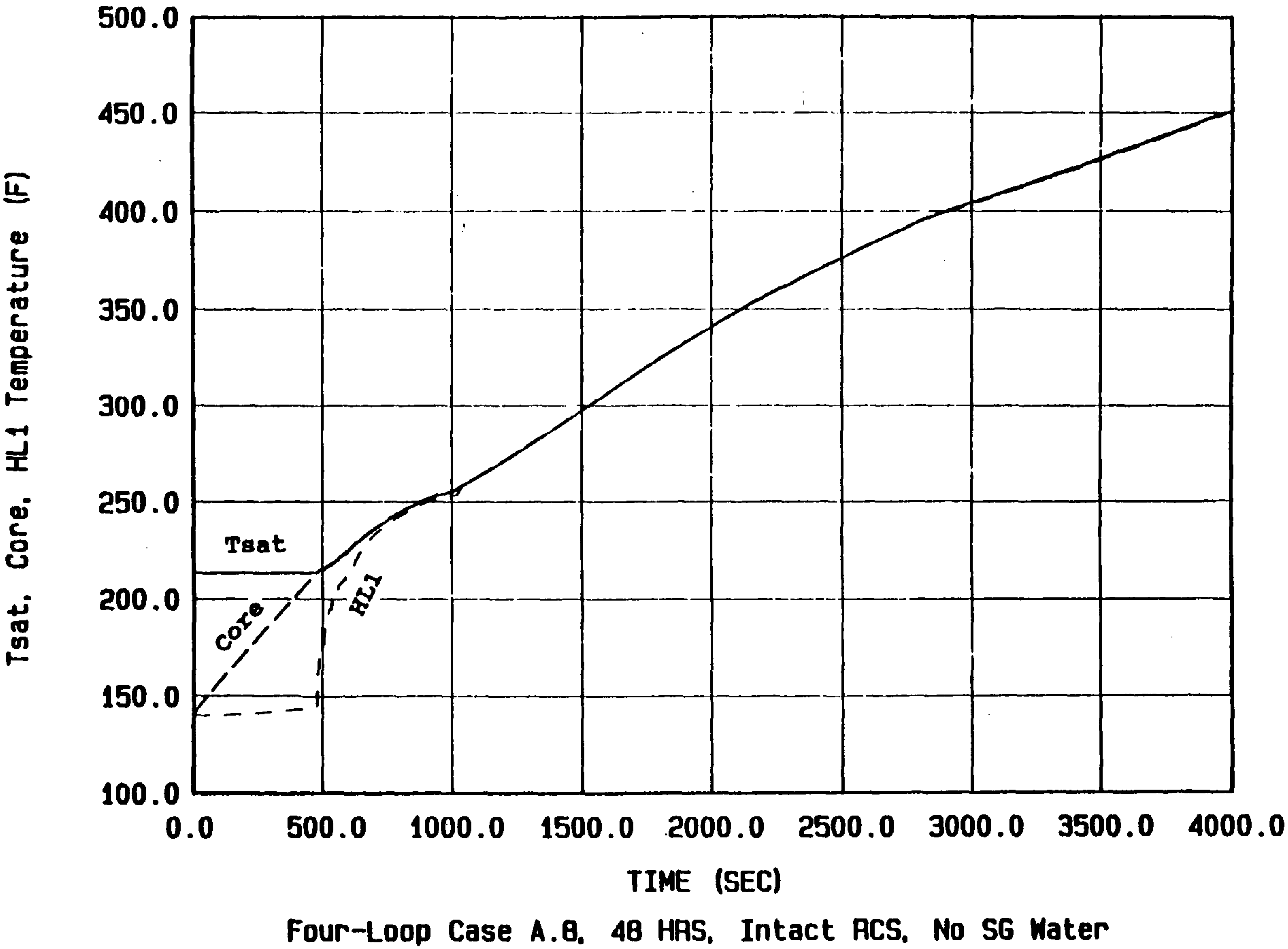


Figure 3.3.3-2 Four Loop Case A.8, Tsat, Core and Hot Leg 1 Temperatures

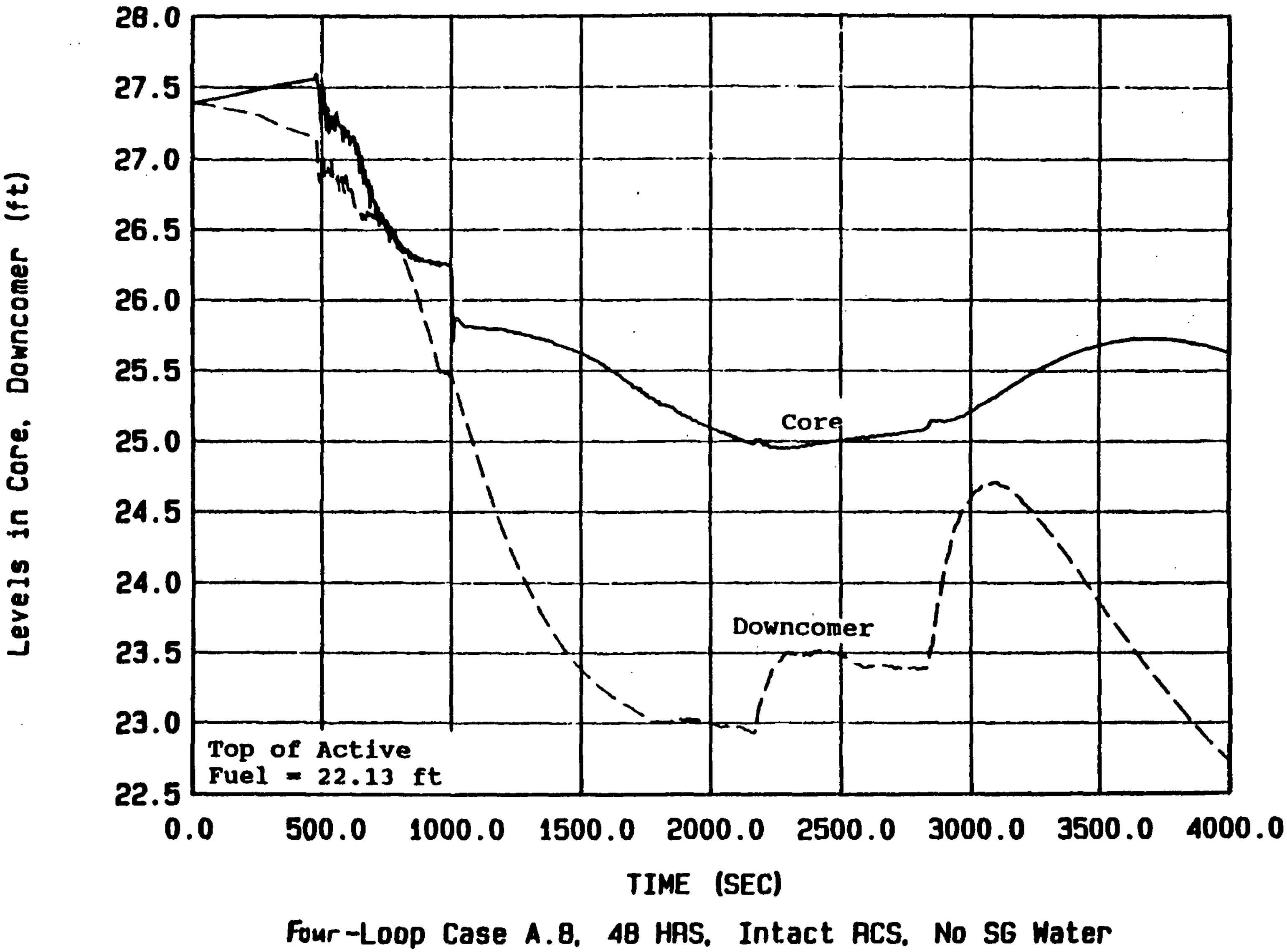


Figure 3.3.3-3 Four Loop Case A.8, Levels in Core and Downcomer

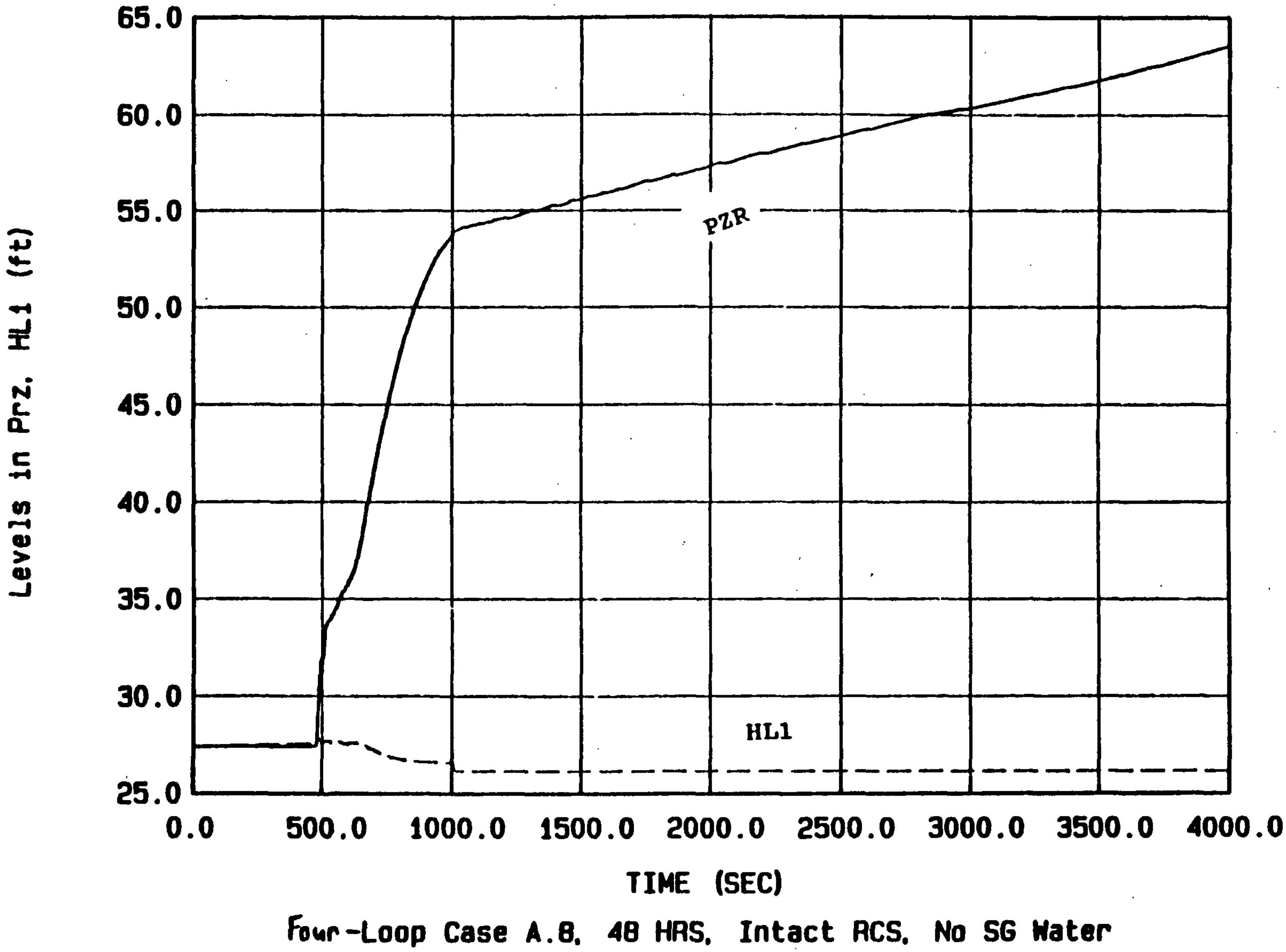


Figure 3.3.3-4 Four Loop Case A.8, Levels in Pressurizer, Hot Leg 1

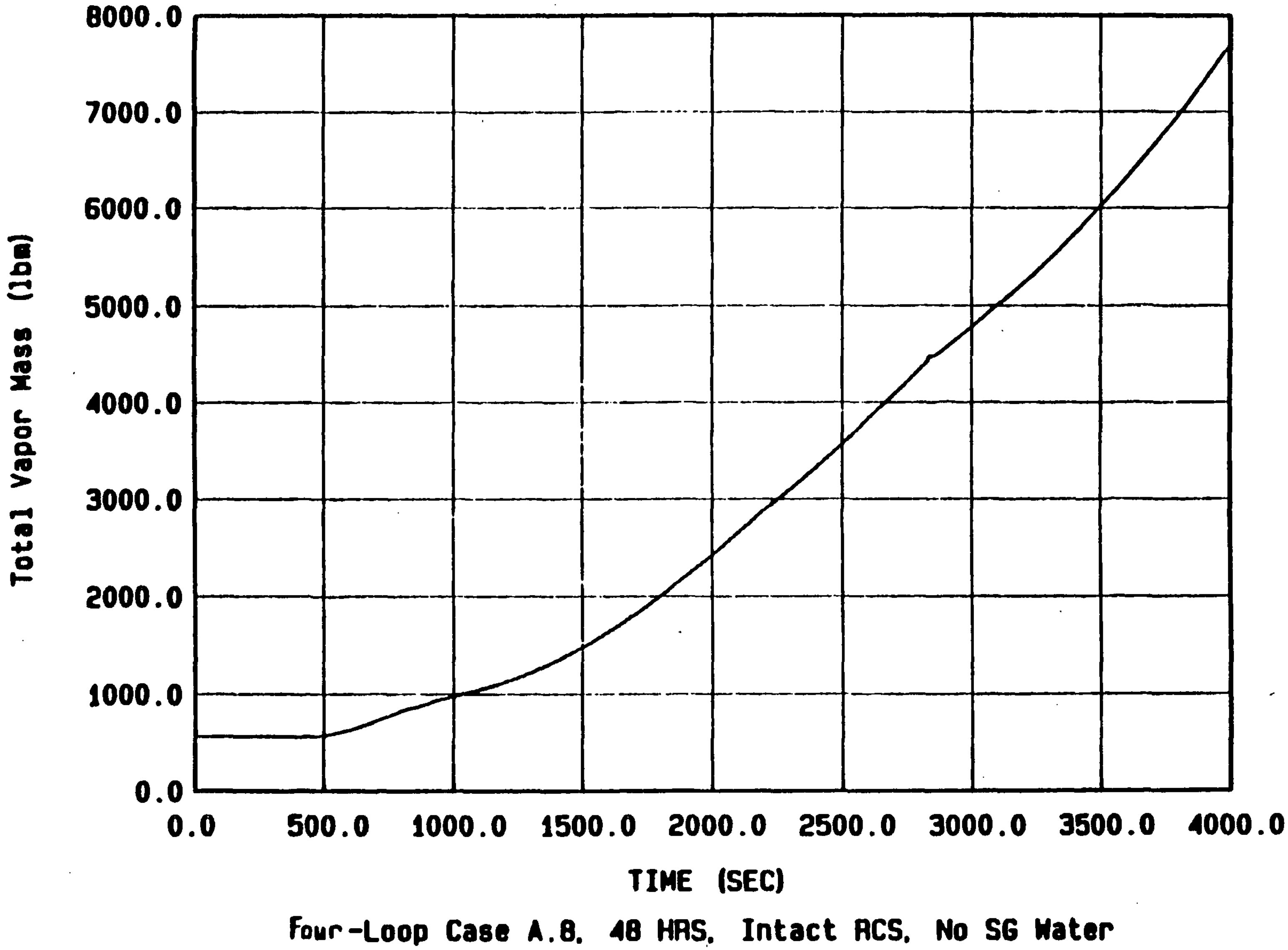


Figure 3.3.3-5 Four Loop Case A.8, Total Vapor Mass

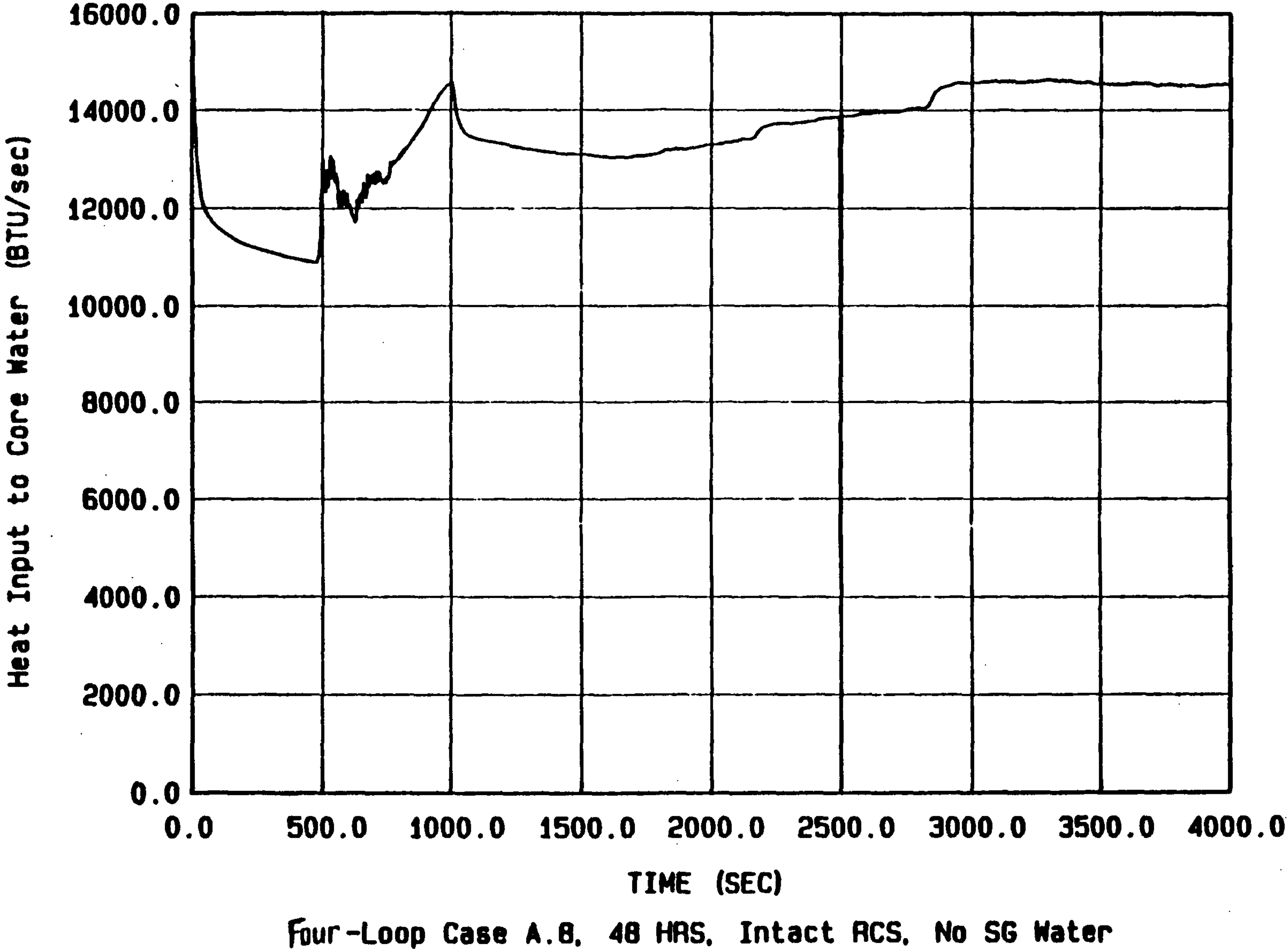


Figure 3.3.3-6 Four Loop Case A.8, Heat Input to Core Water

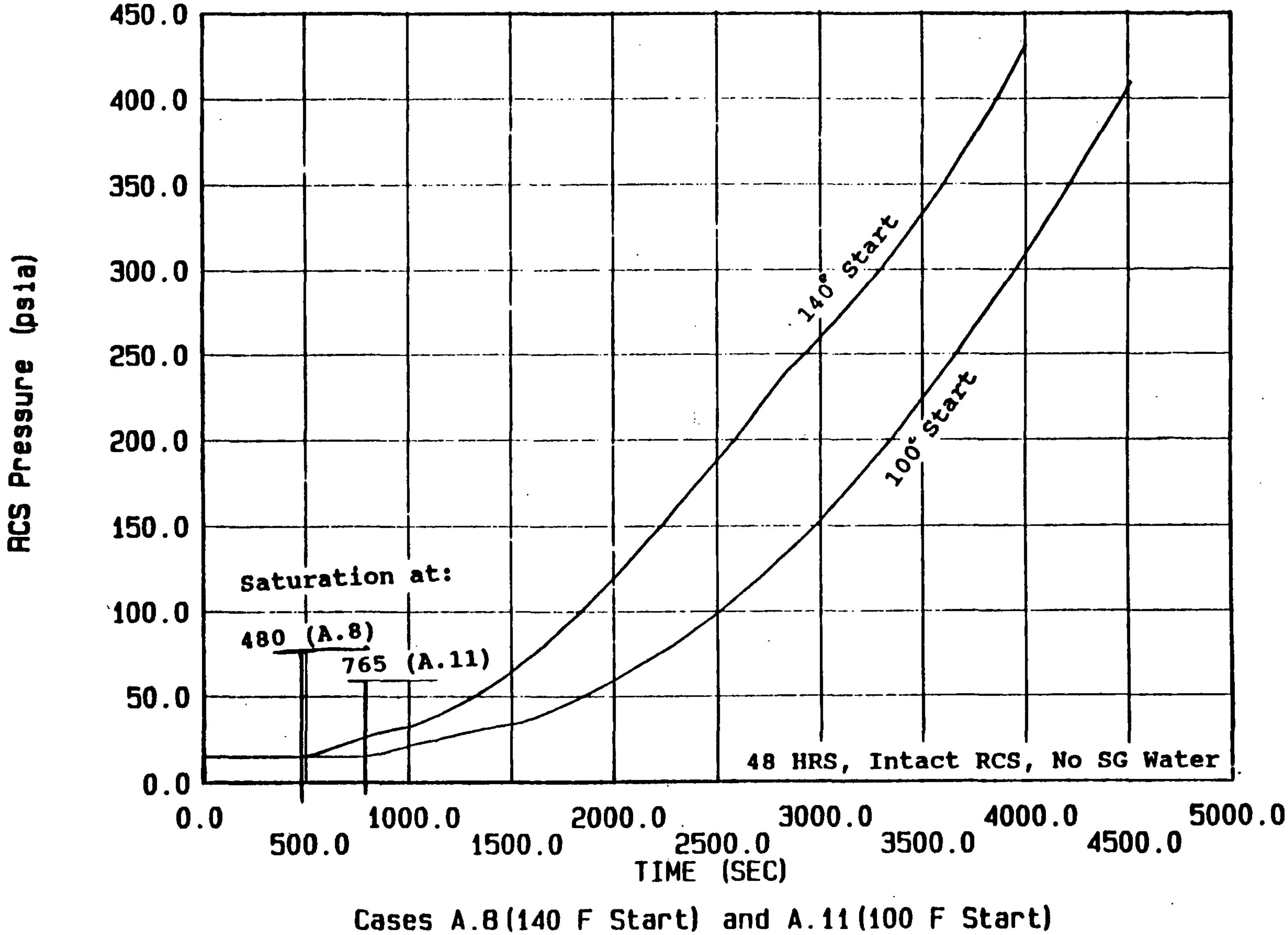
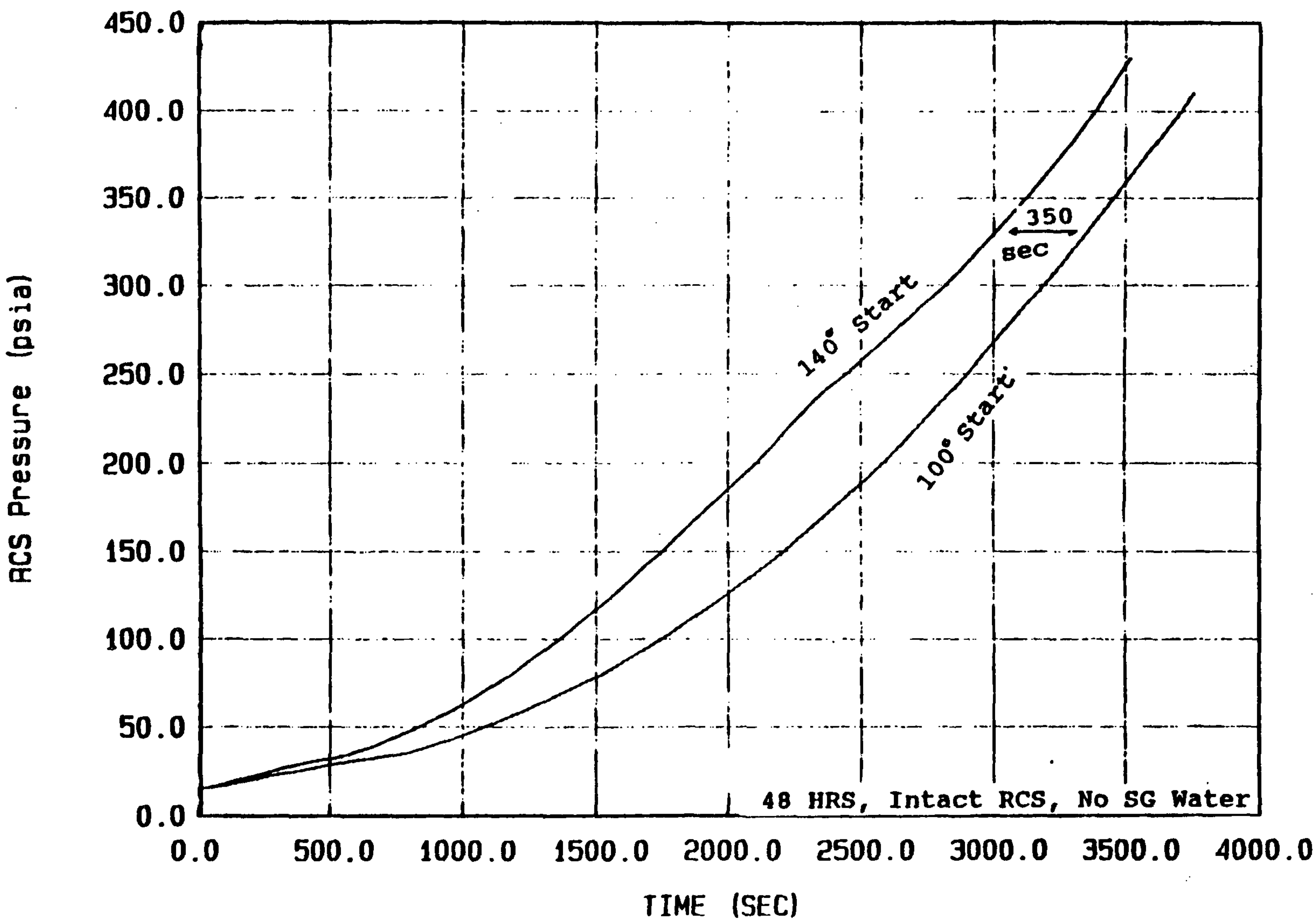


Figure 3.3.4-1 Four Loop Cases A.8 and A.11 Pressurization Comparison



A.8 and A.11 Cases, Time set to 0 at RCS Boil

Figure 3.3.4-2 Four Loop Cases A.8 and A.11 Pressurization Comparison

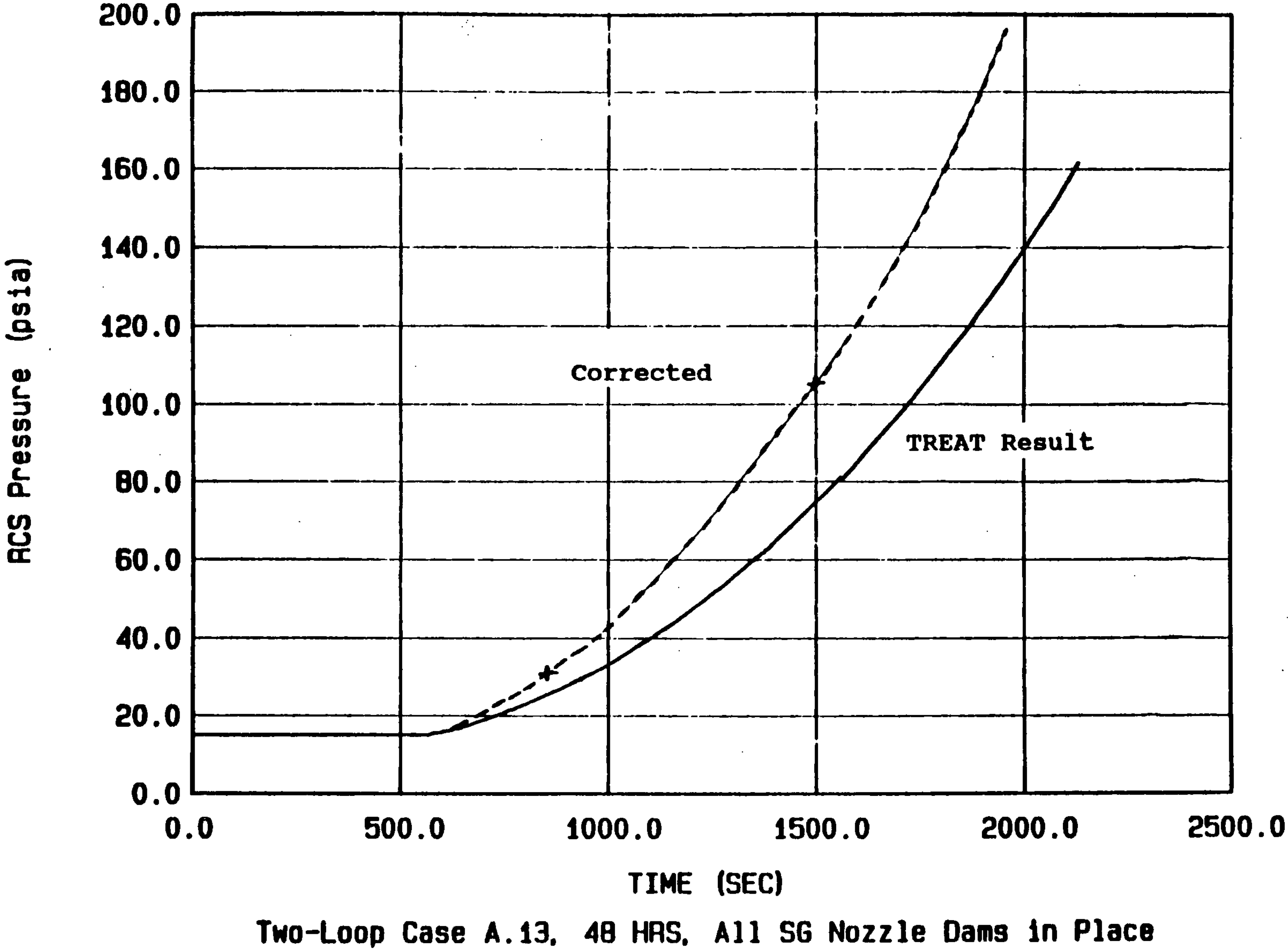
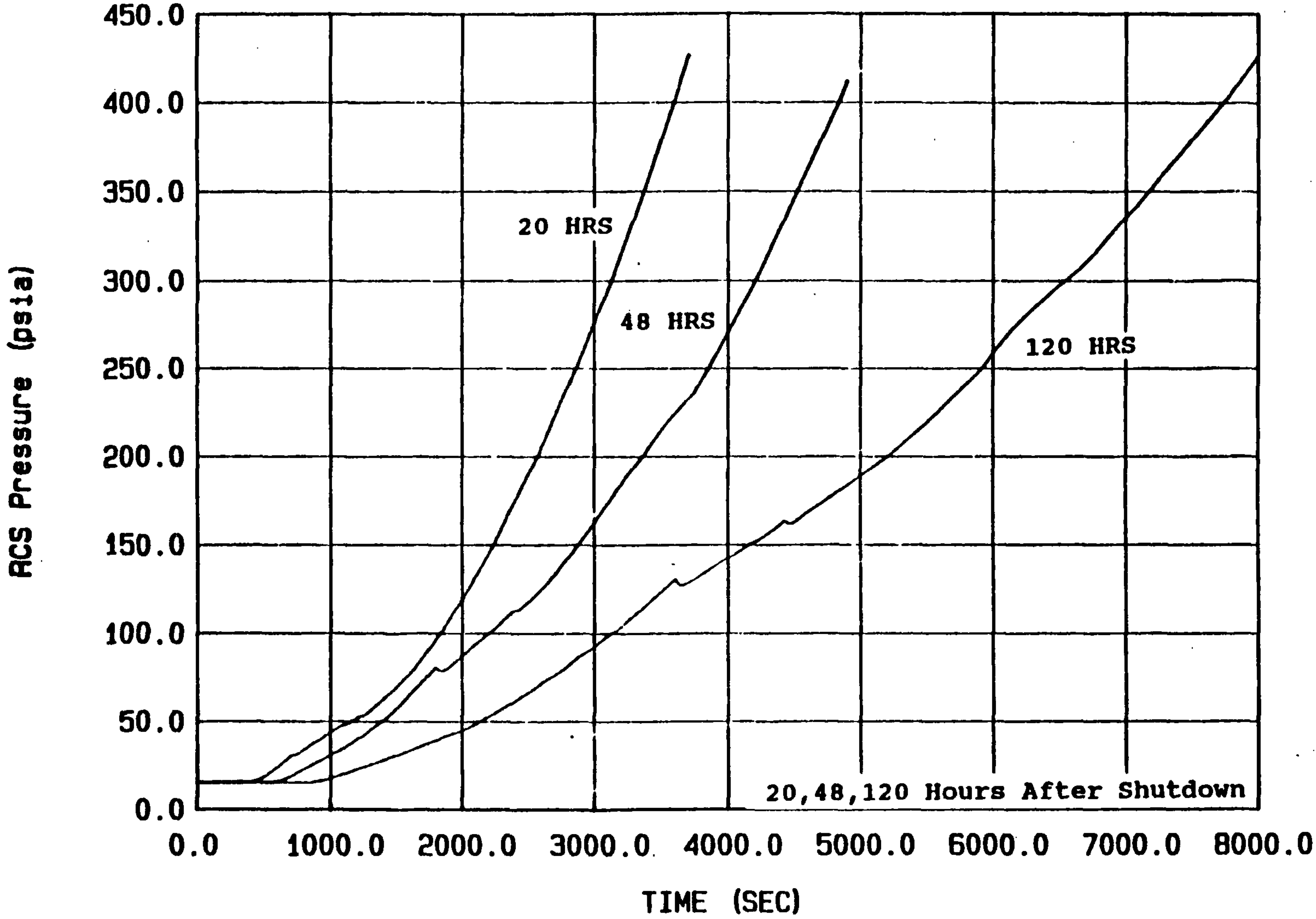
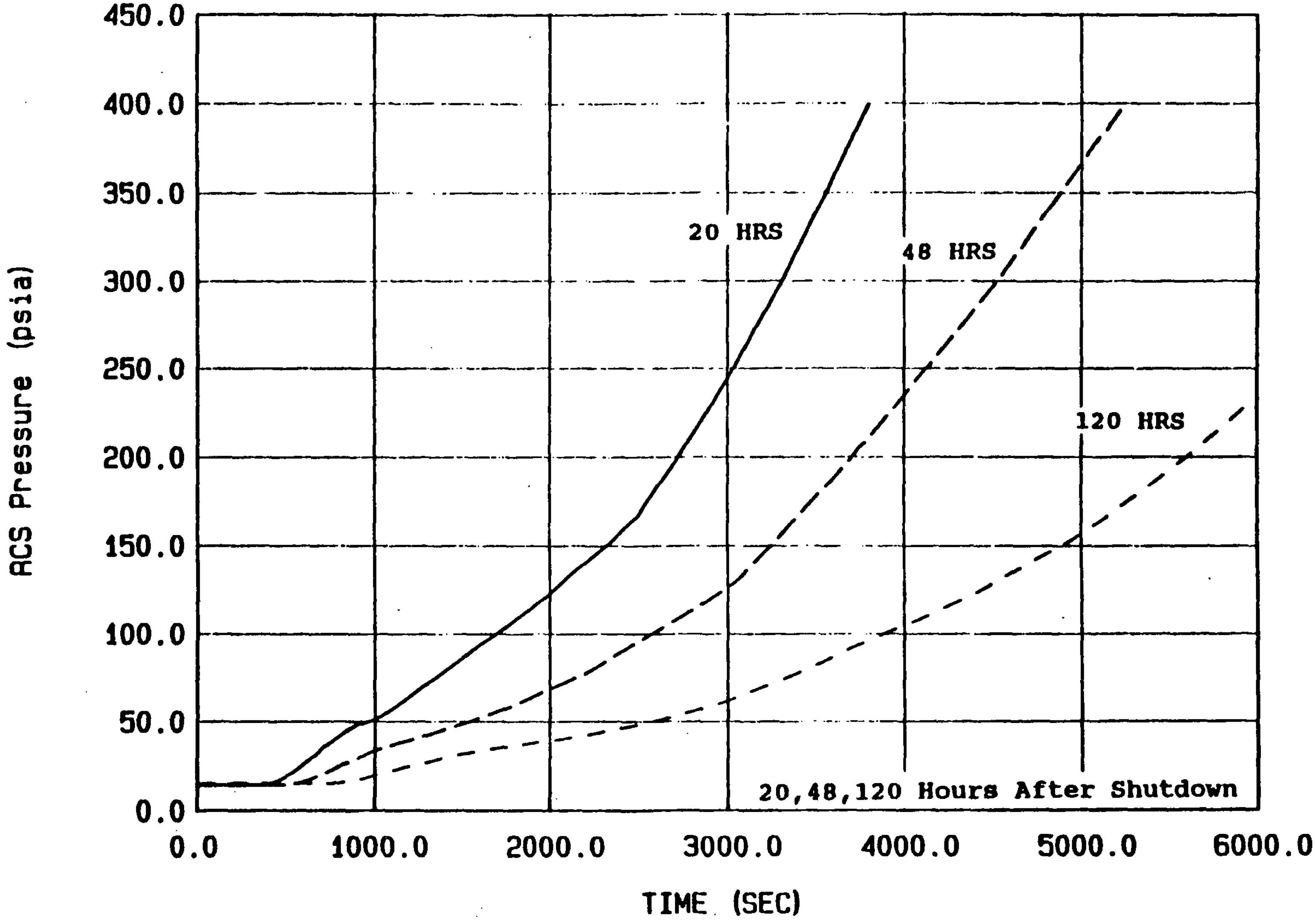


Figure 3.3.5-1 Two-Loop Case A.13, RCS Pressure Transient with SG Nozzle Dams



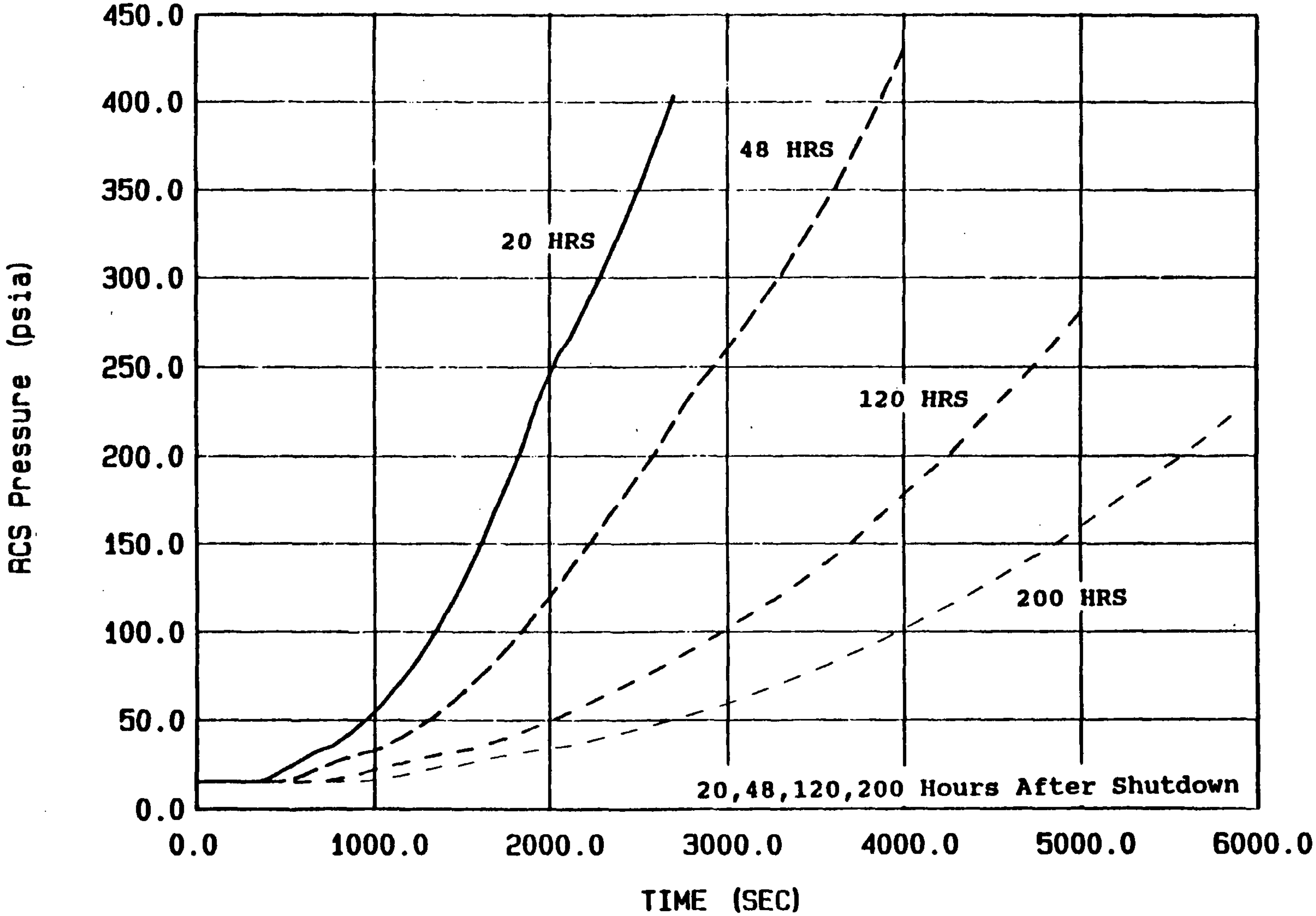
Cases A.1, A.2, A.3, 140°F, Intact RCS, No SG Water

Figure 3.3.6-1 Two-Loop Pressurization Comparison



Cases A.4, A.5, A.6, 140 ^{0}F, Intact RCS, No SG Water

Figure 3.3.6-2 Three-Loop Pressurization Comparison



Cases A.7, A.8, A.9, A.10 140^{0}F, Intact RCS, No SG Water

Figure 3.3.6-3 Four-Loop Pressurization Comparison

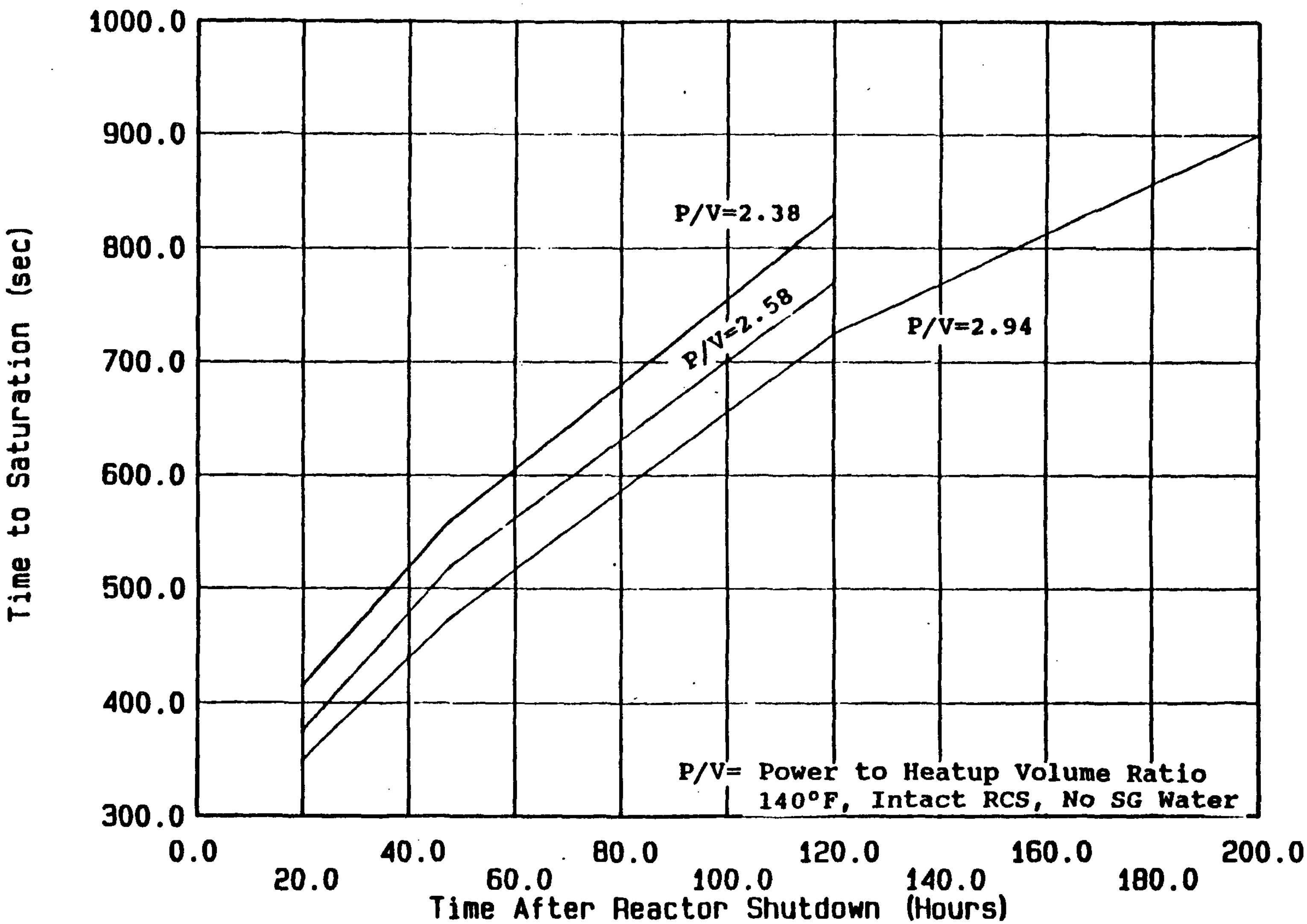


Figure 3.3.6-4 Time to Reach Boiling

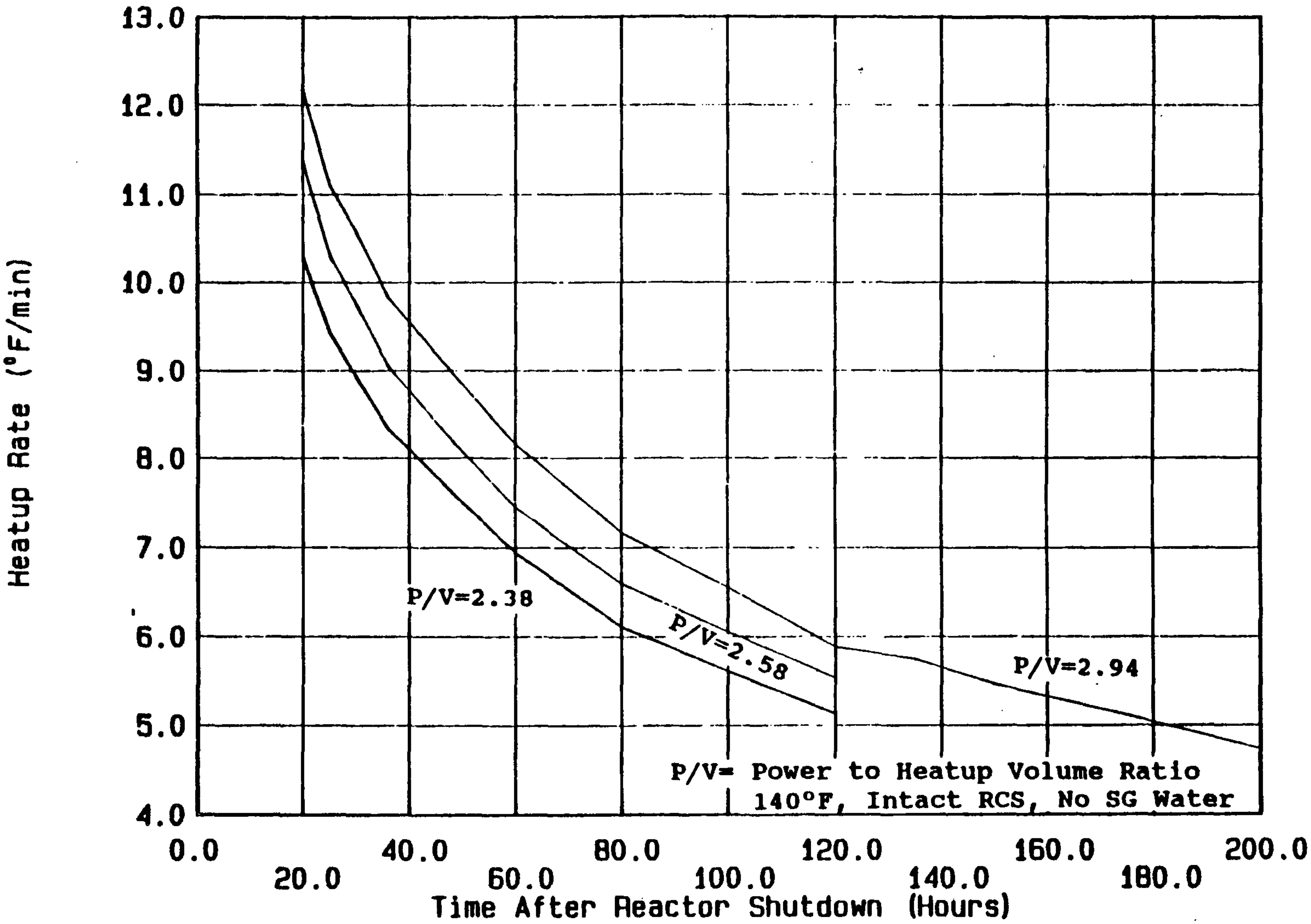


Figure 3.3.6-5 Heatup Rate

3.4 Large Vent Cases

The large vent cases were performed to determine the time to core uncovery for situations in which a loss of RHR cooling occurs while at mid-loop conditions and a large vent path above the core, such as a hot side SG or pressurizer manway or some other large vent path, is assumed open. All steam generators were assumed to be in dry layup so condensation would not occur.

Since the vent path is assumed to be above the core, the steam generated by the boiling core is able to pass through the opening without causing the RCS to pressurize significantly. Without makeup water to replace the steam boiled off, the core will eventually uncover. Two representative transients are described in the following section. In the first case, all RCS inventory is lost by simple boil-off, the situation expected when the vent is several feet or more higher than the initial RCS water level. In the second case, the bottom of the opening coincides with the top of the hot leg (similar to a hot side SG manway or open loop isolation valve). For this case, some mixture spills before steady-state boil-off develops.

3.4.1 Typical Large Vent Boil-off Core Uncovery Transient - Case B.5

In the scenario described here, the 3 loop plant is assumed to have been shutdown for 48 hours following an extended period of full power operation at 2441 MWt. Based on the decay heat curve of Section 3.2, the core power is 0.48% of full power or 11.72 MWt. The RCS initial temperature is 140°F at the time RHR cooling is assumed to be lost. The 19 inch diameter vent path assumed in the analysis was large enough to prevent RCS pressure from increasing after the core began to boil.

After RHR cooling is lost, fission product decay heat causes the temperature of the water and metal in the core and upper plenum to increase and the core eventually reaches the boiling point at 520 seconds. Due to the presence of bubbles in the mixture, the upper plenum and hot leg mixture levels rise rapidly just after the core begins to boil as shown in Figure 3.4.1-1. <u>This is not a result of increasing RCS inventory and should not be used as an</u>

indication to restart RHR pumps which may have been tripped due to air entrainment. RCS inventory must be increased before the RHR pumps can be restarted.

The steam production rate can be calculated by dividing the core decay energy by the latent heat of vaporization. In this case, the steam production rate is approximately 11.5 lbm/s. Since makeup is not assumed for this analysis, the RCS liquid mass inventory decreases at the same rate, 11.5 lbm/s as shown in Figure 3.4.1-2. This causes the downcomer level to slowly decrease. The upper plenum and hot legs also begin to decrease and the hot legs are completely drained approximately 4700 seconds after RHR cooling is lost. The core collapsed level is predicted to fall to the top of the active fuel by 6000 seconds. The actual mixture level in the core, however, does not reach the top of the active fuel until 6500 seconds.

The time to boil off all of the liquid mass above the top of active fuel, once boiling has started, can be estimated by dividing the initial mass above the core (which includes water in the downcomer and cold legs) by the steam production rate. For the 3-loop plant, this mass is approximately 60000 pounds, so the boil off time is approximately 5200 seconds. This estimate does not account for heat which is absorbed by the metal in the core, upper plenum and hot legs. The time taken to heat the fluid to boiling (approximately 500 seconds for the given initial conditions) is also not included in this estimate.

Including these delays due to absorption of energy in the metal plus the initial time to boiling, TREAT predicts that 60000 pounds of mass will be boiled off at approximately 6000 seconds after RHR has been lost. At this time, the core mixture level (which includes bubbles) is approximately 1 ft above the top of the core.

The analysis described above was repeated with the opening located at a lower elevation more typical of a SG manway. For this case, the bottom of the opening was set at 27.8 ft, corresponding approximately to the elevation at the top of the hot legs for the 3-loop plant (27.759 ft). The previous analysis indicated that the level in the upper plenum exceeded 28 ft, so it was suspected that modeling the opening at the lower elevation would result in some liquid or mixture spill from the opening.

To simplify the calculations for the analysis with spill, the 'supernode' model discussed in Section 3.2.4 was used. The only significant impact of using this model was that the onset of boiling (for Case B.5, 48 hours after shutdown) shifts from 520 seconds to 570 seconds, following the loss of RHR cooling. This delay of less than one minute is due to heatup of the hot leg water added to the core and upper plenum water in the 'supernode' model. A more significant input change was required to ensure that the swell due to voids was calculated accurately. This swell impacts the amount of mixture that will spill from the opening prior to steady state boil-off. The core bubble rise velocity was changed slightly (reduced) from that used in the previous analysis to make the core void fraction calculated in TREAT more consistent with that expected using the Yeh correlation (discussed in Appendix E and Reference 15). For the steady state boil-off condition in this case, the predicted core averaged void fraction is 28% (the input for the previous run would have been non-conservative since the void fraction at steady state boil-off was less than 20%).

The mixture levels in the upper plenum (core) and downcomer regions for the case with spill are shown in Figure 3.4.1-3. The level in the upper plenum and hot legs swells above the bottom of the manway by 665 seconds (about one minute after boiling starts) and remains above this level until 1500 seconds. The downcomer level decreases faster in this scenario than the previous case without spill (Figure 3.4.1-1) since additional inventory lost as mixture must be replenished with water from the downcomer and cold legs.

The mixture spilling from the opening and the core inlet flow are shown in Figure 3.4.1-4. The core inlet flow increases to about 80 lbm/sec as soon as the upper plenum reaches saturation and starts to swell (570 seconds). At 750 seconds, the spill flow peaks at approximately 60 lbm/sec when the upper plenum level reaches about 28.2 ft (0.4 ft above the bottom of the manway). After this time, the two flows drop off and the mixture flow from the opening decreases to zero after 1500 seconds. The core flow remains positive after this time since this flow partially replaces the core boil-off flow (11.5 lbm/sec).

The integrated mixture and total flows from the opening are shown in Figure 3.4.1-5. The "spill penalty" (the mixture component that was lost through the opening) is 16,375 lbm. This is 27% of the mass (60,000 lbm) predicted to be lost in the simple boil-off case discussed above. Based on the total integrated vent flow and the steady state boil-off, the collapsed core level is estimated to reach the top of the active fuel at approximately 4600 seconds. This time is to be compared to the previous 6000 second result without spill. In reality, due to the increased swell for the case with spill, the mixture level would be about 3 ft above the top of the active fuel at 4600 seconds; the actual mixture level would not be expected to decrease to the top of the active fuel until after 6000 seconds.

3.4.2 Summary of Large Vent Analysis

The large vent analysis was performed to determine a limiting time to core uncovery for the situation in which a large hot leg side or upper plenum opening provides an unobstructed vent path for the air and steam to escape as the water above the core boils off. It applies to an open SG manway (or other large vent path in the hot leg or upper plenum) on the hot or cold leg side provided hot side SG nozzle dams are not in place and hot leg loop isolation valves (if applicable) are not closed. For this bounding calculation, the vent path is demonstrated to be large enough to prevent RCS pressurization significantly above containment pressure. This implies that the vent area should be about 0.5 sq-ft or larger. In the TREAT analysis performed, the vent area was about 2 sq-ft, i.e., the size of a SG manway.

Based on the analyses performed, the time to core uncovery is inversely proportional to the decay heat. If the bottom of the hot side vent is several feet above mid-loop, the RCS inventory loss will be based strictly on simple boil-off. The time to core uncovery will then be directly proportional to the water above the top of the active fuel. This boil-off volume also includes some water in the downcomer (which replenishes water being boiled off) plus water in the cold leg and pump suction piping above the bottom of the cold legs. This boil-off volume is discussed in greater detail in the plant specific application discussion, Section 3.10.2.

If the bottom of the vent coincides with the top of the hot leg (e.g., SG manway or open loop isolation valve on the hot side), part of the boil-off volume will spill due to the swell from void formation before a steady boil-off condition develops. This "spill penalty" is typically 25-35% of the boil-off volume for the range of decay heats and plant sizes studied. This spill shortens the time to core uncovery by a comparable amount.

Using results from the TREAT analyses, the times to core uncovery (based on the collapsed level in the core) are summarized in Table 3.4.2-1. For conservatism, the results tabulated include the 25-35% spill penalty discussed above. With the exception of four higher decay heat cases, the times to core uncovery all exceed one hour. Results can again be graphically represented in terms of the power to heatup volume ratio (P/V), primarily because the boil-off volumes are in almost direct proportion to the initial heatup volumes. Figure 3.4.2-1 shows the core uncovery times for the three P/V ratios used in the analysis. Plant specific application of this data is discussed in Section 3.10.2.

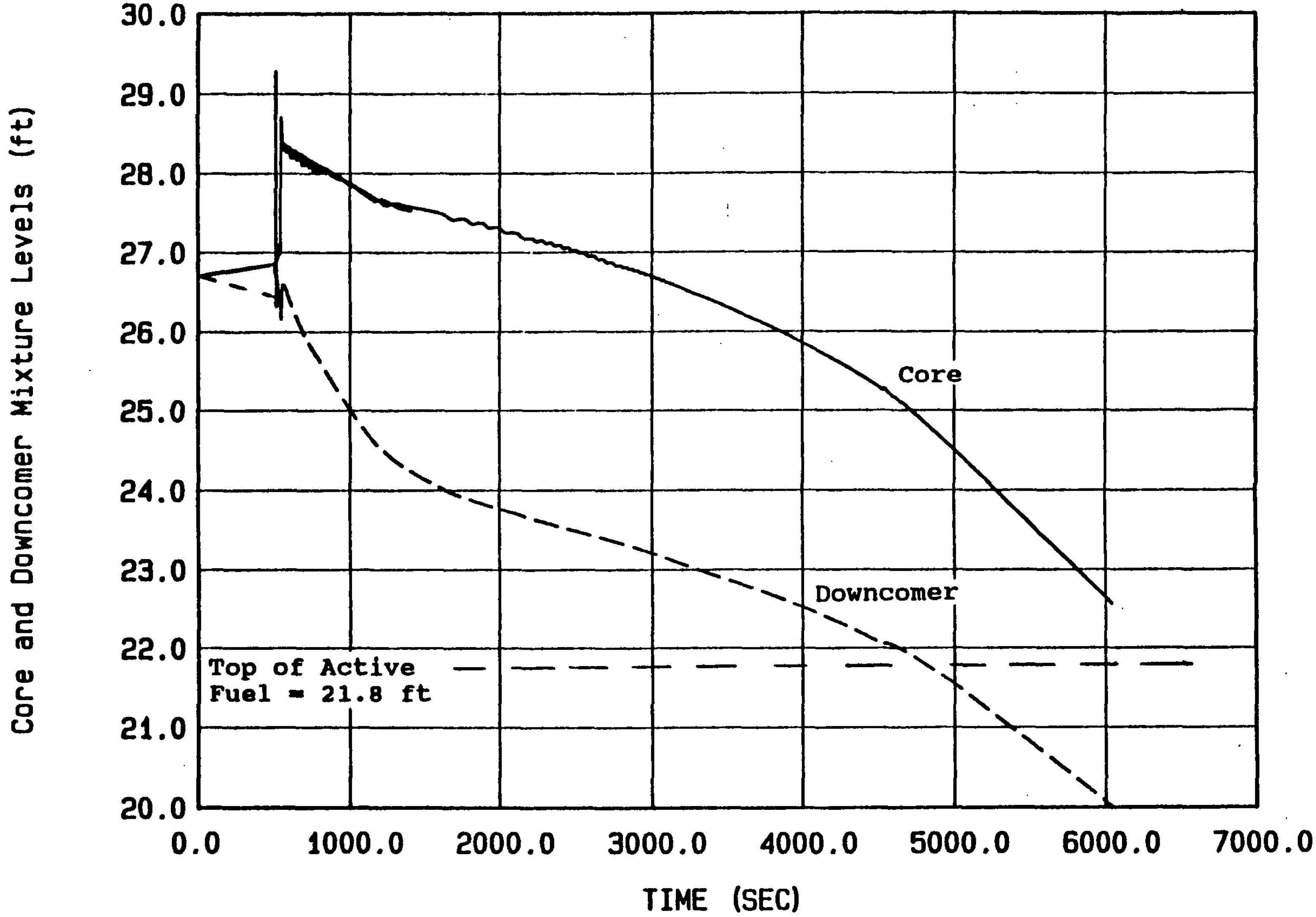
TABLE 3.4.2-1

LARGE RCS VENT SUMMARY

140°F, NO SG CONDENSATION

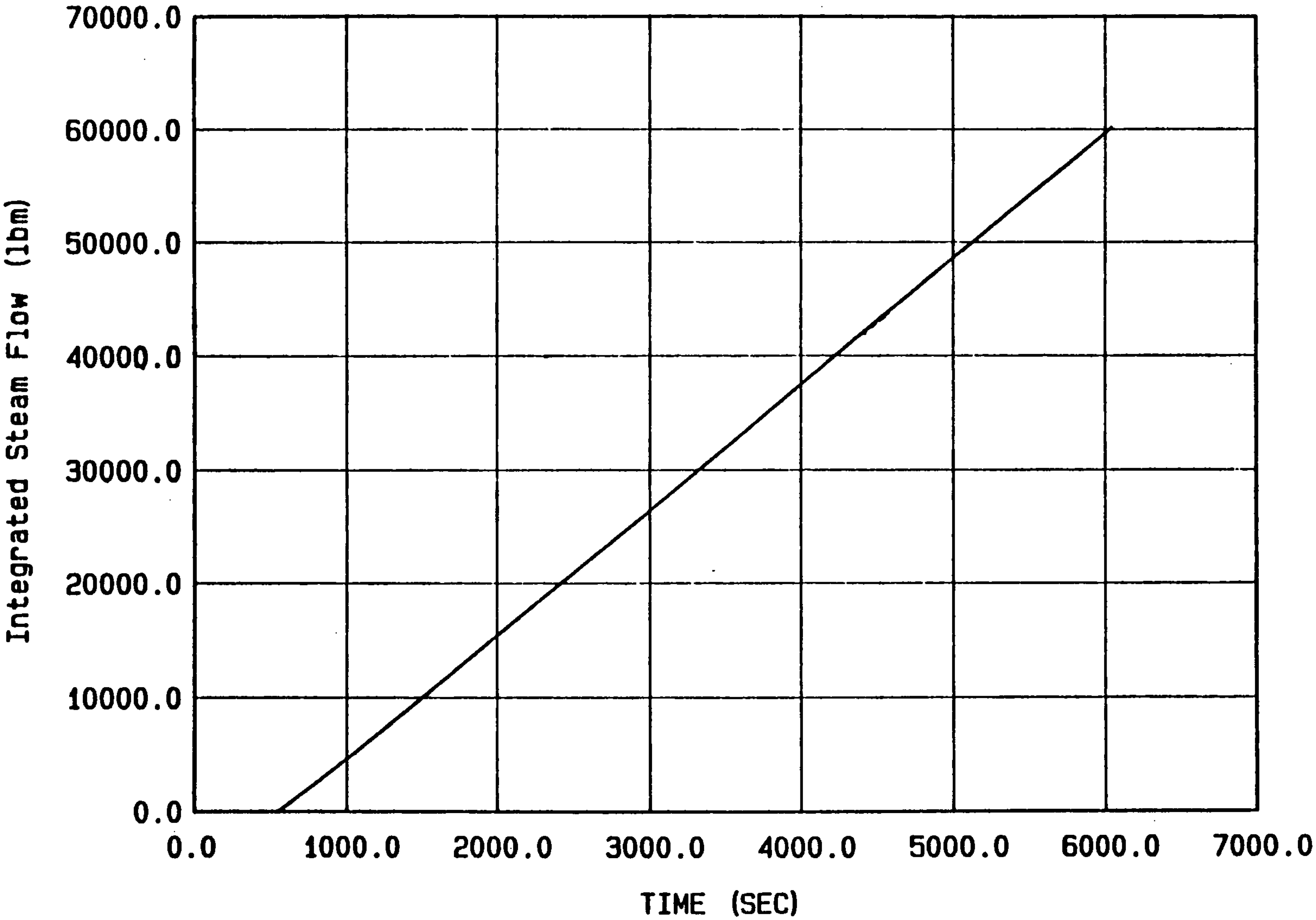
Plant Type	Case	Decay Heat (MWt)	Time After Shutdown (Hours)	Time in Seconds to Reach T_{sat}	Time in Seconds to Reach Core Uncovery*
2-Loop	B.1	9.73	20	415	3600
	B.2	7.30	48	560	5000
	B.3	5.02	120	830	7100
3-Loop	B.4	15.62	20	375	3300
	B.5	11.72	48	520	4600
	B.6	8.06	120	770	6500
4-Loop	B.7	23.7	20	350	2600
	B.8	17.8	48	475	3400
	B.9	12.2	120	725	5100
	B.10	9.62	200	900	6400

* - Based on Collapsed Core Level at the Top of the Active Fuel. These times are corrected for spillage or overflow of mixture due to swell after the RCS starts to boil.



Three-Loop Case B.5, 48 HRS, Large RCS Vent

Figure 3.4.1-1 Three Loop Case B.5, Core and Downcomer Mixture Levels



Three-Loop Case B.5, 48 HRS, Large RCS Vent

Figure 3.4.1-2 Three-Loop Case B.5, Integrated Steam Vent Flow

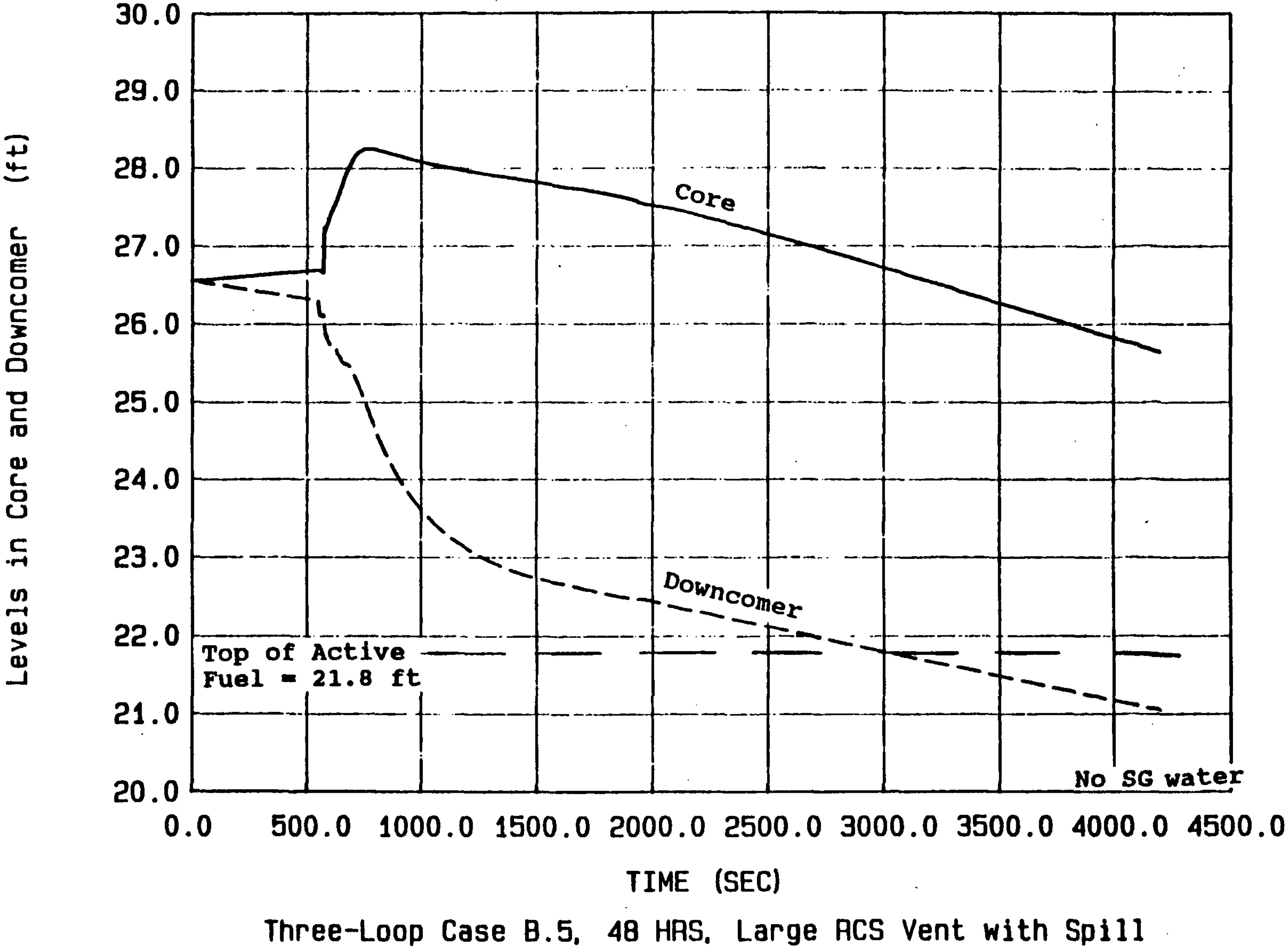


Figure 3.4.1-3 Three-Loop Case B.5, Core and Downcomer Levels (Spill Variation Case)

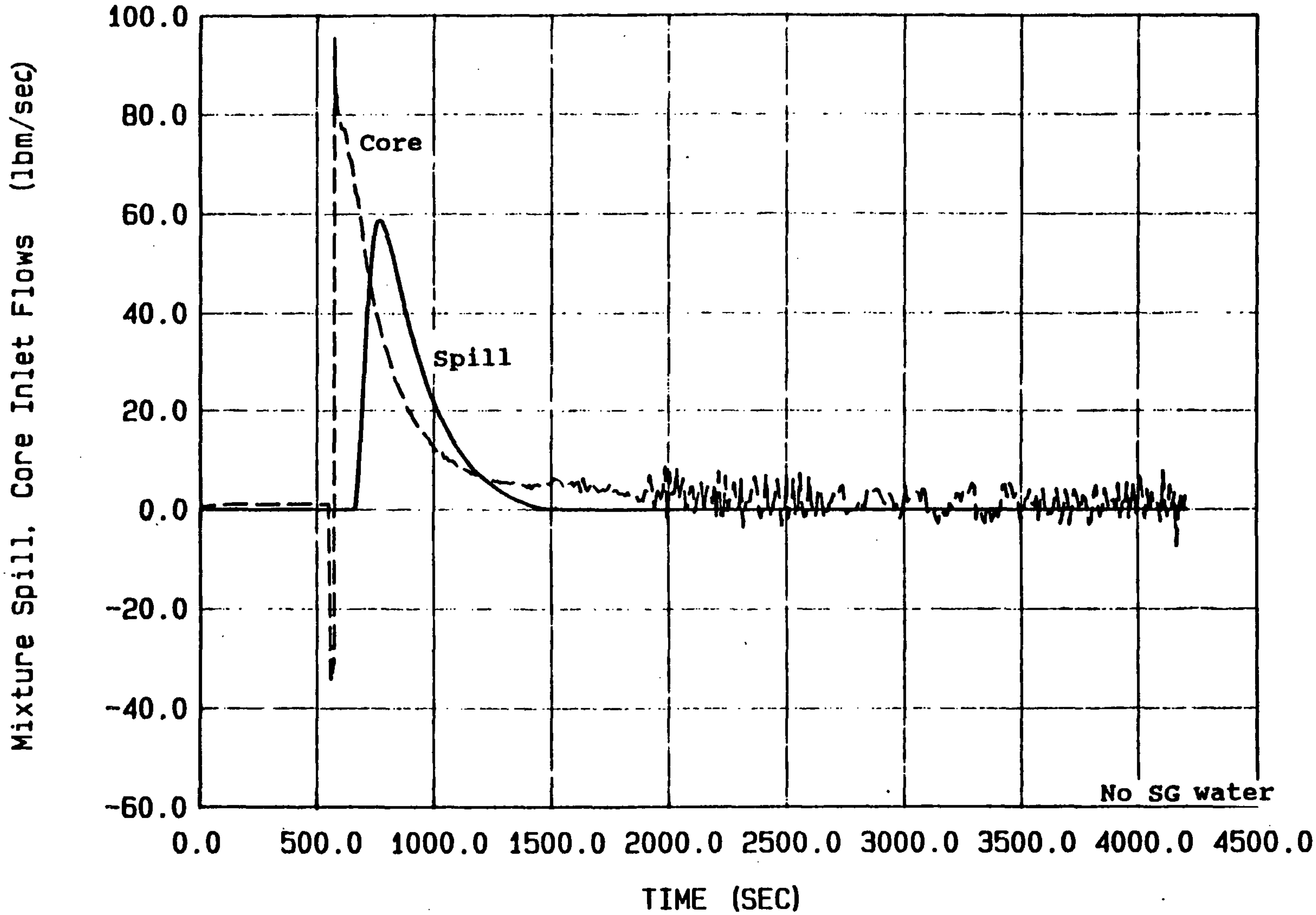


Figure 3.4.1-4 Three-Loop Case B.5, Mixture Spill and Core Inlet Flow (Spill Variation Case)

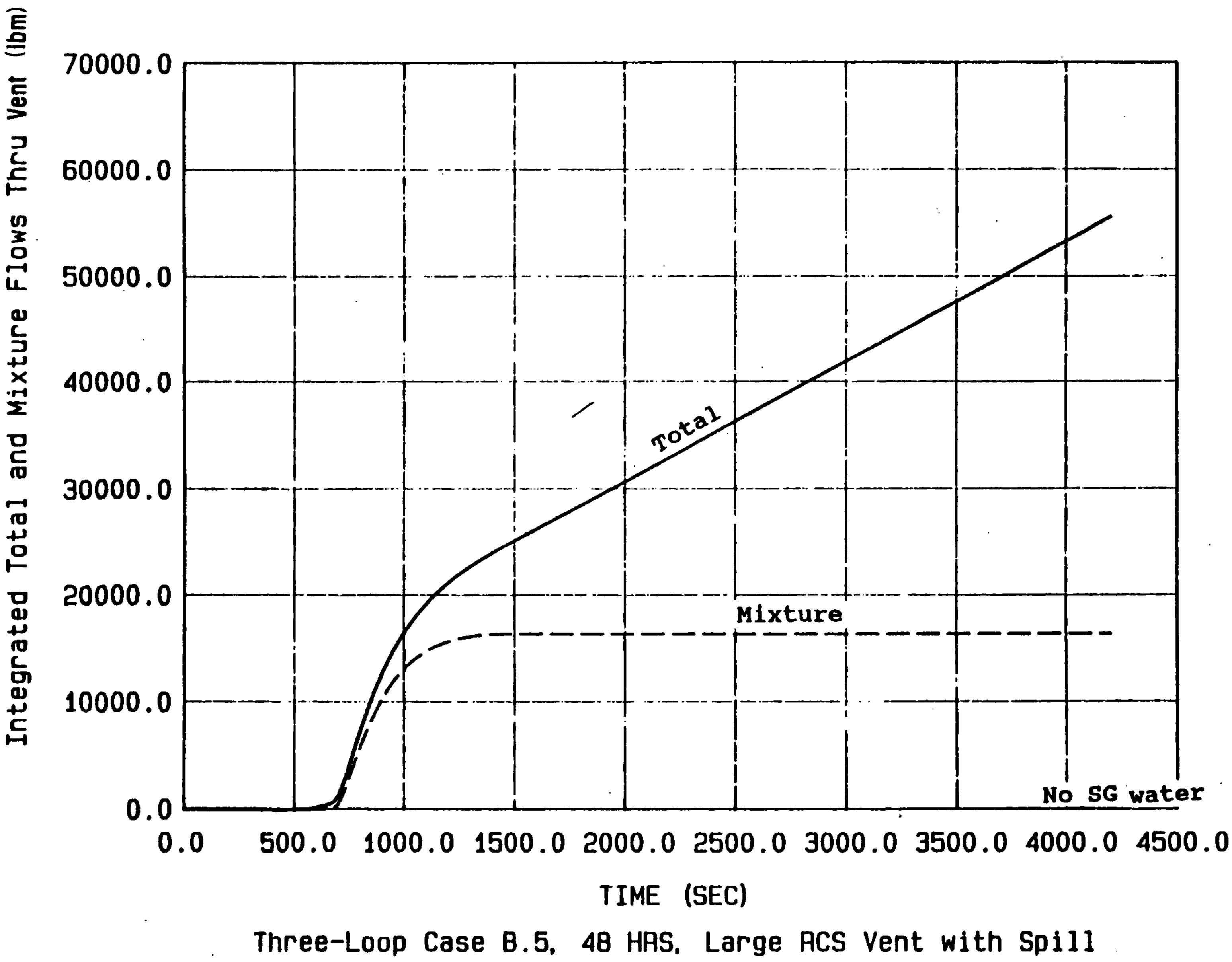


Figure 3.4.1-5 Three-Loop Case B.5, Integrated Spill Flows (Spill Variation Case)

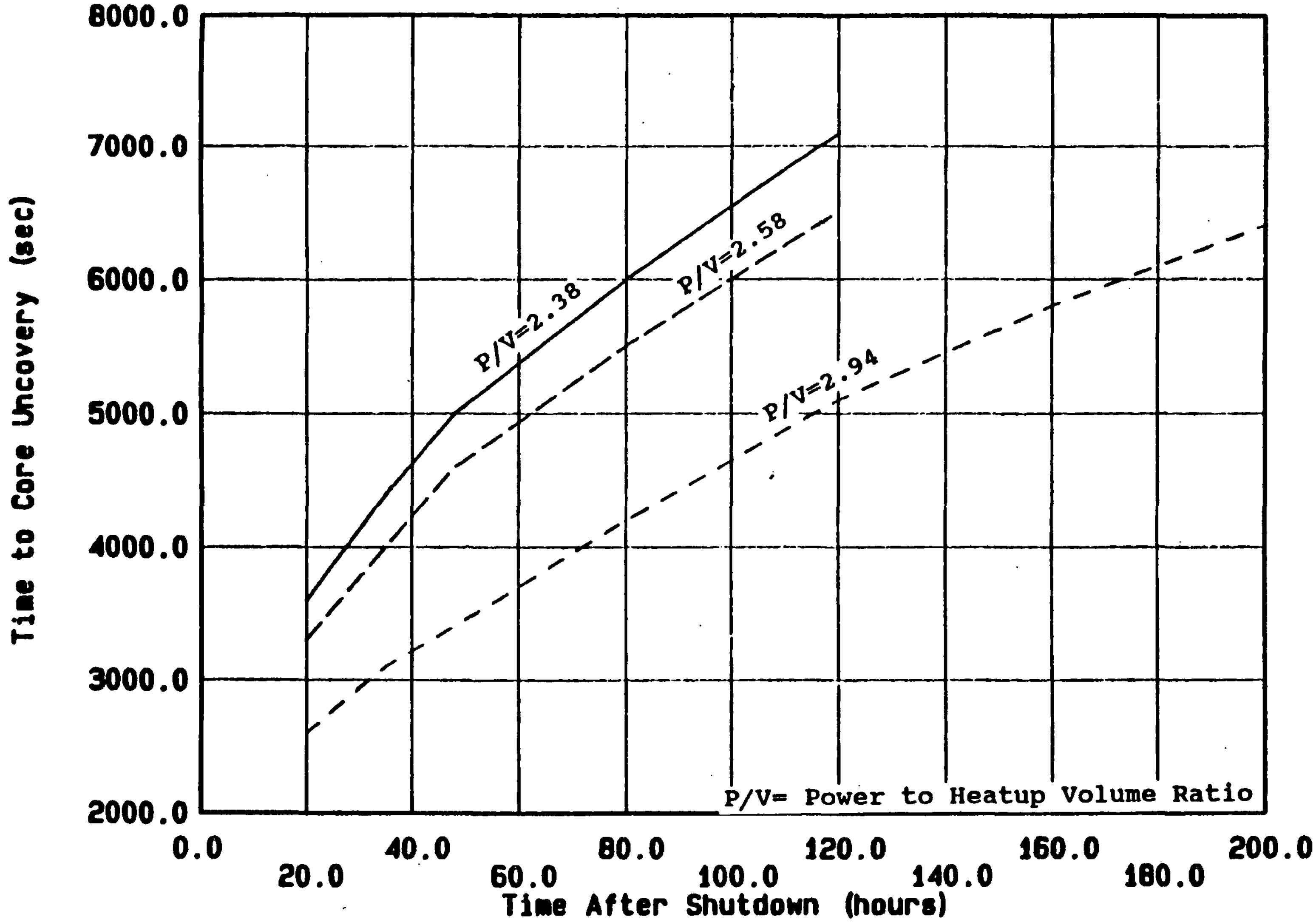


Figure 3.4.2-1 Time to Core Uncovery for Large RCS Vent Analysis, with Initial Liquid Spill

3.5 Steam Generator Nozzle Dam Sensitivity Study

If nozzle dams are installed in one or more of the steam generators, the hot leg and upper plenum regions of the RCS will pressurize significantly faster than the cold leg and downcomer regions. If there are large openings on the cold side, a slight over-pressure in the core soon after saturation is reached will result in RCS inventory loss through the opening and the core level will rapidly drop. The study presented here will quantify the expected RCS and core level response for several scenarios in which one or more hot leg side SG nozzle dams are in place and there are large openings on the cold leg side. The two-loop plant, 48 hours after shutdown, was used for each of the three analyses. The initial 500 seconds of each case is identical with that described in Section 3.3.1 (Case A.2) since boiling does not occur until after this time.

3.5.1 Both Hot Side SG Nozzle Dams in Place, One Cold Side SG Manway Open (Case C.1)

In this study, the RCS hot side is bottled up with the nozzle dams and one of the cold side SG manways is removed. After boiling starts at 560 seconds, the RCS starts to pressurize (Figure 3.5.1-1). The resulting liquid flow spilling from the manway (Figure 3.5.1-2) averages about 500 lbm/sec for a period of 20-30 seconds. During this time, most of the water in the cold leg and pump suction piping in the loop with the opening is expelled. The core and downcomer levels drop several inches (Figure 3.5.1-3) during this period. After 600 seconds, the water level in the loop with the opening is maintained near the bottom of the loop seal piping. Since RCS pressure is not high enough to force the remainder of the water in this loop out the opening, the spill flow decreases until the RCS pressure increases to about 19 psia. By 700 seconds, the RCS has pressurized to 19 psia (4 psi higher than ambient pressure), an amount sufficient to support the column of water equal to the head difference between the bottom of the manway and the loop seal (or pump suction) piping. Thus, the spill from the manway again becomes significant; the core reverse flow is nearly the same as the manway flow after this time. By 770 seconds (13 minutes), the top of the active fuel is uncovered; 10 seconds later, half the core is uncovered.

3.5.2 Both Hot Side SG Nozzle Dams in Place, Large Cold Leg Check Valve Opening (Case C.2)

In this scenario, it is postulated that there is a large opening in one of the cold legs due to removal of a large 12" check valve, e.g., the valve in one of the SI accumulator discharge lines. The opening was modeled near the top of the cold leg and frictional losses in the piping were neglected for conservatism. As in Case C.1, both hot side SG nozzle dams are in place.

Plots of interest for this scenario are given in Figures 3.5.2-1, 3.5.2-2, and 3.5.2-3. As expected, the RCS response is similar to the previous case. In this case, however, there is no gavitational head "hurdle" to overcome, so the flow through the opening is approximately the same as the core reverse flow as soon as boiling starts. The core actually uncovers sooner in this case because of this (670 seconds versus 770 seconds).

3.5.3 No Dams in Loop 1, Hot Side SG Nozzle Dam in Place and Cold Side SG Manway Open in Loop 2 (Case C.3)

Without nozzle dams in the intact loop, it is possible to delay core uncovery for a small period of time since water in the intact loop can help feed the opening. The response for this case is illustrated in Figures 3.5.3-1, 3.5.3-2, and 3.5.3-3. The RCS pressure response up to 700 seconds is similar to that of Case C.1. Pressure then hangs up at the 19 psia level from 700-780 seconds. During this time, the intact loop helps feed the opening and the core flow averages zero. Thus, between 700 and 800 seconds, the core level remains relatively constant. By 800 seconds, pressure again increases and core flow reverses. The top of the core uncovers at 840 seconds and remains uncovered for a prolonged period of time (the analysis was run beyond 900 seconds to confirm this). Comparing the results of this case with the previous one (Case C.1), the intact loop delays core uncovery by approximately one minute.

3.5.4 Summary of SG Nozzle Dam Sensitivity

If the hot leg side is isolated by installation of SG nozzle dams, significant volumes of water can be forced out of large cold side openings if the RCS is allowed to reach saturation and starts to pressurize. For the scenarios studied here, the time to prolonged core uncovery was very short - within several minutes following the start of boiling i.e., as early as 670 seconds (11 min). Installation of cold side SG nozzle dams first will prevent this situation from occurring for the SG manway opening case. However, once the hot leg side dams are in place and the RCS pressurizes above 40 psia (typical test pressure for the nozzle dams), a rapid core uncovery could also result if a cold side dam fails while the hot side is still isolated. Section 3.9 will consider various modes of recovery (e.g., hot leg injection) that can be used to restore level or prevent core uncovery for these cases.

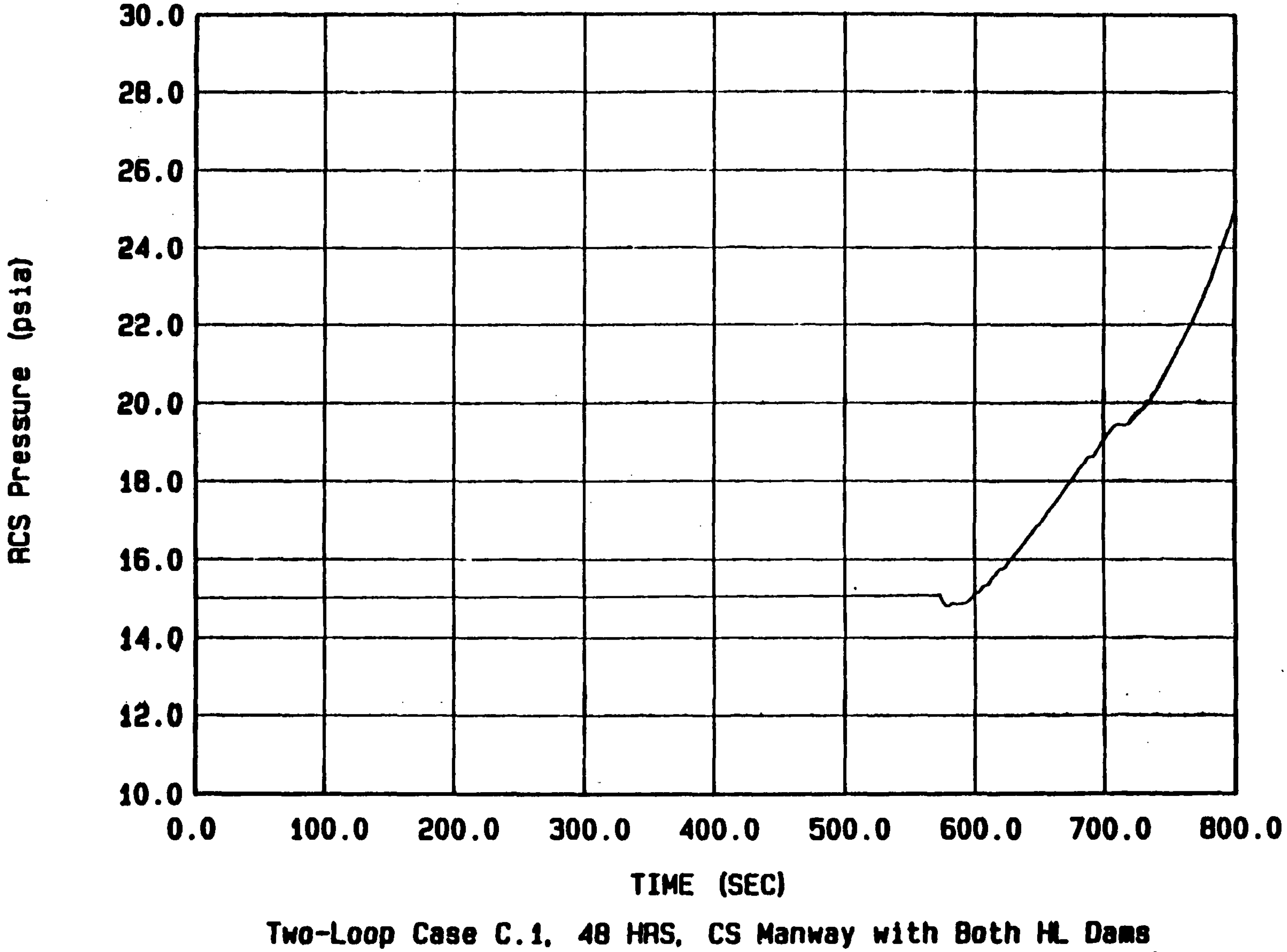


Figure 3.5.1-1 Two-Loop Case C.1, RCS Pressure

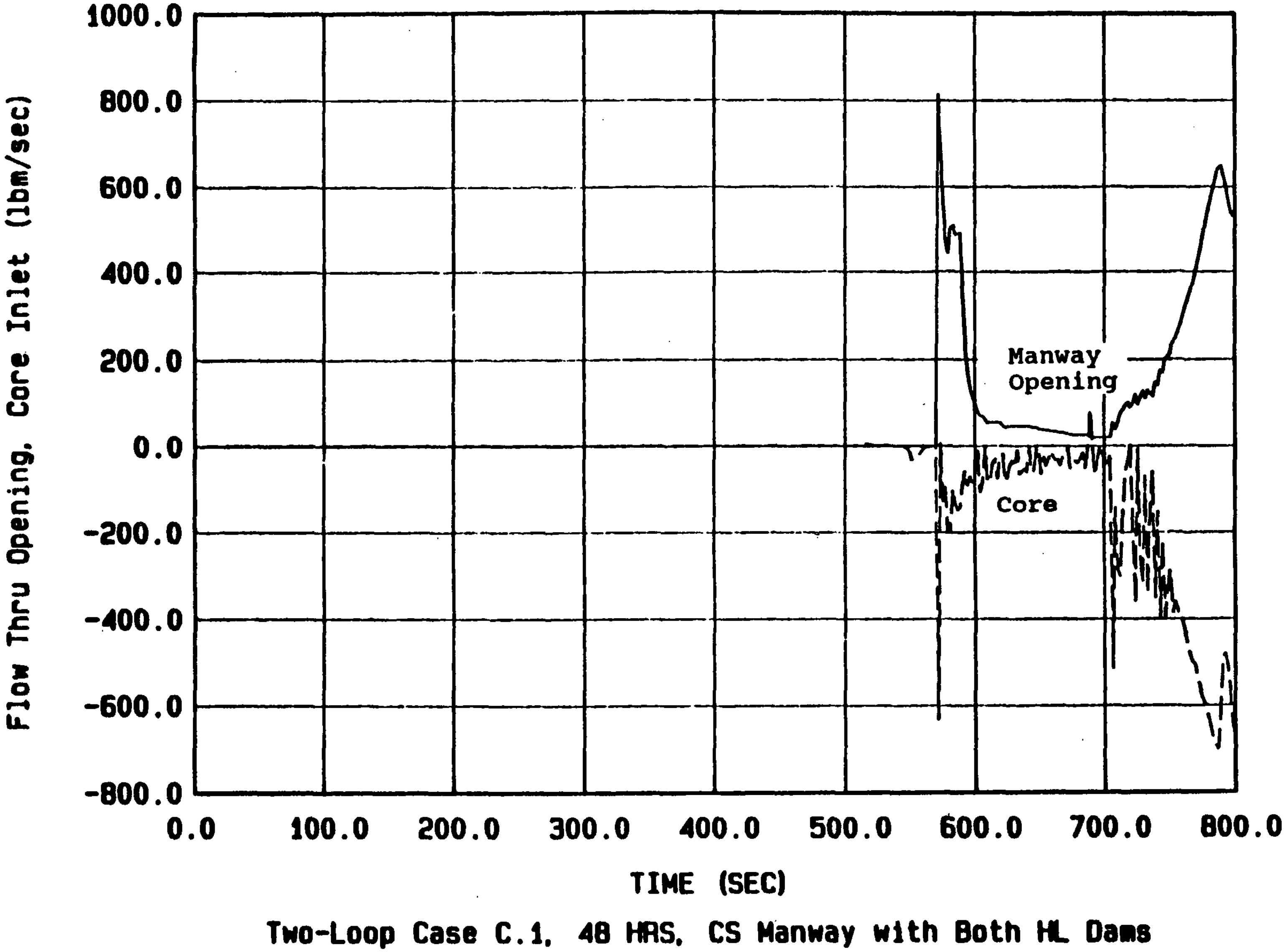


Figure 3.5.1-2 Two-Loop Case C.1, Manway and Core Inlet Flows

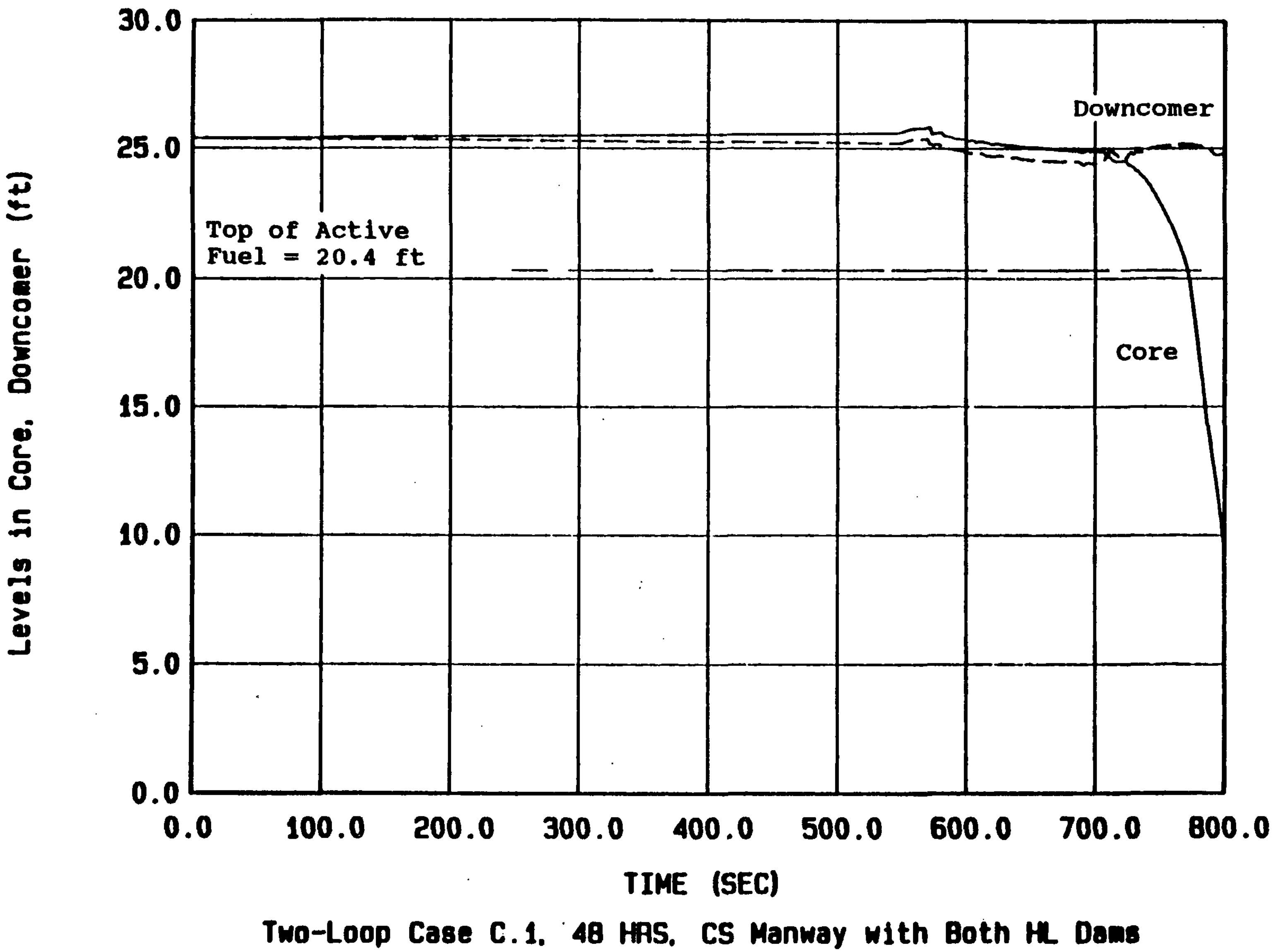


Figure 3.5.1-3 Two-Loop Case C.1, Core and Downcomer Mixture Levels

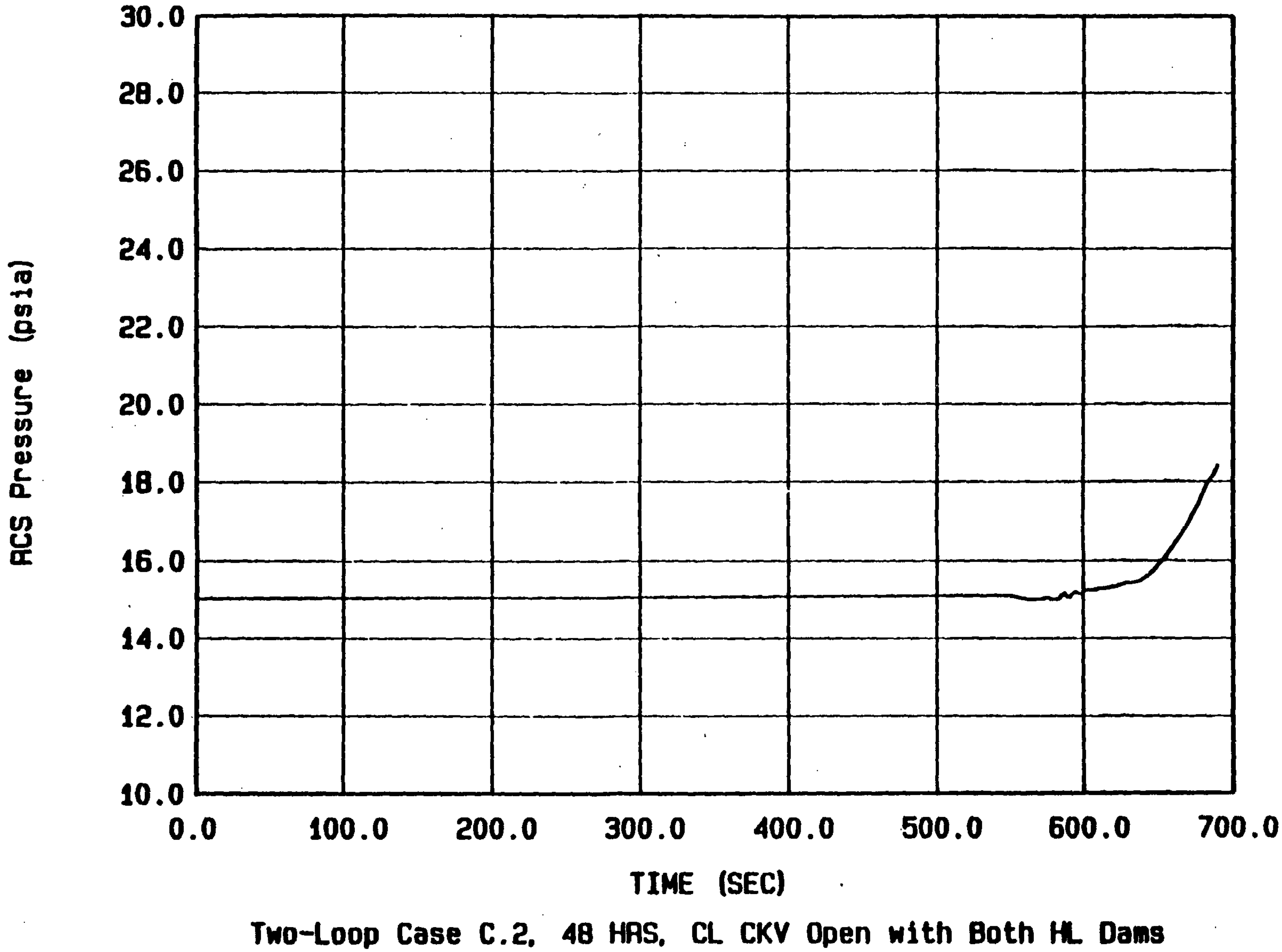
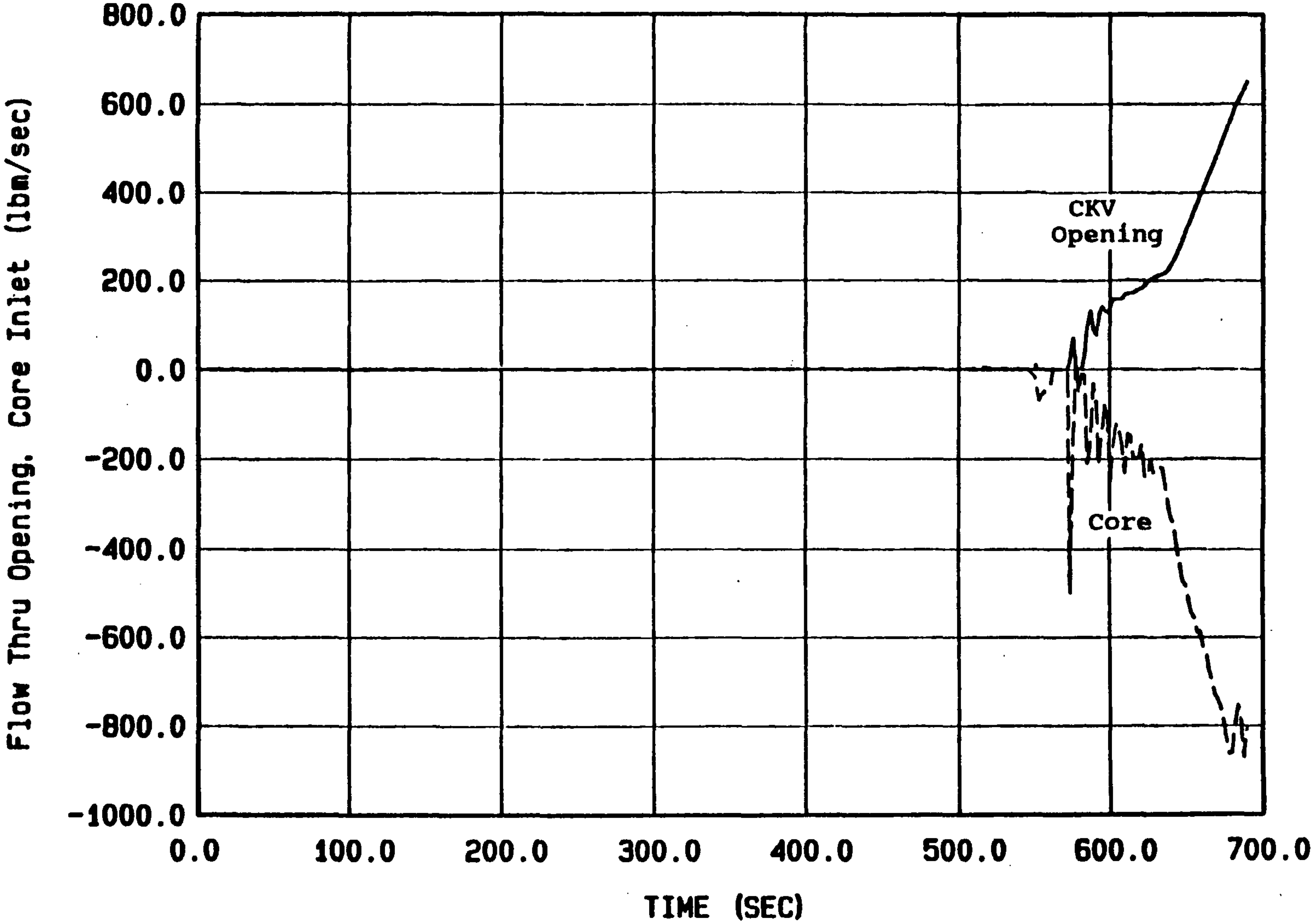


Figure 3.5.2-1 Two-Loop Case C.2, RCS Pressure



Two-Loop Case C.2, 48 HRS, CL CKV Open with Both HL Dams

Figure 3.5.2-2 Two-Loop Case C.2, Check Valve and Core Inlet Flows

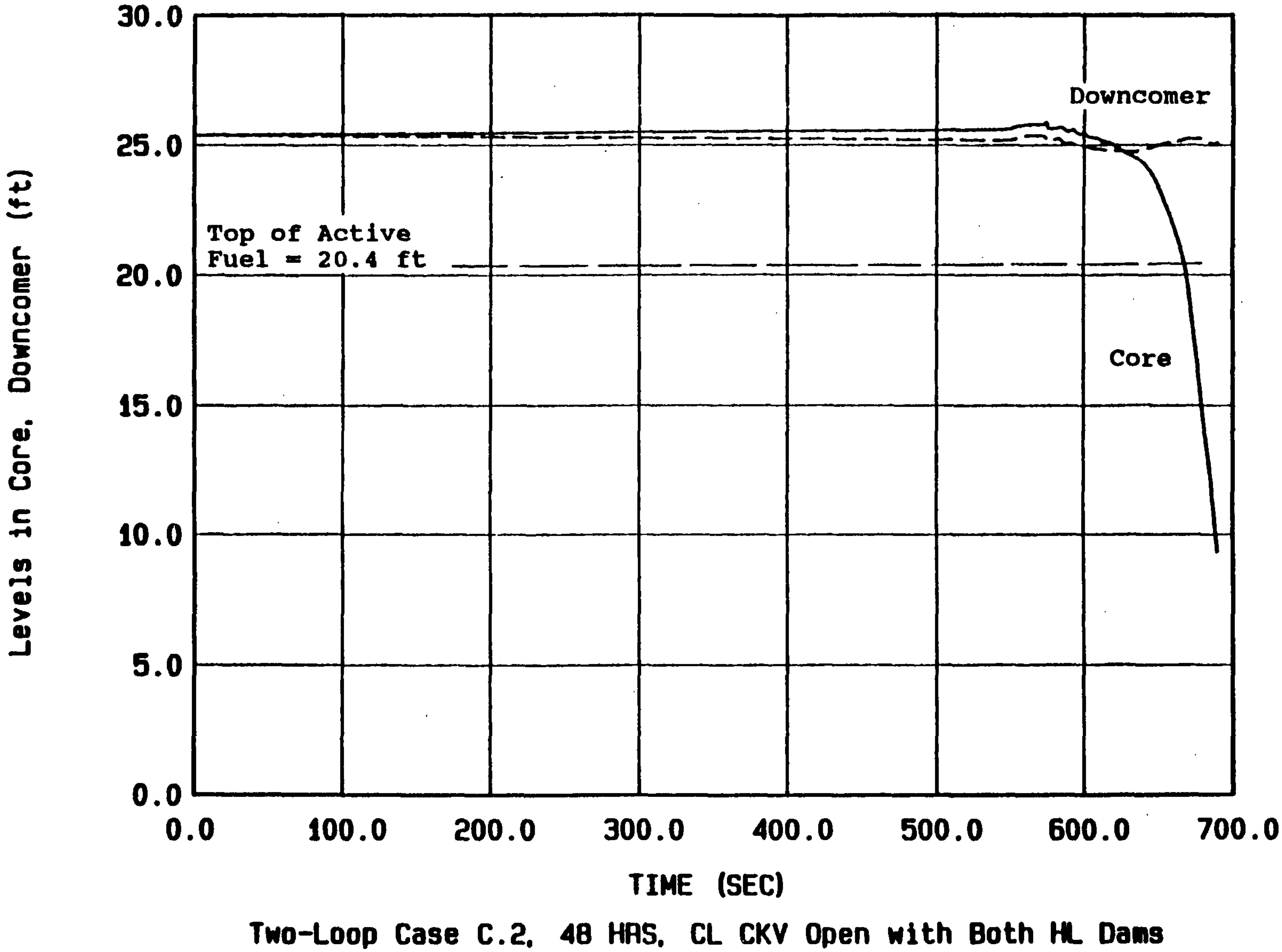


Figure 3.5.2-3 Two-Loop Case C.2, Core and Downcomer Mixture Levels

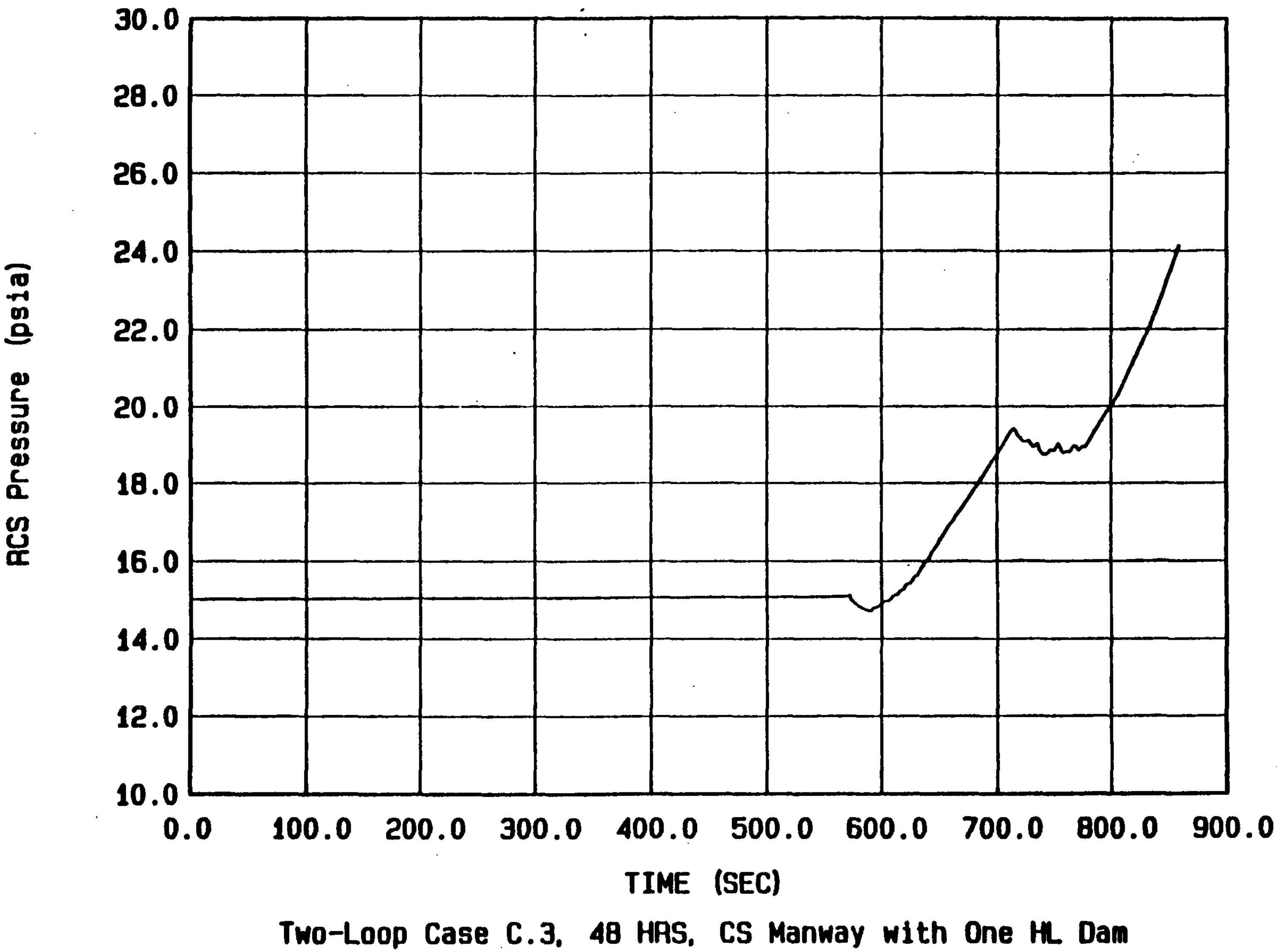


Figure 3.5.3-1 Two-Loop Case C.3, RCS Pressure

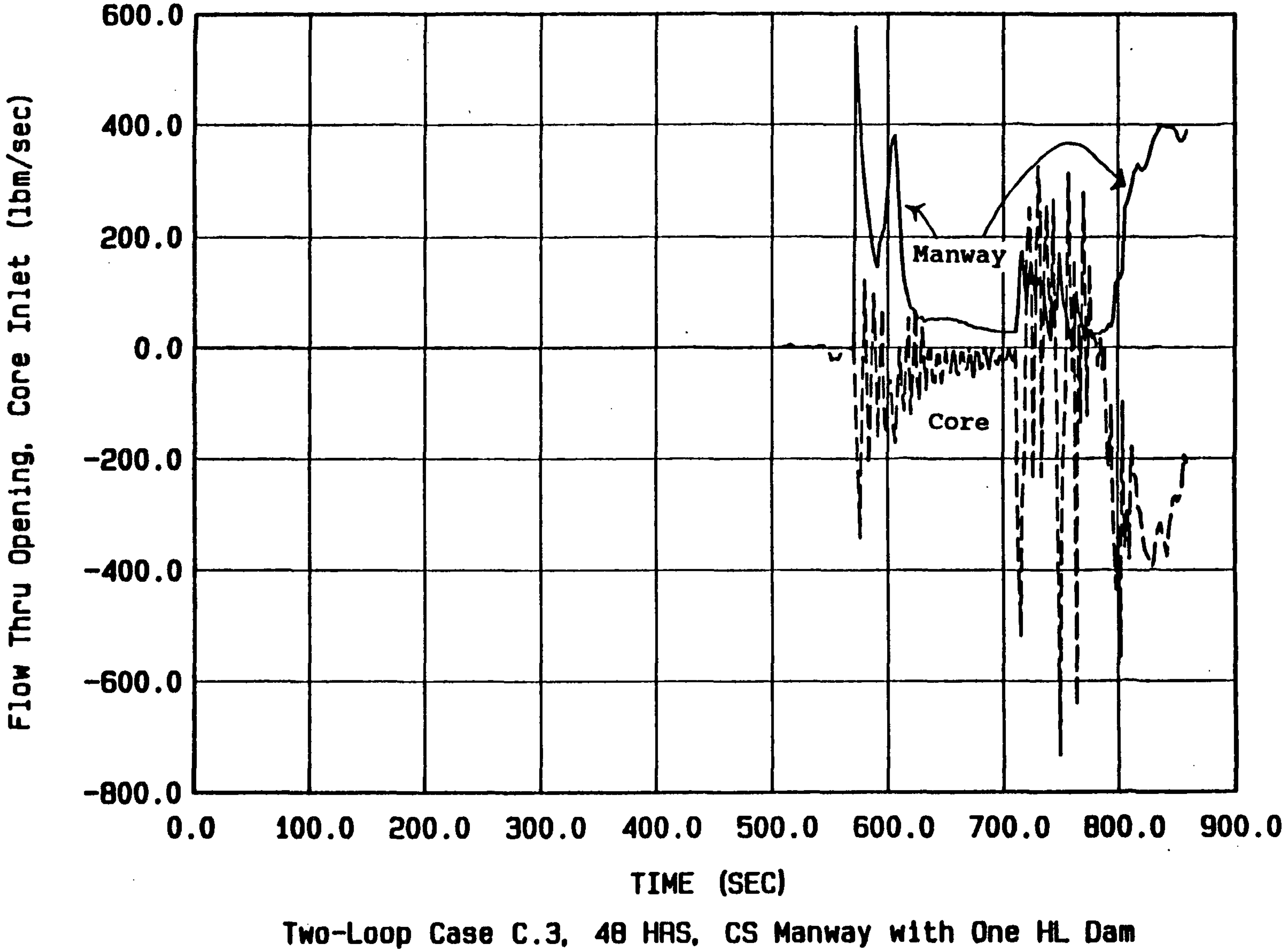


Figure 3.5.3-2 Two-Loop Case C.3, Manway and Core Inlet Flows

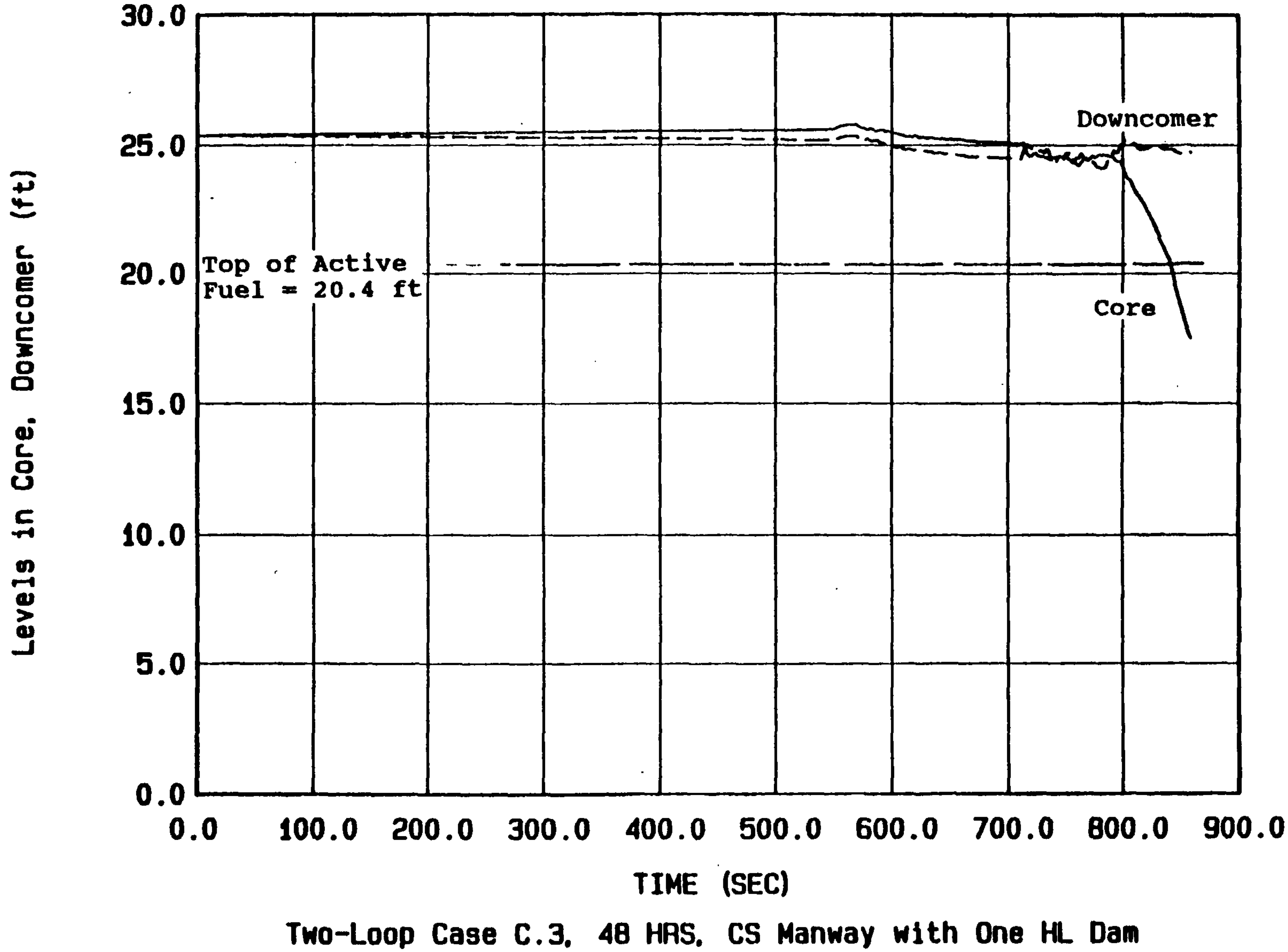


Figure 3.5.3-3 Two-Loop Case C.3, Core and Downcomer Mixture Levels

3.6 Small Vapor Vent Sensitivity Study

Two cases of small vapor vents were analyzed. Both small vent cases showed that the pressurization transient can be slightly mitigated, but as expected the first several hundred psia increase is not substantially delayed. At higher pressures, the vent flow rates become larger and the pressure relief is more significant.

3.6.1 Four-Loop Case, 48 Hours After Shutdown, Small Vent in Upper Head and Top of Pressurizer (Case D.1)

In this scenario, it is assumed that the pressurizer and upper head are each vented to containment through small (3/4" diameter) lines.

Figure 3.6.1-1 compares the pressurization curve for this small vent case with the pressurization curve of the base case A.8. Initially the pressurization rate is identical for both cases and it is not until the vent flows increase that the pressurization drops off for the vented case (see Figure 3.6.1-2). At the end of the vent case run, the pressure is just starting to turn around and tend toward a steady state. However the steady state will be at a very high pressure well over 1000 psia. At one hour into the transient, the pressure is lagging approximately 90 psia behind the base case.

Pressurizer level (Figure 3.6.1-3) increases initially as in the base cases. The level then shrinks about 5 feet as some liquid drains out the surge line and then level steadily increases similar to the base case. At the end of the 5000 second run, the level is 27 ft below the vent so it is not predicted that the vent will relieve any liquid.

This comparison shows that for a typical vented configuration (one or two lines with diameter <3/4"), the RCS pressure transient is not substantially different from that of the all intact case.

3.6.2 Four-Loop Case, 48 Hours After Shutdown, Two PORVs Open (Case D.2)

Figure 3.6.2-1 compares the pressurization curve for this case with that of the base case A.8. The two pressurizer PORVs have a significantly greater area than the small vents in the above case (0.022 versus 0.006 sq-ft). The relief area modeled is equivalent to a relief capacity of 210,000 lbm/hr per valve at the 2350 psia setpoint. It is assumed that the necessary criteria (e.g., electric power, air pressure, etc) are satisfied to maintain the PORVs in the open position. As a result, the pressurization is retarded to a greater extent as more vapor mass is relieved (see Figure 3.6.2-2). However, the benefit gained is once again not as significant over the early portions of the transient as time to 100 psia is only retarded 320 seconds. At the end of the run at 5000 seconds, the pressurization rate has been decreasing for about 1500 seconds and is tending towards a steady state of approximately 400-500 psia.

Figure 3.6.2-3 shows that core level follows the same trends when compared with the base case A.8. The one difference is that the core level drops more significantly at 700 sec due to the increased pressurizer surge line flow. Pressurizer level increases to within 8 feet of the top before slowly draining out the surge line (Figure 3.6.2-4). Despite the large volume of water that entered the pressurizer, the core level was several feet above the top of the active fuel at the end of this 5000 second transient. The corresponding large vent Case B.8 (see Table 3.4.2-1) is clearly a more limiting core uncovery transient.

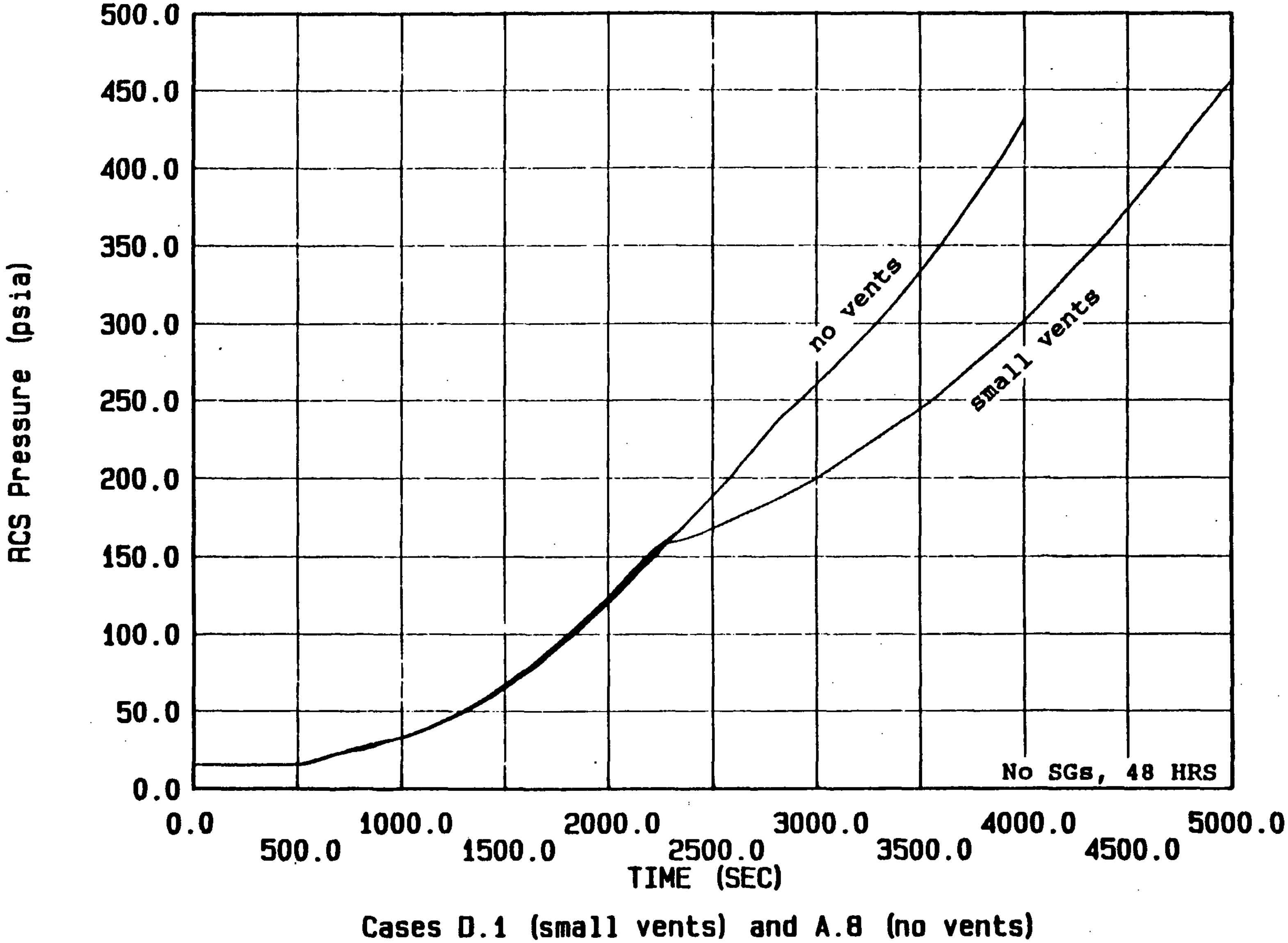


Figure 3.6.1-1 Four Loop Cases D.1 and A.8 Pressurization Comparison

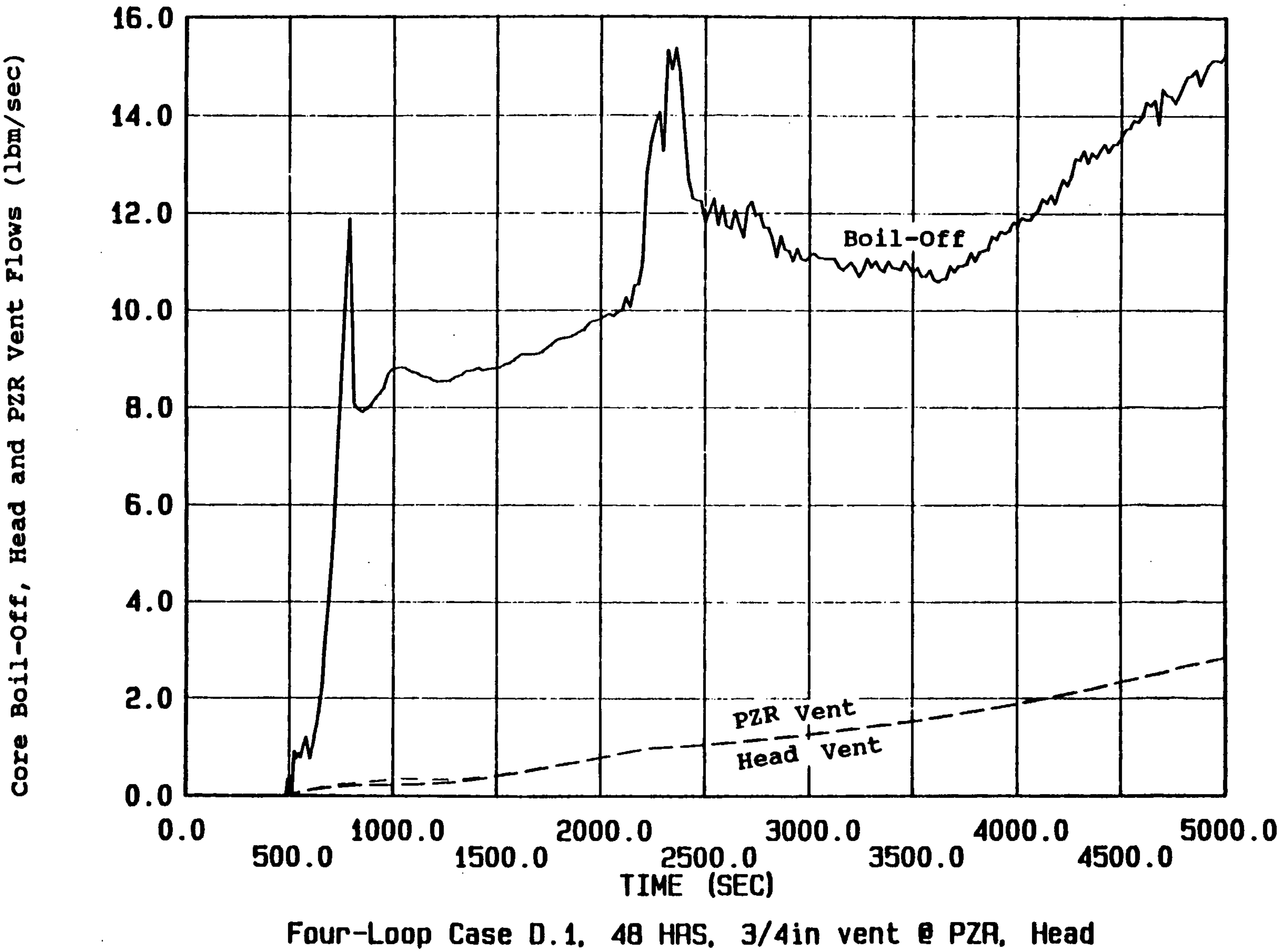


Figure 3.6.1-2 Four-Loop Case D.1, Core Boil-Off, Head Vent and Pressurizer Vent Flows

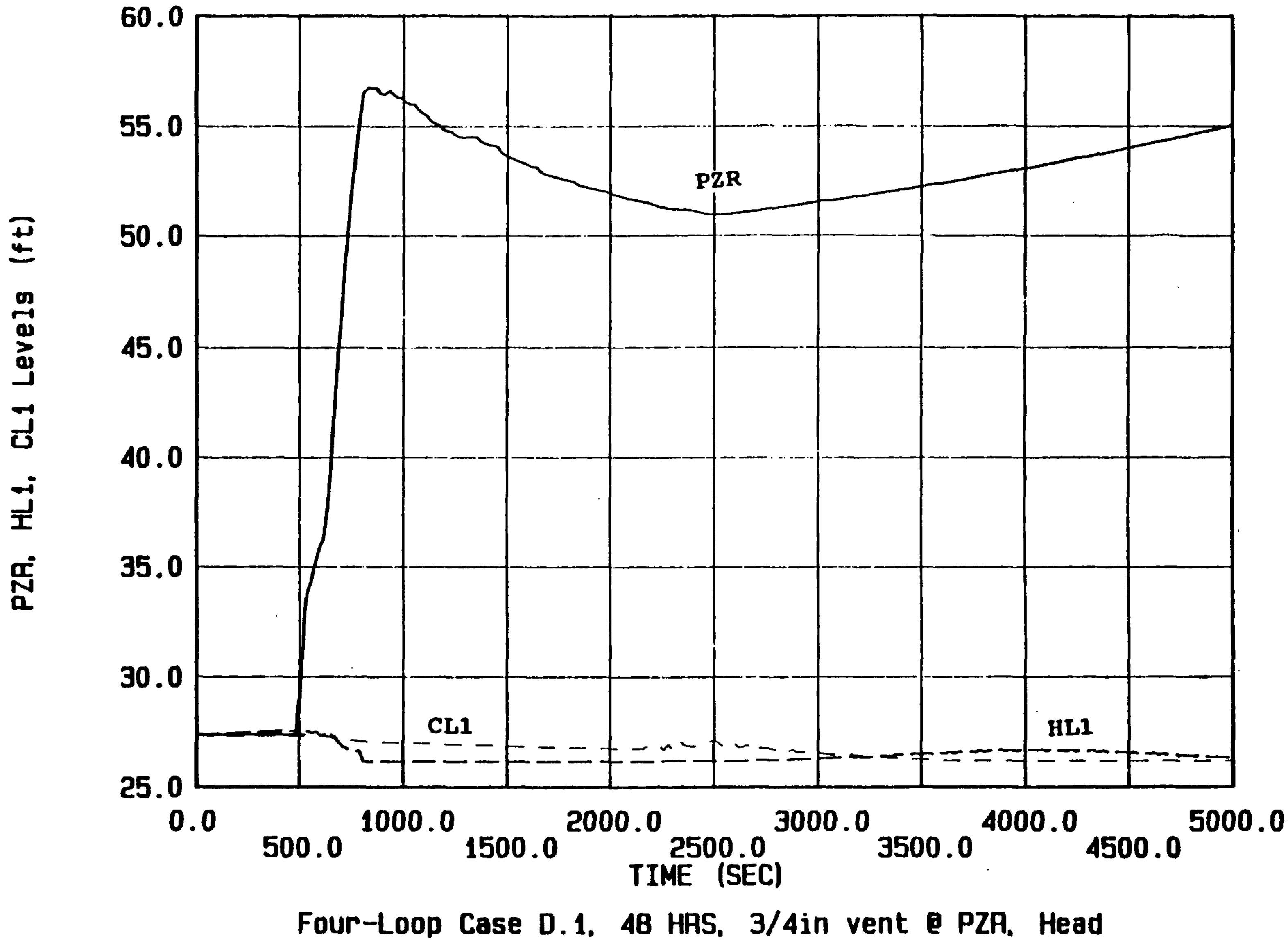
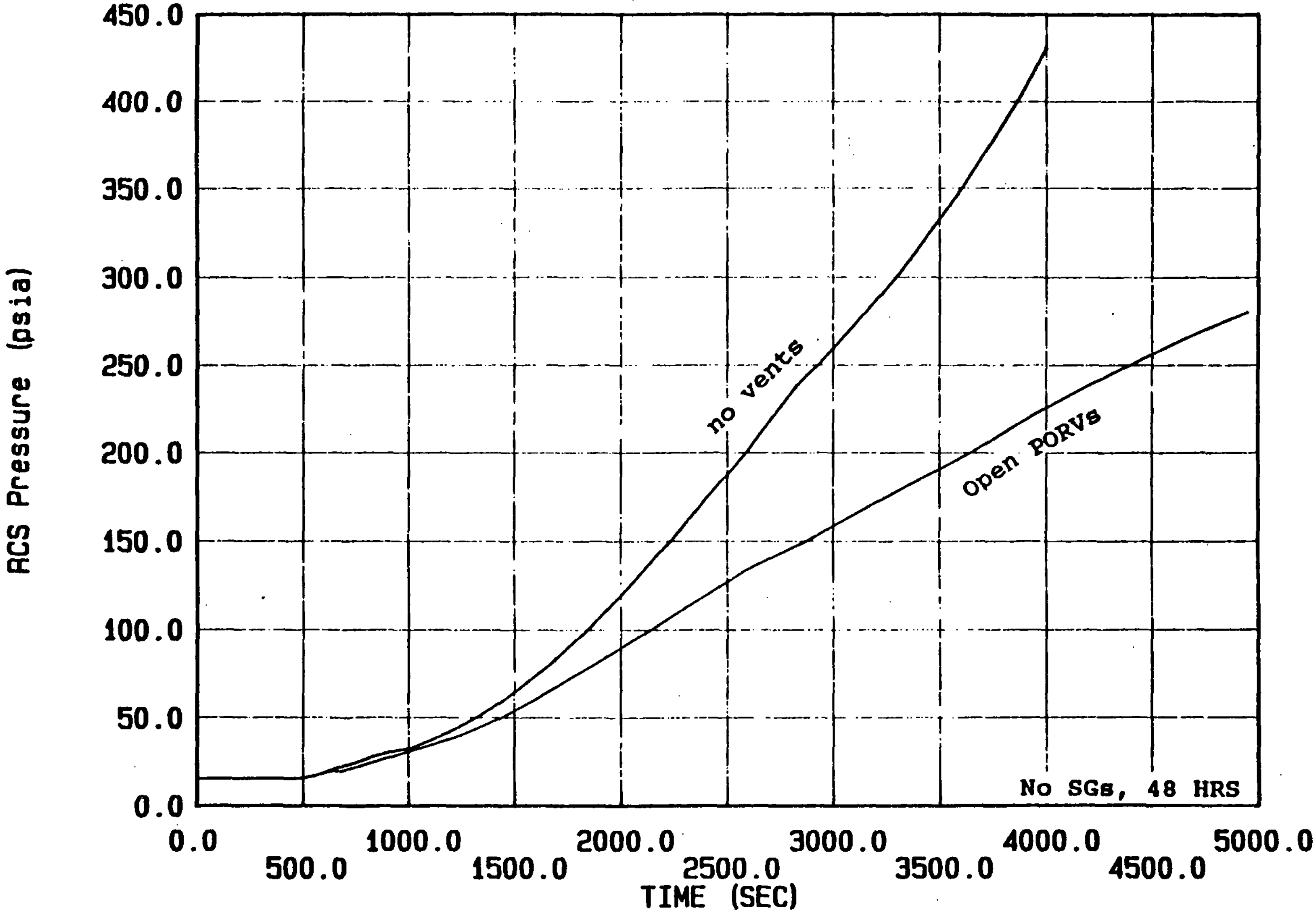


Figure 3.6.1-3 Four Loop Case D.1, Pressurizer, Hot Leg and Cold Leg Levels



Cases D.2 (2 Open PORVs) and A.8 (no vents)

Figure 3.6.2-1 Four Loop Cases D.2 and A.8 Pressurization Comparison

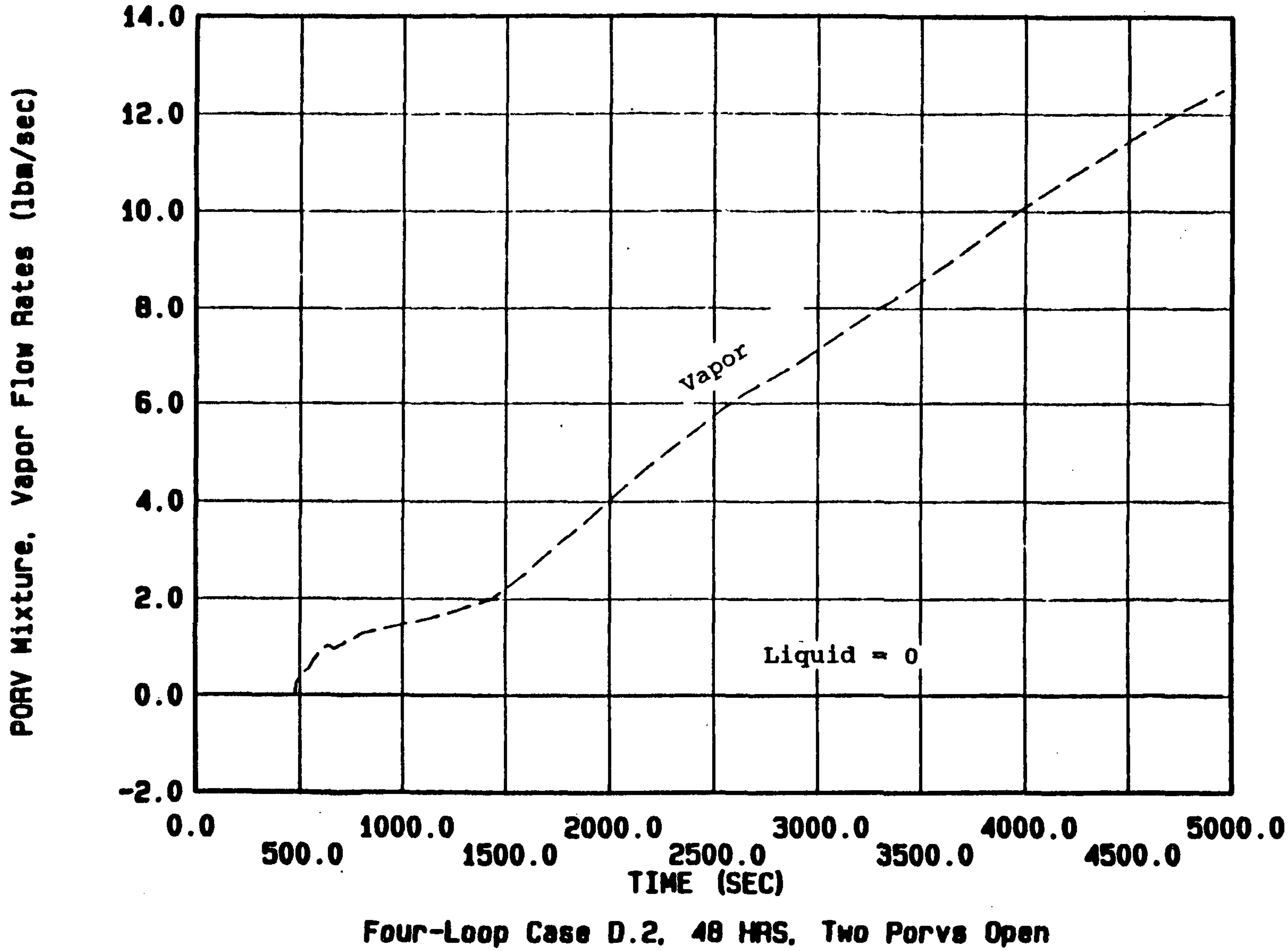


Figure 3.6.2-2 Four Loop Case D.2, PORV Mixture and Vapor Flow Rates

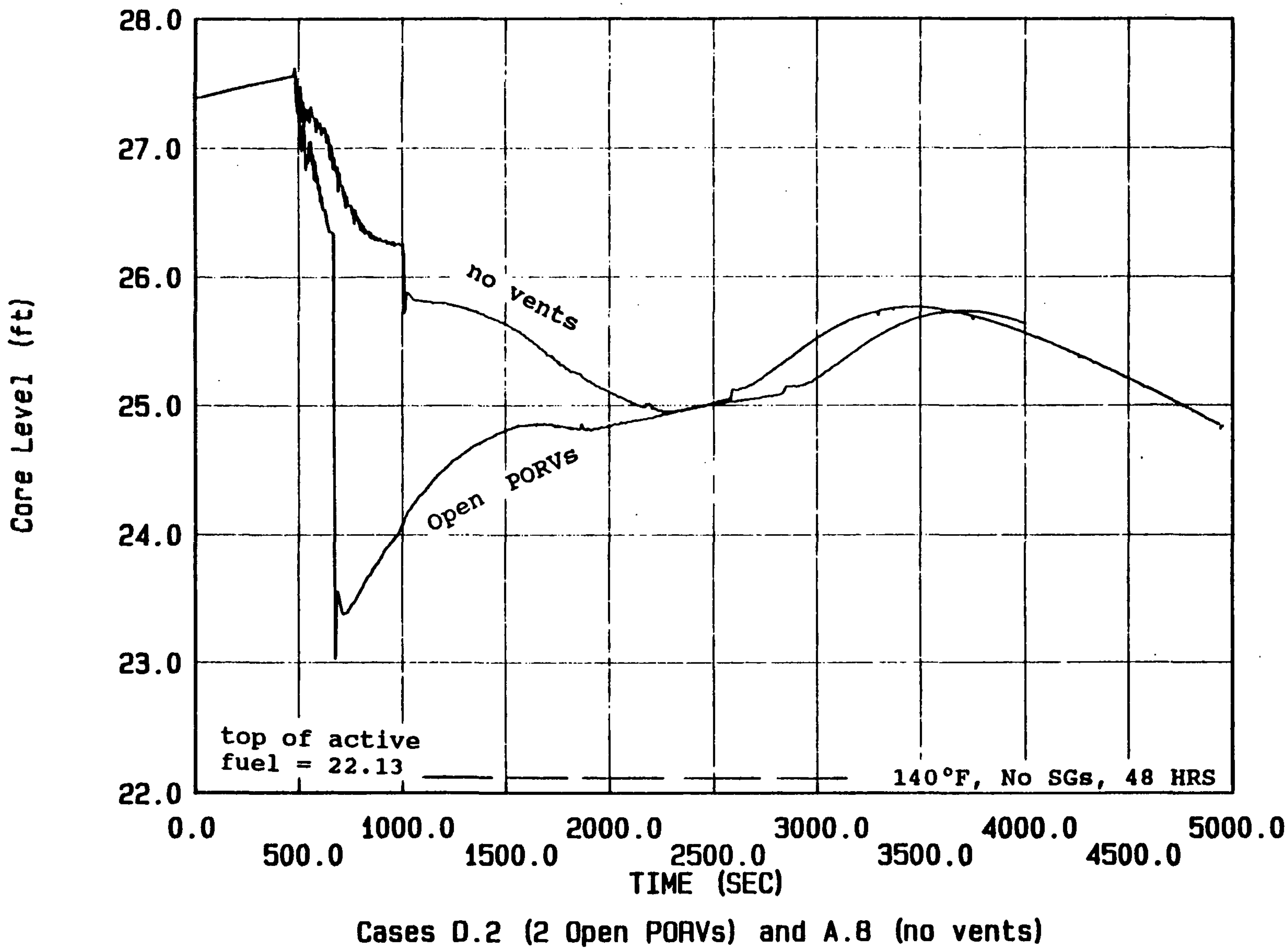


Figure 3.6.2-3 Four Loop Cases D.2 and A.8 Core Mixture Level Comparison

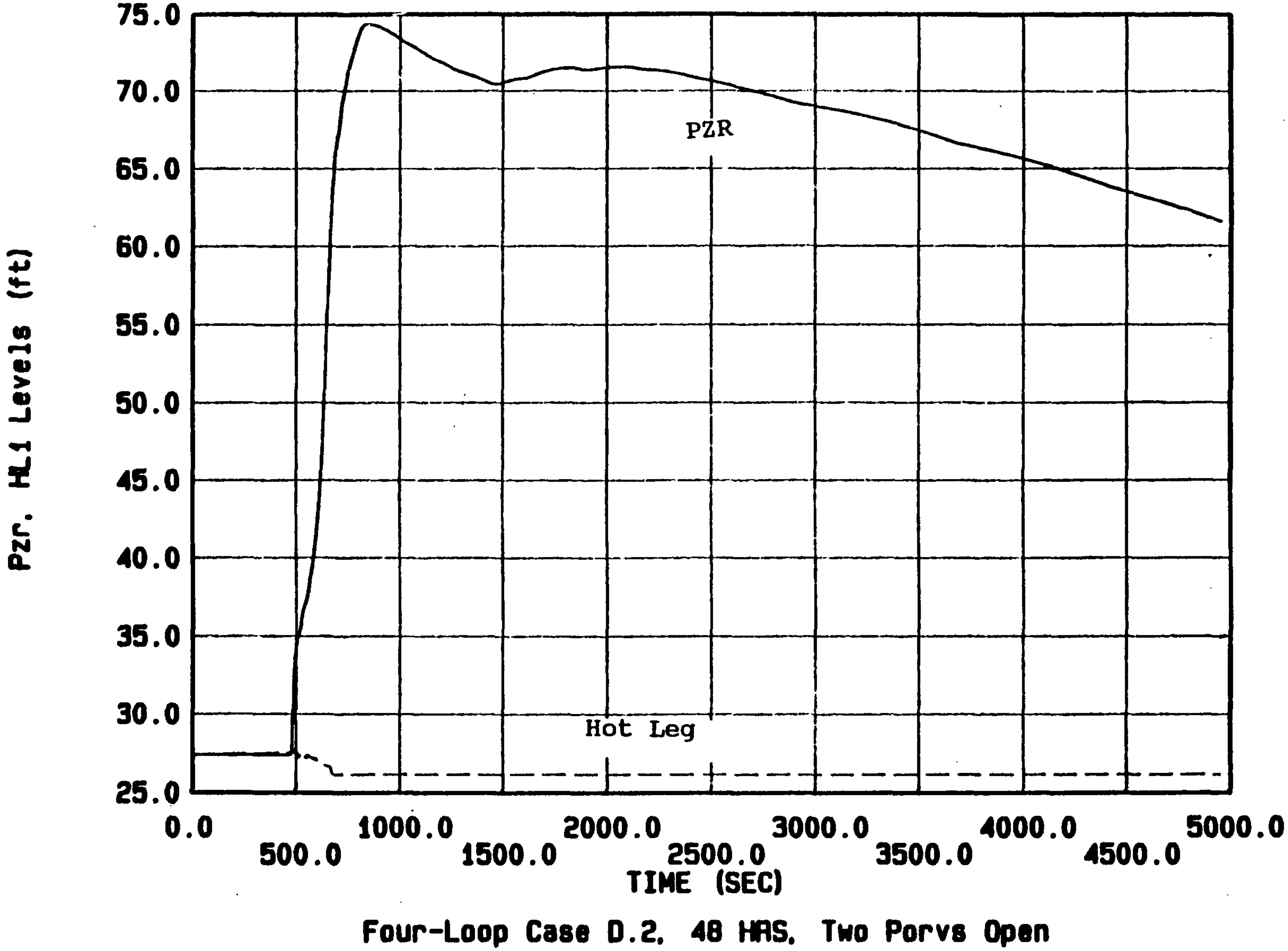


Figure 3.6.2-4 Four Loop Case D.2, Pressurizer and Hot Leg 1 Levels

3.7 Cold Leg Opening Sensitivity Study

Three types of cold leg openings are analyzed in this section.

3.7.1 Four-Loop Case, Small Liquid Opening in Crossover Leg (Case E.1)

This case assumes a small opening in the bottom of the loop 1 crossover leg. The RCS is otherwise intact. The area chosen for the opening was sized to give approximately 100 gpm flow initially, roughly equivalent to two 3/4 inch tygon tube lines (one line would be typical, two bound the 2-loop and 3-loop plants). This scenario in general had no impact on any of the major parameters of interest.

Figure 3.7.1-1 shows the flow rate out the opening. The opening is assumed to be a consequential failure of the tubing, postulated to occur just after the core boils and pressure has climbed to several psia above containment pressure (15 psia). Flow through the opening starts as single phase liquid and increases until 1270 seconds when the crossover leg is drained (see Figure 3.7.1-2). The vent flow then becomes vapor with some condensed steam. From this point on, the system behaves similar to the small vapor vent Case D.1. No core uncovery occurred during this 4700 second scenario.

Figure 3.7.1-3 compares the pressurization transient with the base case A.8 (RCS intact, 48 hours after shutdown). The pressure transient is nearly identical for the first 2000 seconds and then the pressurization is retarded slightly due to the small vent. The event occurring at the end of this run is the pressurizer draining, an event which had not occurred for the base case.

Figure 3.7.1-4 compares core level with the base case A.8. The response is virtually identical except that there is no loop seal clearing for either loop. The core starts to refill at the end of the transient as the pressurizer drains out the surge line.

3.7.2 Cold Leg Check Valve Openings (Cases E.2, E.2a, E.2b, E.2c and E.2d)

The first case analyzed here is similar to Case C.2 (2-loop plant, 48 hrs, 12" check valve opening in Loop 2) except that none of the nozzle dams are in place. The RCS pressure response (Figure 3.7.2-1) is similar to that of Figure 3.5.2-1 up to a time of 680 seconds. In this case without SG nozzle dams, however, the water in the pump suction (loop seal) piping can be discharged to the break thus allowing a vent path for the steam. As the loop seal clears, RCS pressure rapidly drops. The loop seal clearing phenomenon is illustrated in Figure 3.7.2-2, a graph of core level and SG outlet level in the loop with the opening. Note that the core briefly uncovers between 700 and 720 seconds and then recovers after the loop seal clears and the break is able to vent the air and steam. Three shorter duration core uncoveries also occur until the loop seal fully clears and then the level stabilizes at approximately 23 feet after 900 seconds; this level is about 2.5 feet above the top of the active fuel. The remaining figures of interest show the mixture flow from the opening along with core inlet flow (Figure 3.7.2-3) and the vapor vent flow component along with the core boil-off flow (Figure 3.7.2-4). When the loop seal is clear, the liquid flow from the opening and reverse core flows are small. The vapor vent flow and core boil-off flows also peak during these times. After 900 seconds, the vapor flow out the opening matches the core boil-off flow (7 lbm/sec) and RCS pressure stabilizes approximately 0.5 psi higher than containment pressure. This pressure differential would be expected for the vent area (0.56 sq-ft) that was assumed in the analysis.

As a modification on this study, the opening was reduced to model a 6" check valve opening (0.147 sq-ft), the next largest size opening, typical of an SI line (Case E.2a). Figure 3.7.2-5 shows the RCS pressure transient for the 6" check valve case. Since the area of the opening is one-fourth that of the 12" opening, RCS pressure should be higher when the loop seal clears and stabilize at a pressure differential sixteen times higher, i.e., 8 psi higher than containment pressure (or 23 psia). At the end of the 1200 second transient, pressure has reached 21 psia and is slowly increasing, thus confirming the expected behavior. The core uncovery transient is also slower for this case, lasting from 790 to 860 seconds with one shorter uncovery at 880 seconds (Figure 3.7.2-6). At 1200 seconds, the core mixture level stabilizes at 22.6 feet (2.2 feet above the top of the active fuel); this is just slightly lower than the corresponding value extrapolated from Figure 3.7.2-2 (i.e., 22.8 ft) for the 12" opening. Part of this difference is attributable to a reduced core void fraction (0.19 versus 0.26) at the higher RCS pressure. The two level transients are otherwise the same after a period of 20 minutes. The liquid flow through the opening and the core inlet flow are shown in Figure 3.7.2-7. The vapor vent flow and the core boil-off flow are shown in Figure 3.7.2-8.

There are other variations on the cold leg opening study that have been considered. Some of these include SG condensation in one or more of the loops, nozzle dams in some of the SGs, reduction in the size of the opening to include the smaller diameter lines, increasing the size to include the loop isolation valves, and repeating the analysis cases on the 3-loop or 4-loop plants.

Case E.2b is a repeat of 6" opening, Case E.2a, with the SG in the intact loop available as a heat sink. With condensation in the intact loop, the loop seal in the loop with the opening still clears but the RCS pressure transient is lower (Figure 3.7.2-9) since some of the steam produced can condense in the intact loop SG. The core level transient is altered (Figure 3.7.2-10), however, level still stabilizes at a comparable level 2-3 feet above the top of the active fuel. After level stabilizes, some of the core boil-off is condensed in the intact SG; this results in reduced long term RCS inventory loss from the opening.

For the case of increased opening size for the loop isolation valve opening, TREAT simulation was not performed. However, the RCS response can be estimated based on Case E.2. The core uncovery and loop seal clearing transient would be faster since the opening is several times larger. RCS pressure would then stabilize at a value very close to containment pressure (within 0.1 psi). Based on the similarity of the results for Cases E.2 and E.2a, the core level should again stabilize 2-3 feet above the top of the core and then slowly decrease as the core boils off.

The 6" check valve opening for the 4-loop plant has features similar to a smaller opening case on the 2-loop plant. Note that RCS pressure increases to more than 40 psia before the loop seal clears (Figure 3.7.2-11). Pressure also stabilizes at a significantly higher pressure (above 50 psia) since the core boil-off is about twice that of the 2-loop case. Because of the higher stabilization pressure, the core void fraction is only about 5%, so the core level stabilizes approximately one foot above the top of the active fuel. During the period of core uncovery before the loop seal clears, the top of the core is uncovered for several minutes. It should be noted that the void fraction at the end of the transient had been underestimated by about a factor of two to three since a higher core bubble rise velocity corresponding to low RCS pressure had been used as input. If the results are corrected to account for a lower bubble rise velocity at the higher RCS pressure, the core level would have stabilized about two feet above the top of the active fuel instead of one foot. Thus, it appears that for those cases in which the opening is large enough that the loop seal clears, the 4-loop as well as the 2-loop cases predict the core to be covered by about two feet after conditions stabilize and before RCS inventory starts to boil-off at the reduced rate typical of that predicted in the large vent study.

For the smaller cold leg openings, the RCS would pressurize higher and the initial core uncovery/loop seal clearing transient will occur later in time. This could extend the time available for operator action making it possible to prevent a core uncovery altogether. A good example illustrating this situation is the 3" check valve opening for the 4-loop plant (Case E.2d). The RCS pressure transient for this case is shown in Figure 3.7.2-15. Pressure steadily increases during the 1800 second period analyzed, indicating that the loop seal has not cleared. The vent opening has capability of removing most of the boil-off via the hot to cold side vent path (Figure 3.7.2-18). Consequently, the liquid component of the flow through the opening does not increase above 50 lbm/sec (Figure 3.7.2-16). At 1800 seconds, the total flow through the opening is 32 lbm/sec (23-liquid, 9-vapor). The corresponding makeup flow required (230 gpm) is roughly equivalent to two PD charging pumps (for the older 4-loop Indian Point units) or about half the capacity of one centrifugal charging/SI pump injecting in the normal charging mode for most of the remaining 4-loop (and 3-loop) plants. This is a significant finding. It implies that the core level transient should turn around before the top of the active fuel is uncovered, if action is taken to establish normal charging flow by 1800 seconds (or 30 minutes). Referring to Figure 3.7.2-17, the core level at 1800 seconds is 1.5 feet above the top of the active fuel. By establishing charging flow at 1800 seconds, it should be possible to prevent core uncovery altogether for this case.

To summarize the RCS and core level response for this cold leg opening study, the large check valve opening cases (6", 12" and loop isolation valve) would be characterized by an initial period of RCS pressurization after boiling starts to occur. As water is forced out of the opening, the water levels in the core and pump suction (loop seal) piping decrease until the loop seal clears and provides a vent path for the steam and air. Following the subsequent depressurization as the loop seal clears, the level in the core increases to cover the active fuel, typically by more than one or two feet.

For smaller opening cases, the RCS inventory loss would progress at a slower rate. This would give the operator additional time to restore makeup and prevent a slower prolonged core uncovery. In the case of a 3" check valve opening for a 4-loop plant, the RCS inventory loss at 30 minutes is about 230 gpm and the core level is 1.5 feet above the top of the fuel. The corresponding makeup required to prevent core uncovery is within the capability of normal charging flow, so core uncovery can likely be prevented altogether if makeup is initiated by 30 minutes.

3.7.3 Cold Side SG Manway Opening without Nozzle Dams (Case E.3)

Since there are no significant obstructions between the hot leg and the manway opening, this case behaves like the large vent case without liquid spill analyzed in Section 3.4. The two-loop plant, 48 hours after shutdown was analyzed. The decay heat is 0.48% of full power or 7.3 MWt. The initial RCS temperature is 140°F at the time RHR cooling is lost.

The mixture levels in the core/upper plenum and downcomer regions are shown in Figure 3.7.3-1. The core level transient closely resembles the corresponding level transient for the 3-loop plant presented in Figure 3.4.1-1. Similar to the 3-loop run, the core collapsed level is predicted (extrapolated) to reach the top of the active fuel at 6500 seconds, after 40000 lbm of water is boiled off. The core/upper plenum void fraction is approximately 27% at steady state boil-off, so the actual mixture level in the core will be at least 2 feet higher than the top of the active fuel at 6500 seconds. Note that if the manway were located on the hot leg side of the SG, a 26% "spill penalty" would be expected for this case. The corresponding time to core uncovery (based on the collapsed core level) would then be about 5000 seconds (Case B.2, Table 3.4.2-1).

3.7.4 Impact of Core Uncovery on the Cold Leg Opening Study

In many of the cold leg opening scenarios investigated in Section 3.7.2, the top one-third of the active fuel uncovers for a brief period of time until water in the pump suction or loop seal piping in the loop with the opening is expelled. After this loop seal clears, there is a vent path for the air and boil-off steam to escape and level in the core typically stabilizes two feet above the active fuel prior to the comparatively slow inventory loss due to boil-off. The duration of the core uncovery differed for the various cases analyzed. Typical times ranged from less than 30 seconds for the 12" valve opening for the 2-loop plant (Case E.2) to about three minutes for the 6" opening for the 4-loop plant (Case E.2c).

Based on an average rod power of 6 kW/ft at full power and assuming a representative but high decay heat power of 0.48% (at 48 hours after shutdown, Figure 3.2.4-1), the adiabatic heatup rate for a 0.35" diameter fuel rod (conservatively small) is estimated to be 50°F/minute. In the extreme situation in which a "hot spot" three times the average remains uncovered for a period of 5 minutes, the fuel temperature would remain less than 1000°F. Since fuel damage would not occur until the cladding reaches a much higher temperature (greater than 1800°F), the short duration core uncovery transients predicted in the cold leg opening cases do not present a problem.

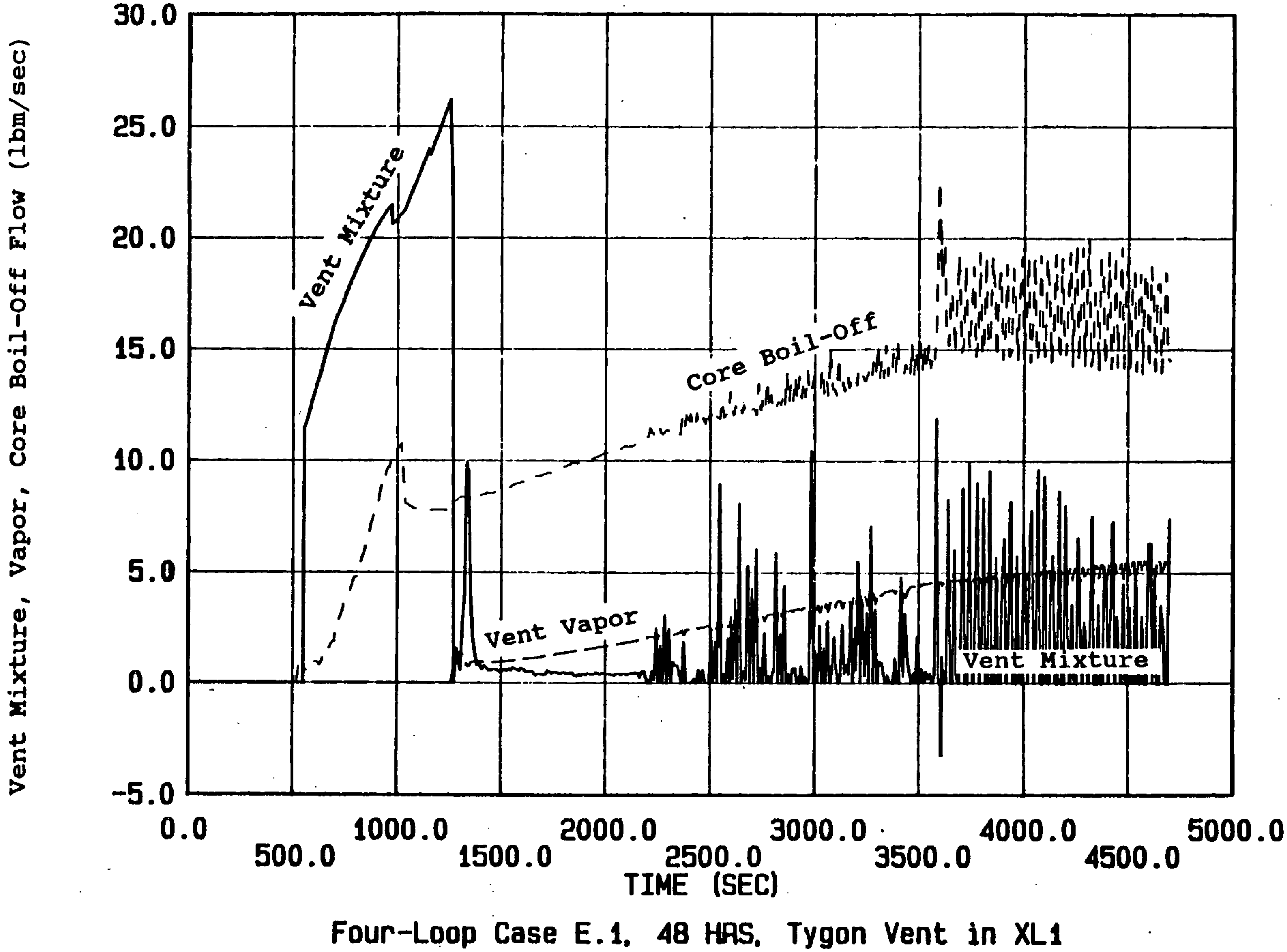


Figure 3.7.1-1 Four-Loop Case E.1, Vent and Core Boil-Off Flow

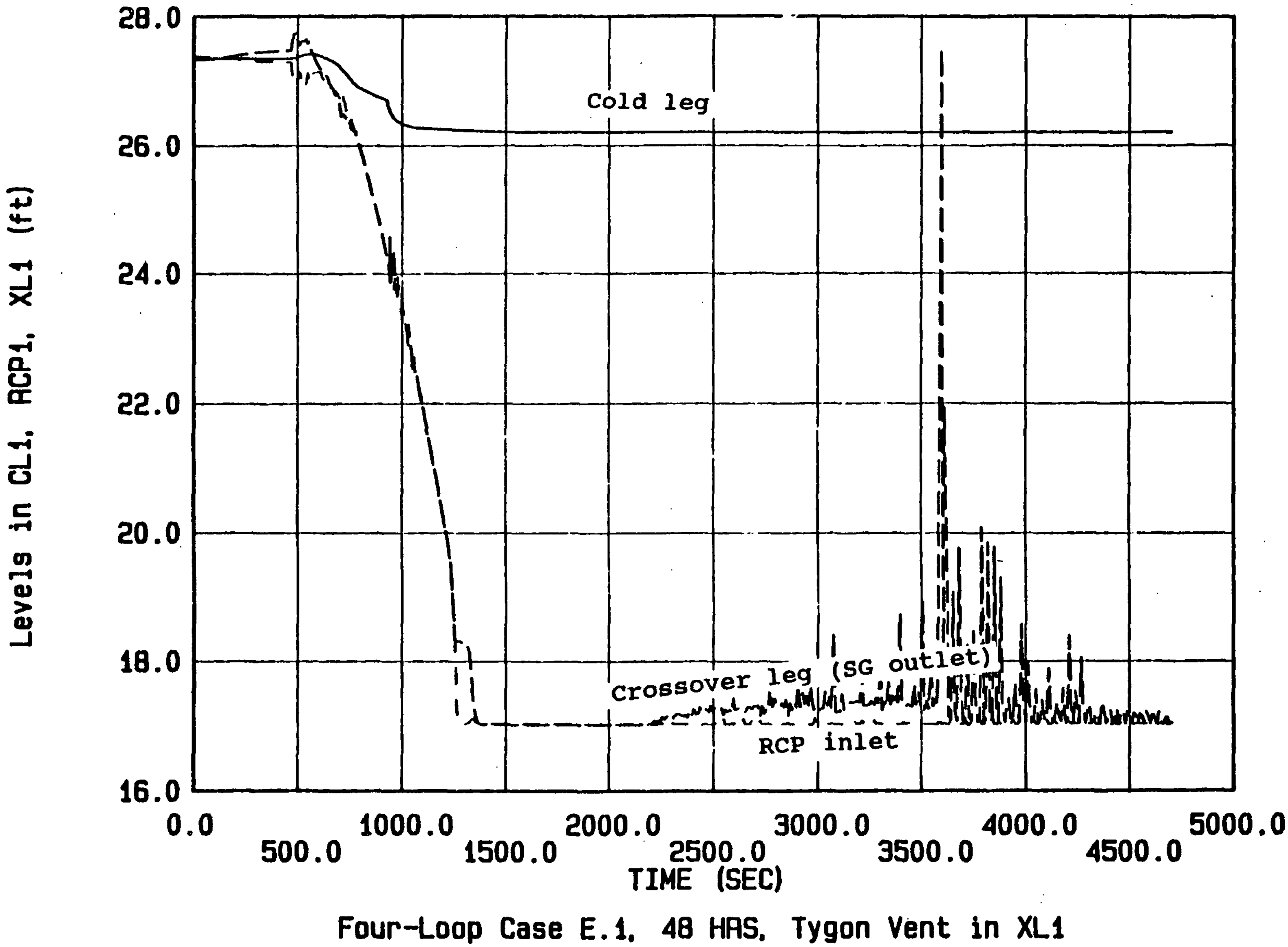
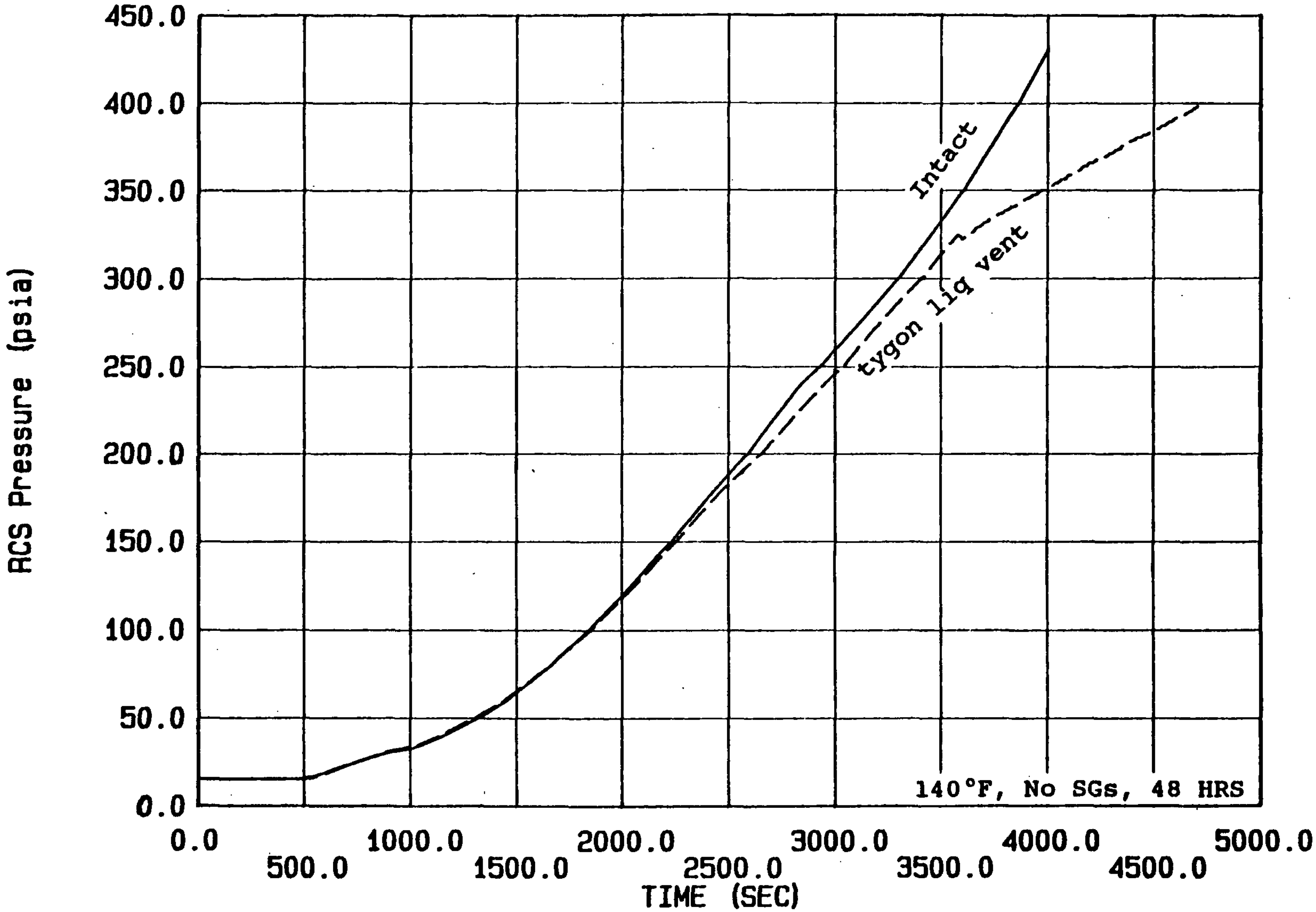
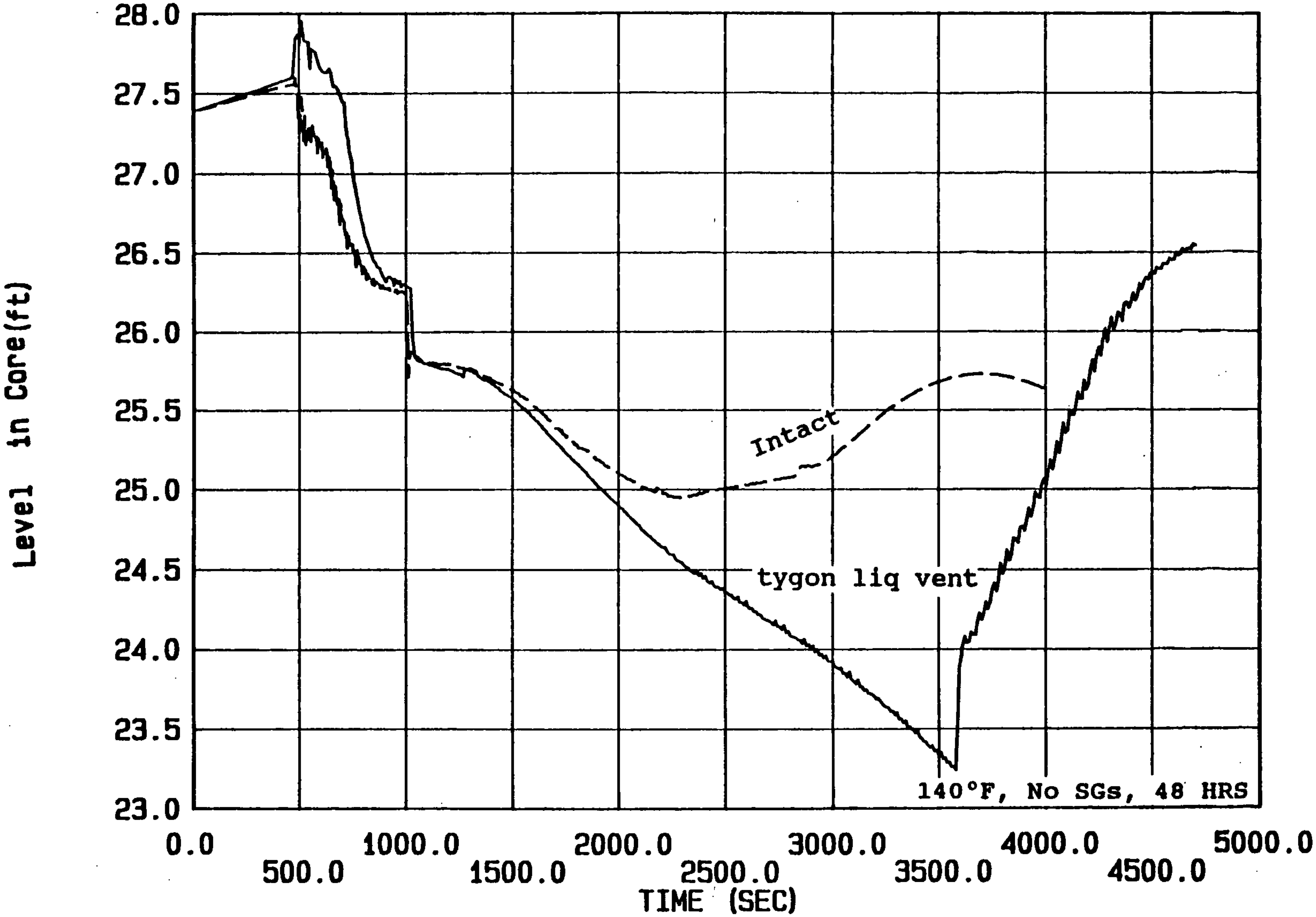


Figure 3.7.1-2 Four-Loop Case E.1 Elevations in Vented Cold Leg Nodes



Cases E.1 (tygon vent in XL1) and A.8 (Intact RCS)

Figure 3.7.1-3 Four-Loop Cases E.1 and A.8 Pressure Comparison



Cases E.1 (tygon vent in XL1) and A.8 (Intact RCS)

Figure 3.7.1-4 Four-Loop Cases E.1 and A.8 Core Level Comparison

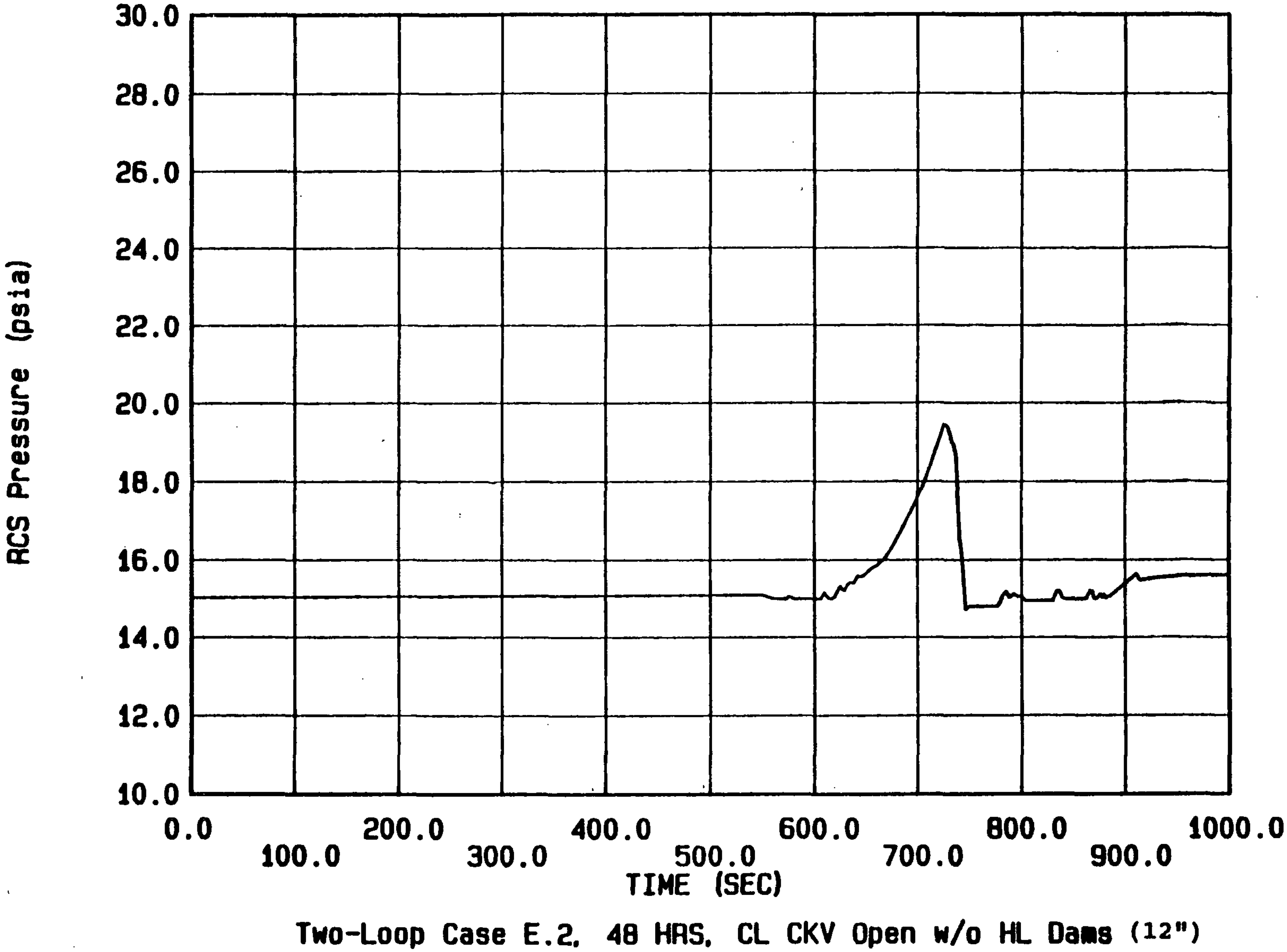
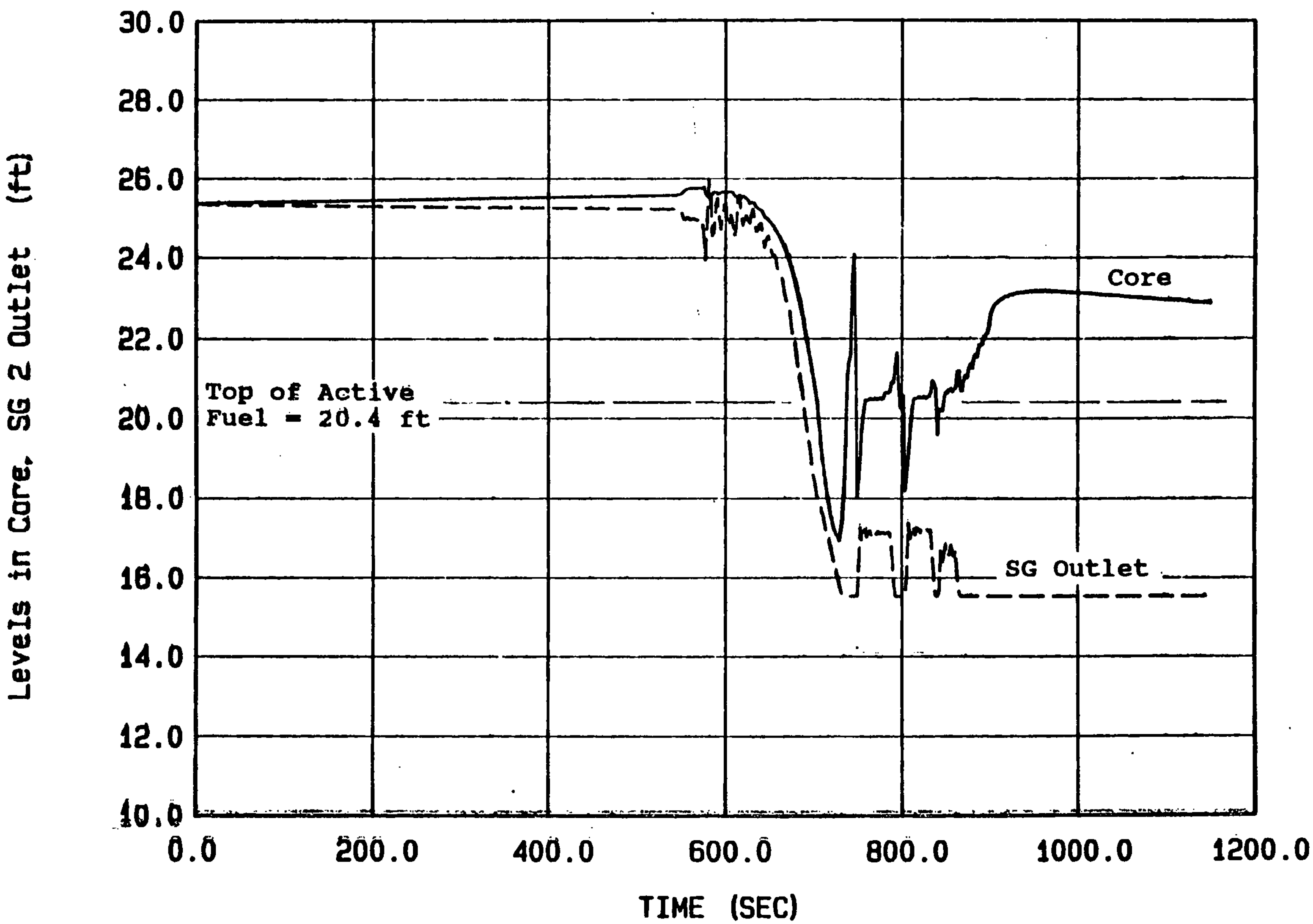


Figure 3.7.2-1 Two-Loop Case E.2, RCS Pressure



Two-Loop Case E.2, 48 HRS, CL CKV Open w/o HL Dams (12")

Figure 3.7.2-2 Two-Loop Case E.2, Core and SG Outlet Mixture Levels

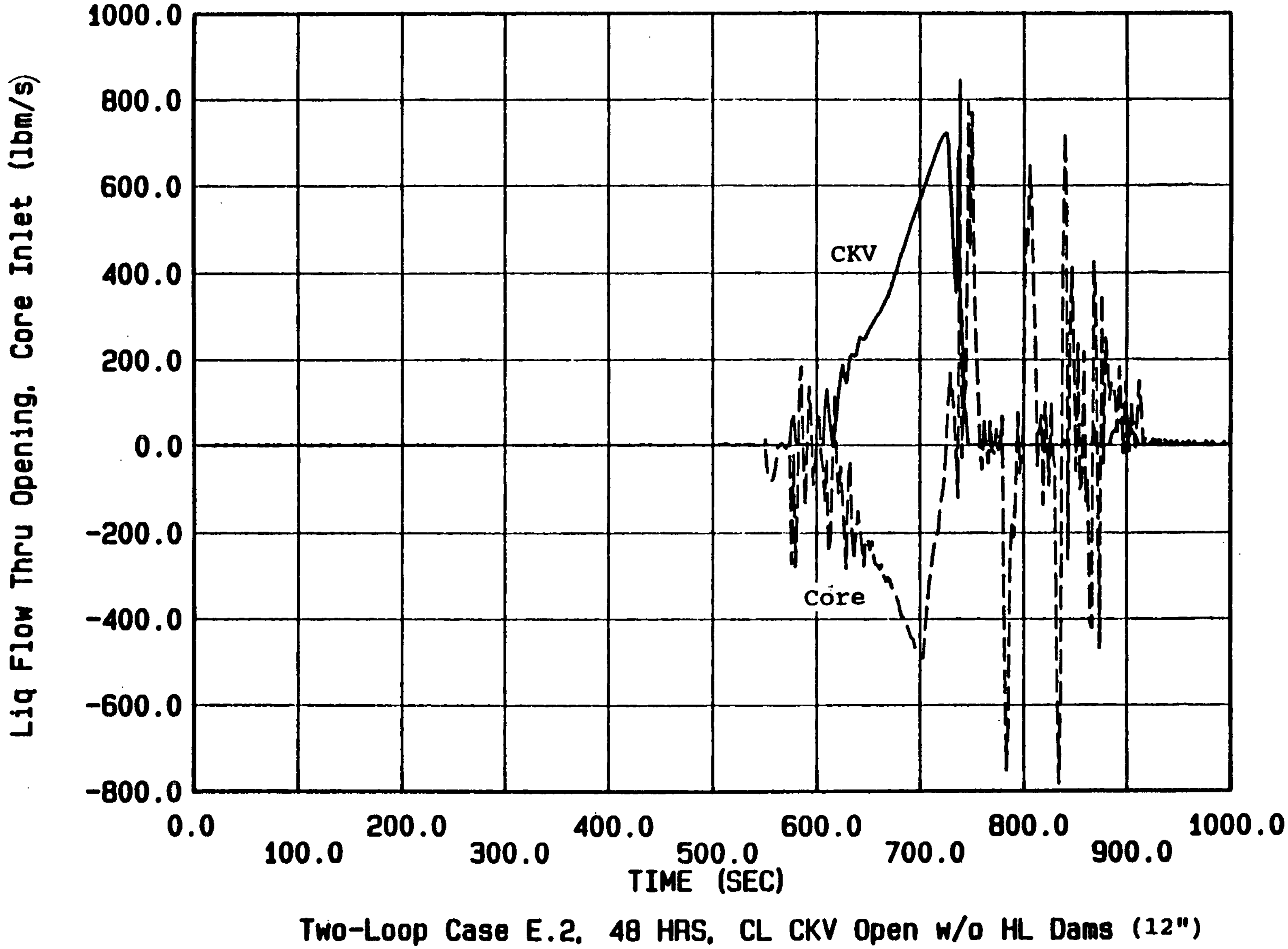


Figure 3.7.2-3 Two-Loop Case E.2, Check Valve and Core Inlet Flows

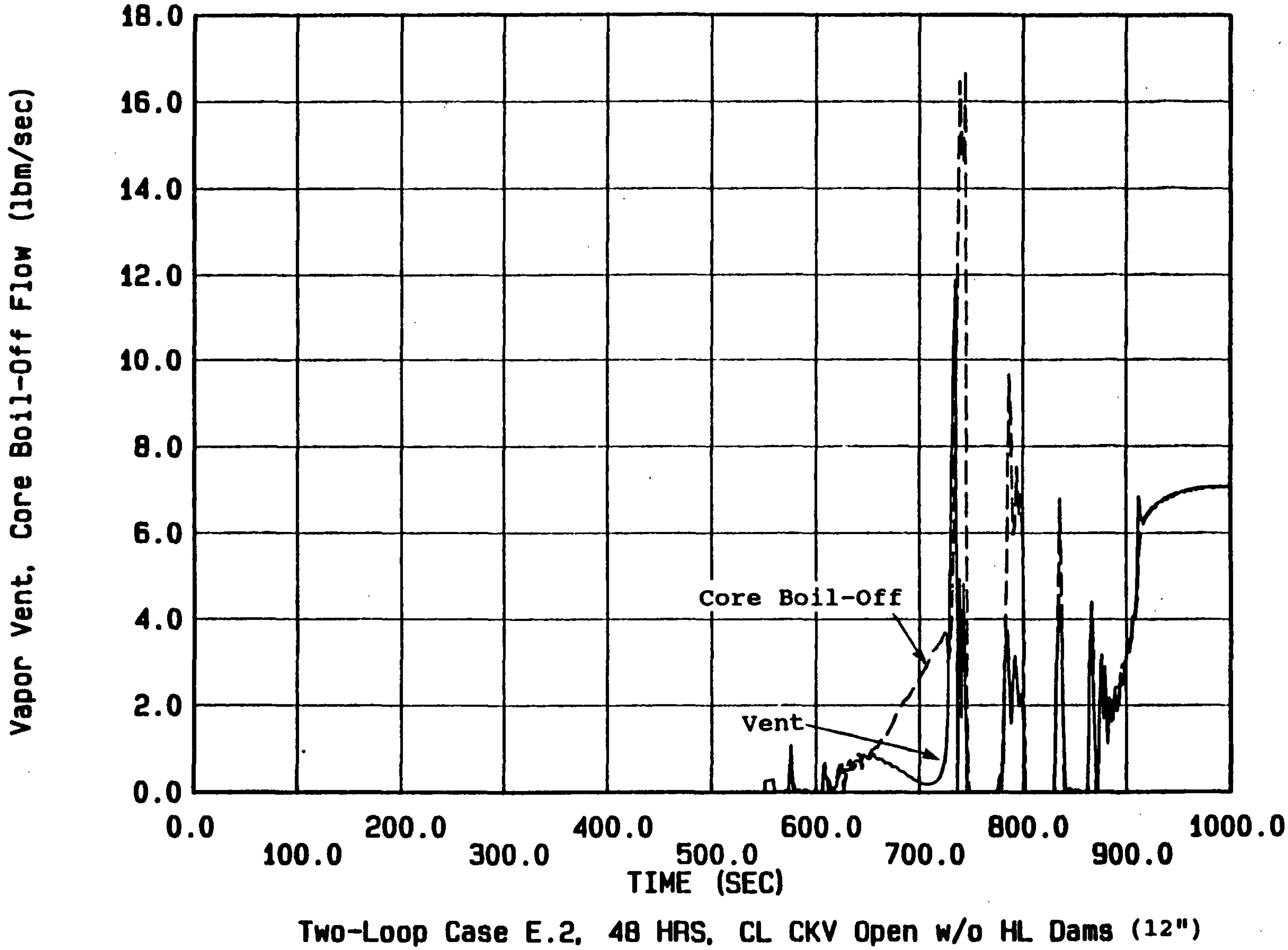


Figure 3.7.2-4 Two-Loop Case E.2, Vapor Vent and Core Boiloff Flows

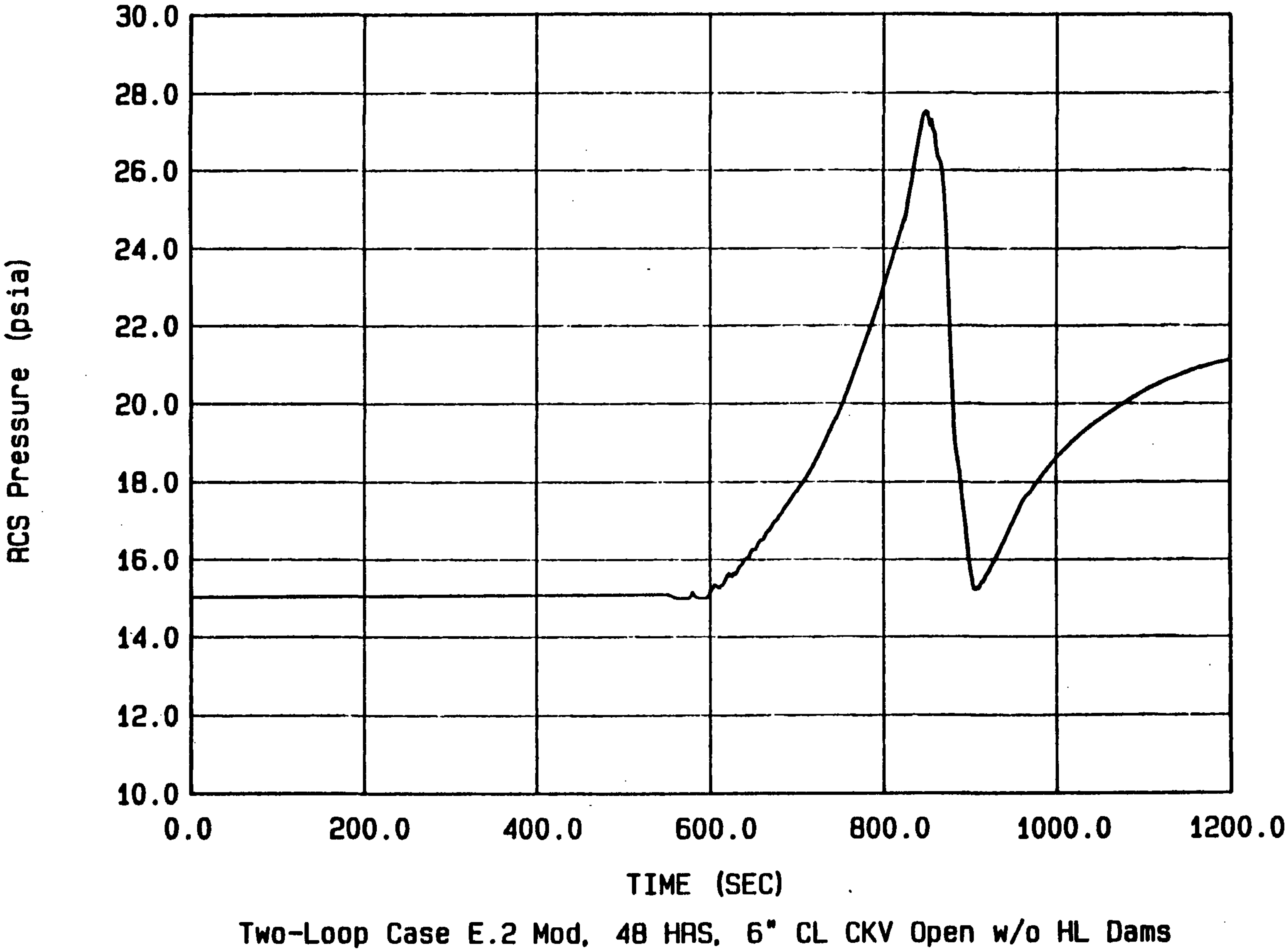


Figure 3.7.2-5 Two-Loop Case E.2a, RCS Pressure

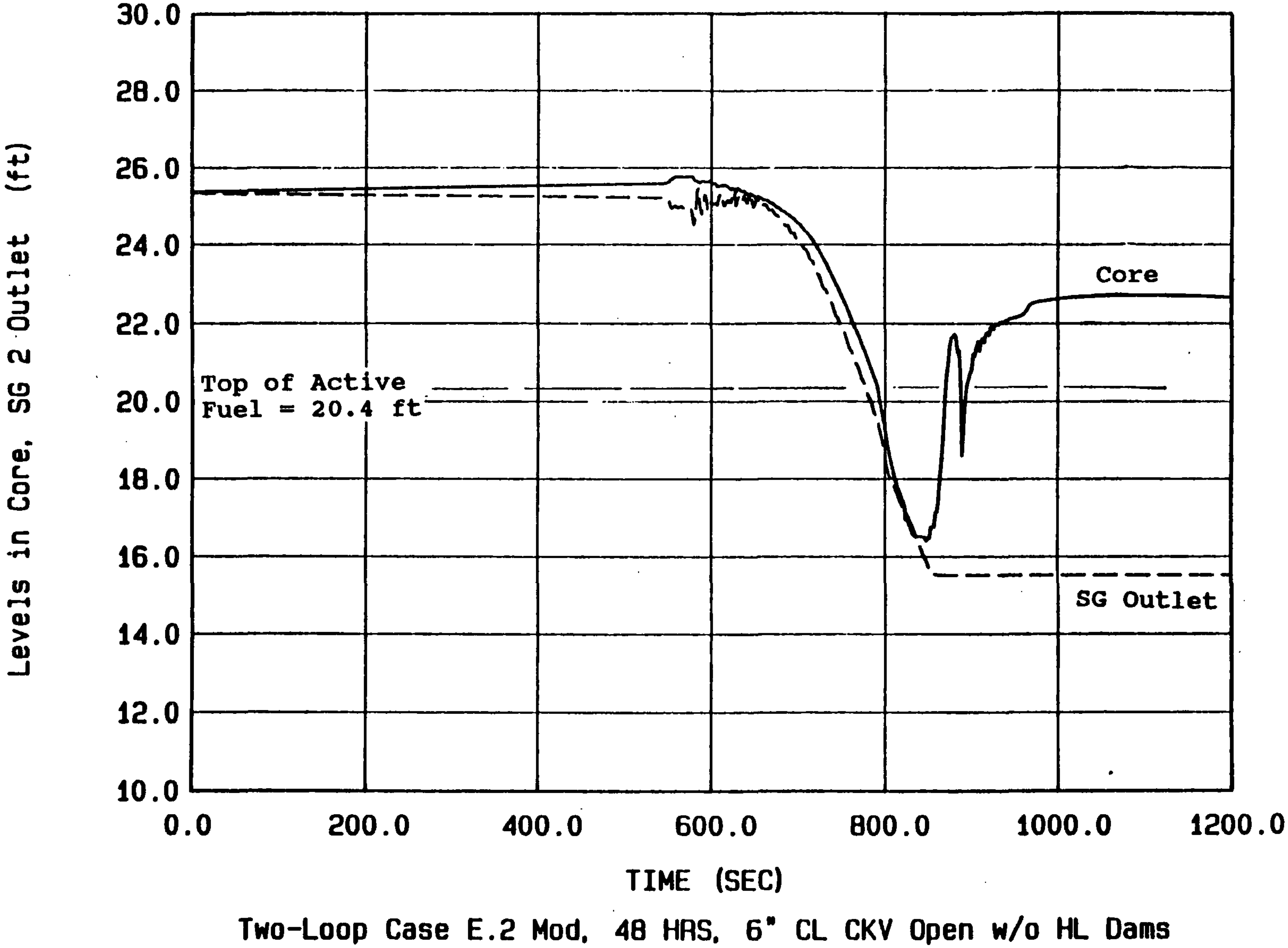


Figure 3.7.2-6 Two-Loop Case E.2a, Core and SG Outlet Mixture Levels

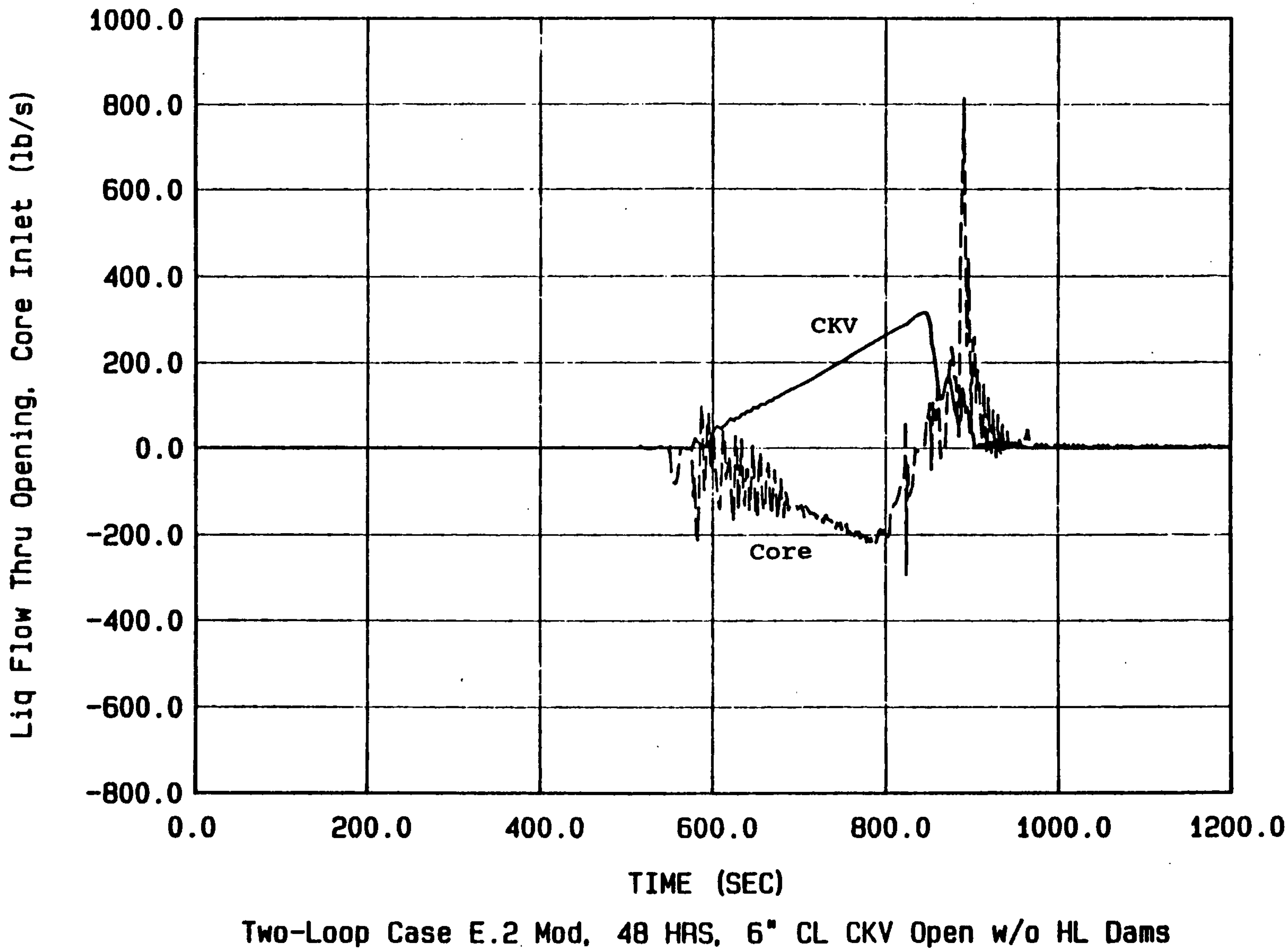


Figure 3.7.2-7 Two-Loop Case E.2a, Check Valve and Core Inlet Flows

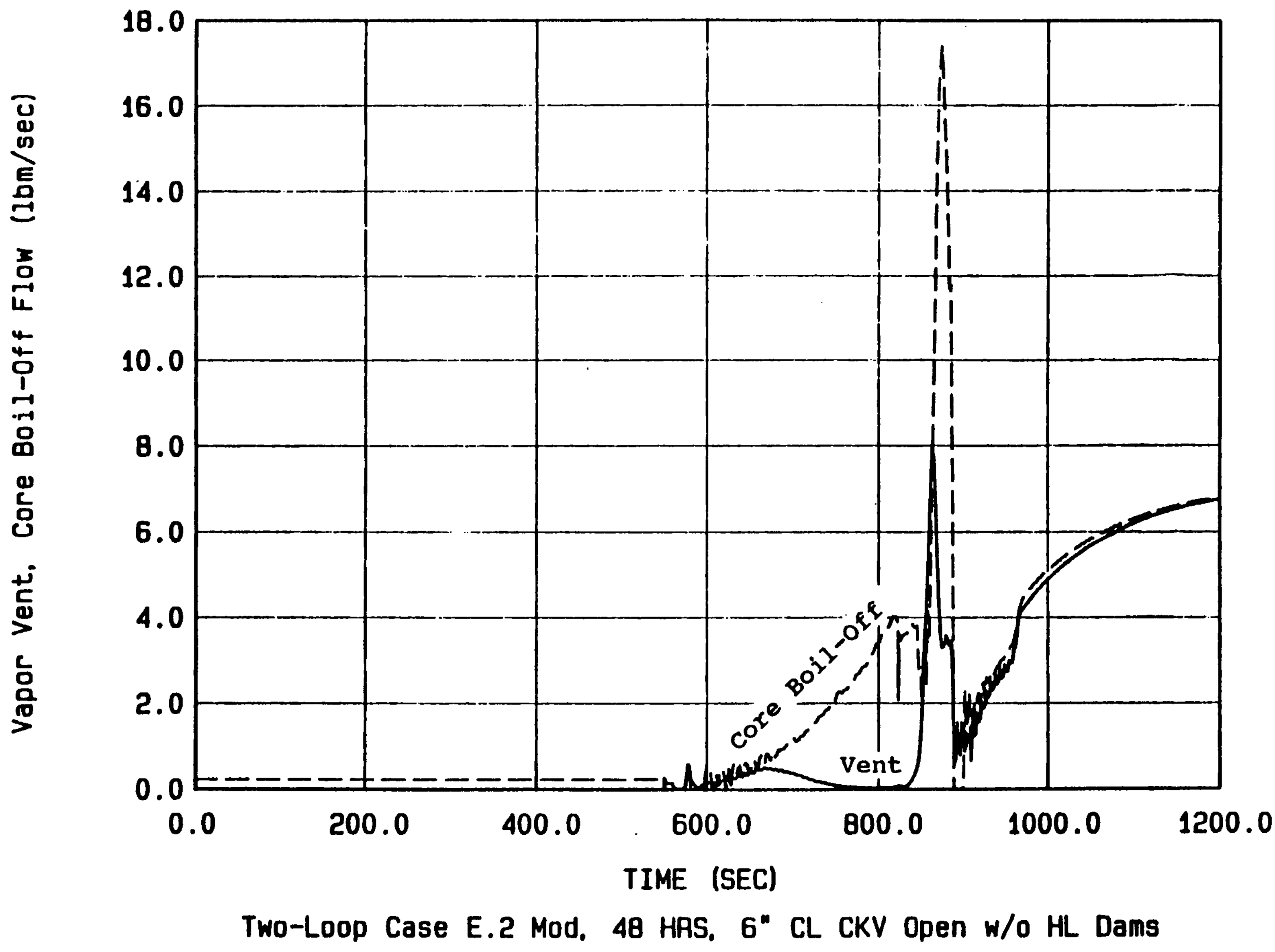


Figure 3.7.2-8 Two-Loop Case E.2a, Vapor Vent and Core Boiloff Flows

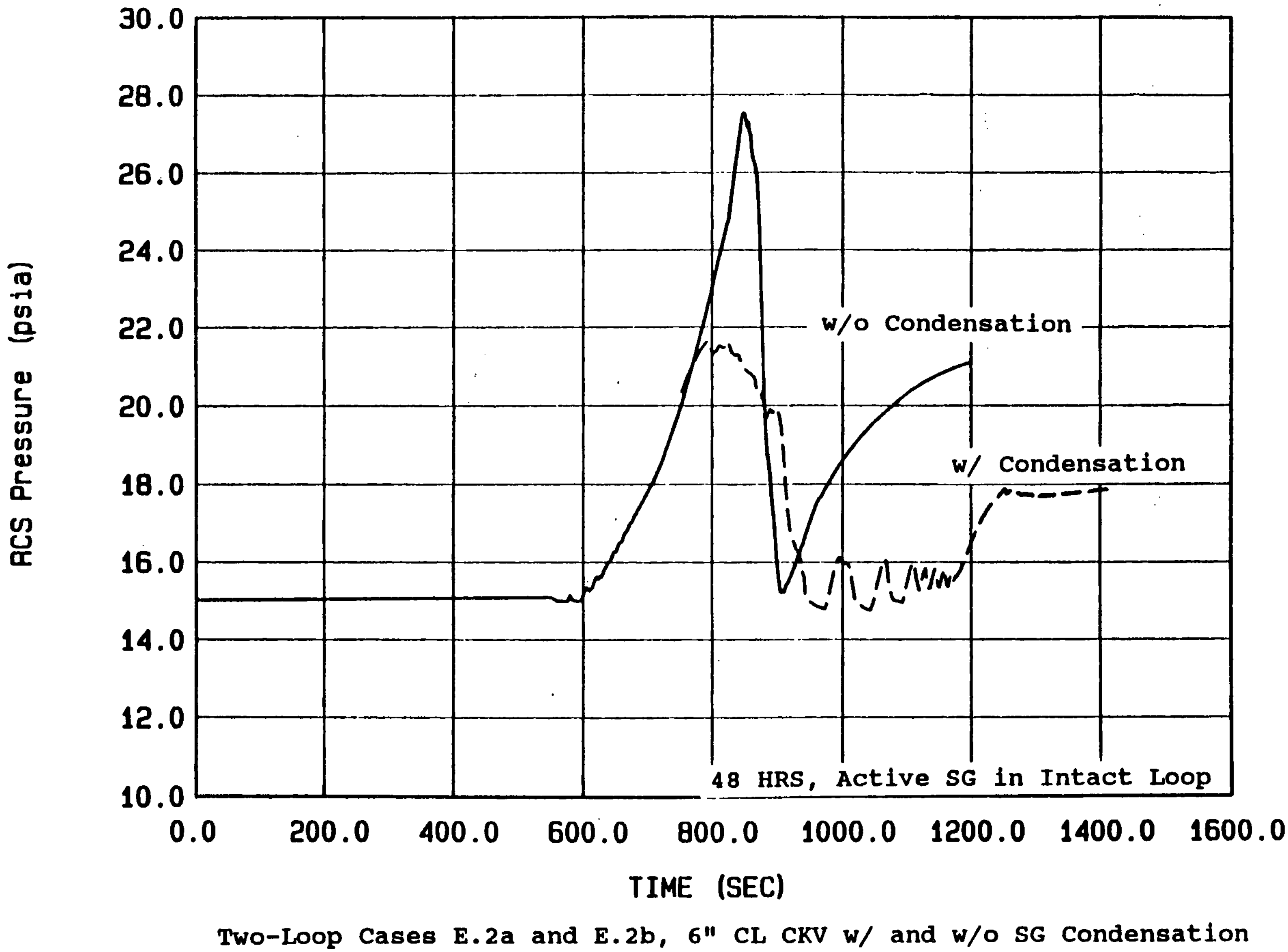
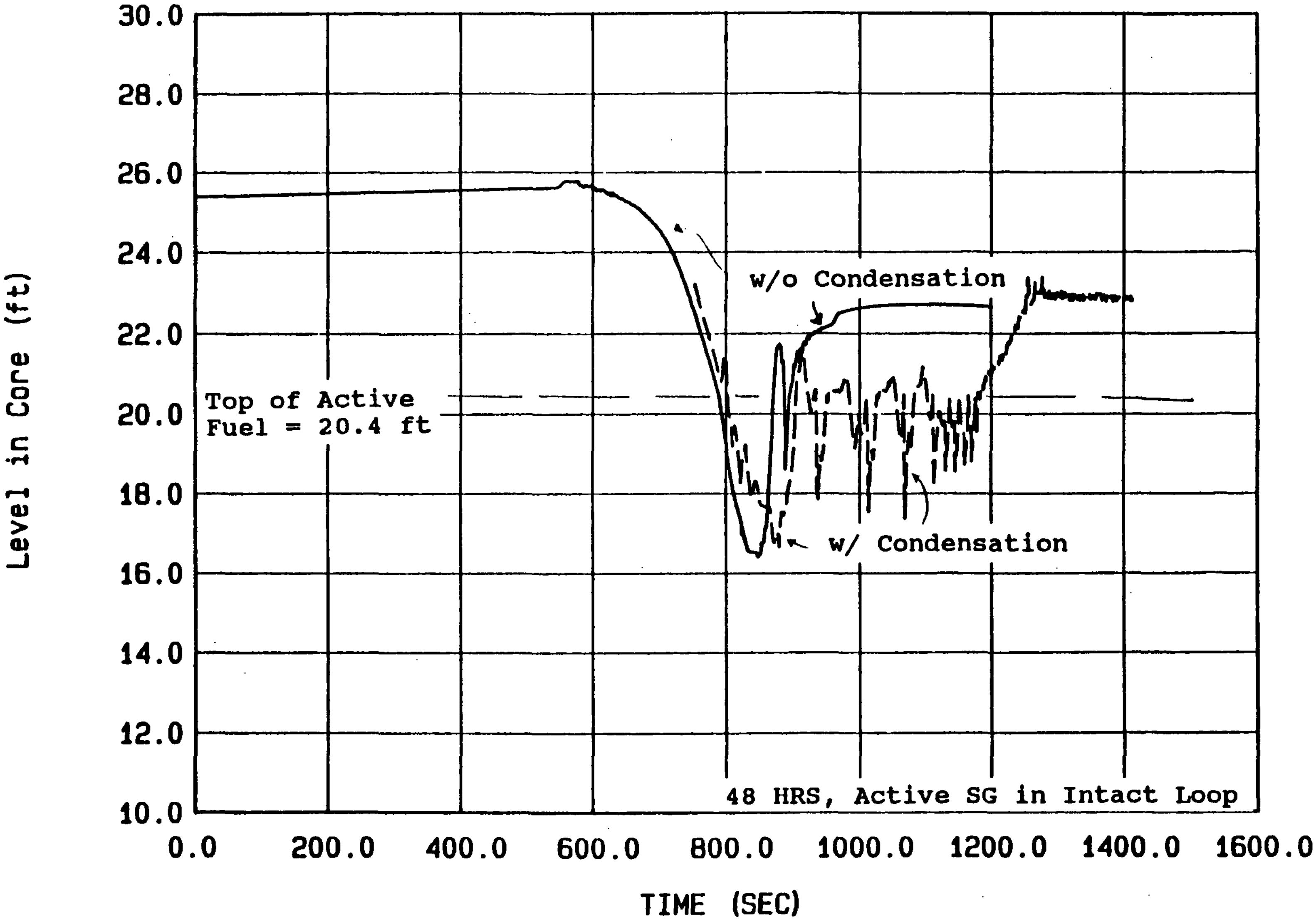


Figure 3.7.2-9 Two-Loop Case E.2a and E.2b, RCS Pressure Comparison



Two-Loop Cases E.2a and E.2b, 6" CL CKV w/ and w/o SG Condensation

Figure 3.7.2-10 Two-Loop Case E.2a and E.2b, Core Mixture Level Comparison

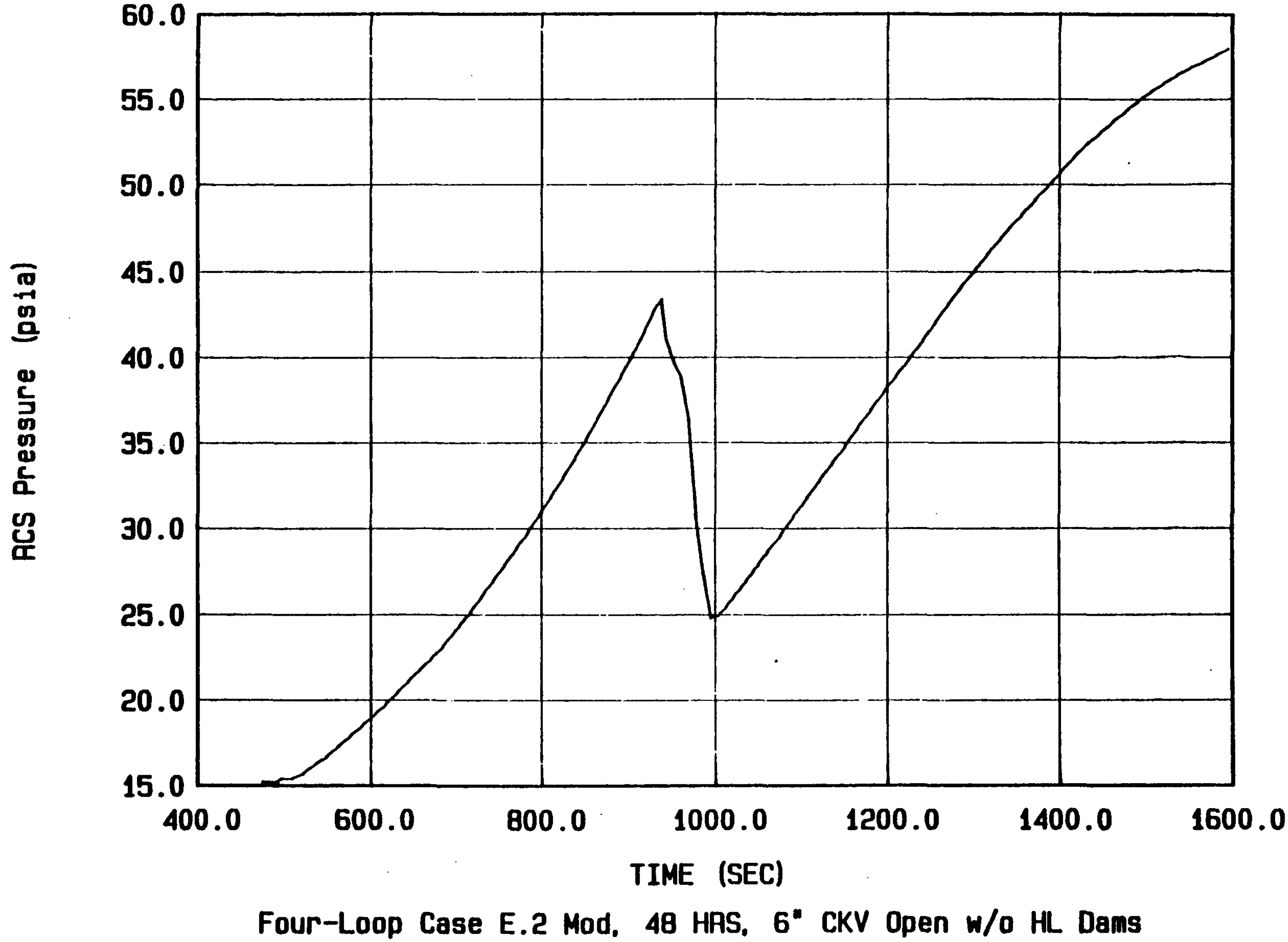


Figure 3.7.2-11 Four-Loop Case E.2c, RCS Pressure

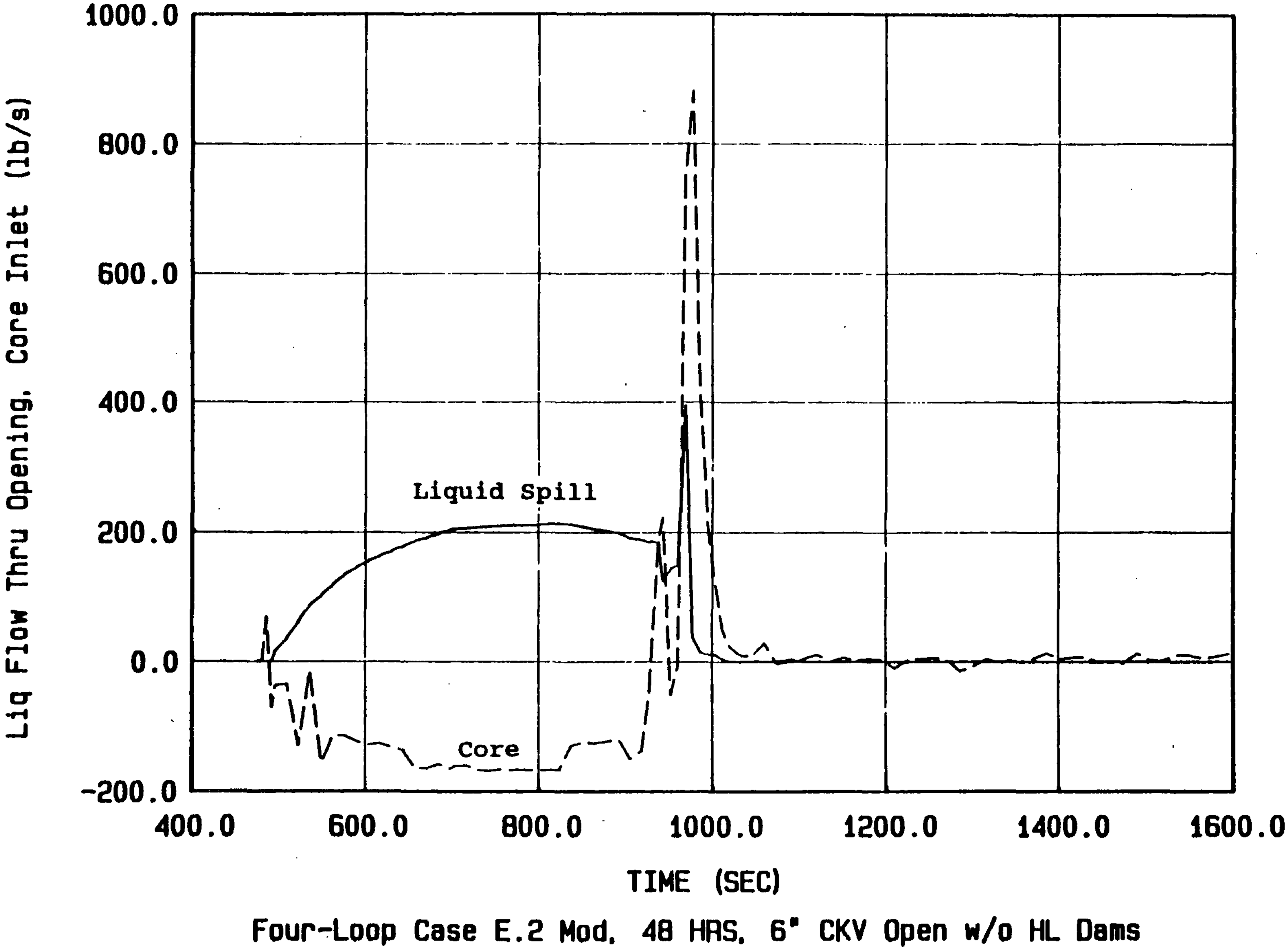


Figure 3.7.2-12 Four-Loop Case E.2c, Check Valve and Core Inlet Flow

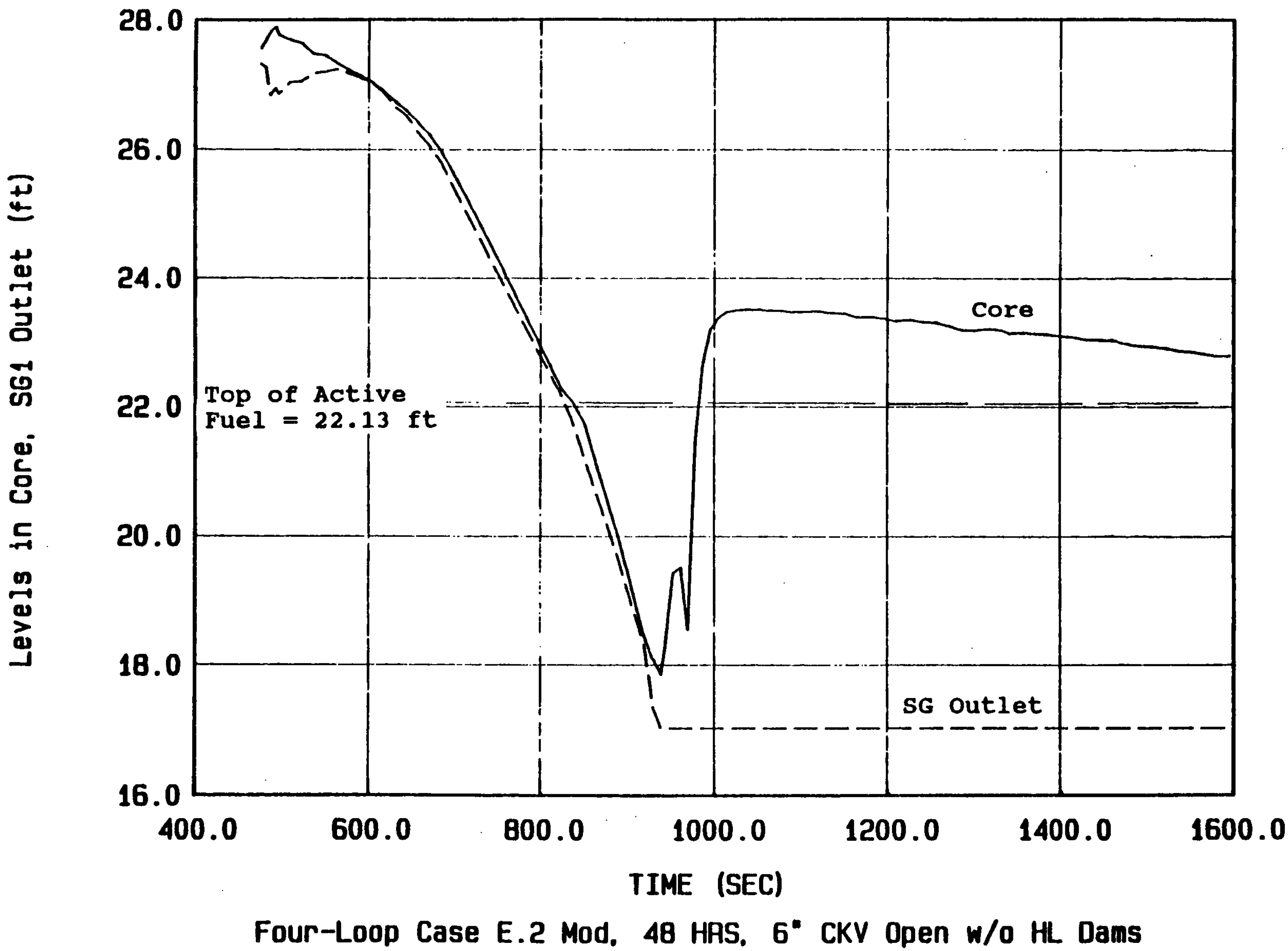


Figure 3.7.2-13 Four-Loop Case E.2c, Core and SG Outlet Mixture Levels

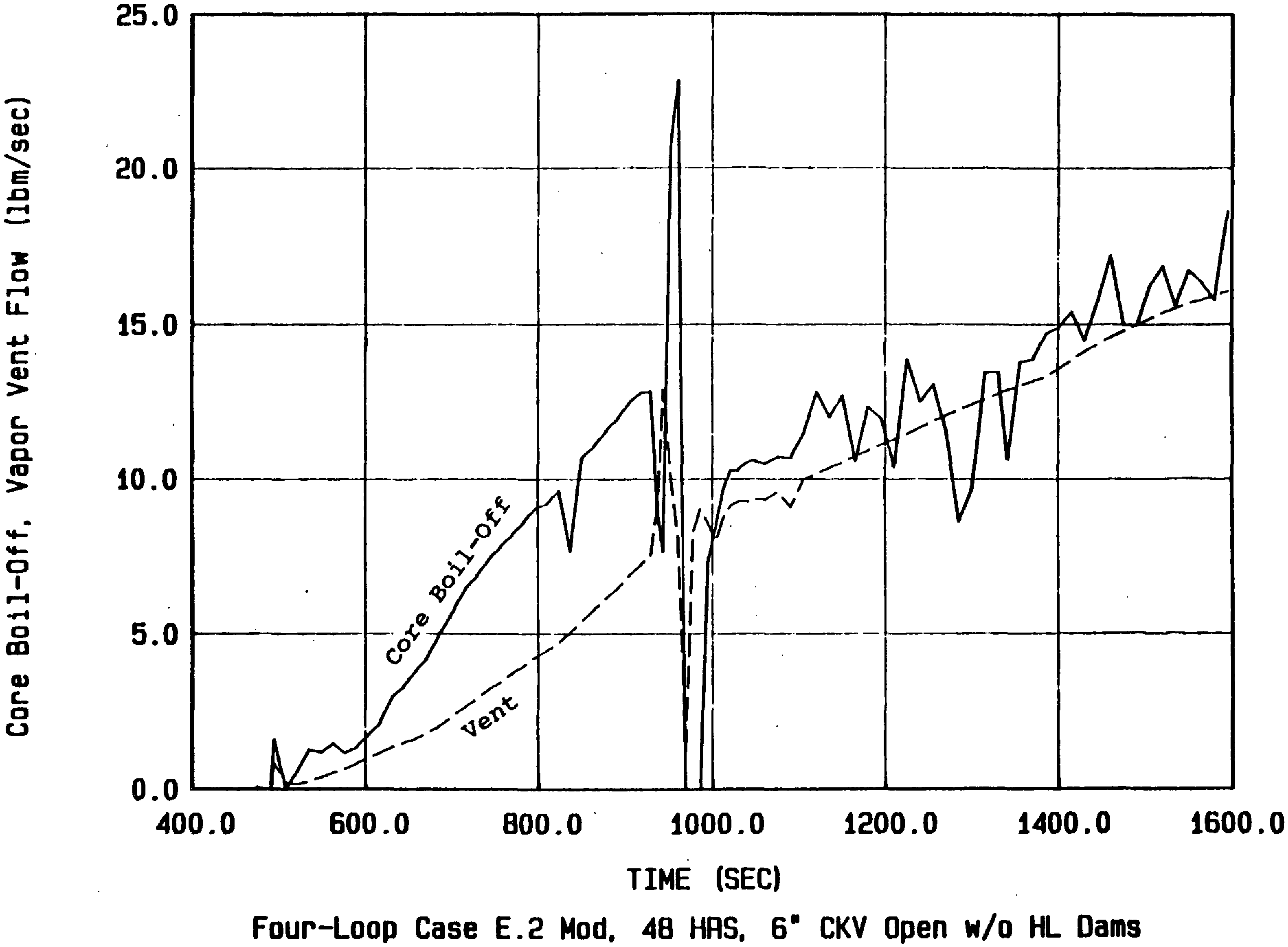


Figure 3.7.2-14 Four-Loop Case E.2c, Vapor Vent and Core Boiloff

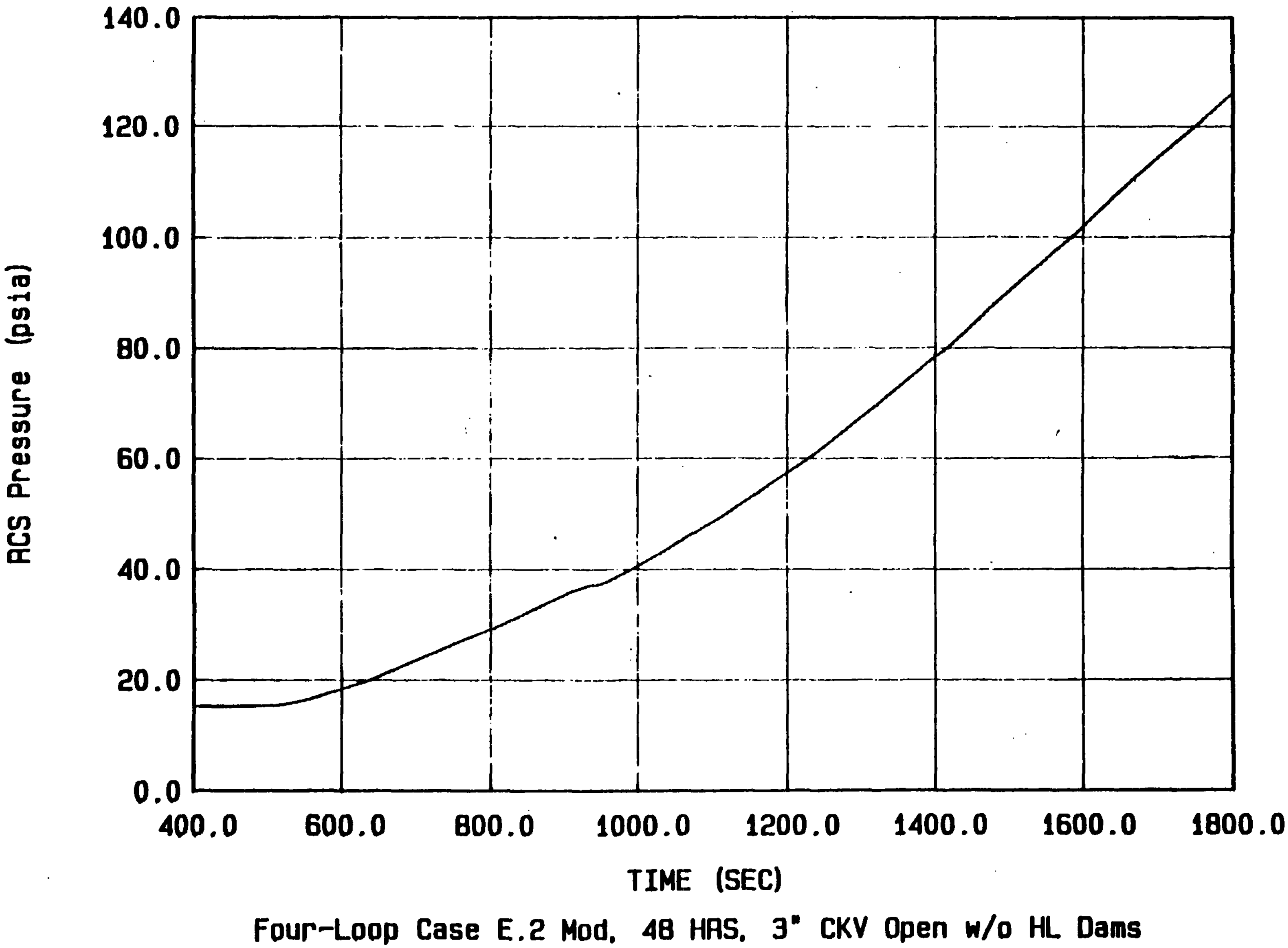


Figure 3.7.2-15 Four-Loop Case E.2d, RCS Pressure

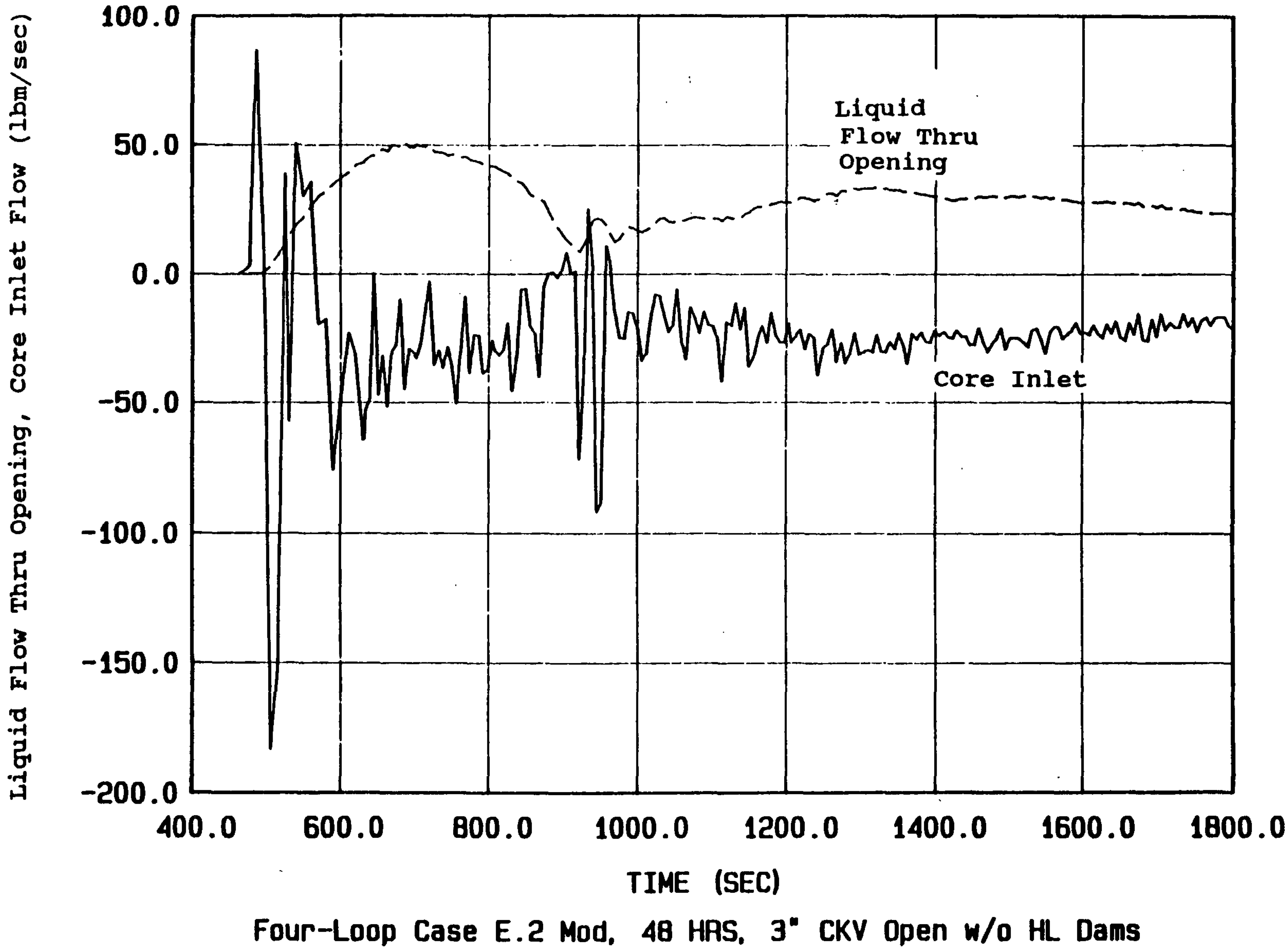


Figure 3.7.2-16 Four-Loop Case E.2d, Check Valve and Core Inlet Flow

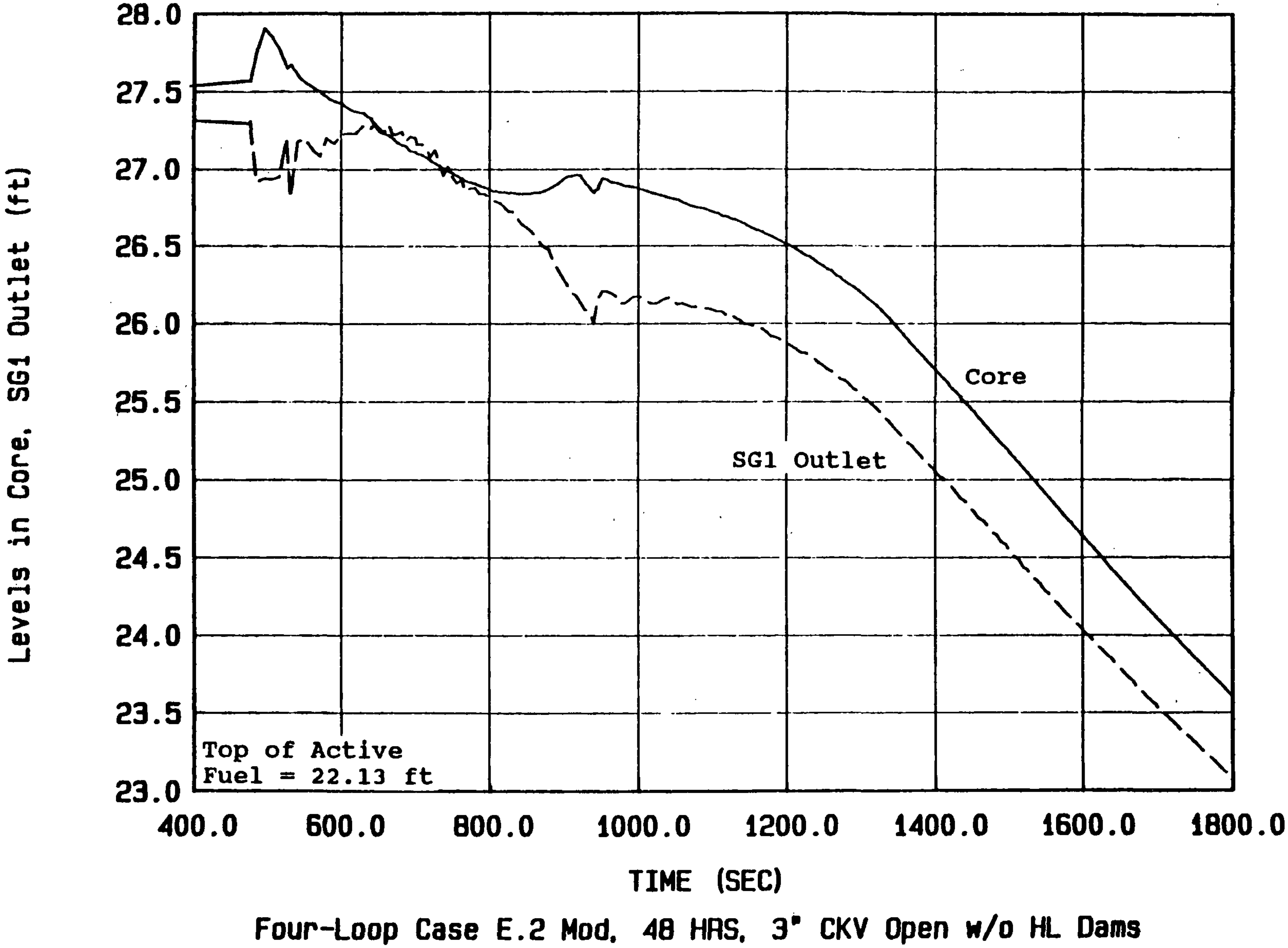


Figure 3.7.2-17 Four-Loop Case E.2d, Core and SG Outlet Mixture Levels

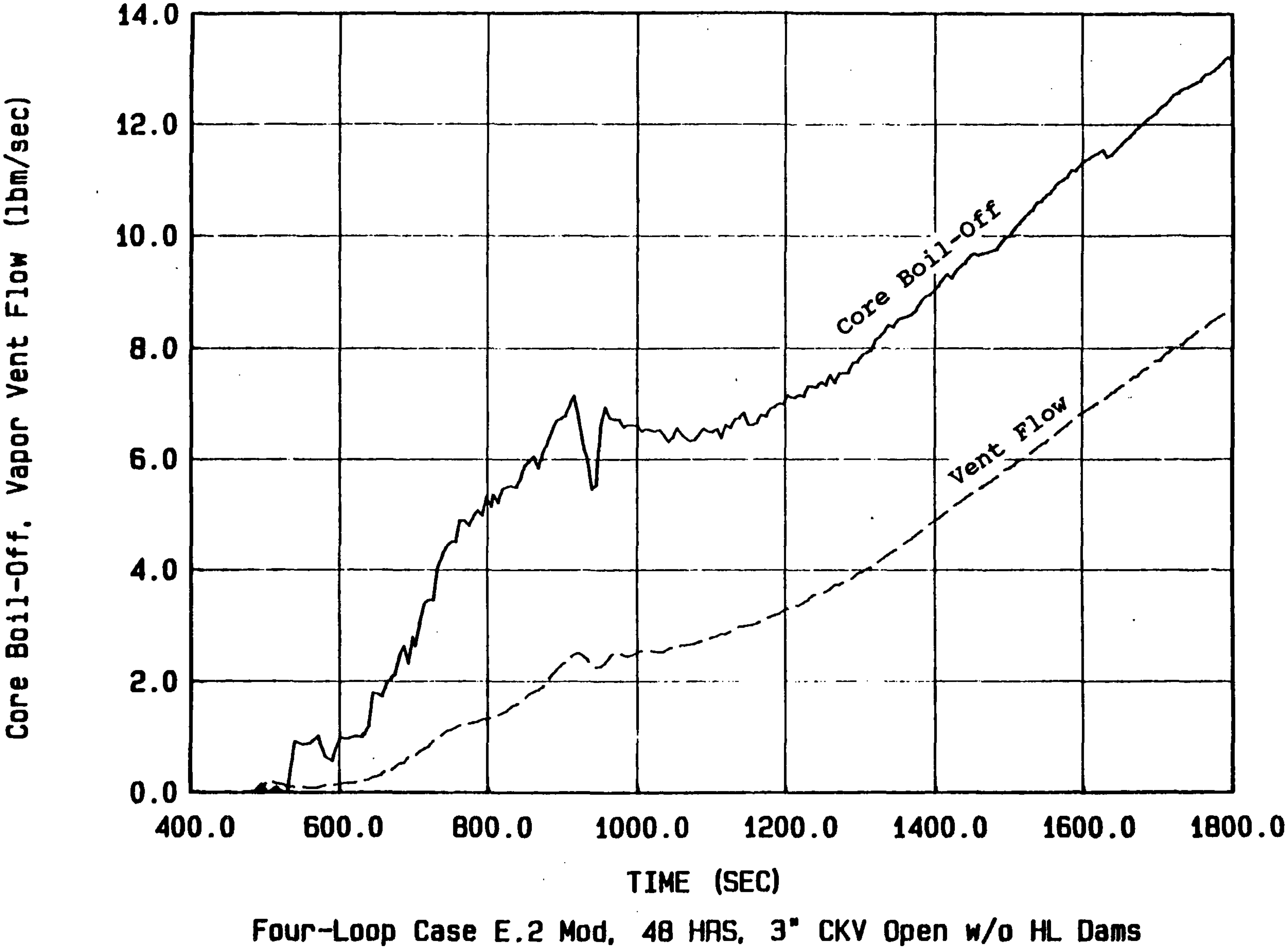


Figure 3.7.2-18 Four-Loop Case E.2d, Vapor Vent and Core Boiloff

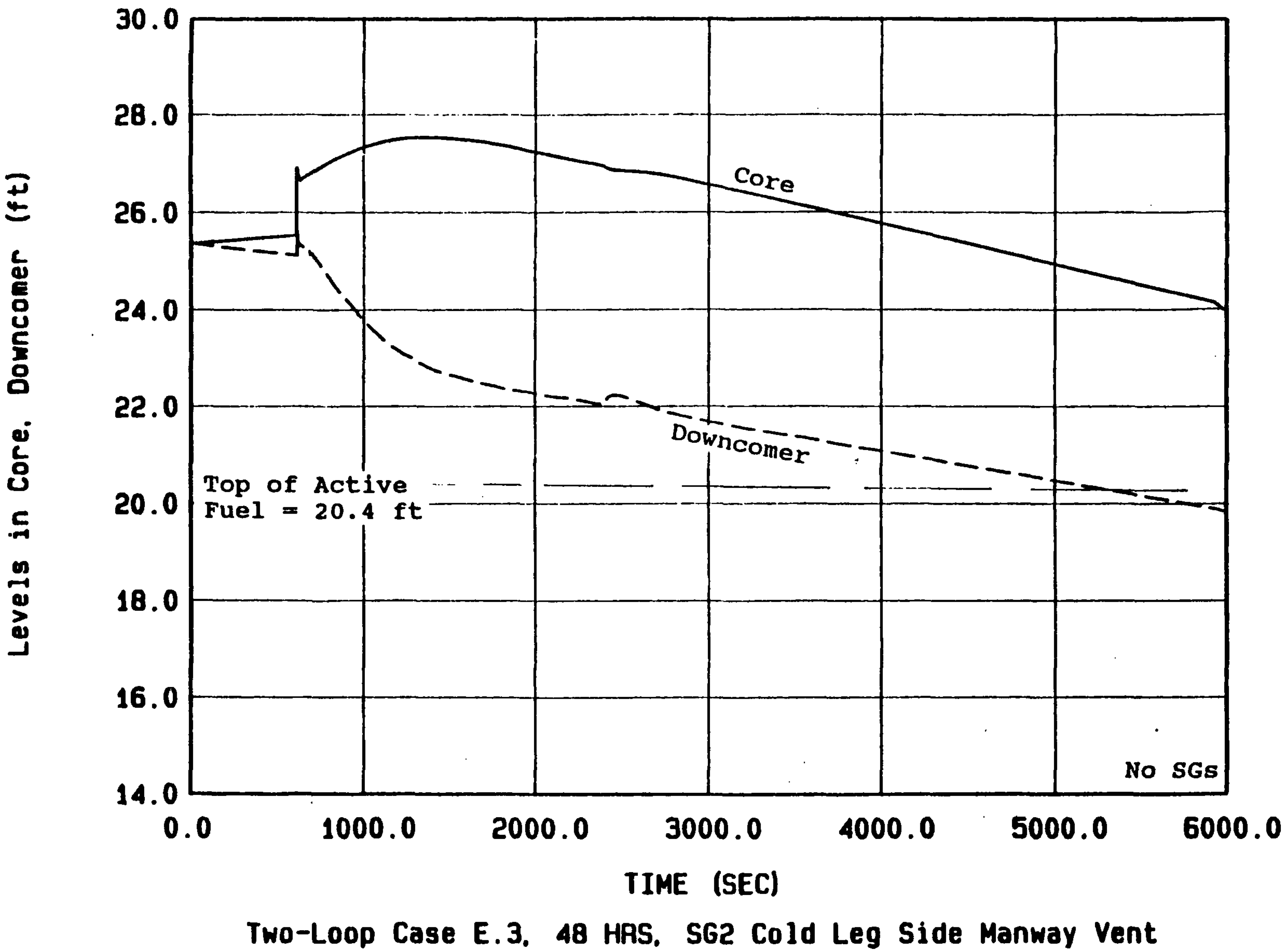


Figure 3.7.3-1 Two-Loop Case E.3, Core and Downcomer Mixture Levels

3.8 Steam Generator Condensation Cases

Both the overall heat transfer coefficient and heat transfer area are important in determining the amount of condensation. At low pressures, steam is less dense than air and will not penetrate into the downhill section of the SG tubes under natural circulation conditions. This leaves approximately half of the SG tube area for condensation. The heat transfer coefficient is sensitive to the amount of non-condensible gas present. The condensation heat transfer coefficient can vary between 1000 and 50 BTU/hr-ft^2-F, depending upon the amount of non-condensible gas present (Reference 18). As steam condenses on the condensing surface, a layer of non-condensible gas is left behind. As this layer builds up, the condensation rate degrades since steam must first diffuse through this layer of gas. Thus, even a small amount of non-condensible gas in the system will cause the condensation rate to decrease significantly.

This section presents the results of seven analyses in which the number of available steam generators and time after shutdown were varied. These analyses were performed to determine the effects of condensation on the RCS heatup and pressurization rates following the loss of RHR during mid-loop operation. The results of these analyses can be used to determine the number of SGs required to maintain the RCS pressure at a low level (e.g. below the RWST gravity feed pressure head) for an extended period.

3.8.1 Typical Condensation Transient Results (Case F.1)

Condensation increases the amount of time available for the operator to take recovery actions, for example realigning flowpaths to provide RWST gravity head flow to the RCS through either the SI or charging lines. Condensation reduces the RCS pressurization rate following the loss of RHR during mid-loop operation. This is illustrated in Figure 3.8.1-1. Figure 3.8.1-1 presents a comparison of the RCS pressurization rates with and without condensation for a 2-loop plant in which only one of the two SGs was filled with water. A loss of RHR cooling 48 hours after shutdown was assumed.

After the loss of RHR cooling, the core and upper plenum temperatures begin to increase and eventually reach saturation at about 600 seconds (10 minutes). A short while later, enough steam has been generated to increase the partial pressure of steam at the entrance to the SG tubes to the saturation temperature of the SG tube walls and condensation begins. The heat removed by the condensation process increases rapidly as the condensing steam generator draws more steam from the upper plenum than the non-condensing steam generator. This is illustrated in Figures 3.8.1-2 and 3.8.1-3. Air, brought along with the steam is left behind and forced over to the downside of the steam generator.

As the SG tube temperature increases, steam condensation lessens and approaches a lower steady state value. The secondary fluid also begins to slowly heat-up to saturation. The energy removed by condensation is less than the heat transferred to the core fluid as shown in Figure 3.8.1-4 so the RCS continues to heat-up and pressurize but at a slower rate (Figure 3.8.1-1).

Eventually, the condensing SG reaches saturation and boiling begins. At this point, the secondary side heat transfer coefficient increases rapidly which causes the condensation heat removal rate to increase briefly until a new steady state condition is reached (Figure 3.8.1-4).

After this, the RCS and SG pressures both increase slowly (Figure 3.8.1-5). For this analysis, it was assumed that the operator opened the SG relief valve (if not open initially) to reduce the SG pressurization rate. This was the only operator action taken. Eventually both pressures will stabilize when the SG PORV is capable of relieving enough steam to match the core decay heat generation (7.3 MWt). The SG pressure would be approximately 50 psia when this occurs. The mode of decay heat removal described here could persist for several hours (until most of the secondary water is boiled away) or longer if the SG water is refilled with AFW.

3.8.2 RCS Pressurization Rate as a Function of the Number of Condensing Steam Generators

The effect of increasing the number of condensing steam generators on the RCS pressurization rate was determined by performing 5 analyses in which the fraction of available steam generators was varied between 1.0 and 0.25. For example, a single steam generator on a 4 loop plant represents 0.25 available, 1 SG on a 3 loop plant represents 0.33 available, etc. All 5 cases assumed a loss of RHR 48 hours after shutdown during mid-loop operation. The initial RCS temperature and pressure were 140°F and 15 psia, respectively. The initial steam generator levels were assumed to be at 5% narrow range i.e., tubes covered.

Table 3.8.2-1 presents a summary of the time to reach 40 psia (a typical gravity feed pressure head is 25 psig) as a function of the number of condensing steam generators. Without condensation, all 3 plants reached 40 psia at approximately 1200 seconds. Increasing the number of steam generators available for condensation resulted in an increase in the time to reach 40 psia. Figure 3.8.2-1 shows the RCS pressurization rate comparison with varying numbers of condensing steam generators. Ideally, the plant should consider maintaining 50% or more of the steam generators available for condensation to increase the allowable operator recovery action time. This would be 1 SG on a 2 loop plant, 2 SGs on a 3 loop plant and 2 SGs on a 4 loop plant.

3.8.3 RCS Pressurization Rate as a Function of the Decay Heat and Number of Steam Generators

The number of SGs with water has a significant impact on the RCS pressurization rate following loss of RHR cooling at mid-loop conditions. This pressure reduction is even more pronounced at lower decay heat rates. Figure 3.8.3-1 shows RCS pressure for case A.8 (48 hrs after reactor shutdown) and A.9 (120 hrs after shutdown). The smaller decay heat results in a 700 second delay before RCS pressure reaches a typical RWST gravity feed limit of 40 psia. With water in one SG, the pressures for the two decay heat cases reach 40 psia at 1600 and 2500 seconds, respectively, a time difference of 900 seconds (Figure 3.8.3-2). Finally, with water in all four SGs, pressures reach 40 psia at 4350 and 6500 seconds, a difference of 2150 seconds. This information is summarized in Table 3.8.2-1.

TABLE 3.8.2-1

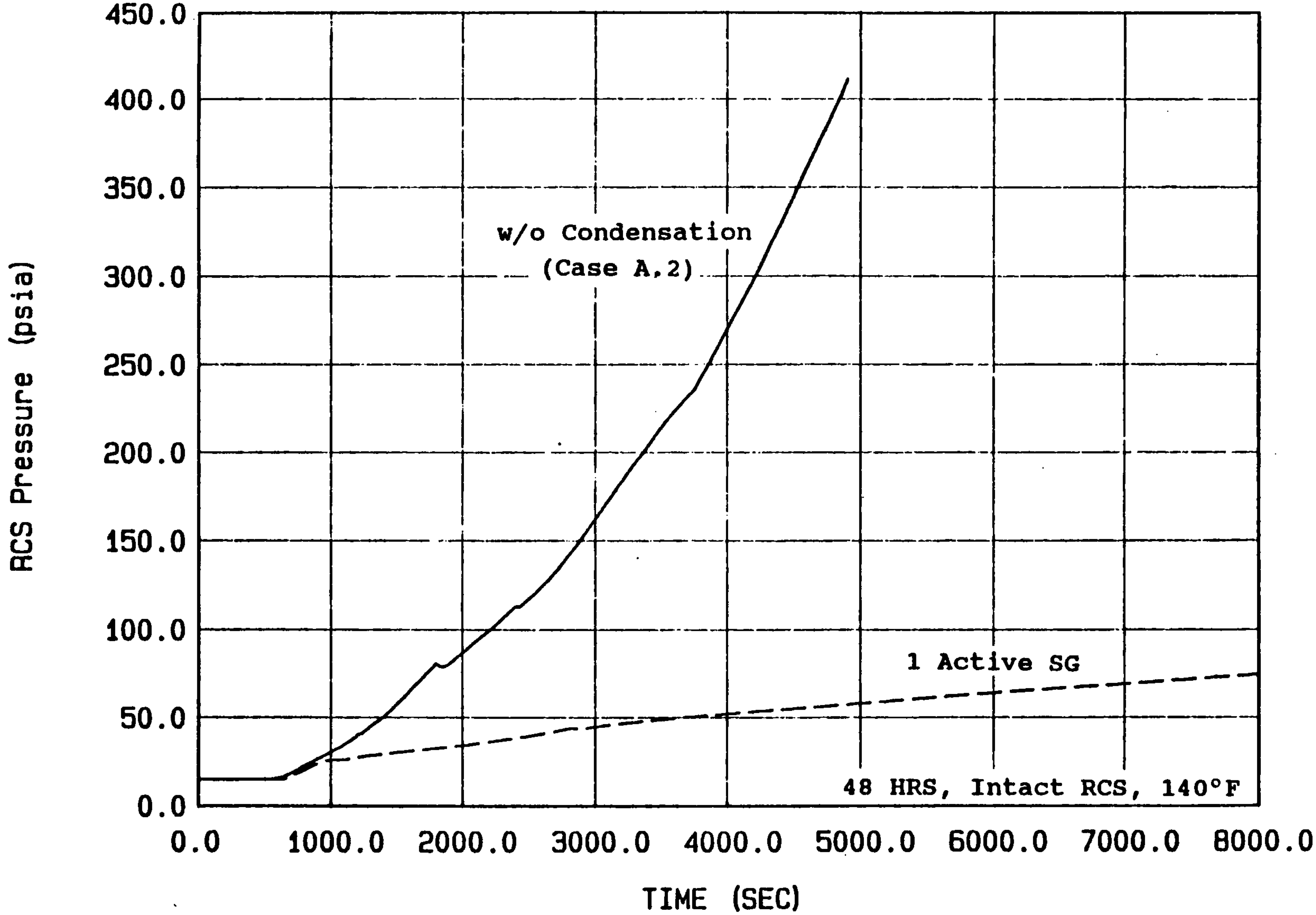
SUMMARY OF SG CONDENSATION CASES

48 hours After Shutdown

Fraction of Available SGs	Time to 40 psia (seconds) 2 Loop	3 Loop	4 Loop
0.0	1200	1190	1150
0.25			1600
0.33		2160	
0.50	2525		
0.66		3395	
1.0			4355

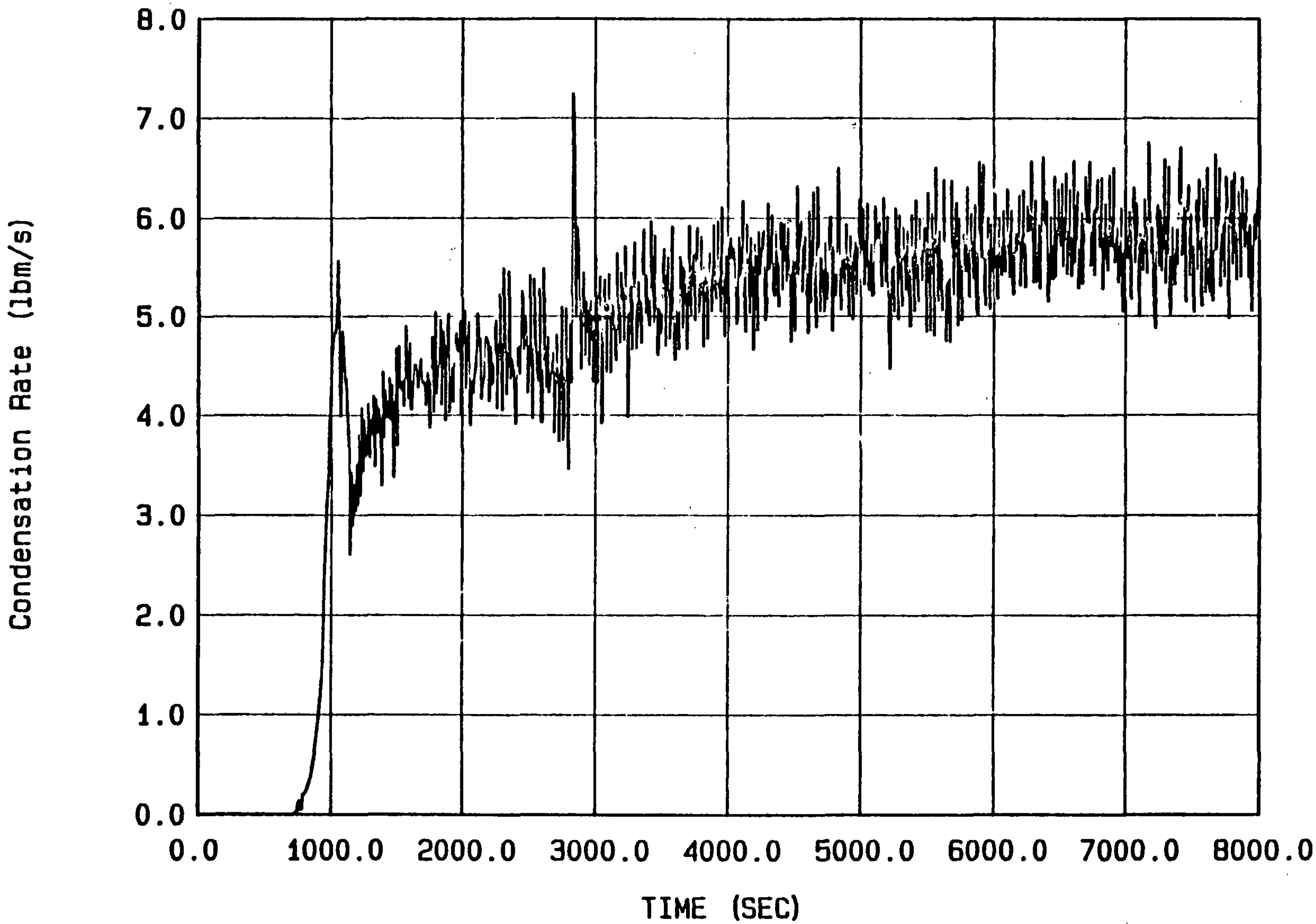
120 hours After Shutdown

Fraction of Available SGs	2 Loop	3 Loop	4 Loop
0.0			1850
0.25			2500
1.0			6500



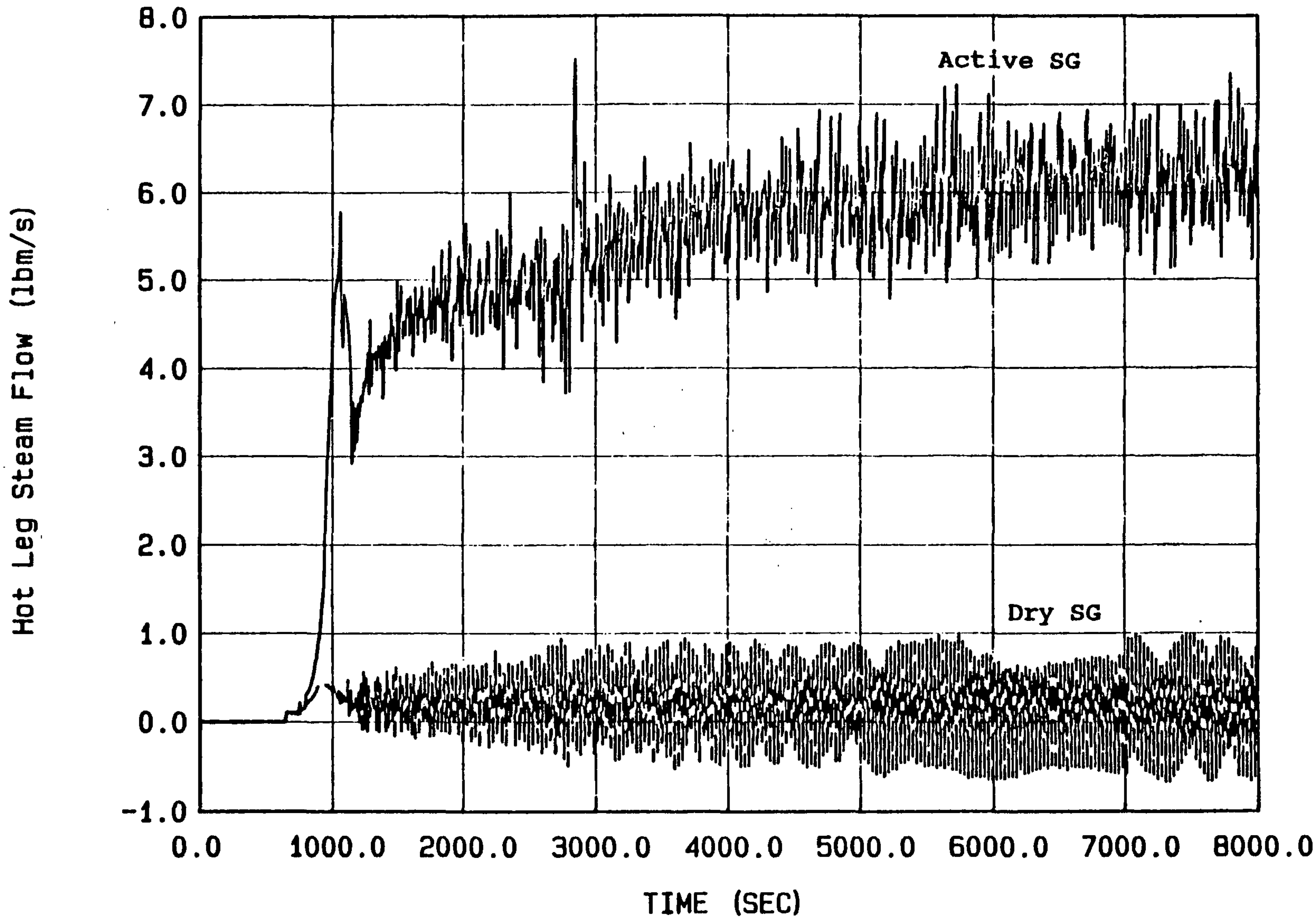
Two-Loop Case F.1, 48 HRS, 1 of 2 SGs Available

Figure 3.8.1-1 Two-Loop Case F.1, Comparison of Pressurization Rates



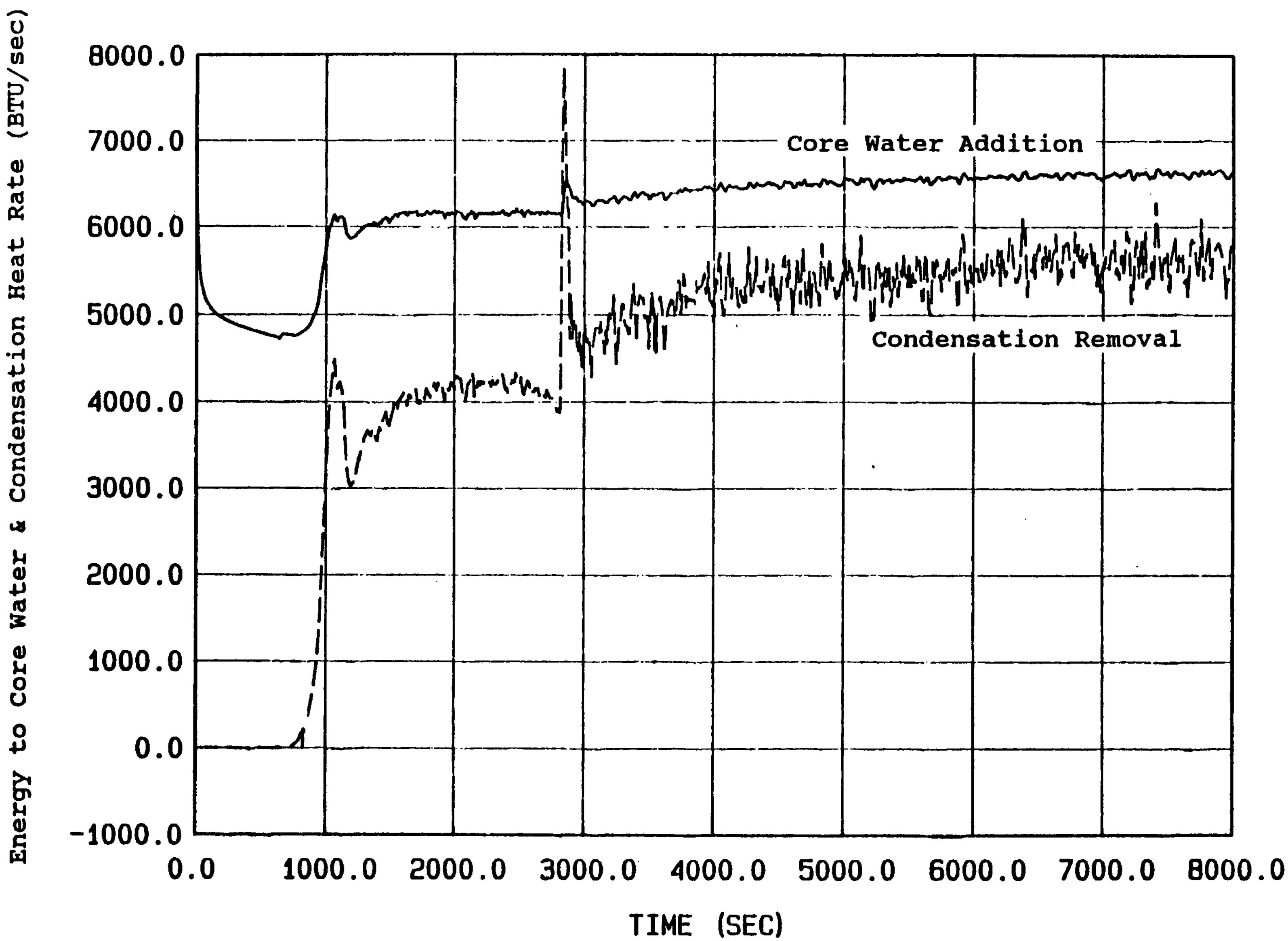
Two-Loop Case F.1, 48 HRS, 1 of 2 SGs Available

Figure 3.8.1-2 Two-Loop Case F.1, Condensation Rate



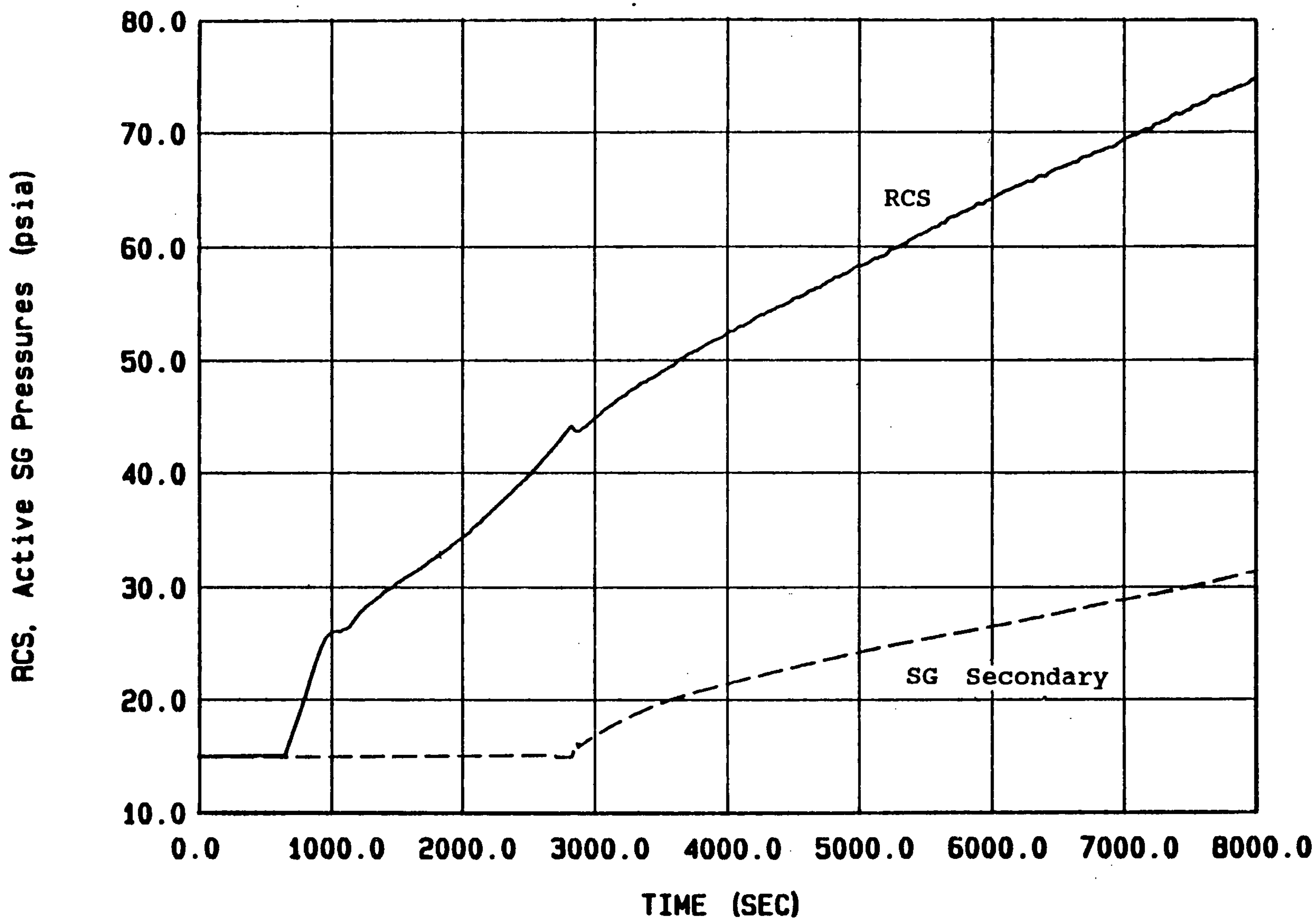
Two-Loop Case F.1, 48 HRS, 1 of 2 SGs Available

Figure 3.8.1-3 Two-Loop Case F.1, Hot Leg Steam Flow Comparison



Two-Loop Case F.1, 48 HRS, 1 of 2 SGs Available

Figure 3.8.1-4 Two-Loop Case F.1, Comparison of Energy Addition to Core Water and Removal Due to SG Condensation



Two-Loop Case F.1, 48 HRS, 1 of 2 SGs Available

Figure 3.8.1-5 Two-Loop Case F.1, RCS and SG Secondary Pressure Comparison

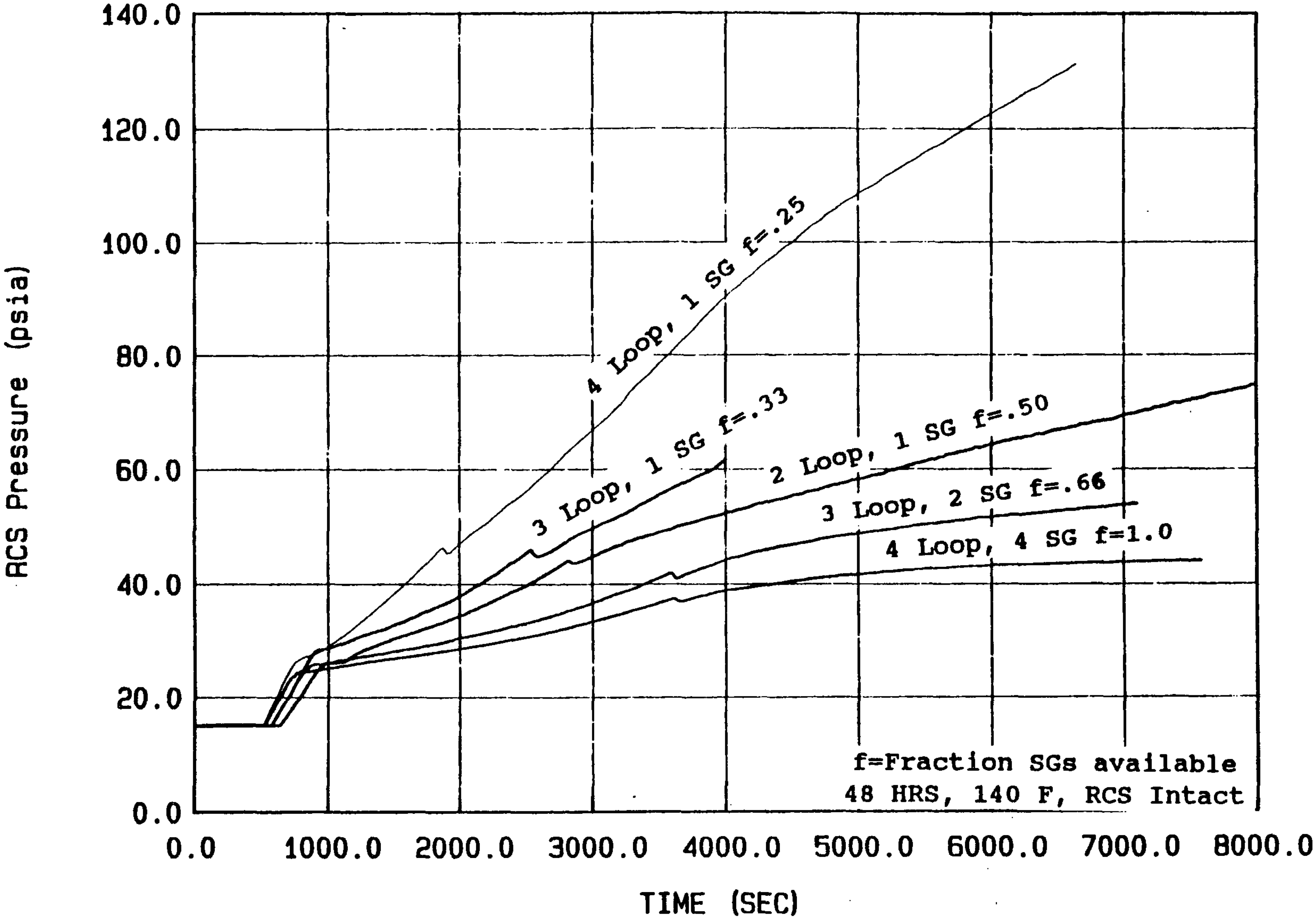


Figure 3.8.2-1 RCS Pressurization Rate Comparison with SGs

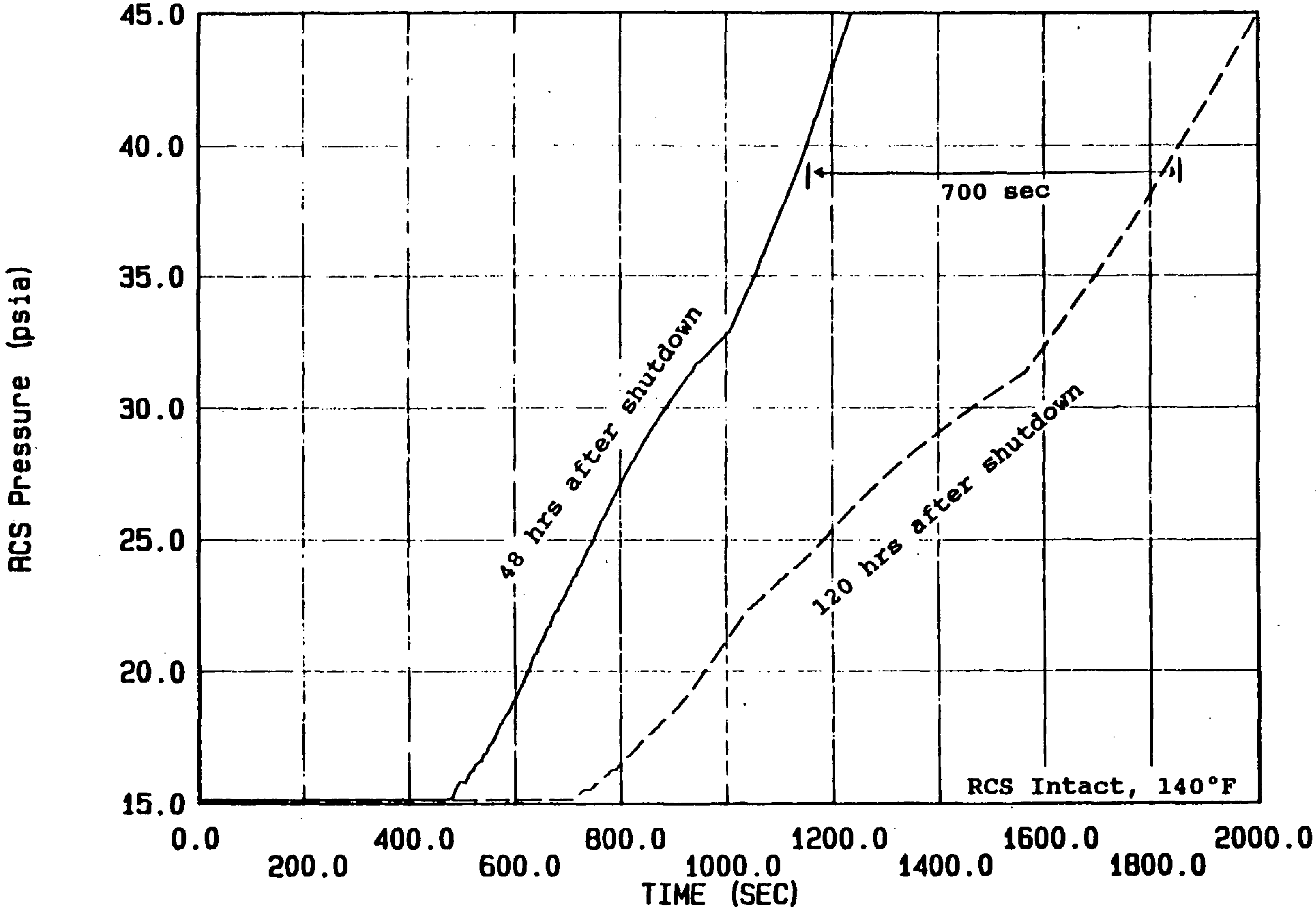


Figure 3.8.3-1 Four Loop Cases A.8 and A.9 Decay Heat Effect on Pressure w/ No SGs

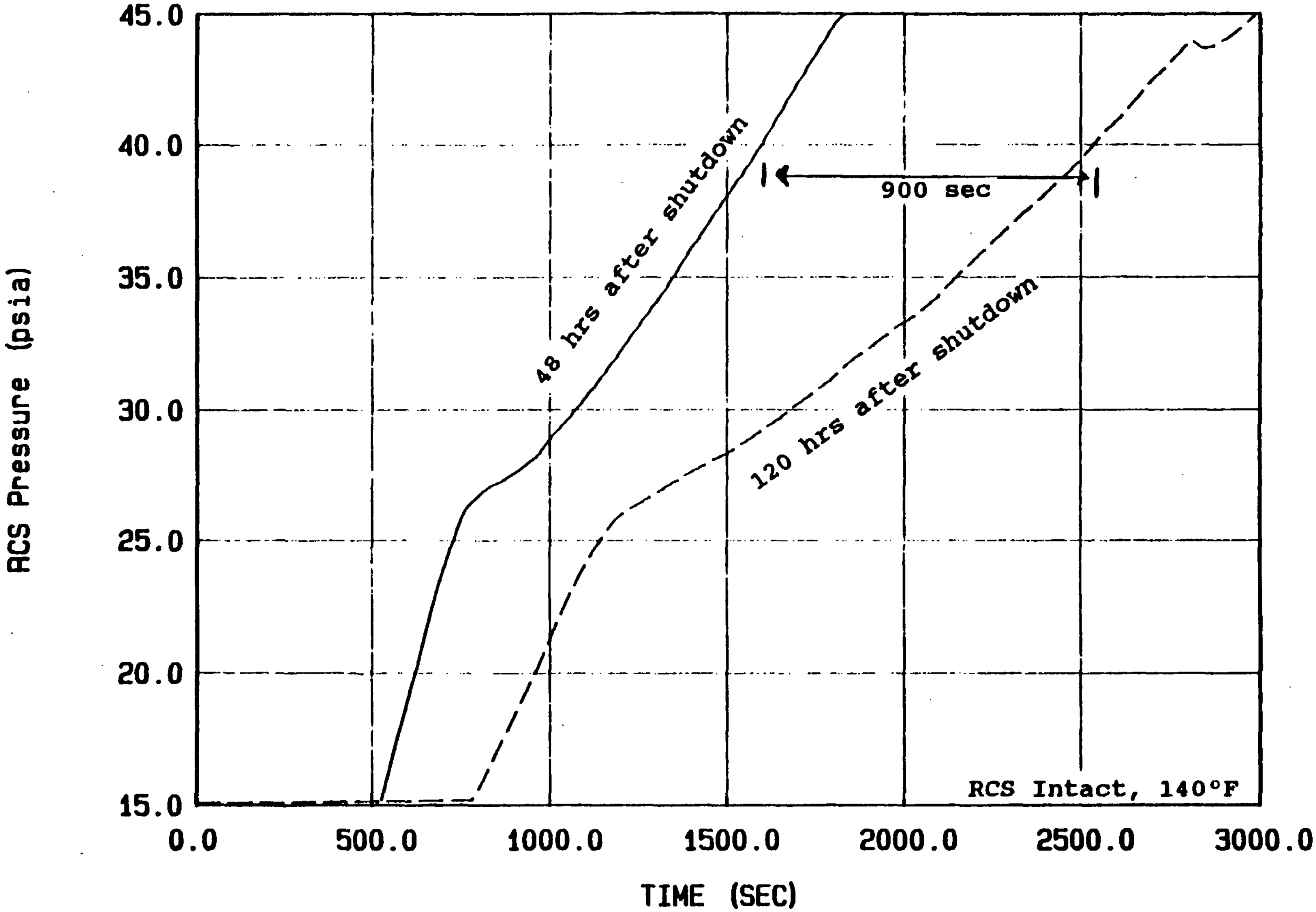


Figure 3.8.3-2 Four Loop Cases F.4 and F.6 Decay Heat Effect on Pressure w/ 1 SG

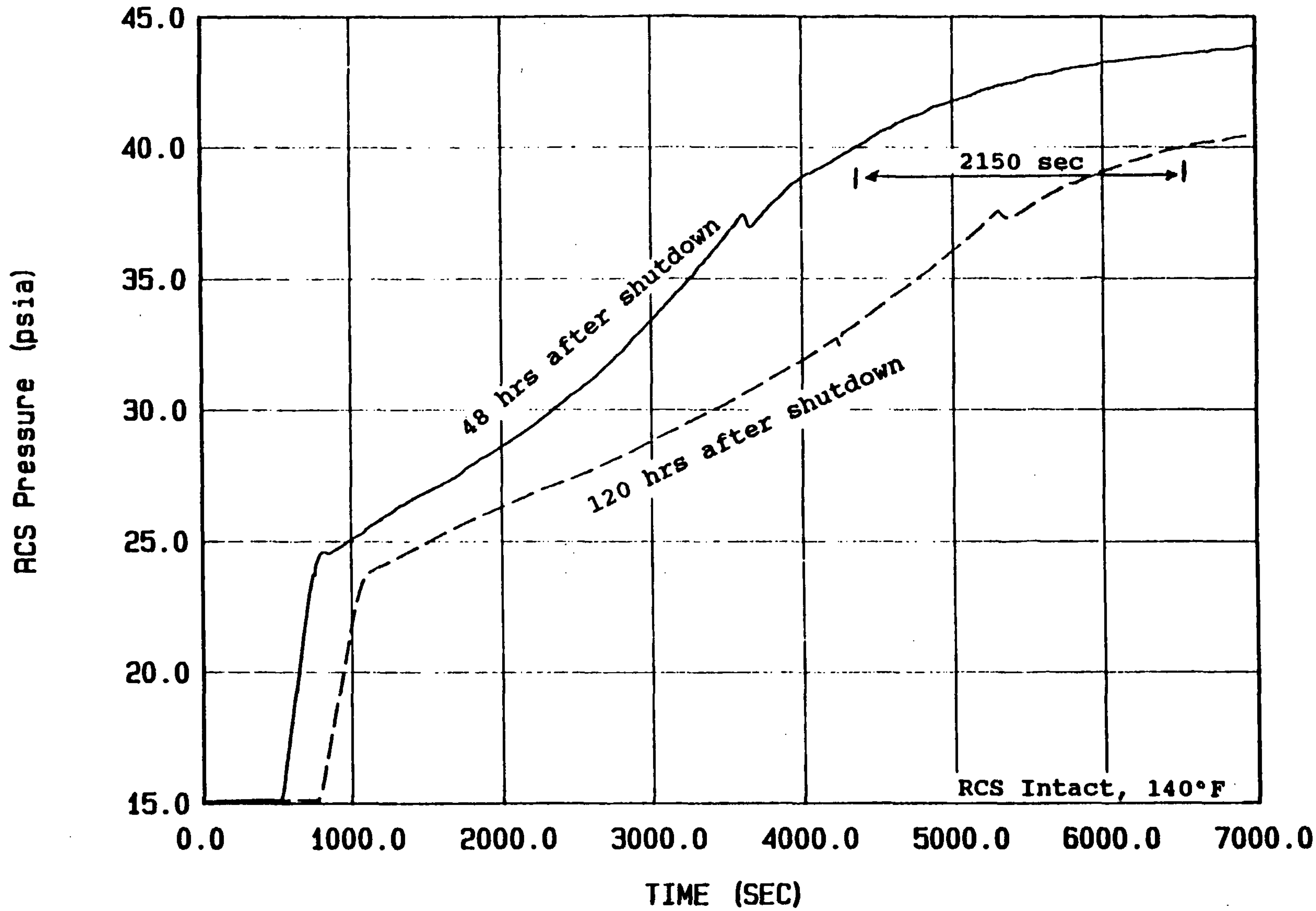


Figure 3.8.3-3 Four Loop Cases F.5 and F.7 Decay Heat Effect on Pressure w/ 4 SGs

3.9 Recovery Analyses

The recovery analysis investigate various methods for increasing RCS inventory to allow eventual return to RHR cooling. In some cases, alternate modes of cooling are demonstrated that may be used in the interim until RHR cooling can be reestablished.

3.9.1 RCS Inventory Recovery Using RWST Gravity Feed

In cases G.1 and G.2, a typical RWST gravity feed lineup through the CVCS normal charging lines from the RWST was modeled. The head vs flow curve was taken from a typical 3-loop plant although the 2-loop plant was used for the runs. The RWST was input as being 65 feet above the cold legs (90% full for the reference data used). For this geometry and flow resistance, the charging line provides 40 gpm flow at 30 psia in the RCS and no flow above 43 psia.

Case G.1, a restart of Case A.2, assumes the RCS is intact, no SGs are available for condensation, and the decay heat is based on 48 hours after shutdown. In this case, the RWST lineup is established 16 minutes into the loss of RHR transient. RCS pressure is about 30 psia at this time. Case G.2, a restart of Case F.1, assumes one of the SGs is filled with water. For this case the RWST lineup is established 30 minutes into the transient. The RCS pressure transients for both cases are shown in Figure 3.8.1-1. In Case G.1, approximately 1200 lbm of liquid inventory is injected into the RCS before the RCS pressurization shuts off the RWST flow. Case G.2 recovers more significantly with 3330 lbm of inventory added. The RWST gravity feed flows are shown on Figure 3.9.1-1. These liquid inventories add approximately .75" and 2.0" respectively to the liquid levels throughout the RCS.

In summary, gravity feed may be successful in restoring RCS level to allow restart of the RHR pumps. It should be noted that there are other gravity drain lineups which offer paths of less resistance that may be more successful in recovering inventory (RHR and Safety Injection). The effectiveness of gravity feed recovery is very strongly influenced by the RCS pressurization rate. The slower pressurization rate caused by the availability of SG condensation significantly improves the operators chances of successful gravity feed and subsequent RHR recovery. First because retarding the pressurization allows a greater operator reaction time. Secondly, assuming a given operator action, SGs will prolong the time over which the RWST feed is effective.

3.9.2 Four-Loop Recovery Case, 120 gpm Charging Flow Makeup (Case G.3)

This case demonstrates recovery of RCS inventory with forced makeup 30 minutes after loss of RHR, for a four loop plant. The system conditions are: intact RCS, 48 hour decay heat power, and no SGs with water. The recovery strategy is to establish 120 gpm charging (equivalent to one PD pump in a 4-loop plant) at 1800 seconds. The PDP injects into the loop 1 cold leg. The recovery action can be judged by comparison with the base case A.8 results.

Figure 3.9.2-1 shows that the PDP is effective at turning around the core level decrease and in fact continues to raise the level. Figure 3.9.2-2 shows the increase in core inlet flow up to the value of the PDP input. Figure 3.9.2-3 is an overlay of the pressurization plot with the same curve from the base case. The pressurization is retarded slightly due to the mixing of the colder water from the downcomer forced into the core at the PDP flow rate. The reduction in core boil-off causes this reduction in pressure.

In summary, this method of recovery will, while not able to stop the pressurization, clearly be successful at maintaining and increasing core level so that RHR can be recovered before RCS pressure increases above the 400 psia RHR cut-in pressure.

3.9.3 Three-Loop Recovery Case G.4, 90 gpm Charging Makeup for Large RCS Vent (Case G.4)

This recovery analysis was performed using the 3 loop plant, 48 hours after shutdown. A large steam vent path was assumed and all SGs were dry. The recovery method used in this analysis was to initiate 90 gpm of charging (typical for a 3 loop plant) just prior to core uncovery. Note, 90 gpm of charging flow is approximately 12.5 lbm/s. The core boil-off rate, 48 hours after shutdown is about 11.5 lbm/s for the 3 loop plant modeled here. Therefore, the available charging flow is only slightly greater than the boil-off rate. The purpose of this analysis was to determine if that amount of charging flow this late in the transient was able to restore RCS inventory and prevent core uncovery.

This case is simply a continuation of Case B.5 (with spill) discussed in Section 3.4.1. The core mixture level and downcomer level is shown in Figure 3.9.3-1. The 90 gpm of charging flow was started at 4200 seconds (70 minutes) and began to fill the cold legs and downcomer. The core mixture level eventually began to turn around and recover at 4600 seconds. This successful recovery demonstrates RCS inventory increase while maintaining adequate core cooling via boil-off. This mode of cooling will be stable for an extended period of time (hours) until RCS inventory has increased enough to allow RHR cooling to be reestablished.

3.9.4 Recovery Analysis for Cold Leg Openings, With and Without SG Nozzle Dams

Sections 3.5 and 3.7.2 present analysis for various cold leg opening cases without operator recovery actions. In this section, recovery analysis for some of these cases will be investigated. All analyses are performed for the two-loop plant, 48 hours after shutdown. A summary of results for this study is provided in Table 3.9.4-1. Selected parameters of interest are given in Figures 3.9.4-1 through 3.9.4-12.

In the first recovery analysis, Case G.5 considers the case of the 12" check valve opening without SG nozzle dams in place, a restart of Case E.2 described in Section 3.7.2. At 30 minutes (1800 seconds), 55 gpm (7.55 lbm/sec) charging flow is initiated, injecting into the intact loop cold leg. This flow rate corresponds to the charging capability of one PD pump for the 2-loop plant and exceeds the core boil-off rate due to decay heat (q/h_{fg} = 7.1 lbm/sec) by only a few percent. Recall from Case E.2, that RCS pressure increased slightly until the loop seal cleared and then stabilized between 15 and 16 psia after 900 seconds. Figure 3.9.4.4-1 illustrates that the pressure is maintained almost constant for this 3 hour recovery transient. Levels in the core and downcomer are shown in Figure 3.9.4-2. Note that after the makeup starts, the rate of decrease of the core and downcomer level decreases by about a factor of two. The reason the levels did not turn around completely at this time was that about half the makeup flow initially injected went to refill the partially depleted cold leg piping of the intact loop. During the earlier loop seal clearing transient, some of the water in this piping was also forced into the downcomer. After the water level in the intact loop reached the bottom of the cold leg, most of the water was free to flow into the downcomer and restore level in the core. After 4000 seconds, the levels do finally turn around and start to increase. (Note: the change in slope at 3100 seconds occurs when the core level reaches the area change at the top of the core.) This transient was designed to illustrate a marginally acceptable case, i.e., one in which the minimum acceptable amount of makeup (boil-off plus 6%) delivered at 30 minutes proves to be sufficient to recover the core with no significant uncovery. <u>A makeup rate two to three times higher than boil-off would be recommended to cause level to recover faster</u>.

Case G.5a considers the same 12" check valve opening case, this time with hot leg nozzle dams in place. Cold leg injection at the 55 gpm flow rate will not be sufficient to recover the core, so this study considers the possibility of hot leg injection at an earlier time (11 minutes), i.e., about 100 seconds after boiling starts. Figure 3.9.4-3 shows the RCS pressure transient for this case. The core and downcomer level responses are given in Figure 3.9.4-4. Because the sensible heat removed by the cold (100°F) makeup water is not appreciable at this low flow rate, the recovery scenario looks almost the same as the previous case without operator action, Case C.2. Case G.6b investigates the possibility for core recovery for this case at a higher hot leg injection flowrate.

In Case G.6, both hot leg nozzle dams were assumed to be in place and a manway on the cold side of one of the SGs was removed (Case C.1 restart). At 11 minutes, 360 gpm (50 lbm/sec) cold leg SI was used in an attempt to restore level in the core. Safety injection caused a slight reduction in RCS pressure from 700-800 seconds (Figure 3.9.4-5) at the 4 psig "hurdle" previously noted in Cases C.1 and C.3. Unfortunately, not enough cold water was able to reach the core to prevent boiling, so RCS pressure continued to increase and core level eventually dropped (Figure 3.9.4-6). During the 700-800 second, core flow averages close to zero (Figure 3.9.4-7). After 800 seconds, the core flow reverses resulting in continued core uncovery.

In Case G.6a, the same scenario is repeated with hot leg injection. At the 360 gpm makeup rate, the SI water has a heat removal capability of 6000 BTU/sec when heated from 100°F to the core temperature of 220°F. This is about 87% of the core decay heat (6915 BTU/sec), so recovery may be possible for this case. After hot leg injection starts at 660 seconds, the RCS pressurization rate slows considerably (Figure 3.9.4-8). Levels in the core and downcomer also recover (Figure 3.9.4-9). Since the heat removal capability is slightly less than the core decay heat, the RCS temperature rise is reduced and temperature slowly increases at the end of the transient (Figure 3.9.4-10). Based on this analysis, hot leg injection will be effective at preventing core uncovery for the hot leg nozzle dam cases with a large cold side opening if the injection rate is high enough, i.e., if the sensible heat addition required to heat the makeup water to saturation is approximately equal to the decay heat.

Case G.6b considers a similar recovery scenario for the 12" check valve opening. In this transient, 360 gpm hot leg injection is again initiated at 660 seconds. The addition of this cold water is immediately effective in reducing the RCS pressure (Figure 3.9.4-11). At the time injection flow is started, the core level is about one foot above the top of the core (faster uncovery transient than the previous case). The level decrease is slowed and finally core level is turned around after 720 seconds. This and the previous Case G.6a analysis demonstrate successful core recovery using hot leg injection for the large cold leg openings with hot leg nozzle dams in place.

Section 3.10.4 summarizes the various recovery considerations for cold leg openings with and without nozzle dams.

3.9.5 Two-Loop Recovery Case, SG Refill with RWST Gravity Feed (Case G.7)

This recovery analysis was performed with the 2 loop plant, 48 hours after shutdown. Initially both SGs were in dry layup at the time RHR cooling was lost. The recovery method used in this analysis was to begin refilling one of the steam generators at 15 minutes and allow RWST gravity feed to begin at 30 minutes. The purpose of this analysis was to determine if refilling the steam generator would significantly decrease the RCS pressurization rate and therefore increase the time available for the operator to align RWST gravity feed.

As the steam generator begins refilling, a large fraction of core decay heat is removed by condensation as shown in Figure 3.9.5-1. This does retard the RCS pressurization rate, as shown in Figure 3.9.5-2, however it is not enough to cause the RCS pressure to remain below the 40 psia gravity feed limit long enough for a significant amount of RWST water to be fed to the RCS. Therefore, this was not a successful recovery action for this case in the time frame assumed for operator response.

If the steam generator was filled earlier or at a faster rate or decay heat were reduced (longer time after shutdown), more RWST water could have been gravity fed to the RCS. Also, if gravity feed could have been initiated earlier, more water could have been fed to the RCS. Thus, refilling the SG may be an effective means for restoring RCS inventory by RWST gravity feed if some of the plant conditions are altered slightly. Regardless of the success of gravity feed, the SG will provide a beneficial heat sink for decay energy removal until RCS inventory and RHR cooling can be restored by other means.

3.9.6 Four-Loop Recovery Case, Bleed and Feed (Case G.8)

For this recovery case, the RCS bleed and feed technique is evaluated. One high pressure safety injection pump coupled with one open pressurizer PORV is used. The conditions at the time of feed and bleed initiation are taken as those at the end of the base case A.8 run, 4000 seconds after loss of RHR, 431 psia. This is a unique case for several reasons. First, it represents recovery from a late high pressure condition. Secondly, if bleed and feed is maintained, this case establishes a true steady state condition.

Two variations of this case were run. The first assumed a constant 450 gpm at 100°F, the other used a constant 225 gpm makeup. It should be noted that 450 gpm represents a more realistic high pressure SI flowrate that may be within the capacity of one charging/SI pump in the normal charging mode, for some plants. Figure 3.9.6-1 compares the pressurization plots for the two variations. The 450 gpm injection was sufficient to reduce the steady state pressure to approximately 220 psia. However, 225 gpm resulted in a 510 psia steady state. The lower SI flow case is not capable of removing all the decay heat from the core at subcooled conditions. Thus, pressure rises and two-phase relief maintains the steady state. Figures 3.9.6-2 and 3.9.6-3 show the SI and PORV flows for the two variations. The high flow case equalizes at a subcooling of about 15°F. In both cases, the core remains covered and level stabilizes well above mid-loop.

TABLE 3.9.4-1

COLD LEG OPENING RECOVERY ANALYSIS SUMMARY
TWO-LOOP PLANT, 48 HOURS AFTER SHUTDOWN

Recovery Case	Restart Case	HL Dams Status	Cold Leg Opening	Makeup Flow (gpm)	Makeup Location	Does Core Recover?
G.5	E.2	No Dams	12" CKV	55 gpm at 30 min	Cold Leg	Yes
G.5a	C.2	Both in Place	12" CKV	55 pgm at 11 min	Hot Leg	No
G.6	C.1	Both in Place	SG CS Manway	360 gpm SI at 11 min	Cold Legs	No
G.6a	C.1	Both in Place	SG CS Manway	360 gpm SI at 11 min	Hot Legs	Yes
G.6b	C.2	Both in Place	12" CKV	360 gpm SI at 11 min	Hot Legs	Yes

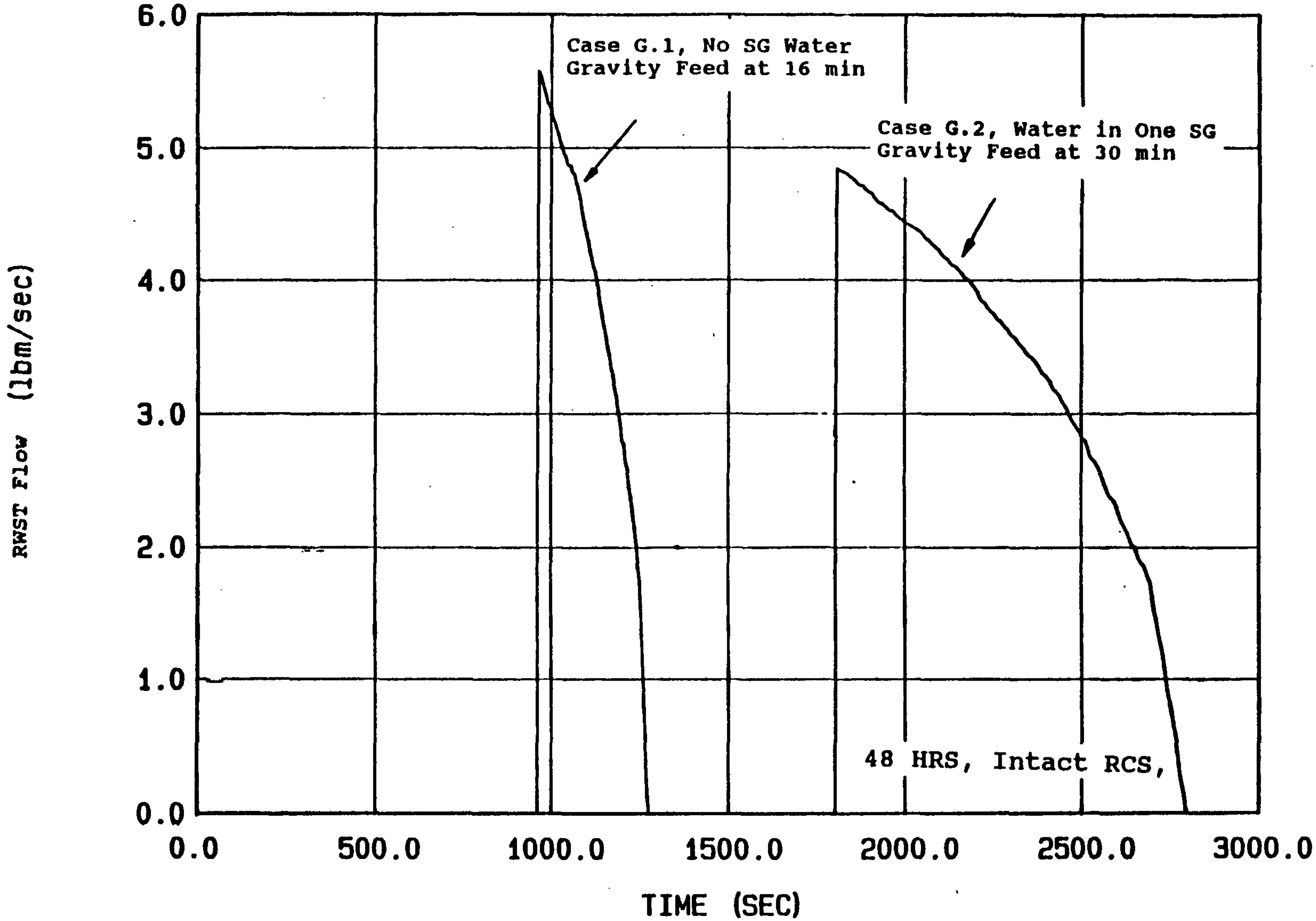


Figure 3.9.1-1 Two-Loop Cases G.1 and G.2 RWST Gravity Feed Comparison

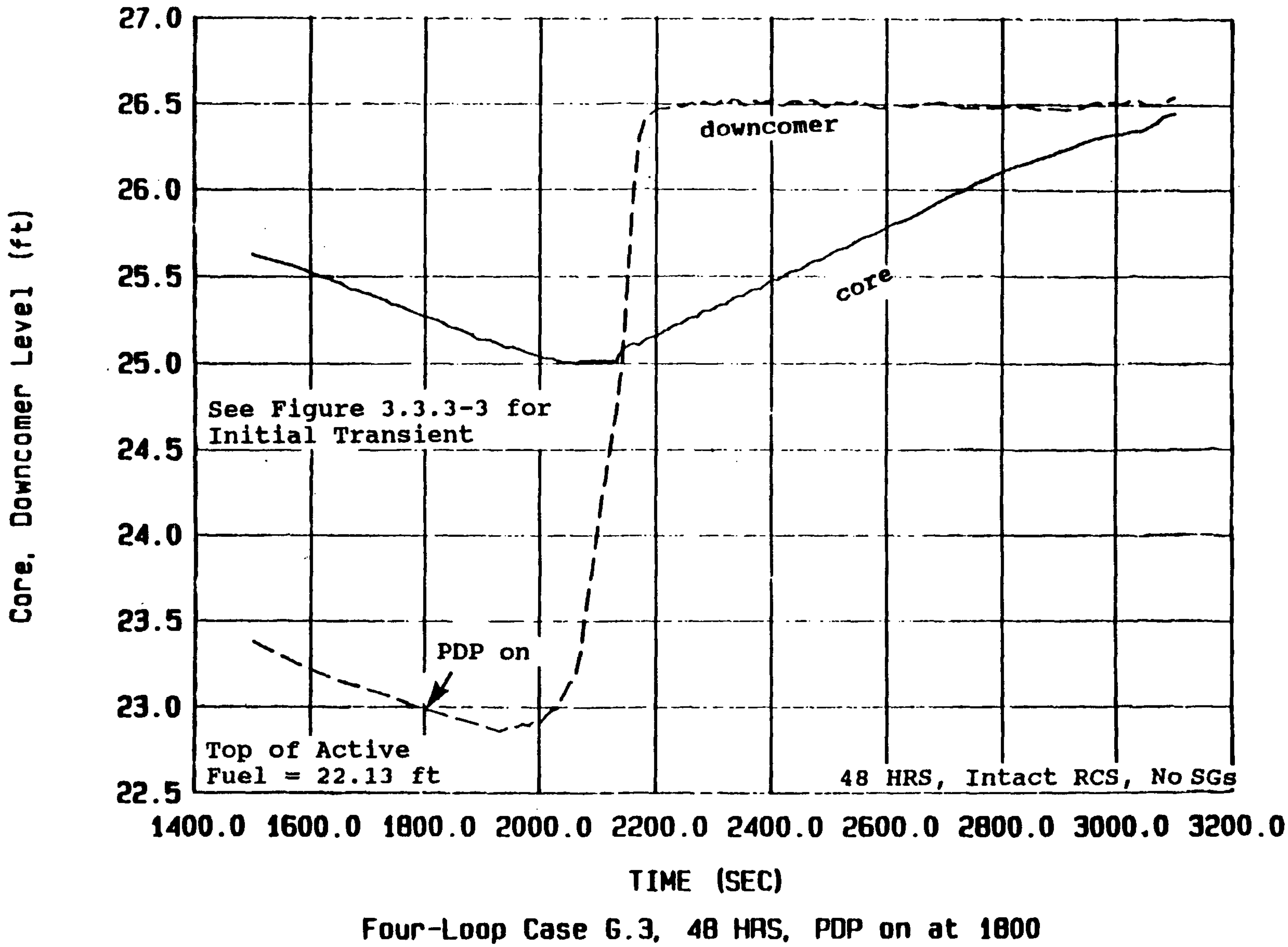


Figure 3.9.2-1 Four Loop Case G.3, Core and Downcomer Mixture Levels

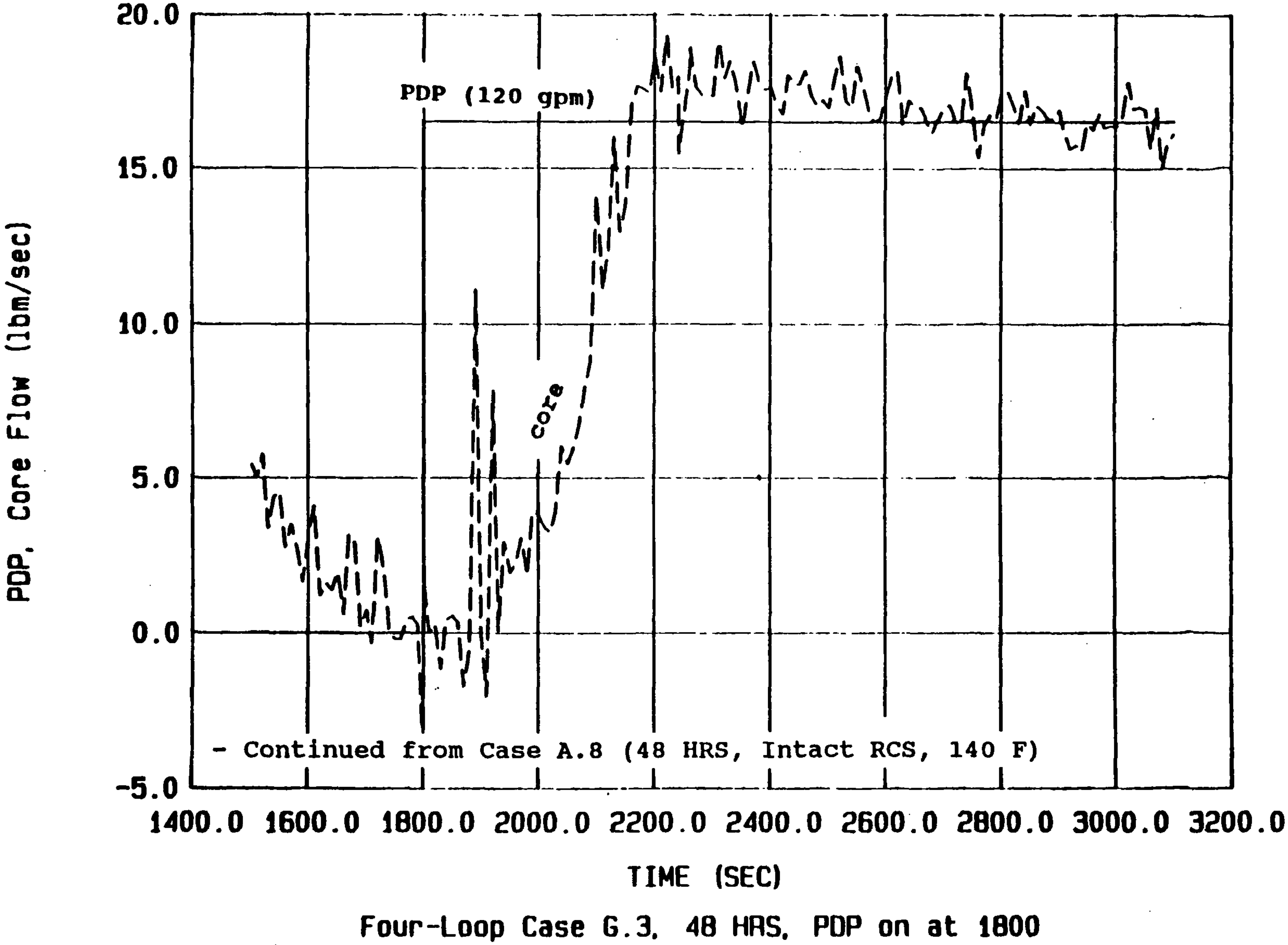
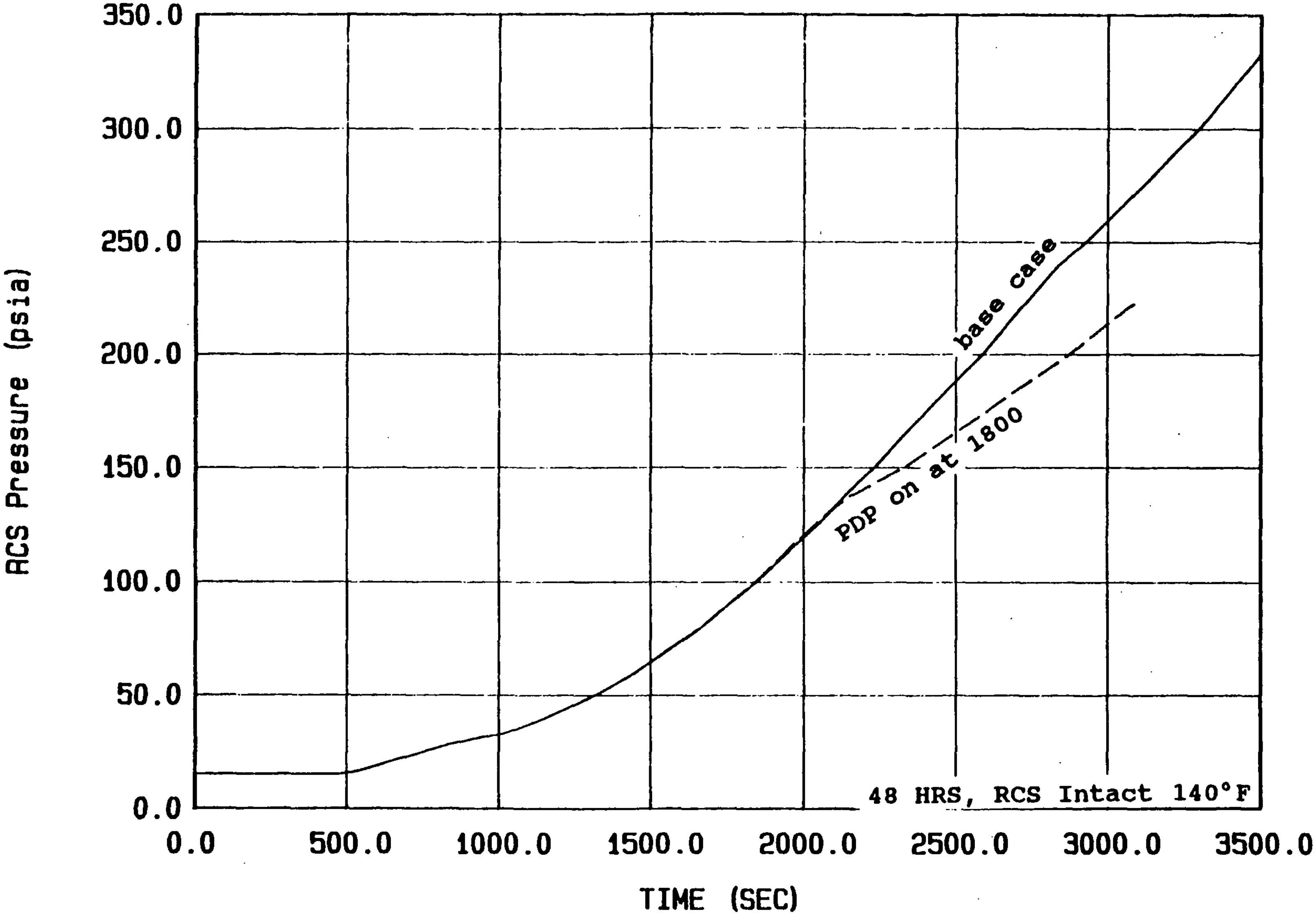


Figure 3.9.2-2 Four Loop Case G.3, PDP and Core Flow



Cases G.3 (PDP Recovery) and A.8 (base case)

Figure 3.9.2-3 Four Loop Case G.3 and A.8 Pressurization Comparison

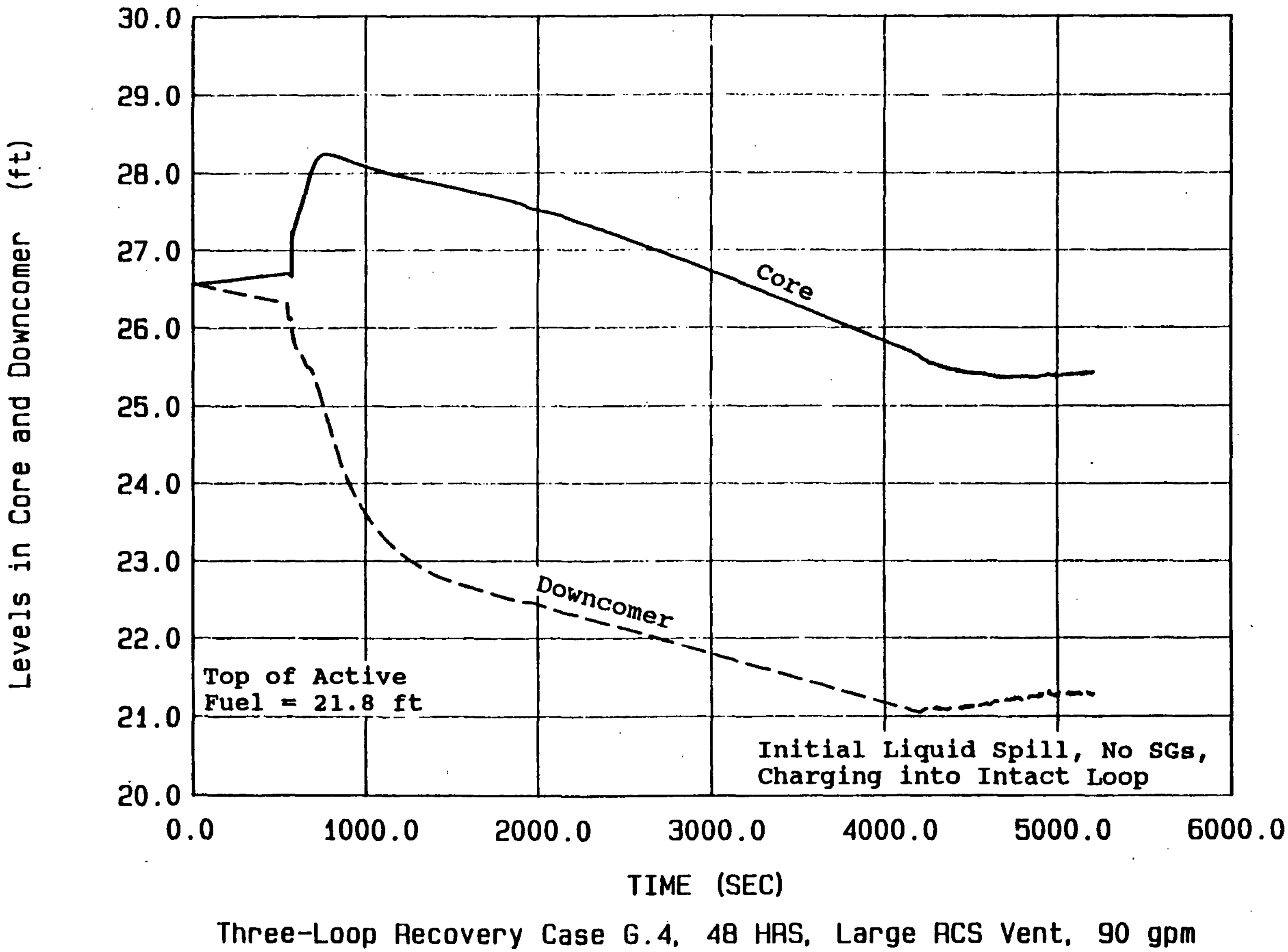


Figure 3.9.3-1 Three-Loop Case G.4, Core and Downcomer Mixture Levels

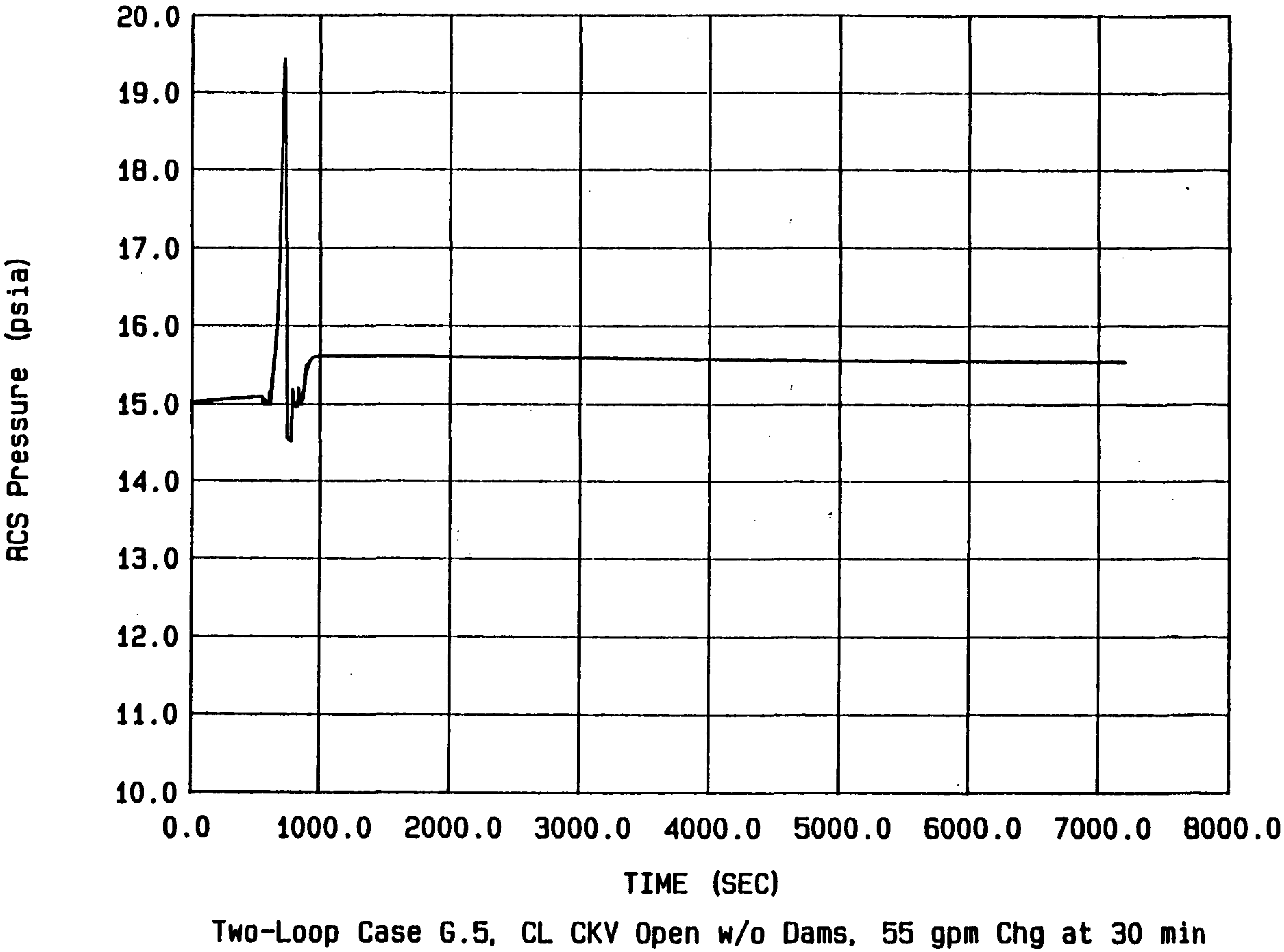


Figure 3.9.4-1 Two-Loop Case G.5, RCS Pressure

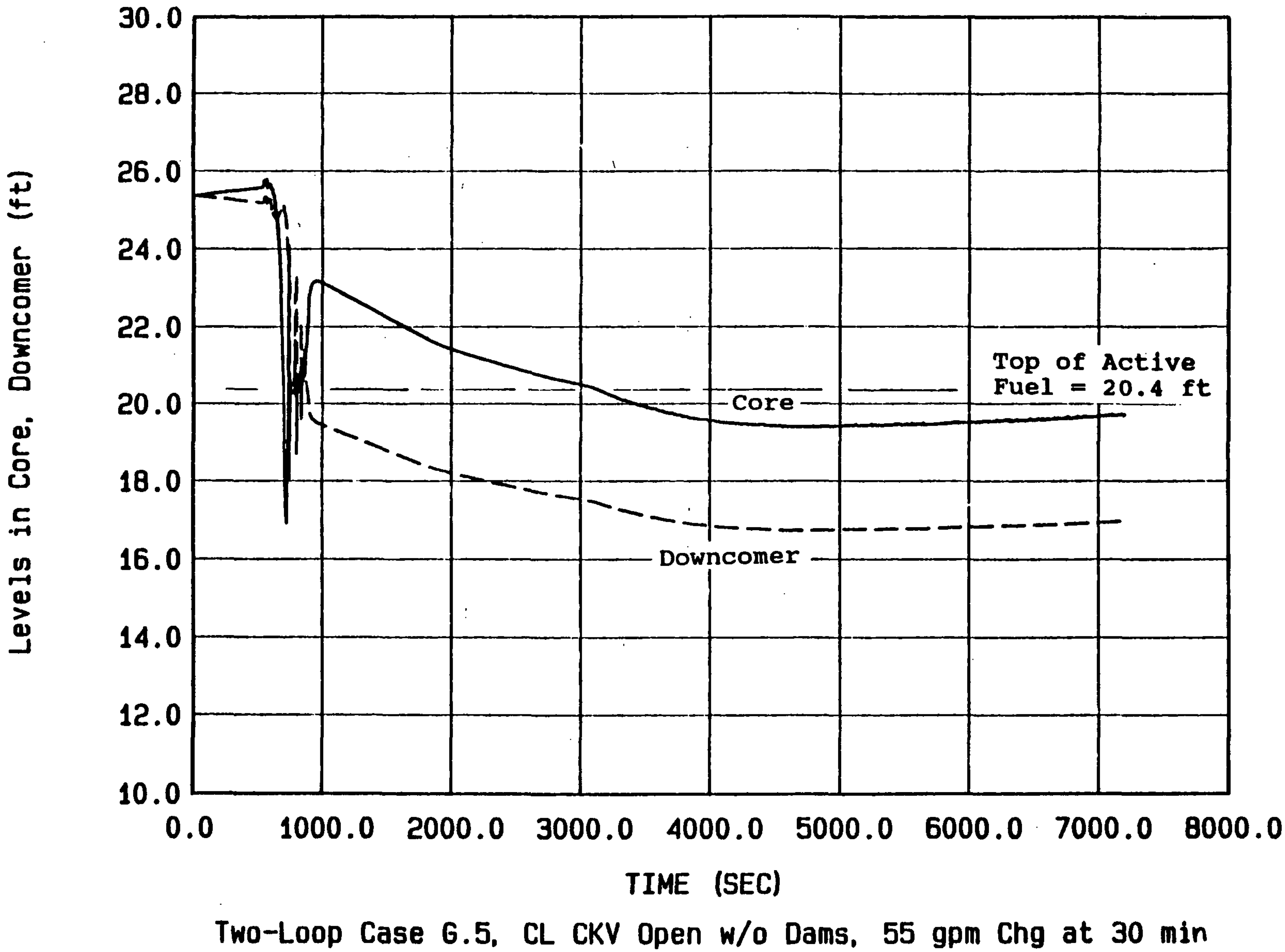


Figure 3.9.4-2 Two-Loop Case G.5, Core and Downcomer Mixture Levels

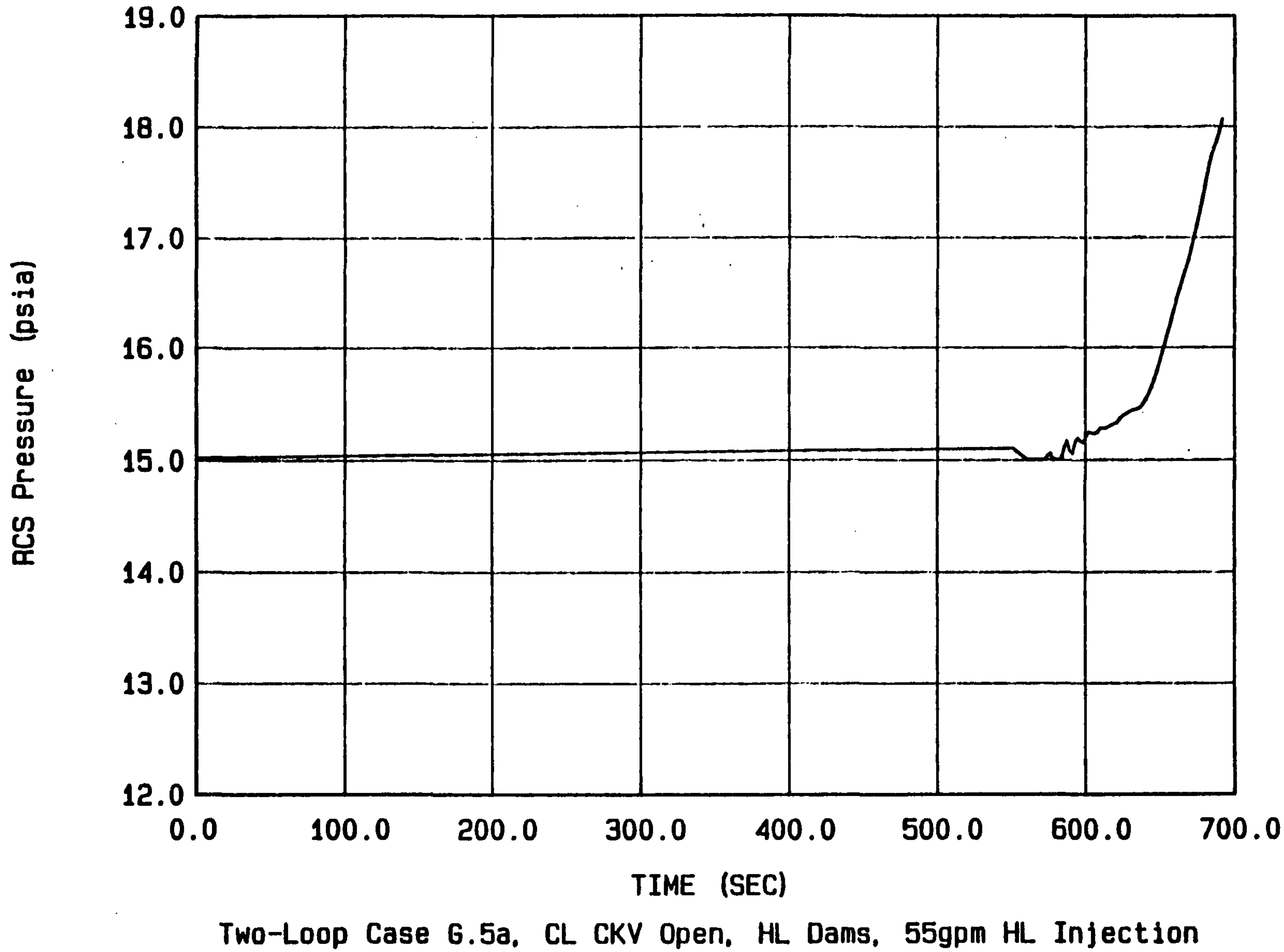


Figure 3.9.4-3 Two-Loop Case G.5a, RCS Pressure

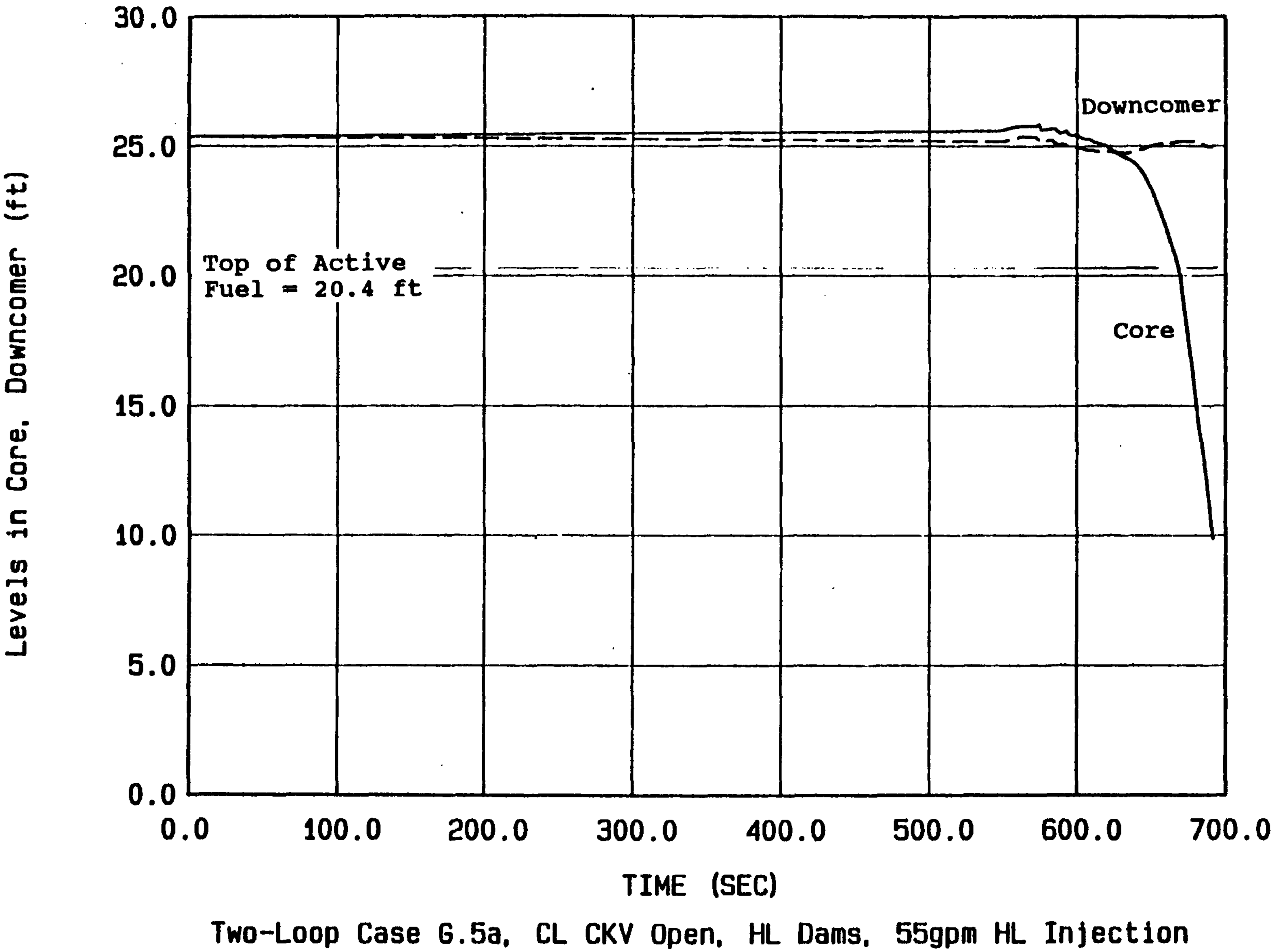
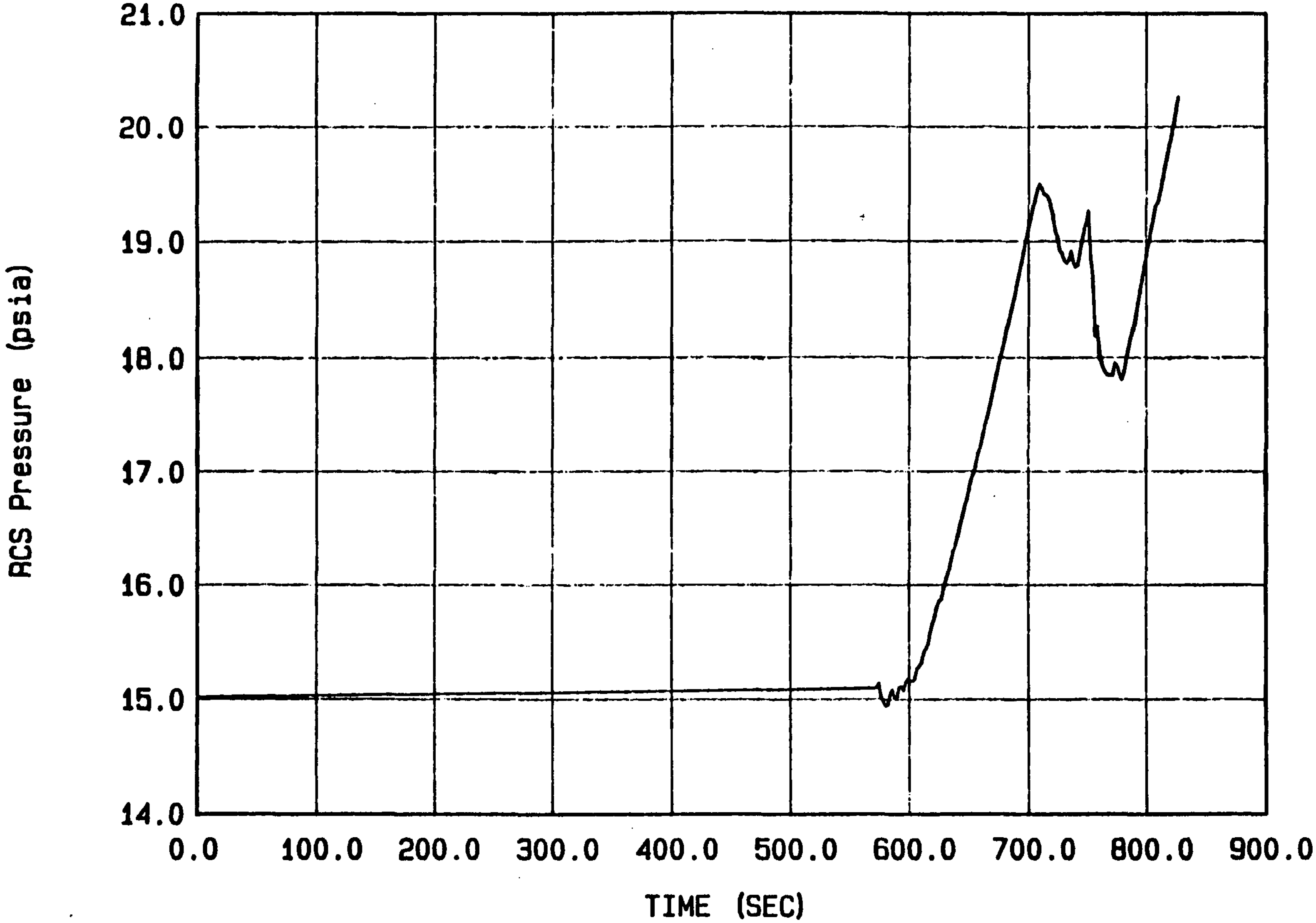


Figure 3.9.4-4 Two-Loop Case G.5a, Core and Downcomer Mixture Levels



Two-Loop Case G.6, CS Manway, HL Dams, 360 gpm CL SI

Figure 3.9.4-5 Two-Loop Case G.6, RCS Pressure

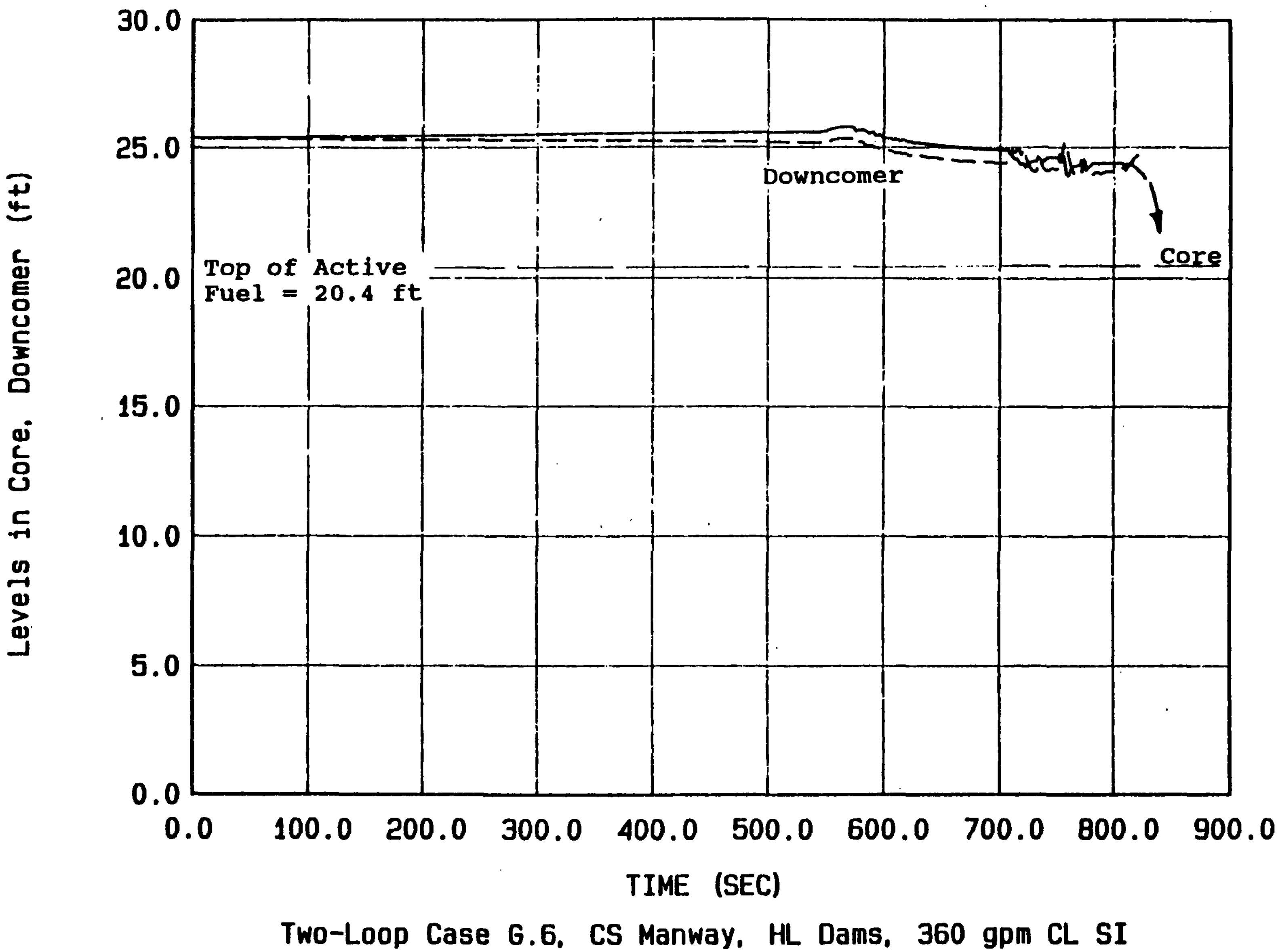


Figure 3.9.4-6 Two-Loop Case G.6, Core and Downcomer Mixture Levels

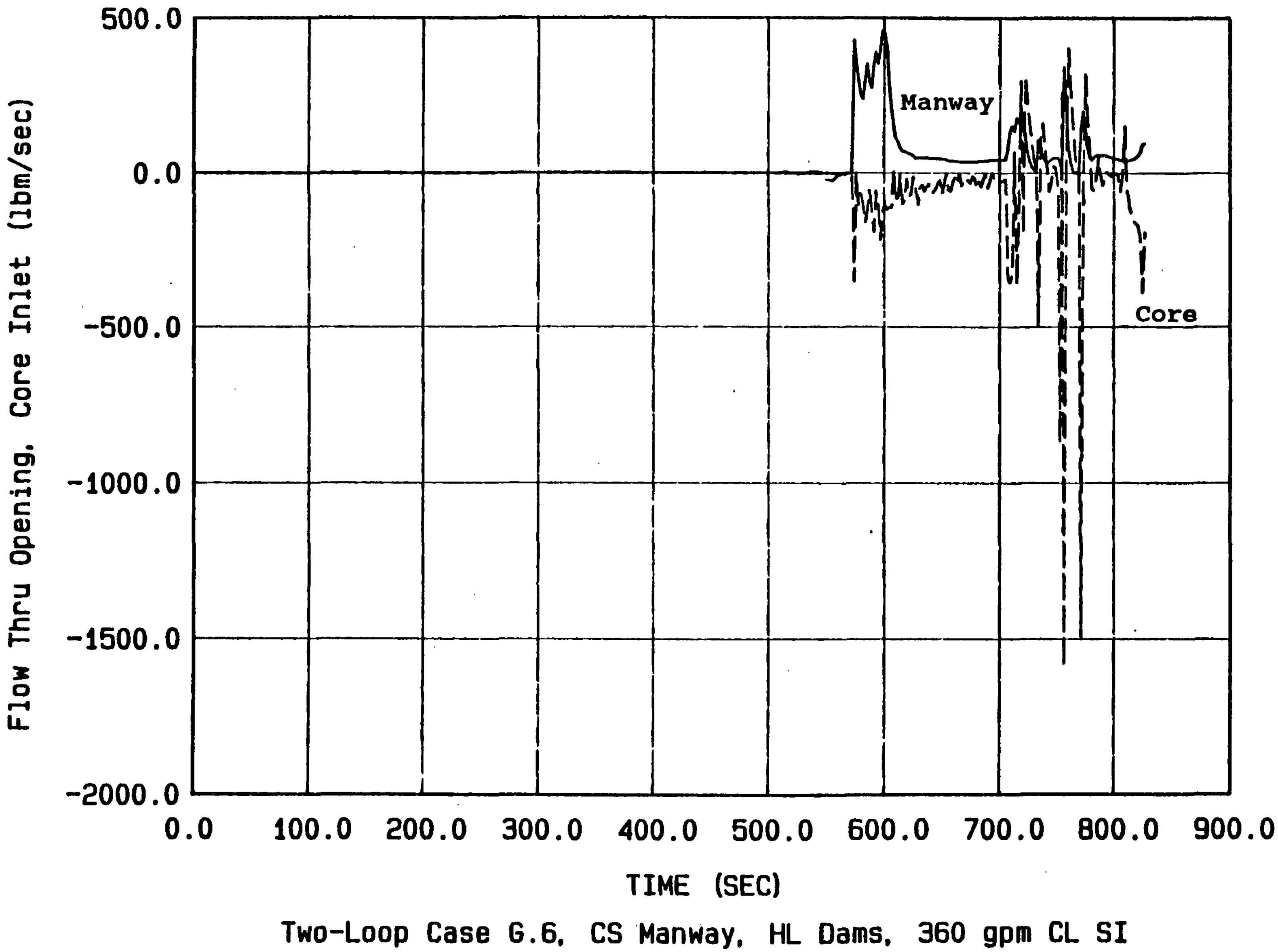


Figure 3.9.4-7 Two-Loop Case G.6, Manway and Core Inlet Flows

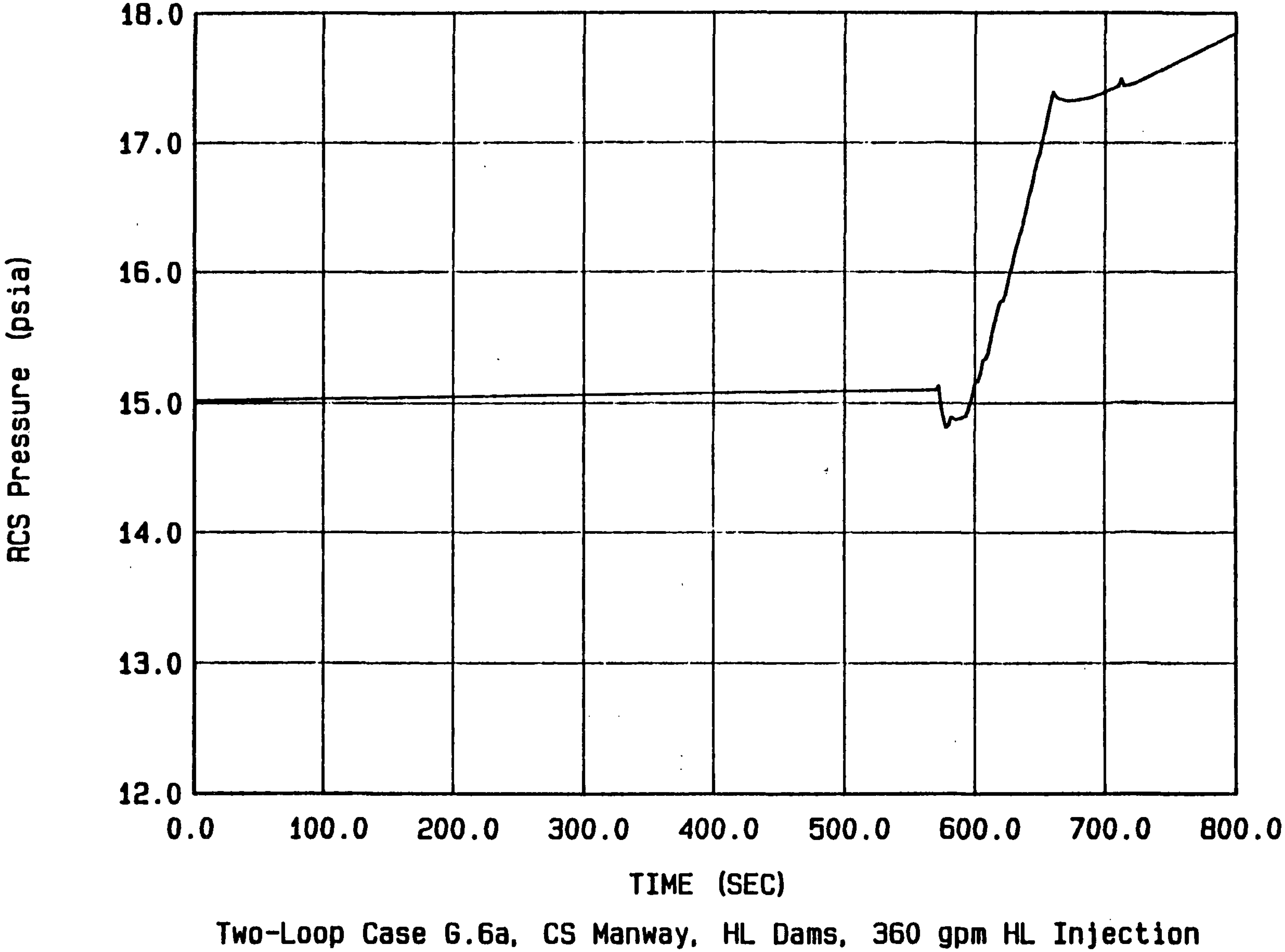


Figure 3.9.4-8 Two-Loop Case G.6a, RCS Pressure

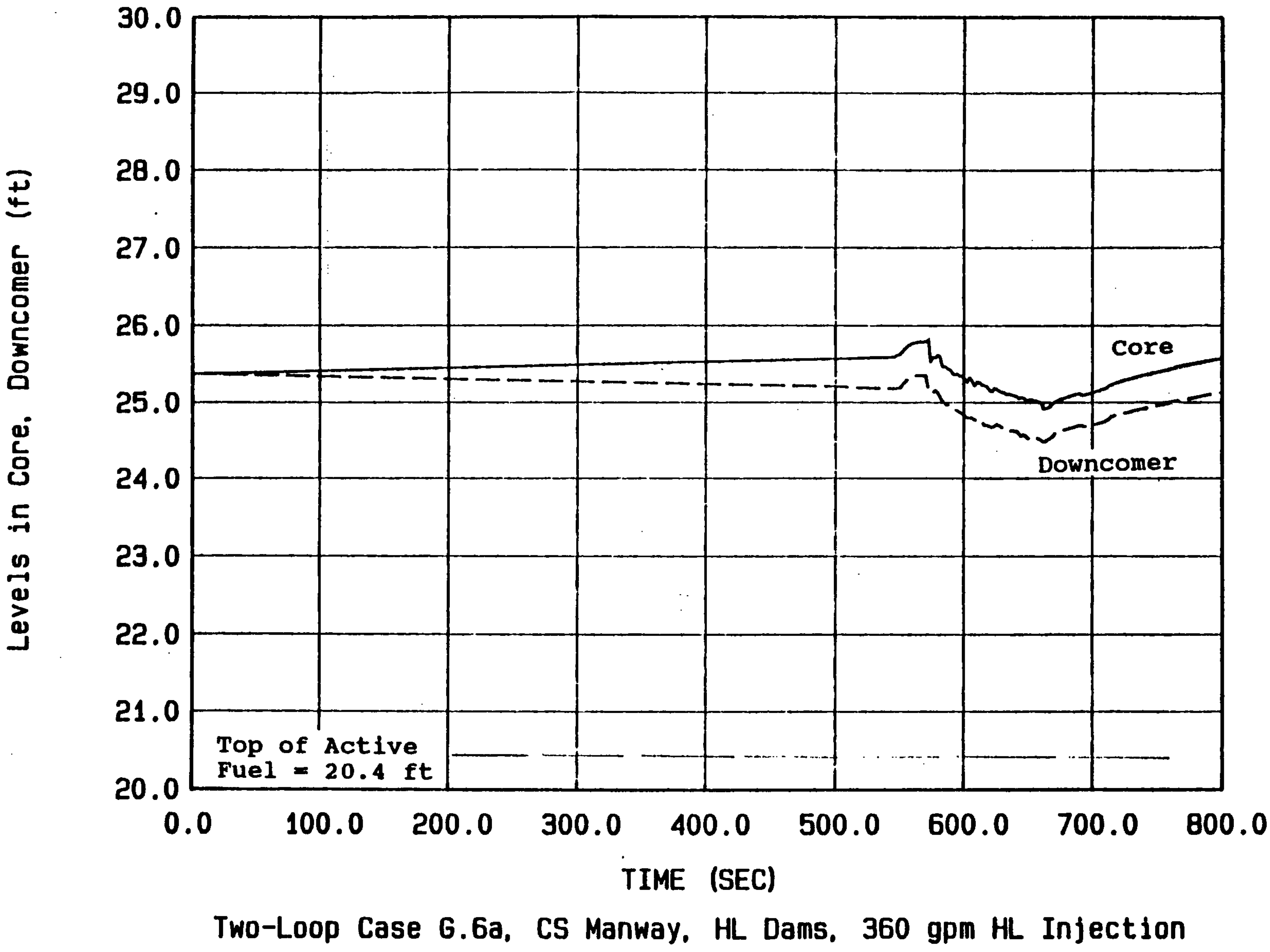
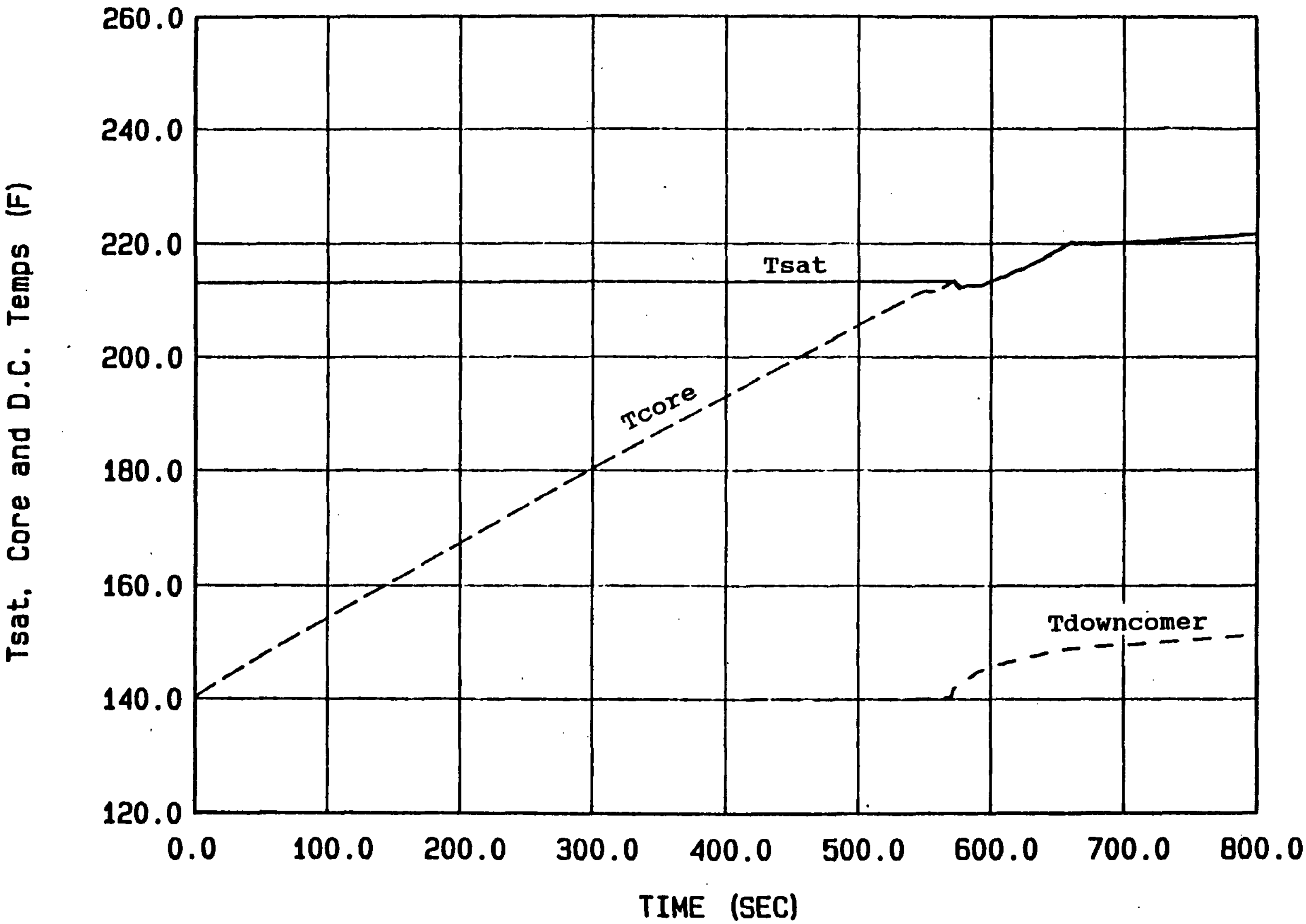


Figure 3.9.4-9 Two-Loop Case G.6a, Core and Downcomer Mixture Levels



Two-Loop Case G.6a, CS Manway, HL Dams, 360 gpm HL Injection

Figure 3.9.4-10 Two-Loop Case G.6a, Temperature Comparison

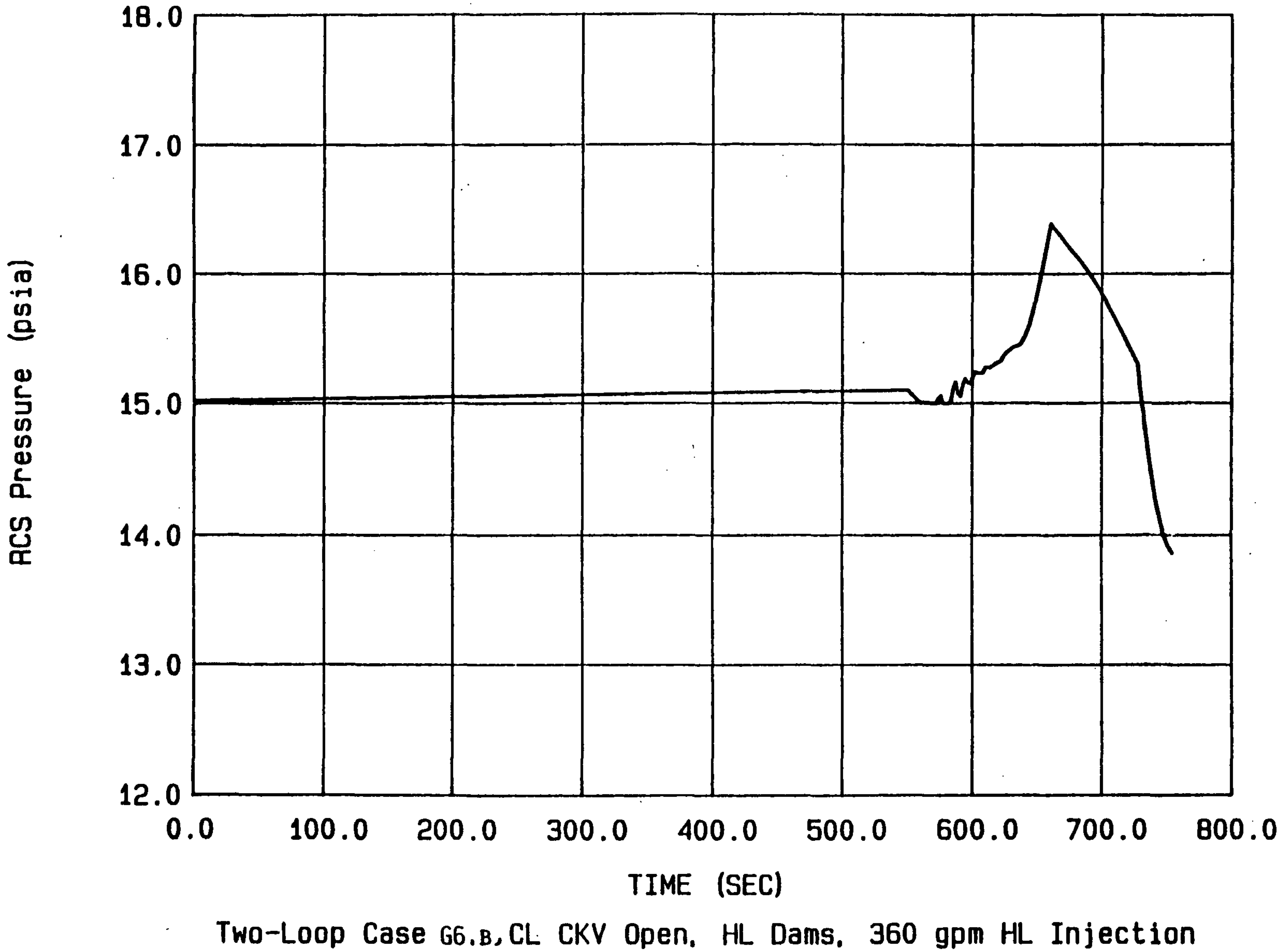


Figure 3.9.4-11 Two-Loop Case G.6b, RCS Pressure

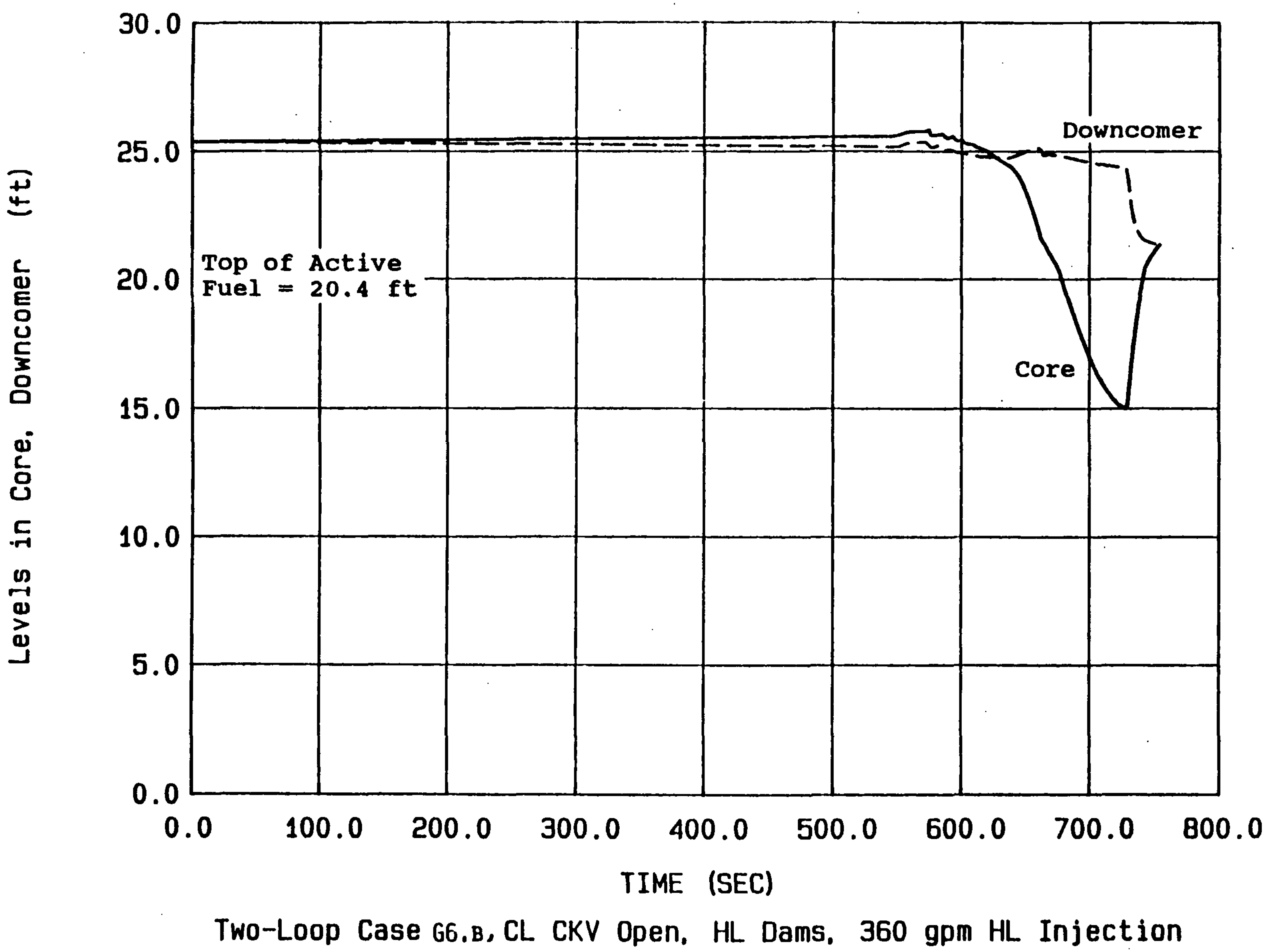
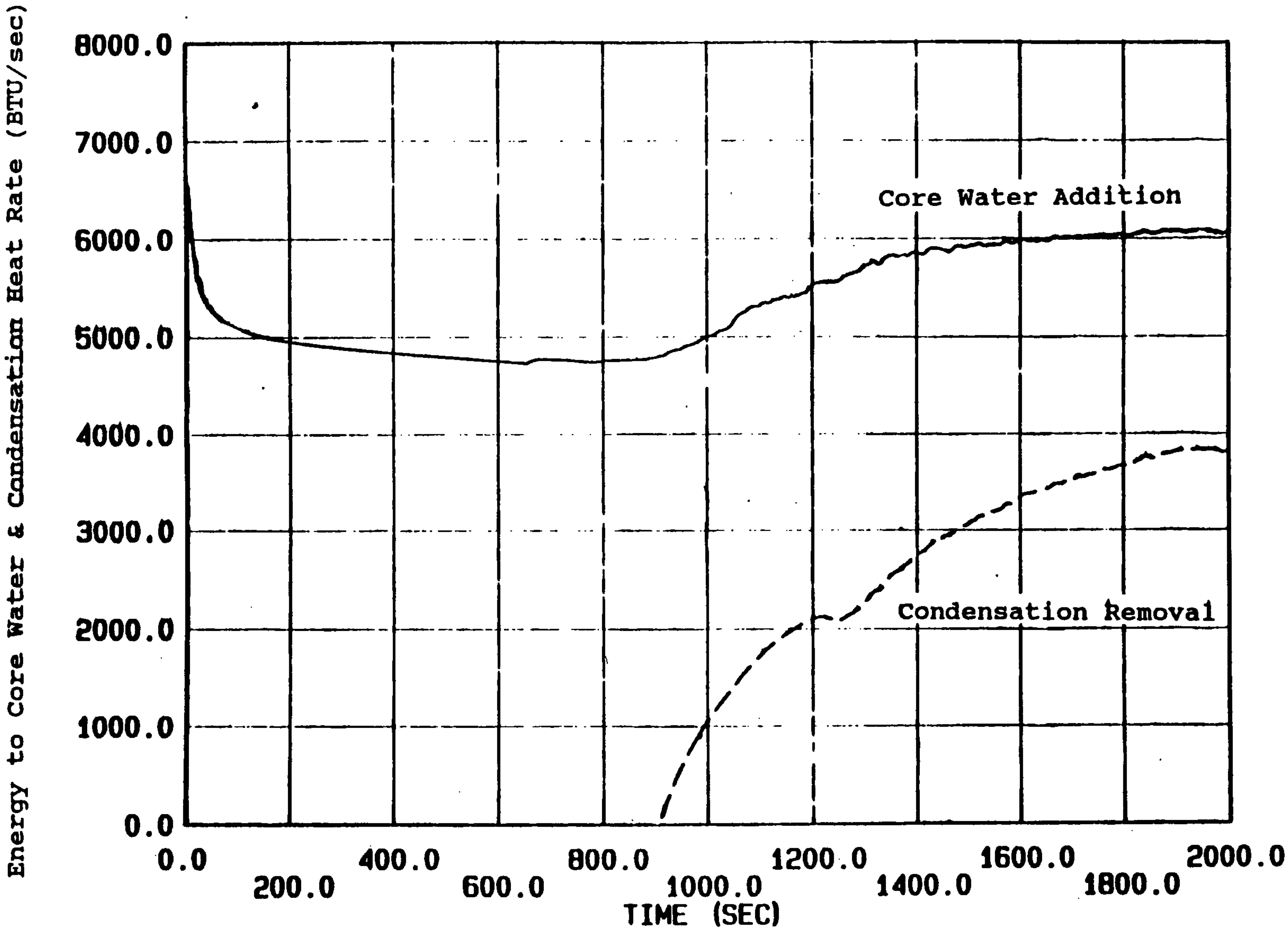


Figure 3.9.4-12 Two-Loop Case G.6b, Core and Downcomer Mixture Level



Two-Loop Case G.7, 48 HRS, 1 of 2 SGs Available

Figure 3.9.5-1 Two-Loop Case G.7, Comparison of Energy Addition to Core Water and Removal Due to SG Condensation

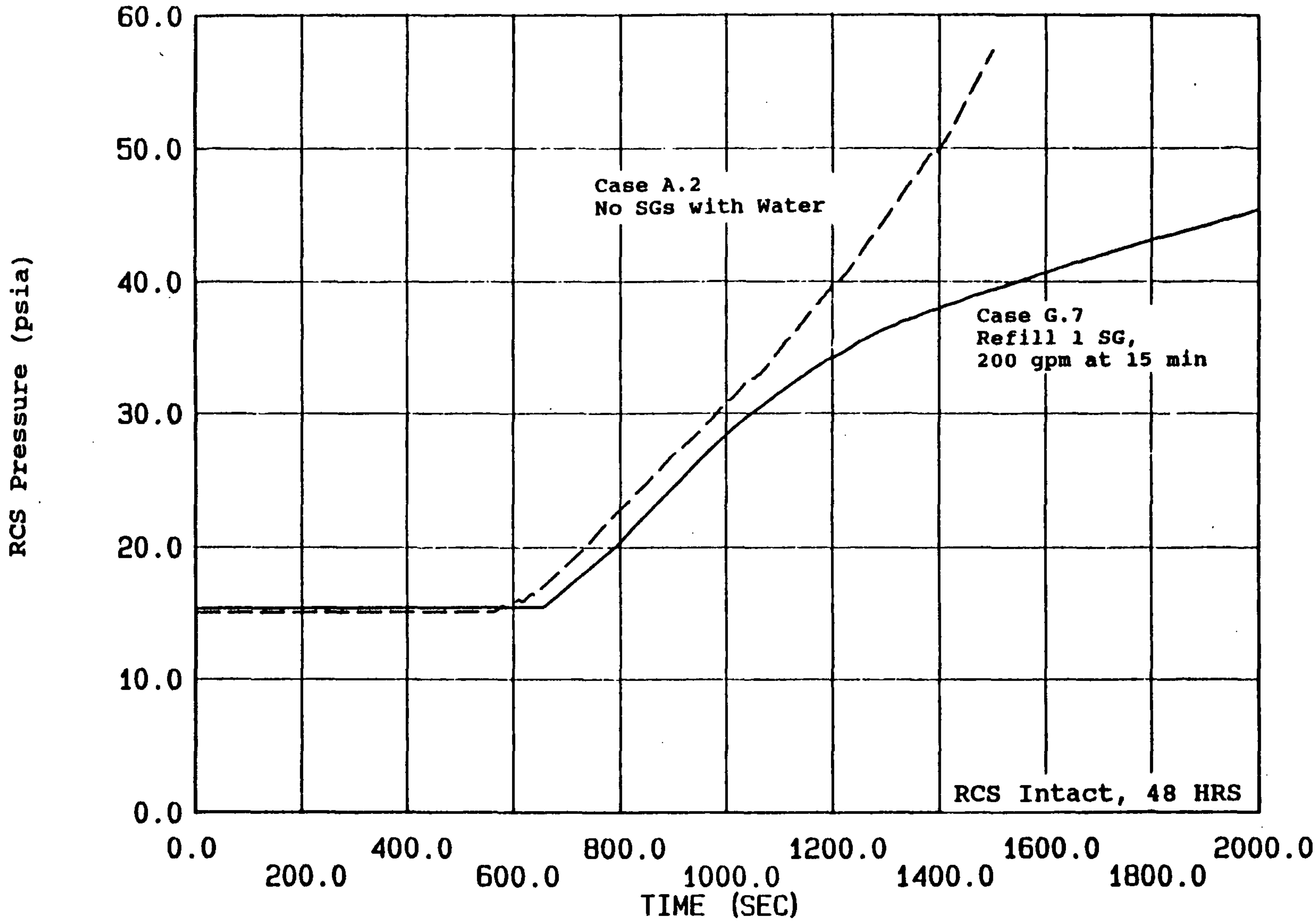


Figure 3.9.5-2 Two-Loop Cases G.7 and A.2 RCS Pressure Comparison

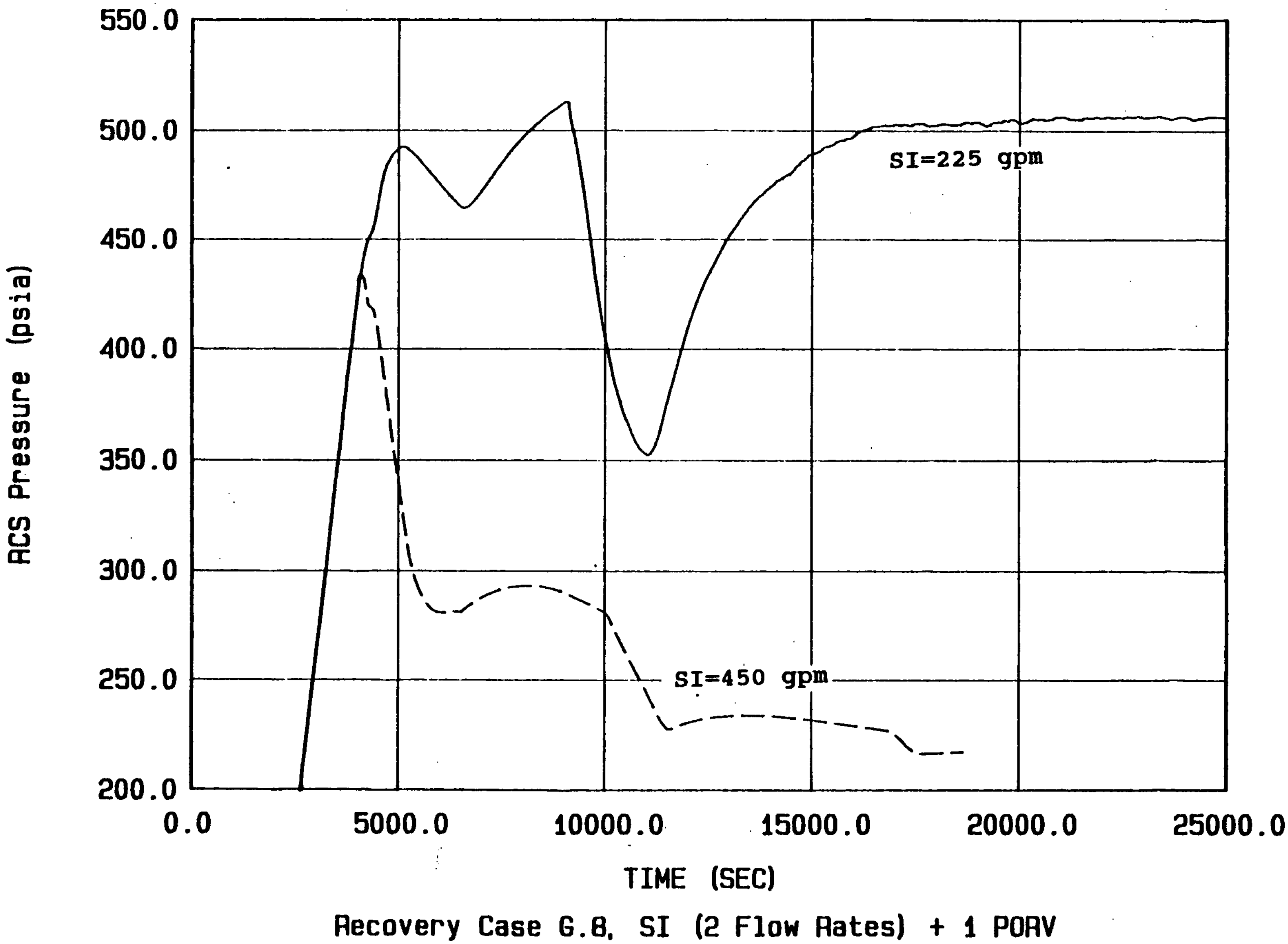


Figure 3.9.6-1 Four Loop Case G.8, Pressure Comparison for Two Flow Rates

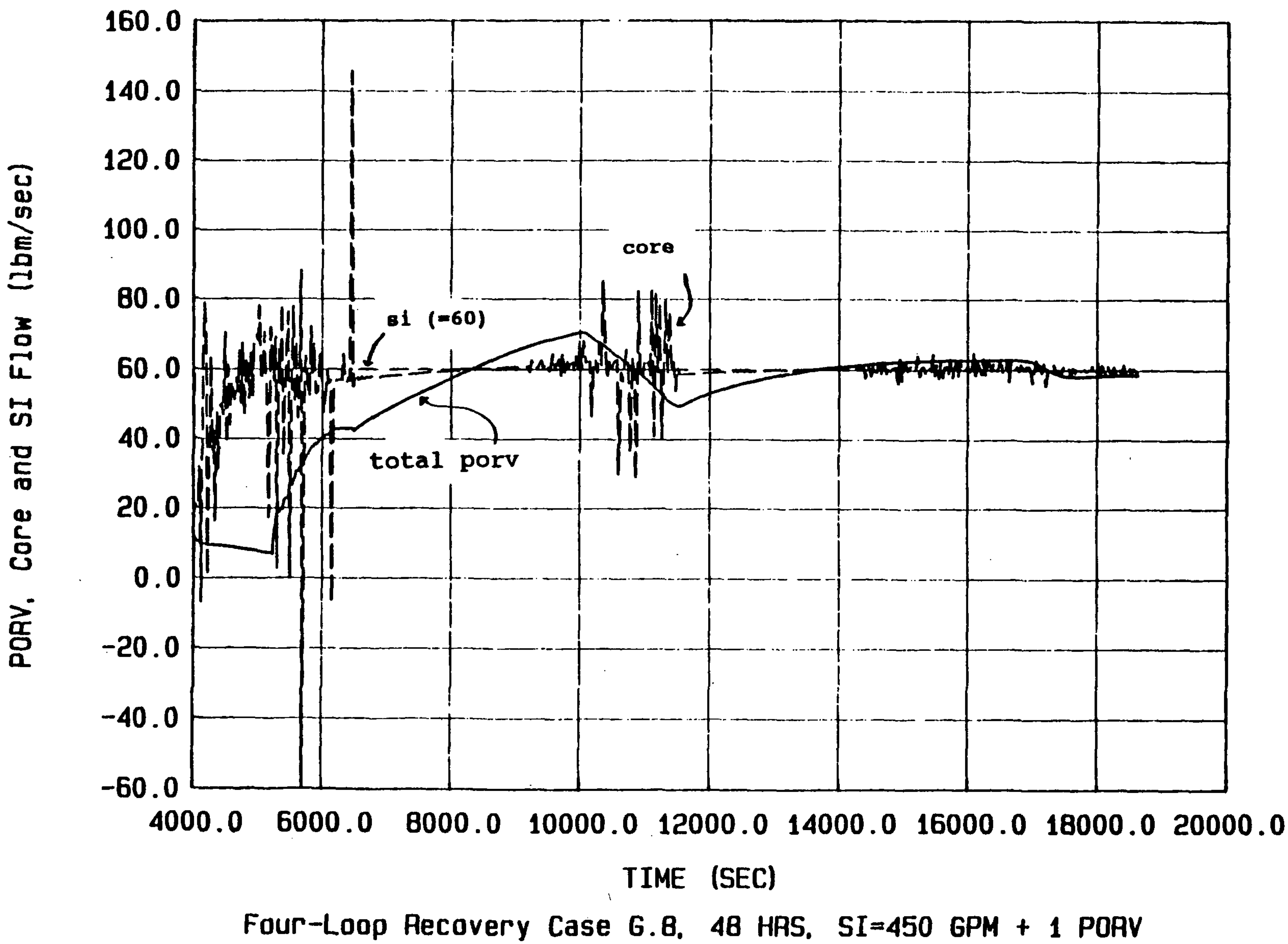


Figure 3.9.6-2 Four Loop Case G.8, PORV, Core and SI Flowrates

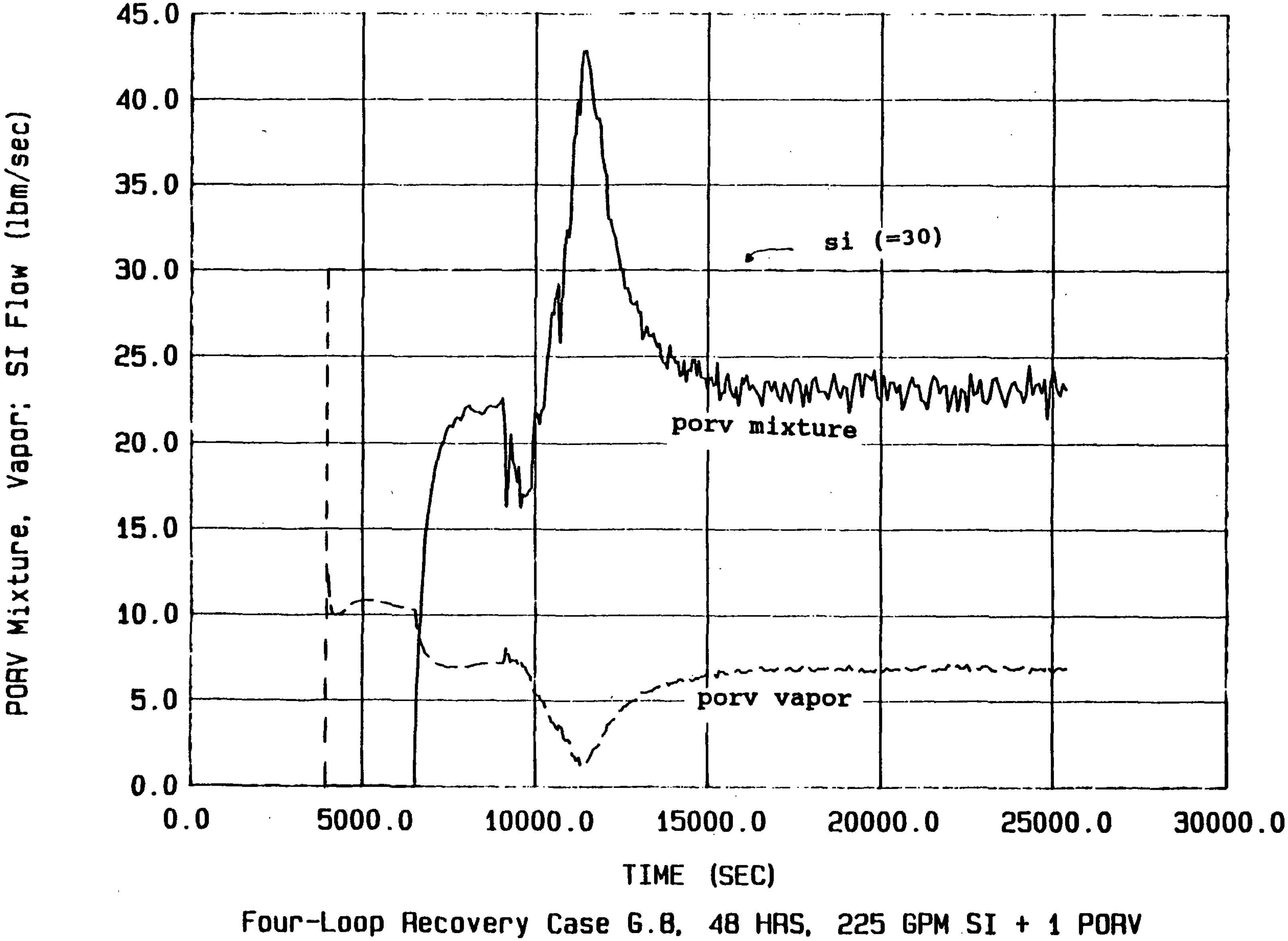


Figure 3.9.6-3 Four Loop Case G.8, PORV Mixture, Vapor and SI Flowrates

3.10 Plant Specific Application of Thermal Hydraulic Analysis Results

This sections provides guidance to utilities for using the results of the thermal hydraulic analysis. Discussed are methodologies for calculating initial heatup rate and time to saturation following loss of RHR cooling while loops are at partially filled conditions. Methodologies are also suggested for determination of boil-off times to core uncovery for the large vent or hot side opening scenarios. Considerations related to the various sensitivity studies are also identified. These include various modes of recovery, cold leg openings with and without SG nozzle dams, decay energy removal and pressure stabilization for various combinations of SGs with and without water, and considerations for RCS makeup with hot leg versus cold leg injection.

3.10.1 Plant Specific Determination of Heatup Rate and Time to Saturation

For plant specific applications, the utility can apply the results previously described for the initial heatup and time to boiling in several manners. Three identified options are discussed in this section.

Option 1. The easiest method to use in determining the heatup rate and time to saturation (versus time after reactor shutdown) would be to determine the initial power to heatup-volume ratio (P/V) that best applies to the plant and then simply use the curves from Section 3.3.6 that corresponds to, or bounds the plant. A tabulation of the P/V ratios for all the WOG plants is provided in Section 3.2.2. Some heatup-volume adjustments may be applied if the initial water level at the time RHR cooling is lost differs significantly from mid-loop (volume adjustments are discussed in a later paragraph). Since the initial heatup rate is almost constant, the time to saturation can be determined from the heatup rate curves or by adjustment of the time to saturation curves which were based on an initial RCS temperature of 140°F and a saturation temperature of 213°F.

Option 2. For plants with different P/V ratios but the same heatup-volumes as analyzed in the base case analysis, a second method can be used to adjust for differences in the decay heat power and shutdown times. Results from Section 3.3.6 are adjusted to reflect the power and decay heat for the given plant. Since most WOG plants fall in this category, a typical example is provided below:

Plant Type	Reference Plant Core Power	Decay Heat at 48 Hrs	Desired Plant Core Power	Equivalent Time After Shutdown
2-Loop	1520 MWt	7.30 MWt	1650 MWt	60 hrs
3-Loop	2441 MWt	11.7 MWt	2775 MWt	66 hrs
4-Loop	3700 MWt	17.8 WMt	3411 MWt	38 hrs

The equivalent times after shutdown tabulated above were determined using the decay heat curve provided in Section 3.2.4. The utility may use a less conservative decay heat curve if more appropriate.

Option 3. The initial heatup rates can be predicted by hand calculation by accounting for the thermal capacities of the water in the core, upper plenum, a portion of the hot legs (30% is suggested in NUREG-1269, Reference 9), plus the fuel. For the two-loop plant analyzed, these thermal capacities are as follows:

Initial heatup-volume water: (see Section 3.2)	(61.35)(1.0)(640)	= 39,260 BTU/deg-F
121 fuel assemblies, 14x14 std:	(0.06)(154,519)	= 9,270 BTU/deg-F
Total thermal capacity		= 48,530 BTU/deg-F

Based on the decay heat assumed at 48 hrs (7.3 MWt = 6920 BTU/sec), the initial heatup rate should be 8.56°F/min; this corresponds to a time to saturation (from 140°F) of 8.53 min = 510 seconds. The actual time to saturation was predicted to be 560 seconds, i.e., 10% longer, so there is a slight benefit from modeling the additional heat sinks that were considered in the analysis with TREAT.

Water Level Variations. Water levels for the loops-partially-filled condition are not always at mid-loop. Previous heatup calculation results can be altered to reflect changes due to variations in the RCS water level. The hot leg water contributes little to the heatup volume, so calculations can be simplified by accounting only for changes in the upper plenum water. The following data gives the upper plenum water volume changes for a 6" change in level for the three plants used in the analyses:

2-Loop	30 cu-ft
3-Loop	45 cu-ft
4-Loop	60 cu-ft

Based on this data, a 6" increase (decrease) in water level would cause a 5% decrease (increase) in the initial heatup rate and a corresponding increase (decrease) in the time to saturation. Thus, small variations in the water level do not have a major impact on the initial heatup calculations.

3.10.2 Limiting Time to Core Uncovery for Large Vent Cases

Analogous to the previous section on initial heatup rate, three options can be considered for determination of the time to core uncovery for the large vent cases. It should be emphasized here that this section applies only to large hot leg side or upper plenum openings (about 0.5 sq. ft. or larger) that provide an unobstructed vent path for the air and steam. It also applies to an open SG manway on the hot or cold leg side, provided hot side SG nozzle dams are not in place or hot leg loop isolation valves are not closed.

Option 1. For a quick estimate, the P/V curves provided in Section 3.4.2 can be used to estimate the time to core uncovery. These curves will also provide a conservative estimate for the time to core uncovery since they include the 25-35% "spill penalty" discussed in Section 3.4.1. This approach will be valid for standard plant sizes primarily because the the heatup-volumes previously described in Section 3.2.2 are almost in direct proportion to the boil-off volume of water initially above the top of the active fuel. The boil-off water above the top of the active fuel refers to the following:

1. hot leg water
2. upper plenum water above the top of the active fuel
3. downcomer water above the elevation corresponding to the top of the active fuel
4. cold leg and pump suction water above the bottom of the cold legs

Note that by the time this volume of water is boiled off (or spilled), the core collapsed level will be near the top of the active fuel. The actual core mixture level will typically be one to three feet higher (refer to Section 3.4.1). The core void fraction at the low RCS pressures and decay heat powers of interest here is typically around 20% to 30%; this swell effect provides additional margin to core uncovery ranging from 500 to 1500 seconds.

For the three plants analyzed, the initial heatup volumes (water in the core, upper plenum, and portion of the hot legs) and boil-off volumes described above compare as follows:

Plant	Heatup Volume	Boil-off Volume	Boil-off Mass
2-Loop	640 cu-ft	655 cu-ft	40,000 lbm
3-Loop	945 cu-ft	980 cu-ft	60,000 lbm
4-Loop	1260 cu-ft	1290 cu-ft	79,000 lbm

About half the boil-off water noted above is from the upper plenum contribution. Thus, it is expected that the simplified P/V approach will also provide a reasonable estimate for time to core uncovery for some of the non-standard plant sizes noted in Section 3.2.2.

Option 2. As in the previous Option 2 described in Section 3.10.1, a reasonably accurate time to core uncovery can be obtained for the standard plant sizes by using the data of Section 3.4.2 and adjusting the results to reflect the correct decay heat. The example previously provided in Section 3.10.1 for Option 2 also applies here. Note that the TREAT calculations were performed based on an initial RCS temperature of 140°F, so results can be adjusted (using the previously determined heatup rate) to adjust for this potential difference.

Option 3. Again, the approach outlined here would be useful for the non-standard sized plants. It involves determination of the boil-off volume described in Option 1. When this volume of water is boiled-off, its enthalpy will have changed (approximately) by the following amount, assuming 140°F initial temperature:

$$\begin{aligned} h_g(15\ \text{psia}) &= 1151\ \text{BTU/lbm} \\ \underline{h_f(140\ \text{F})} &= \underline{108\ \text{BTU/lbm}} \\ \text{delta-h} &= 1043\ \text{BTU/lbm} \end{aligned}$$

For the 3-loop plant, 48 hrs after shutdown, the decay heat is 11,100 BTU/sec. The boil-off volume (60,000 lbm) will be depleted in an estimated time of 5600 seconds. The time actually taken to boil off this amount of water was about 6000 seconds (Case B.5, without spill, Section 3.4.1). The difference (7%) is attributable to changes in the sensible heat of the core water and energy absorbed by various heat sinks modeled in the TREAT analysis.

The above approach is valid only for the "non-spill" cases where the bottom of the opening or vent path is located at an elevation several feet (or higher) above mid-loop. If the bottom of the opening coincides with the top of the hot leg (e.g., an open SG manway or loop isolation valve on the hot side), a "spill penalty" in the range of 25-35% of the boil-off mass would apply, based on analysis for the 2, 3, and 4-loop reference plants. Similar spill penalties can be expected for non-standard plant sizes if certain geometrical proportions in the core and upper plenum regions can be demonstrated. In particular, if the distance from the top of the active fuel to mid-loop is half the height of the active fuel (or less) and if the flow area in the upper plenum region is twice the core flow area (or more), a "spill penalty" of 40% of the boil-off mass is judged to be conservative.

Level variations. For cases without spill, level variations have a significant impact on the time to core uncovery since the hot and cold leg piping volumes become important. For a 6" level variation about mid-loop, the boil-off volume for the 2-loop plant analyzed changes approximately 155 cu-ft, i.e., 24% of the boil-off volume. Similar percentage changes would be expected for the 3-loop and 4-loop plants.

The "spill penalty" previously noted, however, effectively negates any increase in time to core uncovery for cases with RCS level initially above mid-loop. This is because most of the additional water above mid-loop in the hot legs and upper plenum (plus some water in the cold legs and downcomer) would spill out the opening after the RCS reaches saturation.

If the initial water level is below mid-loop, it is recommended that the net boil-off (i.e., boil-off without spill - spill penalty) be adjusted based on the reduction noted above. This will be conservative since spill becomes less of a concern as the level is decreased. As an example, the boil-off mass without spill at mid-loop is 40,000 lbm for the 2-loop plant (see Option 1). The maximum spill penalty (for P/V=2.38, 20 hours after shutdown) is 27% of this value. If the level in the RCS is initially 6" below mid-loop, the effective boil-off mass would be as follows:

$$(40{,}000\ \text{lbm}) \times \underbrace{(1 - .27)}_{\text{spill correction}} \times \underbrace{(1 - .24)}_{\text{level correction}} = 22{,}200\ \text{lbm}$$

At a boil-off rate of 9.5 lbm/sec (decay heat = 9.73 MWt in Table 3.4.2-1), this mass would be depleted (spilled plus boiled-off) in 2300 seconds. As noted in Section 3.10.1, the time to boiling would be reduced 5% due to the the level adjustment. Using results from Table 3.4.2-1, boiling would occur at 415 x 0.95 = 394 seconds. Thus, the total time to core uncovery would be about 2700 seconds. This is 25% less than the time given in Table 3.4.2-1. As expected, this reduction is nearly the same as the level correction used in estimating the boil-off mass.

In applying these corrections to the 3-loop (P/V = 2.58) and 4-loop (P/V = 2.94) plants, the maximum spill penalties (at 20 hours after shutdown) are 29% and 37%, respectively. At 48 hours after shutdown (or longer), the spill penalties for the 2, 3, and 4-loop plants are 26, 27, and 35% of the boil-off masses at mid-loop, respectively.

3.10.3 Plant Specific Pressurization Rate

The pressurization rate following a loss of RHR cooling during mid-loop operation is dependent on: the decay heat rate, the initial RCS vapor volume, the size and location of any open vent paths and the number of SGs available for condensation. The number of variables involved makes it difficult to estimate a plant specific pressurization rate, so only qualitative results will be presented here.

Pressurization Rate w/o SGs

Results for the heatup rates for typical 2, 3 and 4 loop plants at various decay heat levels were presented in Section 3.3 as a function of the power-to-heatup volume ratio. The pressurization rate for this case can be qualitatively described by a different ratio, the power-to-vapor volume ratio. This ratio is the full thermal reactor power divided by the initial vapor volume at mid-loop conditions. The power-to-vapor volume ratios for the 2, 3 and 4 loop plants used in this study are presented below.

2-Loop - P/V_g = 0.40 MWt/ft^3

3-Loop - P/V_g = 0.37 MWt/ft^3

4-Loop - P/V_g = 0.44 MWt/ft^3

Plants with a higher power-to-vapor volume ratio will pressurize faster than plants with lower ratios. This can be seen by comparing the times to reach 200 and 400 psia presented in Section 3.3. The 3 loop plant, which has the smallest power-to-vapor volume ratio, takes the longest time to reach 200 and 400 psia. Note, the comparison breaks down at lower pressures since some of the core decay energy goes into heating up metal in the core and upper plenum.

The utility can calculate the power-to-vapor volume ratio for their plant and compare it with the values above to determine which of the 3 pressurization transients is more applicable to their plant.

Pressurization Rate with Condensing Steam Generators

As shown in Section 3.8, condensation is an effective method of removing core decay heat and reducing the RCS pressurization rate following the loss of RHR cooling during mid-loop operation. Increasing the number of condensing steam generators reduces the RCS pressurization rate and allows the operator more time to attempt to restore RCS inventory and RHR cooling capability.

Figure 3.8.2-1 can be used to determine the reduced pressurization rate when one or more SGs is filled with water (to at least 5% narrow range level) during mid-loop operation. Ideally, the plant should consider maintaining 50% or more of the steam generators available for condensation to increase the allowable operator recovery action time. This would be 1 SG on a 2 loop plant, 2 SGs on a 3 loop plant and 2 SGs on a 4 loop plant.

3.10.4 Considerations for Cold Leg Openings and SG Nozzle Dams

Previous sections considered loss of RHR cooling at mid-loop conditions for various cases of cold leg openings, other vent paths, and SG nozzle dam configurations. If variations in plant type, time after shutdown, and number of SGs with secondary water are taken into account, a complete description of the RCS response following loss of RHR cooling for these cases would become an exhaustive study. Despite the complexity added by these other parameters, it is possible to simplify the results and recommend certain types of recovery actions for a number of general cases of interest. This section describes a number of these recommendations and considerations.

If there is a large cold leg opening and SG nozzle dams are installed in all the SGs (or in the SG in the loop with the opening), a slight increase in RCS pressure following the onset of boiling will result in a rapid RCS inventory loss. A prolonged core uncovery will start within minutes after boiling starts if operator action is not taken to increase inventory. For these scenarios, the only recovery method that was found to be acceptable was hot leg injection. For this to be successful, the energy removal capability of the makeup flow, when heated to saturation, should roughly match or exceed the decay heat generated in the core. For example, in Case G.6a of Section 3.9.4, heatup of 360 gpm (50 lbm/sec) water from 100°F to 220°F (refer to Figure 3.9.4-10) requires 6000 BTU/sec heat addition, just slightly less than the core decay heat used in the analysis (7.3 MWt = 6915 BTU/sec). The core level successfully recovered but the core water continued to gradually boil since the decay heat exceeded the sensible heat addition to the cold SI water. For utility application, a simple energy balance calculation can be performed to determine if the hot leg injection flow will be adequate. Typically, one high-pressure SI pump aligned to the RWST will be adequate for restoring RCS inventory. Again it should be emphasized that for the SG nozzle dam configurations discussed, it will be necessary to initiate hot leg injection early (prior to or within minutes after boiling starts) to avoid significant core uncovery. If the reactor has only been shutdown for two or three days, the operator would need to take action in about 10 minutes following loss of RHR cooling at mid-loop conditions.

If SG nozzle dams are not installed in the loop with the cold leg opening, the RCS response immediately after boiling occurs will only be slightly different. Later in time, however, the two cases become fundamentally different. If the opening is large (6-12" check valve opening or open loop isolation valve), the mixture level in the core and SG outlet of the loop with the opening will decrease until the loop seal (pump suction) piping in the loop with the opening clears and provides a vent path for the air and steam to escape. The core briefly uncovers during this period but does not heatup significantly since the core decay heat is comparatively small. The core level will then recover and stabilize typically about two feet above the top of the active fuel. The level will then slowly decrease based on the boil-off at a rate typical of that for the large RCS vent cases (Sections 3.4 and 3.10.2). Because of the initial RCS depletion, however, it will be necessary to provide makeup at a time earlier than that prescribed for the large RCS vent. Case G.5 of Section 3.9.4, a recovery scenario designed to be just marginally acceptable for the two-loop plant at a time 48 hours after shutdown, assumed operator action at 30 minutes to provide normal charging makeup to the intact loop cold leg at a rate of 55 gpm. This rate was only a few percent higher than the core boil-off rate q/h_{fg}, where q is the core decay heat. In this scenario, the very top of the core did uncover, primarily because half the makeup injected was used to refill the partially depleted pump suction piping of the intact loop. After this volume filled to the bottom of the cold leg, almost all of the makeup went into the vessel and level in the core subsequently increased. Based on this description, it is recommended that makeup be established to an intact loop cold leg charging (or alternate charging) path at a rate at least two to three times the core boil-off rate. Note that this makeup requirement is less than the previous requirement for hot leg injection since for the later case, the injection flow had to be high enough to match decay heat without boiling. For the cold side opening cases without dams, the makeup flow must exceed boil-off but not necessarily suppress boiling. This will ensure core level turns around as soon as injection starts. For most 3-loop and 4-loop plants, this makeup rate would be within the capacity of one centrifugal charging/SI pump. However, for 2-loop and other low-pressure plants, this would require two or possibly all three PD charging pumps to be in service. If this proves to be too restrictive, the utility may elect to use one high-pressure SI pump to supply the required makeup. Hot leg injection may be preferred over cold leg injection, particularly if the cold leg opening is a result of check valve removal in one of the cold leg SI lines.

For smaller cold leg opening cases, the RCS will deplete at a slower rate making it possible to prevent core uncovery altogether if sufficient makeup is provided early enough in the transient. In the case of a 3" check valve opening for the 4-loop plant described in Section 3.7.2, the RCS inventory loss at 30 minutes was about 230 gpm and the core level was 1.5 feet above the top of the fuel. In keeping with the previous guidance, makeup flow in the intact loop cold leg at double this rate will again allow refill of the intact loop cold leg. The excess would be sufficient to provide enough positive core flow to stabilize core level. The resulting makeup flow (460 gpm) is comparable to the charging flow from one centrifugal charging/SI pump in many 3-loop and 4-loop plants. Thus, it should be possible to recover from this loss of RHR cooling scenario without core uncovery with normal charging flow alone. Longer times after shutdown, one or more SGs with water in the secondary side, and increased hot to cold side communication (e.g., through open pressurizer spray lines) may all have a positive impact on preventing core uncovery and reducing the makeup flow requirement. These things should be considered in defining the appropriate operator recovery guidance.

In addition to the makeup requirements described above, some recommendations can be made related to SG manway removal and SG nozzle dam installation. The cold side SG manway opening with hot leg nozzle dams in place is one of the more limiting core uncovery scenarios because the hot side is bottled up and not capable of venting the core boil-off. Although not explicitly analyzed, removal of a hot side manway would also prove to be limiting if the hot side dam is in place since RCS inventory could still be lost at a rapid rate by reverse flow through the SG tubes. If the cold side nozzle dams are installed first (for either manway opening case), however, the vent will effectively shift to the hot side and core uncovery would not be expected for at least one hour (refer to Section 3.4 or 3.10.2). In other words, at two days shutdown time, this simple change to the order in which the nozzle dams are installed changes the potential core uncovery time from about 10 minutes to more than one hour. Once the hot side nozzle dams are in place, however, a rapid core uncovery could result if the RCS pressurizes and one of the cold side SG nozzle dams fails while the hot side remains isolated. Since dams are typically tested to only 40 psia, this failure could occur early in the transient after boiling occurs. Therefore, <u>if RHR is lost when nozzle dams are installed, hot leg injection should be initiated prior to or within minutes after boiling starts.</u>

For other cold leg openings, the core uncovery time would be delayed if outage planning could allow for check valve removal at the same time when SG nozzle dams are not in place. If a SG manway or the upper head is removed, the RCS inventory loss would be limited to simple boil-off through the hot side vent path.

3.11 Summary and Conclusions

The thermal hydraulic analysis for loss of RHR cooling at mid-loop conditions was performed with several objectives in mind.

- o Provide generic loss of RHR cooling analysis for a wide range of plant parameters and configurations.

- o Calculate the thermal hydraulic analysis requirements of Generic Letter 87-12:

    1. Calculation of the time to saturation,
    2. Calculation of the time to core uncovery, prior to core damage,
    3. Calculation of the pressurization transients, including the effect of non-condensibles.

- o Define minimum constraints, equipment availability, and other operational considerations to ensure coolable core geometry.

- o Evaluate various recovery strategies for loss of RHR cooling.

Sections 3.3 through 3.9 described the analyses in greater detail. Section 3.10 describes how the generic results can then be applied on a plant specific basis. The following information summarizes some overall conclusions related to the thermal hydraulic analysis.

For mid-loop operation prior to a typical refueling (5 days after reactor shutdown, RCS initial temperature of 100°F), the RCS would be expected to reach saturation in about 20 to 30 minutes after the loss of RHR cooling. However, at more limiting conditions for mid-loop operation (e.g., 48 hours after reactor shutdown, 140°F initial RCS temperature), the RCS could start to boil in less than 10 minutes. After the RCS reaches saturation, the response will depend on a number of parameters. In addition to decay heat or time after shutdown, the RCS configuration is important. The typical response of the RCS can be described by denoting the RCS configuration in one of five categories:

1. RCS intact, no water in the SGs. It is also assumed that there are no obstructions to the flow of vapor such as SG nozzle dams or closed loop isolation valves (LIVs) on the hot leg side. This category also applies for a typical vented configuration that can be considered nearly intact, i.e., one or two small vent lines less than 3/4" diameter open to containment, two pressurizer PORVs open to the PRT or containment, up to a limiting vent size of approximately 0.05 sq-ft.

2. RCS intact, water in the secondary side of half or more of the SGs. The water level in the SGs is assumed to be above the bottom of the narrow range and there are no obstructions to the flow of vapor and condensate for these SGs on the primary side.

3. Large hot side opening or vapor vent (about 0.5 sq-ft or greater), also with unobstructed flow path to the opening.

4. Cold side opening (greater than 0.05 sq-ft), again without loop obstructions (SG nozzle dams or closed LIVs).

5. Large cold side opening and the loop with the opening isolated. The loop would be considered isolated due to installation of SG nozzle dams or closure of the LIVs.

For the first configuration, the RCS will pressurize to 400 psia in one or more hours following loss of RHR cooling. The exact time to 400 psia depends on the decay heat and vent size (if applicable). If the pressure is maintained below this typical RHR cut-in pressure, inventory loss through RHR relief valves or via the cold over-pressure system will be avoided. To increase inventory and allow eventual recovery of RHR cooling, RWST gravity feed may be successful if initiated by 15-20 minutes, i.e., before the RCS pressure reaches a typical gravity feed limit of 30-40 psia. Otherwise, the RCS inventory can be increased with charging flow or other means or forced makeup. If RHR cooling can not be reestablished easily but feedwater can be added to half or more of the SGs, decay heat removal using the secondary heat sink will provide interim cooling for an extended period of time (hours). This alternate mode of decay heat removal is discussed in the next paragraph. As a last resort, interim cooling for this intact RCS configuration can also be provided after the RCS pressure reaches 400 psia by bleed and feed using one pressurizer PORV and one high-pressure SI pump.

If half or more of the SGs have water (Configuration 2), the RCS pressure will be significantly reduced due to SG condensation of boil-off steam. Thus, it may be possible to increase RCS inventory by RWST gravity feed at a later time (e.g., 30 minutes). If RHR cooling can not be reestablished, water in the SGs will provide a secondary heat sink for an interim period of time. This mode of cooling can be used for several hours or longer, i.e., until most of the secondary water is boiled away. An even longer period of time is possible if feedwater can be added to the SGs to make up for boil-off.

For the third configuration (large hot side opening with unobstructed flow path), the RCS inventory will be depleted at the boil-off rate (typically 100 gpm for a 4-loop plant) at some point in time after the RCS reaches saturation. If the bottom of the opening coincides with the top of the hot leg (e.g., hot side SG manway or LIV open for repair or inspection), some two-phase mixture will spill out the opening due to fluid swelling before a stable boil-off condition is achieved. The resulting time to core uncovery, including this "spill penalty", typically exceeds one hour if the reactor has been shutdown for more than 48 hours. To restore RCS inventory, it is recommended that makeup be added to one of the cold legs at a rate two to three times boil-off before the core uncovers. This rate is typically within the capacity of two positive-displacement charging pumps for most low-pressure plants or within the capacity of one centrifugal charging/SI pump injecting in the normal charging mode for most high-pressure plants. This mode of recovery will be sufficient to ensure adequate decay heat removal until RHR cooling can be restored.

For the fourth configuration (large cold side opening cases without loop obstructions such as SG nozzle dams or closed LIVs), the RCS response may be slightly different from that described above for the hot side opening. If the opening is due to removal of a cold side SG manway, the RCS response is similar to an opening on the hot side without mixture spilling; this situation would be bounded by the large hot side opening case described since there would be no spill penalty. If there is a large cold leg opening (e.g., 6" or 12" check valve opening), the RCS will pressurize until the water in the pump suction (loop seal) piping is expelled. The core may uncover briefly during this transient but not long enough for fuel temperatures to become excessive. After the loop seal clears, a vent path to the opening is provided and the core level will stabilize above the top of the active fuel. The RCS inventory will then be depleted at the boil-off rate. Establishing charging flow to an intact loop cold leg within 30 minutes following loss of RHR cooling at a rate exceeding the boil-off rate will typically be sufficient to prevent a subsequent core uncovery for this case. A makeup rate two to three times the boil-off rate is again recommended to allow faster recovery. If the cold leg opening is in the loop with the charging connection, alternate charging could be used for makeup. Note that the recommended recovery actions and makeup requirements for this case are similar to those described above for the hot side vent. A faster operator action time (30 versus 60 minutes), however, is required because the inventory loss through the opening prior to stable boil-off would be higher in the case of the cold leg opening.

The case of primary concern involves loss of RHR cooling when there is a large cold side opening and the loop with the opening is isolated (Configuration 5). Under this postulated condition, the RCS will pressurize faster in the upper plenum than in the cold leg, following the loss of RHR cooling. RCS inventory will then be forced out of the cold side opening at a rapid rate. Typically, the core will become uncovered within several minutes after the onset of boiling, i.e., as early as ten minutes following loss of RHR cooling. Because the SG nozzle dams (or closed loop isolation valves) do not allow a vent path to the opening, the core will remain uncovered for a prolonged period of time unless actions are taken to restore RCS inventory in a timely manner.

Therefore, it is important to avoid getting into this configuration if at all possible. To avoid prolonged core uncovery for this scenario, it was found that hot leg injection at a sufficiently high rate would be effective in suppressing boiling and refilling the RCS. The hot leg injection flowrate is considered high enough if the core residual heat is less than the sensible heat required to raise the temperature of the makeup water to saturation. This flow is typically within the capacity of one high-head SI pump for a 2-loop plant. One or possibly two high-pressure SI pumps would be required for comparable conditions in most 3-loop and 4-loop plants. Note that it was not possible to demonstrate successful recovery using cold leg injection at comparable flowrates since the amount of cold water reaching the core was not adequate to suppress boiling. Thus, only hot leg injection is recommended to increase RCS inventory.

For the case of the SG manway opening, the scenario described above would be made less severe if the cold side SG nozzle dams are installed first and removed last. Prior to installation of the hot side SG nozzle dams, the manway openings on either hot or cold sides of the SG would provide a large vent path for the air and steam. The time to core uncovery would then be greatly extended (bounded by the large hot side vent case). Once the hot side nozzle dams are in place, however, a similar rapid core uncovery scenario could develop if the RCS pressurizes and a cold side SG nozzle dam fails before a hot side dam fails. Thus, it is recommended that if RHR is lost when nozzle dams are installed, hot leg injection should be initiated prior to or within minutes after boiling starts. It is also recommend that RCS level be raised above mid-loop after nozzle dams are installed to minimize the potential for loss of RHR cooling under this configuration.

These five configurations are not mutually exclusive, so some evaluation may be required to determine which description best applies to a given situation. For each of the five RCS configurations described above, there is one or more methods identified for increasing RCS inventory. In the event RHR cooling can not be easily reestablished, at least one alternate mode of decay heat removal has also been identified.

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APPENDIX A

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LITERATURE SEARCH BIBLIOGRAPHY

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APPENDIX B

TEST FACILITY DESCRIPTION

B.0 TEST FACILITY DESCRIPTION

B.1 General Description

A flow diagram of the test model is shown on Figure B.1, and Figure B.2 is a layout drawing of the model. The model simulated the RCS hot leg/RHR suction interfaces for the various plant RHR pipe sizes and arrangements. (Section 2.3 of this report describes the method of sizing of the interfaces.) The loop contained a tank, piping, pump, valves, void fraction meter and instrumentation.

During operations the pump circulates water through the tank and loop piping. The water level is lowered for the different flowrates until the vortex is formed and air entrainment limits are established for each piping arrangement. The scale used for modeling was 0.23 times the full scale, based on factors discussed in Section 2.3.

B.2 Description of Equipment

Table B.1 contains a summary of equipment parameters.

Holdup Tank

The tank was a rectangular shape construction using polypropylene sheets welded and framed with wood. The dimensions of the tank are shown on Figure B.2.

The tank internals consisted on two baffles, suction nozzle, discharge piping and calibration connections, in addition to drain connections.

Two baffles were installed to reduce potential wave action caused by the discharge flow. This design virtually eliminated induced waves at the main loop suction piping. The suction nozzle was shaped to model, as close as practical, the Reactor Vessel hot leg nozzle configuration. The smooth nozzle shape and chamfered edges reduced entrance turbulence.

The discharge piping from the pump was piped down into and discharged at the bottom of the tank. This arrangement reduced the number of tank connections, reducing leakage problems.

Calibration connections were attached to the tank between the two baffles to calibrate the flow measurement meters. See Appendix C for an explanation of the calibration method.

RCS Loop Piping (Pipe Segments P1 through P4)

The modeled RCS loop piping transports the water from the tank to the pump suction piping (RHR piping). The piping is made from clear acrylic materials. The piping dimensions are in Table B.1. The pipe modeled a representative pipe length between the tank and the RHR suction piping and modeled the Steam Generator inlet piping.

- o Segment P1 and P2 represent the hot leg piping from the reactor vessel to the RHRS inlet. Two segments were used to facilitate construction. The length of this pipe does not explicitly model actual plant installations.

- o Segment P3 is actually three interchangeable spool pieces consisting of a section of loop piping which contains the RHR piping configuration. Three spool pieces were assembled from acrylic material to represent 14", 12" and 6" RHRS nozzle configurations. The spool pieces were rotated to 0, 45, 60 and 90 degree angles (from the horizontal axis) representing the various plant arrangements. (See Figure B.2). Table B.2 lists the various plant arrangements which were modeled.

  The spool piece dimensions are given in Table 1. The tee connection for each spool piece was approximately 2 feet long and the I.D.'s were 1.25", 2.25" and 2.75" representing the appropriate plant configurations.

RHRS Inlet Piping (Pipe Segments P5 through P8)

This piping transported fluid from the hot leg model to the recirculation pump. It is all horizontal or sloped down (i.e., no local high points exist).

- o Pipe segment P5 is integral with pipe segment P3 (spool piece). Three sizes were used (1 1/2", 2 1/2" and 2 1/2" ID), corresponding to nominal pipe sizes of 6", 12" and 14", respectively.

- o Pipe segment P6 represents three specially constructed plastic spool pieces, corresponding to the three sizes used for segment P5. Each segment contains probes which provide input into the void fraction meter (refer to Appendix D). This segment is flanged to facilitate change-out.

- o Pipe segment P7 is 2" ID plastic pipe which routs flow to the vicinity of the recirculation pump. It is flanged to facilitate layout.

- o Pipe segment P8 is 2" flexible hose, which matches inlet hard pipe to the recirculation pump inlet nozzle.

Pump Discharge Piping (Pipe Segments 9 through 14)

This piping directs fluid from the recirculation pump to the holdup tank, and contains flow control and flow measurement capability.

- o Pipe segment P9 is 2" plastic pipe which connects the recirculation pump discharge nozzle to the flow control and measurement paths. It contains valve V1 and pump discharge pressure gage PI-3.

- Pipe segment P11 is 1" plastic pipe which is used for lower flow rates (up to 20 gpm). It contains valve V3 and flow measurement gage FI-2. This segment is parallel to P10.

- Pipe segments P12 and P13 are 2" plastic pipe which returns flow to the bottom of the holdup tank. Segment P13 contains valve V4.

- Pipe segment P14 was used for flow instrument calibration. Appendix C discussed the calibration. This segment contains valve V5.

<u>Pump</u>

The pump is a Grainger-Teel self priming, 2 H.P., No. IP897 centrifugal type with a design point of 103 gpm at 30 Ft head. The pump is driven by 230 VAC single phase power supply.

The pump flow capability includes simulated actual plant flowrates up to 3000 gpm.

<u>Valves</u>

A number of valves were used for flow control, isolation and drain functions.

- Valve V1 is used to provide part of the required pressure loss to obtain a desired flow. It is used in conjunction with V2 or V3. The valve is a 2" ball valve.

- Valve V2 is used to "fine tune" flow control for higher flow rates (20 gpm to 100 gpm). It is closed when lower flows are needed. It is a 2" ball valve.

- Valve V3 is used to "fine tune" flow control for flows less than 20 gpm. It is closed when higher flows are needed. It is a 1" ball valve.

- Valves V4 and V5 are used to select the discharge flow path into the holdup tank. Valve V4 is normally open and V5 is closed. They are 2" ball valves.

- Valves V6 and V7 are holdup tank and recirculation pump drain valves. They are 3/4" globe valves.

B.3 Instrumentation

Flow

Flow during the test was monitored by 2 flow gauges in each of the parallel paths (segments P10 and P11) downstream of the pump.

The gauges were direct reading flow orifices from RCM Industries, made of plastic material. The parameters are as follows:

- FI-2. 1" - 3 to 20 gpm range, No. 9858K53
- FI-1. 2" - 15 to 100 gpm range, No. 9858K55

Pressure

Three pressure gauges were used to monitor the pump inlet and outlet conditions.

The parameters are as follows:

- PI-1 and PI-2: these suction gauges had a 0 to 30" Hg (absolute) and a 0 to 5 psig range, respectively.

- PI-3: this discharge gauge had a 0 to 60 psig range

Temperature

Two thermocouples were used to measure water temperature and were connected to direct readout digital gauges during the test.

- o T-1: tank temperature measurement and;
- o T-2: the water temperature in the pump suction downstream of the void meter.

Level Measurement

Level measurement readings were taken at the following system locations:

- o L-1: holdup tank level
- o L-2: entrance level to main loop pipe
- o L-2: upstream of the RHR Suction Nozzle
- o L-3: downstream of the RHR Suction Nozzle
- o L-5: downstream of void meter

Tygon hose of 1/2" diameter was routed from the measurement point to the readout location on the end of the main loop piping.

Void Fraction Meter

Refer to Appendix D.

TABLE B.1

EQUIPMENT PARAMETER SUMMARY

Holdup Tank			
Dimensions			
		Height	48"
		Width	24"
		Length	71.5"
Material		Polypropylene	
Other		Baffles divide into three sections	
Main Loop Piping (Segments Pipe P2)			
Dimensions			
		Inside Diameter	7"
		Outside Diameter	7.5"
		Length	76"
Spool Piece (Segment P3 and P5)			
Dimensions			
	Main Loop Piping Section (P3)		
		Inside Diameter	7"
		Outside Diameter	7.5"
		Length	6"
	RHR Suction Piping Inside Diameters (P5)		
		Arrangement 1	1.25"
		Arrangement 2	2.25"
		Arrangement 3	2.75"
Recirculation Pump			
	Type	Horizontal Centrifugal	
	Design Flow		103 gpm
	Design Head		30 feet
	Manufacturer		Grander-Teel
	Model Number		1P897
Valves (V1 through V5)			
	Type		Ball Valves
	No of Valves		5
	Sizes of Valves		
		Four Valves	2"
		One Valve	1"

TABLE B.2

RCS/RHRS INTERFACES MODELED
BY TEST FACILITY

Plant Configuration Nozzle angle/nominal size degree / inch	Model Configuration Nozzle angle/size degree / inch (ID)
45 / 14	45 / 2.75
45 / 12	45 / 2.25
45 / 6	45 / 1.25
90 / 14	90 / 2.75
90 / 12	90 / 2.25
90 / 6	90 / 1.25
0 / 12	0 / 2.25
0 / 6	0 / 1.25
60 / 14	60 / 2.75
60 / 12	60 / 2.25

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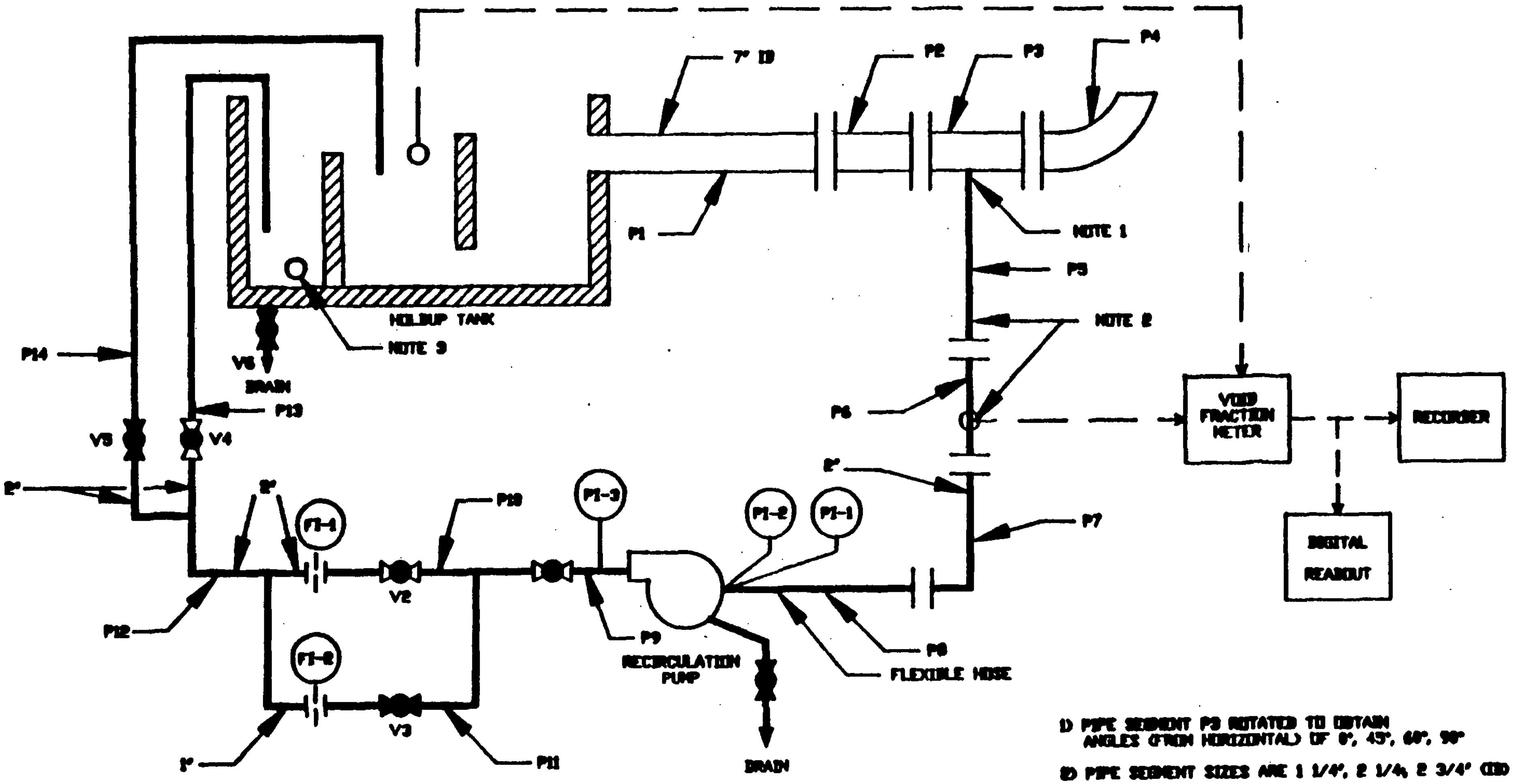

1) PIPE SEGMENT P3 ROTATED TO OBTAIN ANGLES (FROM HORIZONTAL) OF 0°, 45°, 60°, 90°
2) PIPE SEGMENT SIZES ARE 1 1/4", 2 1/4", 2 3/4" (ID)
3) SEALED DRAIN CONNECTION

FIGURE B.1

TEST SYSTEM FLOW DIAGRAM

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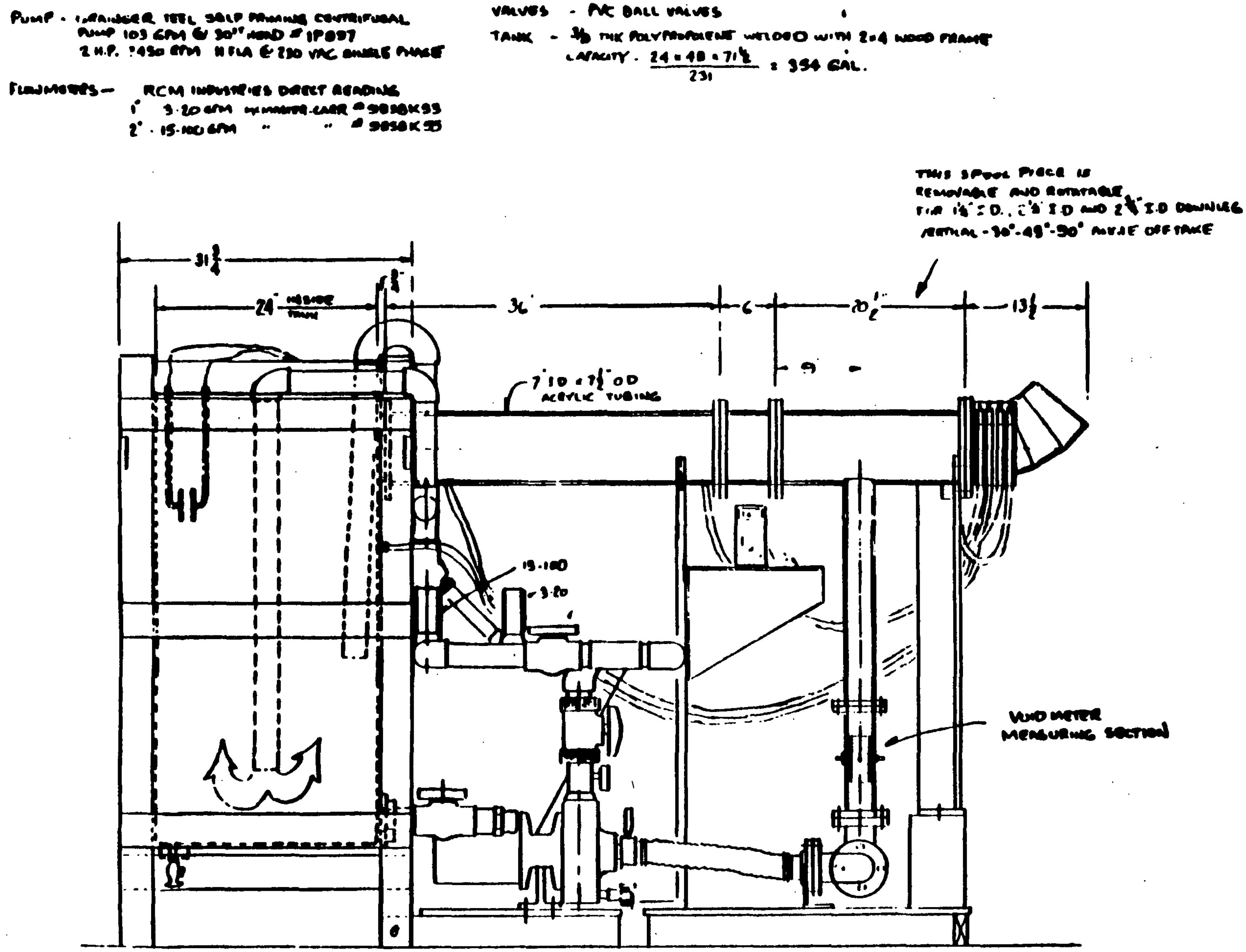

FIGURE B.2 (Sheet 1 of 3)

WESTINGHOUSE MID-LOOP TEST RIG - SIDE VIEW

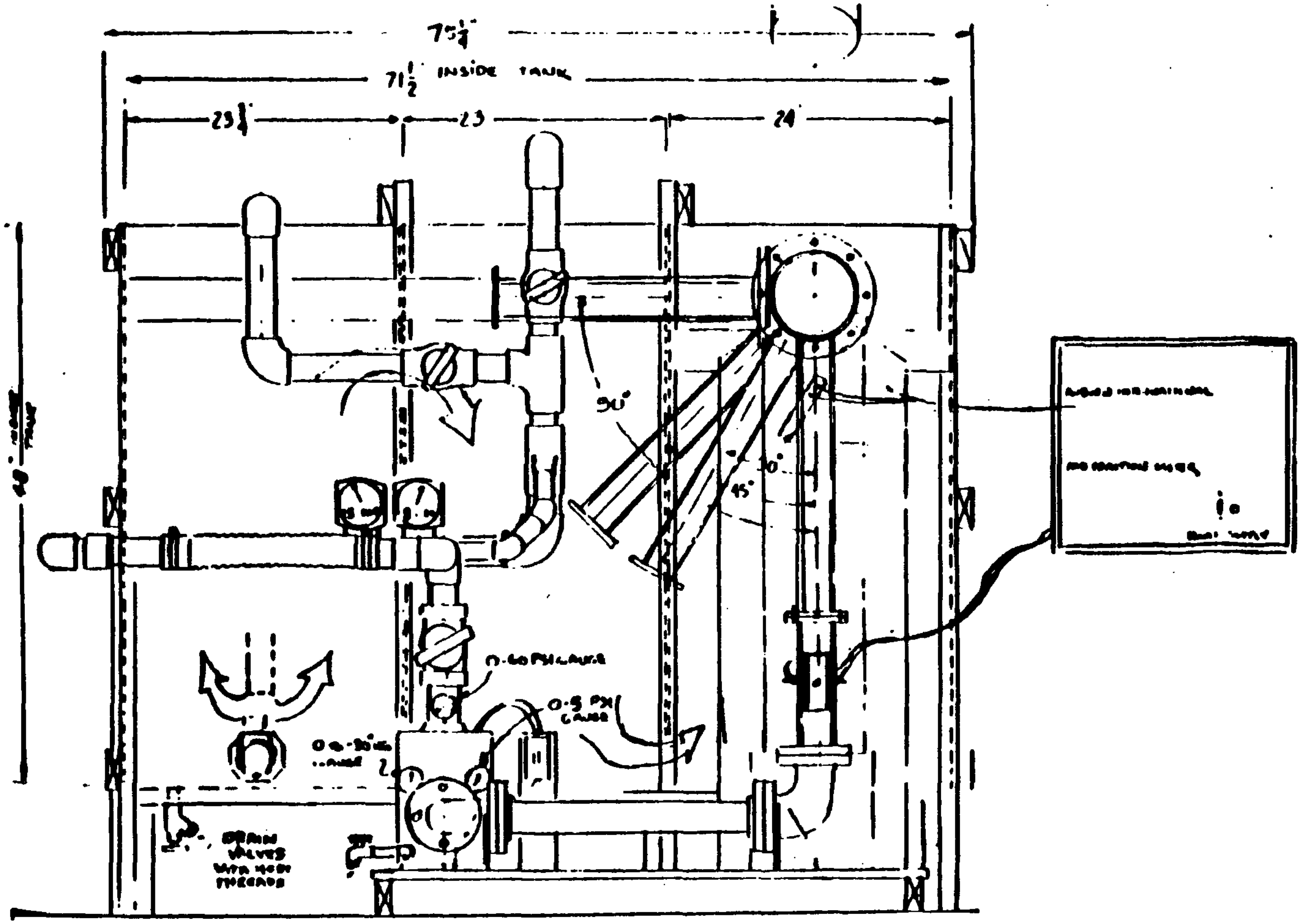

FIGURE B.2 (Sheet 2 of 3)

WESTINGHOUSE MID-LOOP TEST RIG - END VIEW

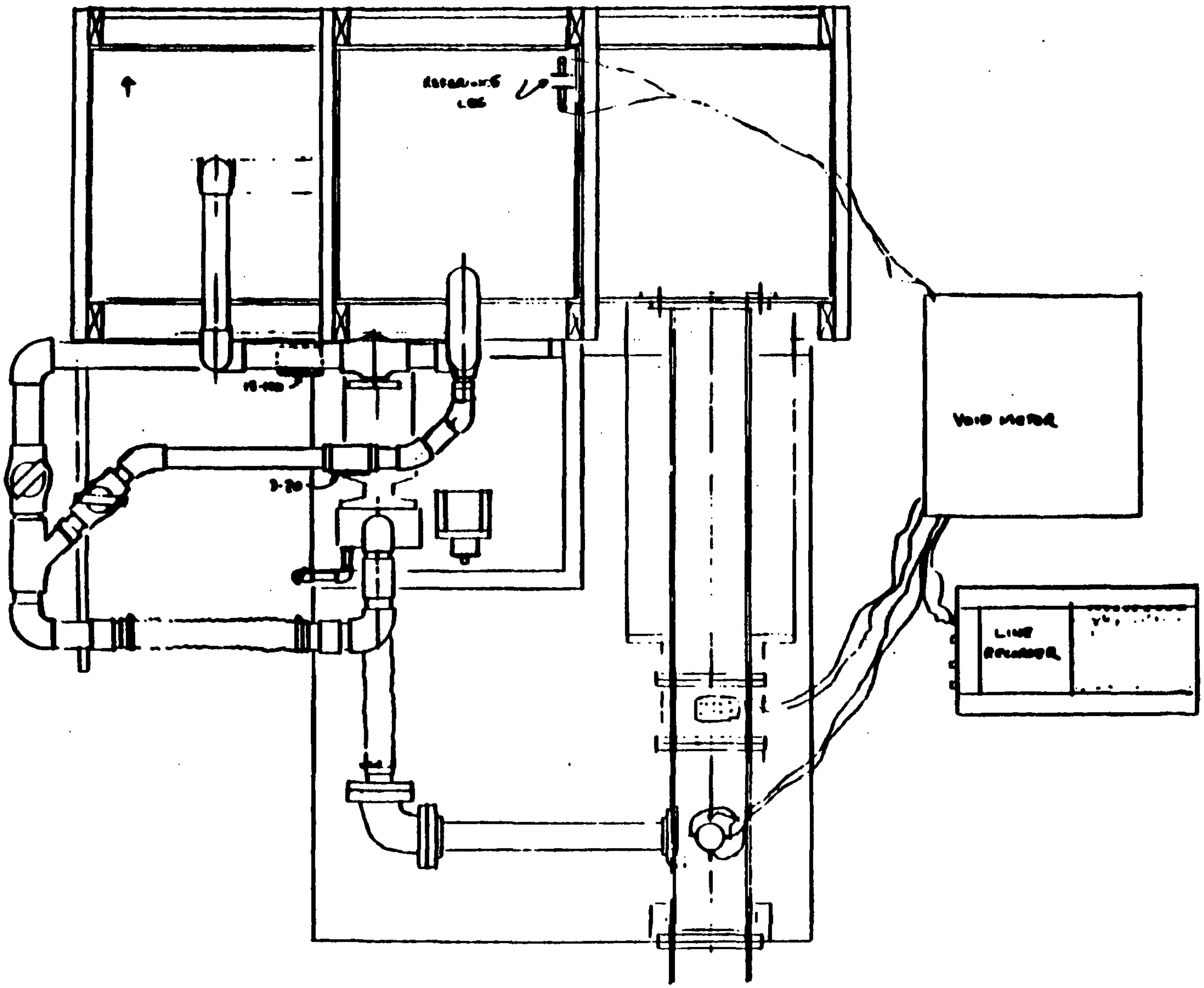

FIGURE B.2 (Sheet 3 of 3)

WESTINGHOUSE MID-LOOP TEST RIG - TOP VIEW

APPENDIX C

INSTRUMENTATION CALIBRATION

C.0 INSTRUMENTATION CALIBRATION

C.1 Introduction

This section explains the calibration methods used for the flow and temperature instrumentation. The discharge and suction pressure instrumentation was not calibrated, since they were used only for information purposes. The void fraction meter calibration is contained in Appendix D. Since level was determined using tubing as a manometer, no calibration was necessary.

C.2 Flow Measurement

One section of the holdup tank was sealed off, and the volume vs. height in this section was determined using a graduated beaker. For the actual flow instrument calibration, the following was done.

1. The two sections of the holdup tank closest to the hot leg were filled. The recirculation pump was run, directing flow into the third (initially empty) calibrated tank section. The indicated flow was recorded, and the time was measured using a stopwatch. The flow instrument total volume (flow times time) was compared to the tank calibrated volume.

2. The calibrated tank section was emptied to the other sections using a temporary connection to the pump suction (see Note 3 on Figure B.1 of Appendix B), and opening valve V5 and closing valve V4.

3. Steps 1 and 2 were repeated for other measured flows. Table C.1 contains the results of the flow calibration runs.

C.3 Temperature Measurement

The thermocouples were calibrated by inserting them into an ice bath and into boiling water. Table C.2 contains these results.

TABLE C.1

FLOW CALIBRATION

Calculated Reference Flow (gpm)	Measured Flow (gpm)	Percent Difference
10.4	10	-4.0
11.9	11	-8.2
16.7	16	-4.4
20.1	21	+4.3
20.4	19.5	-4.6
23.2	25	+7.2
29.9	30	+0.3
53.0	51	-3.9
74.0	70	-5.7
90.8	89	-2.0
98.5	98.5	0

AVE = -1.9%

TABLE C.2

THERMOCOUPLE/READOUT CALIBRATION

Reference Temperature (°F)	Thermocouple Tag No. 7A-5546	Tag No. 7A-5541
Ice Bath (32°F)	29°F	31°F
	30°F	32°F
Boiling (212°F)	211°F	213°F
	211°F	213°F
Ambient	73°F	75°F
	73°F	75°F

APPENDIX D

VOID FRACTION METER
DESCRIPTION/CALIBRATION

D.0 VOID FRACTION METER DESCRIPTION/CALIBRATION

D.1 Introduction

To obtain accurate measurement of the air entrained in the simulated RHR liquid flow, instrumentation to determine the void fraction was used. This appendix contains information on the instrumentation used for the tests.

Direct measurements of local void fraction in the scale hot leg/RHR line simulation were made using a void meter manufactured by Auburn International (Model Number 1081). The meter actually determined the liquid fraction between a set of electrodes (probes) in the RHR line simulation by measuring the conductivity of the liquid medium enclosed within the electrodes and compared that measurement to a reference conductivity. The void fraction (α) was taken as the compliment of the liquid fraction ($1-\alpha$).

The cylindrical cross-section of the RHR line simulation suggested the use of a Model 1081 void meter. This meter utilized four electrodes, connected in pairs that faced each other across a flow channel, with a rotating two-phase electrical current applied to the electrodes. A schematic planar layout of the Model 1081 void fraction probes as installed in a typical RHR line simulation used in the test program is shown in Figure D-1.

The liquid fraction at the location of the probes is determined by taking the ratio of the electrical resistance across the flow channel being monitored to the electrical resistance across a reference set of electrodes maintained in a solution with no voids. Typically, the meter is calibrated prior to testing by means of setting two points on the calibration curve. The two points used are void meter readings with the flow channel empty (totally voided or α = 1.0) and with the flow channel filled with the working fluid (no voids or α = 0.0).

The response of the meter to voids between the two limits is not linear. Thus, an in-situ calibration was performed to determine the appropriate correlation for actual void fraction versus measured void fraction between the channel empty-channel full end points. Three different sizes of RHR line simulations were used in the test program. Each RHR line simulation utilized a probe size designed to provide the optimum coverage of the flow channel. Thus, each RHR line simulation had a unique size probe. So, as to provide for the greatest possible confidence in reducing the test data, in-situ calibration tests were performed for each probe size used.

This Appendix describes and reports the in-situ calibration tests performed to support the use of the Model 1081 Auburn International void meter in the mid-loop vortex generation test program.

D.2 Calibration Test Objective

The objectives of the calibration tests performed with the prototypic RHR line simulation model hardware and the Auburn International void meter were:

- Determine the performance of the Model 1081 void meter between calibration extremes (α = 0.0 and α = 1.0) for each of the three size RHR line simulations to be tested.

- Develope the appropriate data base to develop a calibration for actual versus measured void fraction where the meter performance is not linear.

- Define the sensitivity of the void meter readings to the positioning of void simulations within the flow channel bounded by the inside diameter of the RHR line simulations; evaluate uncertainty in measured void due to position of void in flow channel, if warranted.

By accomplishing the preceding objectives, the capabilities and limitations of the Auburn International void meters and associated probes as installed and used in each of the three different size RHR line simulations were determined.

D.3 Calibration Description

As described in Appendix B, the RHR line simulations were constructed from sections of plastic pipe that were bolted together to form the desired hot leg/RHR line junction simulation. The void meter probes were always located in a vertical run of the RHR simulation line. As identified in Section D.1, a typical cross section of the void meter installation is shown in the schematic diagram of Figure D-2.

A schematic diagram of the hardware arrangement employed for the calibration tests is given in Figure D-2. The instrumented section of tubing was filled with water from the holdup tank. The holdup tank also served to provide a reference measurement of liquid conductivity. The instrument channels connected to both the reference probes and the RHR line simulation were calibrated prior to testing by setting the zero and full-scale readings with the flow channels between the probes empty and full, respectively, per manufacturer's procedure.

In general, the calibration procedure consisted of the following steps;

- o Fill the test section with water from the holdup tank to the bottom of the top flange of the RHR line simulation.

- o Insert a simulated void from the top of the model section downward to the bottom plate elevation.

- o Record void meter reading directly from the digital volt meter (DVM) display.

- o Remove the void simulation, and refill the test section with water from the holding tank, if required, such that the void meter probes are covered with water.

The preceding steps were repeated for each void simulation tested. This process was performed with each of the three different size RHR line simulations to establish an actual versus indicated void fraction calibration for each size of tubing used in the actual testing.

D.4 Calibration Data

The data collected from the calibration testing are presented in the following sections.

D.4.1 Response to Known Cylindrical Voids

Eleven void simulations of differing sizes were used to define the performance of the Model 1081 void meter and its associated electrodes as installed in the hot leg/RHR line simulations tested. The void simulations were cylindrical rods made of plexiglass, a non-conductive material. Each void simulation was inserted into the scaled RHR line such that the centers of the model cross section and the void simulation cross section coincided, resulting in a uniformly thick water-filled annular space between the RHR line and void simulations, the output of the void meter was recorded, and the void simulation was then withdrawn from the model. This process was repeated three times for each of the eleven void simulations used. The dimensions of the void simulation used, the calculated void fraction for the void simulation, and the corresponding three outputs for the Model 1081 void meter for each void simulation tested are listed in Tables D-1, D-2, and D-3 for the 1.25 inch, 2.25 inch, and 2.75 inch ID RHR simulations, respectively.

D.4.2 Regions of Sensitivity

The sensitivity of the Model 1081 void meter as utilized in the scale hot leg/RHR line model to a known void simulation was defined by positioning a cylindrical void simulation of known diameter at discrete locations within the instrumented RHR line section and recording the resulting void meter readings. Two different sizes of cylindrical void simulations were used for this series of calibration tests. As was the case with the calibration test described in Section D.4.1, the void simulations were lengths of plexiglass rods. The positioning of the void simulations is shown in Figure D-3. The sizes of the void simulations and the data from the tests are given in Tables D-4 and D-5 for RHR line simulation sizes of 2.25 inches and 2.75 inches, respectively. This calibration test was not performed for the 1.75 inch RHR line simulation due to difficulties associated with positioning the void simulations accurately within the small flow channel.

D.5 Discussion

A brief discussion of the calibration data presented in the preceding section follows.

D.5.1 Non-Linearity of Response

The data of Tables D-1, D-2, and D-3 indicate that the Model 1081 void meter as utilized in the scale model RHR line simulation does not provide a linear response to increasing void fraction over the range of void simulations tested. However, void fractions in excess of about $\alpha = 0.10$ were beyond the parameter range to be tested. Over the range of void fractions of $0.0 \leq \alpha \leq 0.10$, the calibration data could be reasonably approximated by the following linear equations.

<u>1.25 Inch RHR Simulation</u>

$$\alpha_{Act} = 1.25\ (\alpha_{Meas})$$

<u>2.25 Inch RHR Simulation</u>

$$\alpha_{Act} = 1.35\ (\alpha_{Meas})$$

<u>2.75 Inch RHR Simulation</u>

$$\alpha_{Act} = 1.56\ (\alpha_{Meas})$$

where

α_{Act} = the actual void fraction in the flow channel

α_{Meas} = the void fraction in the flow channel as measured by the Model 1081 void meter.

The preceding three equations were found to a good fit to the calibration data for the respective RHR line simulation sizes over the void fraction range of $0.0 \leq \alpha_{Meas} \leq 0.10$.

D.5.2 Regions of Sensitivity

The data of Tables D-4 and D-5 show that, for the void meter/probe design used in the test program, the indicated liquid fraction is somewhat sensitive to the static positioning of a void simulation in the field of measurement. During the actual testing, it was observed that the ingested void either tended to form a vapor core or, due to the high level of mixing induced by the flow passing through elbows upstream of the void meter probes, the voids tended to be homogeneously distributed throughout the flow. In either case, the voids ingested by the flow do not maintain a static position as they pass through the void meter probes. Therefore, it was concluded that the observed sensitivity of measured void fraction to positioning of a void simulation in the measurement field was not applicable to the dynamic flow process obtain during testing. Rather, the calibration data of Tables D-1, D-2, and D-3 were judged to be applicable for reduction of the test data.

D.6 Summary

Calibration tests were performed for the Model 1081 void meter/probe design combination using prototypic scale model hot leg/RHR line test hardware. The calibration test established the response of the void meter/probe design combination for each of the three sizes of RHR line simulations tested. The sensitivity of the void meter probe response to the static positioning of a void simulation in the flow field was also established, but was subsequently determined to be not applicable to the experimental data due to the dynamic characteristics of the vapor and liquid flow as they passed through the void meter probes.

Table D-1
Hot Leg/RHR Line Vortex Generation Test
Response of Model 1081 Void Meter
to
Cylindrical Void Simulations
RHR Line Simulation Id = 1.75 Inches

Simulated Void Diameter (Inches)	Calculated Void Fraction α_{calc}	Measured Liquid Fraction - $(1-\alpha_{Meas})$		
		Trial Number		
		1	2	3
0.193	0.024	0.982	0.984	0.974
0.252	0.041	0.966	0.967	0.962
0.376	0.090	0.927	0.922	0.925
0.440	0.124	0.915	0.896	0.901
0.506	0.164	0.880	0.883	0.875
0.565	0.204	0.858	0.851	0.840
0.754	0.364	0.730	0.738	0.733
0.875	0.490	0.650	0.649	0.651
0.995	0.634	0.470	0.503	0.502
1.125	0.810	0.260	0.283	0.283
1.135	0.824	0.240	0.257	0.244

Table D-2
Hot Leg/RHR Line Vortex Generation Test
Response of Model 1081 Void Meter
to
Cylindrical Void Simulations
RHR Line Simulation Id = 2.25 Inches

Simulated Void Diameter (Inches)	Calculated Void Fraction α_{calc}	Measured Liquid Fraction - $(1-\alpha_{Meas})$ Trial Number 1	2	3
0.194	0.007	0.995	0.994	0.996
0.251	0.012	0.992	0.991	0.991
0.375	0.028	0.975	0.979	0.982
0.433	0.037	0.971	0.972	0.970
0.502	0.050	0.964	0.961	0.965
0.562	0.062	0.957	0.951	0.954
0.755	0.112	0.914	0.912	0.915
0.868	0.149	0.888	0.876	0.886
1.050	0.218	0.824	0.824	0.828
1.120	0.248	0.799	0.795	0.800
1.503	0.446	0.638	0.638	0.643

Table D-3

Hot Leg/RHR Line Vortex Generation Test

Response of Model 1081 Void Meter

to

Cylindrical Void Simulations

RHR Line Simulation Id = 2.75 Inches

Simulated Void Diameter (Inches)	Calculated Void Fraction α_{calc}	Measured Liquid Fraction - $(1-\alpha_{Meas})$		
		Trial Number		
		1	2	3
0.194	0.005	0.998	0.998	0.998
0.258	0.009	0.993	0.994	0.995
0.380	0.019	0.986	0.988	0.987
0.568	0.043	0.972	0.970	0.972
0.880	0.102	0.933	0.931	0.931
0.990	0.130	0.905	0.907	0.905
1.138	0.171	0.890	0.887	0.887
1.508	0.301	0.806	0.808	0.806
2.010	0.534	0.622	0.618	0.624
2.275	0.684	0.480	0.475	0.475
2.520	0.840	0.307	0.302	0.301

Table D-4

Hot Leg/RHR Line Vortex Generation Test

Sensitivity of Model 1081 Void Meter/Probe Design

to

Void Location

RHR Line Simulation ID = 2.25 Inches

Simulated Void Diameter (Inches)	Calculated Void Fraction α_{calc}	Measured Liquid Fraction - $(1-\alpha_{Meas})$ Void Position Number								
		1	2	3	4	5	6	7	8	9
0.375	0.028	0.974	0.982	0.990	0.983	0.976	0.982	0.989	0.981	0.978
0.502	0.050	0.960	0.968	0.982	0.969	0.961	0.969	0.977	0.968	0.964

Table D-5

Hot Leg/RHR Line Vortex Generation Test

Sensitivity of Model 1081 Void Meter/Probe Design

to

Void Location

RHR Line Simulation ID = 2.75 Inches

Simulated Void Diameter (Inches)	Calculated Void Fraction α_{calc}	Measured Liquid Fraction - $(1-\alpha_{Meas})$ Trial Number 1	2	3	4	5	6	7	8	9
0.508	0.034	0.920	0.986	0.942	0.977	0.960	0.998	0.923	0.978	0.982
0.990	0.130	0.848	0.942	0.841	0.892	0.851	0.944	0.856	0.891	0.914

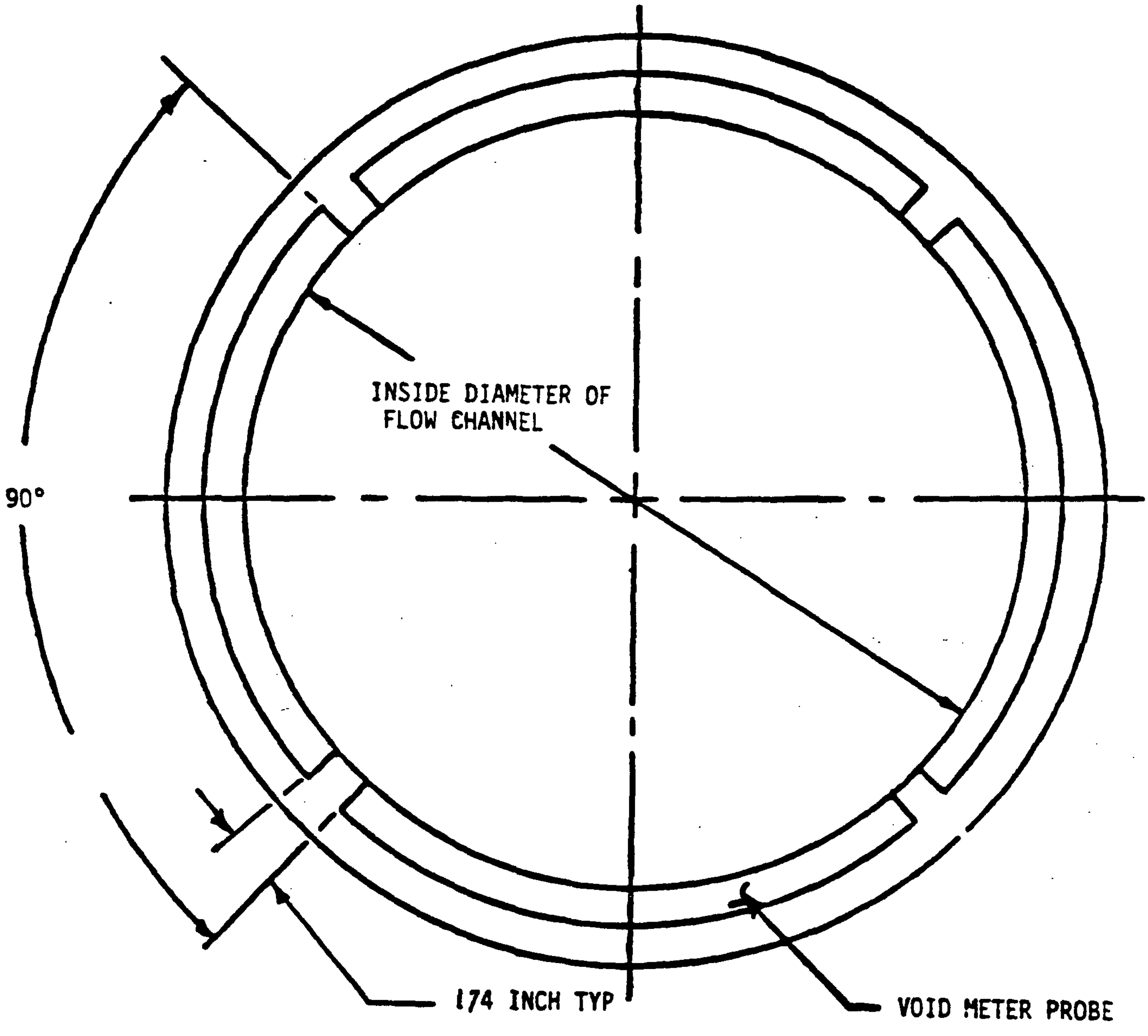

FIGURE D-1 SCHEMATIC OF TYPICAL AUBURN VOID METER PROBE INSTALLATION

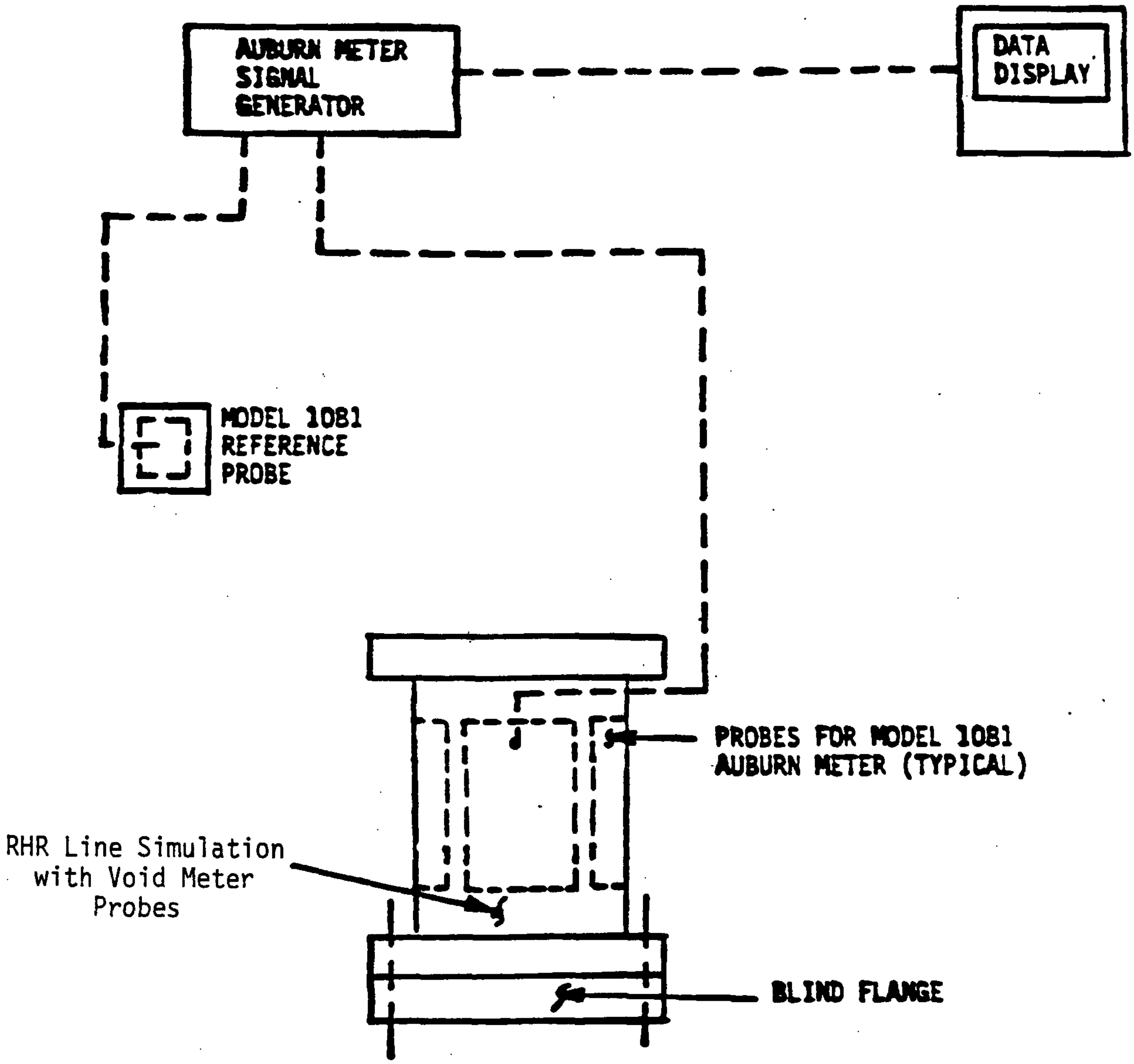

FIGURE D-2 SCHEMATIC OF AUBURN VOID METER ELECTRICAL HOOK-UP FOR CALIBRATION TESTING

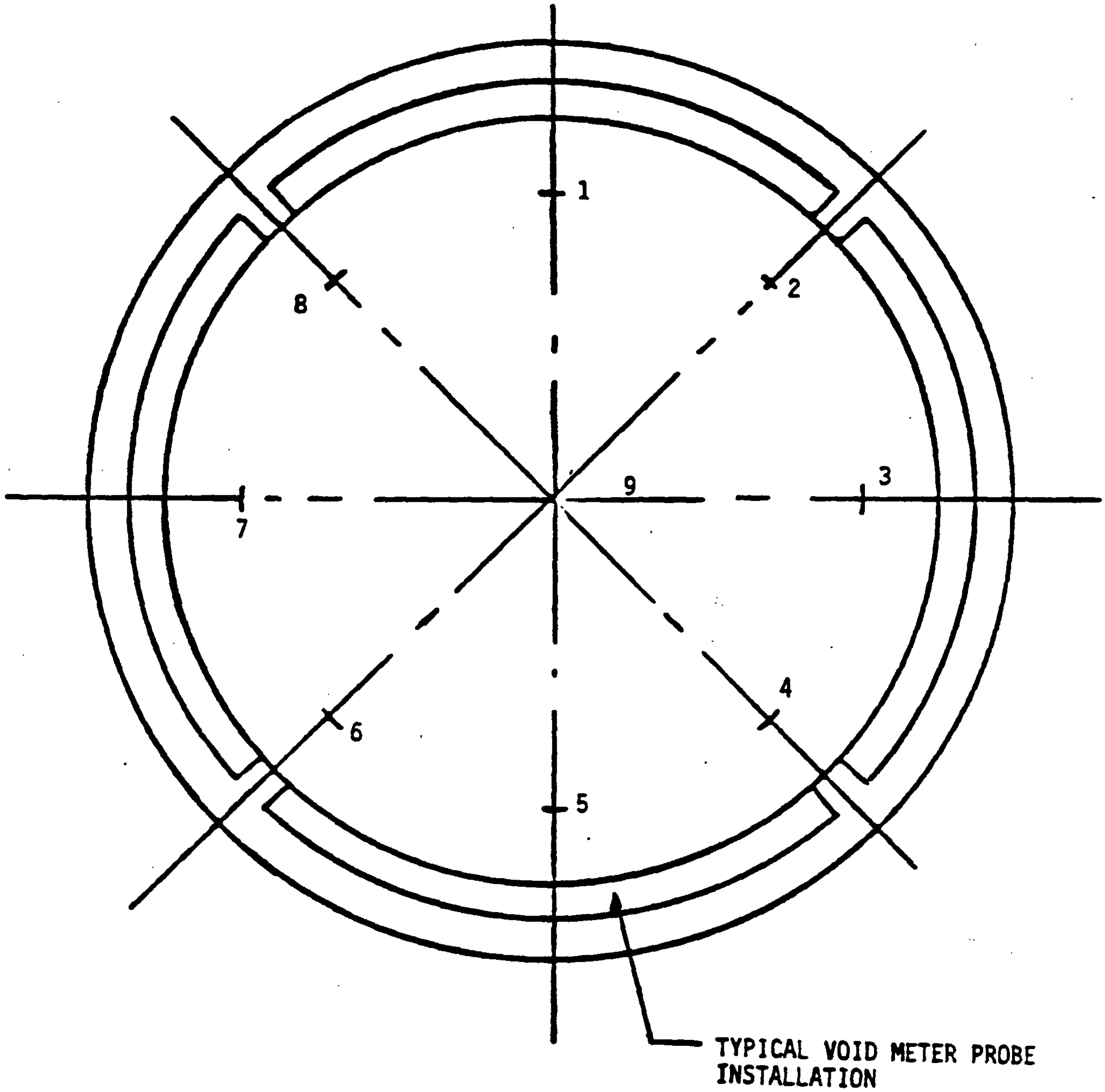

FIGURE D-3 SCHEMATIC OF VOID SIMULATION LOCATIONS, VOID METER SENSITIVITY TESTS

APPENDIX E

TREAT-NC MODEL DESCRIPTION

E.0 TREAT-NC MODEL DESCRIPTION

E.1 Analysis Model General Description

TREAT (Transient Real-time Engineering Analysis Tool) is an interactive engineering simulation program based upon first principles of a single component two-phase fluid. Each fluid control volume (fluid node) is divided into an upper and lower region. In general, the lower region will contain subcooled or low quality saturated fluid. The upper region usually contains either superheated or high quality saturated steam. A more complete description of the TREAT model can be found in Reference 13.

TREAT-NC is an extension of TREAT which includes a non-condensible gas along with steam in the upper region of a TREAT fluid node. The addition of non-condensible gas required modifications to the mass and energy conservation equations along with a new method for computing the global (system) pressure. These changes were made while retaining the essential features of TREAT's numerics.

Separate mass conservation equations along with revised mass transport coefficients were required to model the transport of the steam and non-condensible gas masses. Vapor flowing into a node is partitioned into steam and non-condensible gas according to the upstream mass fraction, i.e., the fraction of gas to toal vapor mass in the upper region of the upstream node. All non-condensible gas entering the lower region of a node is assumed to pass through into the upper region (i.e., non-condensible gas is not allowed to remain in the lower region). The model does allow water to be absorbed into the non-condensible gas bubbles as they pass through the lower region.

The energy conservation equations in TREAT-NC compute the energy of the combined non-condensible gas and steam components. The change in energy is partitioned between the non-condensible gas and steam components and multiplied by the component enthalpies. As in the mass equations, non-condensible gas bubbling through the lower region carries away some additional energy as water evaporates into the bubbles. This can result in evaporative cooling of the lower region, even if the air temperature is somewhat higher than the water temperature. As the non-condensible gas bubbles through the lower region, heat is transferred between the gas bubbles and the liquid to bring the non-condensible gas into equilibrium with the lower region.

Once the mass and energy inventories are known, an iteration is performed to partition the total energy into the non-condensible gas and steam portions. Simultaneously, the global pressure is partitioned between the non-condensible gas partial pressure and the steam partial pressure. In addition to the preceding nodal partial pressure calculations, the entire system pressure (global pressure) is computed.

The fluid properties used in TREAT-NC differ from those in TREAT. TREAT-NC uses piecewise linear tables for all steam phases with extensions to very low (less than .1 psia) steam partial pressures. In addition, TREAT-NC uses ideal gas properties for the non-condensible component. The default properties used are for air but other properties can be used instead.

TREAT has always used a predictor-corrector method to solve the energy equations. TREAT-NC continues to use the same procedure except requires an additional property evaluation at the predicted conditions. These conditions use old time pressure but with under-relaxed values of the new time enthalpy. This method is as stable and almost as efficient as its predecessor in TREAT.

E.2 TREAT Manway Opening Model

In addition to the revisions made to TREAT to add non-condensibles, some special modifications were made to allow the very large openings present whenever the manway is removed. This required an additional calculation in the mass and energy equations to compute the effect of a large opening on the system pressure. This term, in the form of a derivative, is fed into the orifice equation used to compute the vapor flow rate through the manway. In this way, a single implicit flow link is introduced into TREAT-NC. Because the pressure at the opening may be less than the system pressure (because of the manometer effect of water in the loop seal), a lagged pressure drop is also incorporated into this orifice equation.

If water is forced out of the core because of boiling, the fluid mixture level may reach the elevation of the open manway. A spill flow model to compute liquid flow through the manway opening was added to TREAT-NC. This model is based upon the equations used for analyzing flow over a weir.

Together, the spill flow and the orifice model form the TREAT-NC manway flow model.

E.3 TREAT Condensation Model

The heat and mass transfer coefficients are very sensitive to the amount of non-condesible gas present. For example, the condensation heat transfer coefficient can vary between 1000 and 50 BTU/hr-ft^2-F, depending upon the amount of non-condensible gas present (Reference 18). As steam condenses on the condensing surface, a layer of non-condensible gas is left behind. As this layer builds up, the condensation rate degrades since steam must first diffuse through this layer of gas. Thus, even a small amount of non-condensible gas in the system will cause the condensation rate to decrease significantly.

The heat transferred from the bulk vapor to the liquid condensate film on the SG tube wall is composed of 2 parts; heat transferred through the boundary layer by convection and latent heat released by condensation at the fluid film surface. At steady state, the sum of these 2 processes will equal the heat transferred through the liquid film to the SG tube wall.

The Nusselt film condensation correlation is used to determine the heat transferred through the film on the tube wall. The Reynolds analogy is used to determine the mass transfer coefficient for the diffusion of steam through the boundary layer to the condensate film surface. An iterative process was used to compute the film surface temperature and to solve for the heat and mass transfer rates.

E.4 TREAT Void Fraction Calculations

The void fraction in the mixture region of the node is determined by the input bubble rise velocity for the node, the corresponding interface areas, and the steam or boil-off flow from the node. At low pressures typical of mid-loop operation, the steam density is low and the resulting void fractions would be comparatively high. The corresponding bubble rise velocities would also be high when compared to values expected at higher pressure.

For the mid-loop application, the core bubble rise input is selected or adjusted so that the TREAT core void fraction is consistent with the result predicted by the Yeh correlation. This correlation is derived in Appendix B of Reference 15 and is used to determine the void fraction at the core exit. Assuming a linear void distribution up the core and an upper plenum void fraction the same as the core exit (in the approximate 6 ft distance above the core to mid-loop), the void fraction used for back-calculation of the bubble rise velocity for the TREAT single node core/upper plenum model is taken to be 67% (length averaged) of the value given in Equation (B.9) of Reference 15.

An accurate prediction for the core void fraction is required in some of the transients, particularly the large RCS vent cases with spill (Section 3.4) and the cold leg opening study (Section 3.7). For these cases, the RCS pressure remains near 15 psia (ambient pressure) and the core void fraction is typically 20-30% after a steady boil-off condition develops.