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TITLE **LOS ALAMOS PWR FEED-AND-BLEED STUDIES SUMMARY RESULTS AND CONCLUSIONS**

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LOS ALAMOS PWR FEED-AND-BLEED STUDIES SUMMARY RESULTS AND CONCLUSIONS*

by

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ABSTRACT

The adequacy of shutdown decay heat removal in pressurized water reactors (PWRs) is currently under investigation by the Nuclear Regulatory Commission. One part of this effort is review of feed-and-bleed procedures that could be used if the normal cooling mode through the steam generators was unavailable. Feed-and-bleed cooling is effected by manually activating the high-pressure injection (HPI) system and opening the power-operated relief valves (PORVs) to release the core decay energy.

The feasibility of the feed-and-bleed concept as a diverse mode of heat removal has been evaluated at the Los Alamos National Laboratory. The TRAC-PF1 code has been used to predict the expected performances of the Oconee-1 and Calvert Cliffs-1 reactors of Babcock and Wilcox and Combustion Engineering, respectively, and the Zion-1 and H. B. Robinson-2 plants of Westinghouse. Feed and bleed was successfully applied in each of the four plants studied, provided it was initiated no later than the time of loss-of-secondary heat sink.

Feed and bleed was successfully applied in two of the plants, Oconee-1 and Zion-1, provided it was initiated no later than the time of primary system saturation. Feed and bleed in Calvert Cliffs-1 when initiated at the time of primary system saturation did result in core dryout; however, the core heatup was eventually terminated by coolant injection. Feed and bleed initiation at primary system saturation was not studied for H. B. Robinson-2.

Insights developed during the analyses of specific plant transients have been identified and documented. Based on the detailed results from the specific plant studies and the insights developed, feed-and-bleed feasibility statements for the four plants studied in detail are extended to larger groups of PWRs for which specific, detailed analyses have not been performed. These extension statements are largely based on inspection for similarity of HPI delivery characteristics and PORV relief capacities.

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1. INTRODUCTION

The U. S. Nuclear Regulatory Commission (NRC) has identified a number of nuclear-safety issues requiring further investigation. These have been designated as unresolved safety issues (USIs), and action plans have been prepared to resolve them. This paper describes one part of the effort to resolve USI A-45, Shutdown Decay-Heat Removal[1].

Feed and bleed has been proposed as one method of removing decay heat from pressurized water reactors (PWRs) following total loss of feedwater (LOFW). Feed and bleed is a procedure in which coolant is injected into the primary system by safety and/or non-safety grade systems (feed), absorbs the core-decay heat, and is released to the containment (bleed) through the power-operated relief valves (PORVs). Feed-and-bleed procedures are of interest because they would use equipment already existing in the plants. The specific steps taken in the feed-and-bleed procedure consist of (1) locking open the pressurizer PORVs, (2) initiating safety-injection (SI) flow, and (3) tripping the reactor-coolant pumps (RCPs).

This study had several objectives. The first was to evaluate the success or failure of feed and bleed for a limited number of PWRs. A detailed evaluation was performed for four plants. They were the Oconee-1 and Calvert Cliffs-1 plants of Babcock and Wilcox (B&W) and Combustion Engineering (CE), respectively, and the Zion-1 and H. B. Robinson-2 plants of Westinghouse (W). Zion-1 and H. B. Robinson-2 are W 4-loop and 3-loop plants, respectively. A W 2-loop plant was not studied in detail. Existing detailed models of each plant were adapted to study feed-and-bleed transients and a general system thermal-hydraulics computer code was used to simulate in detail the performance of each plant following selected initiating events. The second study objective was to identify both plant specific and generic insights about the feed-and-bleed procedure based on the detailed plant analyses performed. The final study objective was to extend the plant-specific conclusions to the broadest possible group of PWRs.

2. METHOD

The detailed plant models were developed at the Los Alamos National Laboratory in recent years. The Oconee-1[2], Calvert Cliff-1[3], and H. B. Robinson-2[4] plant models were developed for pressurized thermal shock studies. The Zion-1 model was developed specifically for the feed-and-bleed study. The transients were calculated using the TRAC-PF1 computer code[5]. The TRAC-PF1 code was developed at Los Alamos National Laboratory under the sponsorship of the NRC to provide advanced best-estimate predictions of postulated accidents in light-water reactors. Major code features include a full two-fluid (six-equation) hydrodynamics model to describe steam-water flow, a flow-regime dependent constitutive equation package, a comprehensive heat-transfer modeling capability, and an efficient computational algorithm for one-dimensional components. In addition, the vessel can be modeled in three-dimensions if accurate calculation of complex multidimensional flow patterns inside the reactor vessel is important during the transient.

Because there is interest in the plant transition from reactor trip to both a hot, pressurized holding condition and to hot shutdown (entry conditions for either the residual-heat-removal (RHR) or low-pressure-injection (LPI) systems), we have identified criteria to measure the success or failure of a feed-and-bleed procedure in each case. For transition from reactor trip to a hot, pressurized holding condition, we define success as attainment of a stable primary system having the following three characteristics. First, the primary-system pressure is above the actuation pressures for both the LPI system and accumulators. Second, primary system and vessel mass inventories are stable or increasing. Third, fuel-rod cladding temperatures are near or below the primary saturation temperature with no departure from nucleate boiling (dryout).

This is a short-term success criterion in that further actions must be taken within a limited time to insure long-term success. Such actions include restoration of secondary-side cooling or initiation of suction from the containment sump combined with pumping the sump fluid to the high-pressure injection (HPI) system inlet pressure. For transition from reactor trip to hot shutdown, we define success as completion of a controlled primary-system depressurization and cooldown to achieve conditions permitting long-term cooling using either the RHR system or the LPI system taking suction from the containment sump.

Initially, we identified a common set of initiating events for loss-of-secondary cooling. The events were a LOFW event induced by a loss-of-offsite power, a LOFW initiator with offsite power available, and other events combined with a LOFW. These were a main-steamline break, a main-feedline break, and a single-tube steam-generator tube rupture. We determined that the response of the plant to the LOFW initiator was the best indicator of plant response and critical timing during a feed-and-bleed procedure. Therefore, only LOFW initiator results are reported here. Additional results are presented in the final study report[6].

3. DETAILED PLANT RESULTS

In the following sections we briefly describe each plant for which detailed plant transient analyses were performed and summarize key results.

3.1 Calvert Cliffs-1

Calvert Cliffs-1 is a 2700 MWt C-E PWR operated by Baltimore Gas and Electric Company. The plant has two hot legs and four cold legs. The two steam generators are vertical shell and U-tube units. The reactor coolant is circulated by four RCPs. An electrically heated pressurizer is connected to the hot leg of one loop. Primary system overpressure protection is provided by two PORVs and two spring-loaded safety relief valves (SRVs) connected to the pressurizer. The SI system includes HPI and LPI capability as well as charging flow and accumulators. Three charging pumps deliver a small flow totaling 8.3 kg/s (18 lbm/s) independent of primary system pressure. The HPI pumps have a shutoff pressure of 8.8 MPa (1275 psia). Above this pressure, only charging flow is possible. Four accumulators are provided, each connected to one of the four cold legs. Shutdown cooling can be initiated when the primary pressure and temperature are below 2.08 MPa (300 psia) and 422 K (300°F), respectively.

Two Calvert Cliffs-1 LOFW transients will be discussed in detail because they display the important systems interactions during a feed-and-bleed procedure for plants lacking a high-pressure SI capability. The first transient assumed the operators initiated feed and bleed at the time of loss-of-secondary heat sink. This occurred at 1250 s when the steam-generator secondaries boiled dry. We assumed that the feedwater flow dropped to zero instantly at the start of the transient. The primary system pressure for this transient is shown in Fig. 1. The pressure dropped rapidly to the saturation pressure of the hottest fluid in the primary following action by the operator to lock open both PORVs. HPI flow began as the pressure dropped below the HPI pump shutoff pressure of 8.8 MPa (1275 psia). However, the primary immediately began to repressurize because the vapor generated in the core could not be relieved through the PORVs which first passed two-phase fluid and then liquid beginning at 1500 s. The pressure increased above the HPI shutoff head at 2100 s leaving only the small charging flow to replenish coolant relieved through the PORVs. By 3600 s the liquid level in the vessel upper plenum dropped to the level of the hot legs and provided a vapor path to the PORVs. The primary pressure then began to decline with the greater volumetric removal rate through the PORVs. The pressure declined rapidly at 3800 s as a loop seal cleared, recovered, and then resumed its slow decline until HPI flow recovery occurred at 5600 s. The minimum vessel liquid mass inventory was reached just after HPI initiation but the vessel soon began to refill as shown in Fig. 2. The cladding temperature remained near or below the core average saturation temperature throughout the transient as shown in Fig. 3. We see that the plant was successfully transitioned from reactor trip to a hot pressurized holding condition when the feed-and-bleed procedure was initiated no later than loss-of-secondary heat sink. Although the calculation was not carried out to RHR or LPI system entry conditions, the established rates of depressurization and cooldown, if maintained, would transition the plant to entry conditions using only safety-grade water supplies.

For the second transient we assumed the operators delayed initiating feed-and-bleed following the loss-of-secondary heat sink until the primary system had saturated. This occurred at 2900 s or 27.5 minutes after loss-of-secondary heat sink. The primary pressure for this transient is shown in Fig. 4. Following the LOFW event, the pressure rapidly decreased and stabilized at 13.5 MPa (1960 psig). After loss-of-secondary heat sink at 1250 s, the primary began to repressurize. The PORVs opened initially at 1650 s and cycled irregularly to maintain the system pressure at the PORV setpoint until the feed-and-bleed procedure was initiated at 2900 s. In contrast to the first transient, primary pressure did not initially decrease when the PORVs were locked open. Rather, the primary began to pressurize because the PORVs were passing two-phase fluid, which had a lower rate of volumetric relief than the vapor generation rate in the core. The primary mass depletion was very rapid after the PORVs were locked open and by 3900 s the upper plenum had voided to the hot-leg centerline and established a vapor path from the upper plenum into the hot legs. Once vapor relief through the PORVs was established, primary pressure began to drop rapidly. Following clearance of the loop seal in the pressurizer-loop pump-suction leg, a nearly constant rate of pressure decay was established until the pressure dropped below the HPI shutoff pressure at 6700 s. The vessel liquid mass inventory during the transient is shown in Fig. 5. The rapid inventory decrease following feed-and-bleed initiation and the inventory building following HPI initiation are clearly shown. Core dryout occurred in this transient whereas it did not in the first transient. Core dryout started at 4900 s and cladding temperatures reached 820 K (1016°F) as shown in Fig. 6. Cladding heatup was terminated at 6800 s after HPI was restored as the pressure dropped below the HPI shutoff head. Although the core heatup was terminated before damaging the core, the criteria for a successful feed-and-bleed operation were not satisfied.

We also examined the impact of equipment failures on the ability to conduct a successful feed-and-bleed operation at the time of loss-of-secondary heat sink. We found that if only one of the two PORVs were available, a core dryout would occur and the feed-and-bleed procedure would fail. We also found that if only one of the two normally available HPI system pumps were available, a core dryout would occur and the feed-and-bleed procedure would fail.

3.2 Oconee-1

Oconee-1 is a 2584 MWt B&W PWR operated by Duke Power Company. The plant has two hot legs and four cold legs. The two steam generators are vertical once-through units. The reactor coolant is circulated by four shaft-sealed

RCPs. An electrically heated pressurizer is connected to the hot leg of one loop. Primary system overpressure protection is provided by a single PORV and two SRVs connected to the pressurizer outlet. The SI system includes the HPI system, the LPI system and accumulators. The HPI system differs from that of Calvert Cliffs-1 in that a large coolant flow [26.90 kg/s (59.14 lb/s)] can be delivered at the PORV setpoint by the two normally used HPI pumps. Two accumulators are provided, each attached directly to a reactor-vessel core-flooding nozzle. Shutdown cooling can be initiated when the primary pressure and temperature are below 2.5 MPa (365 psia) and 422 K (300°F), respectively.

We examined the response of Oconee-1 to several LOFW initiators. In each case we assumed the main feedwater flow dropped instantly to zero at the start of the transient. The time to loss-of-secondary heat sink with once-through steam generators occurs more rapidly than for systems with U-tube steam generators. We found the steam generators could not remove the decay heat by 60 s and the secondaries were completely dry by 200 s. Because the operator must make a decision to initiate feed and bleed so early in the transient, we turned our attention to determining the success or failure of feed and bleed initiated later in the transient at primary system saturation. We found this to occur at about 1200 s. The primary pressure during this transient is shown in Fig. 7. The decay energy exceeded the energy removed by the steam generators and the pressure and temperature of the primary began to increase. Primary liquid expansion compressed the steam at the top of the pressurizer, and at 140 s the PORV opened. At 400 s, primary liquid expansion filled the steam space in the pressurizer and liquid began to flow out the single PORV. Although the mass flow increased, the volumetric flow was less than the volumetric vapor generation rate in the core and the system pressurized briefly to the SRV setpoint at 500 s. The primary system heated to saturation at 1200 s, at which time the operators were assumed to begin the feed-and-bleed procedure. However, the PORV had already been fully open for some time because of the small relief capacity of the single Oconee-1 PORV. The primary pressure did not begin to decrease until about 3000 s when the relief capacity of the PORV was sufficient. Within the vessel, the minimum vessel liquid inventory was reached at about 1400 s and the core was refilled by 6900 s. At 7000 s, core cooling by water flow alone was sufficient to remove the core decay energy and boiling ceased in the core. This is shown in Fig. 8 which shows the coolant flow becoming subcooled in the hot leg at 7000 s. The cladding temperature remained near or below saturation throughout the course of the transient. Thus, feed and bleed initiated not later than the time of primary system saturation was successfully transitioned to a hot, holding condition.

We also examined the feasibility of cooling and depressurizing the plant to either RHR or LPI system entry conditions. Because of the small PORV relief capacity, the depressurization was slow and an extended transient was envisioned. Therefore, we used TRAC-PF1 to calculate the transient only to 14500 s. We then used linear extrapolation from the calculated primary pressure and temperature curves to predict that RHR conditions would be reached at approximately 22500 s. There was sufficient safety-grade water storage to complete cooling and depressurization to RHR entry conditions.

As with Calvert Cliffs-1, we examined the impact of equipment failures on the ability to conduct a successful feed-and-bleed operation. However, we focused on the unavailability of equipment at the time a containment overpressure signal would be generated, 900 s, rather than at loss-of-secondary heat sink. We did not consider PORV unavailability because Oconee-1 has only a single PORV and feed and bleed would not be possible with the failure of the single PORV to open. We did examine the ability to cool and depressurize the plant to a hot, holding condition using only one of the two HPI pumps normally used. The decreased HPI flow extended the time to key events. For example, the primary pressure did not begin to decrease until 4290 s. The minimum vessel liquid mass inventory was reached at 4000 s and then increased until the end of the calculation at 6800 s. The cladding temperature remained near or below the saturation temperature throughout the transient. Therefore, feed and bleed was successful in Oconee-1 if initiated at the time the containment overpressure signal was generated, even if 50% of the HPI capacity was lost.

3.3 Zion-1

Zion-1 is a 3250 MWt W PWR operated by Commonwealth Edison. The plant has four hot legs and four cold legs. The four steam generators are vertical shell and U-tube units. The reactor coolant is circulated by four RCPs. An electrically heated pressurizer is connected to the hot leg of one loop. Primary system overpressure protection is provided by two PORVs and three SRVs connected to the pressurizer. The SI system includes HPI and LPI capability as well as accumulators. Zion-1 is a high-pressure SI plant:* two safety-grade centrifugal charging pumps deliver a total of 20.6 kg/s (45.4 lb/s) at the PORV setpoint, and two SI pumps provide additional safety-grade coolant flow at intermediate pressures. Four accumulators are provided, each connected to one

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*Westinghouse plants with SI shut-off pressures greater than the PORV setpoint are considered high-pressure (HP) SI plants; Zion-1 is such a plant. Westinghouse plants with shut-off pressures less than 10.3 MPa (1500 psia) are classified as low-pressure (LP) SI plants. Plants with SI shut-off pressures greater than 10.3 MPa but less than the PORV setpoint are classified as intermediate-pressure (IP) SI plants. High-pressure SI systems do not have charging pumps other than in the SI system, whereas LP and IP SI plants have separate high-pressure charging pumps which are part of the chemical and volume control system (non-safety grade) rather than the SI system.

of the cold legs. Shutdown cooling can be initiated when the primary pressure and temperature are below 3.04 MPa (440 psig) and 450 K (350°F), respectively.

Although many Zion-1 LOFW transients were calculated, we are able to provide the most complete picture of the plant feed-and-bleed capability for the procedure initiated at loss-of-secondary heat sink. This occurred at 3000 s when the steam-generator secondaries boiled dry. The primary system pressure for the event is shown in Fig. 9. With the loss-of-secondary heat sink at 3000 s, the primary pressure and temperature began to rise. HPI was initiated and the pressure rise terminated when the operator opened the PORVs shortly thereafter. The primary pressure decreased rapidly to the saturation pressure of the hottest fluid in the primary. The rapid pressure decrease slowed and stalled by 3200 s as the hot, nearly stagnant liquid in the vessel upper head began to boil. The minimum vessel liquid mass inventory was reached at 5000 s as shown in Fig. 10 and the vessel refilling process continued until the end of the calculated transient at 8600 s. Throughout the course of this transient the cladding temperature remained either near or below saturation. In addition, there was sufficient PORV capacity to depressurize the primary even while the primary was receiving the maximum HPI flow. Thus, by the end of the calculated transient the primary was both cooled and depressurized to the RHR entry conditions. However, the calculated cooldown rate was excessive and it is likely that the HPI would be throttled to slow the rate of cooldown for this transient.

We did not directly study the case of feed-and-bleed initiation at primary system saturation (4875 s) for Zion-1. We did examine the case of feed-and-bleed initiation at the time of containment overpressure (4095 s) and found that the plant was successfully transitioned to a hot, holding condition. We also examined a case in which feed only (PORV not locked open but left to cycle at its setpoint) was used after the time of primary system saturation. The Zion-1 HPI delivery rate was sufficiently high, even at the PORV setpoint, to terminate a core heatup. We concluded that feed-and-bleed initiated at the time of primary system saturation would be successful.

We investigated the impact of equipment failures on the ability to conduct a successful feed-and-bleed operation at the time of loss-of-secondary heat sink for Zion-1. We first examined the failure of one of the two PORVs to open. With decreased PORV capacity, less core coolant was lost and the minimum vessel liquid inventory was less than in the nominal case. By 3500 s the vessel liquid mass inventory was increasing. The cladding temperature was near or below saturation throughout the transient. Thus, the transition to a hot, holding condition was successful. We also examined the unavailability of one charging and one SI pump. With the full PORV capacity but reduced coolant injection capacity, the vessel inventory decreased to the lowest level of the cases examined. However, by 6600 s the vessel liquid mass inventory began to increase. Again, the cladding temperature was near or below saturation throughout the transient. The transition to a hot, holding condition was again successful.

3.4 H. B. Robinson-2

H. B. Robinson-2 is a three-loop 2300 MWt PWR operated by Carolina Power and Light Company. The steam generators are vertical shell and U-tube units. The H. B. Robinson-2 plant is a low-pressure SI plant. We performed one LOFW analysis for the H. B. Robinson-2 plant and assumed that the non-safety grade, high-pressure charging pumps were not available. In this configuration the plant HPI system is similar to that of Calvert Cliffs-1. The objective of this limited analysis effort was to verify that W three-loop plant designs with a LP

SI system can be successfully cooled and depressurized using a feed-and-bleed procedure following a LOFW event.

The feed-and-bleed procedure was again initiated at loss-of-secondary heat sink. Because the analysis modeled a delayed reactor trip on low steam-generator liquid level, the loss-of-secondary heat sink occurred at 840 s, which was much earlier than would be the case if the reactor tripped as designed. We assumed the operators detected the steam-generator dryout and initiated feed and bleed at 960 s. The primary pressure (Fig. 11) quickly decreased from the normal operating pressure to 8.2 MPa (1175 psia) and then slowly increased from decay heat addition to about 11.6 MPa (1680 psia) at 2250 s. At that time, the upper plenum and hot legs voided sufficiently for the upper plenum vapor to escape through the PORVs. This high volumetric vapor flow provided pressure relief, and the primary pressure decreased thereafter, reaching the accumulator discharge pressure at 4490 s. The SI flow did not start until 1030 s when the pressure dropped below the shutoff head, and stopped when the primary pressure increased above the SI pump shutoff pressure between 1650 and 2580 s. The SI flow continued uninterrupted thereafter. The minimum vessel liquid inventory was reached at 3500 s and increased thereafter. Fuel cladding temperatures remained near or below saturation throughout the transient. Thus, the feed-and-bleed procedure was effective in transitioning the plant from reactor trip to a hot, holding condition.

4. EXTENSION OF RESULTS

Detailed thermal-hydraulic studies have been performed for at least one plant of each US PWR vendor to determine if feed and bleed is a viable procedure for cooling a reactor following a complete LOFW initiator. Although the viability of a feed-and-bleed operation has been determined for four specific plants, the NRC is desirous of identifying all plants for which feed and bleed can be applied successfully. Clearly, this is an ambitious undertaking. At least four approaches have been identified for meeting this objective. In order of increasing cost and effort they are (1) simple inspection, (2) enhanced inspection, (3) use of simplified plant specific models, and (4) use of detailed models for each plant. This first approach, simple inspection, applies to plants having characteristics similar to those for which detailed studies have been performed. Insights from the detailed studies are heavily weighted in the inspection process. Similar plants are assumed to perform in the same manner as the plants for which detailed calculations have been performed. Those plants judged too dissimilar are excluded from the process and no extension statements are made for those plants. This procedure is not difficult and requires little additional effort to complete. We have the least confidence in this approach of the four described.

The second procedure we call enhanced inspection. It contains all the elements of simple inspection but includes limited plant-specific calculations. The inspection process is enhanced by constructing plant specific feed-and-bleed operating maps[7]. However, we have determined that feed-and-bleed operating maps, although useful for enhancing understanding of the energy and mass relationships during transients for which detailed transient calculations have been prepared, are not useful as predictive tools[8]. Alternative approaches for enhancing the inspection process have not been identified.

The third approach uses all the inspection information but emphasizes the development and use of simplified plant-specific models that are inexpensive but still capture the dominant phenomena of feed and bleed. However, such models would still be manpower intensive and may require an extensive data base to ensure that the plants are properly modeled. The fourth approach is that taken for the four plant-specific studies conducted thus far. Detailed plant-specific models are developed and plant performance simulated using a detailed systems analysis code such as TRAC-PF1 to perform transient calcuiations. Although we have the most confidence in the results produced using this approach, the costs are prohibitive.

Within the time and funding constraints of the USI A-45 program, only the first two approaches were investigated. As previously discussed, the techniques that we had identified for enhanced inspection were inadequate. Therefore, we relied on simple inspection for our extension statements. While realizing the inherent limitations of this method, we believe that the resultant extension statements adequately characterize the ability of given plants to successfully feed and bleed. The process of extension from our insights about plants for which we performed detailed calculations to a broader class of plants is illustrated in Table 1.

We have selected six CE plants for our example: Arkansas Nuclear One-2, Calvert Cliffs-1 and 2, Fort Calhoun-1, St. Lucie-1, and Maine Yankee. Calvert Cliffs-1 is the reference plant for which detailed calculations have been performed. Calvert Cliffs-2 is nearly identical to Calvert Cliffs-1 and so by simple inspection will perform similarly during feed and bleed. Arkansas Nuclear One-2 is not equipped with PORVs; however, it does have a vent valve. We were unable to determine the vent valve relief capacity. Therefore we make not extension statements for this plant. Fort Calhoun-1 has a core thermal rating slightly over half the Calvert Cliffs-1 value. The PORV relief capacity/MWt is greater than Calvert Cliffs-1, the shutoff head is higher, the HPI delivery rate is greater, and the charging delivery rate is also larger. Because Fort Calhoun-1 either meets or exceeds the Calvert Cliffs-1 parameters identified as important to feed and bleed, we state by simple inspection that feed and bleed will also be successful under similar circumstances, e.g., if initiated no later than the loss-of-secondary heat sink. St. Lucie-1 is also similar to Calvert Cliffs-1 and so by simple inspection will perform similarly during feed and bleed. The last plant in Table I, Maine Yankee, is quite different from the reference plant. In fact, this plant more closely resembles W and B&W plants that have high-pressure SI systems. Although not evidenced in Table I, a comparison of Maine Yankee with such plants leads us to state by simple inspection that Maine Yankee can feed and bleed successfully as late as the time of primary system saturation. In contrast, Calvert Cliffs-2, Fort Calhoun-1, and St. Lucie-1, like the Calvert Cliffs-1 reference plant, can feed and bleed successfully only if initiated no later than loss-of-secondary heat sink.

Summary results of our feed and bleed studies are presented in Table II. We have previously discussed the CE results. With the exception of Maine Yankee, we believe the listed CE plants can successfully feed and bleed if the procedure is initiated no later than loss-of-secondary heat sink. We believe that all the B&W plants listed can successfully feed and bleed as late as the time of primary system saturation. The W plants present a more complex picture because the number of loops vary and because there are HP, IP, and LP SI plants. In general, we have used the detailed calculations for Zion-1, a high-pressure SI plant, as the basis for extending to both four-loop and three-loop, HP SI plants. However, we feel less confident with the three-loop extension statements. The H. B. Robinson-2 analysis was performed to permit three types of extension statements: first, to other four-loop and three-loop LP SI plants, second, to increase our confidence in the three-loop, HP SI plant extension statements, and third, to permit us to make extension statements for W two-loop plants with both LP and HP SI systems. Again, we have less confidence in these statements because we have not performed a detailed analysis for a two loop plant. In addition, we do not feel confident in making extension statements for feed-and-bleed success at time of primary system saturation for any LP and IP SI plant.

5. CONCLUSIONS

As we begin our summary statements and conclusions, we wish to emphasize that our studies have assumed that the equipment used to effect a feed-and-bleed procedure is available and operable throughout the course of each transient studied. In the actual plants, this assumption may not be fulfilled. Therefore, we emphasize the need to examine each plant in detail to determine if the required equipment, instrumentation, and procedures are in place to permit the use of feed and bleed as an effective alternate if the normal cooling mode through the steam generators are unavailable. We have concluded the following about the feed-and-bleed procedure.

1. Feed and bleed is a potentially useful alternative method of decay heat removal in PWRs following the loss of normal cooling mode through the steam generators. The method relies on the existence of primary-system PORVs to provide a pathway for the release of core decay heat and sufficient SI capacity to deliver coolant to the primary.

2. The availability of high-pressure SI delivery capacity greatly enhances the reliability of the feed-and-bleed operation. Plants with only low-pressure or intermediate-pressure SI systems must initiate feed and bleed no later than the loss-of-secondary heat sink. Plants with high-pressure SI systems can successfully use feed and bleed until the time of primary system saturation.

3. PORV capacity becomes important during the transition from reactor trip to either RHR or LPI entry conditions if only safety-grade water supplies are considered. Plants with a single, small PORV depressurize slower than plants with two larger PORVs. Safety-grade water supplies may be consumed before RHR or LPI entry conditions are reached.

4. Simple inspection is a useful technique for extending the limited set of detailed plant-specific calculations to a broader set of plants. However, we are less confident in the accuracy of our conclusions reached by simple inspection than those based on detailed plant-specific calculations.

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TABLE I

EXAMPLE OF SIMPLE INSPECTION PROCESS FOR C-E PLANTS
(Data from Ref. [9])

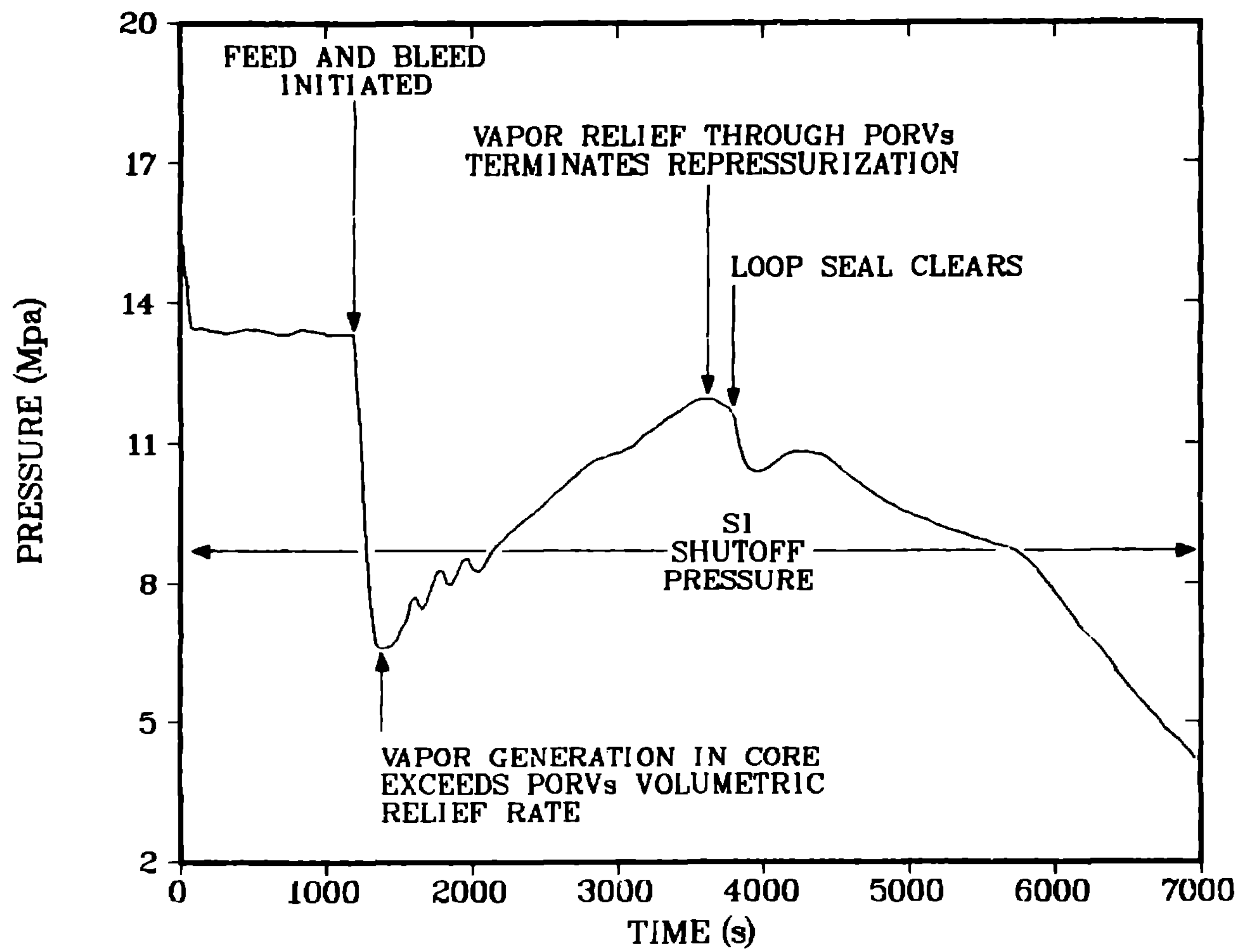
	Arkansas Nuclear One-2	Calvert Cliffs-1, -2	Fort Calhoun-1	St. Lucie-1	Maine Yankee
PORV Capacity (LB/HR/MWT)	Vent Valve[10] (Capacity Unknown)	56.7	69.7	[illegible]9.8	57.0
HPI					
•Shutoff Head (PSI)	1517	1257	1387	1257	2471
•GPM/MWT at 1000 PSIG	0.18	0.16	0.19	0.17	0.27
•GPM/MWT at 1600 PSIG	0	0	0	0	0.21
Charging Capacity (GPM/MWT)	0.05	0.05	0.08	0.05	0.17

TABLE 11

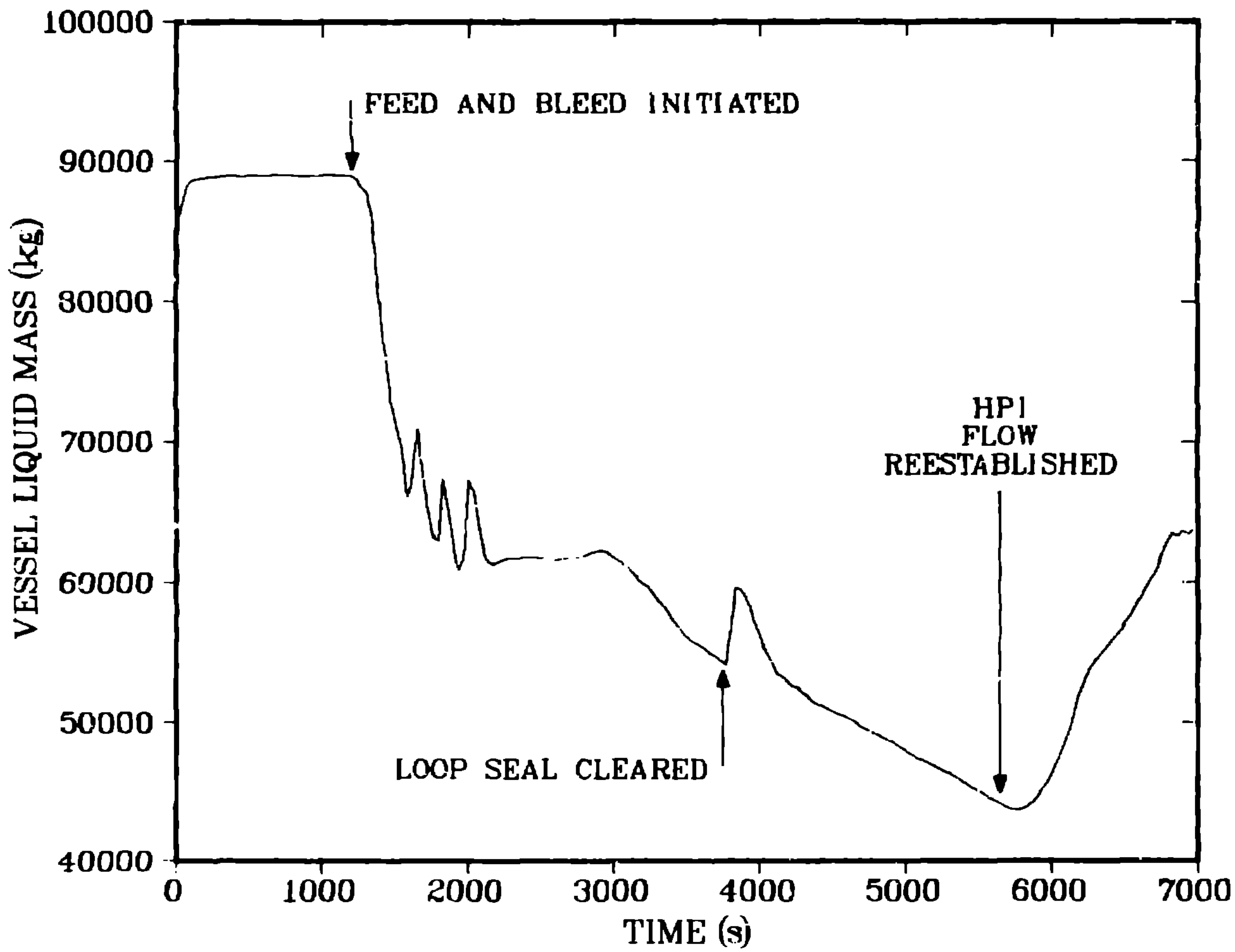
SUMMARY RESULTS

VENDOR	PLANT TYPE		CALCULATION	EXTENSION	LOSHS	SATURATION
C-E	2 × 4 loop LP	SI	Calvert Cliffs-1	Calvert Cliffs-2	Y	N
				Fort Calhoun-1	Y	N
				Maine Yankee	Y	Y
				Millstone-2	Y	N
				Palisades	Y	N
				St. Lucie-1	Y	N
				Ark. Nuclear One-2	NC	NC
B&W	2 × 4 loop HP	SI	Oconee-1	Oconee-2,-3	Y	Y
				Ark. Nuclear One-1	Y	Y
				Crystal River-3	Y	Y
				Three Mile Island-1,2	Y	Y
				Rancho Seco	Y	Y
W	4-loop HP	SI	Zion-1	Zion-2	Y	Y
				DC Cook-1,-2	Y	Y
				Trojan	Y	Y
				Salem-1	Y	Y
				Haddam Neck	Y	Y
	4-loop IP	SI		South Texas-1,-2	Y	NC
	4-loop LP	SI		Indian Point-1,-2	Y	NC
	3-loop HP	SI		Summer	Y	Y
				Shearon Harris-1,-2	Y	Y
				Farley-1,-2	Y	Y
				Beaver Valley-1,-2	Y	Y
				North Anna-1,-2	Y	Y
				Surry-1,-2	Y	Y
	3-loop LP	SI	Robinson-2	Turkey Point-3,-4	Y	NC
	2-loop LP	SI		Prairie Island-1,-2	Y	NC
				Kewaunee	Y	NC
	2-loop LP	SI		Ginna	NC	NC
				Point Beach-1,-2	NC	NC

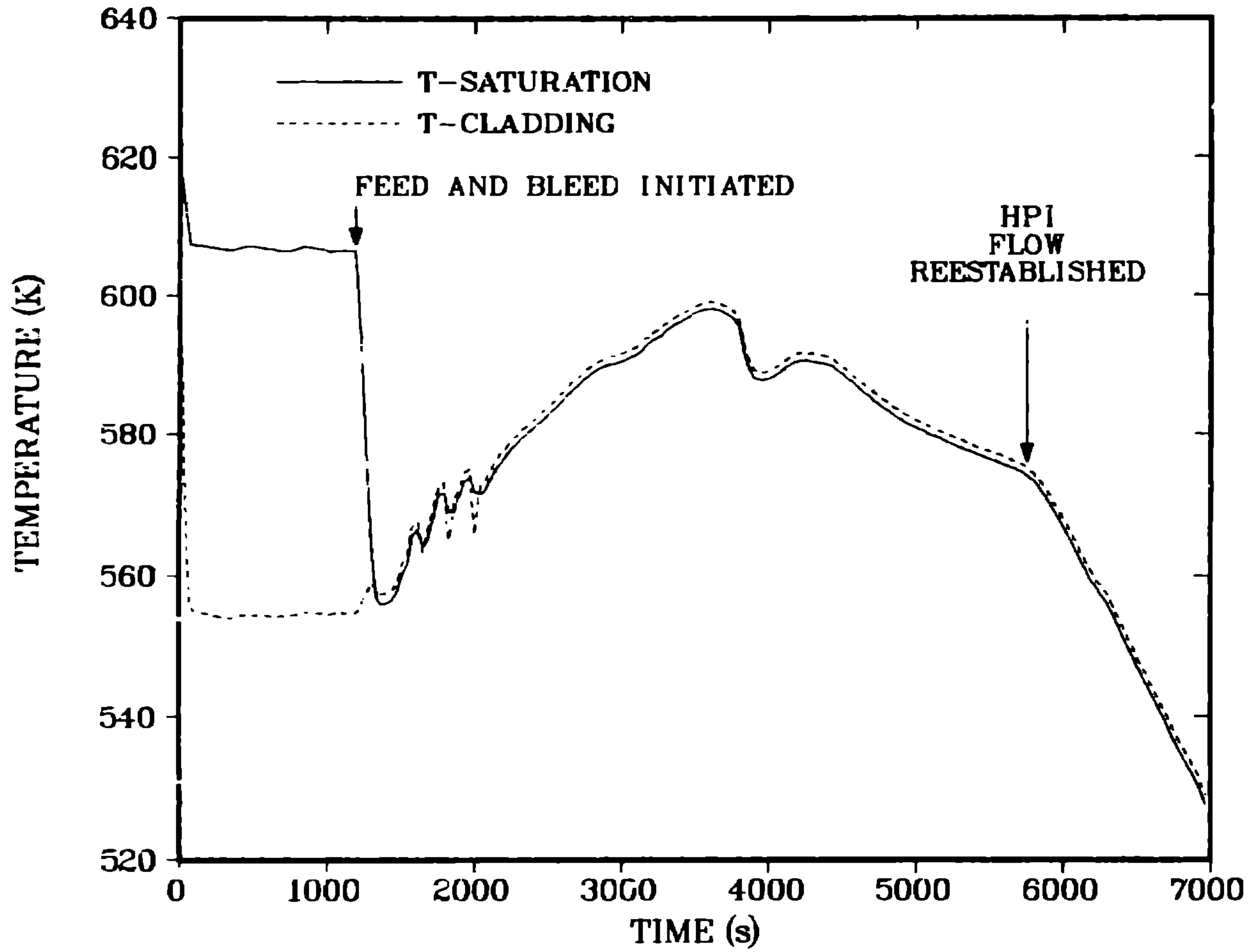
Y = Yes
N = No
NC = No conclusion
LOSHS = loss-of-secondary heat sink



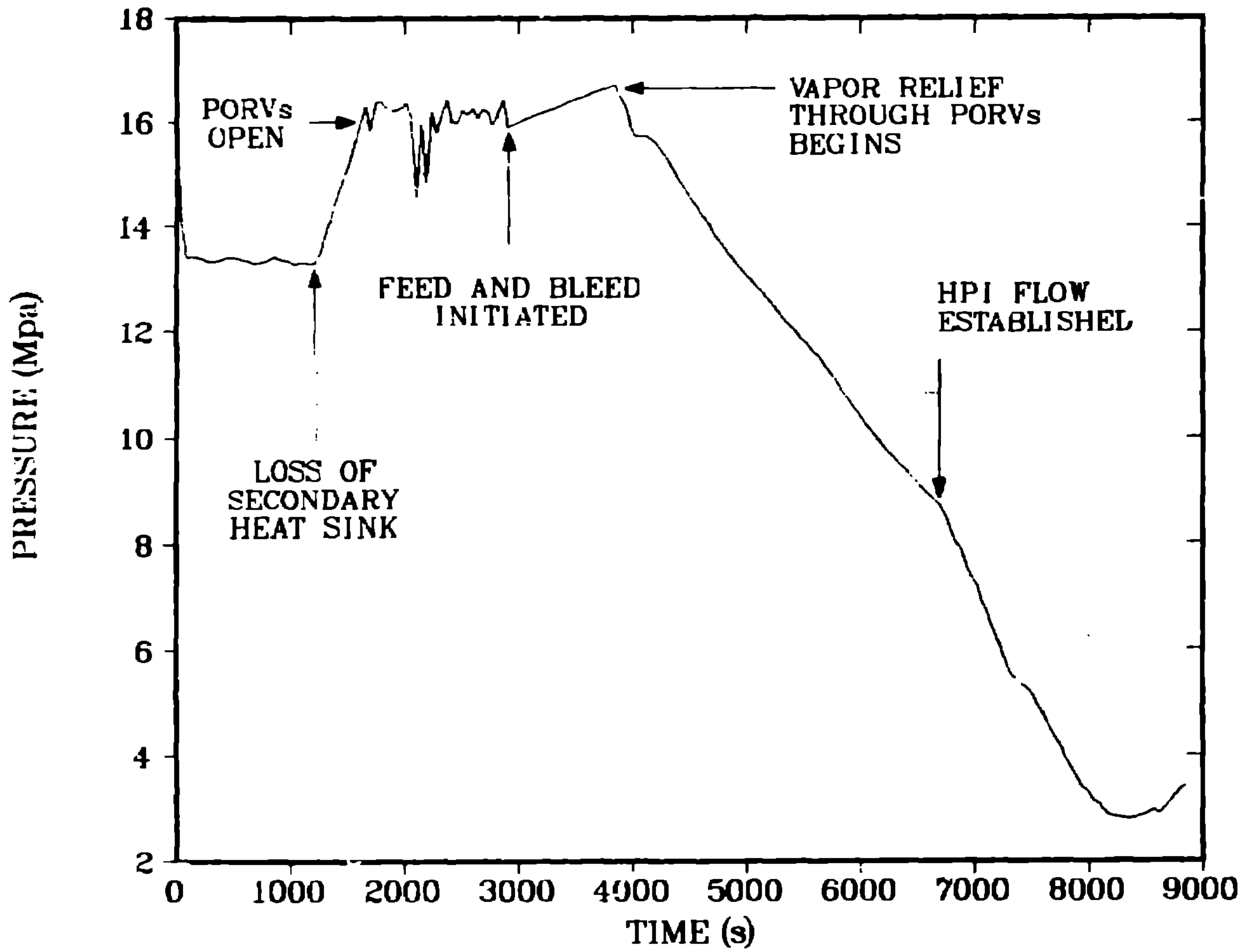
BOYACK,HENNINGER,LIME FIG.1



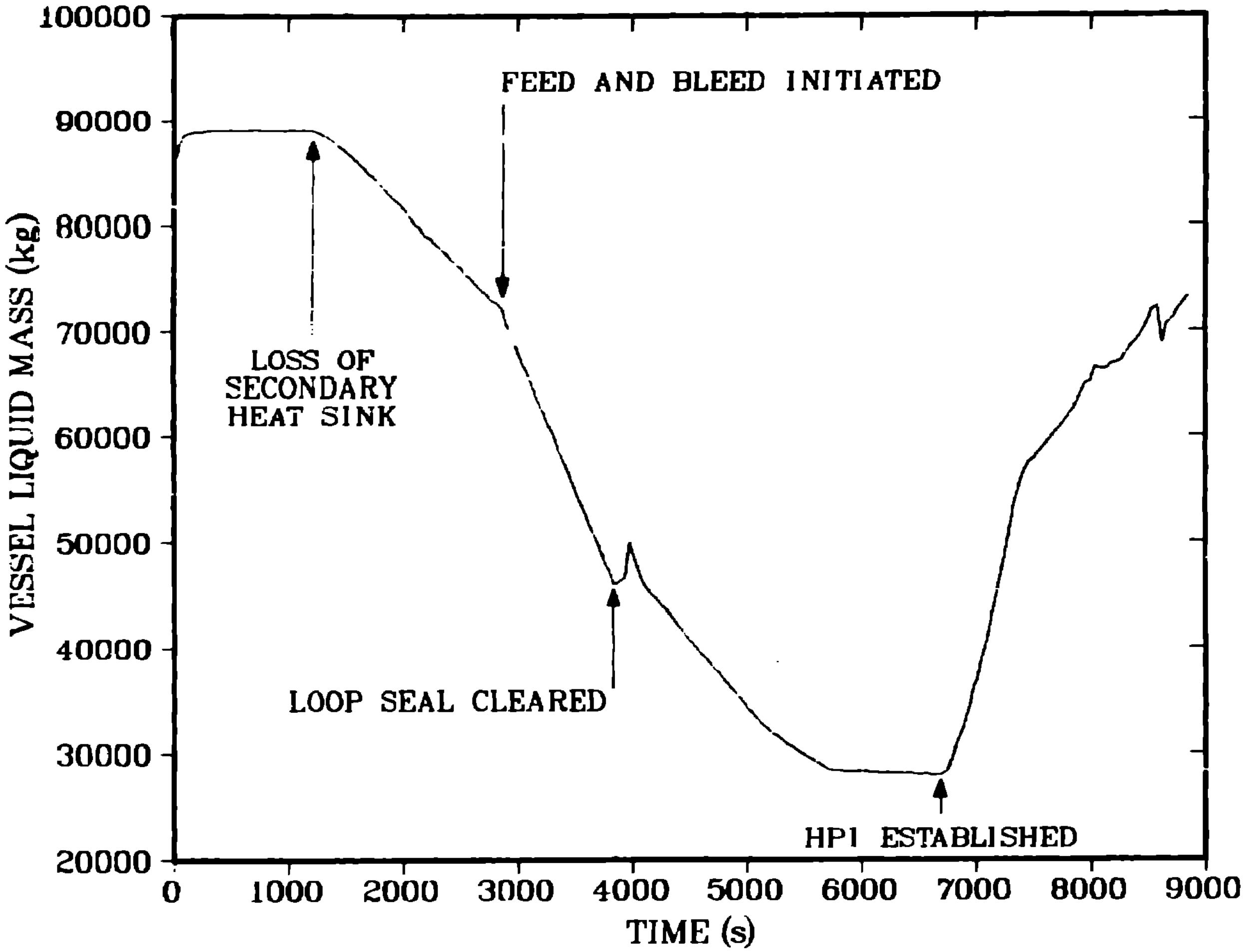
BOYACK,HENNINGER,LIME FIG.2



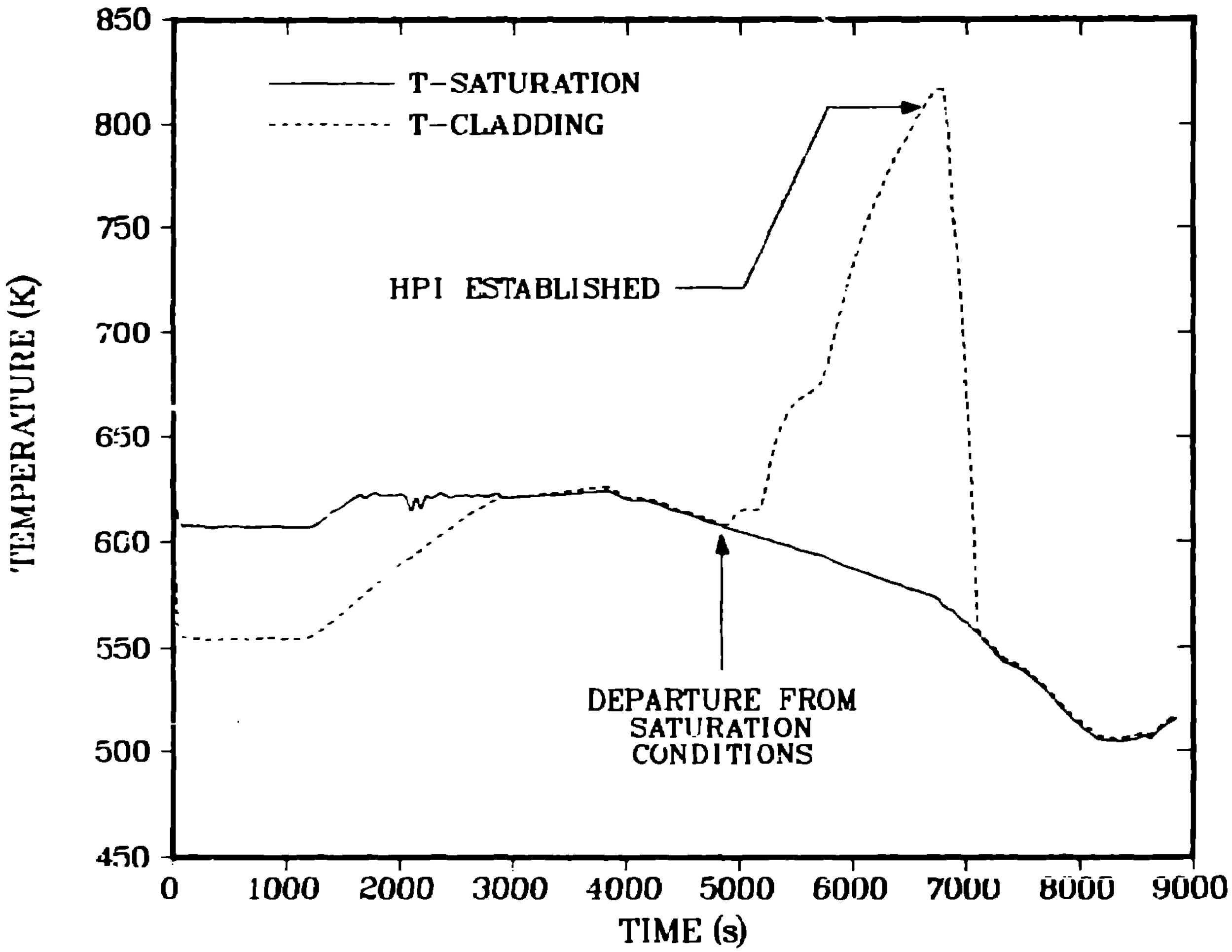
BOYACK,HENNINGER,LIME FIG.3



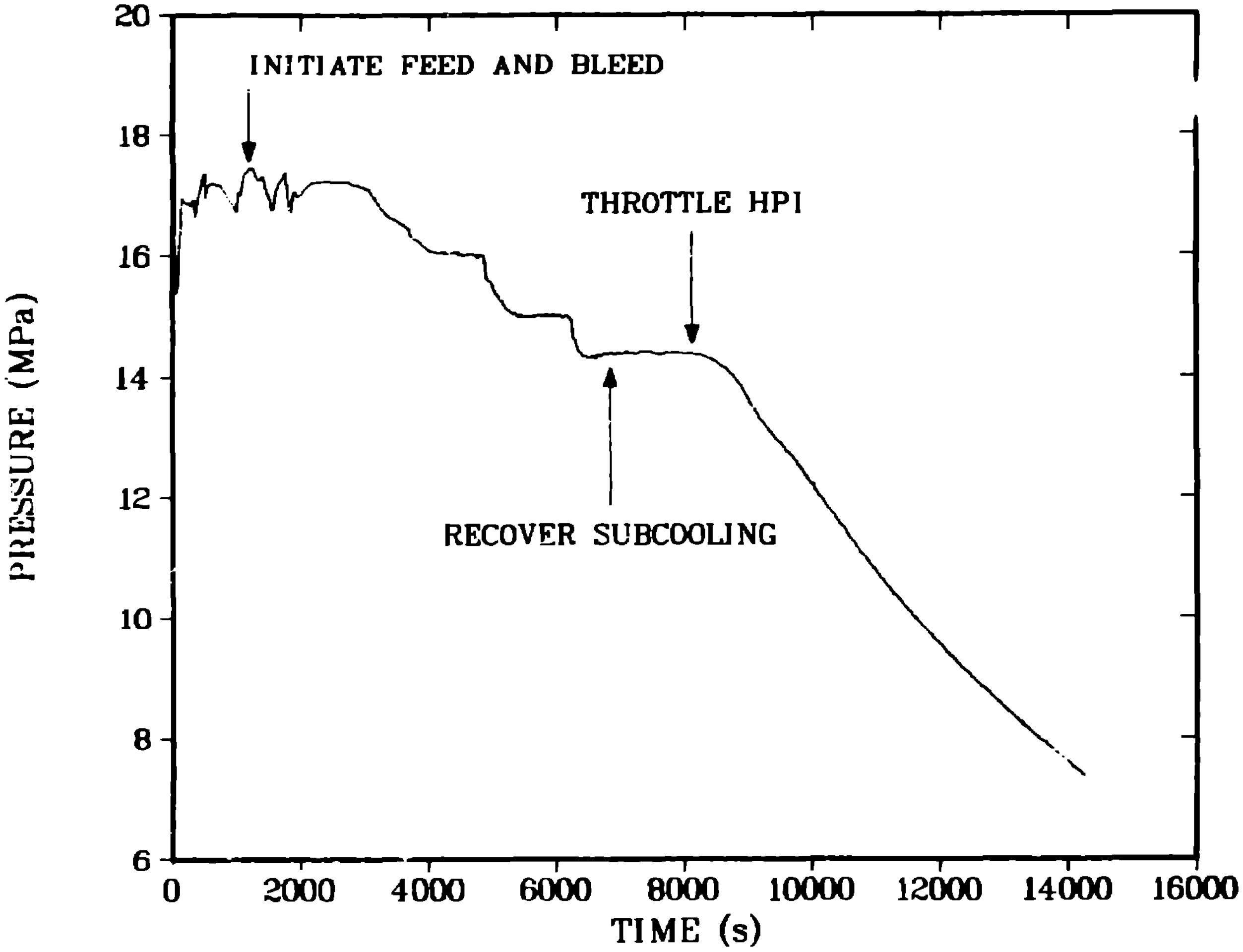
BOYACK,HENNINGER,LIME FIG.4



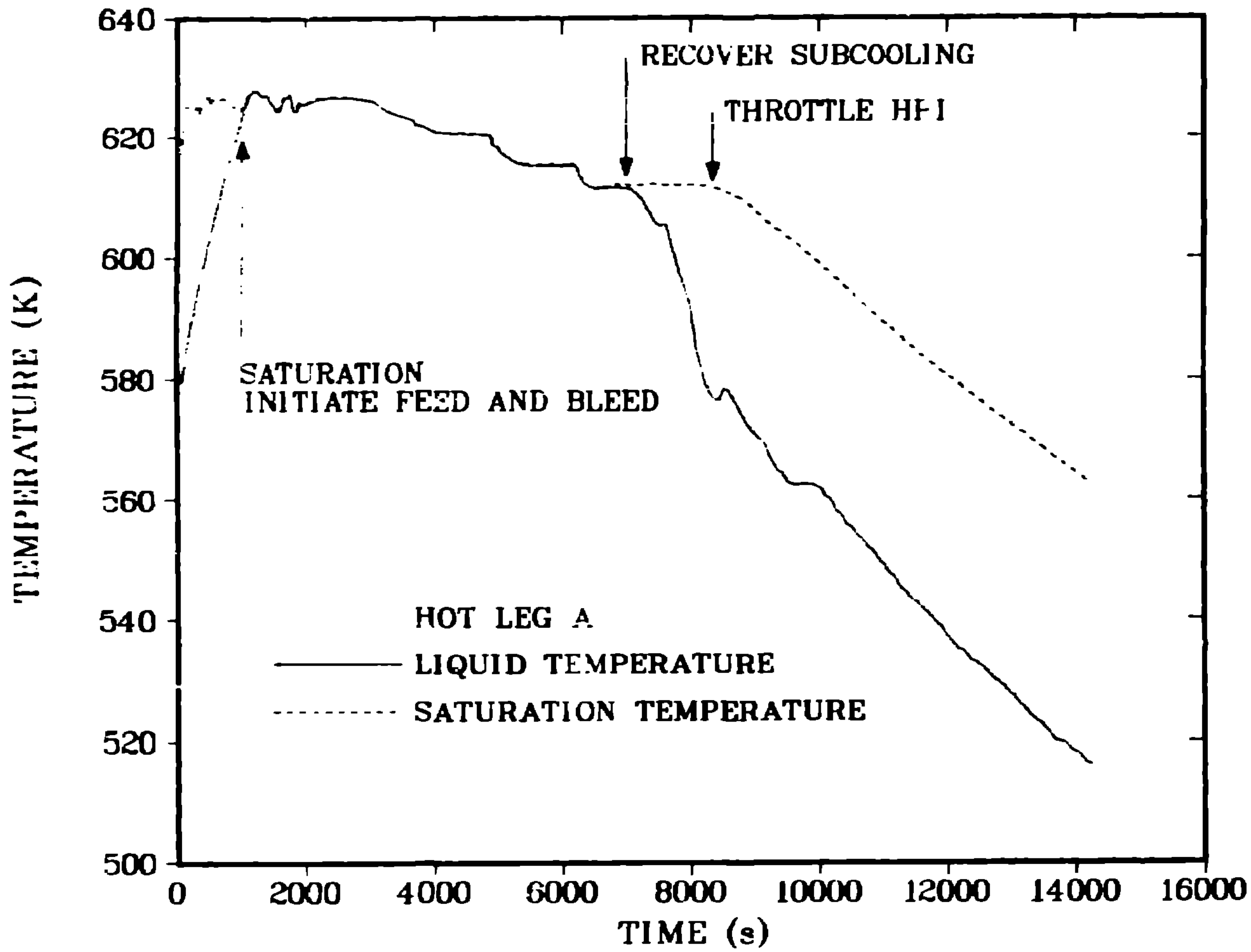
BOYACK,HENNINGER,LIME FIG.5



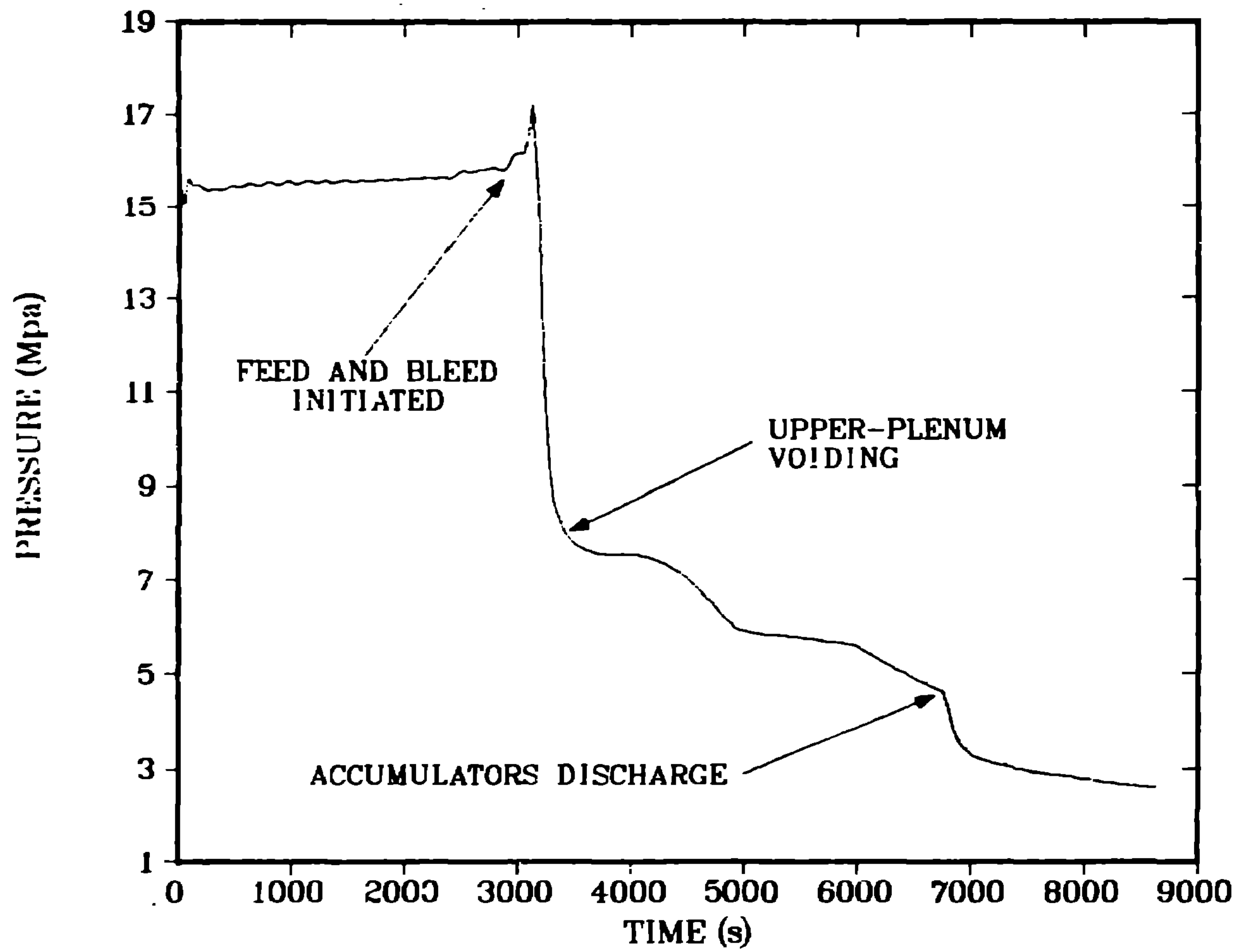
BOYACK,HENNINGER,LIME FIG.6



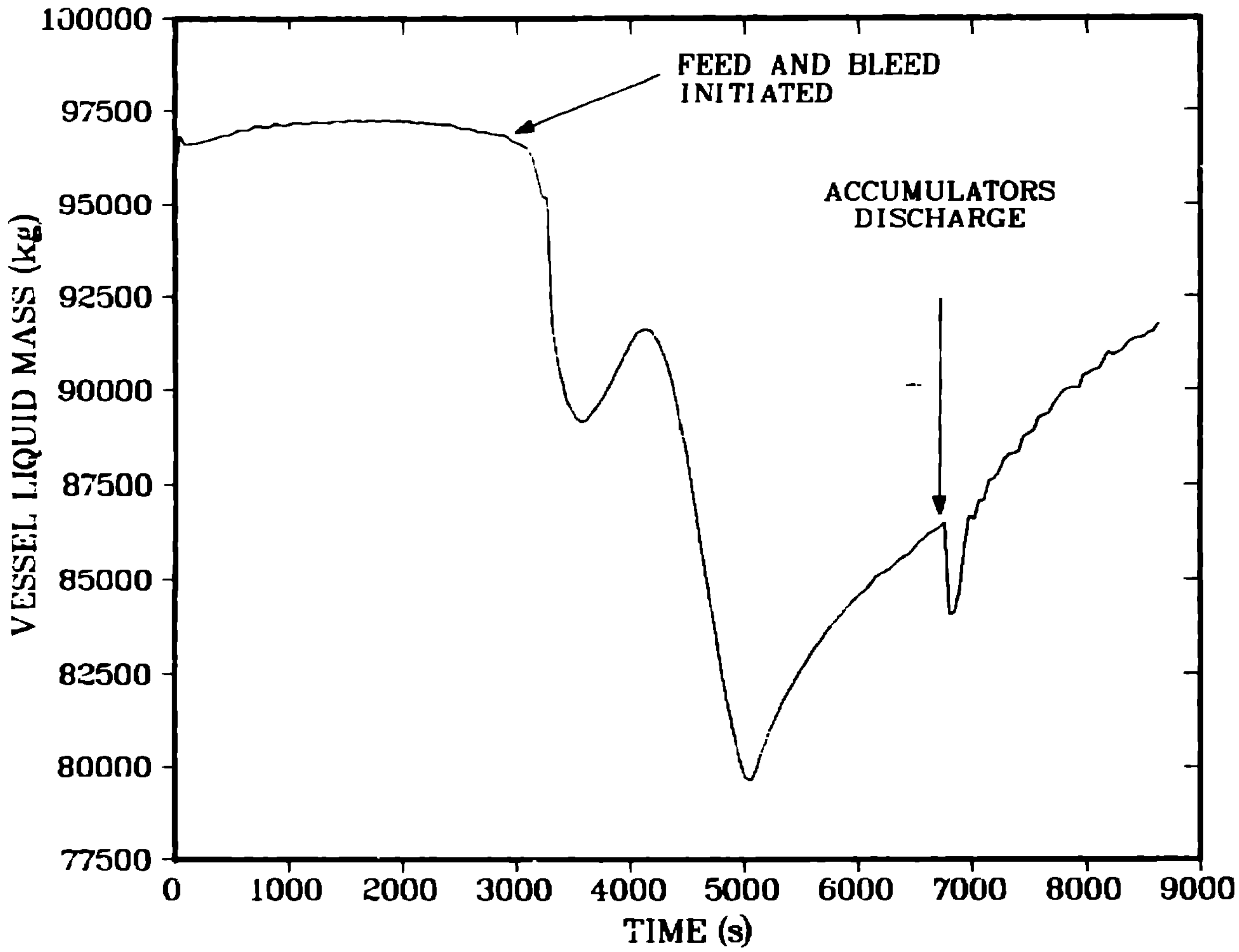
BOYACK,HENNINGER,LIME FIG.7



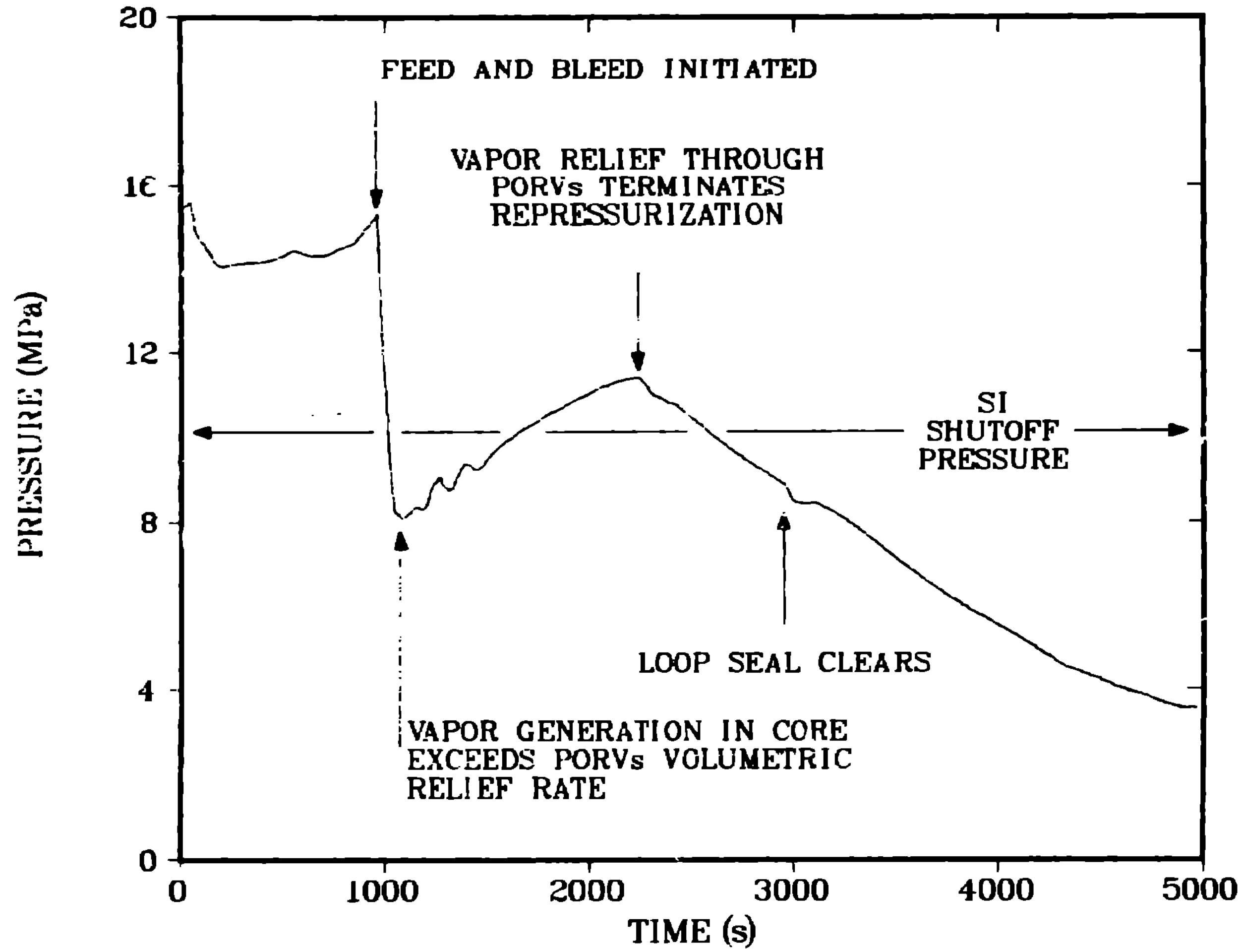
BOYACK,HENNINGER,LIME FIG.8



BOYACK,HENNINGER,LIME FIG.9



BOYACK,HENNINGER,LIME FIG.10



BOYACK,HENNINGER,LIME FIG.11