

## APPENDIX 19E SHUTDOWN EVALUATION

### 19E.1 Introduction

Westinghouse has considered shutdown operations in the design of the AP600 nuclear power plant. The AP600 defense-in-depth design philosophy to provide normally operating active systems and passive safety-related systems gives the AP600 a greater degree of safety during shutdown operations as well as normal power operation when compared to currently operating plants. This appendix presents and evaluates the AP600 design features in the context of the specific shutdown issues identified by the Nuclear Regulatory Commission.

#### 19E.1.1 Purpose

This appendix presents AP600 design features that address the issues of shutdown risk and shutdown safety. This appendix further evaluates these design features with respect to their ability to reduce and or mitigate the consequences of events that can occur during shutdown. This appendix provides both design basis evaluations and a probabilistic risk assessment (PRA) for the plant at shutdown.

#### 19E.1.2 Scope

The scope of this appendix includes discussions of the following:

- Systems designed to operate during shutdown
- Shutdown operations – including maintenance insights, risk management, and Emergency Response Guidelines (ERGs) (Reference 1)
- Safety analyses and evaluations for shutdown operations
- Chapter 16, "Technical Specifications"
- Shutdown risk evaluations – including shutdown PRA results and insights and fire/flood risk
- Compliance with the guidance in NUREG-1449 (Reference 2)

#### 19E.1.3 Background

The Diablo Canyon event of April 10, 1987, and the loss of ac power at the Vogtle plant on March 20, 1990, led the NRC staff to issue NUREG-1449, which provides an evaluation of the shutdown risk issue. The NRC requested that Westinghouse perform a systematic assessment of the shutdown risk issue to address areas identified in NUREG-1449 as applicable to the AP600 design. This assessment is documented in this appendix.

## 19E.2 Major Systems Designed to Operate During Shutdown

Westinghouse has considered shutdown modes, shutdown alignments, and industry issues related to shutdown in the design of the AP600 safety-related and nonsafety-related systems designed to operate or be available during shutdown. This section provides descriptions of the important systems designed to operate during shutdown and includes specific design features that have been incorporated for shutdown operations with a discussion of their operating modes or alignment during shutdown.

In this appendix, references are made to the various AP600 operating modes. The AP600 operating modes have been defined in the Technical Specifications (Tier 2 Information Section 16.1, Table 1.1-1). The mode definitions for the AP600 are similar to that of current Westinghouse pressurized water reactors (PWRs), with the difference being the definition of Mode 4, safe shutdown.

In the AP600, Mode 4 has been redefined as safe shutdown and corresponds to the range of RCS temperature between 420°F and 200°F. The upper temperature limit corresponds to the RCS temperature that can be achieved by the passive safety-related systems 36 hours after shutdown. The ability of the passive safety-related systems to achieve Mode 4 within 36 hours is shown in subsection 4.10.2 of this appendix.

### 19E.2.1 Reactor Coolant System

#### 19E.2.1.1 System Description

The reactor coolant system (RCS) is described in Chapter 5 of the Tier 2 Information.

#### 19E.2.1.2 Design Features to Address Shutdown Safety

The AP600 has incorporated design features that address issues related to shutdown operations. This subsection provides a discussion of the RCS design features that are incorporated to address shutdown operations or that are important to minimizing the risk to plant safety during shutdown.

##### 19E.2.1.2.1 Loop Piping Offset

The RCS hot legs and cold legs are vertically offset. This permits draining of the steam generators for nozzle dam insertion with the hot leg level much higher than traditional designs. The RCS must be drained to a level sufficient to provide a vent path from the pressurizer to the steam generators. This loop piping offset also allows an RCP to be replaced without removing the full core.

##### 19E.2.1.2.2 RCS Instrumentation

Instrumentation is provided to monitor the RCS process parameters as required by the PLS and PMS as discussed in Chapter 7 of the Tier 2 Information. This subsection describes RCS instrumentation designed to accommodate shutdown operations.

### RCS Hot Leg Level

There are two safety-related RCS hot leg level channels, one located in each hot leg. These level indicators are provided primarily to monitor the RCS water level during mid-loop operation following shutdown operations. These are totally independent of each other. One level tap is at the bottom of the hot leg, and the other tap is on the top of the hot leg close to the steam generator. The steam generator tap is located at the high point of the tubing run. The level tap for the instrument in the hot leg with the normal residual heat removal system (RNS) step-nozzle suction line connection is between the reactor vessel and the step-nozzle. Figure 19E.2-1 shows a simplified sketch of the RCS level instruments.

These channels provide signals for the following protection functions:

- Isolation of letdown on low level on a one-out-of-two basis
- Actuation of IRWST injection on low (empty) hot leg level on a two-out-of-two basis
- Actuation of fourth-stage ADS valves on low (empty) hot leg level on a two-out-of-two basis

These functions protect the plant during shutdown operations. Letdown isolation assists the operators when draining the RCS to a mid-loop level. If the operators fail to isolate letdown, these channels send a signal to close the letdown valves and stop the draining process.

In the event of a loss of the RNS during shutdown, coolant inventory could be boiled away. When the hot leg water level indicates that the loops are empty, IRWST injection and fourth-stage ADS are actuated 30 minutes after receipt of the empty hot leg level signal.

These channels also provide signals to the letdown flow control valve to control the drain rate of the RCS via the letdown line during the transition to mid-loop operation. When the hot legs are full, the drain rate can proceed at a high level. As the water level is reduced to the hot legs, the drain rate is automatically decreased to a rate of approximately 20 gpm.

These channels are also used to generate the alarms on low hot leg water level. The alarm setpoints are selected to give the operator sufficient time to take the manual actions necessary to prevent the automatic actuation described previously. Indication of these channels is retrievable in the main control room. This variable is used by the operator to monitor the status of RCS inventory following an accident and is, therefore, classified as a post-accident monitoring system (PAMS) variable as discussed in Tier 2 Information Section 7.5.

The accuracy and response time of the hot leg level instruments are consistent with the standard engineered safety features (ESF) actuation discussed in Tier 2 Information Section 7.3. Concerns related to potential problems of noncondensable gases in the hot leg level instrument lines that have been raised in NRC Information Notice 92-54, Level Instrumentation Inaccuracies Caused by Rapid Depressurization (Reference 3), have been

addressed in the layout of the instrument lines. In addition, as the hot leg level instruments are provided primarily for shutdown operations, off-gassing due to sudden depressurization of the RCS in shutdown modes is not a concern.

In the AP600, draining of the RCS to mid-loop conditions is achieved in a controlled manner as discussed in subsection 19E.2.1.2.4. Due to the low RCS drain rate, and the RCS step-nozzle as discussed in subsection 19E.2.1.2.3, the amount of air-entrainment, and therefore RCS level perturbation during mid-loop, is negligible. Draining of the RCS is conducted in a quasi-steady-state, and the reliability of an accurate level reading is high.

### **Pressurizer Level**

A fifth nonsafety-related independent pressurizer level transmitter, calibrated for low temperature conditions, provides water level indication during startup, shutdown, and refueling operations in the main control room and in the remote shutdown workstation. The upper level tap is connected to an ADS valve inlet header above the top of the pressurizer. The lower level tap is connected to the bottom of the hot leg. This provides level indication for the entire pressurizer and a continuous reading as the level in the pressurizer decreases to mid-loop levels during shutdown operations.

### **RCS Hot Leg Wide-Range Temperatures**

The RCS contains two safety-related thermowell-mounted hot leg wide-range temperature detectors, one in each hot leg. The orientation of the resistance temperature detectors enables measurement of the reactor coolant fluid in the hot leg when in reduced inventory conditions. Their range is selected to accommodate the low RCS temperatures that can be attained during shutdown. In addition, at least two incore thermocouple channels are available to measure the core exit temperature during mid-loop RNS operation. These two thermocouple channels are associated with separate electrical divisions.

### **Pressurizer Surge Line Temperatures**

There are three nonsafety-related temperature detectors located on the RCS pressurizer surge line. These instruments monitor the pressurizer surge line fluid temperature during plant normal operations to detect thermal stratification in the surge line. Two of the temperature detectors are on a moderately sloped run approximately midway between the RCS hot leg and the pressurizer. One detector is on the bottom of the pipe and the other detector on the top. The third detector is located on the pressurizer surge line close to the pressurizer nozzle. This detector is used to monitor cold water insurges to the pressurizer during transient operations.

The temperature is monitored at the three locations using strap-on resistance temperature detectors. Temperature indication is provided in the main control room. One low-temperature alarm is provided to alert the operator of thermal stratification in the surge line. This alarm is associated with the detector on the bottom of the pipe.

During shutdown operations, this temperature instrumentation will be monitored to detect possible surge line stratification. If stratification is detected, the operators can increase spray flow to increase the outsurge from the pressurizer and reduce stratification in the surge line.

#### 19E.2.1.2.3 Step-nozzle Connection

The AP600 RNS uses a step-nozzle connection to the RCS hot leg. The step-nozzle connection has two effects on mid-loop operation. One effect is to lower the RCS hot leg level at which a vortex occurs in the residual heat removal pump suction line due to the lower fluid velocity in the hot leg nozzle. This increases the margin from the nominal mid-loop level to the level where air entrainment into the pump suction begins.

Another effect of the step-nozzle is that, if a vortex should occur, the maximum air entrainment into the pump suction as shown experimentally will be no greater than 5 percent (Reference 4). The RNS pumps can operate with 5% air-entrainment. As discussed in NUREG-0897 (Reference 5), low levels of air ingestion can be tolerated, and a pump inlet void fraction of 5% has been shown experimentally to reduce the pump head less than 15%. At this level of degradation, the RNS pumps would maintain decay heat removal. The step-nozzle thereby precludes air binding of the pump and will allow for RNS pump operation with low water levels in the hot leg.

#### 19E.2.1.2.4 Improved RCS Draindown Method

During the cooldown operations, the RCS water level is drained to a mid-loop level to permit steam generator draining and maintenance activities. The AP600 has improved the reliability of draindown operations by incorporating a dedicated drain path to be used to reduce the water level in the RCS controlled in the main control room. In current plants, various drain paths can be used either locally or remotely from the control room. These drain paths include the safety-related residual heat removal system, loop drain valves, and letdown. The result is that draining of the RCS can be difficult to control, and perturbations in water level can occur due to inadvertent system manipulations of which the operators are not always aware.

The AP600 RCS drain path is via the CVS letdown line from the RNS cross-connect provided to maintain full RCS purification flow during shutdown. The letdown line flow control valve controls the letdown rate, which controls the RCS draindown rate. At the appropriate time during the cooldown, the operator initiates the draindown by placing the CVS letdown control valve into a refueling draindown mode. At this time, the makeup pumps are turned off and the letdown flow control valve controls the drain rate to the liquid radwaste system at an initial maximum rate of 100 gpm. The rate is reduced once the level in the RCS is to the top of the hot leg. The letdown rate is manually controlled based upon the difference in flow instruments readings in the CVS letdown line and injection line. The letdown flow control valve as well as the letdown line containment isolation valve receives a signal to automatically close once the appropriate level is attained. Alarms actuate in the control room if the RCS level falls below the automatic letdown valve closure setpoint so that the operator is alerted to manually isolate the letdown line. Furthermore, an automatic

isolation of the letdown line is actuated on low hot leg level. This draindown method provides a reliable means of attaining mid-loop conditions.

#### 19E.2.1.2.5 ADS Valves

The ADS first-, second-, and third-stage valves, connected to the top of the pressurizer, are open whenever the core makeup tanks (CMTs) are blocked during shutdown conditions while the reactor vessel upper internals are in place. This provides a vent path to preclude pressurization of the RCS during shutdown conditions if decay heat removal is lost. This also allows the IRWST to automatically provide injection flow if it is actuated on a loss of decay heat removal. In addition, two of the four ADS fourth-stage valves are required to be available during reduced inventory operations to preclude surge line flooding following a loss of the RNS. The effectiveness of the ADS valves and IRWST injection to mitigate loss of the RNS during shutdown is shown in subsection 19E.4.8.5 of this appendix.

#### 19E.2.1.2.6 Steam Generator Channel Head

The AP600 steam generator is a vertical-shell U-tube evaporator with integral moisture separating equipment. The generator is discussed in Tier 2 Information subsection 5.4.2.

On the primary side, the reactor coolant flow enters the primary chamber via the hot leg nozzle. The lower portion of the primary chamber is hemispherical and merges into a cylindrical portion, which mates to the tubesheet. This arrangement provides enhanced access to all tubes, including those at the periphery of the bundle, with robotics equipment. This feature enhances the ability to inspect, replace, and repair portions of the AP600 unit compared to the more hemispherical primary chamber of earlier designs. The channel head is divided into inlet and outlet chambers by a vertical divider plate extending from the apex of the head to the tubesheet.

The reactor coolant enters the inverted U-tubes, transferring heat to the secondary side during its traverse, and returns to the cold leg side of the primary chamber. The flow exits the steam generator via two cold leg nozzles to which the canned-motor RCPs are directly attached.

The AP600 steam generator channel head has provisions to drain the head. For minimizing deposits of radioactive corrosion products on the channel head surfaces and for enhancing the decontamination of these surfaces, the channel head cladding is machined or electropolished for a smooth surface. The large primary manways provide enhanced access capability compared to the manways in previous model steam generators.

The steam generator is equipped with permanently mounted nozzle dam brackets, which are designed to support nozzle dams during refueling operations. The design pressure of the nozzle dam bracket and nozzle dam is selected to withstand the RCS pressures that can occur during the shutdown events. The analyses presented in subsection 19E.4.8.5 show that the maximum pressure following a loss of shutdown cooling in Mode 5 with the RCS pressure boundary open is less than 32 psia. Therefore, the nozzle dam design pressure is least 40 psia.

The AP600 nozzle dams can be installed with the hot leg water level at the nominal water level for mid-loop operations. The nozzle dams can be inserted via the steam generator manway. The ADS valves connected to the pressurizer are open during all reduced inventory operations including nozzle dam installation, and provide a vent path to preclude pressurization of the reactor coolant system following a loss of decay heat removal when the nozzle dams are installed.

## **19E.2.2 Steam Generator and Feedwater Systems**

### **19E.2.2.1 System Description**

This section discusses the AP600 steam generator system (SGS) and the main and startup feedwater system (FWS) designs as they relate to shutdown operations. These systems are discussed in Chapter 10 of the Tier 2 Information.

### **19E.2.2.2 Design Features to Address Shutdown Safety**

#### **19E.2.2.2.1 Feedwater Control**

The AP600 provides improvements in feedwater control that minimizes the probability of loss of feedwater transients during low power and shutdown modes. The main feedwater pumps are capable of providing feedwater during all modes of operation, including plant startup and standby conditions. In addition, the startup feedwater pumps are automatically started in the event that the main feedwater pumps are unable to continue to operate. The startup feedwater pumps are also automatically loaded on the diesels for operation following a loss of offsite power.

#### **19E.2.2.2.2 Safety-Related Actuation in Shutdown Modes**

The AP600 has safety-related actuations associated with the SGS that are operable during shutdown modes. These include the PRHR HX actuation on low steam generator level during shutdown modes, and this is discussed in subsection 19E.2.3 of this appendix. Also included is the isolation of the main steam line on a high (large) negative rate of change in steam pressure. This safety-related signal is provided to address a steam line break that could occur in Mode 3 or 4. If actuated, this signal causes the MSIVs to close to thus terminate the blowdown of the SGS following a steam line break. This signal is placed into service below the setpoint that disables the low steam line pressure signal (P11) that actuates steam line isolation as discussed in Tier 2 Information Section 7.3. When the operator manually blocks the low steam line pressure signal, the steam line high pressure-negative rate signal is automatically enabled.

This signal is operable during Mode 3 when a secondary side break or stuck open valve could result in the rapid depressurization of the steam line(s). In Modes 4, 5, and 6, this function is not needed for accident detection and mitigation. Subsection 19E.4.2.3 discusses steam line break events that could occur in shutdown modes. Operability of this actuation logic is discussed in the AP600 Technical Specifications (Tier 2 Information Section 16.1).

### 19E.2.2.2.3 Steam Generator Cooling in Shutdown Modes

As discussed previously, the secondary side of the steam generators can be cooled during shutdown by recirculating their contents through the blowdown system heat exchanger. This feature reduces the challenges to low-temperature overpressure events. During RCS water-solid operation, heat input from the steam generators is capable of challenging the low-temperature relief valve. The Technical Specifications prevent the operators from starting an RCP with the steam generator secondary side temperature more than 50°F higher than the primary side, with the pressurizer water-solid. With the RCS water-solid, the heat input that could occur would cause the system to be pressurized to the setpoint of the low-temperature overpressure relief valve in the RNS.

When the RCPs are operating, the secondary side of the steam generator is cooled by steaming to the MSS. Once the RNS is aligned, and steaming to the MSS is decreased, the secondary side of the steam generators is cooled by operation of the RNS. However, once the RCPs are tripped, water does not circulate through the primary side of the tubes and the secondary side of the steam generators remains at elevated temperature. With the ability to cool the secondary side via the blowdown system, the AP600 reduces the probability that an RCP would be started with the secondary side of the generator at elevated temperature to thus reduce the risk of a low temperature overpressure event. This mode of cooling also makes the equipment available for maintenance at the earliest time in an outage.

The AP600 has also incorporated steam generator fluid thermocouples to monitor the temperature of the fluid in the secondary side of the steam generator. This improves the ability of the operators to monitor this temperature to prevent them from inadvertently starting an RCP with the secondary side at elevated temperatures.

## 19E.2.3 Passive Core Cooling System

### 19E.2.3.1 System Description

The passive core cooling system (PXS) is described in Tier 2 Information Section 6.3.

### 19E.2.3.2 Design Features to Address Shutdown Safety

A significant improvement in shutdown safety for the AP600 is the availability of a dedicated safety-related system that can be automatically or manually actuated in response to an accident that can occur during shutdown. In current plants, the safety-related systems that mitigate the consequences of an accident are also the operating systems that are used for decay heat removal. In the AP600, nonsafety-related active systems provide the first level of defense, while the passive safety-related systems are available during shutdown modes to mitigate the consequences of an accident. This design approach results in a significant improvement in the AP600 shutdown risk.

#### 19E.2.3.2.1 Core Makeup Tanks

The CMTs provide RCS makeup. During shutdown, the CMTs are available in Modes 3, 4, and 5, until the RCS pressure boundary is open and the pressurizer water level is reduced. During power operation, the CMTs are automatically actuated on various signals including a safeguards actuation signal (low RCS pressure, low RCS temperature, low steam line pressure, and high containment pressure) and on low pressurizer water level. See Tier 2 Information Chapter 7 for a description of the AP600 PMS actuation logic. In shutdown modes, portions of the safeguards actuation signal are disabled to allow the RCS to be cooled and depressurized for shutdown. For instance, the low RCS pressure and temperature, and low steam line pressure signals are blocked in Mode 3 prior to cooling and depressurizing the RCS. Therefore, during shutdown Modes 3, 4, and 5, the primary signal that actuates the CMTs due to a loss of inventory is the pressurizer level signal. In Mode 5, with the RCS open (in preparation for reduced inventory operations), the low pressurizer level signal is blocked prior to draining the pressurizer. Therefore, in Mode 5 with the RCS open, the CMTs are not required to be available and the RCS makeup function is provided by the IRWST.

The CMTs also provide an emergency boration function for accidents such as steam line breaks. However, the signals that provide the primary protection for this function (low steam line pressure, low RCS pressure, and low RCS temperature) are blocked in Mode 3 as discussed above. Prior to blocking these signals in Mode 3, the Technical Specifications require that the RCS be sufficiently borated. For these events, the pressurizer level signal provides automatic actuation of the CMTs for a steam line break that might occur due to the RCS shrinkage that would occur. This event is discussed in subsection 19E.4.2.3 of this appendix.

#### 19E.2.3.2.2 Accumulators

The PXS accumulators provide safety injection following a LOCA. In Mode 3, the accumulators must be isolated to prevent their operation when the RCS pressure is reduced to below their set pressure. The accumulator isolation valves are closed when the RCS pressure is reduced to 1000 psig to block their injection when the RCS pressure is reduced to below the normal accumulator pressure. Analysis is provided in subsection 19E.4.7 of this appendix that shows the plant response to LOCAs that could occur at shutdown without the accumulators aligned.

#### 19E.2.3.2.3 In-containment Refueling Water Storage Tank

The IRWST provides long-term RCS makeup. During shutdown, the IRWST is available until Mode 6, when the reactor vessel upper internals are removed and the refueling cavity flooded. At that time, the IRWST is not required, due to the large heat capacity of the water in the refueling cavity.

The IRWST injection paths are actuated on a low-2 CMT water level. This signal is available in shutdown Modes 3, 4, and 5, with the RCS intact. When the RCS is open to transition to reduced inventory operations, the CMT actuation logic on low pressurizer level

is removed, and the CMTs can be taken out of service. For these modes, automatic actuation of the IRWST can be initiated (on a two-out-of-two basis) on low hot leg level. However, manual actuation of the IRWST is relied upon to meet the design basis safety analysis case provided in Section 19E.4 of this appendix for loss of inventory/cooling events that occur during these conditions.

#### **19E.2.3.2.4 Passive Residual Heat Removal Heat Exchanger**

The PRHR HX provides decay heat removal during power operation and is required to be available in shutdown Modes 3, 4, and 5, until the RCS is open. In these modes, the PRHR HX provides a passive decay heat removal path. It is automatically actuated on a CMT actuation signal, which would eventually be generated on a loss of shutdown decay heat removal, as shown in the analysis provided in Section 19E.4 of this appendix. In modes with the RCS open (portions of Mode 5 and Mode 6), decay heat removal is provided by "feeding" water from the IRWST and "bleeding" steam from the ADS.

#### **19E.2.3.2.5 Reduced Challenges to Low-Temperature Overpressure Events**

Another design feature of the PXS that reduces challenges to shutdown safety is the elimination of high-head safety injection pumps in causing low temperature overpressure events. In current plants, during water solid operations that may be necessary to perform shutdown maintenance, the high-head safety injection pumps are a major source of cold overpressure events. To address this, plants are required to lock out safety injection pumps to prevent them from inadvertently causing a cold overpressure event. This eliminates a potential source of safety injection for a loss of inventory event that could occur at shutdown. With the AP600 PXS, the CMTs are never pressurized above RCS pressure and are, therefore, not capable of causing a cold overpressure event. Therefore, they are not isolated until the pressurizer is drained for mid-loop. Low-temperature overpressure events are discussed in subsection 19E.4.10.1.

#### **19E.2.3.2.6 Discussion of Safe Shutdown for AP600**

The functional requirements for the PXS specify that the plant be brought to a stable condition using the PRHR HX for events not involving a loss of coolant. For these events, the PXS, in conjunction with the passive containment cooling system (PCS), has the capability to establish long-term safe shutdown conditions, cooling the RCS to less than 420°F within 36 hours, with or without the RCPs operating.

The CMTs automatically provide injection to the RCS as the temperature decreases and the pressurizer level decreases, actuating the CMTs. The PXS can maintain stable plant conditions for a long time in this mode of operation, depending on the reactor coolant leakage and the availability of ac power sources. For example, with a technical specification leak rate of 10 gpm, stable plant conditions can be maintained for at least 10 hours. With a smaller leak, a longer time is available. However, in scenarios when ac power sources are unavailable for as long as 24 hours, the ADS will automatically actuate.

For LOCAs and other postulated events where ac power sources are lost, or when the CMT levels reach the ADS actuation setpoint, the ADS initiates. This results in injection from the accumulators and subsequently from the in-containment refueling water storage tank, once the RCS is nearly depressurized. For these conditions, the RCS depressurizes to saturated conditions at about 240°F within 24 hours. The PXS can maintain this safe shutdown condition indefinitely.

The primary function of the PXS during a safe shutdown using only safety-related equipment is to provide a means for boration, injection, and core cooling. Analysis is provided in subsection 19E.4.10.2 of this appendix that verifies the ability of the AP600 passive safety systems to meet the safe shutdown requirements.

### 19E.2.3.3 Shutdown Operations

Operation of the PXS during operating modes and during accident events including shutdown events is discussed in Tier 2 Information subsection 6.3.3. The following is a discussion of a loss of shutdown cooling during reduced inventory operations which can be a limiting shutdown event.

#### 19E.2.3.3.1 Operation During Loss of Normal Residual Heat Removal Cooling During Mid-loop Events

During RCS maintenance, the most limiting shutdown condition anticipated is with the reactor coolant level reduced to the hot leg (mid-loop) level and the RCS pressure boundary opened. It is normal practice to open the steam generator channel head manway covers to install the hot leg and cold leg nozzle dams during a refueling outage. In this situation, the RNS is used to cool the RCS. The AP600 incorporates features to reduce the probability of losing RNS. However, because the RNS is nonsafety-related, its failure has been considered.

In this situation, core cooling is provided by the safety-related PXS, using gravity injection from the IRWST, while venting through the ADS valves (and possibly through other openings in the RCS). Note that with the RCS depressurized and the pressure boundary opened, the PRHR HX is unable to remove the decay heat because the RCS cannot heat sufficiently above the IRWST temperature.

During plant shutdown, at 1000 psig, the accumulators are isolated to prevent inadvertent injection. Prior to draining the RCS inventory below the no-load pressurizer level, the CMTs are isolated by closing the inlet MOVs to preclude inadvertent draining into the RCS while preparing for mid-loop operation. Although these tanks are isolated from the RCS, the valves can be remotely opened by the operators to provide additional makeup water injection.

Prior to initiating the draindown of RCS to mid-loop level, the automatic depressurization first-, second-, and third-stage valves are opened. This alignment provides a sufficient RCS vent flow path to preclude system pressurization in the event of a loss of nonsafety-related decay heat removal during mid-loop operation. The ADS first- to third-stage valves are

required to be opened before blocking the CMTs. They are required to remain open until either the RCS level is increased and the RCS is closed, or until the upper core internals are removed and the refueling cavity flooded. Note that the upper internals can restrict the vent flow path and prevent water in the refueling cavity from draining into the RCS unless ADS valves are open.

The IRWST injection squib valves and fourth stage ADS valves are automatically opened if the RCS hot leg level indication decreases below a low setpoint. A time delay is provided to provide time for the operators to restore nonsafety-related decay heat removal prior to actuating the PXS. The time delay with an alarm in the containment serves to protect maintenance personnel. Once the IRWST injection valves and fourth stage ADS valves open, the IRWST provides gravity-driven injection to cool the core. Containment recirculation flow would be automatically initiated when the IRWST level dropped to a low level to provide long-term core cooling.

Subsection 19E.4.8.5 provides the analysis of the loss of the RNS during mid-loop operations. Table 19E.2.3-1 provides the results of calculations performed to demonstrate the amount of time between a loss of RNS that could occur at mid-loop until core uncover. This calculation is performed with the RCS water level at the nominal mid-loop water level and is performed with conservative, design basis assumptions for decay heat. As described previously and shown in Table 19E.2-1, the operators have a significant amount of time to actuate gravity injection before core uncover. In addition, the PMS, on a two-out-of-two basis, provides a signal to actuate the IRWST when the hot legs empty.

This arrangement provides automatic core cooling protection, in mid-loop operation, while also providing protection (an evacuation alarm and sufficient time to evacuate) for maintenance personnel in containment during mid-loop operation.

Containment closure capability is required to be maintained during mid-loop operation, as discussed in subsection 19E.2.6.2 of this appendix. With the containment closed, containment recirculation can continue indefinitely with decay heat generating steam condensed on the containment vessel and drained back into the IRWST and/or the containment recirculation.

## **19E.2.4 Normal Residual Heat Removal System**

### **19E.2.4.1 System Description**

The normal residual heat removal system (RNS) is discussed in subsection 5.4.7 of the Tier 2 Information.

### **19E.2.4.2 Design Features to Address Shutdown Safety**

The AP600 has incorporated various design features to improve shutdown safety. The RNS features that have been incorporated to address shutdown safety are described in this subsection.

#### 19E.2.4.2.1 RNS Pump Elevation and NPSH Characteristics

The AP600 RNS pumps are located at the lowest elevation in the auxiliary building. This location provides the RNS pumps with a large available NPSH during all modes of operation including RCS mid-loop and reduced inventory operations. The large NPSH provides the pumps with the capability to operate during mid-loop conditions with saturated fluid in the RCS without throttling the RNS flow. This allows for the RNS pumps to be restarted and operated with saturated RCS conditions that might occur following a temporary loss of RNS cooling.

The plant piping configuration, piping elevations and routing, and the pump characteristics allow the RNS pumps to be started and operated at their full design flow rates without the need to reduce RNS pump flow to meet pump NPSH requirements. This eliminates the potential failure mechanism that exists in current PWRs, where failure of an air-operated control valve can result in pump runout and cavitation during mid-loop operations.

#### 19E.2.4.2.2 Self-Venting Suction Line

The RNS pump suction line is sloped continuously upward from the pump to the RCS hot leg with no local high points. This eliminates potential problems with refilling the pump suction line if an RNS pump is stopped due to pump cavitation and/or excessive air entrainment. With the self-venting suction line, the line will refill and the pumps can be immediately restarted once an adequate level in the hot leg is re-established.

#### 19E.2.4.2.3 IRWST Injection via the RNS Suction Line

During shutdown modes, initiating events such as the loss of the nonsafety-related RNS are postulated. Such events would require IRWST injection as discussed in subsection 19E.2.3 of this appendix, and as shown in the accident analyses provided in Section 19E.4. For initiating IRWST injection, the operation of PXS squib valves in the IRWST injection line is required. However, the operators can use the RNS pump suction line that connects to the IRWST to provide controlled IRWST injection. This flow path, shown in Figure 19E.2.4-2, connects the IRWST directly to the RCS via the RNS hot leg suction isolation valves and provides a diverse method for IRWST injection. In addition, it would be the preferred method of providing IRWST injection because the flow would be controllable by the operation of the IRWST suction line isolation valve. The RNS isolation valve is equipped with a throttle capability to provide the operators with the capability to control the injection flow via this path. The operator would monitor the RCS hot leg level while controlling flow through this valve. This path provides IRWST injection regardless of whether the RNS pumps are operating.

#### 19E.2.4.2.4 Codes and Standards/Seismic Protection

The portions of the RNS located outside containment (that serve no active safety functions) are classified as AP600 equipment Class C so that the design, manufacture, installation, and inspection of this pressure boundary is in accordance with the following industry codes and standards and regulatory requirements: 10 CFR 50, Appendix B (Reference 6); Regulatory

Guide 1.26, quality group C (Reference 7); and ASME Boiler and Pressure Vessel Code, Section III, Class 3 (Reference 8). The pressure boundary is classified as seismic Category I.

#### **19E.2.4.2.5 Increased Design Pressure**

The portions of the RNS from the RCS to the containment isolation valves outside containment are designed to the operating pressure of the RCS. The portions of the system downstream of the suction line containment isolation valve and upstream of the discharge line containment isolation valve are designed so that its ultimate rupture strength is not less than the operating pressure of the RCS. The design pressure of the RNS is 900 psig, which is 40 percent of operating RCS pressure.

#### **19E.2.4.2.6 Reactor Coolant System Isolation Valve**

The RNS contains an isolation valve in the pump suction line from the RCS. This motor-operated containment isolation valve is designed to the RCS pressure. It provides an additional barrier between the RCS and lower pressure portions of the RNS.

#### **19E.2.4.2.7 Normal Residual Heat Removal System Relief Valve**

The inside containment RNS relief valve is connected to the residual heat removal pump suction line. This valve is designed to provide low-temperature, overpressure protection of the RCS as described in Tier 2 Information subsection 5.2.2. The valve, connected to the high-pressure portion of the pump suction line, reduces the risk of overpressurizing the low-pressure portions of the system.

#### **19E.2.4.2.8 Features Preventing Inadvertent Opening of Isolation Valves**

The RCS isolation valves are interlocked to prevent their opening at RCS pressures above 450 psig. Tier 2 Information Section 7.6 discusses this interlock. The power to these valves is administratively blocked during normal power operation.

In addition, these valves are interlocked with the RNS/IRWST isolation valves to prevent their opening with the RNS open to the IRWST. This precludes the blowdown of the RCS to the IRWST through the RNS upon system initiation.

#### **19E.2.4.2.9 RCS Pressure Indication and High Alarm**

The AP600 RNS contains an instrumentation channel that indicates pressure in each normal residual heat removal pump suction line. A high-pressure alarm is provided in the main control room to alert the operator to a condition of rising RCS pressure that could eventually exceed the design pressure of the RNS.

### 19E.2.5 Component Cooling and Service Water Systems

The AP600 service water system and component cooling water system are described in Tier 2 Information subsections 9.2.1 and 9.2.2 respectively.

### 19E.2.6 Containment Systems

#### 19E.2.6.1 System Description

The containment systems are described in Tier 2 Information Section 6.2.

#### 19E.2.6.2 Design Features to Address Shutdown Safety

The AP600 has addressed the issue of containment closure at shutdown and incorporated the following requirements in the Technical Specifications (Tier 2 Information Chapter 16). In shutdown Modes 3 and 4, containment status is the same as at-power. Specifically, containment integrity is required, the major equipment hatches are closed and sealed, and containment air locks and isolation valves are operable.

In Modes 5 and 6, containment closure capability is required during shutdown operations when there is fuel inside containment. Containment closure is required to maintain, within containment, the cooling water inventory. Due to the large volume of the IRWST and the reduced sensible heat during shutdown, the loss of some of the water inventory can be accepted. Further, accident analyses provided in Section 19E.4 of this appendix show that containment closure capability is not required to meet offsite dose requirements. Therefore, containment does not need to be leak-tight as required for Modes 1 through 4.

In Modes 5 and 6, there is no potential for steam release into the containment immediately following an accident. Pressurization of the containment could occur only after heatup of the IRWST due to PRHR HX operation (Mode 5 with RCS intact), after heatup of the RCS with direct venting to the containment (Mode 5 with reduced RCS inventory or Mode 6 with the refueling cavity not fully flooded), or after heatup of the RCS and refueling cavity (Mode 6 with refueling cavity fully flooded). To limit the magnitude of cooling water inventory losses and because local manual action may be required to achieve containment closure, the containment hatches, air locks, and penetrations must be closed prior to steaming into containment.

The containment equipment hatches, which are part of the containment pressure boundary, provide a means for moving large equipment and components into and out of containment. If closed, the equipment hatch is held in place by at least four bolts. If open, each equipment hatch can be closed using a dedicated set of hardware, tools, and equipment. A self-contained power source is provided to drive each hoist while lowering the hatch into position. Large equipment and components may be moved through the hatches as long as they can be removed and the hatch closed prior to steaming into the containment.

The containment air locks, which are also part of the containment pressure boundary, provide a means for personnel access during Modes 1, 2, 3, and 4 unit operation. Each air

lock has a door at both ends. The doors are normally interlocked to prevent simultaneous opening when containment operability is required. During periods of unit shutdown when containment closure is not required, the door interlock mechanism may be disabled, allowing both doors of an air lock to remain open for extended periods when frequent containment entry is necessary. Temporary equipment connections (for example, power or communications cables) are permitted as long as they can be removed to allow containment closure prior to steaming into the containment.

Containment spare penetrations, which also provide a part of the containment boundary, provide for temporary support services (electrical, I&C, air, and water supplies) during Modes 5 and 6. Each penetration is flanged and normally closed. During periods of plant shutdown, temporary support systems may be routed through the penetrations; temporary equipment connections (for example, power or communications cables) are permitted as long as they can be removed to allow containment closure prior to steaming into the containment.

The spare penetrations must be closed or, if open, capable of closure prior to reaching boiling conditions within reactor coolant inventory. Temporary containment penetrations that may be employed during shutdown modes must have a design pressure equal to the containment design pressure of 45 psig.

Containment penetrations, including purge system flow paths, that provide direct access from containment atmosphere to outside atmosphere must be isolated or isolatable on at least one side. Isolation may be achieved by an operable automatic isolation valve or by a manual isolation valve, blind flange, or equivalent.

The fuel transfer canal may be opened to provide for the transfer of new and spent fuel into and out of containment during Modes 5 and 6. At times when the canal is opened, it must be isolatable on at least one side by closure of the flange within containment or the gate valve outside containment.

## **19E.2.7 Chemical and Volume Control System**

### **19E.2.7.1 System Description**

The chemical and volume control system (CVS) is described in Tier 2 Information subsection 9.3.6.

### **19E.2.7.2 Design Features to Address Shutdown Safety**

The AP600 CVS is a nonsafety-related system. However, portions of the system are safety-related and perform safety-related functions, such as containment isolation, termination of inadvertent RCS boron dilution, RCS pressure boundary preservation, and isolation of excessive makeup.

Boron dilution events during low power modes can occur for a number of reasons, including malfunctions of the makeup control system. Regardless of the cause, the protection is the

same. The CVS is designed to avoid and/or terminate boron dilution events by automatically closing either one of two series, safety-related valves in the demineralized water supply line to the makeup pump suction to isolate the dilution source. Additionally, the suction line for the CVS makeup pump is automatically realigned to draw borated water from the boric acid tank. The automatic boron dilution protection signal is safety-related and is generated upon any reactor trip signal, source-range flux multiplication signal, low input voltage to the Class 1E dc and uninterruptible power supply system battery chargers, or a safety injection signal.

The safety analysis of boron dilution accidents is provided in Tier 2 Information Chapter 15 and is discussed in subsection 19E.4.5 of this appendix. For dilution events that occur during shutdown, the source-range flux-doubling signal is used to isolate the line from the demineralized water system by closing the two safety-related remotely operated valves. The three-way pump suction control valve aligns the makeup pumps to take suction from the boric acid tank and, therefore, stops the dilution.

For refueling operations, administrative controls are used to prevent boron dilutions by verifying that the valves in the line from the demineralized water system are closed and locked. These valves block the flow paths that can allow unborated makeup water to reach the RCS. Makeup required during refueling uses borated water supplied from the boric acid tank by the CVS makeup pumps.

During refueling operations (Mode 6), two source-range neutron flux monitors are operable to monitor core reactivity. This is required by the plant Technical Specifications (Tier 2 Information Chapter 16). The two operable source-range neutron flux monitors provide a signal to alert the operator to unexpected changes in core reactivity. The potential for an uncontrolled boron dilution accident is precluded by isolating the unborated water sources. This is also required by the plant Technical Specifications.

## **19E.2.8 Spent Fuel Pool Cooling System**

### **19E.2.8.1 System Description**

The spent fuel pool cooling system (SFS) is discussed in Tier 2 Information subsection 9.1.3.

### **19E.2.8.2 Design Features to Address Shutdown Safety**

The AP600 has incorporated various design features to improve shutdown safety. The SFS features that have been incorporated to address shutdown safety are described in this subsection.

#### **19E.2.8.2.1 Seismic Design**

The spent fuel pool, fuel transfer canal (FTC), cask loading pit (CLP), cask washdown pit (CWP), and gates from the spent fuel pool-CLP and FTC-spent fuel pool are all integral with the auxiliary building structure. The auxiliary building is seismic Class I design and

is designed to retain its integrity when exposed to a safe shutdown earthquake (SSE). The suction and discharge connections between the spent fuel pool and RNS are safety Class C, which is also seismic Class I. The emergency makeup water line from the PCS water storage tank to the spent fuel pool actually connects with the RNS pump suction line. This emergency makeup line is also safety Class C and seismic Class I. The spent fuel pool level instruments connections to the spent fuel pool are safety Class C, seismic Class I, and have 3/8-inch flow restricting orifices at the pool wall to limit the amount of a leak from the pool if the instrument or its piping develops a leak.

The refueling cavity is integral with the containment internal structure, and as such, is seismic Class I, and is designed to retain its integrity when exposed to an SSE. In addition, the AP600 has incorporated a permanently welded seal ring to provide the seal between the vessel flange and the refueling cavity floor. This refueling cavity seal is part of the refueling cavity and is seismic Class I. Figure 19E.2-3 is a simplified drawing of the AP600 permanent reactor cavity seal. The cavity seal is designed to accommodate the thermal transients associated with the reactor vessel flange.

### **19E.2.9 Control and Protection Systems**

The AP600 control and protection systems support the operations necessary for the AP600 to achieve shutdown. These systems consist of a nonsafety-related plant control system (PLS), a safety-related protection and safety monitoring system (PMS), and a nonsafety-related diverse actuation system (DAS). These systems are discussed in Tier 2 Information Chapter 7.

### **19E.3 Shutdown Maintenance Guidelines and Procedures**

This section presents an overview discussion of AP600 shutdown maintenance guidelines and procedures captured as part of the AP600 design and design certification program. Shutdown maintenance requirements and guidelines have been identified in various licensing submittals, such as the AP600 Technical Specifications, (Tier 2 Information Section 16.1), and the design reliability assurance program, (Tier 2 Information Section 17.4).

Shutdown procedures have been addressed in the AP600 design certification program by the submittal of the AP600 Emergency Response Guidelines (ERGs) (Reference 1), which include shutdown emergency procedures.

While ultimately the responsibility of shutdown maintenance and shutdown risk management is the responsibility of the combined operating license (COL) applicant, this section summarizes the major shutdown maintenance guidelines and procedures that have been identified.

#### **19E.3.1 Maintenance Guidelines and Insights Important to Reducing Shutdown Risk**

This section presents an overview of AP600 shutdown maintenance guidelines and insights, captured as part of the AP600 design and design certification program, which are either required for plant safety or are effective at reducing shutdown risk.

**19E.3.1.1 Availability Requirements for Safety-Related Systems**

Availability controls of the AP600 safety-related systems are provided by the Technical Specifications. These availability requirements cover all modes of operation including shutdown.

**19E.3.1.2 Availability Guidelines for Regulatory Treatment of Nonsafety Related (RTNSS) - Important Systems**

Availability guidelines for RTNSS-Important systems are discussed in the AP600 Design Reliability Assurance Program, Tier 2 Information Section 17.4.

**19E.3.1.3 Reactor Coolant System Precautions and Limitations at Shutdown**

Precautions and limitations for RCS operation at shutdown are considered to minimize the risk to plant safety at shutdown. The most important of these are captured in the AP600 Technical Specifications. However, other precautions and limitations associated with maintenance and operation at shutdown have been identified during the design of the AP600. These are based on both the past operating experience of PWRs, as well as the designer's knowledge of the unique AP600 design features. A summary of these precautions and limitations that apply to shutdown maintenance and operation is provided in this section.

**19E.3.1.3.1 General Shutdown**

Precautions and limitations for general shutdown are as follows:

- To provide mixing, at least one reactor coolant pump (RCP) or a normal residual heat removal pump should be in service while chemicals are being added to the system or the boron concentration is being changed. This requirement is included in the AP600 Technical Specification 3.3.9
- Reactor coolant samples must be taken at the regular intervals to check coolant chemistry, activity level, and boron concentration as specified in the appropriate Technical Specifications including 3.1.1, 3.4.11, and 3.1-1. In addition, during shutdown modes, more frequent checks on RCS boron concentration should be made when changes in RCS boron concentration are being made.
- When the RNS is in operation, the reactor coolant temperature should not exceed 350°F. The reactor coolant pressure should be limited to avoid approaching the RNS relief valve setpoint.
- The maximum allowable heatup and cooldown rates for the RCS are provided in the Technical Specifications.
- During cooldown, the RCPs located in the loop containing the pressurizer spray line should be operated to provide adequate pressurizer spray.

- The accumulators must be isolated prior to reducing the RCS pressure to the accumulator pressure (637 to 769 psig). The LOCA analyses presented in this appendix assume that the accumulators are isolated 2.78 hours after reactor shutdown.

#### 19E.3.1.3.2 Water-Solid Operation

Precautions and limitations for water-solid operation are as follows:

- The RNS inlet line should not be isolated from the reactor coolant loop unless there is a steam bubble in the pressurizer or the makeup pumps are stopped. This precaution provides relief valve protection of the RCS when it is at low pressure and water-solid.
- Whenever the plant is water-solid and the reactor coolant pressure is being maintained by the letdown containment isolation ORC valve, the RNS should remain open to the reactor coolant loops to maintain sufficient letdown flow through the bypass line from the RNS to the letdown heat exchanger, until a steam bubble is formed in the pressurizer. During this mode of operation, the isolation valve in the bypass line from the RNS to the letdown heat exchanger should be in the full-open position and the letdown orifice bypass valve should also be open.
- If all RCPs are stopped and the reactor coolant temperature is greater than 200°F, the first pump should be restarted until a steam bubble has formed in the pressurizer. This precaution will minimize the pressure transient when the first pump is started. The steam bubble will accommodate the resultant expansion.
- When the reactor coolant pressure is being maintained by the letdown containment isolation ORC valve, changes to the flow rate through the RNS loop by throttling of valves or starting and stopping the RNS pumps will result in changes to the reactor coolant pressure.
- Whenever the reactor coolant temperature is above 160°F, at least one RCP should be in operation.

#### 19E.3.1.3.3 Steam Generators

Precautions and limitations for steam generators are as follows:

- During cooldown, all steam generators should be connected to the steam header to provide uniform cooldown of the reactor coolant loops.
- During steam plant warmup and at hot standby, draw steam slowly and regulate feedwater additions carefully to avoid rapid cooling of the reactor coolant.
- During cooldown, once RNS is in operation, and after the RCPs have been tripped, actions should be taken to cool the contents of the steam generator secondary side,

either by recirculation and cooling of this water or by draining the contents via the blowdown lines.

#### 19E.3.1.3.4 Surge Line

During heatup and cooldowns, the temperature difference between the pressurizer and the hot legs should be less than 320°F. This prevents unacceptable stress levels in the surge line.

#### 19E.3.1.3.5 Reduced-Inventory Operations

Precautions and limitations for reduced-inventory operations are as follows:

- The timing of the initiation of draindown is highly dependent of the scenario that requires the drained condition. However, in order to drain down to mid-loop conditions, the reactor coolant pumps must be tripped, and the RCS temperature must be less than saturation. Typically, the reactor coolant pumps operate until the RCS temperature is reduced to less than 160°F. For a refueling outage, the transition to reduced inventory conditions should typically begin about 3-4 days after shutdown. For a forced outage condition, reduced inventory operations should not begin until the RCS temperature is less than 160°F.

The time after shutdown directly affects the time that the RCS would boil and the rate at which inventory would be depleted following a loss of cooling event. Table 2.3-2 presents the time to reach saturation, and the time to core uncover for a loss of heat sink event initiated from mid-loop conditions at 28 hours after shutdown. For loss of heat sink events initiated earlier, the time to reach saturation and the time to uncover the core would be slightly decreased. The performance of the IRWST injection, in conjunction with ADS, is sufficient to mitigate the consequences of the event.

The time after shutdown impacts the requirements for containment closure during shutdown as discussed in subsection 19E.2.6.2 of this appendix (and captured in the Technical Specifications). For reduced inventory conditions, if the time to steaming (inside containment) following a loss of heat sink event is less than the time required to close the containment equipment hatches, then these hatches should be closed. If the time after shutdown is sufficiently long, such that steaming to containment would not occur prior to the containment hatches being able to be closed, then the equipment hatches could be open, with the ability to close them.

- As the RCS is drained, the rate of change in water level will vary non-linearly for a given drain rate due to the geometry of the RCS and the offset hot leg and cold leg piping. It is important to drain the RCS at a low rate to minimize the possibility of overdraining the system. Evaluations have been performed that indicate that a drain rate of 20 gpm is sufficient once the water level has been reduced to the top of the hot leg.

- After maintenance operations that result in draining the RCS, the system should be refilled with borated makeup water at the prevailing RCS boron concentration via the chemical and volume control system (CVS) makeup pumps. If the RCPs are drained, the pumps should be refilled with borated water via the pump drain line so that the pump is completely filled with borated water.
- After maintenance operations on the CVS purification loop (demineralizer, filters, and heat exchangers), the system should be purged, draining potential unborated water to the liquid radwaste system, and refilling it with borated water from the RCS. These operations should not be conducted at mid-loop or reduced inventory operations to avoid an inadvertent drop in RCS water level during mid-loop.
- The RCS hot leg level instruments should be operable and available prior to reduced inventory operations. Their automatic actuation functions are required to be operable in shutdown modes as described in Technical Specification 3.3.2.

### 19E.3.2 Shutdown Risk Management

This appendix contains insights of which Westinghouse is currently aware and which are related to AP600 design certification.

### 19E.3.3 Shutdown Emergency Response Guidelines Overview

The AP600 ERGs (Reference 1) provide functional guidance for responding to accidents and transients that affect plant safety during shutdown modes of operation (operational Modes 5 and 6). The shutdown ERGs consist of a shutdown safety status tree for monitoring the critical safety functions and six shutdown guidelines for responding to the respective challenges to plant safety.

The shutdown safety status tree provides a systematic method of determining the safety status of the plant. This status tree represents the critical safety functions that are of concern during plant shutdown conditions. Prior to this shutdown condition, the plant can be in any state ranging from heatup and pressurization (from 200°F to no-load temperature) to full power operation. Under these conditions (plant Modes 4 through 1), plant monitoring and response to a reactor trip or requirement for safety injection are covered by the optimal recovery guidelines, status trees, and function restoration guidelines of the at-power ERGs.

By using the shutdown status tree, plant conditions are monitored during plant shutdown after entering Mode 5 while normal operating procedures are in use for plant shutdown operations. The shutdown safety status tree is arranged so that the functions are checked in order of importance. Core cooling during shutdown conditions is addressed first. During plant shutdown conditions, the RNS provides core cooling, which requires adequate RCS inventory to operate properly. RCS inventory checks are made first to show core cooling will not be interrupted because of inadequate RCS inventory and as an early symptom to a loss of shutdown core cooling. After adequate RCS inventory is checked, RNS operation is checked to verify shutdown core cooling is being provided by the RNS. After RNS

operation is verified, containment radiation is checked so that an unexpected uncontrolled release will not occur because containment integrity may be breached during plant shutdown maintenance activities. Core reactivity is then checked by monitoring source range flux doubling as an early symptom of an unintended RCS boron dilution, which should occur at a slow enough rate to allow appropriate action to be taken to reestablish shutdown margin. RCS cold overpressure symptoms of RCS pressure and temperature are monitored for maintaining the RCS pressure boundary integrity safety function.

Lastly, RCS temperature change, aside from any normal expected RCS temperature change, is used as an early symptom for potential degradation of the core cooling safety function and the RCS pressure boundary integrity safety function. The shutdown safety status tree is considered to be satisfied when all status tree blocks have been satisfied. If a challenge is identified during the monitoring of the tree, the tree directs plant operators to one of the appropriate six shutdown guidelines for mitigating actions.

The format and arrangement of the shutdown ERG documentation is similar to the at-power ERGs consisting of guidelines and background documents. Implementation of the shutdown ERGs into plant procedures will also be similar to the at-power ERGs with the task allocation between the man and the computer for doing this to be decided when designing features of the man-machine interface system.

## **19E.4 Safety Analyses and Evaluations**

### **19E.4.1 Introduction**

This section reviews each of the design basis accidents (DBAs) and transients presented in the AP600 Tier 2 Information Chapter 15, with respect to lower power and shutdown modes. In subsections 19E.4.2 through 19E.4.9, evaluations or analyses are performed for each case of the transient and LOCA analyses for events occurring at low power and shutdown operations, including the reduced reactor coolant system (RCS) inventory and refueling operations. The evaluations discuss the effects of key plant parameters (for example, plant control parameters, neutronic and thermal hydraulic parameters, and engineering safety features [ESFs]) on plant transient response (such as departure from nucleate boiling ratio [DNBR], peak pressure, and peak cladding temperature). The limiting case for each event category is identified. For those limiting cases bounded by the cases analyzed at power conditions, supporting rationales are provided.

For those events where analyses are presented in the shutdown modes, a discussion of the adequacy of the codes used is presented in subsection 19E.4.1.2.

In subsection 19E.4.10, additional analyses and evaluations demonstrate that the passive systems can bring the plant to a stable, safe condition and maintain this condition.

#### **19E.4.1.1 Matrix of Tier 2 Information Chapter 15 Events**

Table 19E.4.1-1 provides a list of AP600 Tier 2 Information Chapter 15 events. This table categorizes the events as "E" (requiring evaluation), "A" (requiring analysis), or "n/a" (not

applicable). The "n/a" events are bounded by at-power analyses or current Tier 2 Information analyses.

The events denoted by an "n/a" in Table 19E.4.1-1 are as follows:

- Boron dilution design basis transient explained in Tier 2 Information subsection 15.4.6 because it explicitly considers all modes such that no analysis or evaluation is required for this appendix
- Rod cluster control assembly (RCCA) withdrawal at-power explained in Tier 2 Information subsection 15.4.2 because this event occurs only at-power

#### 19E.4.1.2 Adequacy of Codes Used for Analyses from Shutdown Conditions

Each analysis subsection in this Section 19E.4 discusses the appropriate code used for each analyses. Generally, LOFTRAN-AP is used for transient analyses, which require AP600 design features (core makeup tanks [CMT] and passive residual heat removal heat exchanger [PRHR HX], etc.); LOFTRAN for transient analysis, which is independent of the special AP600 design features; LOFTTR2-AP for steam generator tube ruptures; NOTRUMP for small-break LOCAs; and WCOBRA/TRAC for large-break LOCAs.

The adequacy of LOFTRAN-AP, LOFTTR2-AP, NOTRUMP, and WCOBRA/TRAC to accurately represent shutdown conditions in the AP600 is discussed in this subsection.

The LOFTRAN-AP and LOFTTR2-AP codes are not needed for AP600 safety analyses initiated in lower modes. Therefore, their adequacy is not discussed in this appendix. The LOCA codes (NOTRUMP and WCOBRA/TRAC) are used to analyze AP600 events at shutdown.

Shutdown events involve lower core power levels than full-power Tier 2 Information LOCA analyses. In that sense, the demands on a thermal-hydraulic computer code used to analyze the shutdown events are less than at full power. Codes that have been qualified for use in full-power AP600 events should capably evaluate the more benign transient conditions at shutdown. Moreover, as discussed below, specific qualification exists for application of the Westinghouse LOCA codes to AP600 shutdown cases.

The applicability of WCOBRA/TRAC to pressurized water reactor (PWR) large-break LOCA events has been established through an extensive set of test simulations (WCAP-12945, volumes 1-5) (Reference 13). The applicability of the models in WCOBRA/TRAC to AP600 large-break LOCA analysis has been documented in WCAP-14171, revision 1 (Reference 14). Through an extensive review of the pertinent phenomena, WCAP-14171, revision 1, shows that WCOBRA/TRAC can accurately represent a large-break LOCA for the AP600; it also provides specific validation for the downcomer injection location.

The Phenomena Identification Ranking Table (PIRT)-based (Reference 15) AP600 large-break LOCA phenomena, for which the code has been shown applicable in WCAP-14171 at full power, to a large extent remain applicable at shutdown conditions. Items ranked high

in importance remain so for a postulated large-break LOCA occurring at shutdown, and none of the phenomena that are not ranked high become highly important, with one exception: the reliance on a different passive safety system, the CMTs, to mitigate the event when the accumulators are isolated. As at full power, condensation of steam in the PRHR HX has a small effect on the AP600 large-break LOCA analysis and does not require specific validation. WCAP-14171 identifies the means by which the uncertainty associated with important parameters in the PIRT is quantified under the best-estimate LOCA methodology used for the full-power emergency core cooling system (ECCS) analysis. Instead of dealing with uncertainty methodology, a conservative prediction of the shutdown large-break LOCA ECCS performance is obtained by using the 10 CFR 50, Appendix K (Reference 16), decay heat function.

A significant change at shutdown conditions is the low-power level in effect. WCOBRA/TRAC has been used to analyze the long-term cooling portion of the Oregon State University (OSU) facility integral tests (WCAP-14776) (Reference 18). This effort validates that at core decay power levels comparable to those which prevail during shutdown, WCOBRA/TRAC is qualified to analyze AP600 phenomena. The same version of WCOBRA/TRAC is used in both short-term large-break LOCA and long-term cooling analyses of the AP600. In summary, the WCOBRA/TRAC computer code has been shown to apply to large-break LOCA events for the AP600 at shutdown conditions.

The NOTRUMP computer code has been shown (WCAP-14807) (Reference 19) to effectively model small-break LOCA phenomena of importance to the AP600. The phenomena ranked HIGH in importance in the WCAP-14807 PIRT are also highly important for a small-break LOCA occurring after the accumulators are isolated during Mode 3 in the AP600, except for the accumulator phenomena. In its validation against the OSU test data, NOTRUMP modeled AP600-specific tests which were initiated at power levels comparable to shutdown power values. All tests at the OSU facility were initiated from a simulated decay power level. Furthermore, the typical initial fluid pressure and temperature of 380 psia and 420°F in the OSU facility tests are similar to the AP600 RCS values during Mode 3 shutdown operations, the shutdown mode in which decay heat is at its highest.

Gravity drain phenomena predominate during small-break LOCA events. For analyzing such events in the lower shutdown modes, the NOTRUMP code validation performed against both single-effects tests, including the CMT test facility, and OSU remain applicable. At these lower modes, phenomena ranked high in the WCAP-14807 PIRT remain high in importance, until the reactor pressure becomes so low that critical flow modeling is no longer relevant. Further, there are no phenomena of high importance during small-break LOCA shutdown events that are not covered by the tests at OSU. Therefore, the NOTRUMP prediction of small-break LOCA events initiated from shutdown conditions in the AP600 has been validated by NOTRUMP simulations of single-effects tests and the OSU tests.

## 19E.4.2 Increase in Heat Removal from the Primary System

### 19E.4.2.1 Feedwater System Malfunctions Which Increase Heat Removal from the Primary System

Faults that decrease feedwater temperature or increase feedwater flow can be postulated in the feedwater system. These faults could increase heat removal from the primary system, which reduces RCS temperature. The reduction in RCS temperature could lead to an increase in core power generation (due to a negative moderator temperature coefficient) and result in a reduction in margin-to-core design limits. Unchecked, excessive feedwater flow could also result in overfilling the steam generators.

Discussions and analyses, initiated from Modes 1 and 2, of RCS cooldowns caused by feedwater system malfunctions are presented in the AP600 Tier 2 Information, subsections 15.1.1 and 15.1.2. Subsection 15.1.1 covers reductions in feedwater temperature, and subsection 15.1.2 covers increases in feedwater flow. Modes 1 and 2 are the limiting initial conditions for feedwater system induced RCS cooldown transients.

Protection against feedwater system induced cooldown transients is provided by the protection and safety monitoring system (PMS) through automatic functions that trip the reactor and isolate the feedwater system. The protection functions are available in all modes during which the feedwater system is in operation. Reactor trip includes overpower  $\Delta t$ , high power-range nuclear flux, high intermediate-range nuclear flux, or high source-range nuclear flux. The PMS closes the main feedwater control valves on low-1 RCS average temperature signal. The PMS also closes the main feedwater isolation valves and trips the booster/main feedwater pumps when RCS average temperature decreases below the low-2 RCS  $T_{avg}$  setpoint. These protection functions are arranged to detect symmetrical plant transients with a channel out of service and a single channel failure.

Additional PMS functions are provided to detect and protect against asymmetrical feedwater system malfunctions. Automatic reactor trip, closure of the main feedwater control and isolation valves, closure of the startup feedwater control and isolation valves, tripping of the booster/main feedwater pumps, and tripping of the startup feedwater pumps occur if the level in a single steam generator is above the high-2 water level setpoint. Similar actions occur if cold leg temperature in a single RCS loop decreases below the low  $T_{cold}$  setpoint. The high-2 steam generator level setpoint is active in Modes 1 through 4 unless the various feedwater valves are closed. This ensures that the steam generators cannot inadvertently be overfilled. The low  $T_{cold}$  signal is available in Modes 1 through 3. In Mode 3 prior to blocking the low  $T_{cold}$  signal, the RCS must be borated to cold shutdown conditions. With the RCS borated, no feedwater malfunction can be postulated to cool the RCS such that a core power excursion would occur.

The feedwater malfunction associated with a drop in feedwater temperature is less severe as power level is decreased. Normal operating feedwater temperature decreases as plant power level decreases. Therefore, if a fault suddenly reduces the feedwater temperature, the maximum change in feedwater temperature will occur if the plant is operating at full power.

As discussed in subsection 19E.2.2 of this appendix, in Modes 2 and below, feedwater entering the steam generators is routed through the startup feedwater control valves. The maximum achievable flow rate through the startup feedwater path is much less than when flow is being controlled by the main feedwater control valves. Therefore, failure of a main feedwater control valve in Mode 2 and below is not likely. The assumption of a failed open startup feedwater control valve, in Mode 2 and below, will result in a relatively slow transient due to low feedwater flow rate.

The most severe RCS cooldowns caused by feed system malfunctions will occur in Modes 1 or 2. In Modes 3 or 4, RCS cooldowns due to feedwater malfunctions would be precluded, inconsequential, or less severe than in Modes 1 or 2. The analyses presented in the AP600 Tier 2 Information bound the consequences of this class of events initiated in the shutdown modes.

#### 19E.4.2.2 Excessive Increase in Secondary Steam Flow

An excessive increase in secondary steam flow (excessive load increase) is caused by a rapid increase in steam flow that results in a power mismatch between the reactor core power and the steam generator load demand. The plant control system (PLS) is designed to accommodate a 10-percent step load increase in steam flow in the range of 25 to 100 percent of full power. Analyses results for a 10-percent step increase in steam flow are presented in Tier 2 Information subsection 15.1.3. The analyses are performed for Mode 1 from full-power initial conditions. Depending upon the plant and PMS characteristics (setpoint uncertainties), a reactor trip signal may or may not be generated for an excessive load increase from full power.

An excessive load increase in Mode 1 is considered limiting because an excessive load increase at full power will put the plant at the highest achievable power level. Load increases at less than full power, or during startup (Mode 2), will not reach as high a power level. The excessive load increase, in Mode 2, will not be as severe as the Mode 1 excessive load increase.

In Mode 3, the excessive load increase may be considered to be a simple steam release because there can be no load, per se, when the turbine is off-line and the core is subcritical. The Mode 3 load increase will be less limiting than the Mode 1 or Mode 2 case because the core is already subcritical. Automatic safeguards actuation signals may not be available if blocked by the operator (blocking is necessary to depressurize and cool down the RCS). However, the RCS must be borated to meet shutdown margin requirements at cold shutdown (200°F) prior to blocking automatic safeguards actuation signals to prevent a return to criticality in the event of a cooldown.

The Mode 4 situation is bounded by Mode 3 because pressure and temperature conditions in the primary and secondary systems are reduced. At some point in Mode 4, the RNS will be placed in service. In Modes 5 and 6, the RNS should be in operation. Any steam release will have little or no effect upon the core.

### 19E.4.2.3 Credible and Hypothetical Steamline Breaks

The spurious opening of a steam generator safety or relief valve is a Condition II event and referred to as a credible steam line break. This event affects the core like a load increase but the analysis assumptions that are applied are different. The credible steam line break is usually assumed to be an unisolatable, uncontrolled steam release, which causes a non-uniform core cooldown (typical of an open safety valve) during the period immediately following a reactor trip which inserts all but the most reactive rod cluster control assembly (RCCA). The resulting reactivity excursion may be large enough to overcome the shutdown margin and return the core to critical, especially when there is little or no decay heat (with power peaking in the region of the stuck RCCA). The credible steam line break is analyzed in Mode 2, and the results are presented in Tier 2 Information subsection 15.1.4. The assumptions used in the analysis lead to a more severe, post-trip transient than will result from a load increase initiated in Mode 1.

In Mode 1, prior to reactor trip, the transient characteristics of an inadvertent opening of a steam generator safety or relief valve are similar to the excessive load increase. A reactor trip signal, if needed, may result from overpower  $\Delta T$  logic. After the reactor trip, the concern becomes a possible return to criticality with the most reactive RCCA stuck in the fully withdrawn position, leading to high local power levels. However, a post-trip return to criticality is less likely when this event occurs in Mode 1 than in Mode 2 because there will be more decay heat present, which tends to retard the cooldown.

In Mode 3, results are expected to be better than the Mode 2 case because pressure, temperature, and flow conditions will be less limiting. An occurrence in Mode 4 will be less severe than in Modes 2 or 3 due to the lower initial RCS temperature, and an effective decoupling of the secondary system from the primary system as the reactor coolant pumps (RCPs) are removed from service and the RNS is started. Automatic safeguards actuation signals are available through Mode 3, until the RCS is borated and the automatic safeguards signals are blocked (see excessive load increase discussion). Both CMTs continue to be available for automatic actuation on low-2 pressurizer level or manual actuation through Mode 4 with the RCS not being cooled by the RNS (see Technical Specification LCO 3.5.2). In Mode 4 with the RNS in operation and in Mode 5 with the RCS pressure boundary intact, one CMT is available for activation if needed.

Any cooldown in Modes 5 and 6 caused by depressurization of the secondary system is meaningless because the RCS is already cold, and the RNS system effectively decouples the steam generators from the core.

The steam line rupture is a Condition IV event, producing a greater uncontrolled steam release than the spurious opening of a steam generator safety valve (described above), but the relative effects in the various modes and requirements for protection equipment are the same. This is the most severe cooldown event.

#### 19E.4.2.4 Inadvertent PRHR HX Operation

Inadvertent actuation of the PRHR HX causes an injection of relatively cold water into the RCS. This produces a reactivity insertion in the presence of a negative moderator temperature coefficient. Because the PRHR HX is connected to only one RCS loop, the cooldown resulting from its actuation is asymmetric with respect to the core. Inadvertent actuation of the PRHR HX could lead to an asymmetric power increase and a reduction in margin-to-core design limits.

A limiting analyses of an inadvertent actuation of the PRHR HX heat exchanger is presented in subsection 15.1.6 of the AP600 Tier 2 Information. The analysis in the Tier 2 Information is initiated in Mode 1 from hot full-power conditions. This is the most limiting case.

The PRHR HX heat transfer rate is a function of the inlet temperature to the heat exchanger and the flow rate through the heat exchanger. PRHR HX heat transfer rate is higher with high flow rates and high inlet temperatures. Therefore, the maximum heat removal rate will occur when the plant is at full-power condition with forced RCS flow and a high hot leg temperature. At plant full-power conditions, the PRHR HX heat removal rate is approximately 10 percent of full power. At hot zero power (HZP) conditions with natural circulation, heat removal by the PRHR HX is approximately 1.5 percent to 2 percent of full power.

The heat sink for the PRHR HX is the in-containment refueling water storage tank (IRWST), in which the heat exchanger is submerged. Prior to actuation of the PRHR HX, the fluid within the heat exchanger is in thermal equilibrium with the fluid in the IRWST. Thus, the PRHR HX is initially filled with relatively cold fluid which is at containment ambient temperature. When the PRHR HX is actuated, the initial fluid outsurge is fluid at containment ambient temperature. Once the original fluid in the PRHR HX is purged, the out-flow temperature trend of the heat exchanger is set by the temperature entering the heat exchanger from the RCS hot leg minus the temperature drop through the heat exchanger. Thus, the outlet fluid temperature is limited by the cooling capacity of the PRHR HX.

If the reactor is at power (Mode 1 or 2) when the PRHR HX is inadvertently actuated, a cooldown induced increase in core power will occur. The transient response will have two parts. As the cold fluid from the PRHR HX, which is initially at the ambient IRWST temperature, enters the RCS, a large core power increase will occur. The magnitude of the power increase is proportional to the volume of the cold fluid in the PRHR HX. Once the original fluid is purged from the PRHR HX, the fluid temperature exiting the PRHR HX increases to a value limited by the cooling capacity of the PRHR HX. Core power will then decrease to a value higher than the initial core power, but in equilibrium with the heat removal capability of the steam generators plus the PRHR HX.

With the assumptions of a protection system channel out of service as allowed by the Technical Specifications, a failure of an additional protection system channel, and maximum instrument uncertainties, the asymmetric core power transient may not result in actuating any overpower reactor trips, such as high nuclear flux or overpower  $\Delta t$ . In this case, the

core power transient is controlled only by the initial volume of cold water in the PRHR HX and the heat removal capability of the heat exchanger.

Higher initial core power will result in the largest achievable core power and in more severe consequences. Therefore, if the reactor is at-power, the full-power case produces the worst results.

In Mode 3, because the reactor is subcritical, inadvertent actuation of the PRHR HX produces a less severe power excursion than if the reactor is at power or at HZP with the reactor just critical. If in Mode 3 below no-load temperature, the cooldown caused by the actuation of the PRHR HX results in the cold leg temperature dropping below the low  $T_{\text{cold}}$  safeguards signal setpoint. This function actuates a reactor trip, initiates boration by the CMTs, and most importantly, trips all the RCPs. When the RCPs trip, natural circulation flow begins in the RCS and the PRHR HX loop. When natural circulation flow is initiated, the heat removal capability of the PRHR HX decreases to approximately 1.5 percent of full power and the severity of the transient is minimized. With the RCS in natural circulation, the cooldown rate of the RCS is also slowed. If criticality is obtained, boration by the CMTs will bring the core subcritical again.

The low  $T_{\text{cold}}$  safeguards signal may be blocked by the operator in Mode 3 to allow plant depressurization and cooldown to lower modes. However, prior to blocking the low  $T_{\text{cold}}$  safeguards signal, the RCS is borated to the shutdown margin requirements at cold shutdown (200°F). Therefore, in Mode 3 with safeguards signals blocked or in Mode 4, cooldown of the RCS by inadvertent actuation of the PRHR HX will not result in a reactivity excursion, which produces a power increase.

In Modes 5 and 6, the RCS will be borated such that a cooldown-induced power excursion could not be postulated. The RCS will be at 200°F or less, and with initial RCS temperatures this low, no significant cooling of the RCS by inadvertent actuation of the PRHR HX could be postulated.

### **19E.4.3 Decrease in Heat Removal by the Secondary System**

#### **19E.4.3.1 Loss of Load and Turbine Trip**

Discussions and analyses of the consequences of loss of load, turbine trip, inadvertent closure of main steam isolation valves (MSIVs), or loss of condenser vacuum are presented in Tier 2 Information subsections 15.2.2 through 15.2.5. These events are characterized by a rapid reduction in steam flow from the steam generators. This results in an increase in steam pressure and a heatup of the primary side if the reactor power is not reduced. The effects of the primary to secondary power mismatch during these events are mitigated by tripping the reactor and opening secondary and primary side safety valves. The severity of these events is increased if the primary to secondary power mismatch is increased. Therefore, the most severe results occur if the plant is initially operating in Mode 1 at maximum-rated plant power conditions rather than lower power conditions. The turbine is off-line below Mode 1 and transients related to turbine-related faults cannot occur.

In Modes 2, 3, or 4, the plant may be removing decay heat by dumping steam to the condenser. In Mode 4 when the RCS is below 350°F, decay heat is removed using the RNS. In Modes 2, 3, or 4, the transient response to a loss of condenser vacuum or inadvertent MSIV closure is bounded by the turbine trip analysis from full power because the power mismatch is low. Decay heat removal can still be accomplished by the steam generators through atmospheric steam relief through power-operated relief valves (PORVs) if available or through steam generator safety valves, which are available through Mode 4 (see Technical Specification LCO 3.7.1). Additionally, decay heat can be removed with the PRHR HX, which is available through Mode 5 with the RCS intact (see Technical Specifications LCO 3.5.4 and 3.5.5).

#### 19E.4.3.2 Loss of ac Power

A discussion and an analysis of a loss of ac power event is provided in Tier 2 Information subsection 15.2.6. The loss of ac power results in the loss of forced primary coolant flow and the loss of main feedwater flow. This results in a heatup and pressurization of the RCS. If the reactor is at power, the event is mitigated by tripping the reactor. The reactor may be automatically tripped on low RCP speed, low RCS flow, low steam generator level, or several other primary side heatup signals. Also reactor trip may occur due to the loss of power to the control rod drive mechanisms.

Following reactor trip, the PRHR HX is activated for decay heat removal. Automatic PRHR HX actuation on low steam generator level is available in Modes 1 through 3 and in Mode 4 when the RCS is not being cooled by the RNS. The most limiting case for loss of ac power would be if the plant were at full rated power. This will result in the highest decay heat levels and stored energy in the RCS and the heat removal capability of the PRHR HX will be maximized. In Modes 4 or 5 with the RNS in operation, the plant response to a loss of ac power is the same as the loss of RNS cooling as discussed in subsection 19E.4.8.5 of this appendix.

#### 19E.4.3.3 Loss of Normal Feedwater

The main feedwater system is in operation during Modes 1 and 2. The startup feedwater system is used in Mode 2 below approximately 2 percent power, in Mode 3, and in Mode 4 before the RNS is aligned. In Mode 4 with the RNS aligned and in Modes 5 and 6, the feedwater system is not used, and therefore, loss of feedwater events are irrelevant.

A discussion and an analysis of a loss of normal feedwater event from rated full-power conditions are provided in Tier 2 Information subsection 15.2.7. The loss of normal feedwater flow results in a heatup and pressurization of the RCS. If the reactor is at-power, the event is mitigated by tripping the reactor on low steam generator level.

Following reactor trip, the PRHR HX is activated for decay heat removal. Automatic PRHR HX actuation on low steam generator level is available in Modes 1 through 3 and in Mode 4 when the RCS is not being cooled by the RNS. The most limiting case for a loss of normal feedwater is with the plant initially at full rated power. This case will have the highest decay heat levels and stored energy in the RCS and the heat removal capability

of the PRHR HX will be maximized. The Tier 2 Information analysis initiated from full power bounds cases initiated from the shutdown modes.

#### 19E.4.3.4 Feedwater System Pipe Break

Depending upon the size of the break and plant operating conditions, the break could cause either an RCS heatup or an RCS cooldown. The cooldown aspects are less severe than a steam line break, which is discussed in subsection 19E.4.2.3 of this appendix and is not considered in the following discussion.

The main feedwater system is in operation during Modes 1 and 2. The startup feedwater system is used in Mode 2 below approximately 2 percent power, in Mode 3, and in Mode 4 before the RNS is aligned. In Mode 4 with the RNS aligned and in Modes 5 and 6, the feedwater system is not used, and therefore, a loss of feedwater caused by a feedwater system pipe break will not cause a heatup of the RCS.

A discussion and an analysis of feedwater system pipe break from rated full-power conditions are provided in Tier 2 Information subsection 15.2.8. A rupture of a feedwater system pipe results in a loss of feedwater flow causing a heatup and pressurization of the RCS. If the reactor is at-power, the event is mitigated by tripping the reactor on low steam generator level.

Following reactor trip, the PRHR HX is activated for decay heat removal. Automatic PRHR HX actuation on low steam generator level is available in Modes 1 through 3 and in Mode 4 when the RCS is not being cooled by the RNS. The most limiting case for a feedline break occurs with the plant at full rated power. This case will have the highest decay heat levels and the highest stored energy in the RCS and the heat removal capability of the PRHR HX will be maximized.

#### 19E.4.4 Decrease in Reactor Coolant Flow Rate

##### 19E.4.4.1 Partial and Complete Loss of Forced RCS Flow

A partial loss of forced RCS flow may be caused by a mechanical or an electrical failure in an RCP or from a fault in the power supply to the pumps. An RCP failure will result in only the loss of a single RCP. A fault in the power supplies for the RCPs could result only in the loss of one, two, or all four RCPs. There is no credible failure that could result in the loss of three RCPs.

The loss of one or more RCPs reduces the heat removal rate from the primary to the secondary coolant system and thereby causes a heatup in the RCS. The heatup of the RCS results in an increase in RCS pressure and a decrease in margin-to-core design limits (that is, departure from nucleate boiling [DNB]). An occurrence at full power will produce a greater and more rapid heatup than at part-power conditions or low-power conditions in Mode 2. Therefore, for evaluating the maximum RCS pressure or the minimum DNB ratio, analyses are performed at full-power conditions. Analyses for partial loss of forced RCS flow transients are presented in subsection Tier 2 Information 15.3.1. Analyses for a

complete loss of flow are presented in Tier 2 Information subsection 15.3.2. These analyses bound loss of flow events initiated in other modes.

Protection for loss of forced RCS flow events is provided by tripping the reactor. This reduces reactor power and preserves margin-to-DNB limits. The AP600 PMS includes a reactor trip on low RCS flow in any cold leg and a reactor trip on low RCP speed in any two of four RCPs. These two reactor trips are used to detect all possible partial and complete loss of RCS flow transients. Opening of the pressurizer safety valves in conjunction with the reactor trip prevents overpressurization of the RCS.

Below Mode 2, when the core is subcritical, forced RCS flow is not needed because margin-to-DNB is not an issue. It is common to have one or more RCPs out of service below Mode 2 because full RCS flow is no longer needed. In Modes 3 through 5, LCO 3.4.5 of the Technical Specifications (Reference 4.4-2) requires that only three RCPs need to be operating if the reactor trip breakers are closed, to ensure that DNB limits are not exceeded, in the event RCCAs are inadvertently withdrawn. If the trip breakers are open and RCCA withdrawal is precluded, no RCPs are required to be operating in Modes 3 through 5.

Following reactor trip in loss of forced RCS flow events, decay heat removal is required. The PRHR HX or the steam generators can be used for decay heat removal. In the event of a complete loss of forced RCS flow, RCS natural circulation is adequate to remove core decay heat. This is demonstrated by the loss of ac power analysis presented in Tier 2 Information subsection 15.2.6.

#### **19E.4.4.2 Reactor Coolant Pump Shaft Seizure or Break**

An RCP shaft seizure or break results in a partial loss of forced RCS flow. The results are similar to partial loss of flow events discussed in subsection 19E.4.4.2 of this appendix except that the rate of flow reduction is much more rapid if an RCP shaft breaks or seizes. Like the partial loss of flow, a locked or broken RCP shaft reduces the heat removal rate from the primary to secondary coolant system and thereby causes a heatup of the RCS. An occurrence at full power produces the most severe heatup transient. The discussion for the partial loss of flow with respect to limiting modes and protection is applicable to the RCP shaft seizures or breaks.

Analyses and evaluation of RCP shaft seizures and breaks for Mode 1, from full-power conditions, are provided in Tier 2 Information subsections 15.3.3 and 15.3.4. The analyses bound events initiated from the shutdown modes.

#### **19E.4.5 Reactivity and Power Distribution Anomalies**

##### **19E.4.5.1 Uncontrolled RCCA Bank Withdrawal from a Subcritical Condition**

An uncontrolled RCCA bank withdrawal from a subcritical condition could cause a reactivity excursion, which if not terminated by a reactor trip, could result in DNB. Tier 2 Information subsection 15.4.2 presents an analysis for the uncontrolled RCCA bank

withdrawal from a subcritical condition in Mode 2. Assumptions are used that make the analysis bound an occurrence in Modes 2, 3, 4, or 5. Specific conservative assumptions are made for the number of RCPs operating, the reactor trip functions credited, initial RCS temperature, and the magnitude of the reactivity excursion.

A single failure in the rod control system could cause the withdrawal of only one bank, and its withdrawal rate would be expected to be slower than the maximum rod speed possible when in automatic rod control. The analysis assumes the simultaneous withdrawal of the combination of two sequential RCCA banks having the greatest combined worth at the maximum possible speed.

LCO 3.3.1 of the AP600 Technical Specifications gives the operational requirements for reactor trips. The source-range high neutron flux trip must be in operation in Modes 3, 4, and 5 if the reactor trip breakers are closed. If the reactor trip breakers are open, then an RCCA withdrawal is precluded from occurring. The source-range high neutron flux trip is available in Mode 2 if power is below the P-6 interlock. In these instances, the source-range high neutron flux trip would be available to terminate the event, by tripping any withdrawn and withdrawing rods, before any significant power level could be attained. Therefore, DNB would be precluded. The intermediate-range high neutron flux reactor trip is also available in Mode 2. The AP600 Tier 2 Information analysis assumes that reactor trip does not occur until the power-range (low setting) high neutron flux setpoint is reached. No credit is assumed in the analysis for the source-range high neutron flux reactor trip or the intermediate-range high neutron flux reactor trip.

LCOs 3.4.4 and 3.4.5 of the AP600 Technical Specifications give the operation requirements for RCPs. LCO 3.4.4 specifies that in Modes 1 and 2, all four RCPs must be operating. LCO 3.4.5 specifies that in Modes 3, 4, and 5, at least three RCPs must be operating whenever the reactor trip breakers are closed. For minimizing the DNB margin, the AP600 analysis assumed only three RCPs are operating to bound operation in Modes 2, 3, 4, or 5.

The RCS temperature is assumed to be at the HZP value in the analysis. This is more limiting than that of a lower initial system temperature for DNB and core kinetics feedback calculations.

These conservative assumptions result in the core returning to critical and generating power before reactor trip occurs. The analysis presented in the Tier 2 Information bounds the inadvertent RCCA bank withdrawal from a subcritical condition transient in Modes 2 through 5.

#### **19E.4.5.2 Uncontrolled RCCA Bank Withdrawal at Power**

This transient is defined only in Mode 1.

#### **19E.4.5.3 RCCA Misalignment**

RCCA misalignment events are analyzed in Tier 2 Information subsection 15.4.3. RCCA misalignment events include the following:

- One or more dropped RCCAs
- Statically misaligned RCCA
- Withdrawal of a single RCCA

This group of events may result in core radial power distribution perturbations, which may cause allowable design power peaking factors and DNB design limits to be exceeded. Therefore, these events are a concern only in the at-power modes, and the severity will be increased at high power. If the reactor is subcritical, DNB will not be a concern.

Following the dropping of one or more RCCAs while at-power, core power will immediately be reduced. The reduced core power and the continued steam demand to the turbine causes a reactor coolant temperature decrease. If the reactor is in manual control, the core power rises due to moderator feedback to the initial power level at a reduced core inlet temperature. If the reactor is in automatic control, the control system detects the drop in power and initiates withdrawal of a control bank. Power overshoot above the initial power level may occur as the control system withdraws a bank. Following dropping of one or more RCCAs, the most severe results occur when the control system overshoots the initial power level in conjunction with a perturbation in the radial power distribution. This is the most limiting case for this event, and the results are presented in the Tier 2 Information. If the reactor is in any of the subcritical modes, dropping RCCAs will not result in any power transient.

As in the case of dropped RCCAs, statically misaligned RCCAs have no effect in the absence of a critical neutron flux and are not a concern below Mode 2. The most limiting case, and analysis, is for Mode 1 which also bounds Mode 2 operation.

The most limiting case for the withdrawal of a single RCCA is an occurrence while in Mode 1. An occurrence in any of the subcritical modes will have no effect. The shutdown margin requirements are specified in LCO 3.1.1 of the AP600 Technical Specifications. The shutdown margin requirements are determined assuming the most reactive RCCA is fully withdrawn from the core. Therefore, no single RCCA withdrawal initiated from the subcritical modes will insert enough reactivity to attain criticality.

#### **19E.4.5.4 Startup of an Inactive Reactor Coolant Pump at an Incorrect Temperature**

Starting an idle RCP without bringing the inactive pump cold leg temperature closer to the core inlet temperature results in the injection of cold water into the core, which causes a reactivity insertion and subsequent power increase. The consequences of this event are directly related to the temperature difference between the cold leg temperature in the loop with the inactive RCP and the core inlet. The most severe consequences are included when the plant is operating at maximum permissible power level.

Startup of an inactive RCP while in any of the subcritical modes will have relatively little effect upon core temperature because there will be little or no temperature difference between loops. Safety analyses for the inadvertent starting of an RCP are presented in Tier 2 Information subsection 15.4.4. A conservative analysis is performed for Mode 1 operation with the plant initially at 70-percent power. LCO 3.4.4 of the AP600 Technical

Specifications requires all RCPs to be operating in Modes 1 and 2. At-power condition is chosen in the analyses to maximize the inlet temperature differences. This analysis bounds operation in Mode 2 and the subcritical modes.

#### **19E.4.5.5 Chemical and Volume Control System Malfunction That Results in a Decrease in the Boron Concentration in the Reactor Coolant**

Boron dilution analyses and evaluations for Modes 1 through 5 are provided in Tier 2 Information subsection 15.4.6. In Mode 6, administrative controls isolate the RCS from potential sources of unborated water by locking closed specified valves in the chemical and volume control system (CVS) and thereby precludes an uncontrolled boron dilution transient. Makeup needed during refueling is supplied from the boric acid tank which contains borated water.

#### **19E.4.5.6 Inadvertent Loading of a Fuel Assembly in an Improper Position**

Fuel loading errors – such as inadvertent loading of one or more fuel assemblies into improper positions, having a fuel rod with one or more pellets of the wrong enrichment, or having a fuel assembly with pellets of the wrong enrichment – may result in power shapes in excess of design values. Tier 2 Information subsection 15.4.7 presents Mode 1 results for this event. The Tier 2 Information results bound the results for operation in Mode 2. This event is meaningful only if the reactor is at-power and, therefore, not applicable in the subcritical Modes of 3 through 6.

#### **19E.4.5.7 RCCA Ejection**

Analyses for RCCA ejections in Mode 1 and Mode 2 are presented in Tier 2 Information subsection 15.4.8. The cases analyzed in the Tier 2 Information are the most limiting cases. The shutdown margin requirements are specified in LCO 3.1.1 of the AP600 Technical Specifications. The shutdown margin requirements are determined assuming the most reactive RCCA is fully withdrawn from the core. Therefore, the ejection of a single RCCA initiated from the subcritical modes would not insert enough reactivity to attain criticality.

#### **19E.4.6 Increase in Reactor Coolant Inventory**

An increase in RCS inventory could be caused by inadvertent actuation of the CMTs or by malfunctions in the CVS system. Analyses of events that increase the RCS inventory are provided in Tier 2 Information Section 15.5. Tier 2 Information subsection 15.5.1 presents the analysis results for inadvertent actuation of the CMT. Tier 2 Information subsection 15.5.2 contains results from the analysis of a CVS malfunction which increases RCS inventory. These events do not present a challenge to core design limits. If unchecked, these events could lead to an overflow of the pressurizer and possible loss of reactor coolant from the system. The increase in pressurizer water volume is slow during these events and is controlled by the injection rate, core decay heat produced, and heat removal rate from the RCS. While the pressurizer safety valves may open, the steam relief from the pressurizer safety valves is low and no serious challenge to the RCS pressure boundary occurs (if the pressurizer does not fill).

The Tier 2 Information analyses for these events are performed with the plant initially in Mode 1 at full-power conditions. This results in the maximum amount of stored energy in the plant and in the maximum core decay heat. If the plant was assumed to be at part power, or in the subcritical modes, the amount of stored energy and decay heat will be significantly reduced.

If a spurious "S" signal occurs causing the CMTs to be actuated, the reactor is also tripped and the PRHR HX is also actuated. The CMTs will begin injecting cold, borated fluid into the RCS. The injected fluid expands as it is heated in the RCS by decay heat. The expansion is counteracted by decay heat removal through the PRHR HX. The severity of the expansion is increased with higher decay heat levels.

Malfunctions in the CVS, which add excess inventory to the RCS, are protected against by the inclusion of automatic CVS isolation functions in the PMS. If a safeguards signal has occurred (which also would activate the CMTs), the CVS is automatically isolated if the pressurizer level exceeds the high-1 pressurizer level setpoint. Above the high-1 pressurizer level setpoint, there is a high-2 pressurizer level setpoint, which also isolates the CVS. The high-2 pressurizer level function is not interlocked with the safeguards signal. The high-2 function protects in situations where the reactor is at-power or a safeguards signal has not occurred. The high-2 pressurizer level function is available in Modes 1 through Mode 3 and in Mode 4 when the RNS is not operating. These functions effectively prevent overfilling of the pressurizer when the CVS acts alone or where CVS interacts to also cause the CMTs to be actuated.

Isolation of CVS on high-2 pressurizer level is available in Modes 1 through 4 until the plant is operating on RNS. There are applications where the RCS may be filled water-solid when the RNS is in operation. In Modes 4, 5, and 6 when the RNS is in operation, low-temperature overpressure protection (LTOP) of the RCS pressure boundary is provided by the RNS relief valve. A discussion of this is provided in subsection 19E.4.10.1 of this appendix.

#### **19E.4.7 Decrease in Reactor Coolant Inventory**

##### **19E.4.7.1 Inadvertent Opening of a Pressurizer Safety Valve or Inadvertent Operation of the Automatic Depressurization System**

Tier 2 Information subsection 15.6.1 includes analyses and evaluations of the inadvertent opening of a pressurizer safety valve or the inadvertent operation of the automatic depressurization system (ADS). The analyses discussed here and in Tier 2 Information subsection 15.6.1 evaluate the RCS depressurization aspect following these events. Loss of RCS inventory aspects of these events is covered in subsection 19E.4.8.2 of this appendix.

When analyzed as depressurization events, inadvertent opening of primary side relief valves, if the reactor is at-power, could result in exceeding core design limits, specifically DNB criteria. Violation of DNB criteria is not a realistic concern if the reactor is in any of the

subcritical modes. Therefore, these events are analyzed in Mode 1 at the maximum rated power and the analysis performed bounds cases initiated from Mode 2.

#### 19E.4.7.2 Failure of Small Lines Carrying Primary Coolant Outside Containment

This event is reported in Tier 2 Information subsection 15.6.2 as the rupture of a primary coolant sample line; the radiological consequences of this event are analyzed during Mode 1 because the coolant temperature and iodine concentrations bound those that would exist in the other modes. Concerning shutdown risk, the consequences of a sample line break during Modes 2, 3, 4, or 5 are no more severe than if the accident occurs during Mode 1 operation.

#### 19E.4.7.3 Steam Generator Tube Rupture in Lower Modes

The steam generator tube rupture (SGTR) analysis presented in the Tier 2 Information is the limiting case with respect to offsite doses. The Tier 2 Information analysis was performed at full power because this results in the maximum offsite dose. The key inputs from the thermal-hydraulic SGTR analysis performed with the LOFTTR2 computer code to the offsite dose analysis are the amount of flashed primary to secondary break flow and the steam released from the faulted steam generator. Both of these will be significantly reduced at lower power levels and in lower modes of operation.

Margin to overfill analyses are not presented in the Tier 2 Information. The Tier 2 Information does indicate that an analysis was performed to demonstrate margin to steam generator overfill with no operator actions modeled. This is necessary because the dose analysis does not include consideration of water relief from the ruptured steam generator PORV/MSSV. This margin to steam generator overfill analysis was supported by the assertion that an analysis with operator actions modeled will also demonstrate margin to overfill. The overfill analysis with no operator actions discussed in the Tier 2 Information was initiated at full power. WCAP-10698-P-A (Reference 20) indicates that margin to overfill is reduced when the SGTR is initiated at zero power because of the higher initial steam generator secondary liquid inventory. WCAP-10698-P-A concludes that zero power and lower mode SGTR overfill analyses are not limiting, based primarily on more rapid operator responses expected in those conditions. This is discussed further in the Appendices to WCAP-10698-P-A, which include responses to NRC questions regarding this conclusion. When operator actions are credited for AP600 SGTR mitigation, the plant behaves in a manner comparable to a standard Westinghouse PWR and the conclusions of WCAP-10698-P-A apply.

When operator actions are not relied upon and only the AP600 automatic RCS cooling and depressurization are credited, margin to overfill would still be maintained for SGTR events initiated at lower power levels despite the increased initial steam generator secondary side inventory corresponding to the lower initial power assumption. This is because the automatic protection system actions that prevent overfill are independent of the operator actions. For operating plants, there is a set period of time from the start of the event until the operator can reverse the trend toward filling the steam generator. Therefore, the initial margin to overfill directly impacts the final margin. For the AP600, the primary cooldown

and depressurization occur automatically when the PRHR HX is actuated on a low pressurizer pressure "S" signal or low pressurizer level CMT actuation signal. The primary pressure may still be held up by the CVS, until it is isolated on a high steam generator level signal. For the AP600, a higher initial steam generator water level results in the CVS flow being terminated earlier.

In lower modes, the PRHR HX actuation is provided only by the low pressurizer level signal. Although this results in delayed cooling and depressurization, margin to steam generator overfill is still maintained. The increase in mass in the secondary side of the ruptured steam generator is directly related to the reduction in pressurizer water level, because (once the CVS is isolated on high steam generator water level) there is no source of makeup to the RCS. The steam generator secondary side can accommodate the amount of fluid initially contained in the pressurizer and still retain a significant amount of margin to steam generator overfill. The PRHR HX will, therefore, be actuated on low pressurizer water level in sufficient time for the PRHR HX to cool and depressurize the primary and terminate break flow before steam generator overfill will occur.

#### 19E.4.8 Loss-of-Coolant Accident Events in Shutdown Modes

The AP600 Tier 2 Information presents a spectrum of break sizes of the postulated LOCAs at the full-power operating condition. Other things being equal, the reduction in power to decay heat levels associated with shutdown mode operations will make all LOCA events less limiting than those analyzed at full power and reported in Tier 2 Information subsection 15.6.5. However, as the plant proceeds through shutdown modes of operation, various PXS equipment are removed from service at identified points in time. One particularly significant action in the course of taking the AP600 to cold shutdown is the elimination of PXS equipment is the isolation of the accumulators at 1000 psig. This procedural action reduces the capability of the PXS to mitigate LOCAs. For assessing the adequacy of the remaining PXS components to mitigate postulated LOCA events, three events are analyzed, assuming they occur immediately after the isolation of the accumulators: a double-ended cold leg guillotine (DECLG) break, a double-ended rupture of the direct vessel injection (DVI) line, and an inadvertent actuation of the ADS by a spurious signal. Only safety-related systems are modeled in the analysis of these events, which occur during Mode 3.

Depressurization of the AP600 primary system during shutdown operations will be performed with the same care taken to avoid the flashing of liquid in the core and upper head that is taken by current operating plants. Prudent plant operation dictates that subcooling margin be retained as pressure is reduced. Therefore, since the AP600 shutdown operations will be conducted in a prudent, controlled manner, it is anticipated that the RCS temperature will be near the 420°F lower limit of Mode 3 when the accumulators are isolated.

For these analyses, the plant was assumed to be shut down in Mode 3 at steady-state conditions of 1000 psig and 425°F with the accumulators isolated. An initial pressure of 1000 psig is assumed because this is the highest pressure with the accumulators isolated and a hot leg temperature of 425°F is the highest expected temperature when the pressure is 1000 psig. The decay heat level is determined at 2.78 hours after reactor shutdown based

on the time estimate to cool down the plant from full-power operation to 425°F at a cooldown rate of 50°F per hour. The low pressurizer pressure safeguards signal is also assumed to be disabled because the initial pressure is below the setpoint.

AP600 large break LOCA analyses have exhibited little sensitivity to initial RCS fluid temperature. The impact of varying the initial RCS temperature on DECLG break results obtained from WCOBRA/TRAC was identified in order to determine the bounding temperature condition for the AP600 large break LOCA best-estimate methodology analysis. As reported in Tier 2 Information subsection 15.6.5.4A.3.2. The sensitivity of PCT to RCS initial temperature is approximately a 0.5°F increase in PCT per degree F increase in RCS temperature. Because this result is insensitive to RCS temperature, the possibility that the RCS temperature at the time of accumulator isolation might on occasion exceed 425°F is of no concern.

The matrix presented in subsection 19E.4.1 details the relationship between the Tier 2 Information analysis and LOCA-related accidents during the shutdown modes of operation. LOCA analyses performed in Mode 3 bound events that could occur during Modes 3 and 4. After accumulator isolation and prior to normal residual heat removal system operation, the decay power decreases relative to the shutdown Mode 3 LOCA analysis condition with no reduction in safety-related systems available. In addition, reactor coolant system pressure and temperature are reduced. In Mode 4, once the reactor coolant system pressure is reduced to permit operation of the normal residual heat removal system, breaks in the reactor coolant system are not considered credible. Therefore, the Technical Specifications permit isolation of one core makeup tank for Mode 4, once the normal residual heat removal system is aligned, and for Mode 5, with the reactor coolant system pressure boundary intact. The consequences of leaks in the reactor coolant system that can result from operator misalignment of valves are bounded by the Mode 3 LOCA analyses. Specifically, the results of the double-ended break of a DVI line in Mode 3 credit flow from only one core makeup tank and bound leaks that may be postulated when only one core makeup tank is aligned (in applicable portions of Modes 4 and 5). Inadvertent leaks can only drain the reactor coolant system to the bottom of the hot leg, which is above the elevation of the DVI injection line. In addition, the core decay power is less than in the Mode 3 analysis.

Other postulated events involving a decrease in reactor coolant inventory during shutdown presume the loss of RNS cooling during Mode 4 and Mode 5. Subsection 19E.4.8.5.1 presents loss of RCS cooling with the RCS intact; the analysis with the RCS open is presented in subsection 19E.4.8.5.2 in this appendix. As discussed in subsection 19E.4.8.4 of this appendix, among the LOCA-related events that may be postulated to occur in lower modes, these cases may be considered bounding. It is extremely conservative to presume that a DECLG break could occur under the reduced pressure and temperature conditions associated with Mode 3 plant operation. The DECLG break exhibits the limiting calculated peak cladding temperature (PCT) value among the Tier 2 Information cases.

The NOTRUMP computer code (Reference 21) used in the Tier 2 Information analysis, was used in the small-break LOCA cases. The NOTRUMP input was set for the shutdown analyses to comply with AP600 Westinghouse Small-Break LOCA Evaluation Model methodology (WCAP-14601) (Reference 22) to obtain suitable representation of the AP600.

In the Tier 2 Information analysis, the actuation of ADS depressurizes the RCS to accumulator actuation pressure to thereby increase safety injection flow. Therefore, the limiting single active failure for the double-ended direct vessel injection (DEDVI) line break at full power is taken as failure of a set of one first-stage and one third-stage ADS valves to open on demand. For the Mode 3 shutdown LOCA case, reducing the initial venting capability of the RCS to delay accumulator injection does not apply. Thus, for both DEDVI and inadvertent ADS cases, failure of one of the four fourth-stage ADS valves to open on demand is postulated.

#### 19E.4.8.1 Double-ended Cold Leg Guillotine

The DECLG break is analyzed using the WCOBRA/TRAC computer code and the AP600-specific noding presented in WCAP-14171, Revision 1 (Reference 14). Table 19E.4.8-1 summarizes the results.

This case models the double-ended rupture of one of the two cold legs in the RCS loop without the PRHR HX at a pressure of 1000 psig just after the accumulators are isolated. Only the core makeup tanks (CMTs) and IRWST are available to deliver PXS flow. This break evaluates the ability of the plant to withstand a large LOCA during shutdown with its conditions and equipment availability. The limiting discharge coefficient (0.8) is modeled. The analysis is performed with 10 CFR 50, Appendix K (Reference 16), required decay heat, and Technical Specification/Core Operating Limits Report maximum peaking factors.

The break is assumed to open instantaneously at 0.0 seconds. The subcooled discharge from the broken cold leg (Figure 19E.4.8-1) causes a rapid RCS depressurization (Figure 19E.4.8-2). In Figure 19E.4.8-1, the positive flow direction is the normal operation direction. The reversal of flow entering the vessel to flow out of the break is shown. Due to high-1 containment pressure, an "S" signal is generated at 1.8 seconds, and following a 1.2-second delay, the isolation valves on the CMT and PRHR HX outlet lines begin to open. The signals also trip the RCPs after a 16.2-second delay. The limiting discharge coefficient of 0.8 identified in full-power LOCA analyses is assumed.

Within a few seconds, the collapsed liquid level drops within the upper plenum due to voiding (Figure 19E.4.8-3). The downcomer collapsed liquid level (Figure 19E.4.8-4) quickly falls below the elevation of the cold legs; the elevation of the top of the core is 18.8 feet. Because the RCS fluid enthalpy is lower than the full-power value, the RCS depressurization rate is decreased from the Tier 2 Information cases and more of the initial inventory is retained in the reactor vessel.

CMT injection from both tanks replenishes the RCS mass inventory (Figure 19E.4.8-5). Injection from the CMTs as the RCS pressure declines terminates the peak cladding temperature (PCT) transient because the stable injection of water from the CMTs exceeds the break flow. The core collapsed level refills are as shown in Figure 19E.4.8-6. The pressure is low enough that the IRWST injection will begin once the CMTs drain to the low-2 level actuation setpoint. The maximum PCT value is approximately 1200°F for this bounding break size, and all the 10 CFR 50.46 (Reference 23) acceptance criteria are met.

### 19E.4.8.2 Inadvertent Actuation of Automatic Depressurization System Results

An inadvertent ADS signal is spuriously generated, and the first-stage ADS valves open. The plant, which is shut down at 1000 psig, is depressurized via the ADS alone. Only safety-related systems that are in service are assumed to operate in this analysis. The second- and third-stage ADS valves actuate based on the design time delays. At the 20-percent tank level, the fourth-stage ADS valves, which are on the hot legs, receive signals to open. Three of the four fourth-stage ADS paths are assumed to open; one of the paths fails to open as the assumed single active failure.

The scenario analyzed is the same inadvertent ADS actuation considered in Tier 2 Information Chapter 15. The sequence of events for the transient is given in Table 19E.4.8-2.

The transient is initiated by the opening of the two first-stage ADS paths. The total throat area of the valves is 9.2 in<sup>2</sup>. The opening of the ADS valves causes the primary pressure to fall rapidly (Figure 19E.4.8-7). The accumulators are isolated and thus accumulator injection does not occur. Flow of fluid toward the open ADS path causes the pressurizer to fill by about 100 seconds (Figure 19E.4.8-8), and the ADS flow becomes two-phase. A level begins to form in the upper plenum at about 110 seconds and drops to the hot leg elevation (Figure 19E.4.8-9). Although a safeguards signal is not obtained on low-pressurizer pressure, the ADS opening results in a CMT actuation signal, which opens the valves isolating the CMTs, and injection of cold water begins (Figure 19E.4.8-10); the PRHR HX is also actuated by the CMT actuation signal.

The mixture level in the CMTs is constant until about 350 seconds, then the tanks begin to drain. The RCPs begin to coast down due to an automatic trip signal following a 16.2-second delay. The second-stage ADS actuation at 70 seconds accelerates the depressurization transient slightly. At about 220 seconds following the ADS actuation, enough mass has been discharged that a mixture level forms in the downcomer (Figure 19E.4.8-11). CMT injection flow increases at approximately 350 seconds and the mixture level in the CMT falls steadily after that time.

The levels in the CMTs eventually reach the fourth-stage ADS setpoint. Vent paths, opened from the hot legs, begin discharging fluid. The increased depressurization reduces the flow from ADS stages 1, 2, and 3. The single active failure assumed is that one of the four fourth-stage ADS valves fails to open, maximizing the resistance to depressurizing the RCS to achieve IRWST injection.

The reduced flow through ADS stages 1 through 3 allows the pressurizer level to fall, and these stages begin to discharge only steam after 1645 seconds. By 1820 seconds, the CMTs are empty and delivery ceases. At 2030 seconds, the RCS pressure has fallen enough to allow gravity drain from the IRWST to begin (Figure 19E.4.8-12). The calculation was stopped with a quasi-steady-state condition existing in the RCS with the IRWST delivery exceeding the ADS flows (which are removing the decay heat) and the RCS inventory slowly rising. Core uncover does not occur; the upper plenum mixture level remains well above the top of the core elevation (18.8 feet) throughout the transient (Figure 19E.4.8-9).

The minimum RCS mass inventory for this case is approximately 146,000 pounds (Figure 19E.4.8-13), which is above the Tier 2 Information case minimum inventory. Thus, the consequences of inadvertent ADS actuation during shutdown without the accumulators is bounded by the full-power analysis in the Tier 2 Information.

### 19E.4.8.3 Double-ended Direct Vessel Injection Line Break Results

This case models the double-ended rupture of the DVI line at the nozzle into the downcomer. The broken loop injection system (consisting of a CMT and an IRWST delivery line) is modeled to spill completely out of the break. The accumulators are isolated, and thus accumulator injection does not occur. The injection line break evaluates the ability of the plant to recover from a moderately large break with only half of the total available emergency core cooling system (ECCS) capacity available. The venturi installed in the AP600 DVI nozzles provides a 4-inch-diameter flow restriction, which has been modeled in NOTRUMP. The accident analyzed is the same as the DVI line break considered in the Tier 2 Information. The sequence of events for this analysis is presented in Table 4.8-3 and a discussion of the results follows.

The break is assumed to open instantaneously at 0 seconds. The subcooled discharge from the downcomer nozzle (Figure 19E.4.8-14) through a 4-inch-diameter venturi causes a rapid RCS depressurization (Figure 19E.4.8-15). Although an "S" signal does not occur on low-pressurizer pressure, a CMT actuation signal is generated on low pressurizer level at approximately 18 seconds and following a 1.2-second delay, the isolation valves on the CMT tank delivery and cold leg balance lines begin to open. The opening of the PRHR HX isolation valve on a CMT actuation signal starts the flow through the heat exchanger. The broken loop CMT discharges directly to the containment (Figure 19E.4.8-16), and a small circulation flow provides some injection from the intact loop CMT (Figure 19E.4.8-17).

As the pressure falls, the RCS fluid saturates, and at about 50 seconds, a mixture level forms in the upper plenum and then falls to the hot leg elevation (Figure 19E.4.8-18). The upper parts of the RCS start to drain, and a mixture level begins to form in the downcomer at about 100 seconds (Figure 19E.4.8-19) and falls to the elevation of the break at about 300 seconds. Two-phase discharge then occurs from the downcomer side of the break.

At about 110 seconds, the fluid at the top of the broken loop CMT saturates and a level forms and starts to fall. The first-stage ADS setpoint is reached, and after an appropriate delay, the two first-stage paths are opened at 342 seconds. The ensuing steam discharge from the top of the pressurizer increases the RCS depressurization rate.

At about 350 seconds, the fluid at the top of the intact loop CMT saturates and the mixture level in the tank starts to fall slowly. CMT injection after 350 seconds slows the rate of decrease in the downcomer mixture level and eventually causes the level to rise (Figure 19E.4.8-19). The level in the upper plenum also decreases to about the break elevation and then the level begins to increase (Figure 19E.4.8-18). The two second-stage ADS valves begin to open at 412 seconds, following the timer delay between the actuation of the first two stages of the ADS. The third-stage ADS valves open at 532 seconds

because of the time delay of 120 seconds for the actuation of this stage of the ADS. At 388 seconds, the broken loop CMT level reaches the fourth-stage ADS setpoint, but the fourth-stage ADS valves do not open until 652 seconds because the minimum time delay is 120 seconds between the actuation of the final two stages of the ADS. Three of the four fourth-stage ADS paths are assumed to open; one of the paths fails to open as the assumed single active failure. Two-phase discharge ensues through the fourth-stage path. By 458 seconds, the broken loop CMT empties.

After the broken loop CMT empties, injection continues from the intact loop CMT as the RCS pressure declines slowly. At 820 seconds, the intact loop CMT has not yet emptied, yet the RCS pressure has fallen to the point that IRWST injection begins. Injection from the IRWST increases as the primary pressure decreases, and the CMT flow rate decreases as the CMT empties. The CMT and IRWST injection causes the mixture level in the upper plenum to increase and level off at the hot leg elevation. The downcomer level also increases and stabilizes at about the break elevation. After the intact loop CMT empties at 2020 seconds, the IRWST injection flow eventually becomes greater than the break and ADS flows, resulting in a slow rise in RCS inventory (Figure 19E.4.8-20). The minimum RCS mass inventory of 119,000 pounds is greater than the corresponding Tier 2 Information DEDVI break value. Thus, the consequences of a DEDVI break during shutdown without accumulators is bounded by the full-power analysis in the Tier 2 Information.

#### 19E.4.8.4 Spectrum of Small-Break LOCAs

The small-break LOCA analyses in the Tier 2 Information Chapter 15 included an analysis of a no-break case due to the inadvertent opening of the 4-inch stage 1 ADS valves due to a spurious signal, as well as analyses for a spectrum of small-break LOCAs. The breaks analyzed included a DEDVI, a 2-inch break in a cold leg with CMT balance line connections, a double-ended rupture of a CMT balance line, a 2-inch break in the RCS loop with the PRHR HX, and a 10-inch cold leg break. The Tier 2 Information Chapter 15 analyses include the DEDVI and inadvertent ADS cases as limiting small-break LOCAs with respect to providing safety injection delivery to limit core uncover and ADS depressurization capability to achieve IRWST injection, respectively. Therefore, analyses were performed for these two limiting cases under shutdown conditions. The analyses for the DEDVI break and inadvertent ADS actuation cases under shutdown conditions with the accumulators isolated have demonstrated that the results are bounded by the respective full-power analyses in the Tier 2 Information. For at-power events, the limiting small break LOCA case in terms of the minimum RCS inventory is the 10-inch break; therefore, it too is analyzed for the same Mode 3 condition as the DEDVI and inadvertent ADS actuation cases. It is considered that analyses for the remaining spectrum of small-break LOCAs for shutdown conditions are not required because the bounding small-break LOCA analyses in Chapter 15 of the Tier 2 Information are analyzed during shutdown operations.

The 10-inch cold leg break is located in one of the cold legs connected to a core makeup tank. The break size is large enough that the balance line may be severed. Because the affected balance line is modeled as severed, the CMT connected to the broken cold leg is initially unable to inject into the reactor vessel.

The break is assumed to open instantaneously at 0.0 seconds. Figures 19.E.4.8-21 to 19.E.4.8-25 present important results. The initial subcooled break flow causes a rapid depressurization (Figure 19E.4.8-21). Although an "S" signal does not occur due to low pressurizer pressure, one is generated due to high containment pressure early in the event. This leads to opening of the CMT and PRHR isolation valves, and an automatic trip of the reactor coolant pumps. Figure 19E.4.8-22 shows the injection flow rate from the intact loop CMT.

A mixture level quickly forms in the upper plenum during the 10-inch cold leg break (Figure 19E.4.8-23) and falls below the hot leg elevation before 200 seconds have elapsed. The mixture level in the upper plenum remains at least one foot above the elevation of the top of the active fuel. The downcomer liquid voids due to the flashing early in the transient, and the mixture level falls below the DVI nozzle elevation (Figure 19E.4.8-24) approximately 250 seconds into the transient. It then recovers due to CMT injection to the DVI nozzle elevation by 1000 seconds.

The decrease in CMT level causes ADS Stage 1 to actuate at 693 seconds, followed by ADS Stage 2 at 763 seconds and ADS Stage 3 at 883 seconds. The depressurization due to the 10-inch break is such that the pressure effect of ADS Stage 1-3 actuation is not apparent in Figure 19E.4.8-21. ADS Stage 4 actuates at 1398 seconds, and the impact of ADS Stage 4 operation is barely noticeable in the pressure trace. The IRWST begins to inject shortly after actuation of ADS Stage 4. The increase in primary system inventory associated with IRWS injection is shown in Figure 19.E.4.8-25. As in the Tier 2 Information subsection 15.6.5.4B analysis, the minimum inventory of the 10-inch cold leg break (64,000 lbm) is lower than that of the DEDVI case. Nevertheless, the core remains covered throughout the 10-inch cold leg break transient occurring during Mode 3 operation of the AP600; the DECLG break reported in Tier 2 Information subsection 4.8.1 is the limiting case break.

#### 19E.4.8.5 Loss of RNS Cooling

The RNS is used to reduce the temperature of the RCS during the second phase of plant cooldown, following the first cooldown phase, which is accomplished using the main steam system (MSS). Following initial cooldown, the RNS is used to remove heat from the core and RCS during the plant shutdown. The RNS is designed for the initiation of operation at 4 hours following reactor shutdown, after the first phase of cooldown by the MSS has reduced the RCS to less than or equal to 350°F and 450 psig. The RNS is capable of reducing the temperature of the RCS from 350°F to 120°F within 96 hours after shutdown and maintaining the reactor coolant temperature at or below 120°F for the plant shutdown.

Analyses have been performed to determine the plant response to a loss of RNS cooling in Mode 4 with the RCS intact and in Mode 5 with the RCS open, and the results are discussed in the following subsections. These analyses were performed using the NOTRUMP computer code (Reference 21), and the NOTRUMP input used for the analyses complies with the AP600 Westinghouse Small-Break LOCA Evaluation Model methodology (WCAP-14601) (Reference 22). These analyses bound loss of decay heat removal events

that can occur during Modes 4, 5, and 6. The Mode 5 evaluation bounds this event for Mode 6 due to the higher decay heat levels. In Mode 6, the water in the refueling cavity provides a large heat sink. Following a loss of decay heat removal, the water in the refueling cavity would heat up and begin to boil (9 hours). Prior to this, the operators are required to close containment. If no action were taken, the water level in the refueling cavity could fall to the level of the top of the core (5 days). Prior to this time the operators are required to align IRWST injection and eventually containment recirculation to provide long term core cooling.

#### 19E.4.8.5.1 Loss of RNS Cooling in Mode 4 with RCS Intact

For this analysis, it is assumed that the RNS has just been placed in operation at 4 hours after reactor shutdown with the RCS at 350°F and 450 psig (464.7 psia). It is assumed that a loss of offsite power occurs, resulting in a loss of flow through the RNS, and thus in a loss of RNS cooling. The MSS is assumed to be unavailable for heat removal, although the steam generator secondary side is assumed to be at saturated conditions for 350°F with the normal water level. Because the Mode 4 plant conditions assumed for the analysis are more limiting than Mode 5 conditions, this analysis is also applicable for a loss of RNS cooling in Mode 5 when the RCS is intact.

It is assumed that only one CMT is available for injection because the Technical Specifications permit one CMT to be taken out of service in Mode 4. Although all of the fourth-stage ADS valves are available in Mode 4, the Technical Specifications permit one of the fourth-stage ADS valves to be out of service in Mode 5 when the RCS is intact. Thus, it was assumed that only three of the fourth-stage ADS valves are available for operation in order to bound the equipment availability in Mode 5. However, one of the three available fourth-stage ADS valves is assumed to fail to open on demand as the single failure, consistent with the single failure assumption used for the small-break LOCA analyses for shutdown conditions.

The accident analyzed is a loss of RNS cooling, which is assumed to result in a complete loss of heat removal for the RCS. The sequence of events for this analysis is presented in Table 19E.4.8-4.

Following the loss of RNS cooling, there is no mechanism for heat removal from the RCS, and the core decay heat generation causes the reactor coolant temperature and pressure to increase. Although the MSS is assumed to be unavailable for heat removal, the steam generators represent a heat sink which slows the rate of heatup of the reactor coolant. The fluid temperature at the core outlet for the transient is shown in Figure 19E.4.8-26. The reactor coolant heatup causes the system pressure to increase as shown in Figure 19E.4.8-27 until the pressure reaches the RNS relief valve setpoint of 563 psig (577.7 psia) at approximately 1400 seconds. The normal relieving capacity of the RNS relief valve is 555 gpm, and the pressure is maintained at the relief valve setpoint as the temperature continues to increase and reactor coolant is discharged from the relief valve. The expansion of the water due to the coolant temperature increase also causes the pressurizer level to increase slightly as shown in Figure 19E.4.8-28.

The loss of reactor coolant through the relief valve is not sufficient to remove the core decay heat, and the reactor coolant temperature continues to increase until the core outlet temperature reaches saturation at the relief valve setpoint at approximately 5500 seconds. The generation of steam in the core causes the system pressure to increase above the RNS relief valve setpoint and the pressurizer level to continue to increase. A mixture level begins to form in the upper plenum at approximately 5670 seconds and drops to the top of the hot leg elevation as shown in Figure 19E.4.8-29. At about 6250 seconds, enough mass has been discharged such that a mixture level also forms in the downcomer (Figure 19E.4.8-30), and the downcomer two-phase level begins to decrease. As the boiling front moves lower and lower into the core, more steam generation occurs and the pressure continues to increase. Once the entire core length is boiling, the upper plenum mixture level is within the hot leg perimeter. At approximately 7980 seconds, when steam begins to flow through the relief valve along with liquid, the pressure begins to decrease. The pressurizer level also begins to decrease as water drains from the pressurizer into the reactor coolant system hot leg. However, the voiding in the RCS increases as the pressure decreases, and flashing begins to occur in the pressurizer at approximately 8660 seconds. This additional steam generation causes the pressure to begin to increase, and the relief valve flow becomes solely liquid again. The steam voiding in the pressurizer not only causes the pressure increase, but also facilitates draining, and the pressurizer level continues to decrease.

As the pressurizer level decreases, a CMT actuation signal is generated automatically on low pressurizer level, and following a 1.2-second delay, the isolation valves on the available CMT tank delivery lines open and CMT injection flow is initiated at approximately 9500 seconds as shown in Figure 19E.4.8-31. The opening of the PRHR HX isolation valve on a CMT actuation signal starts the flow through the heat exchanger. The CMT injection causes the reactor coolant pressure to decrease below the RNS relief valve setpoint, and the loss of reactor coolant is terminated at approximately 9700 seconds. As the CMT level decreases (Figure 19E.4.8-32), the first-stage ADS setpoint at 67.5 percent is reached at 10,075 seconds. The second-stage and third-stage ADS valves also open following the timer delays for the actuation of the second- and third-stage ADS valves. The vapor and liquid flow through the ADS valves (Figures 19E.4.8-33 and 19E.4.8-34) results in a rapid depressurization of the reactor coolant system. The CMT reaches the fourth-stage ADS setpoint of 20 percent, and two of the four fourth-stage paths open at 10,895 seconds. As noted previously, it is assumed that one of the fourth-stage paths is out of service, and one path is assumed to fail as the single active failure. The vapor and liquid flow through the fourth stage ADS paths (Figures 19E.4.8-35 and 19E.4.8-36) further reduces the pressure to the point where IRWST injection begins at approximately 11,845 seconds (Figure 19E.4.8-37).

The CMT and IRWST injection reverses the decrease in the core stack and downcomer mixture levels as shown in Figures 19E.4.8-29 and 19E.4.8-30, respectively. As shown in Figure 19E.4.8-29, the core stack mixture level is maintained well above the elevation of the top of the core active fuel (18.8 feet) throughout the transient. At the end of the transient, the core stack mixture level has been restored to within the hot leg perimeter and the downcomer mixture level has been restored to the DVI nozzle elevation. The fluid temperature at the core outlet has also been reduced and is being maintained at less than 250°F. As shown in Figure 19E.4.8-38, the reactor coolant mass inventory twice reaches

a minimum of approximately 120,000 pounds, when the CMT and IRWST injection then increase the inventory. The reactor coolant mass inventory is greater than 150,000 pounds and is slowly increasing at the end of the transient. Thus, it is concluded that the consequences of a loss of RNS in Modes 4 and 5 with the RCS intact are acceptable.

#### 19E.4.8.5.2 Loss of RNS Cooling in Mode 5 with RCS Open

For this analysis, it is assumed that the RNS is in operation in Mode 5 at 24 hours after reactor shutdown with the ADS Stage 1, 2, and 3 valves open and the RCS vented to the IRWST. The reactor coolant temperature is assumed to be at 160°F, and the pressurizer pressure is assumed to be at atmospheric pressure plus the elevation head in the IRWST, or 18.2 psia. The steam generator secondary side is assumed to be drained, and thus, there is no secondary heat sink for this case. It is assumed that the CMTs and the PRHR are not available because the Technical Specifications permit them to be taken out of service when the RCS is open in Mode 5. It is also assumed that only two of the fourth-stage ADS valves are available for potential use by the operators because the Technical Specifications permit two of the fourth-stage ADS valves to be out of service in Mode 5 when the RCS is open. In addition, one of the two available fourth-stage ADS valves is assumed to fail to open on demand as the single failure. The Technical Specifications also permit one of the two IRWST injection paths to be out of service in Mode 5 with the RCS open, and thus, only one of the IRWST injection paths is assumed to be available.

It is assumed that a loss of offsite power occurs, resulting in a loss of RNS flow, and thus a loss of RNS cooling. The sequence of events for this analysis is presented in Table 19E.4.8-5.

Following the loss of RNS cooling, there is no mechanism for heat removal from the RCS and the core decay heat generation results in an increase in the reactor coolant temperature. The fluid temperature at the core outlet for the transient is shown in Figure 19E.4.8-39. The core outlet fluid temperature increases steadily until approximately 3000 seconds when saturation temperature is reached and voiding is initiated in the core. Because the RCS is vented to the IRWST via ADS Stages 1, 2, and 3, the pressure initially remains constant until approximately 3800 seconds as shown in Figure 19E.4.8-40. As the void generation in the system increases, the vapor flow through ADS Stages 1, 2, and 3 is not sufficient to maintain the pressure, and the pressure increases to approximately 30.6 psia and then begins to decrease. As shown in Figure 19E.4.8-41, the pressurizer level also increases as the reactor coolant temperature increases, and the level subsequently reaches the top of the pressurizer as a result of the steam generation in the system. As shown in Figures 19E.4.8-42 and 19E.4.8-43, a mixture of steam and water is discharged via ADS Stages 1, 2, and 3 after the pressurizer fills.

The continued loss of reactor coolant through ADS Stages 1, 2, and 3 causes the pressure to begin to decrease after approximately 5200 seconds. The core outlet temperature is at saturation and also begins to decrease as the pressure decreases. A mixture level begins to form in the upper plenum at approximately 4090 seconds, and the level begins to decrease as shown in Figure 4.8-44, as the voiding continues in the system. At about 5100 seconds, enough mass has been discharged that a mixture level forms in the downcomer

(Figure 4.8-45) and the downcomer level also begins to decrease. The pressurizer level does not decrease significantly due an increasing void fraction in the pressurizer.

As the voiding in the core continues, the core stack mixture level continues to decrease as shown in Figure 19E.4.8-44. The void fraction in the hot legs also increases, and the mixture level in the hot leg begins to decrease after 4000 seconds. The hot leg is empty at approximately 7200 seconds as shown in Figure 19E.4.8-46. This is the normal signal for opening the fourth-stage ADS valves and to initiate IRWST injection when the systems are aligned for automatic actuation. Thus, it is assumed that the operator will initiate manual action at 7200 seconds to open the fourth-stage ADS valves and to open the IRWST flow path to permit IRWST injection when the downcomer pressure is sufficiently low. Thus, discharge through one of the fourth-stage ADS valves is initiated at 7290 seconds as shown in Figures 19E.4.8-47 and 19E.4.8-48. As noted previously, one of the two available fourth-stage ADS paths is assumed to fail to open as the single active failure. The flow through the fourth-stage ADS path results in a further reduction in the pressurizer pressure and a rapid decrease in the pressurizer level. The downcomer pressure is also reduced to the point where IRWST injection is initiated at approximately 7400 seconds (Figure 19E.4.8-49). However, the pressurizer level increases due to subsequent additional void formation at the lower pressure, and the downcomer pressure increases slightly, temporarily terminating the IRWST flow. The downcomer pressure then drops slowly, resulting in sustained IRWST injection at approximately 8204 seconds.

The IRWST injection reverses the decrease in the core stack and downcomer mixture levels as shown in Figures 19E.4.8-45 and 19E.4.8-46, respectively. As shown in Figure 19E.4.8-45, the core stack mixture level is maintained well above the elevation of the top of the core active fuel (18.8 feet) throughout the transient. At the end of the transient, the core stack mixture level has been restored to above the middle of the hot leg elevation and the downcomer mixture level is above the DVI nozzle elevation. The fluid temperature at the core outlet has also been reduced to approximately 250°F. As shown in Figure 19E.4.8-50, the reactor coolant mass inventory reaches a minimum of approximately 170,000 pounds and then begins to increase as a result of the IRWST injection. Thus, it is concluded that when the appropriate operator action is performed, one ADS Stage 4 valve is effective in reducing system pressure so that the consequences of a loss of RNS in Mode 5 with the RCS vented are acceptable.

The analysis presented here is a conservative analysis of a loss of RNS cooling during reduced inventory conditions. During Mode 5, prior to draining to mid-loop conditions, the operator manually opens the ADS Stages 1 through 3 paths to the IRWST. With the RCS "open," the operator then proceeds to slowly drain the RCS to "mid-loop" conditions, for the purpose of performing steam generator maintenance or other maintenance that requires a reduced RCS water level. At this moment, it is postulated that a loss of decay heat removal via the nonsafety-related RNS occurs. A loss of RNS cooling at this time is selected because it is the earliest time the RCS could be placed into a reduced inventory (that is, RCS open) condition. In addition, the backpressure on the reactor vessel, due to the presence of water in the pressurizer, is higher at this time. This presents the most challenging condition for the ADS to depressurize the RCS to IRWST cut-in pressure. This transient represents the most limiting "surge line flooding" scenario, a term commonly used

for operating plants to refer to the phenomenon associated with water in the pressurizer and surge line causing a high backpressure in the RCS, which potentially challenges the ability of the low head safety injection systems to inject properly. In addition, this scenario can potentially challenge the design pressure of temporary nozzle dams placed in the steam generators to facilitate maintenance of the RCS during refueling.

For a loss of the RNS during mid-loop operations, calculations have been performed to determine the time until core uncover would occur. The results of these calculations are presented in Table 19E.2-1 of this appendix. The progression of events following a loss of RNS cooling during mid-loop results in a heatup of the RCS to saturation, followed by a boiling off of the coolant to the IRWST via the ADS Stages 1, 2, and 3 valves. Eventually, the operator actuates the IRWST upon a loss of RCS subcooling, followed by the loss of RCS inventory. The conditions in the RCS following IRWST and fourth-stage ADS actuation are similar to those in this evaluation. As shown in Table 19E.2-1, the operator has at least 100 minutes from the loss of RNS cooling until the onset of core uncover to manually actuate the IRWST and ADS Stage 4. In general, the results of a loss of RNS during mid-loop conditions are similar but slightly less severe to those presented in this evaluation, due to the lower levels of decay heat and to the absence of the initial water inventory in the pressurizer, which serves to reduce the surge line flooding phenomenon that degrades the depressurization capability of the ADS Stages 1 through 3 vent paths.

#### **19E.4.9 Radiological Consequences (Tier 2 Information Section 15.7 and Appendix 15A)**

This section presents evaluations that confirm that the radioactive material releases from the AP600 events postulated to be initiated in a shutdown mode have acceptable consequences.

- The Standard Review Plan (Reference 24) no longer includes the atmospheric releases from radioactive gas waste system failure and radioactive liquid waste system leak or failure events as part of the review. As discussed in Tier 2 Information subsections 15.7.1 and 15.7.2, no analysis for these events is provided in the Tier 2 Information.
- Release of radioactivity to the environment due to a liquid tank failure is addressed in Tier 2 Information subsection 15.7.3 and is not mode dependent.
- The fuel handling accident described in Tier 2 Information subsection 15.7.4, while not mode dependent, is analyzed in the applicable and bounding mode and accounts for spent fuel pool boiling. This accident analysis bounds radioactivity releases from other Tier 2 Information Chapter 15 events during low power and shutdown operations. The LOCA analysis results show PCT remains below 2200°F, and there are no fuel cladding failures.
- The spent fuel cask drop accident described in Tier 2 Information subsection 15.7.5 is not mode dependent.
- Tier 2 Information appendix 15A contains the evaluation models and parameters that form the basis of the radiological consequences analyses for the various postulated accidents. This methodology applies in all modes of operation.

In summary, there are no shutdown risks associated with the radiological consequences methodology or parameters, or the postulated or applicable events, which need to be considered outside the scope of what is already analyzed for AP600 Tier 2 Information Section 15.7.

#### **19E.4.10 Other Evaluations and Analyses**

##### **19E.4.10.1 Low Temperature Overpressure Protection**

For the AP600, the normal residual heat removal system (RNS) suction relief valve is located immediately downstream of the RCS suction isolation valves. This relief valve protects the RNS from overpressurization and provides low temperature overpressure protection (LTOP) for the RCS components when the RNS is aligned to the RCS to provide decay heat removal during plant shutdown and startup operations. The RNS relief valve is sized to provide LTOP by limiting the RCS and RNS pressure to less than the 10 CFR 50 Appendix G (Reference 25) steady-state pressure limit. Tier 2 Information subsection 5.2.2 provides a discussion of the AP600 low temperature overpressure protection design bases.

##### **19E.4.10.2 Shutdown Temperature Evaluation**

In SECY-94-084, Item C, Safe Shutdown (Reference 26), the NRC staff recommended the Commission's approval of 420°F or below, rather than cold shutdown condition as a safe stable condition, which the PRHR HX must be capable of achieving and maintaining following non-LOCA events, predicated on acceptable passive safety system performance and an acceptable resolution of the regulatory treatment of nonsafety systems (RTNSS) issue. The NRC requested a safety analysis to demonstrate that the passive systems can bring the plant to a stable safe condition and maintain this condition so that no transients will result in the specified acceptable fuel design limit and pressure boundary design limit being violated and that no high-energy piping failure being initiated from this condition results in 10 CFR 50.46 (Reference 23) criteria.

As discussed in Tier 2 Information subsection 7.4.1.1, the PRHR HX operates to reduce the RCS temperature to the safe shutdown condition following an event. An analysis of the loss of normal feedwater event demonstrates that the passive systems can bring the plant to a stable safe condition following design basis transients. The results of this analysis are presented in Figures 19E.4.10-1 through 19E.4.10-5. The progression of this event is outlined in Table 19E.4.10-1.

Summarizing this transient, the loss of normal feedwater occurs, followed by the actuation of the PRHR HX on low steam generator wide-range level. The PRHR HX initially operates with high flow due to the operation of the RCPs. Eventually a safeguards actuation signal is actuated on low cold leg temperature, the RCPs are tripped, and the PRHR HX operates with natural circulation flow.

Once actuated, the CMTs operate in recirculation mode, injecting cold, borated water into the RCS. The CMTs operate in conjunction with the PRHR HX to reduce RCS temperature. Once the CMTs are heated up to the RCS temperature (after about 7 hours

of operation), they stop recirculating and the PRHR HX alone removes core decay heat. However, operation of the CMTs in conjunction with the PRHR HX causes the RCS temperature to be reduced to a temperature where the PRHR HX alone is not able to match decay heat at about 4000 seconds. This causes the RCS temperature to increase until the PRHR HX can match decay heat. At about 21,000 seconds, the PRHR HX can match decay heat and it continues to operate to reduce the RCS temperature to below 420°F within 36 hours. As seen from Figure 19E.4.10-1, the cold leg temperature in the loop with PRHR HX is reduced to 420°F at 39,140 seconds, while RCS hot leg temperature in this loop reaches 420°F in 93,690 seconds (approximately 26 hours).

As discussed in Tier 2 Information subsection 7.4.1.1, the PRHR HX capability to meet the safe shutdown temperature is dependent on condensate from the containment shell being returned to the IRWST. The gutter isolation valves can perform their intended function while meeting the single failure criterion. As shown in Figure 19E.4.10-5, the IRWST heats up to saturation in about 18,000 seconds. Once saturated, the IRWST inventory begins to boil, and the steam condenses on the containment shell. If condensate is returned to the IRWST, the PRHR HX could operate indefinitely, provided that the passive containment cooling system (PCS) is available.

As shown in Figure 19E.4.10-6, if condensate is not returned to the IRWST, the IRWST water level drops to the top of the PRHR HX at approximately 30,000 seconds (about 8 hours). The IRWST water level will continue to drop; however, the PRHR HX continues to operate. Although the PRHR HX is not able to match core decay heat indefinitely in this situation, the PRHR HX continues to operate and effectively remove heat from the RCS. The RCS temperature profile as the PRHR HX tubes become uncovered is shown in Figure 19E.4.10-7. This plot was generated by modifying LOFTRAN-AP such that when the IRWST water level reaches the top of a PRHR HX node, heat transfer in that node is turned off. This model conservatively bounds the PRHR HX heat transfer when the water level is below the top of the tube bundle.

As discussed in Tier 2 Information subsection 7.4.1.1, this mode of operation can last for up to 72 hours. However, in about 22 hours after the event, if no ac power is available, or if condensate return is not available, then the operator is instructed to actuate the ADS. Operation of the ADS in conjunction with the CMTs, accumulators, and IRWST reduces the RCS pressure and temperature to below 420°F. Prior to ADS, with no condensate return, the IRWST water level is reduced to approximately the 22-foot level.

Actuation of ADS at this time quickly reduces RCS temperatures to below 420°F. The Tier 2 Information subsection 15.6.5.4b analysis of an inadvertent actuation of ADS at full power takes place from an initial RCS  $T_{avg}$  condition of 565°F, and it shows that the ADS reduces RCS pressure below the saturation pressure (308.8 psia) of the 420°F temperature in less than 5 minutes by venting steam generated due to flashing of liquid. Note that the pressure in the post-shutdown inadvertent ADS actuation case (presented in subsection 19E.4.8.2 of this appendix) drops below 308.8 psia more rapidly, in less than 100 seconds. The ADS operation leads to injection from the PXS, which reduces the reactor lower plenum temperature in the Tier 2 Information full-power case to a value below 200°F before the actuation of ADS stage 4 occurs. Given the much lower RCS energy content and power

level 24 hours after trip and the fact that all of the PXS components are available during this event, the depressurization and energy release that ADS actuation must provide to reach an RCS temperature of 420°F is easily achieved.

Twenty-four hours after reactor trip, the decay heat is less than 1 percent of the full-core power value and the primary temperature is less than 500°F. Due to the extended PRHR HX operation, the level of water in the IRWST is reduced, so there is less head available at the initiation of IRWST injection than exists for a full-power LOCA case. For cases in which only the PXS is available, the Tier 2 Information long-term cooling analysis (Tier 2 Information subsection 15.6.5.4c) bounds the 24-hour IRWST injection condition. It presents sump injection scenarios in which lower levels of saturated water inject to the RCS at higher core power levels. Therefore, the IRWST injects for this postulated event at an adequate rate to provide long-term core cooling. The ADS actuation provides a safety-related method not only to reach an RCS temperature of 420°F but also to achieve core cooling in the long term, if necessary.

## **19E.5 Technical Specifications**

While the Technical Specification guidance provided in NUREG-1449 (Reference 2) relates to existing plant shutdown operation concerns, the underlying concerns relating to causes of events and recovery from those events during shutdown operations are applicable to the AP600. Section 19E.5.1 summarizes the shutdown Technical Specifications. Section 19E.5.2 summarizes the AP600's compliance with SECY-93-190 (Reference 27).

### **19E.5.1 Summary of Shutdown Technical Specifications**

The content of the AP600 Technical Specifications meets the requirements of 10 CFR 50.36 (Reference 28) and is consistent with the guidance provided in NUREG-1431 (Reference 29). For the AP600, passive systems are used to safely shut down the plant. Because this design feature is different from existing plants, and because NUREG-1449 provides a reasonable basis for creating shutdown Technical Specifications, the AP600 Technical Specifications are improved to include specifications for these systems in the shutdown modes. These shutdown specifications are summarized in AP600 Technical Specification Table B 3.0-1 (Tier 2 Information Section 16.1), which provides the passive systems shutdown mode matrix of system versus limiting conditions for operation (LCO), mode applicability, and required end state.

### **19E.5.2 Compliance with SECY-93-190**

SECY-93-190 (Reference 17), published in July 1993, discusses the staff positions preparatory to final staff positions in the area of shutdown and low-power operations. This SECY pre-dates the September 1993 issuance of NUREG-1449 and the April 1995 issuance of NUREG-1431. Given these more current guidelines for shutdown operation Technical Specifications, the AP600 Technical Specifications follow the guidance provided in NUREGs 1449 and 1431, not SECY-93-190.

**19E.6 Shutdown Risk Evaluation**

The "AP600 Probabilistic Risk Assessment (PRA)" (Tier 2 Information Chapter 19) provides an evaluation of the plant risk associated with events at shutdown.

**19E.7 Compliance with NUREG-1449**

The Diablo Canyon event of April 10, 1987, and the loss of ac power event at the Vogtle plant on March 20, 1990, led the Nuclear Regulatory Commission (NRC) staff to issue NUREG-1449, "Shutdown and Low Power Operation at Commercial Nuclear Power Plants in the United States" (Reference 2), to provide an evaluation of the shutdown risk issue. The scope of NUREG-1449 includes subjects such as operating experiences as documented in generic letters, operator training, technical specifications, residual heat removal capacity, temporary reactor coolant boundaries, rapid boron dilution, containment capacity, fire protection, outage planning and control, and instrumentation.

The NRC requested Westinghouse to assess the compliance of AP600 with NUREG-1449. It was recognized that some of the issues discussed in NUREG-1449 are the responsibility of the plant owners because they relate to operation, maintenance, and refueling plans, procedures, and risk management. However, the NRC believed that the level of defense-in-depth against shutdown events would be improved if clear guidance is provided to the areas discussed above by the plant designer. The NRC requested that Westinghouse perform a systematic assessment of the shutdown risk issue to address areas identified in NUREG-1449 as they are applicable to the AP600 design and document the results.

This Appendix provides the systematic assessment of the shutdown risk issue to address areas identified in NUREG-1449. This assessment includes design basis evaluations of events that can occur during shutdown and a probabilistic assessment of plant risk at shutdown. The design of the AP600 builds on the lessons-learned from the industry with regard to shutdown safety, including the guidance provided in NUREG-1449.

**19E.8 Conclusion**

This AP600 Shutdown Evaluation provides a systematic evaluation of the AP600 during shutdown operations. As demonstrated in this appendix, the AP600 is designed to mitigate events that can occur during shutdown modes. In addition, the risk of core damage as a result of an accident that may occur during shutdown has been demonstrated to be acceptably low.

**19E.9 References**

- 1 Letter, Westinghouse to NRC, DCP/NRC1385, AP600 Emergency Response Guidelines.
- 2 NUREG-1449, "Shutdown and Low Power Operations at Commercial Nuclear Power Plants in the United States," September 1993.

- 3 NRC Information Notice 92-54, "Level Instrumentation Inaccuracies Caused by Rapid Depressurization," July 24, 1992.
- 4 Letter, Westinghouse to NRC, DCP/NRC0124, APWR-0452, "AP600 Vortex Mitigator Development Test for RCS Mid-loop Operation," July 6, 1994.
- 5 NUREG-0897, Rev. 1, "Containment Emergency Sump Performance," October 1985.
- 6 Title 10, Code of Federal Regulations, Part 50, Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Processing Plants."
- 7 NRC Regulatory Guide 1.26, "Quality Group Classifications and Standards for Water-, Steam-, and Radioactive-Waste-Containing Components of Nuclear Power Plants," Revision 3, February 1976.
- 8 American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section III, 1988 with 1989 Addenda.
- 9 WCAP-13856, "AP600 Implementation of the Regulatory Treatment of Nonsafety Related Systems (RTNSS) Process Summary Report."
- 10 NRC Generic Letter 88-17, "Loss of Decay Heat Removal," 10 CFR 50.54(f).
- 11 NUMARC 91-06, "Guidelines for Industry Actions to Assess Shutdown Management," December 1991.
- 12 Deleted
- 13 WCAP-12945, Volumes 1-5, "Code Qualification Document for Best Estimate LOCA Analysis."
- 14 Hochreiter, L. E., Kemper, R. M., Bajorek, S. M., and Zhang, J., WCAP-14171, Revision 1, "WCOBRA/TRAC Applicability to AP600 Large-Break Loss-of-Coolant Accident."
- 15 Hochreiter, L. E., Loftus, M. J., Brown, W. L., WCAP 14727, "AP600 Scaling and PIRT Closure Report."
- 16 Title 10, Code of Federal Regulations, Part 50, Appendix K, "ECCS Evaluation Models," January 1, 1996.
- 17 SECY-93-190, "Regulatory Approach to Shutdown and Low-Power Operations," July 12, 1993.
- 18 WCAP-14776, "WCOBRA TRAC Long-term Cooling Final Validation Report."
- 19 WCAP-14807, Revision 1, "NOTRUMP Final Validation Report for AP600."

- 20 Lewis, R. N., Huang, P., Behnke, D. H., Fittante, R. L., and Gelman, A., WCAP-10698-P-A, "SGTR Analysis Methodology to Determine the Margin to Steam Generator Overfill."
- 21 WCAP-14206, "Applicability of the NOTRUMP Computer Code to AP600 SSAR Small-Break LOCA Analyses."
- 22 WCAP-14601, "AP600 Accident Analyses, Evaluation Models."
- 23 Title 10, Code of Federal Regulations, Part 50, (10 CFR 50.46).
- 24 NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," Revision 1, July 1981.
- 25 Title 10, Code of Federal Regulations, Part 50, Appendix G, "Fracture Toughness Requirements."
- 26 SECY-94-084, "Policy and Technical Issues Associated with the Regulatory Treatment of Non-safety Systems in Passive Plant Designs," March 28, 1994.
- 27 NRC letter, SECY-93-190, "Regulatory Approach to Shutdown and Low-Power Operations," July 12, 1993.
- 28 Title 10, Code of Federal Regulations, Part 50.36, "Technical Specifications."
- 29 NUREG-1431, "Standard Technical Specifications – Westinghouse Plants," April 1995.

<b>Table 19E.2-1</b> <b>Evaluation of a Loss of RNS at Mid-loop with no IRWST Injection</b>			
<b>Time After Shutdown</b>	<b>Time to Boiling</b>	<b>Time to Empty Hot Leg</b>	<b>Time to Core Uncovery</b>
28 hours	17 minutes	59 minutes	102 minutes

<b>Table 19E.4.1-1 AP600 Accidents Requiring Shutdown Evaluation or Analysis</b>		
<b>Tier 2 Section</b>	<b>Titles</b>	<b>Evaluation or Analysis Required</b>
15.1	Increase in Heat Removal from the Primary System	
15.1.1	Feedwater System Malfunctions that Result in a Decrease in Feedwater Temperature	E
15.1.2	Feedwater System Malfunctions that Result in an Increase in Feedwater Flow	E
15.1.3	Excessive Increase in Secondary Steam Flow	E
15.1.4	Inadvertent Opening of a Steam Generator Relief or Safety Valve	E
15.1.5	Steam System Piping Failure	
15.1.6	Inadvertent Operation of the Passive Residual Heat Removal Heat Exchanger	E
15.2	Decrease in Heat Removal by the Secondary System	
15.2.1	Steam Pressure Regulator Malfunction or Failure that Results in Decreasing Steam Flow	E
15.2.2	Loss of External Electrical Load	E
15.2.3	Turbine Trip	E
15.2.4	Inadvertent Closure of Main Steam Isolation Valves	E
15.2.5	Loss of Condenser Vacuum and Other Events Resulting in Turbine Trip	E
15.2.6	Loss of ac Power to the Plant Auxiliaries	E
15.2.7	Loss of Normal Feedwater Flow	E
15.2.8	Feedwater System Pipe Break	E
15.3	Decrease in Reactor Coolant System Flow Rate	
15.3.1	Partial Loss of Forced Reactor Coolant Flow	E
15.3.2	Complete Loss of Forced Reactor Coolant Flow	E
15.3.3	Reactor Coolant Pump Shaft Seizure (Locked Rotor)	E
15.3.4	Reactor Coolant Pump Shaft Break	E
15.4	Reactivity and Power Distribution Anomalies	
15.4.1	Uncontrolled Rod Cluster Control Assembly Bank Withdrawal from a Subcritical or Low-Power Startup Condition	E
15.4.2	Uncontrolled Rod Cluster Control Assembly Bank Withdrawal at Power	n/a
15.4.3	Rod Cluster Control Assembly Misalignment (System Malfunction or Operator Error)	E
15.4.4	Startup of an Inactive Reactor Coolant Pump at an Incorrect Temperature	E

<b>Table 19E.4.1-1 (cont.)</b>		
<b>AP600 Accidents Requiring Shutdown Evaluation or Analysis</b>		
<b>Tier 2 Section</b>	<b>Titles</b>	<b>Evaluation or Analysis Required</b>
15.4.6	Chemical and Volume Control System Malfunction That Results in a Decrease in the Boron Concentration in the Reactor Coolant	n/a
15.4.7	Inadvertent Loading and Operation of a Fuel Assembly in an Improper Position	E
15.4.8	Spectrum of Rod Cluster Control Assembly Ejection Accidents	
15.5	Increase in Reactor Coolant Inventory	
15.5.1	Inadvertent Operation of the Core Makeup Tanks (CMT) During Power Operation	E
15.5.2	Chemical and Volume Control System Malfunction That Increases Reactor Coolant Inventory	E
15.6	Decrease in Reactor Coolant Inventory	
15.6.1	Inadvertent Opening of a Pressurizer Safety Valve or Inadvertent Operation of the ADS	E
15.6.2	Failure of Small Lines Carrying Primary Coolant Outside Containment	E
15.6.3	Steam Generator Tube Rupture	E
15.6.5	Loss of Coolant Accidents Resulting from a Spectrum of Postulated Piping Breaks Within the Reactor Coolant Pressure Boundary	E/A
15.7	Radioactive Release From a Subsystem or Component	E

<b>Table 19E.4.8-1 Double-ended Cold Leg Guillotine Break Sequence of Events</b>	
<b>Event</b>	<b>Time (seconds)</b>
Break Open	0.0
"S" Signal Receipt	3
RCPs Start to Coast Down	18
CMT Draindown Begins	30
Lower Plenum Refilled	208

<b>Table 19E.4.8-2 Inadvertent ADS Actuation Sequence of Events</b>	
<b>Case</b>	<b>Time (seconds)</b>
ADS Stage 1 Flow Starts	0.0
CMT Actuation Signal	0.0
PRHR HX Actuation	0.0
RCPs Start to Coast Down	16.2
ADS Stage 2 Flow Starts	70
ADS Stage 3 Flow Starts	190
ADS Stage 4 Flow Starts	1497
CMT Empty	1820
IRWST Injection Starts	2030

**Table 19E.4.8-3**  
**DEDVI Break Sequence of Events**

<b>Case</b>	<b>Time (seconds)</b>
Break Open	0.0
CMT Actuation Signal	18
RCPs Start to Coast Down	34.2
ADS Stage 1 Flow Starts	342
ADS Stage 2 Flow Starts	412
ADS Stage 3 Flow Starts	532
ADS Stage 4 Flow Starts	652
IRWST Injection Starts	820

<b>Table 19E.4.8-4 Loss of RNS Cooling in Mode 4 with RCS Intact Sequence of Events</b>	
<b>Event</b>	<b>Time (seconds)</b>
Loss of RNS Cooling	0
RNS Relief Valve Flow Starts	1400
CMT Actuated	9500
RNS Relief Valve Flow Terminated	9700
ADS Stage 1 Flow Starts	10,075
ADS Stage 2 Flow Starts	10,145
ADS Stage 3 Flow Starts	10,265
ADS Stage 4 Flow Starts	10,895
IRWST Injection Starts	11,845

**Table 19E.4.8-5**  
**Loss of RNS Cooling in Mode 5 with RCS Open**  
**Sequence of Events**

<b>Event</b>	<b>Time (seconds)</b>
Loss of RNS Cooling	0
Hot Leg Empty	7200
ADS Stage 4 Flow Initiated	7290
IRWST Injection Starts	7400

<b>Table 19E.4.10-1</b>	
<b>Sequence of Events Following a Loss of Normal Feedwater Flow with Condensate From the Containment Shell Being Returned to the IRWST</b>	
<b>Event</b>	<b>Time (seconds)</b>
Feedwater is Lost	10.0
Low Steam Generator Water Level (Narrow-Range) Reactor Trip Setpoint Reached	83.9
Rods Begin to Drop	85.9
PRHR HX Actuation on Low Steam Generator Water Level (Wide-Range)	150.9
Low $T_{\text{cold}}$ Setpoint Reached	1069.7
Steamline Isolation on Low $T_{\text{cold}}$ Signal	1081.7
RCP Trip on Low $T_{\text{cold}}$ Signal	1084.7
CMTs Actuated on Low $T_{\text{cold}}$ Signal	1091.7
IRWST Reaches Saturation Temperature	18,540
Heat Extracted by PRHR HX Matches Core Decay Heat	~21,000
CMTs Stop Recirculating	~27,100
Cold Leg Temperature Reaches 420°F (loop with PRHR)	39,140
Hot Leg Temperature Reaches 420°F (loop with PRHR)	93,690

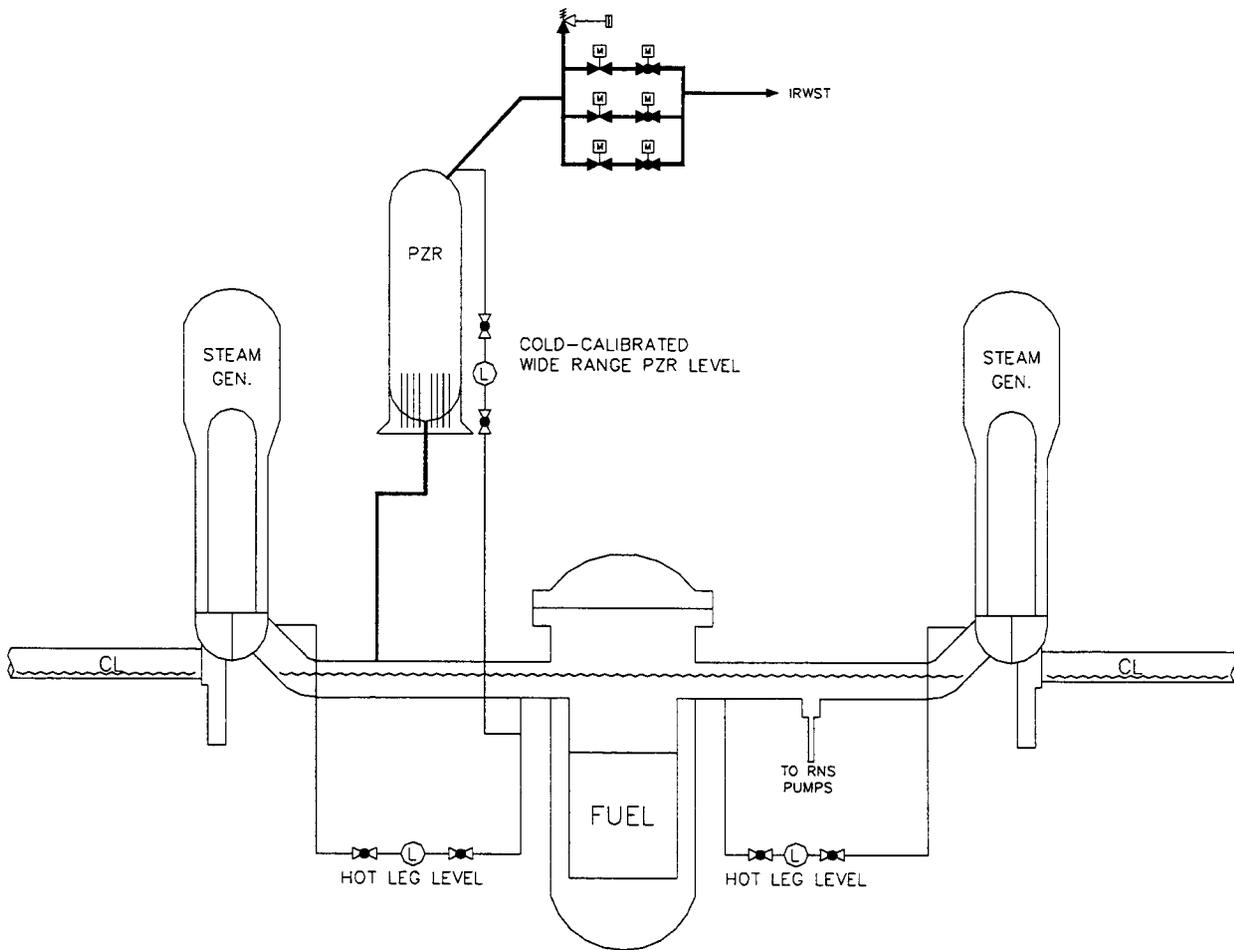


Figure 19E.2-1 Reactor Coolant System Level Instruments Used During Shutdown

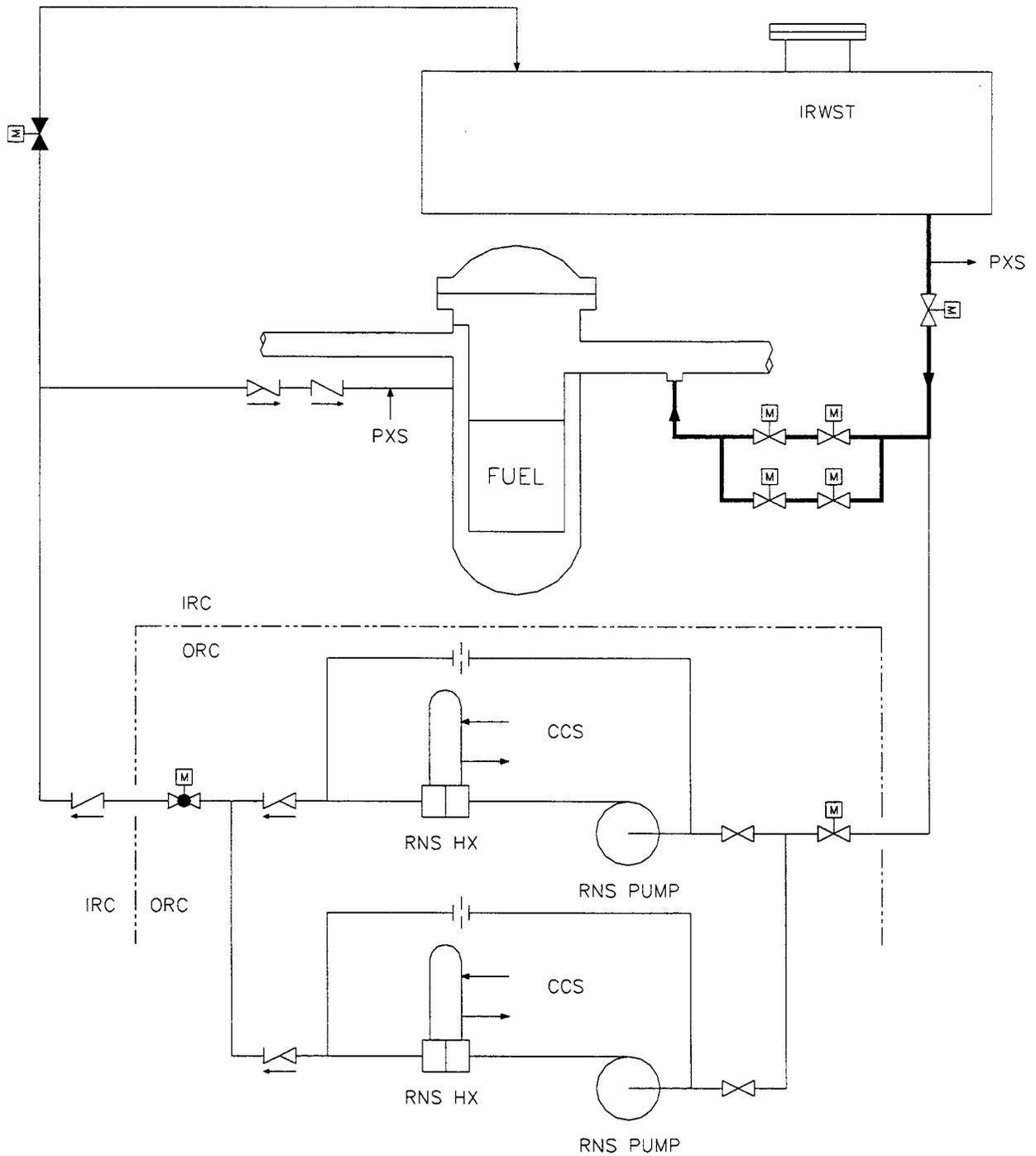


Figure 19E.2-2 IRWST Injection Flow Path

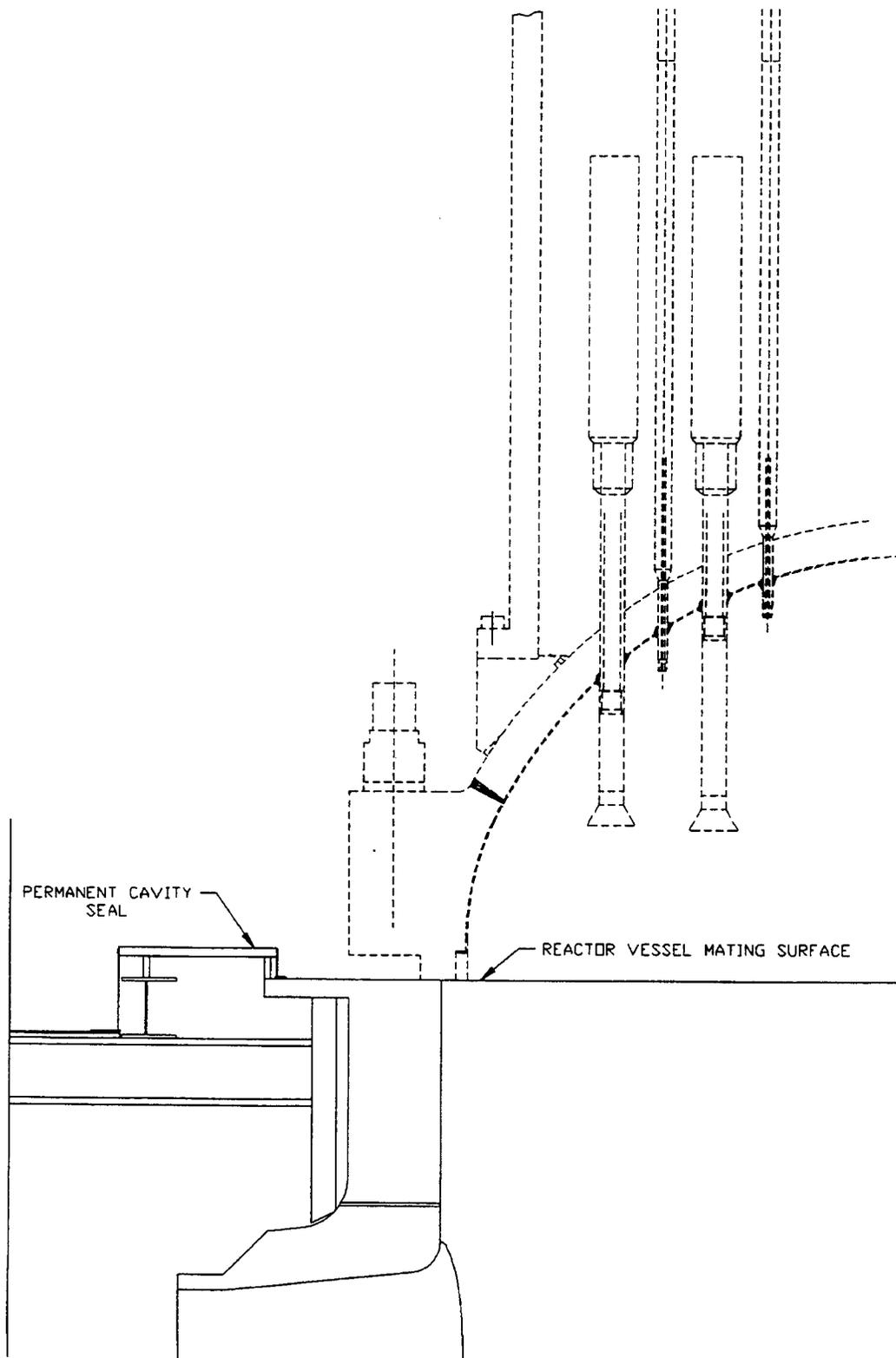


Figure 19E.2-3 AP600 Permanent Reactor Cavity Seal

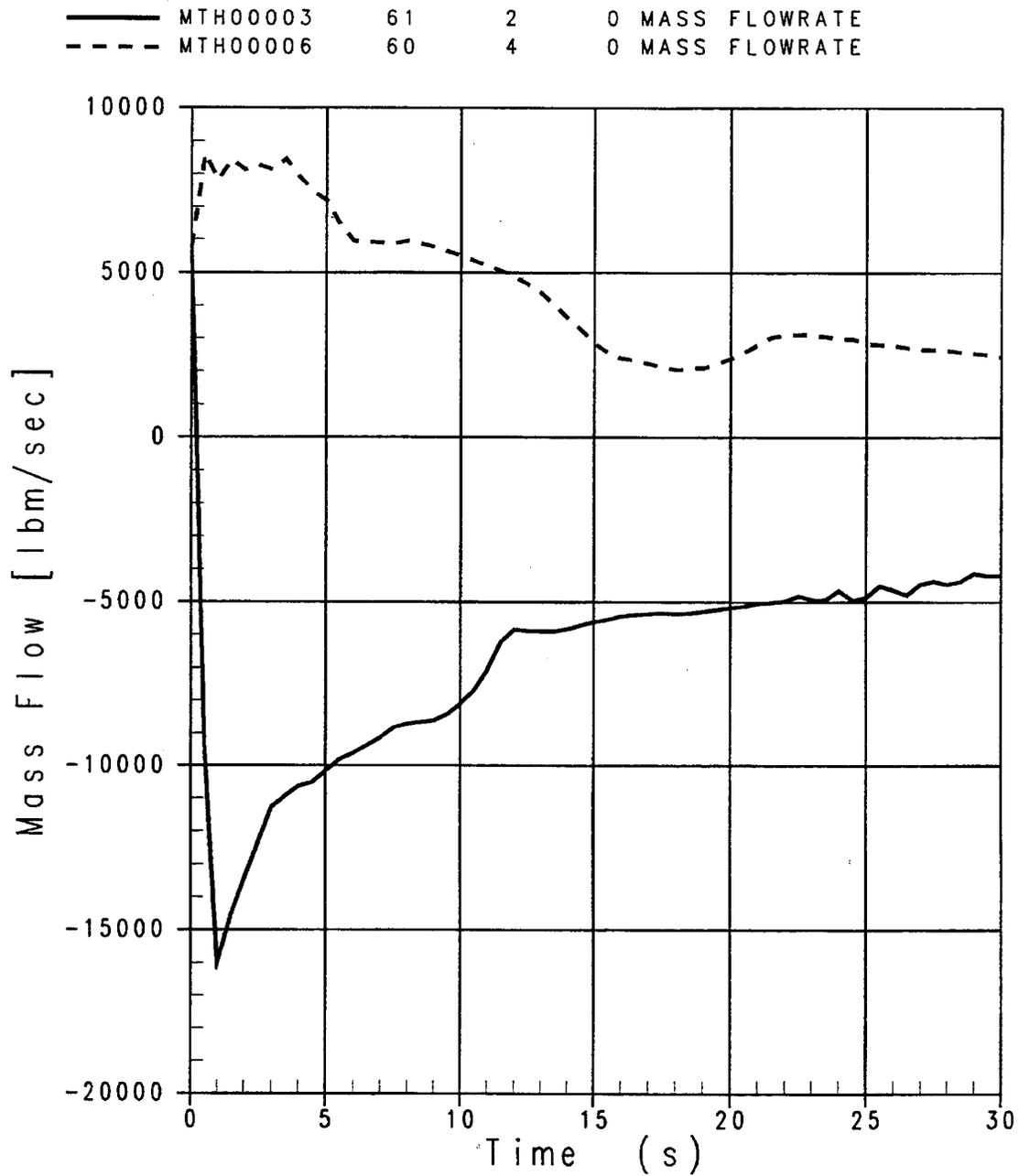


Figure 19E.4.8-1 Mode 3  $C_D = 0.8$  DECLG Break, Break Flow Rates, Vessel and RCP Sides

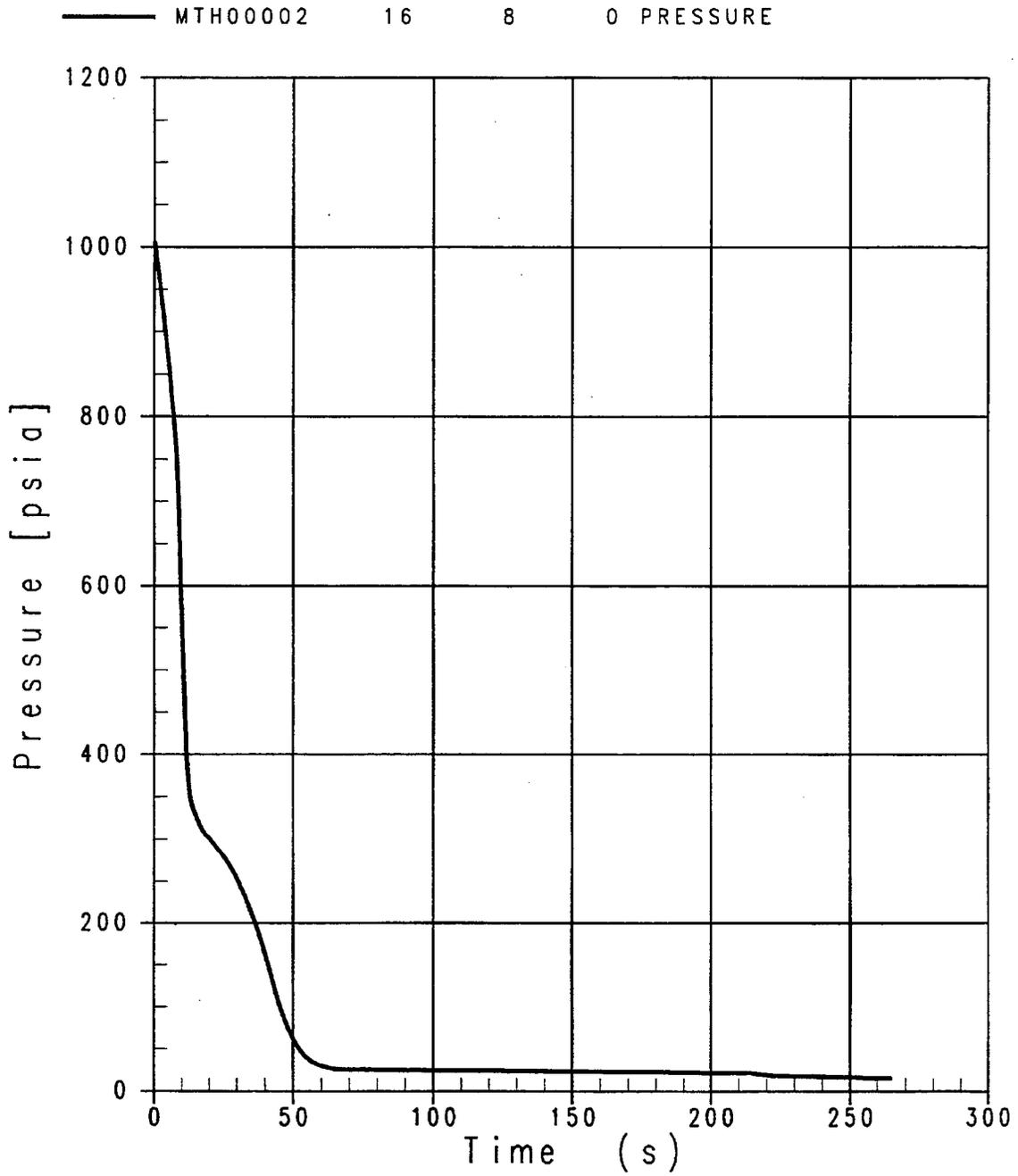


Figure 19E.4.8-2 Mode 3  $C_D = 0.8$  DECLG Break, Pressurizer Pressure

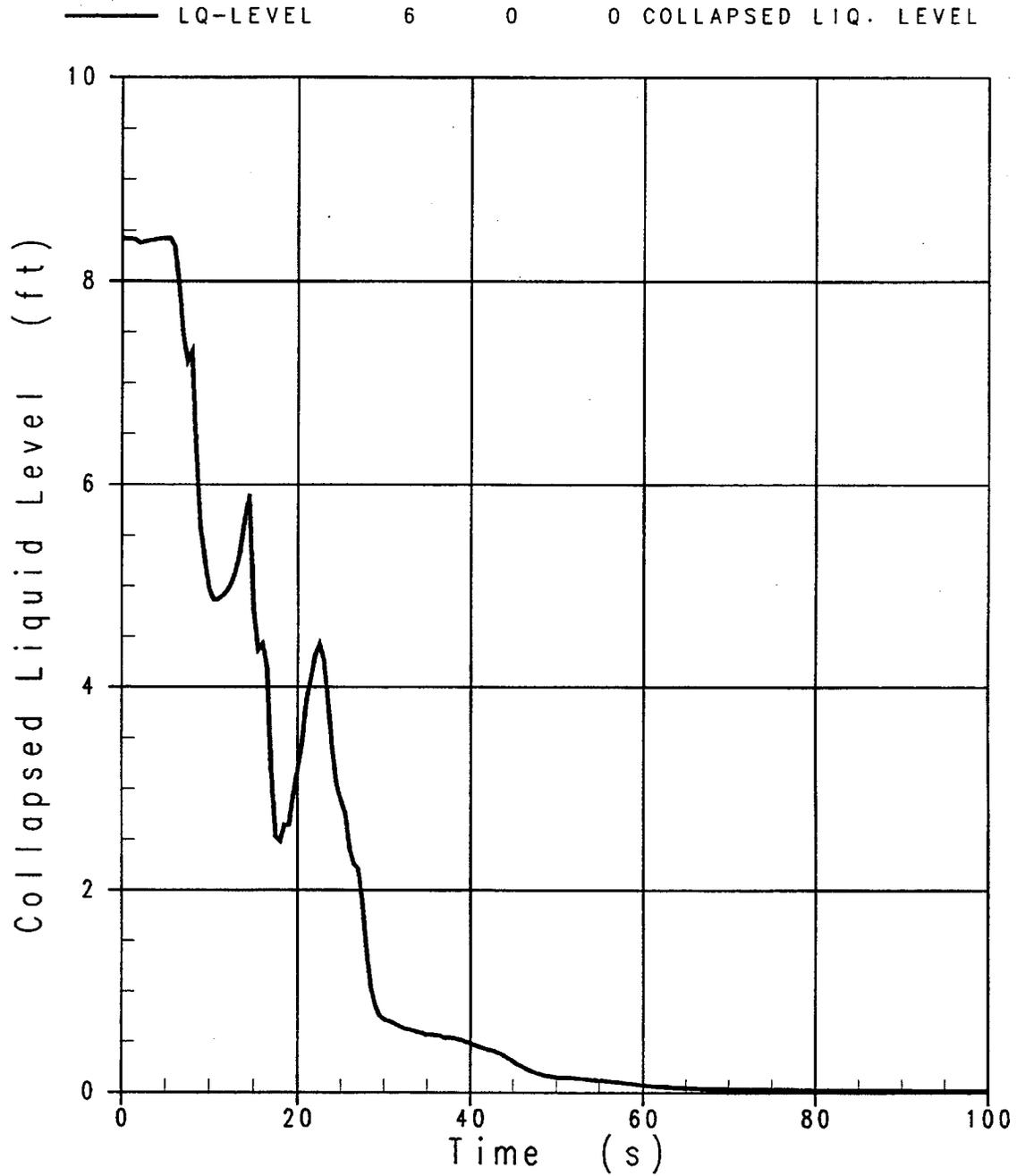


Figure 19E.4.8-3 Mode 3  $C_D = 0.8$  DECLG Break, Upper Plenum Collapsed Liquid Level

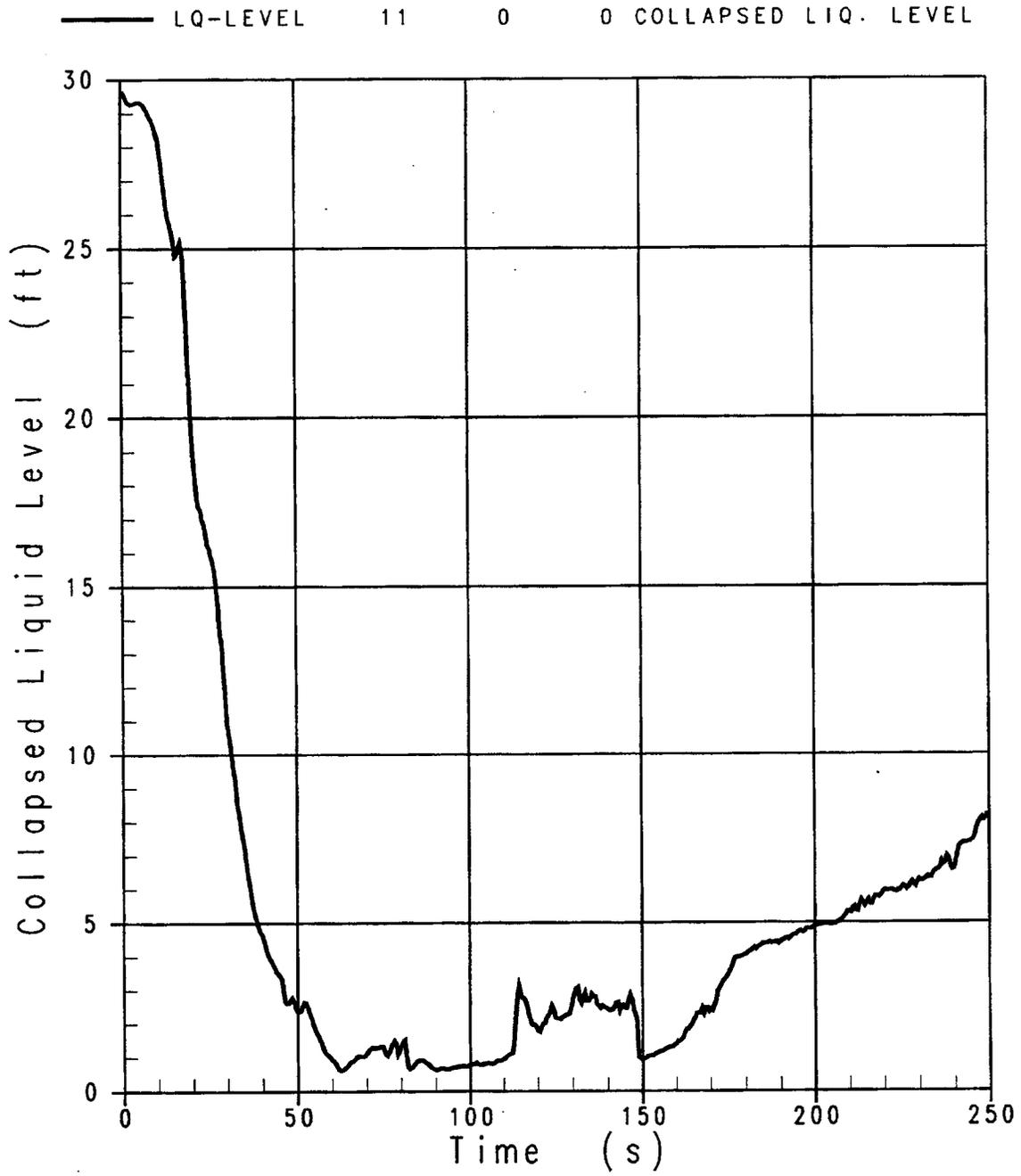


Figure 19E.4.8-4 Mode 3  $C_D = 0.8$  DECLG Break, Downcomer Collapsed Liquid Level

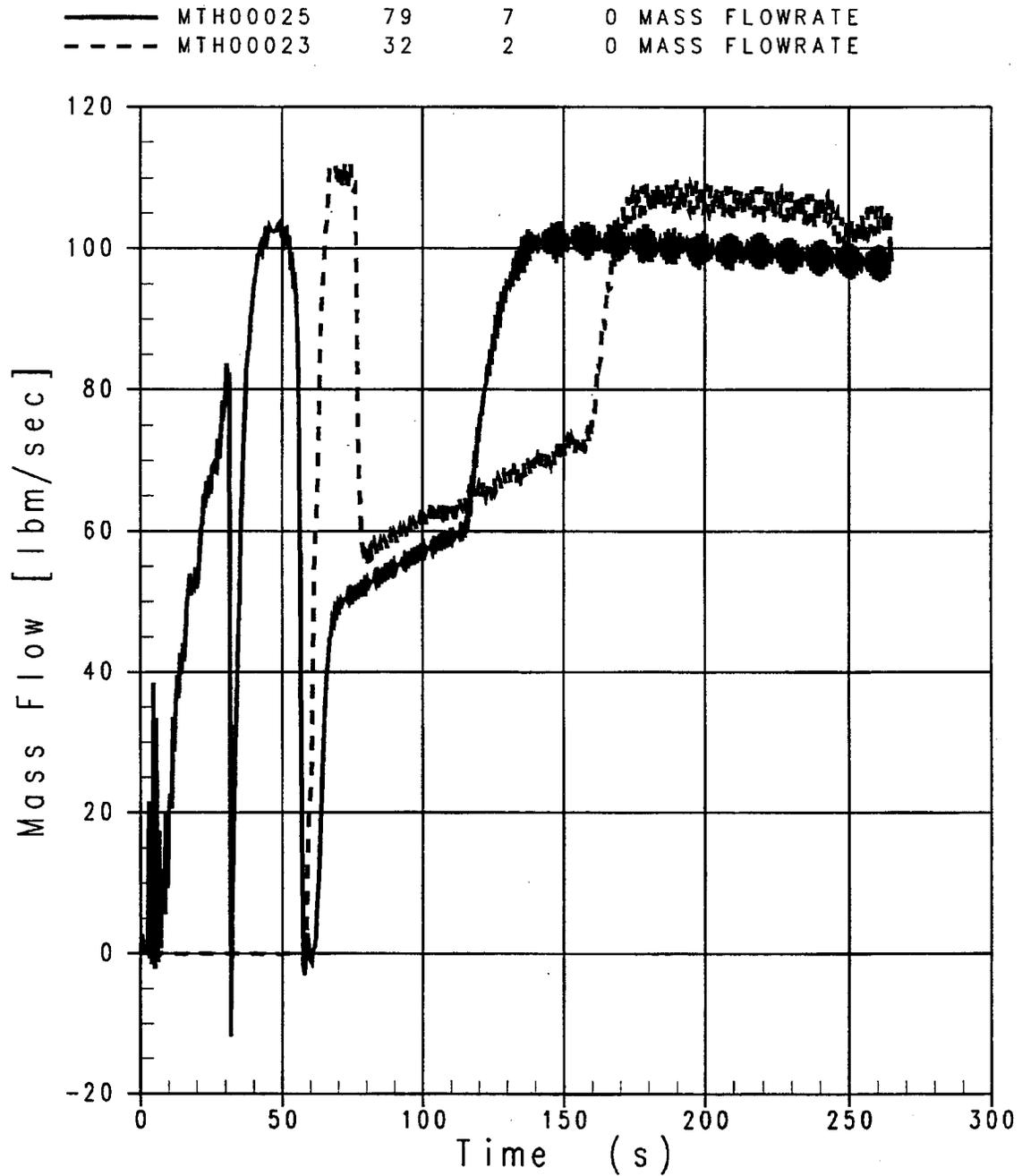


Figure 19E.4.8-5 Mode 3  $C_D = 0.8$  DECLG Break, CMT Flow Rates

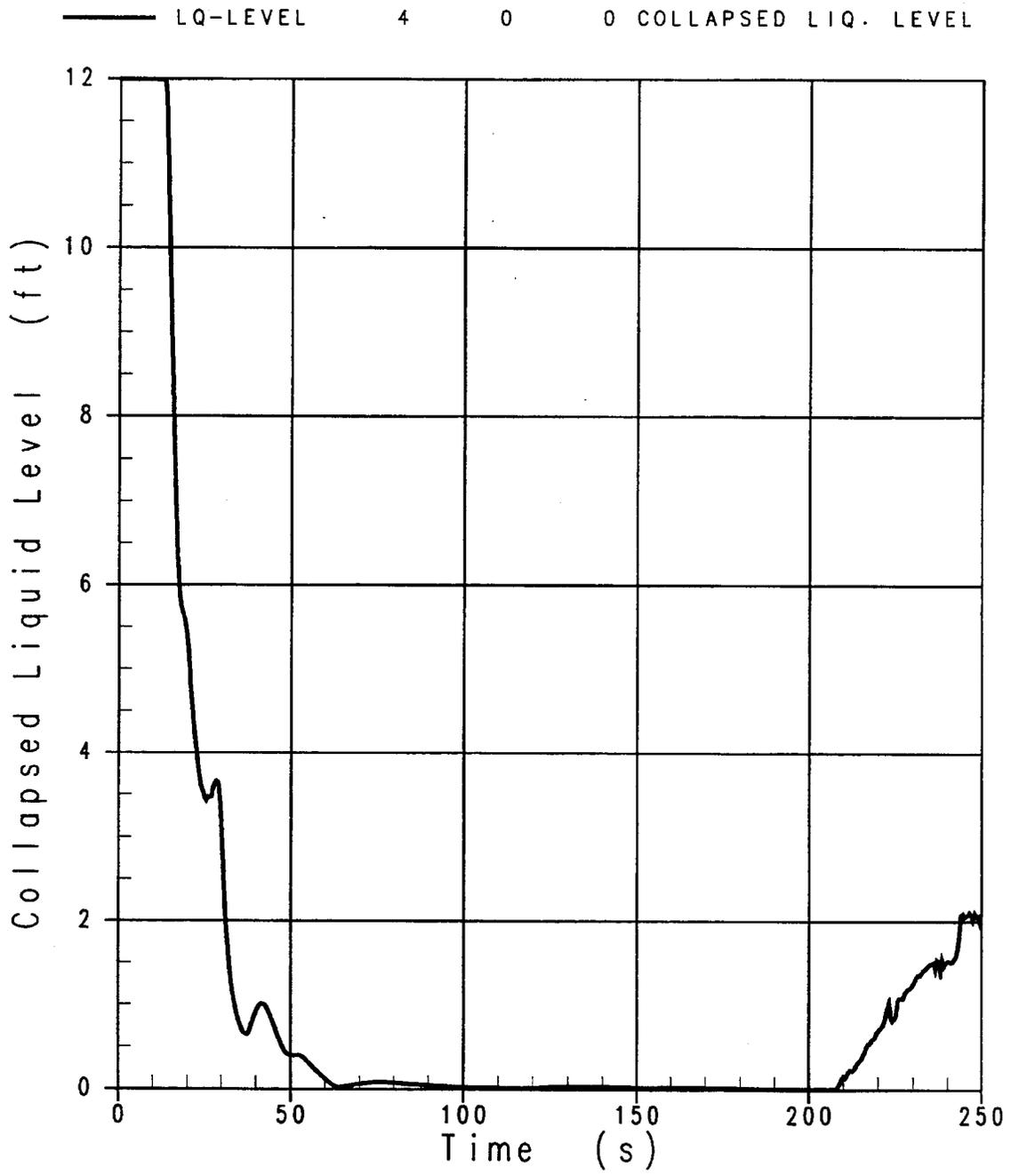


Figure 19E.4.8-6 Mode 3  $C_p = 0.8$  DECLG Break, Core Collapsed Liquid Level

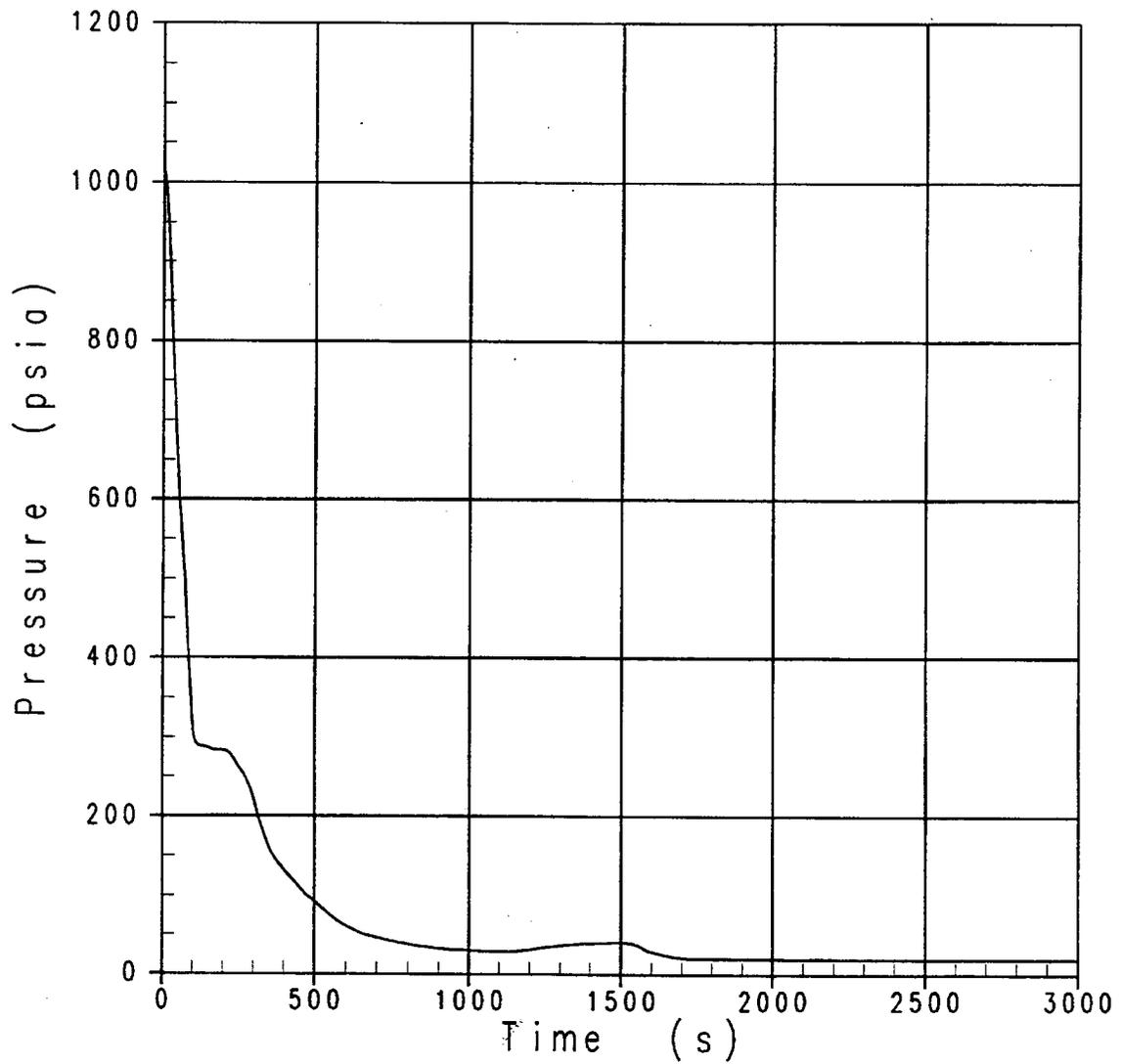


Figure 19E.4.8-7 Pressurizer Pressure, Inadvertent ADS Actuation

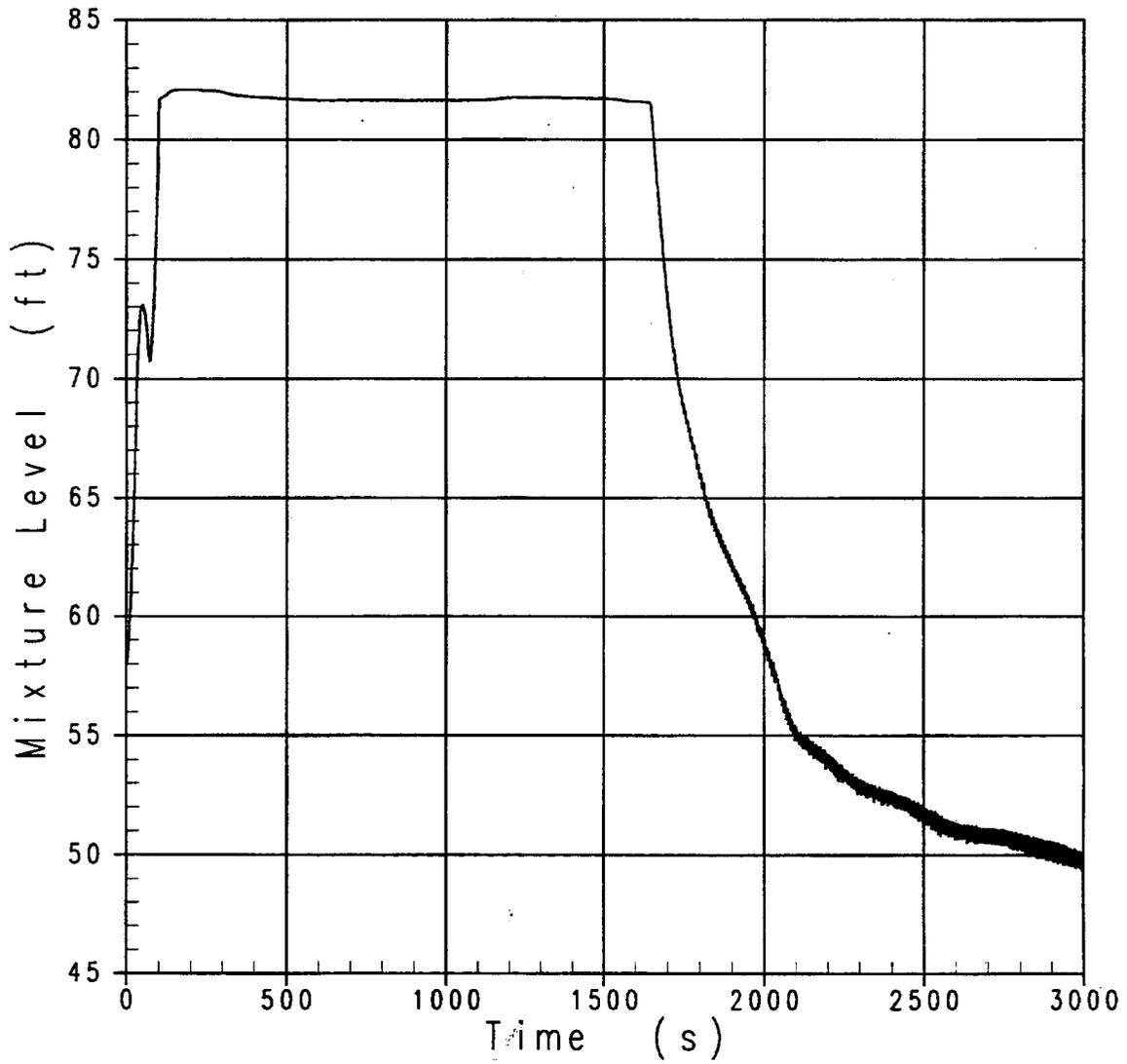


Figure 19E.4.8-8 Pressurizer Level, Inadvertent ADS Actuation

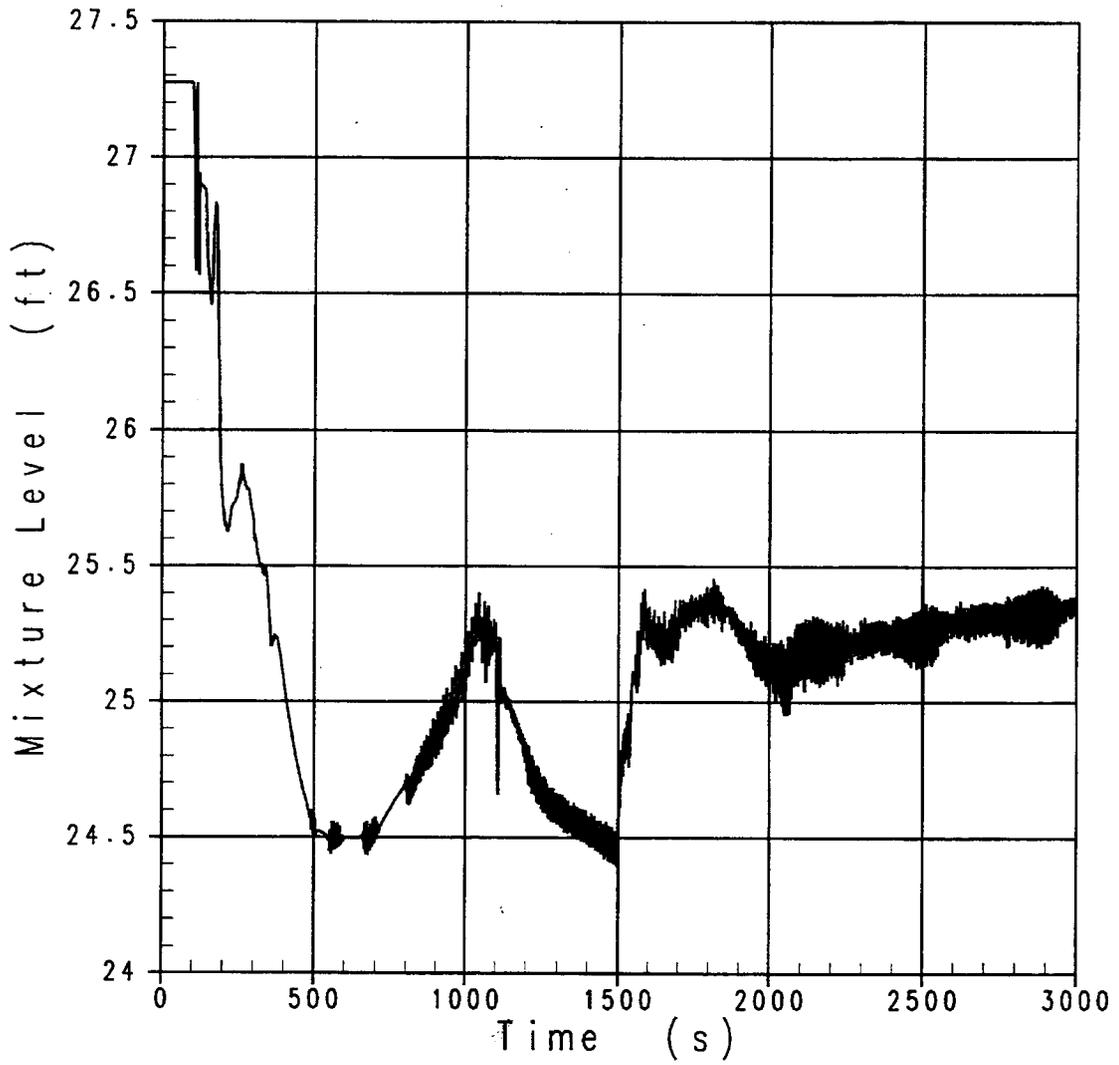


Figure 19E.4.8-9 Core Stack Mixture Level, Inadvertent ADS Actuation

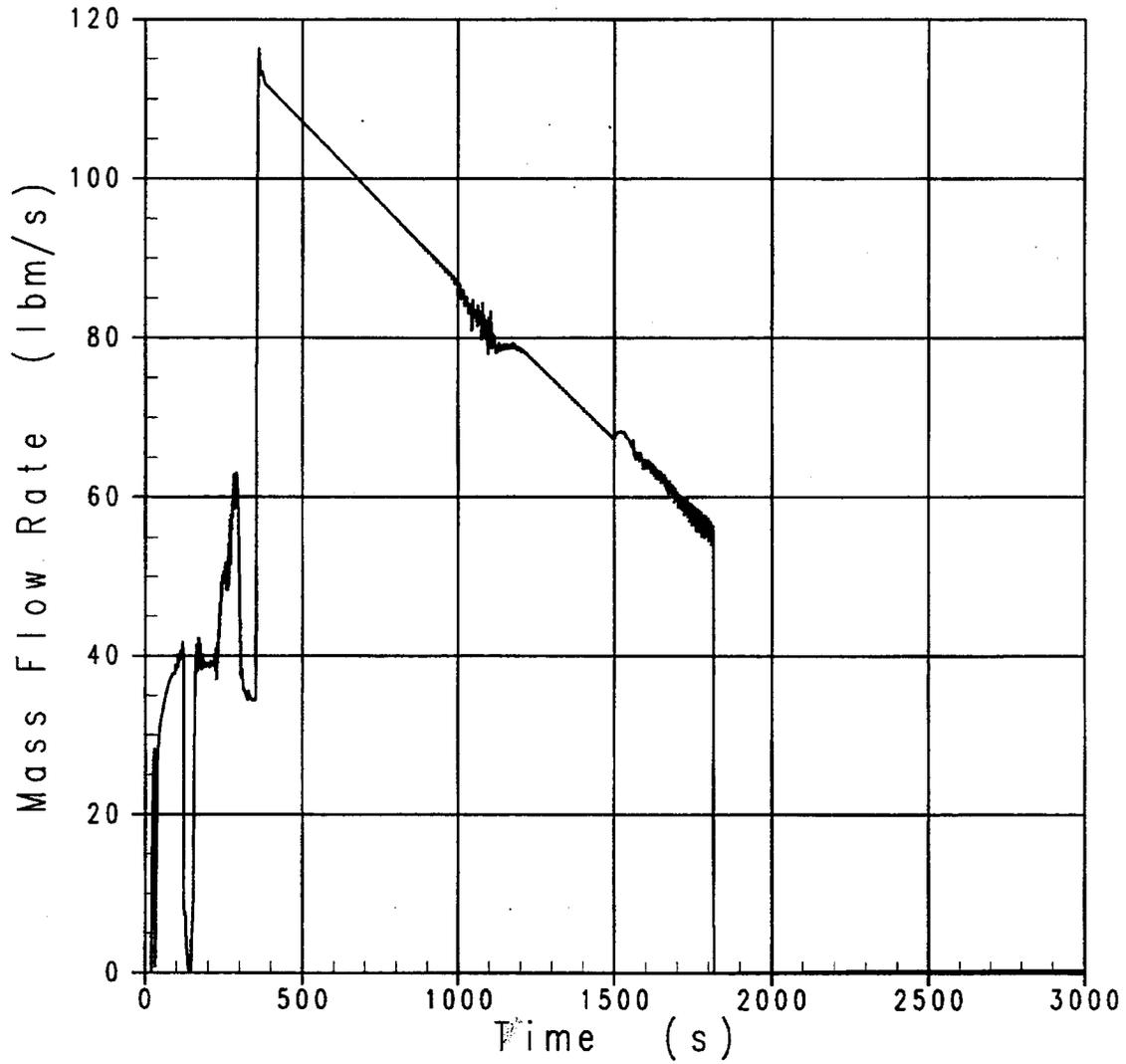


Figure 19E.4.8-10 Loop 1 CMT to DVI Flow, Inadvertent ADS Actuation

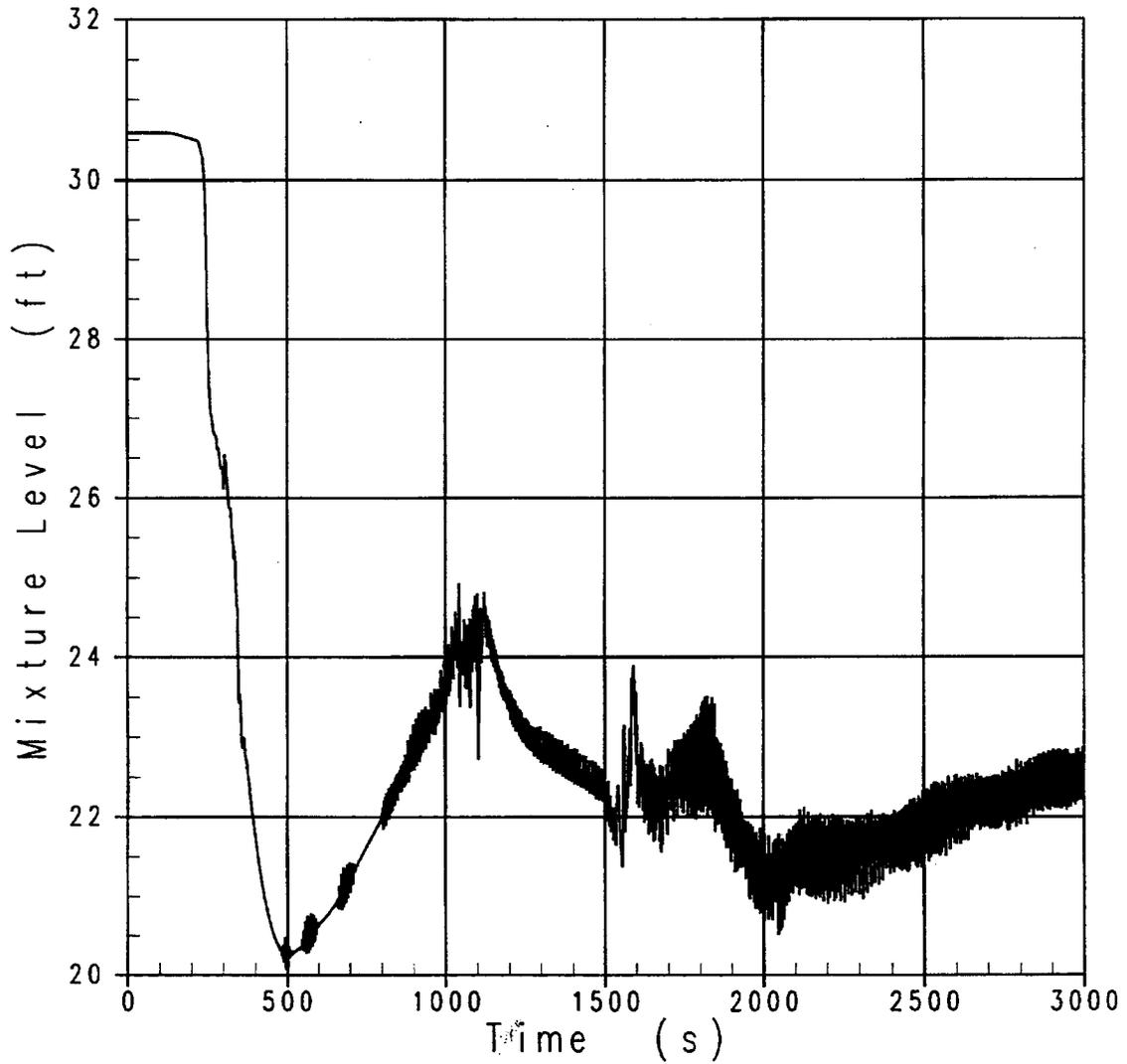


Figure 19E.4.8-11 Downcomer Mixture Level, Inadvertent ADS Actuation

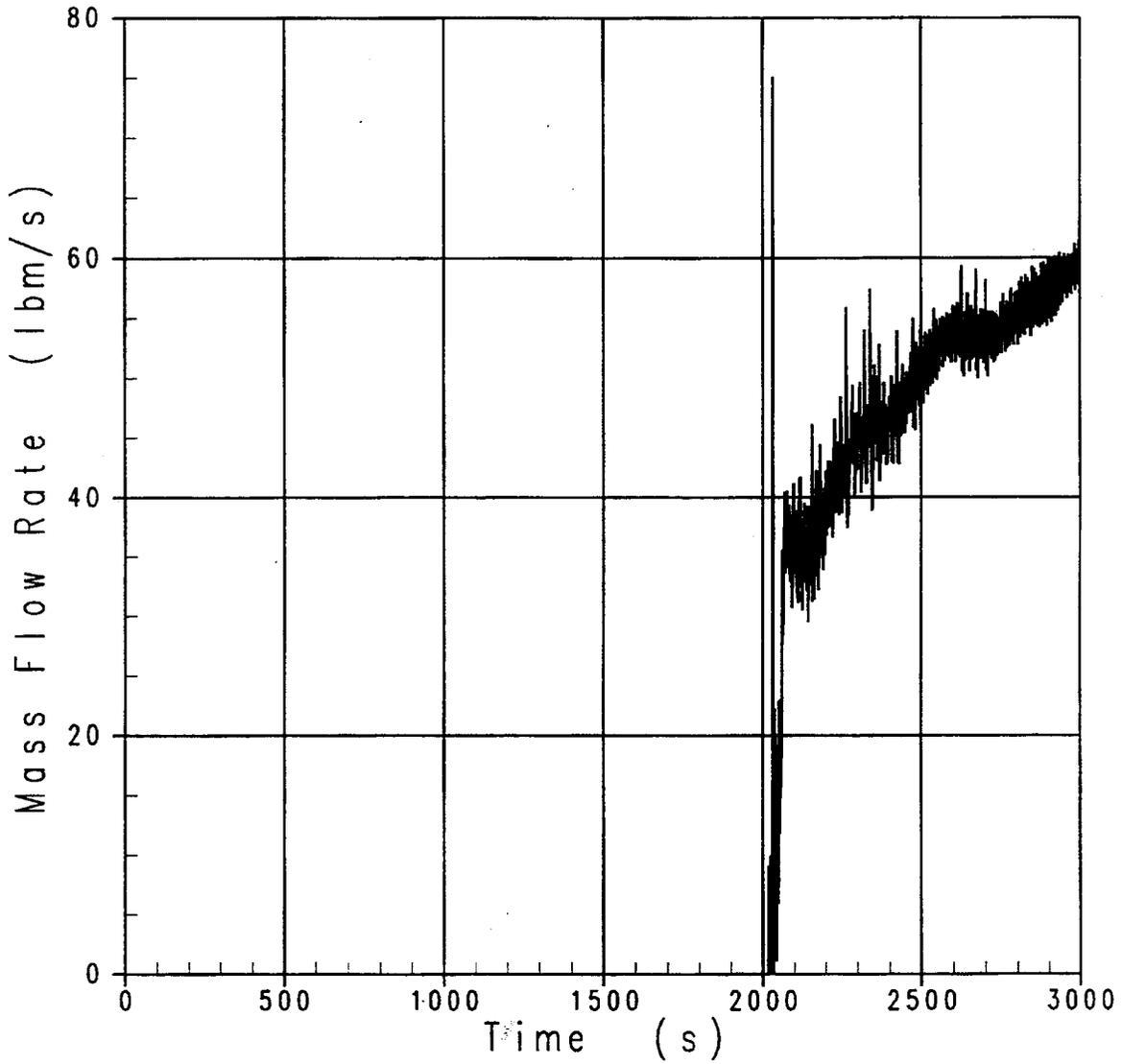


Figure 19E.4.8-12 Loop 1 IRWST Injection Flow, Inadvertent ADS Actuation

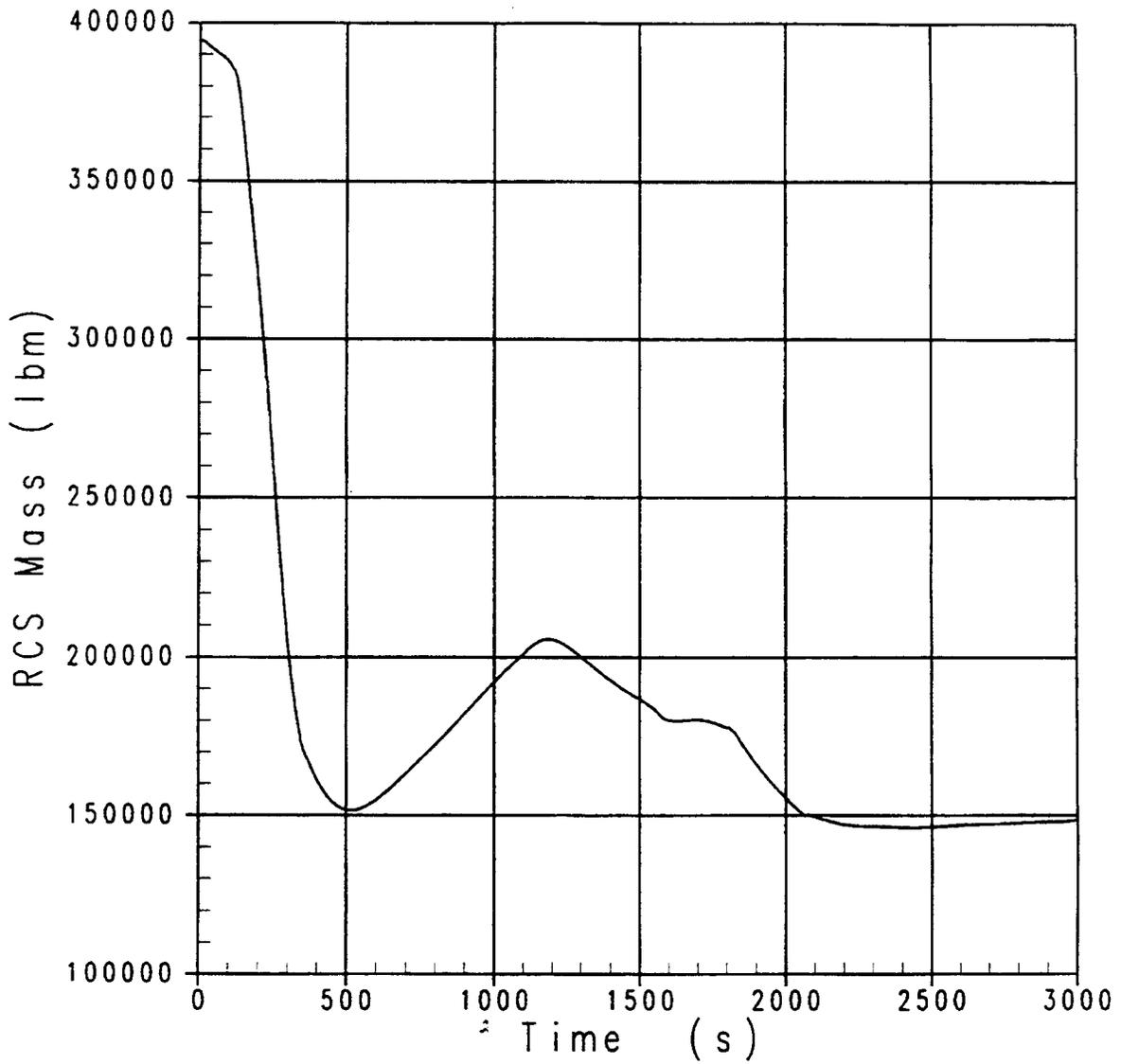


Figure 19E.4.8-13 Primary Mass Inventory, Inadvertent ADS Actuation

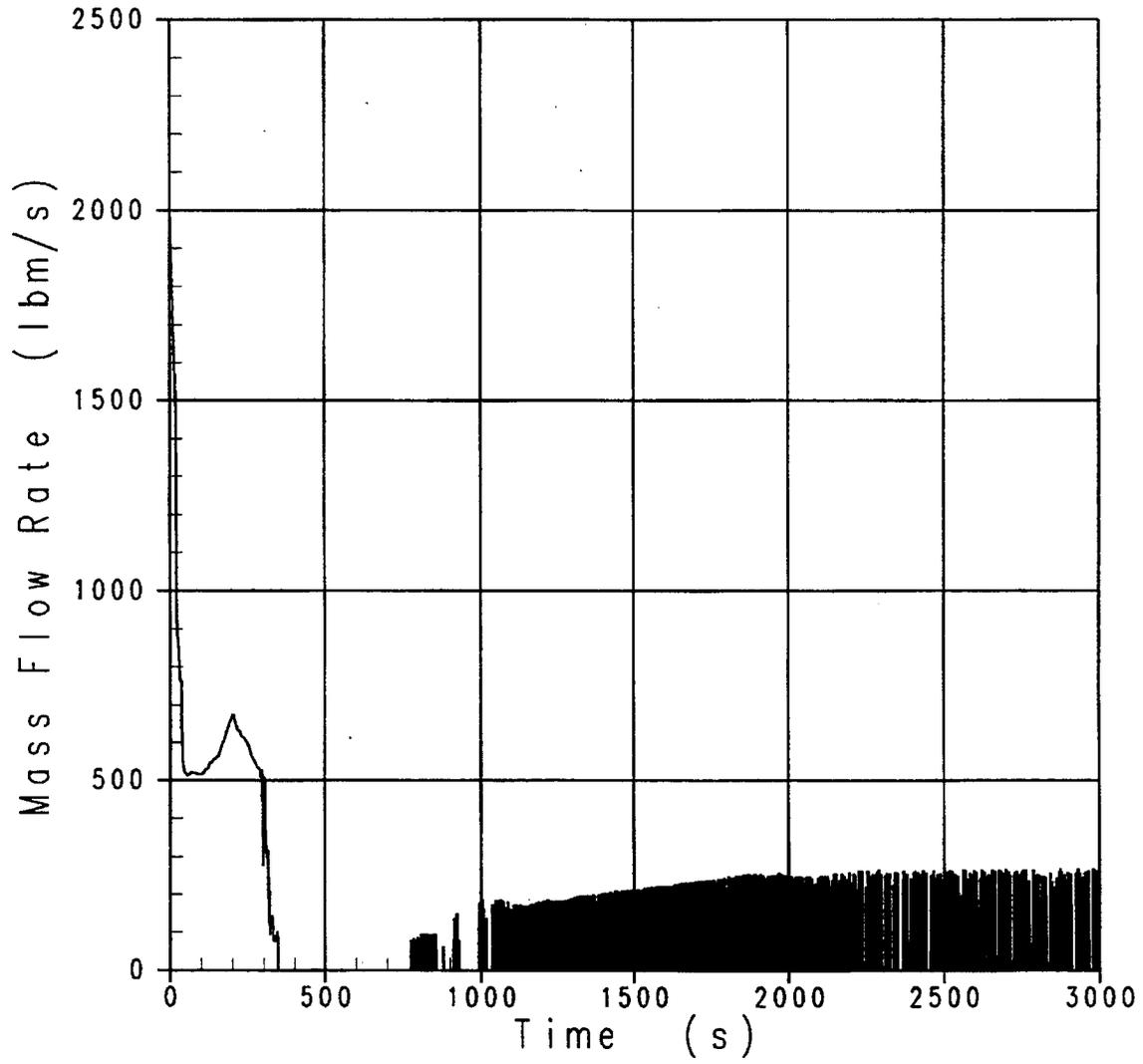


Figure 19E.4.8-14 Break Liquid Flow, DEDVI Break

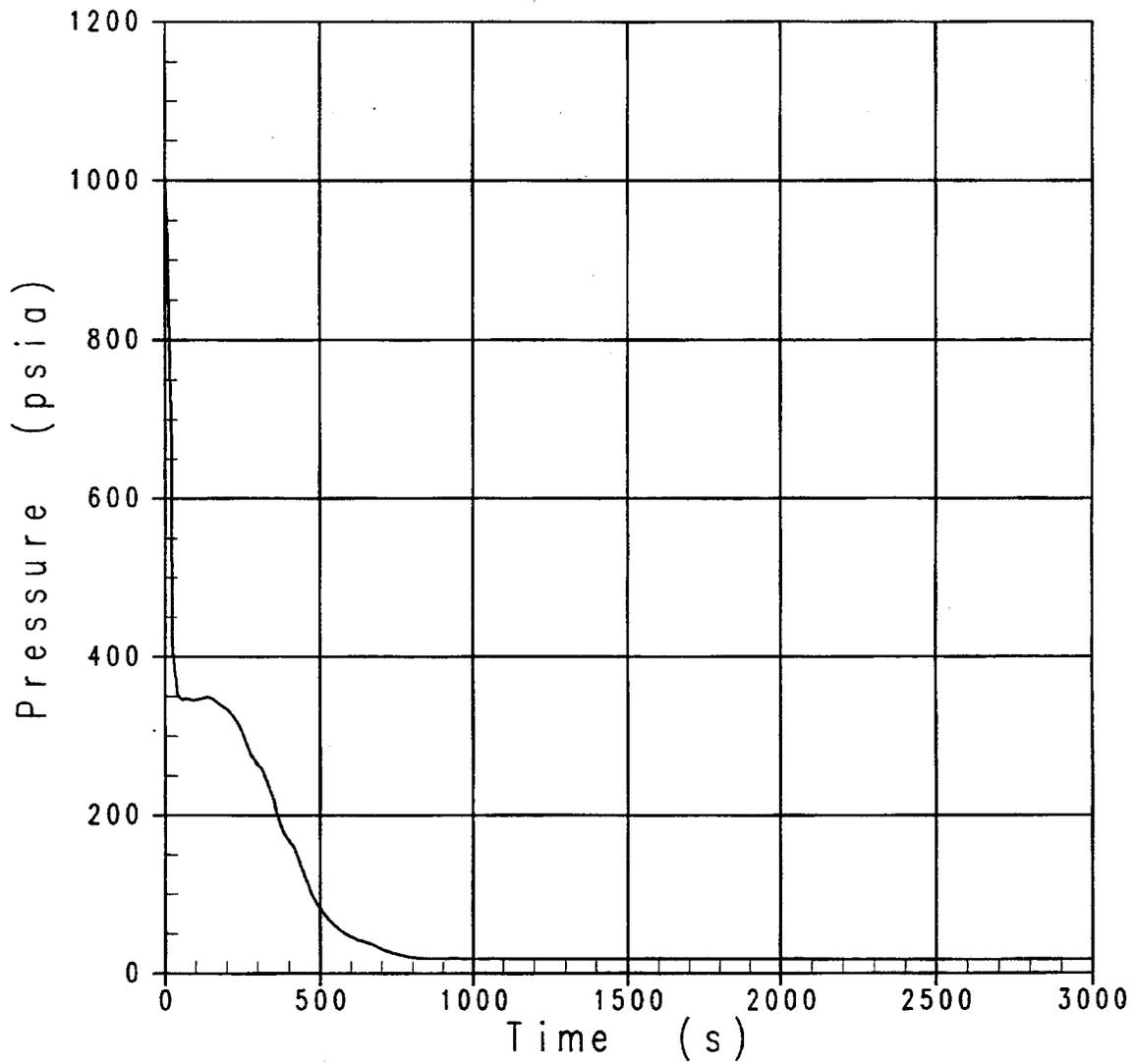


Figure 19E.4.8-15 Pressurizer Pressure, DEDVI Break

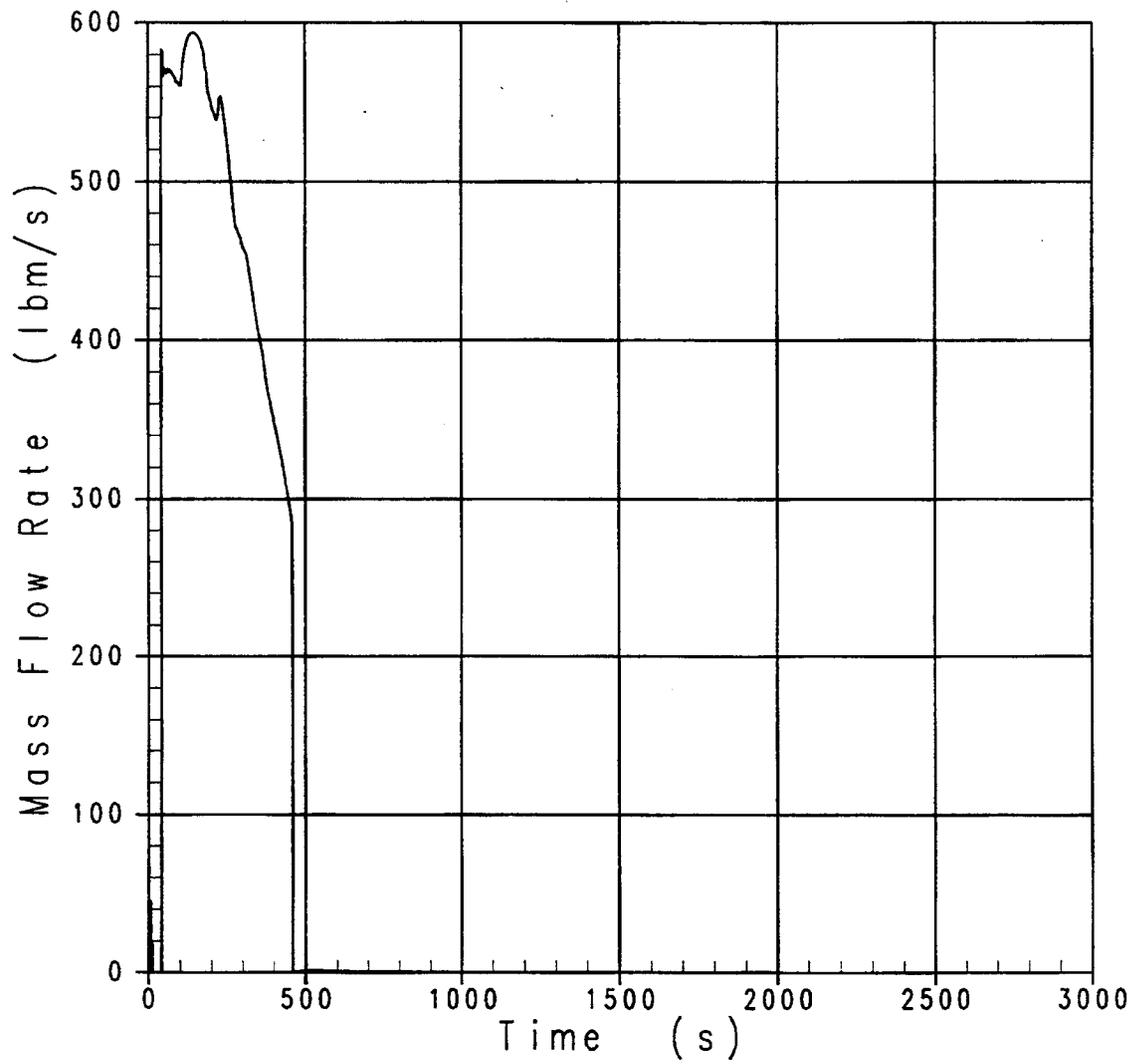


Figure 19E.4.8-16 Loop 1, CMT to DVI Flow, DEDVI Break

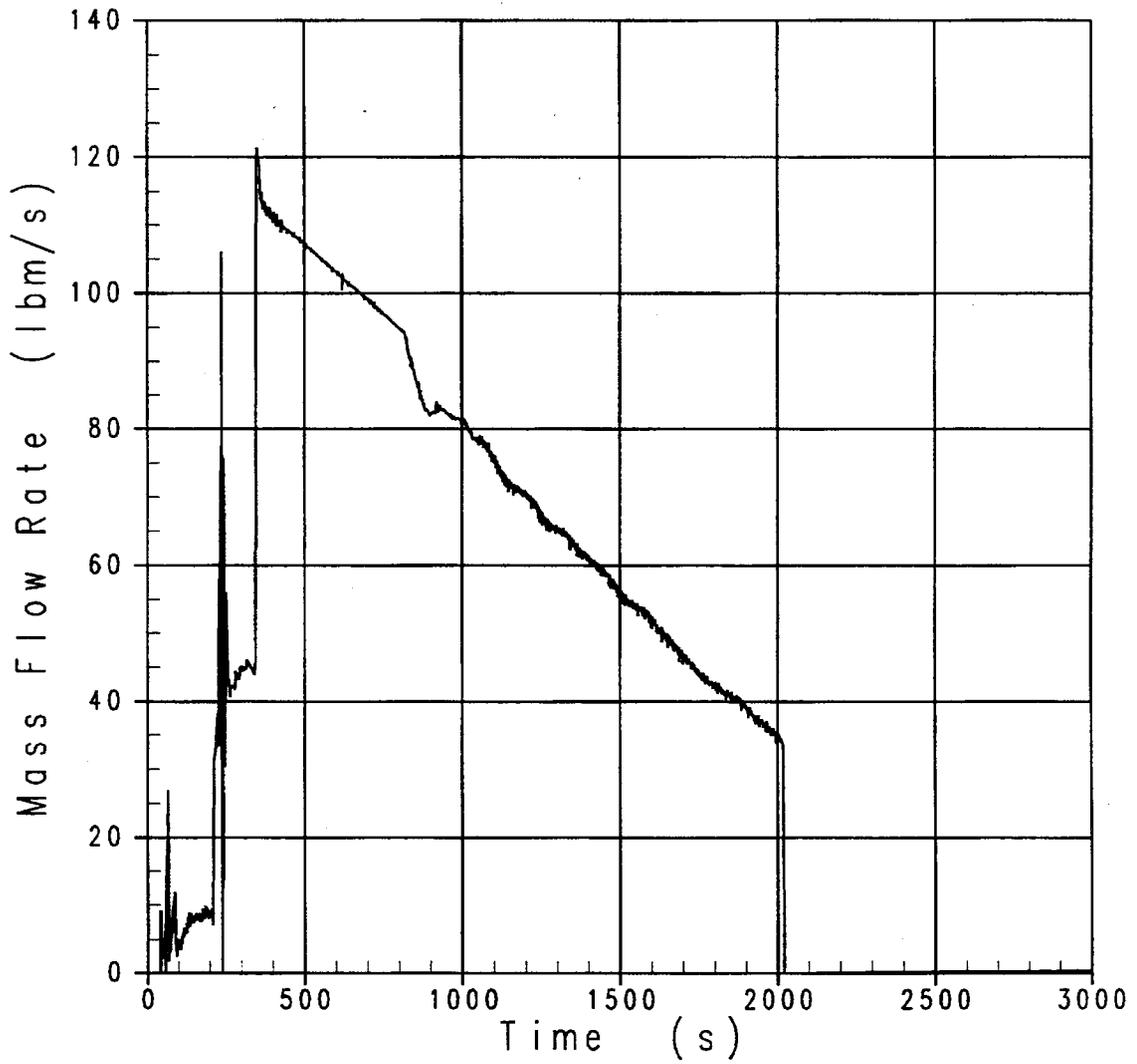


Figure 19E.4.8-17 Loop 2, CMT to DVI Flow, DEDVI Break

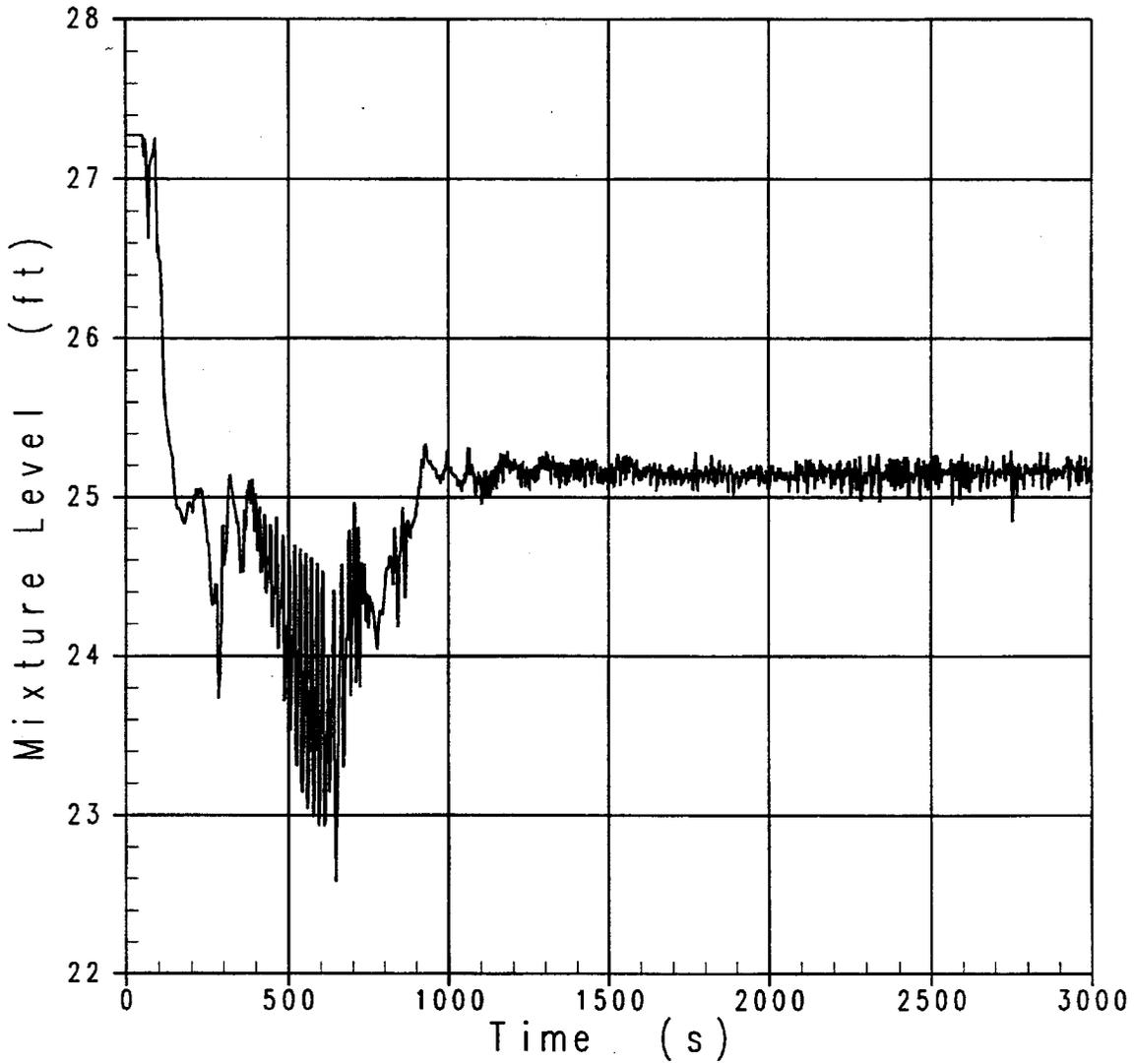


Figure 19E.4.8-18 Core Stack Mixture Level, DEDVI Break

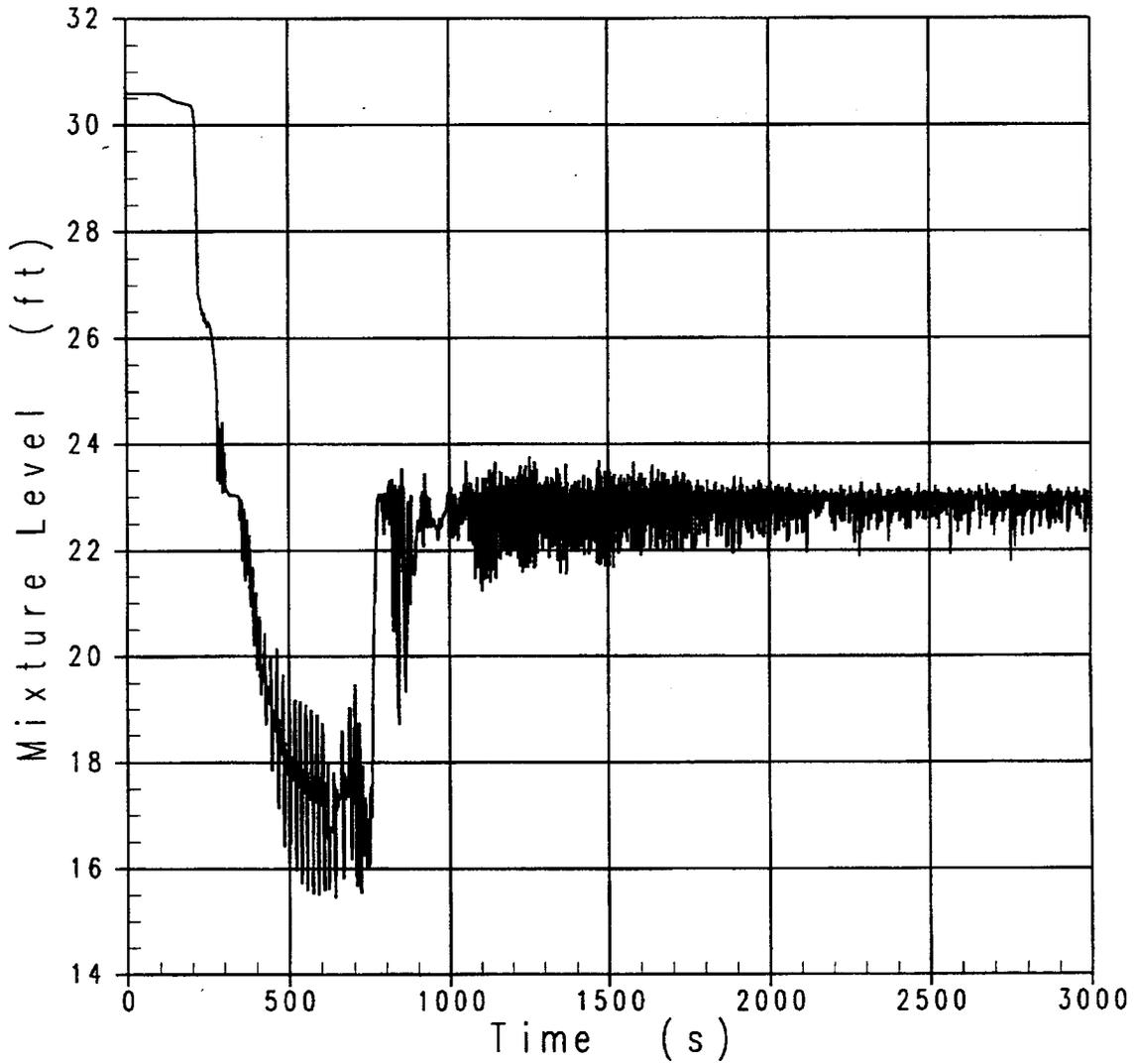


Figure 19E.4.8-19 Downcomer Mixture Level, DEDVI Break

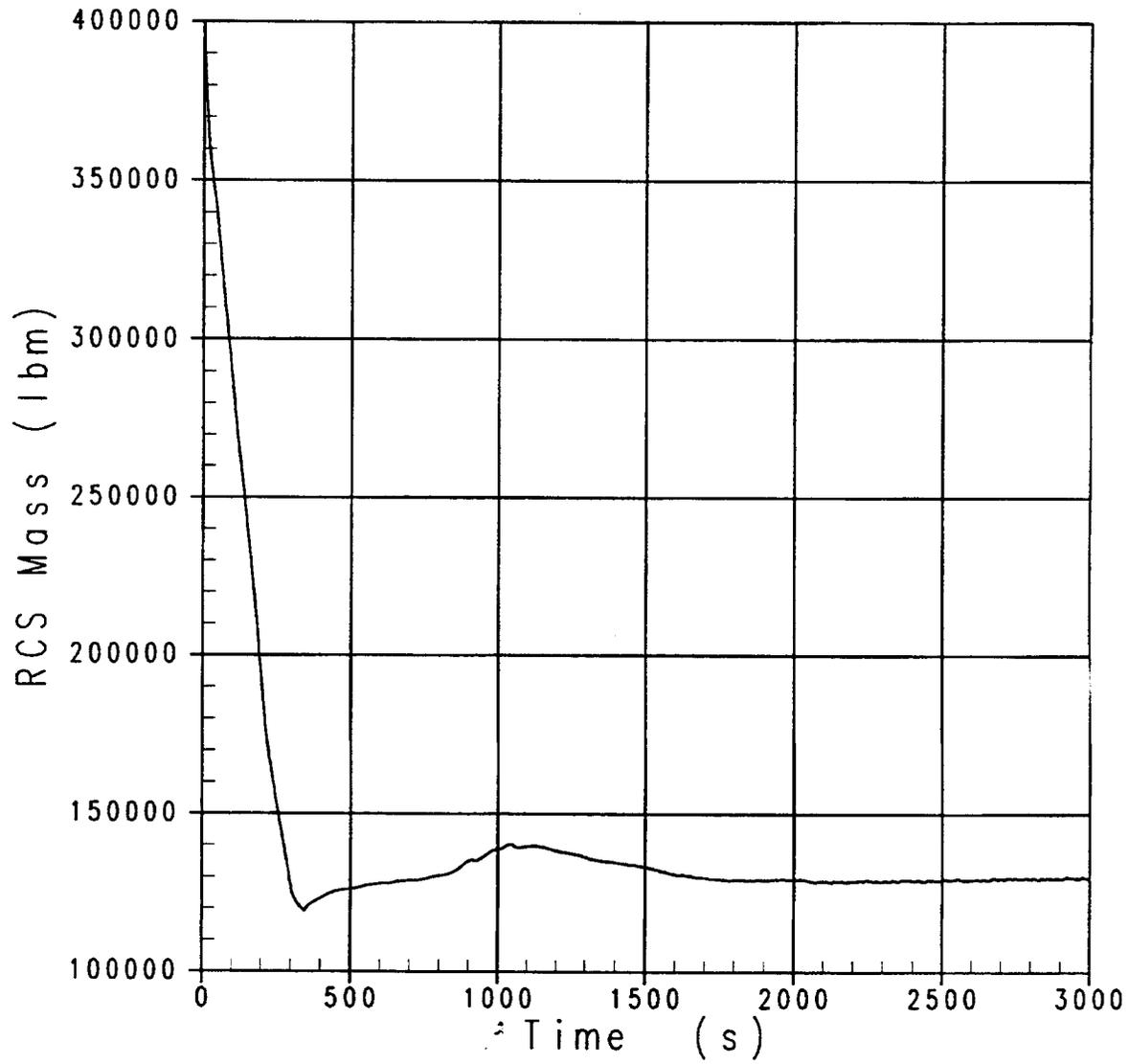


Figure 19E.4.8-20 Primary Mass Inventory, DEDVI Break

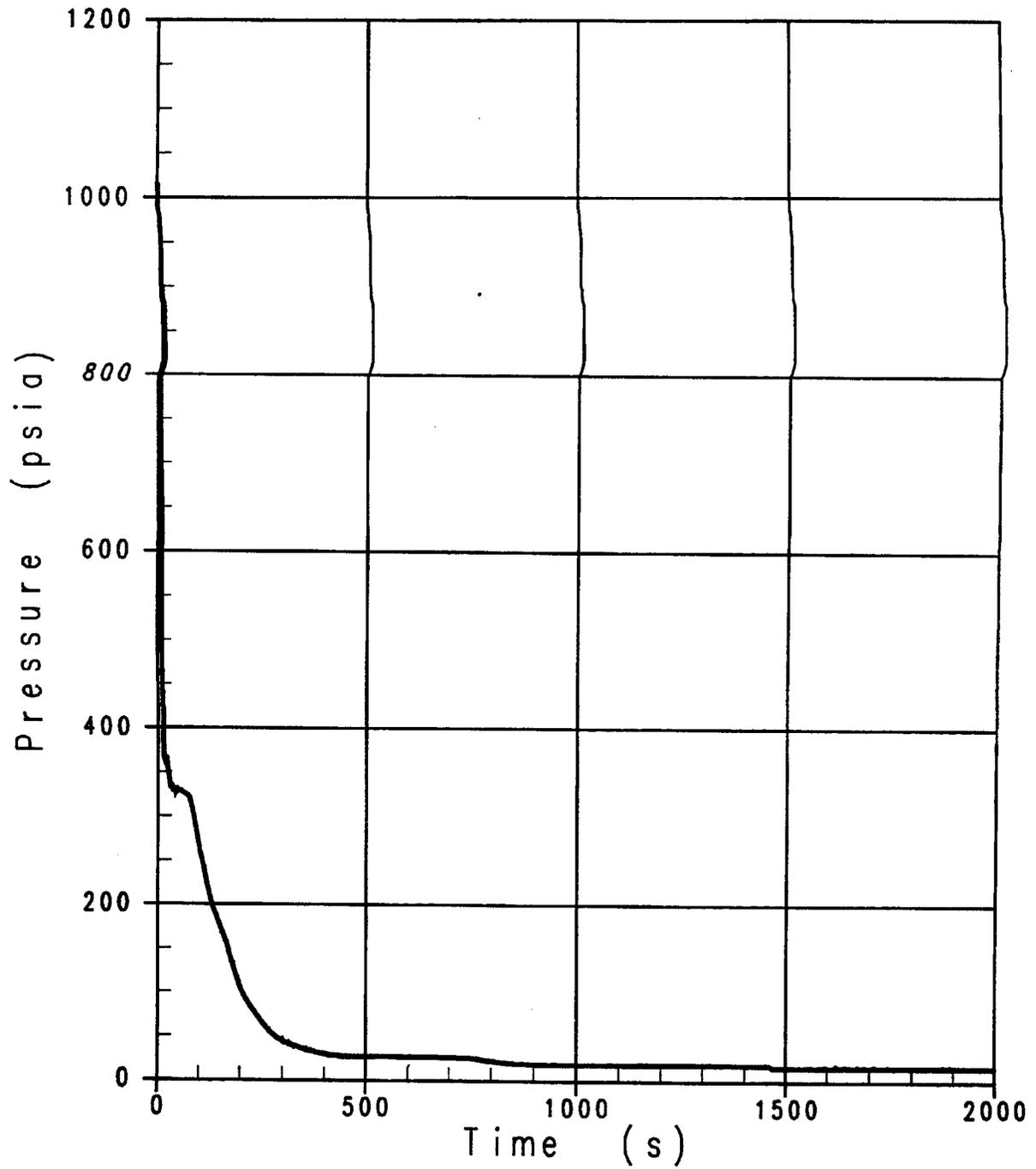


Figure 19E.4.8-21 Pressurizer Pressure, 10-Inch Cold Leg Break

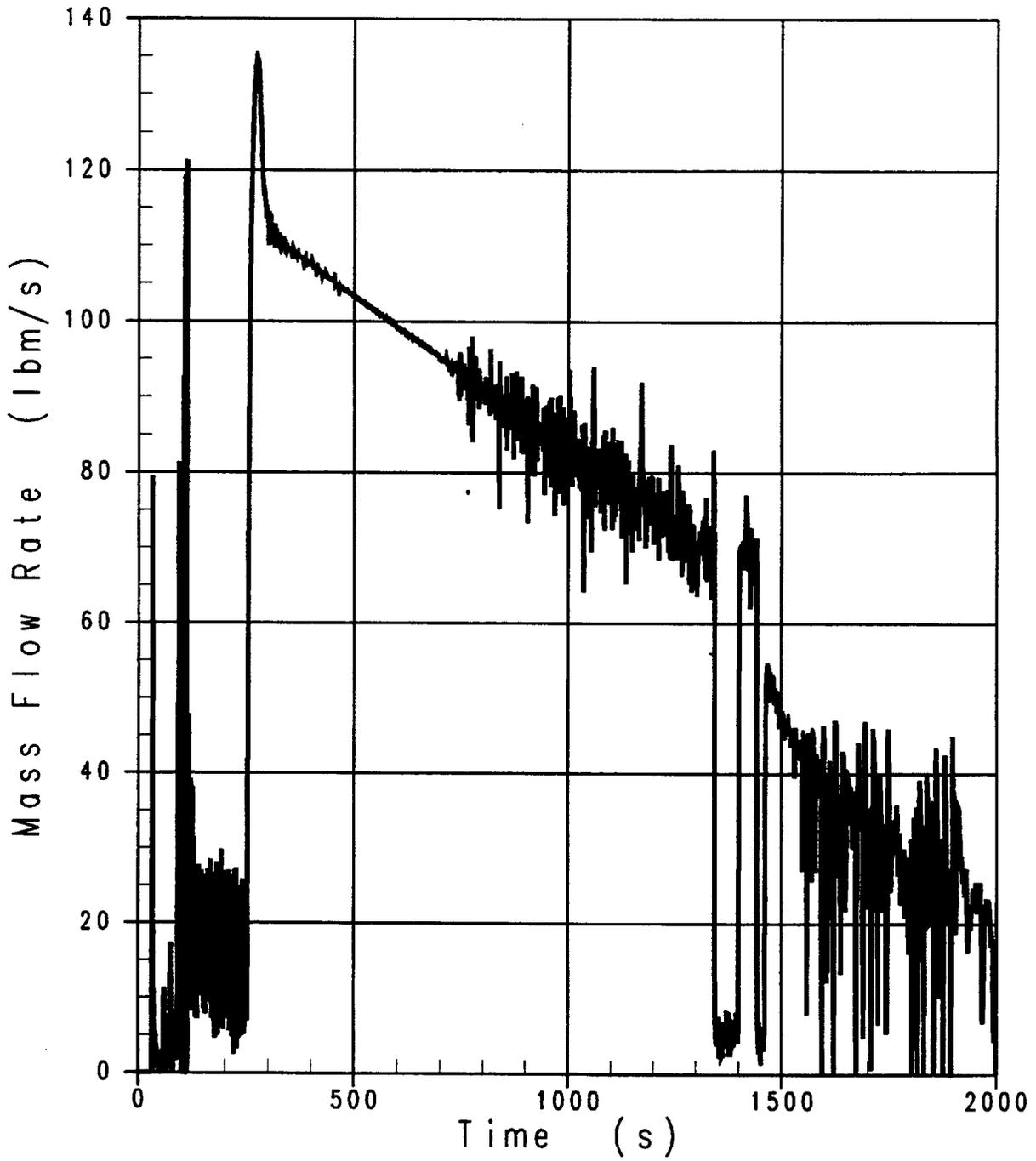


Figure 19E.4.8-22 CMT Injection Flow, 10-Inch Cold Leg Break

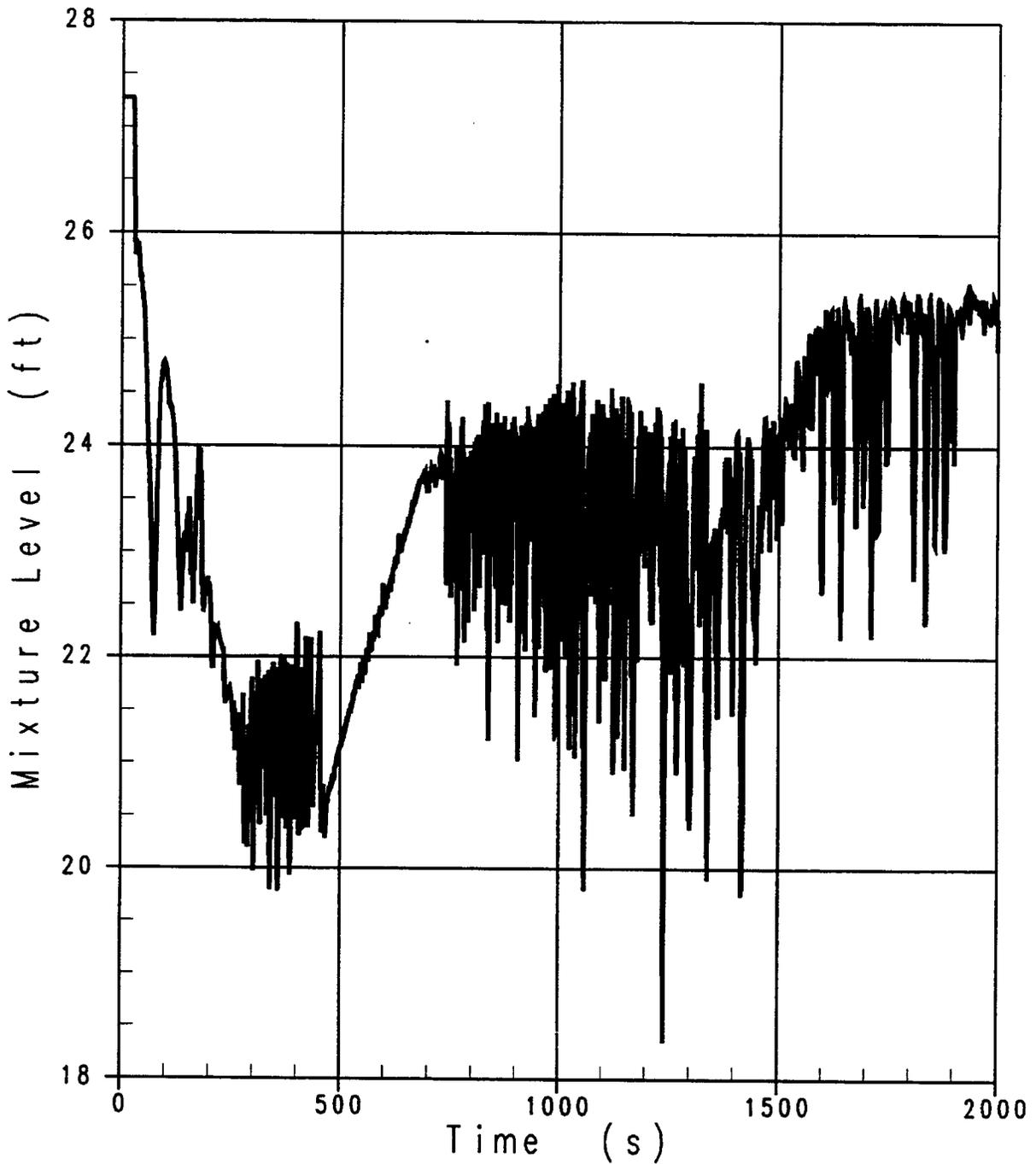


Figure 19E.4.8-23 Core Stack Mixture Level, 10-Inch Cold Leg Break

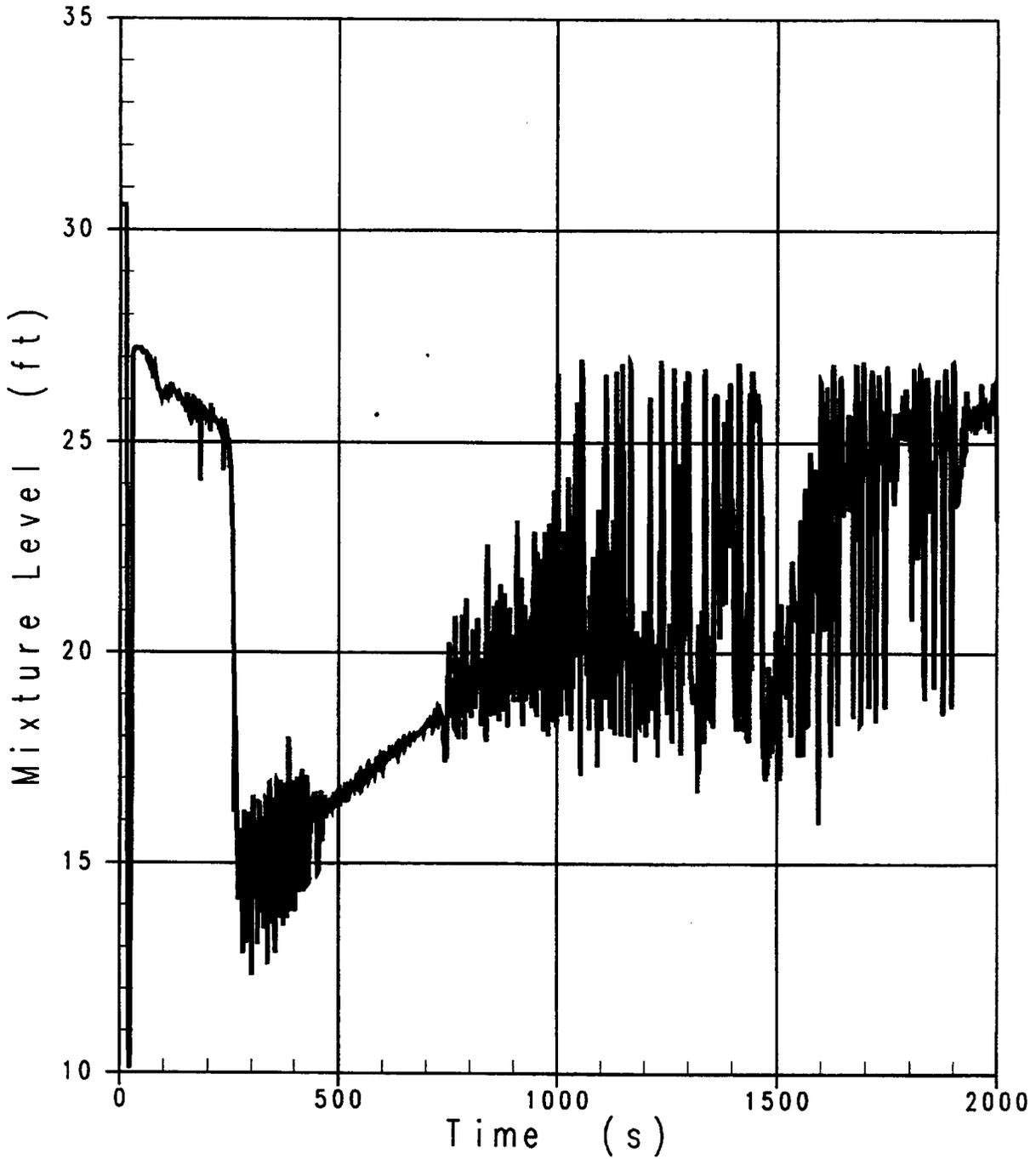


Figure 19E.4.8-24 Downcomer Mixture Level, 10-Inch Cold Leg Break

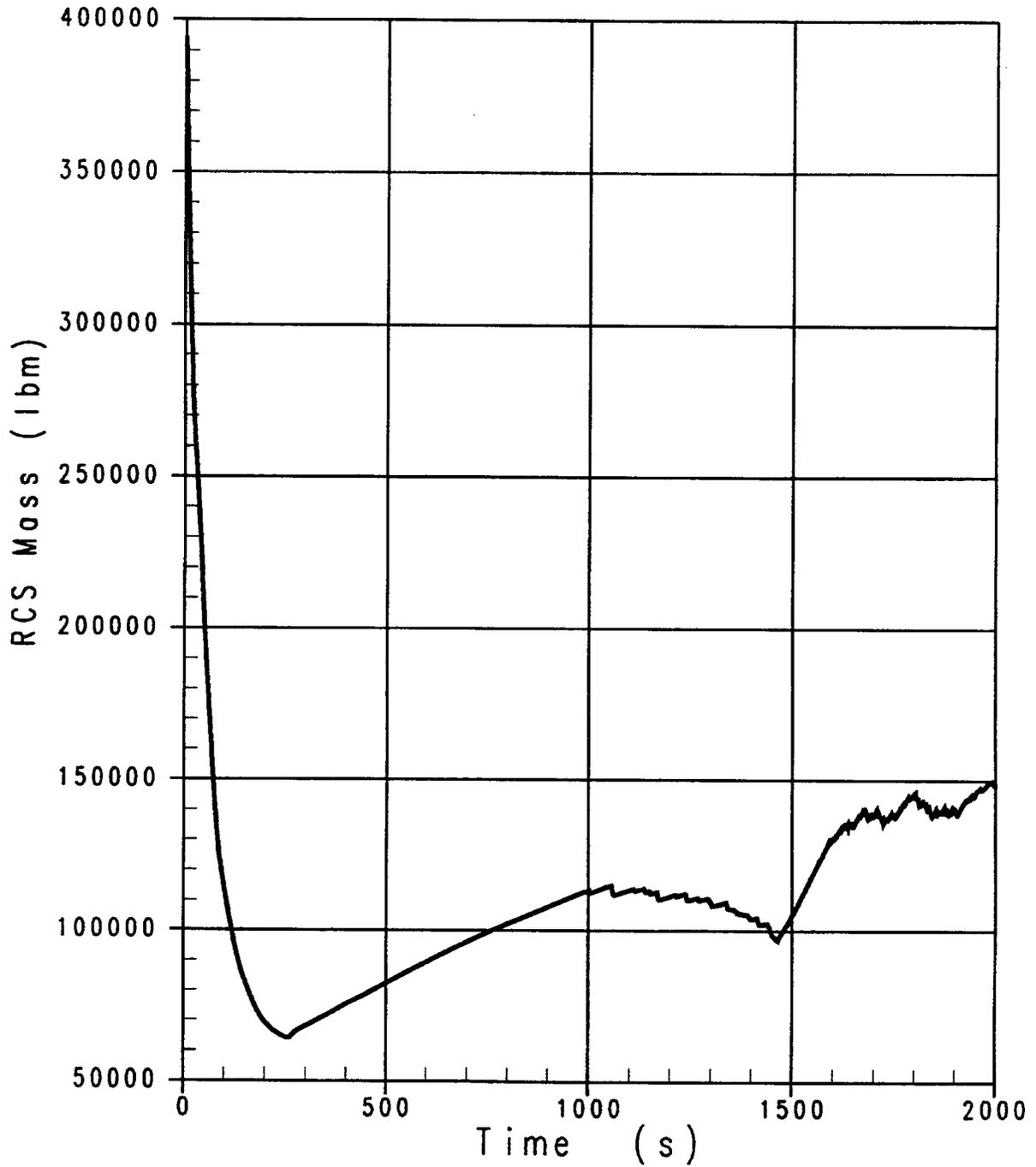


Figure 19E.4.8-25 Primary Mass Inventory, 10-Inch Cold Leg Break

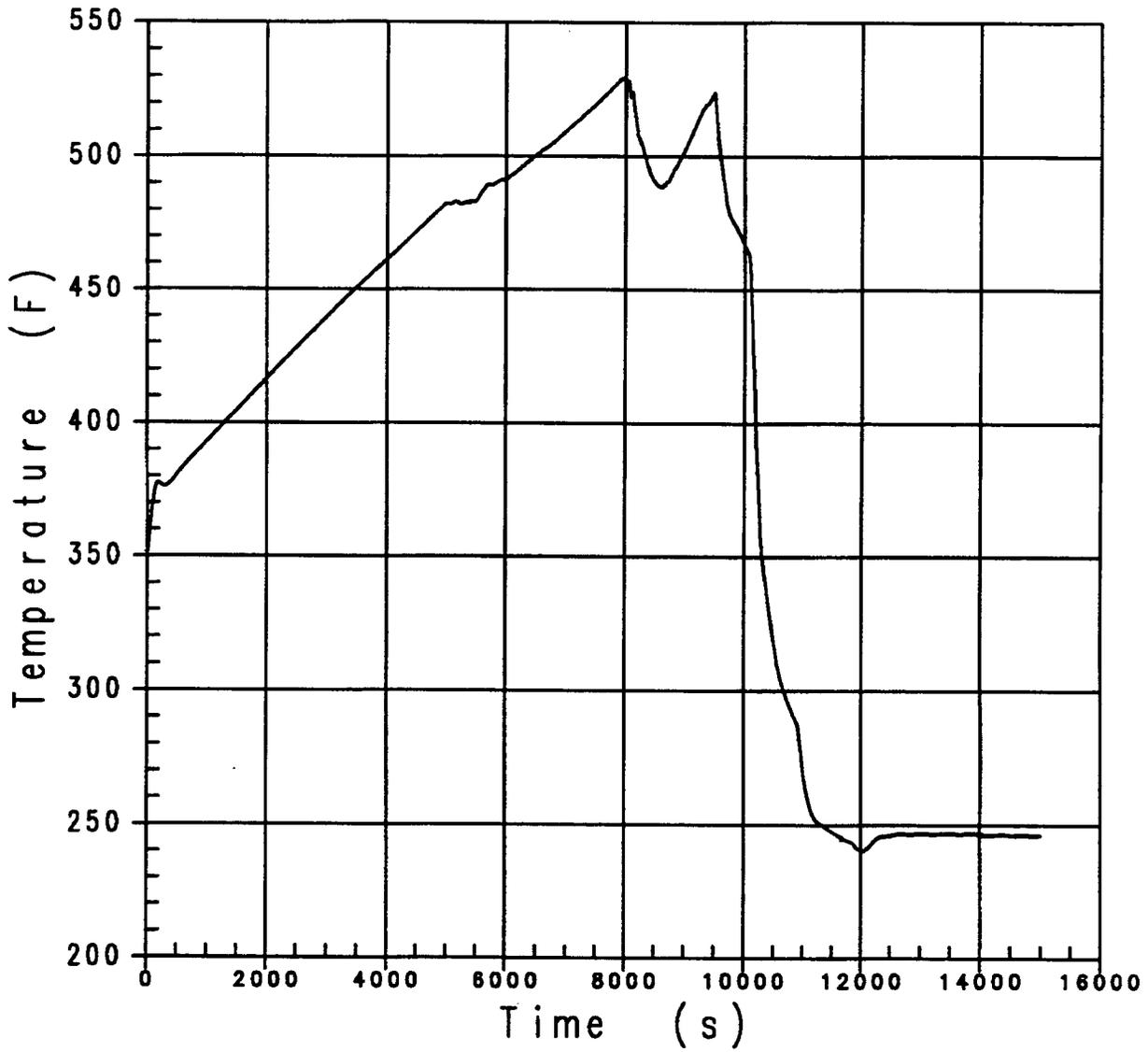


Figure 19E.4.8-26 Core Outlet Fluid Temperature, Loss of RNS in Mode 4 with RCS Intact

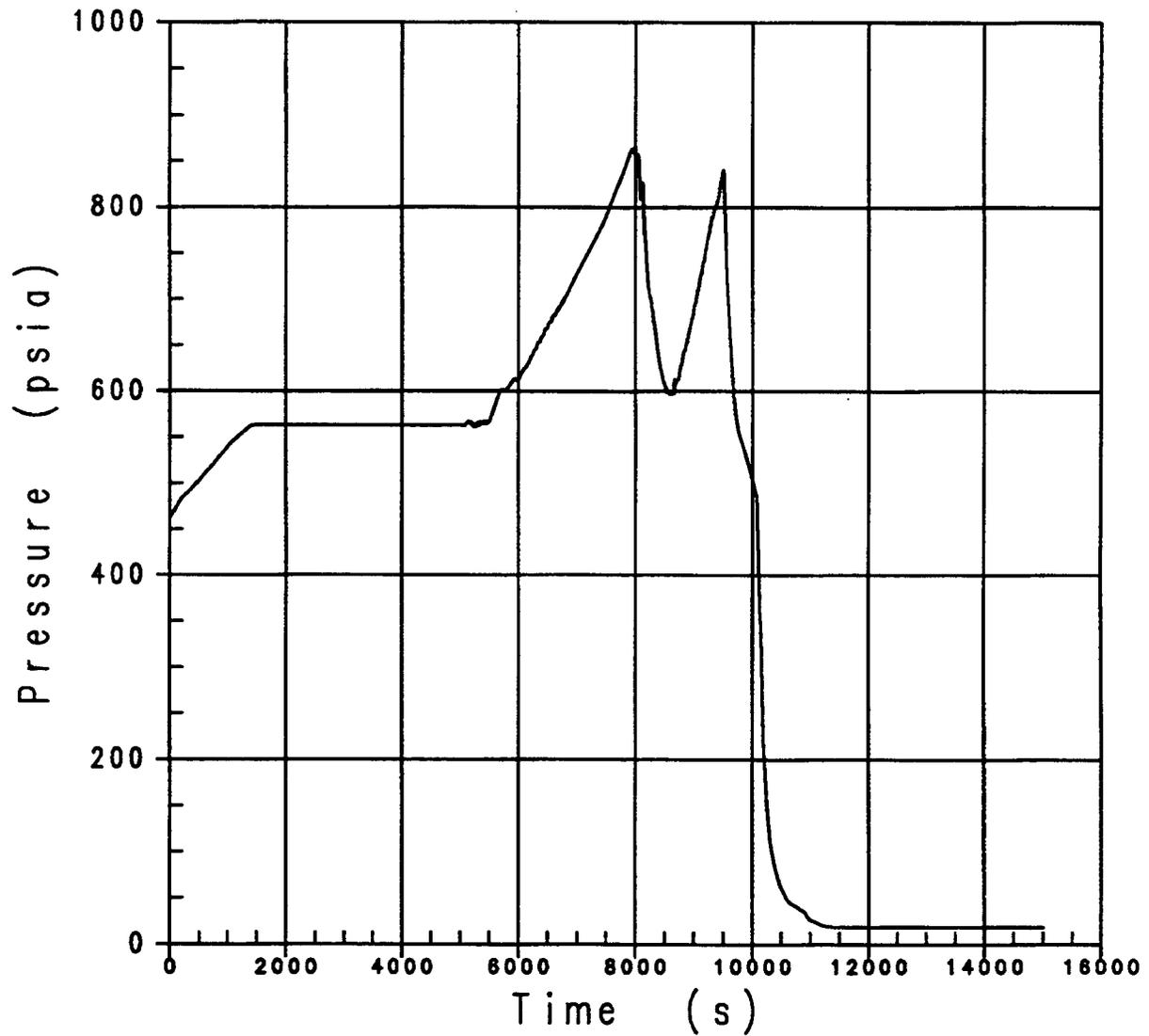


Figure 19E.4.8-27 Pressurizer Pressure, Loss of RNS in Mode 4 with RCS Intact

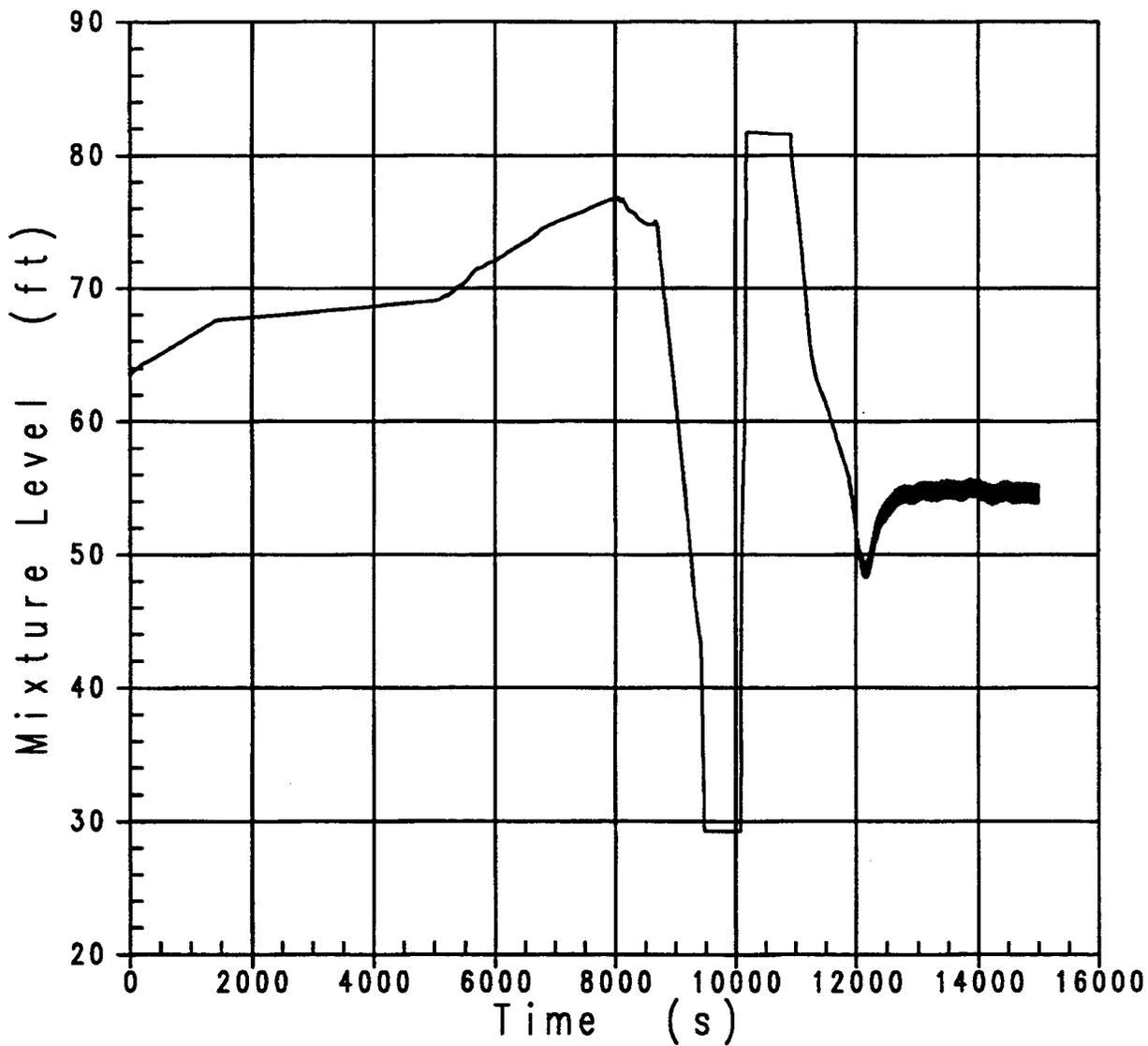


Figure 19E.4.8-28 Pressurizer Mixture Level, Loss of RNS in Mode 4 with RCS Intact

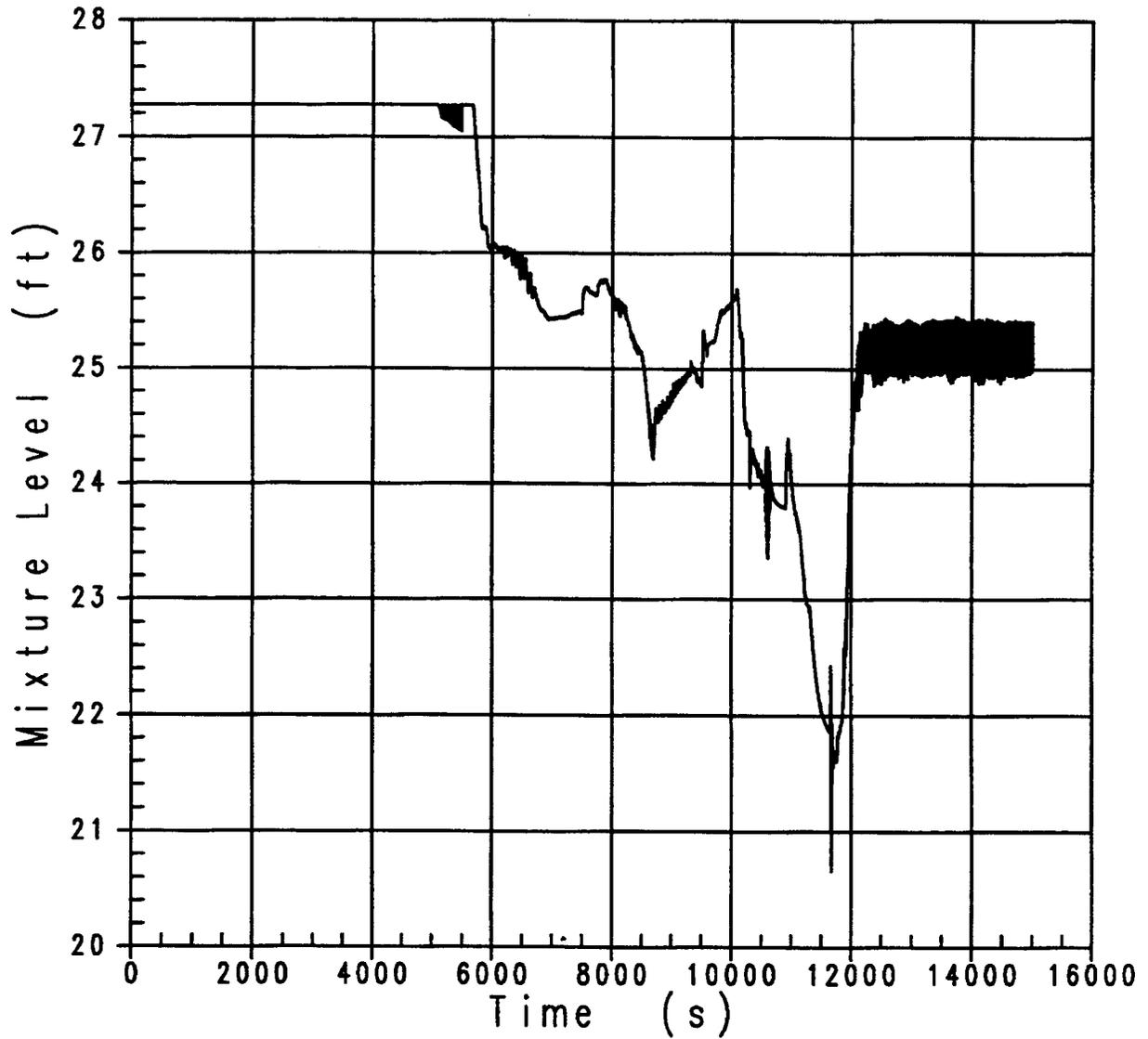


Figure 19E.4.8-29 Core Stack Mixture Level, Loss of RNS in Mode 4 with RCS Intact

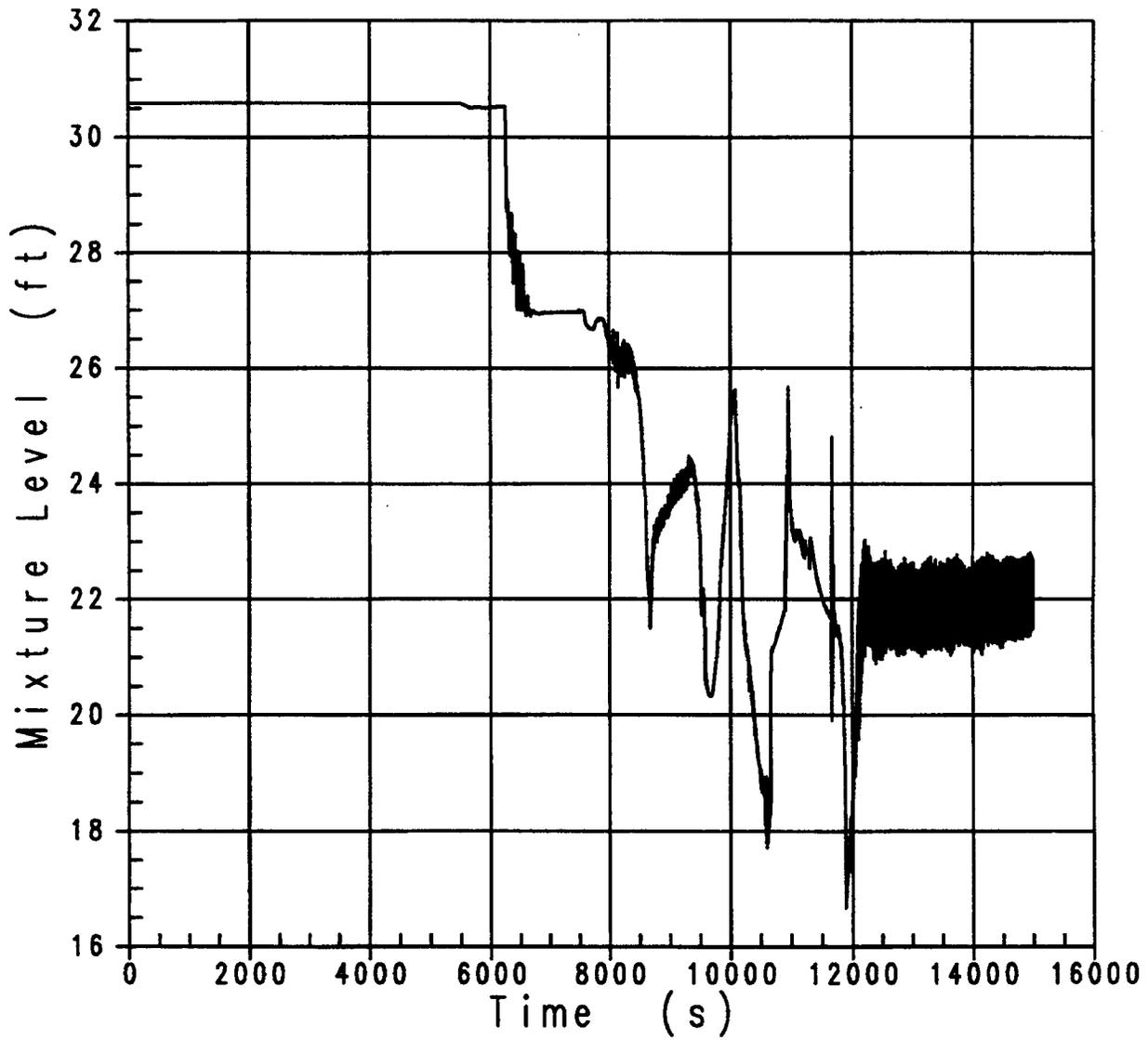


Figure 19E.4.8-30 Downcomer Mixture Level, Loss of RNS in Mode 4 with RCS Intact

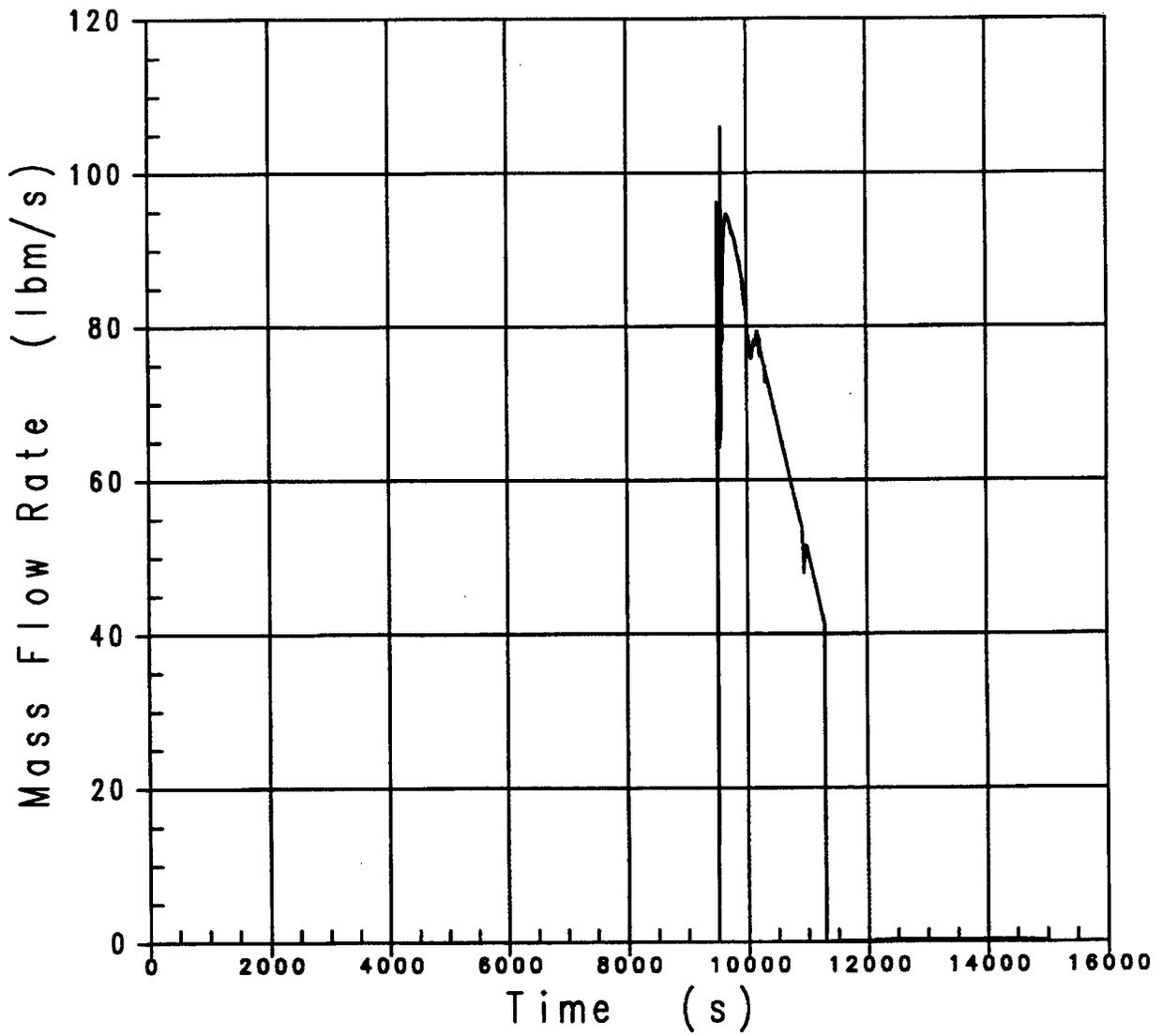


Figure 19E.4.8-31 CMT to DVI Flow, Loss of RNS in Mode 4 with RCS Intact

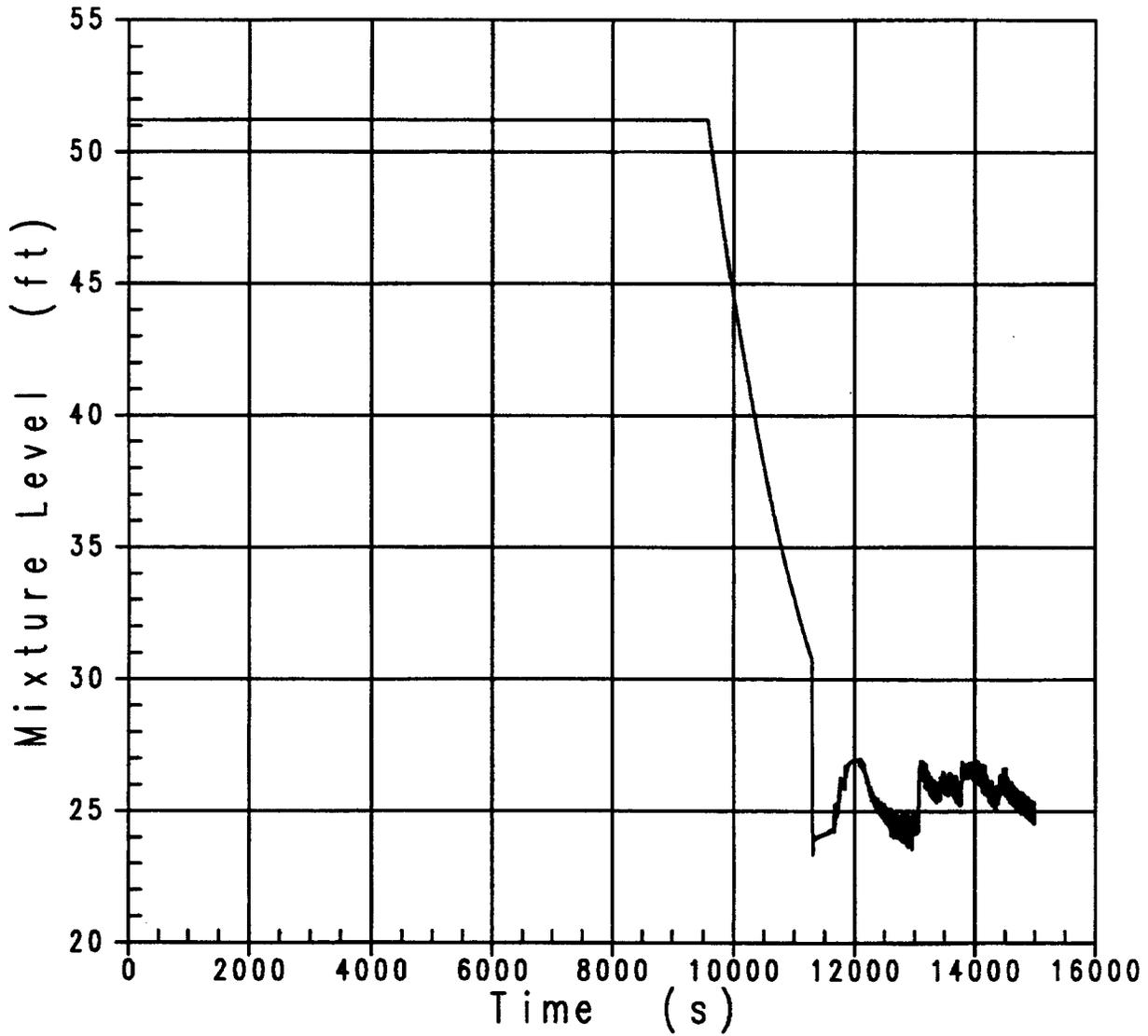


Figure 19E.4.8-32 CMT Mixture Level, Loss of RNS in Mode 4 with RCS Intact

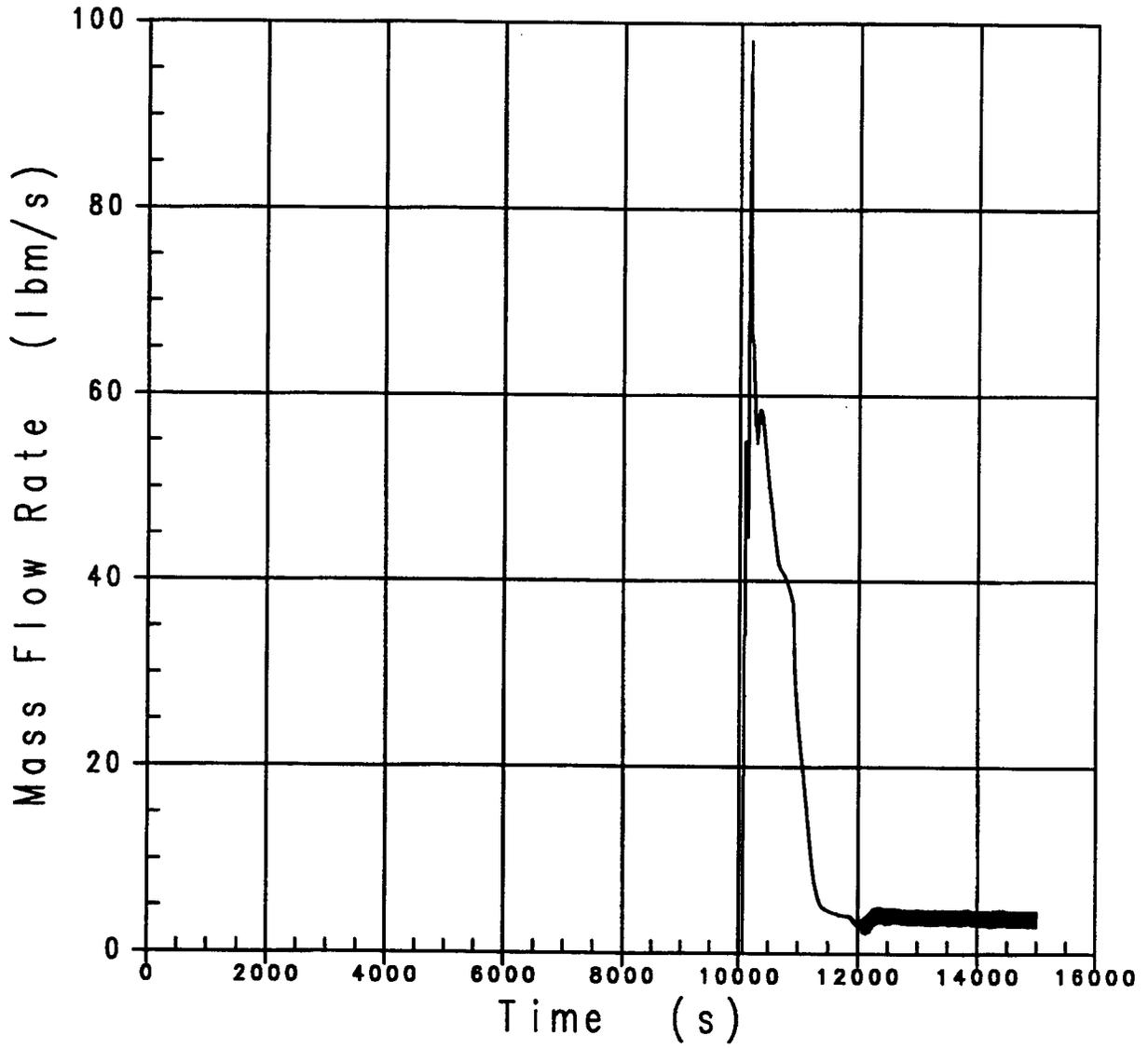


Figure 19E.4.8-33 ADS Stages 1-3 Vapor Flow, Loss of RNS in Mode 4 with RCS Intact

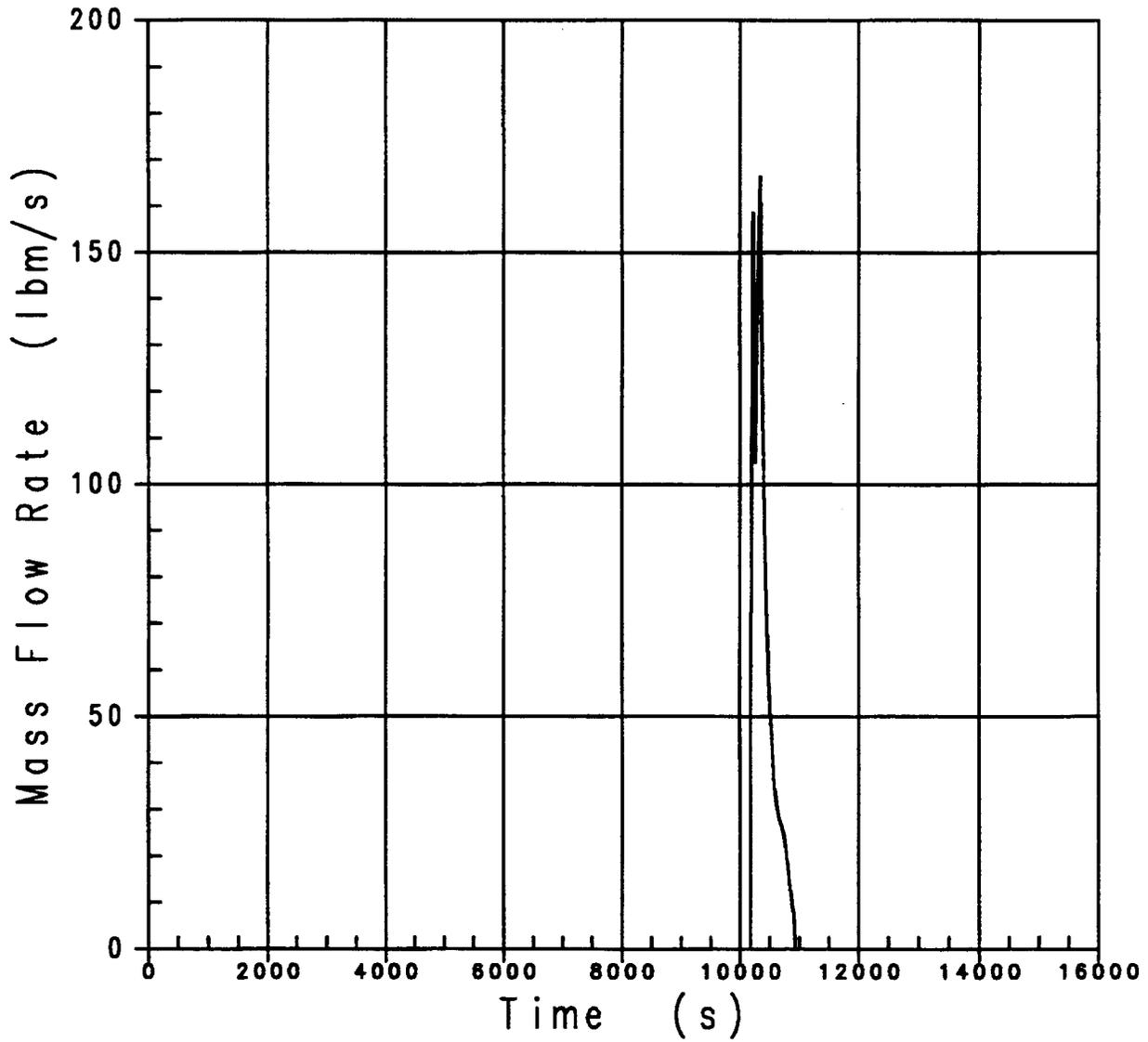


Figure 19E.4.8-34 ADS Stages 1-3 Liquid Flow, Loss of RNS in Mode 4 with RCS Intact

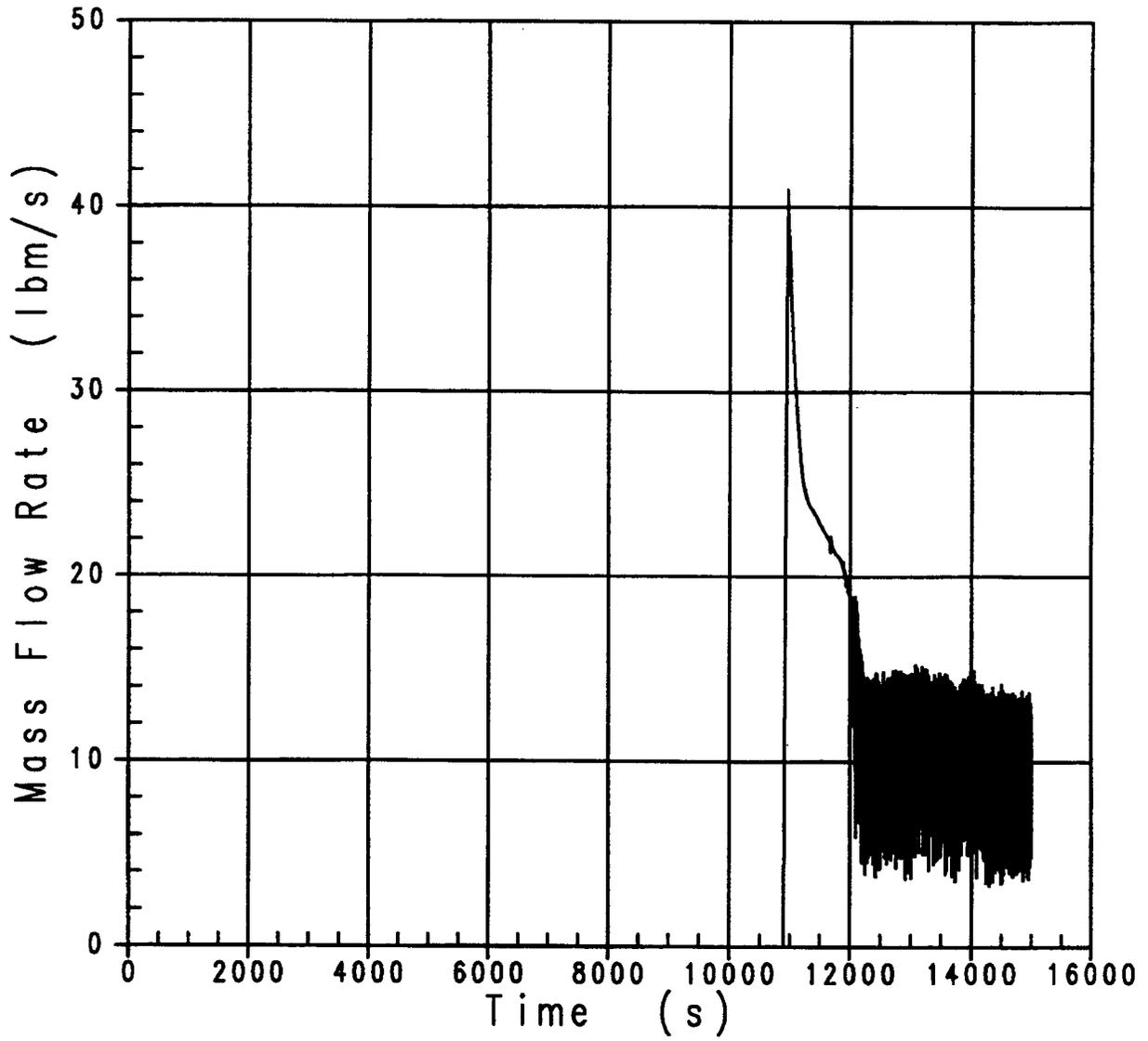


Figure 19E.4.8-35 ADS Stage 4 Vapor Flow, Loss of RNS in Mode 4 with RCS Intact

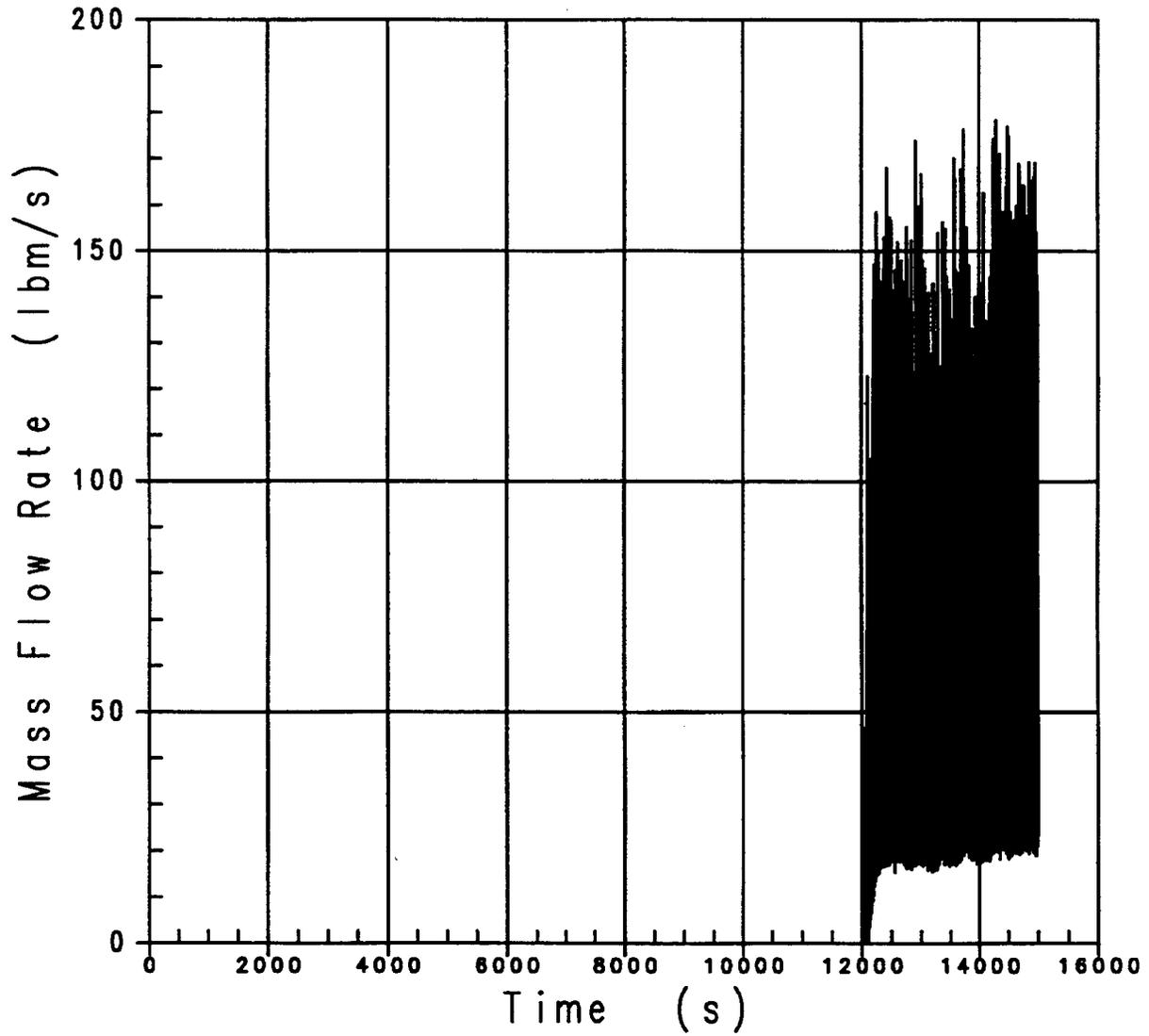


Figure 19E.4.8-36 ADS Stage 4 Liquid Flow, Loss of RNS in Mode 4 with RCS Intact

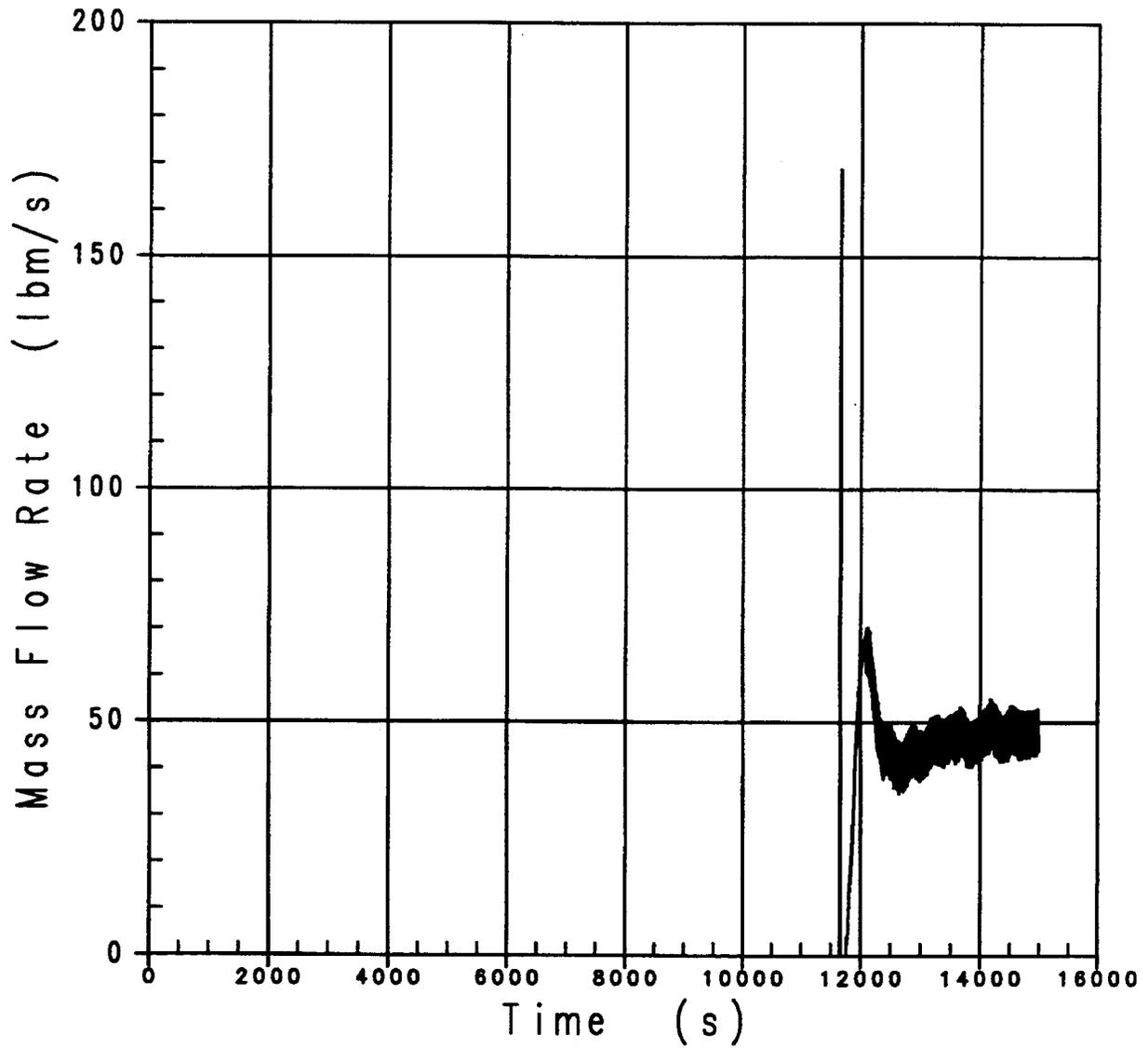


Figure 19E.4.8-37 Loop 1 IRWST Injection Flow, Loss of RNS in Mode 4 with RCS Intact

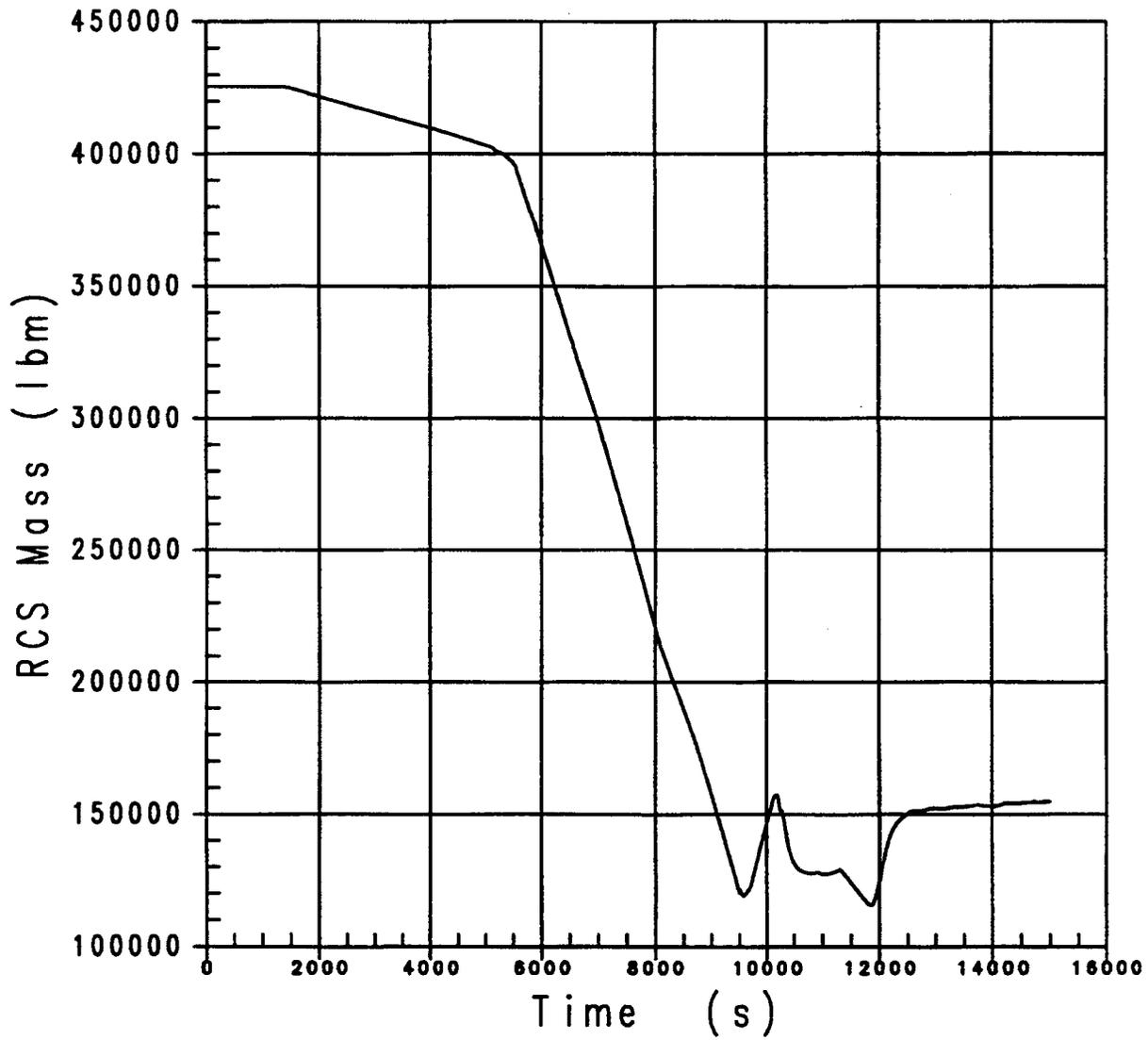


Figure 19E.4.8-38 Primary Mass Inventory, Loss of RNS in Mode 4 with RCS Intact

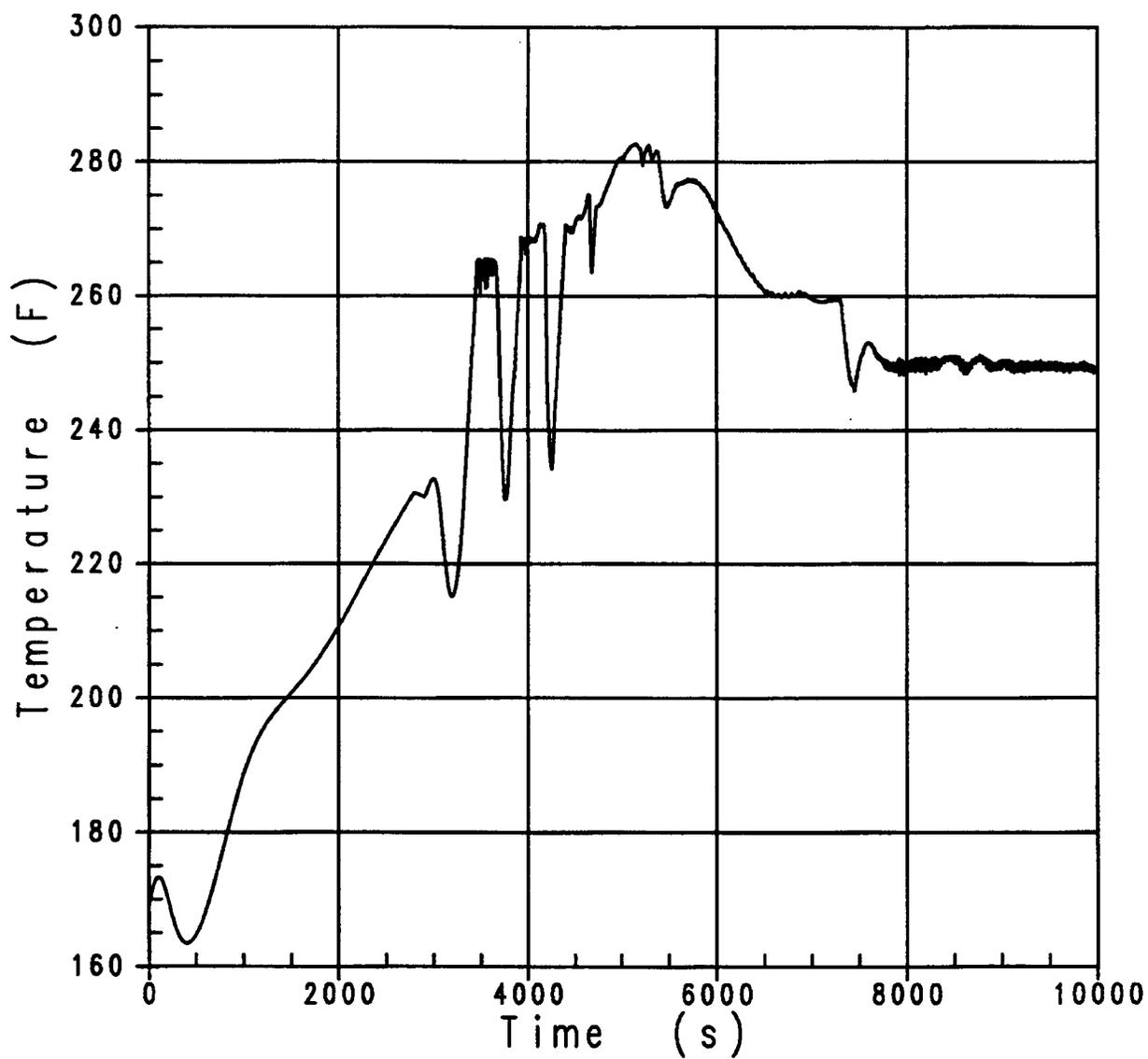


Figure 19E.4.8-39 Core Outlet Fluid Temperature, Loss of RNS in Mode 5 with RCS Open

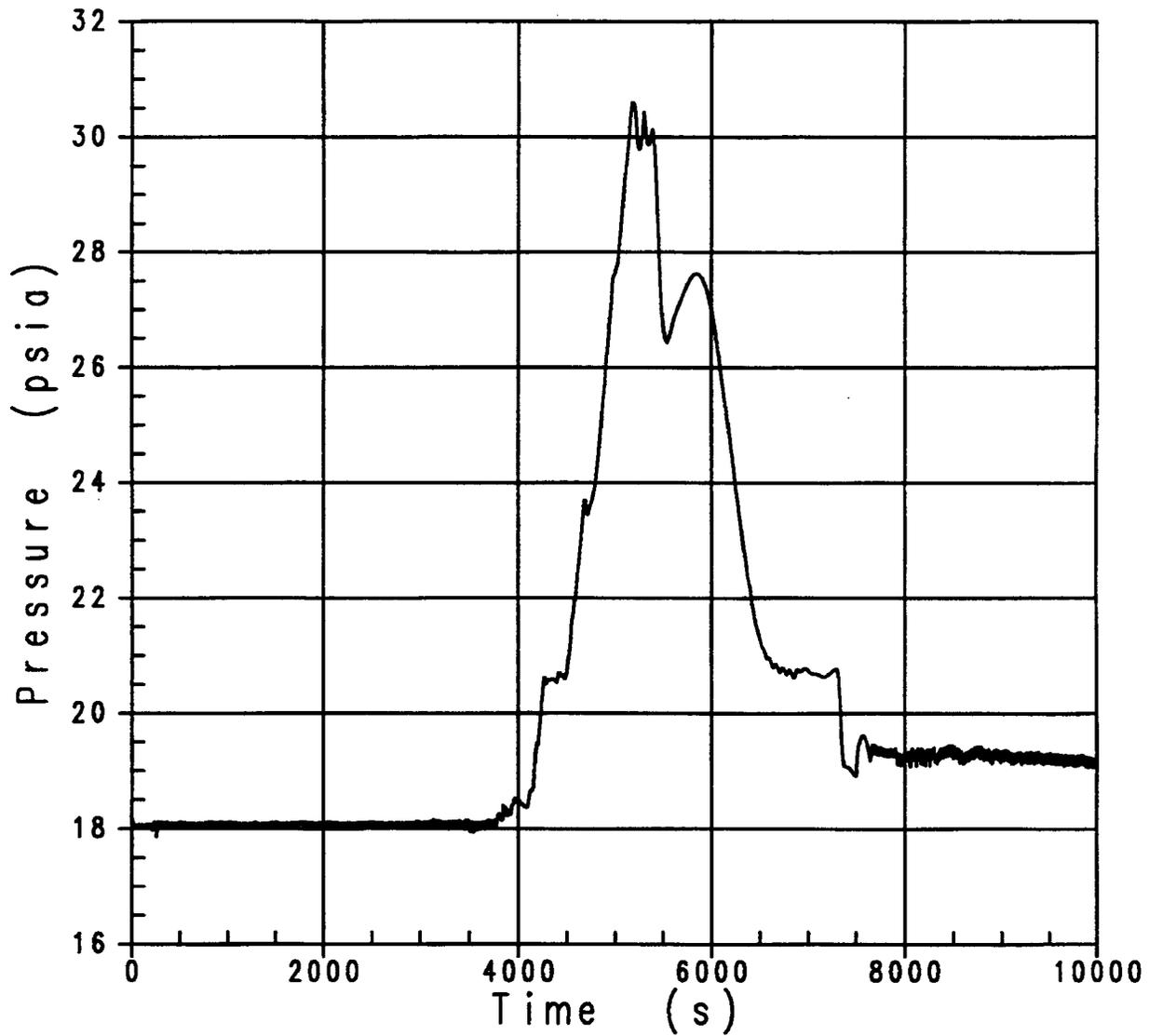


Figure 19E.4.8-40 Pressurizer Pressure, Loss of RNS in Mode 5 with RCS Open

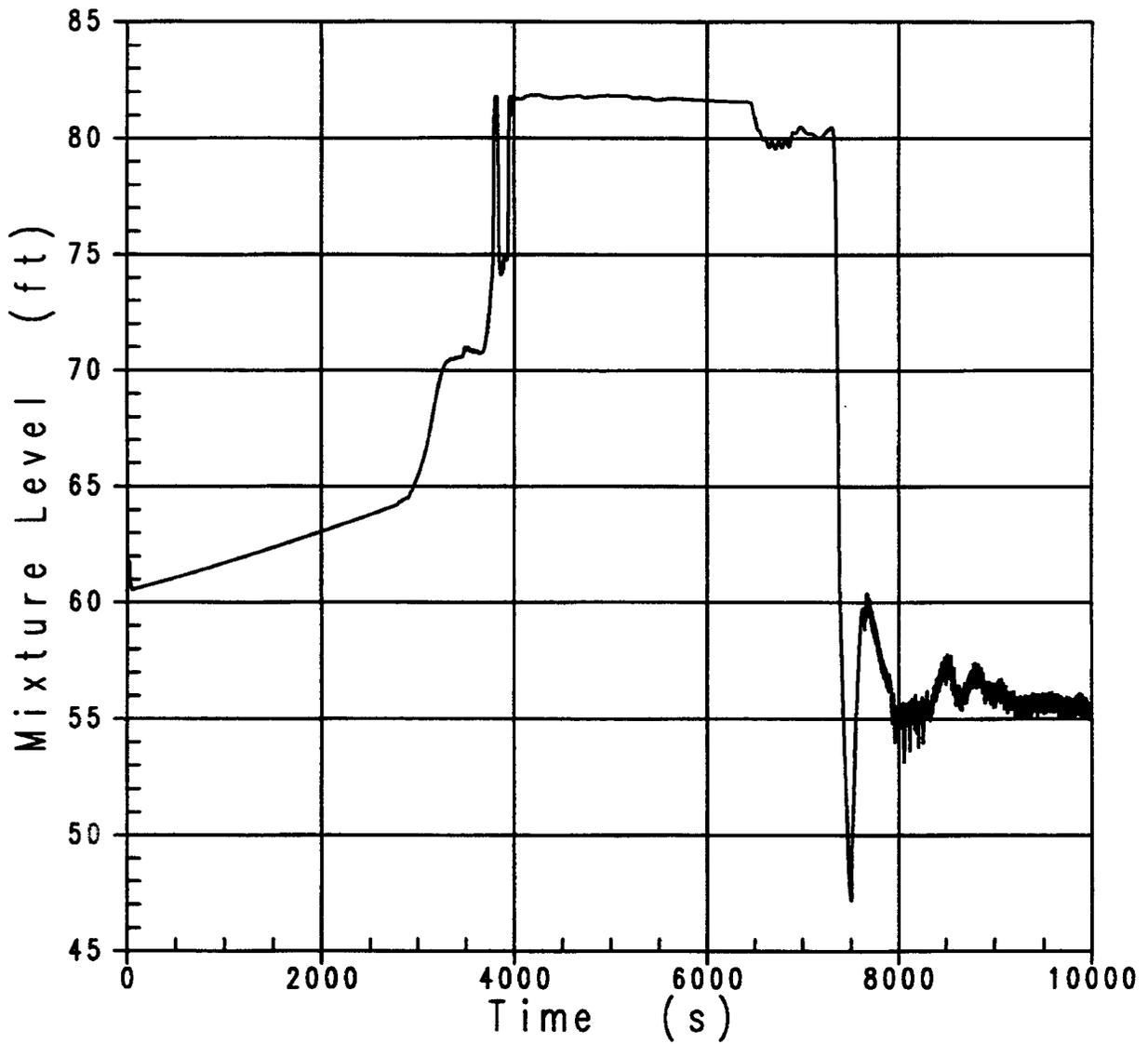


Figure 19E.4.8-41 Pressurizer Mixture Level, Loss of RNS in Mode 5 with RCS Open

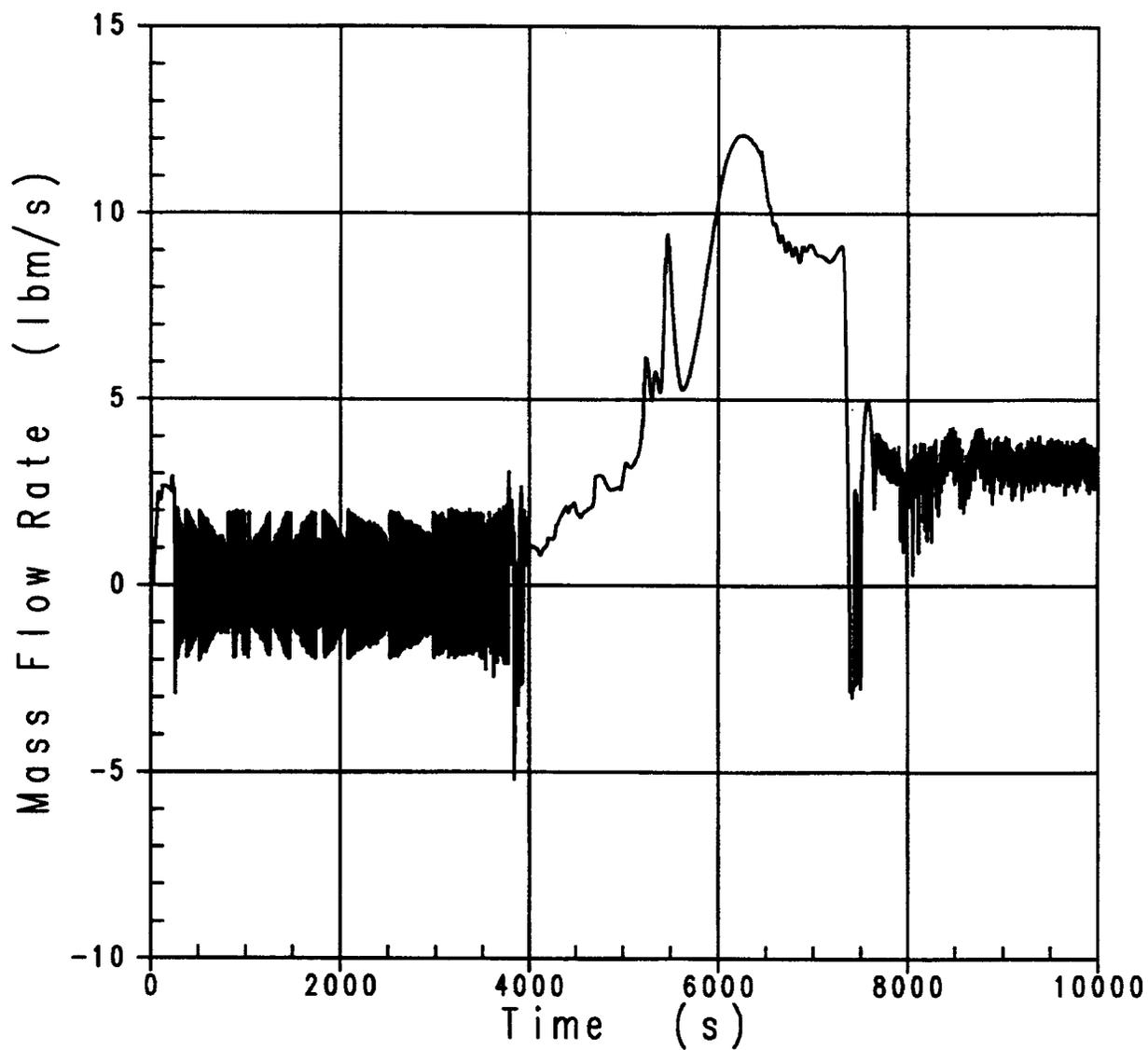


Figure 19E.4.8-42 ADS Stages 1-3 Vapor Flow, Loss of RNS in Mode 5 with RCS Open

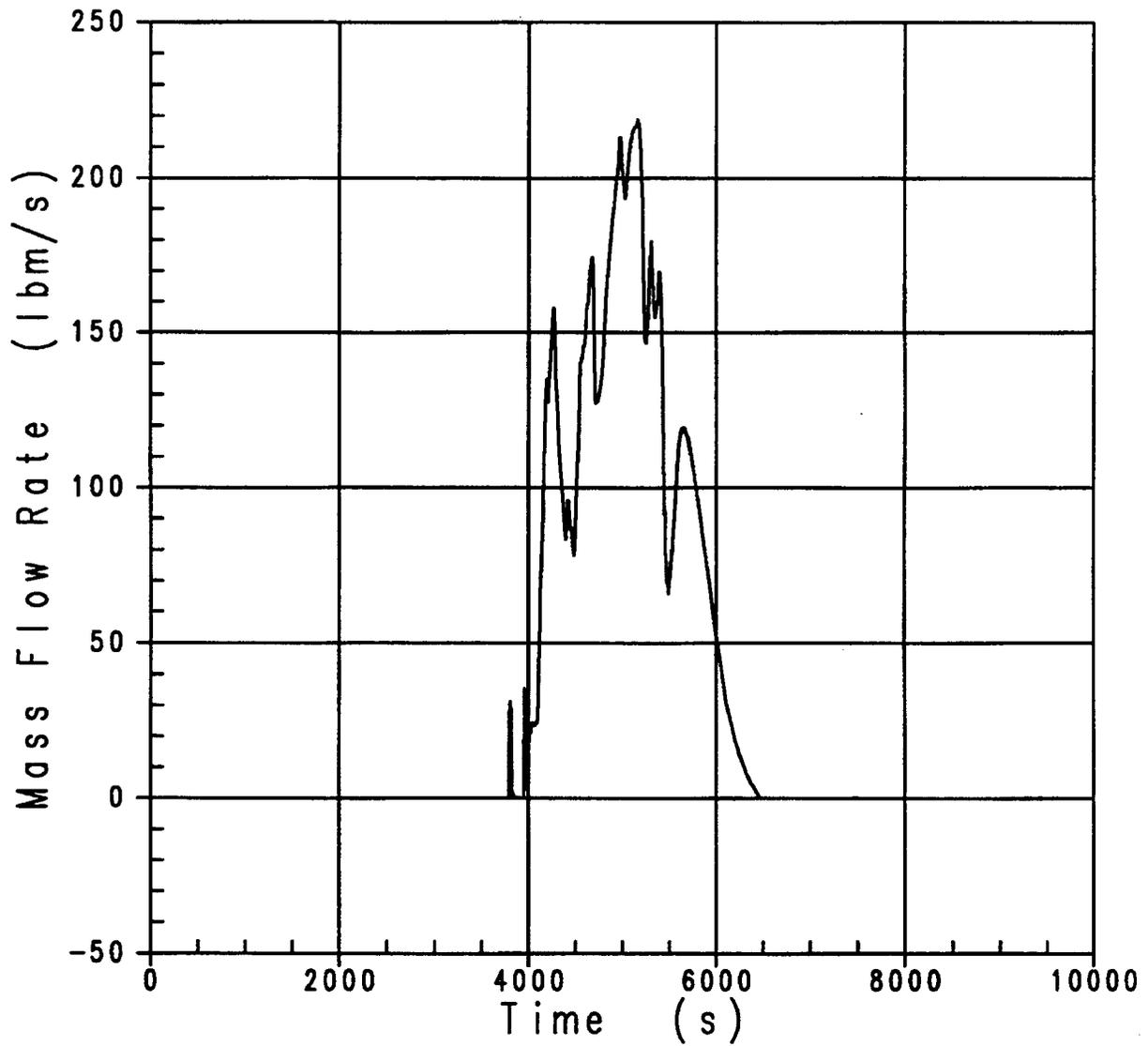


Figure 19E.4.8-43 ADS Stages 1-3 Liquid Flow, Loss of RNS in Mode 5 with RCS Open

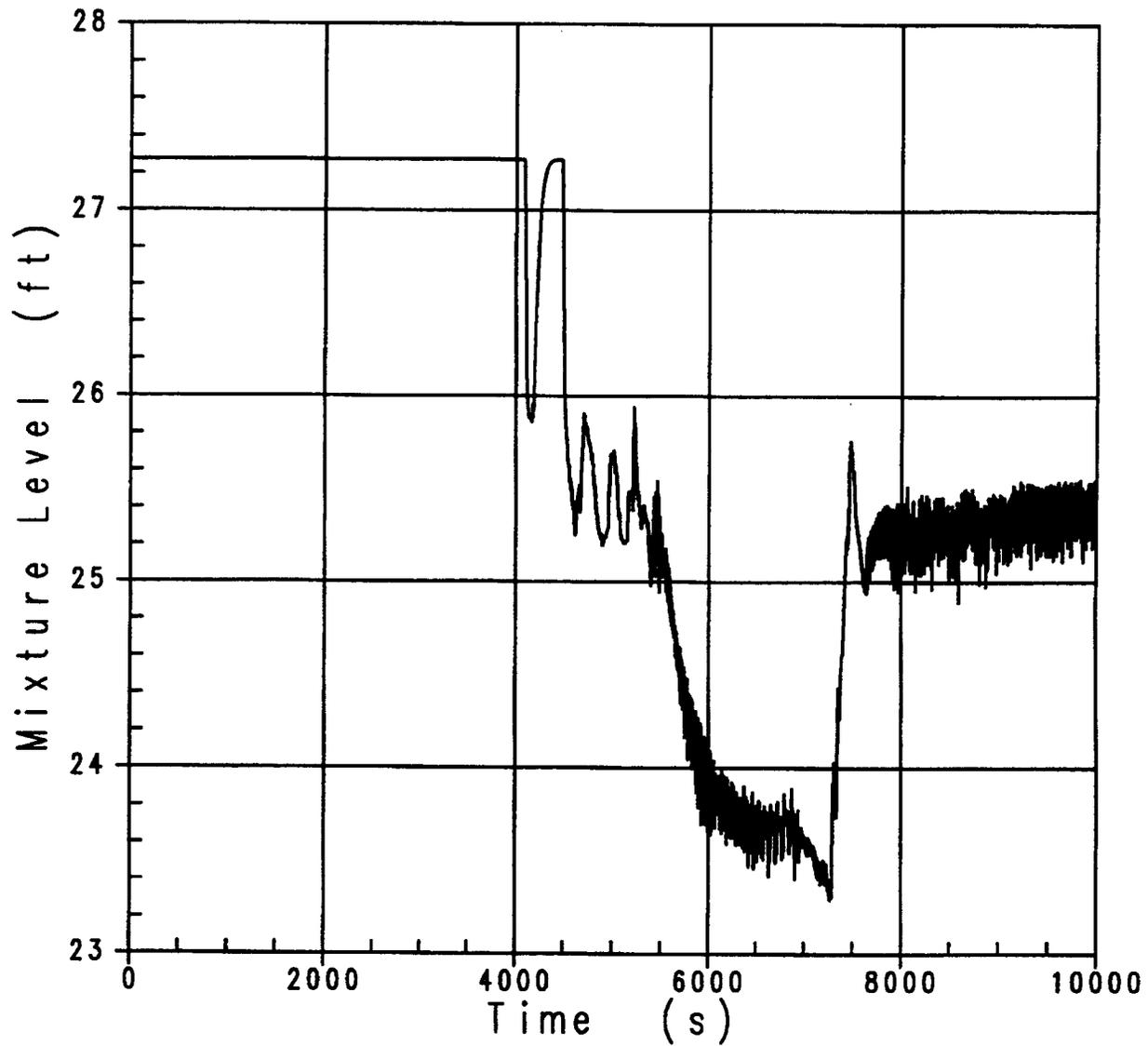


Figure 19E.4.8-44 Core Stack Mixture Level, Loss of RNS in Mode 5 with RCS Open

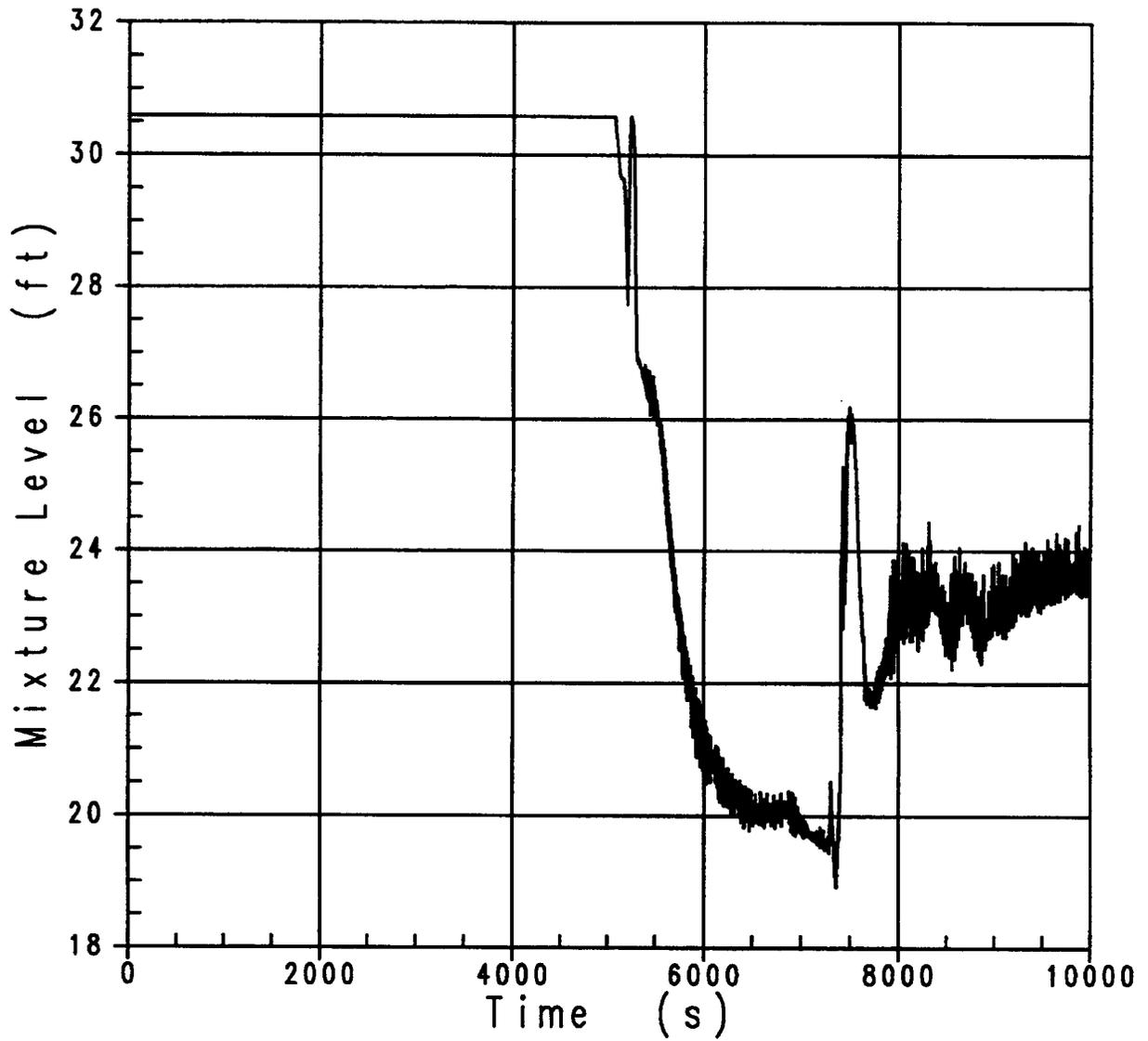


Figure 19E.4.8-45 Downcomer Mixture Level, Loss of RNS in Mode 5 with RCS Open

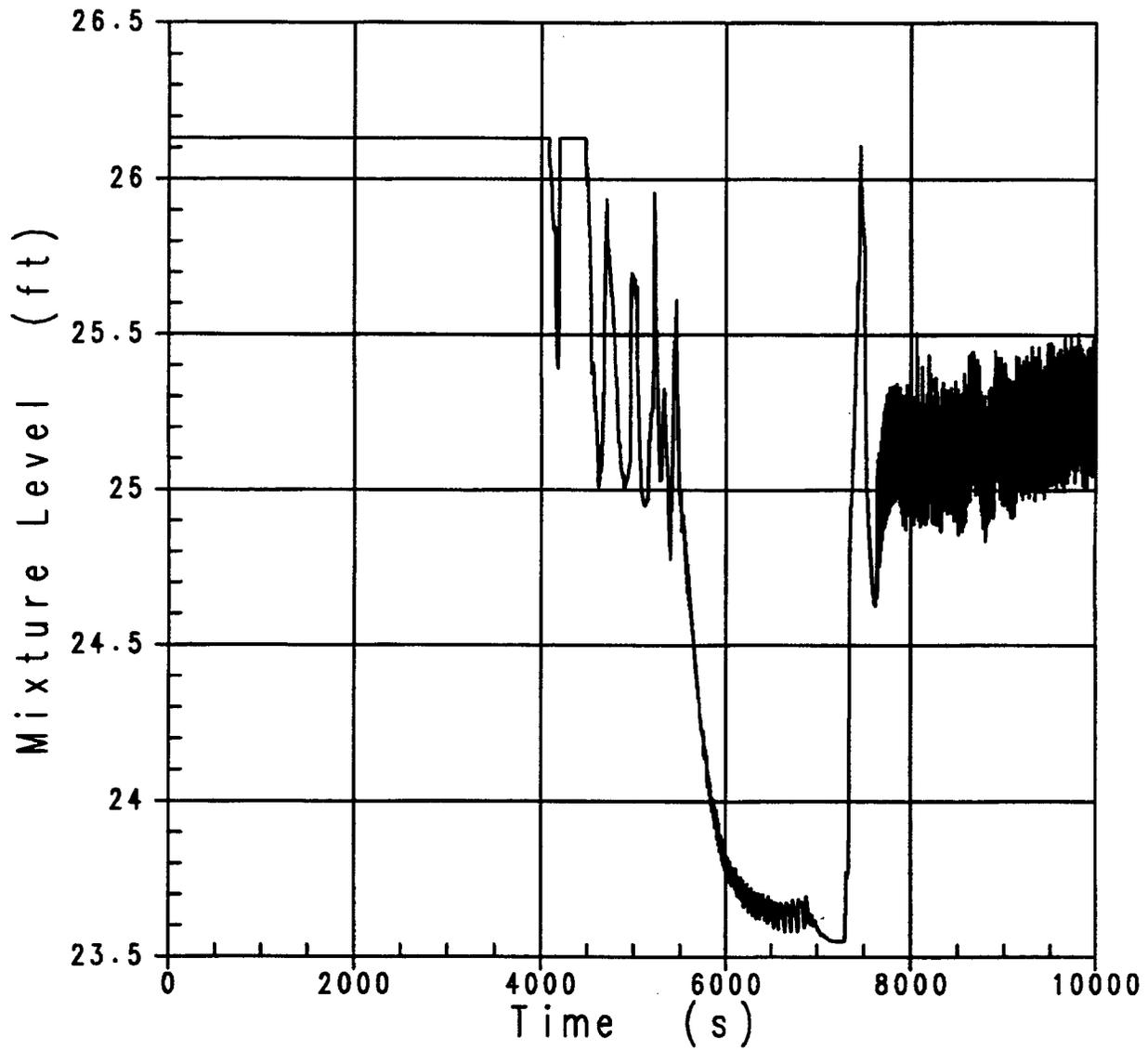


Figure 19E.4.8-46 Loop 1 Hot Leg Mixture Level, Loss of RNS in Mode 5 with RCS Open

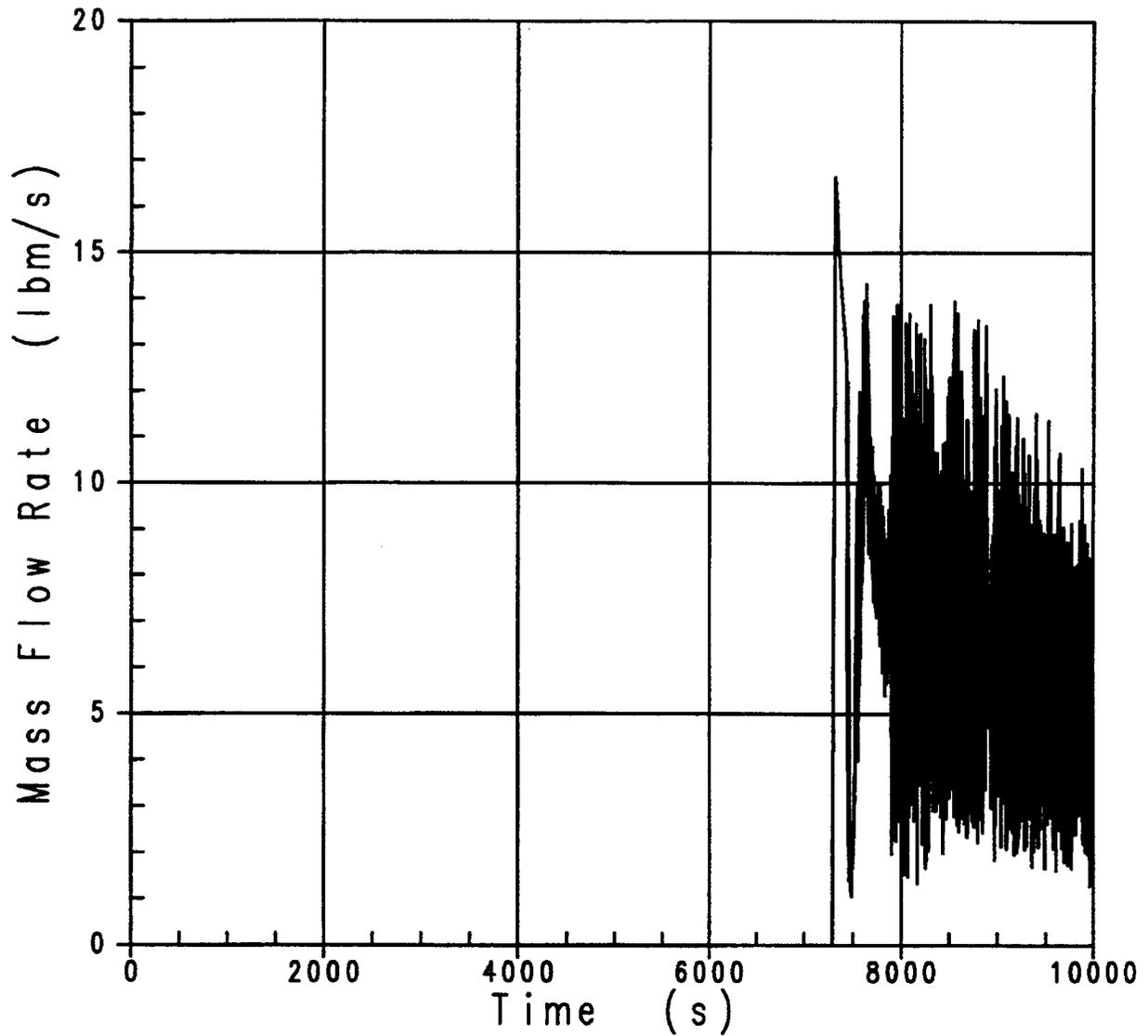


Figure 19E.4.8-47 ADS Stage 4 Vapor Flow, Loss of RNS in Mode 5 with RCS Open

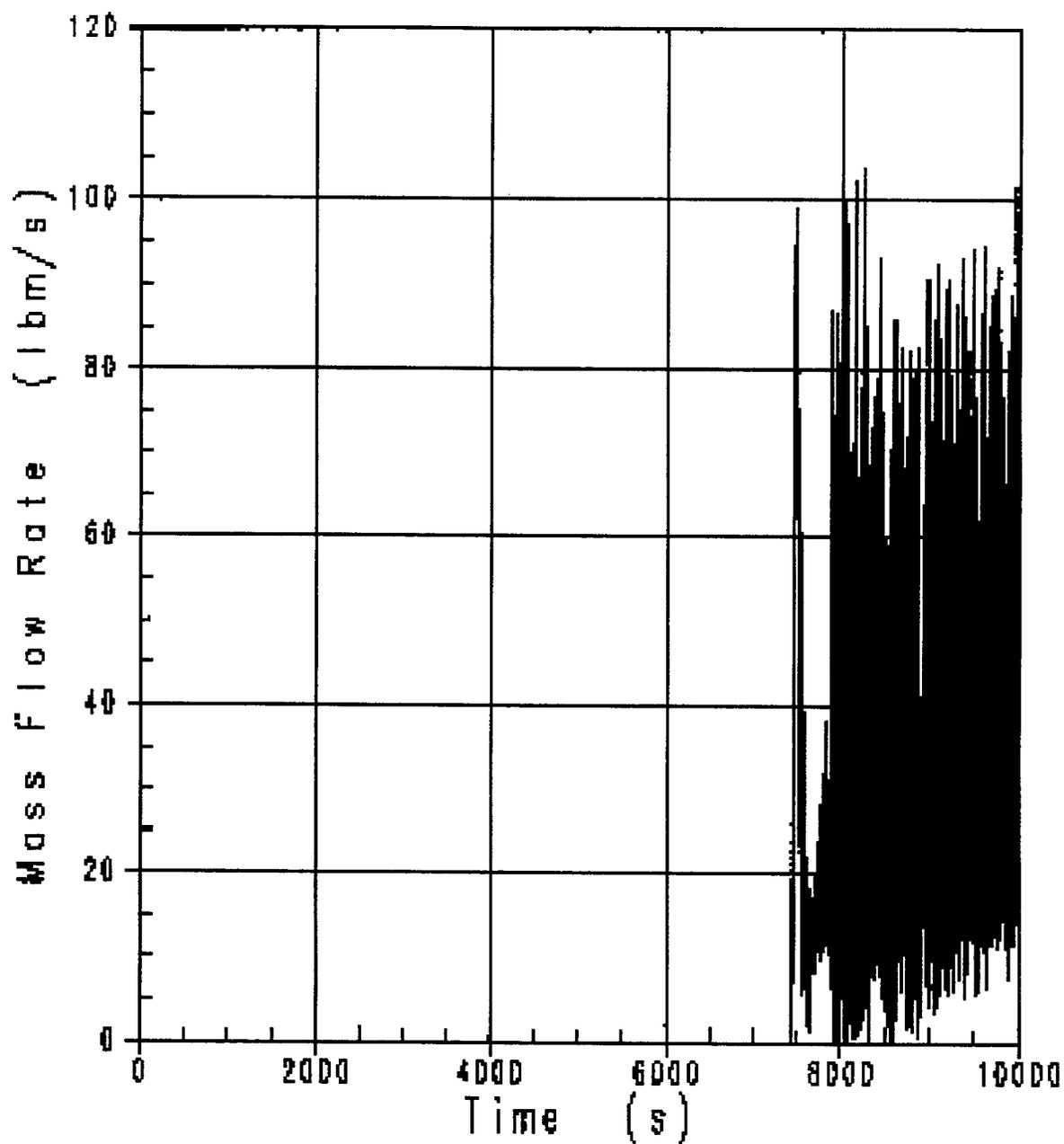


Figure 19E.4.8-48 ADS Stage 4 Liquid Flow, Loss of RNS in Mode 5 with RCS Open

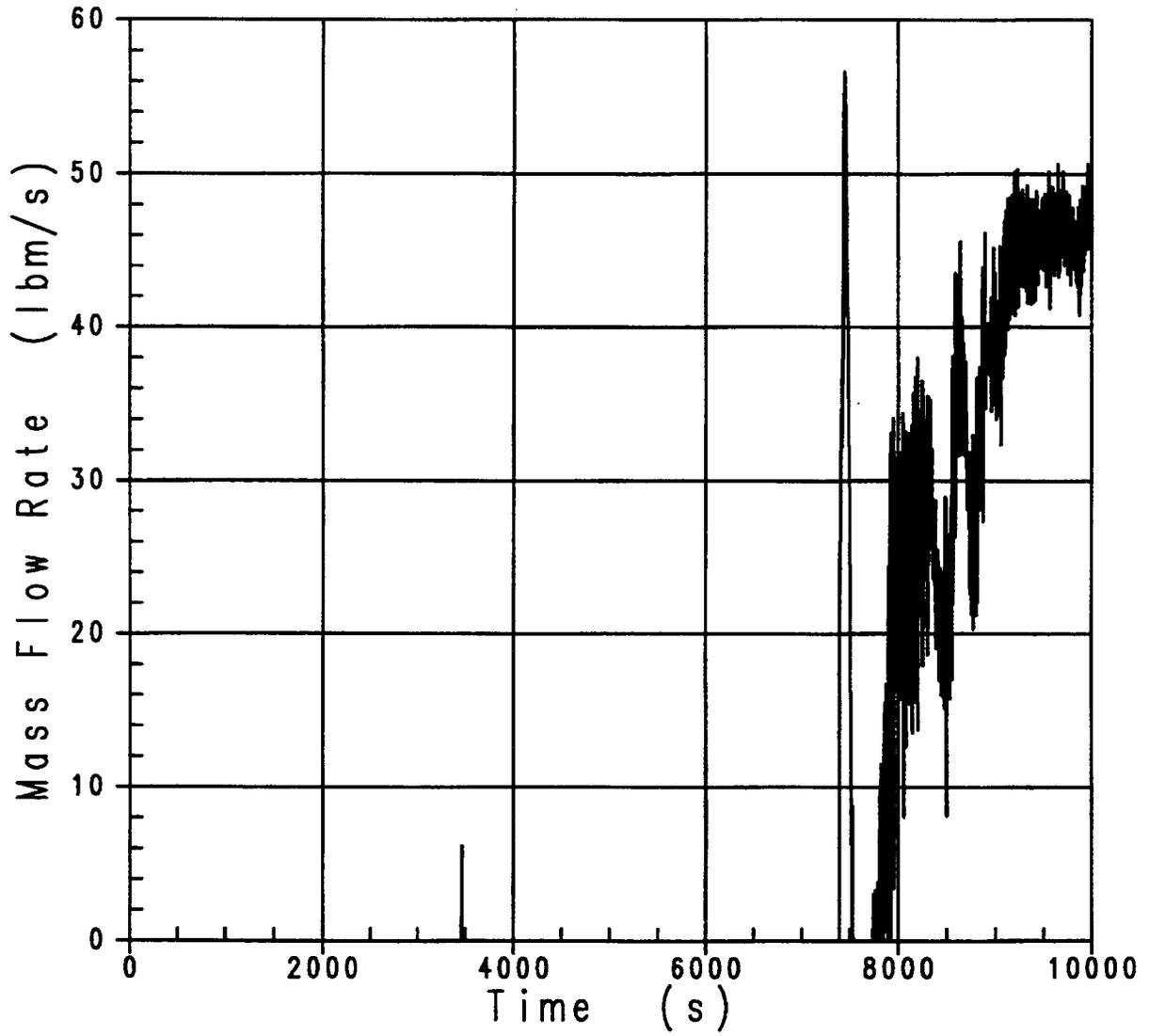


Figure 19E.4.8-49 IRWST Injection Flow, Loss of RNS in Mode 5 with RCS Open

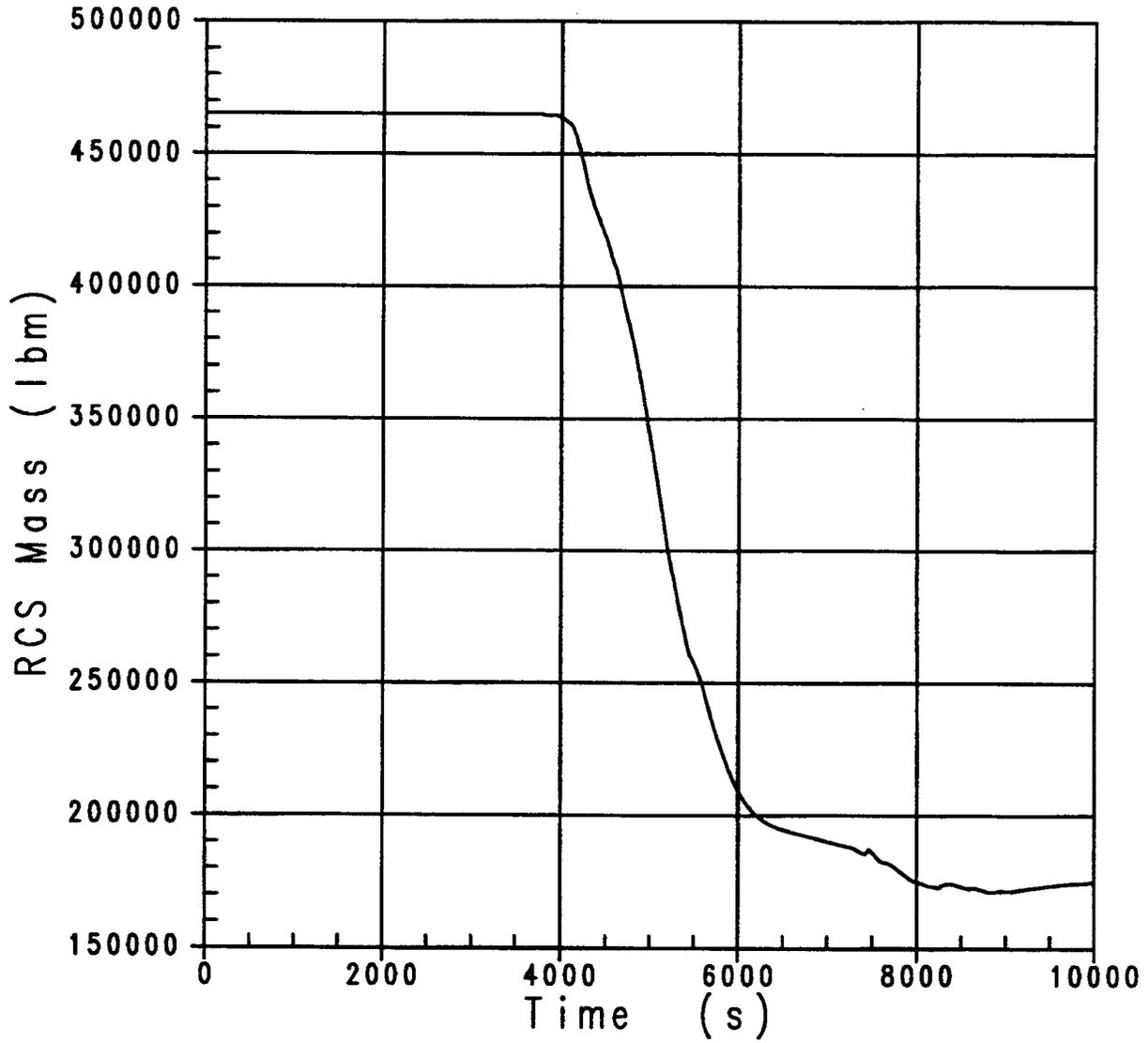


Figure 19E.4.8-50 Primary Mass Inventory, Loss of RNS in Mode 5 with RCS Open

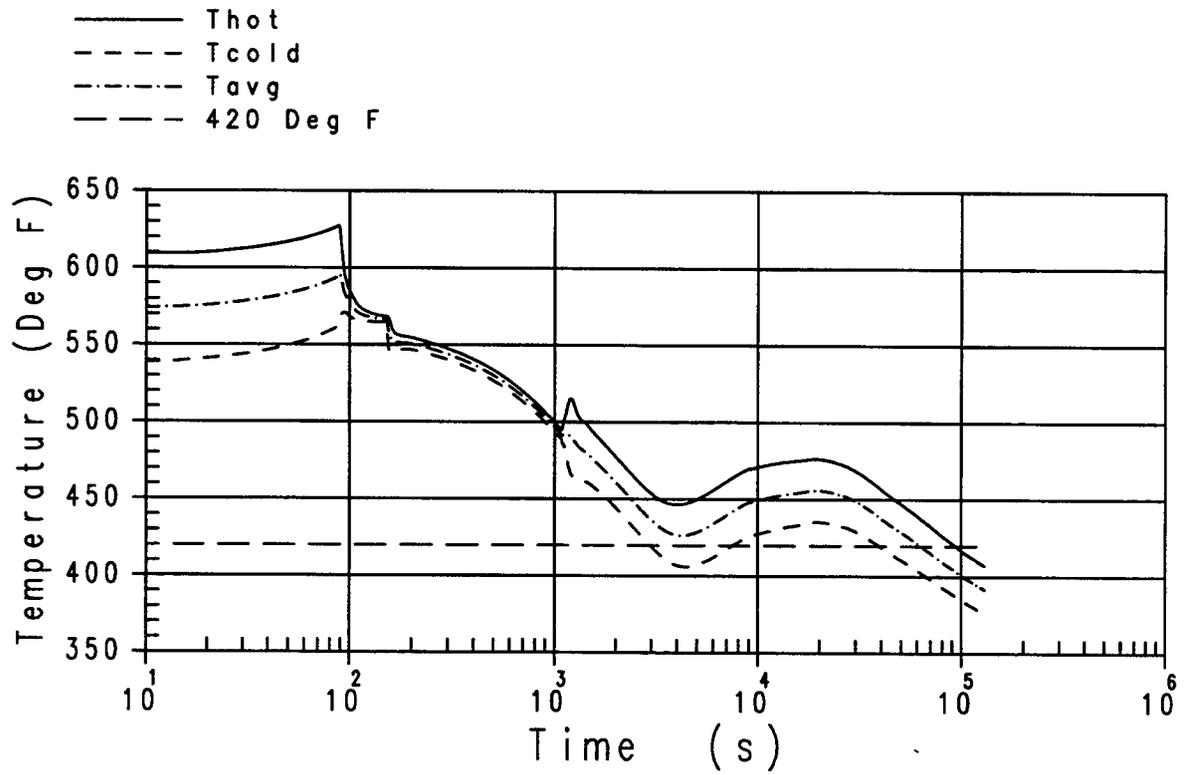


Figure 19E.4.10-1 Shutdown Temperature Evaluation, RCS Temperature (Loop with PRHR HX)

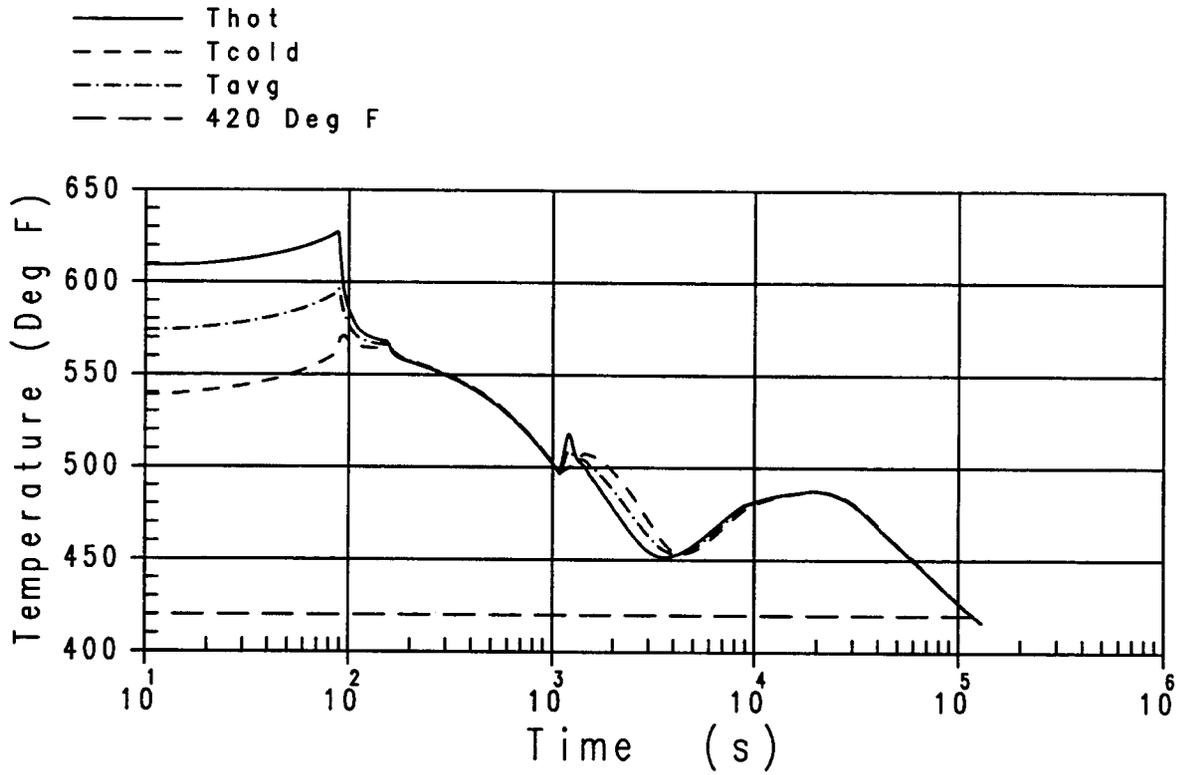


Figure 19E.4.10-2 Shutdown Temperature Evaluation, RCS Temperature (loop Without PRHR HX)

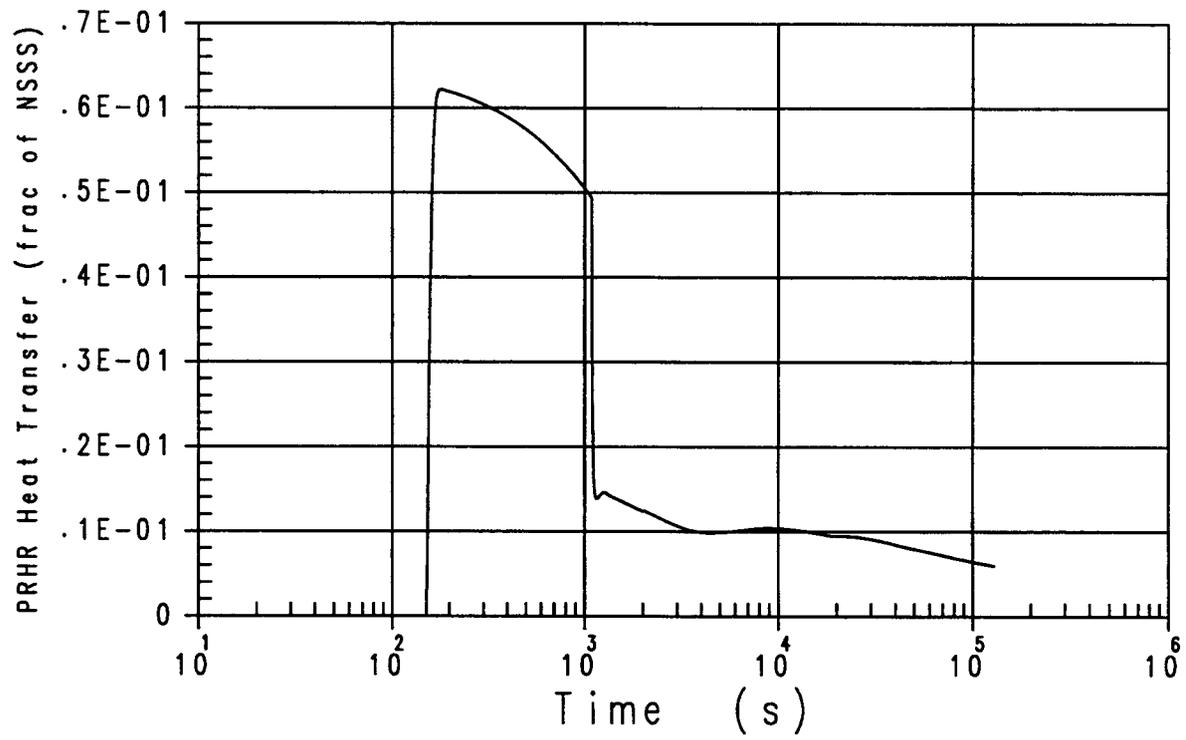


Figure 19E.4.10-3 Shutdown Temperature Evaluation, PRHR Heat Transfer

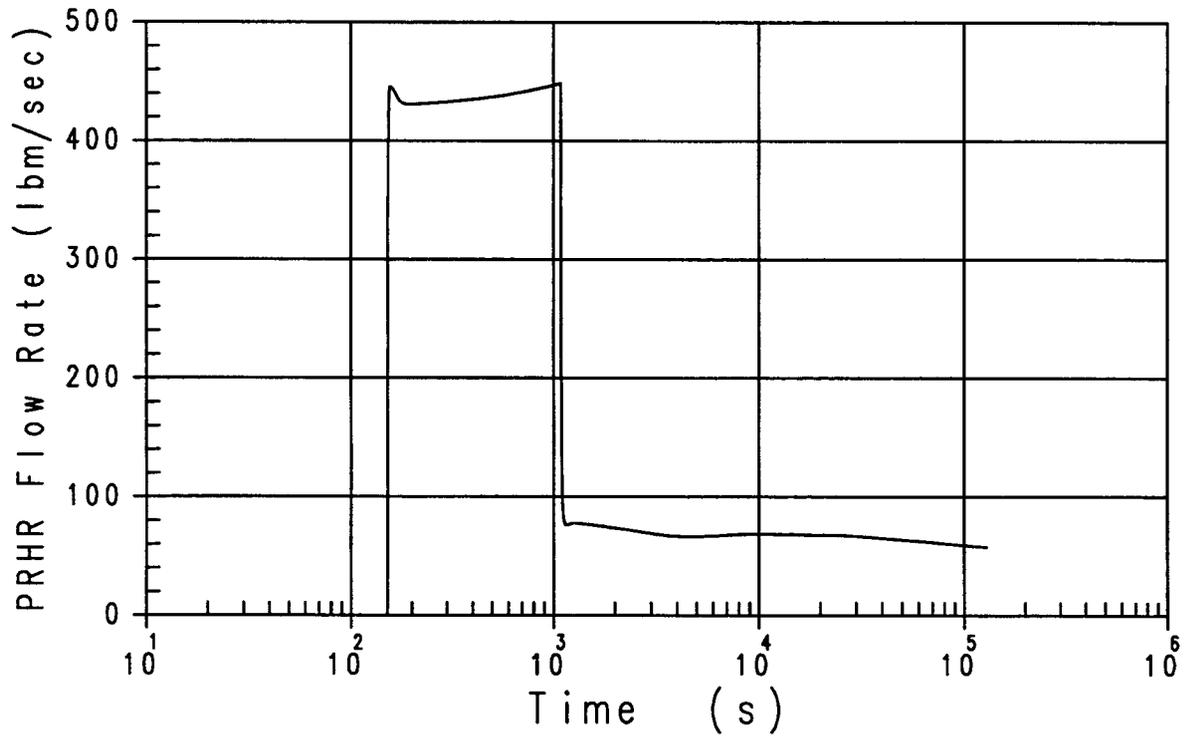


Figure 19E.4.10-4 Shutdown Temperature Evaluation, PRHR Flow Rate

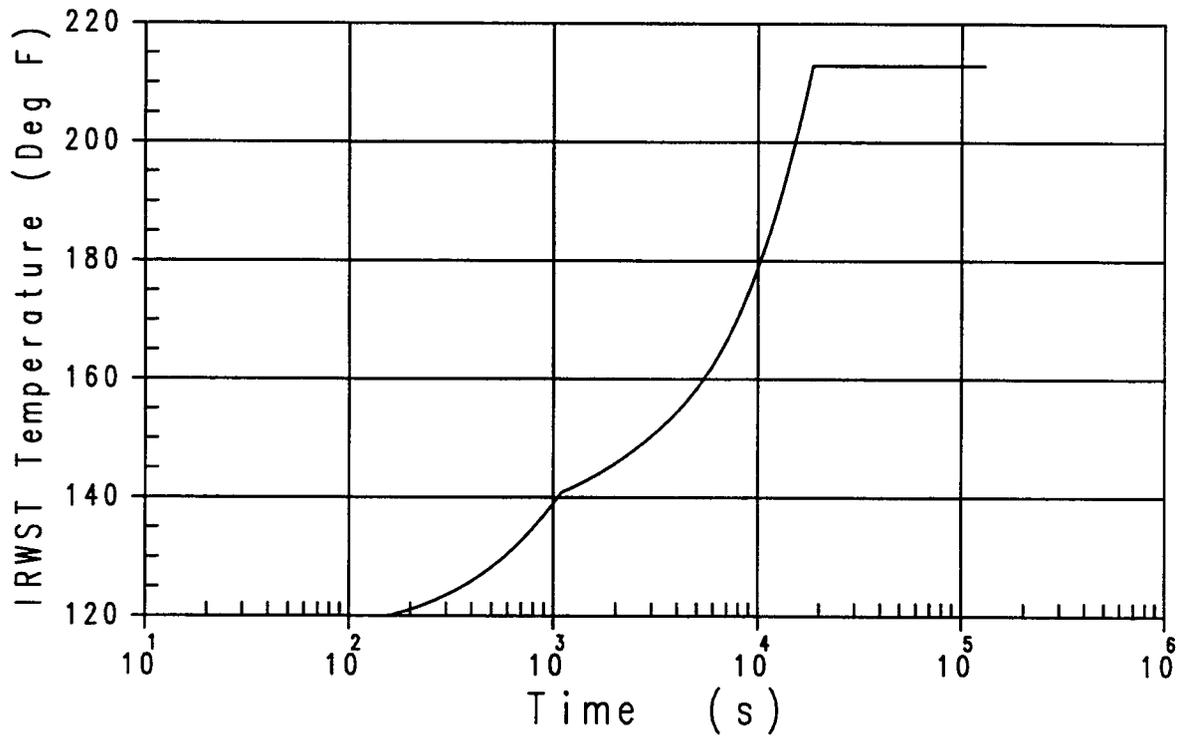


Figure 19E.4.10-5 Shutdown Temperature Evaluation, IRWST Heatup

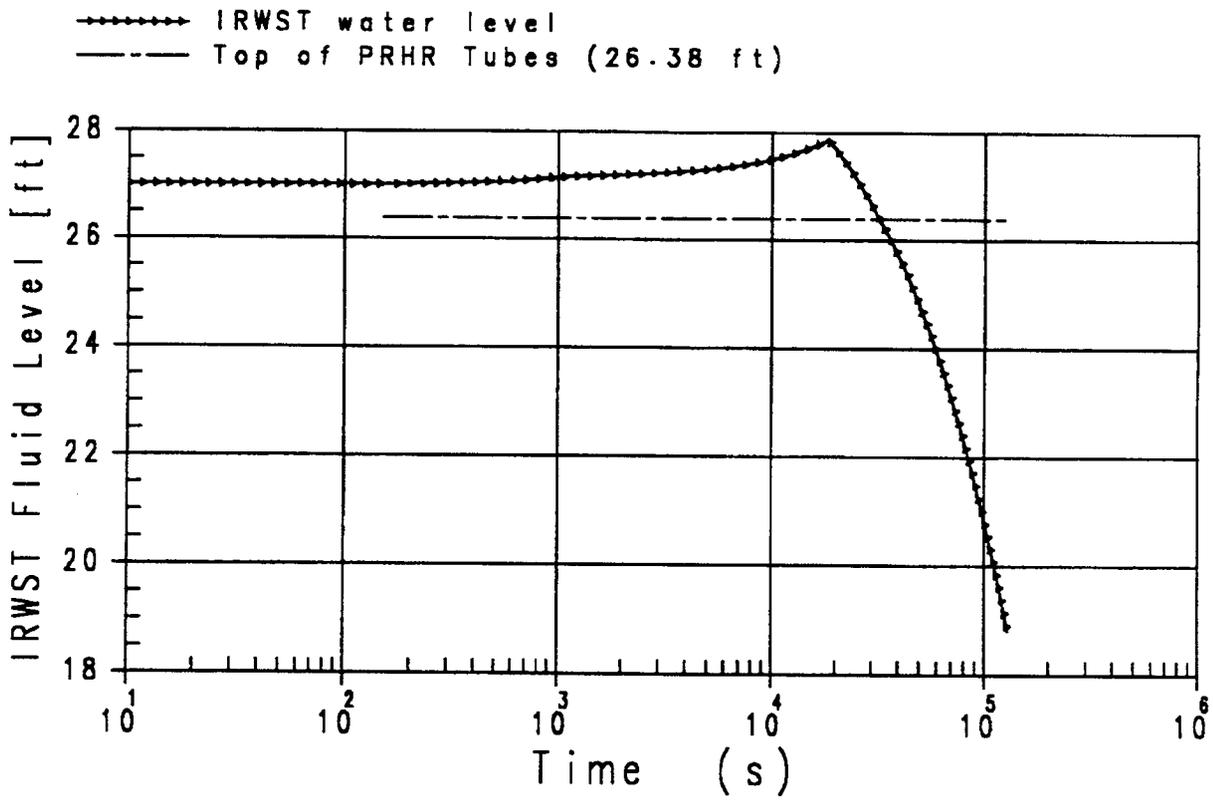


Figure 19E.4.10-6 Shutdown Temperature Evaluation, IRWST Water Level

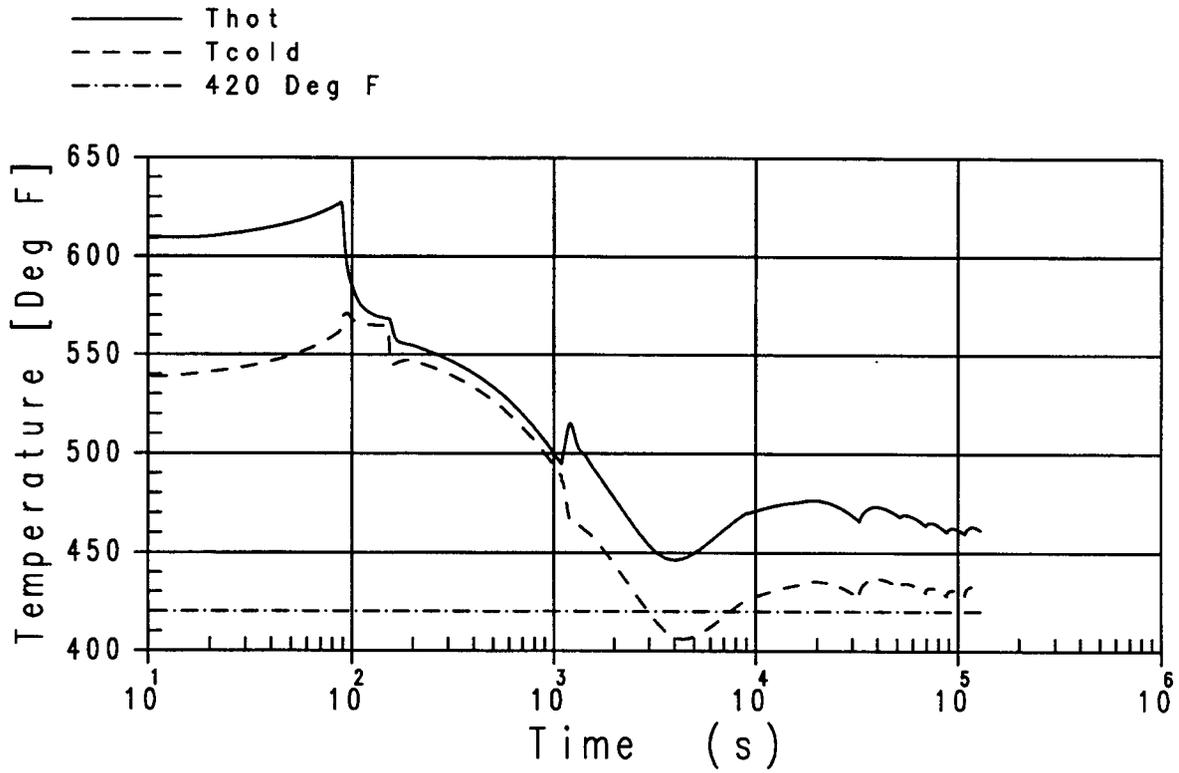


Figure 19E.4.10-7 Shutdown Temperature Evaluation, RCS Temperature, No Condensate Return to IRWST