April 27, 1987

Docket Nos.: 50-390
and 50-391

Mr. S. A. White
Manager of Nuclear Power
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Chattanooga, Tennessee 37402-2801

SUBJECT: RESULTS OF THE DIABLO CANYON UNIT 1 NATURAL CIRCULATION, BORON MIXING, AND COOLDOWN TEST EVALUATION

Re: Watts Bar Nuclear Plant, Units 1 and 2.

Enclosed is a March 3, 1987 letter to Pacific Gas and Electric Company regarding the results of the staff's evaluation of the Diablo Canyon Unit 1 natural circulation, boron mixing, and cooldown test performed to demonstrate conformance with our Branch Technical Position RSB 5-1, "Design Requirements of Residual Heat Removal Systems."

As stated in the Watts Bar Safety Evaluation Report (SER, NUREG-0847, June 1982, Section 5.4.3), TVA committed to demonstrate the ability of the Watts Bar Nuclear Plant to cool down and depressurize the facility, and to demonstrate that boron mixing is sufficient during natural circulation using the results of the Diablo Canyon test. Note that differences between Diablo Canyon and Watts Bar must be discussed in your analysis, along with an analysis of the effect of these differences upon the test results.

If you have any questions concerning this matter, contact Rajender Auluck, Project Manager, at (301) 492-8337.

Sincerely,

Original signed by:

John A. Zwolinski, Assistant Director
for Projects
Division of TVA Projects
Office of Special Projects

Enclosure: Diablo Canyon letter

cc: See next page

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ENCLOSURE

UNITED STATES
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March 3, 1987

Docket Nos. 50-275
and 50-323

Mr. J. D. Shiffer, Vice President
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c/o Nuclear Power Generation, Licensing
Pacific Gas and Electric Company
77 Beale Street, Room 1451
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Dear Mr. Shiffer:

SUBJECT: DIABLO CANYON CONFORMANCE WITH BRANCH TECHNICAL POSITION RSB 5-1 REGARDING NATURAL CIRCULATION, BORON MIXING, AND COOLDOWN

We have completed our review and evaluation of the Diablo Canyon Unit 1 natural circulation, boron mixing, and cooldown test as described in WCAP-11095 (Non-Proprietary) and WCAP-11096 (Proprietary) reports transmitted to us by your letter dated March 25, 1986. We were assisted in our effort by our consultant, Brookhaven National Laboratory (BNL), who performed a simulation of the test utilizing only safety grade equipment. Our evaluation is enclosed, including as an enclosure the BNL report.

As a result of our evaluation and the BNL evaluation we conclude that the basic objectives of the test performed at Unit 1 have been met. We further conclude, that the test can be applied to Unit 2 and that both units meet the intent of our Branch Technical Position RSB 5-1, "Design Requirements of Residual Heat Removal System" for Class 2 plants. The evaluation of this matter is, therefore, complete.

It is our understanding that other Westinghouse plants will rely on the Diablo Canyon test and will reference it regarding RSB 5-1. As stated in our evaluation, because of certain differences between the Diablo Canyon units and other facilities, further information will be required from utilities for those facilities in order to justify application of the Diablo Canyon test to their plants. We have informed Westinghouse and the Westinghouse Owners Group of this position.

Sincerely,

Hans Schierling

Hans Schierling, Senior Project Manager
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Enclosure:
As stated

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8703090344 3 pp.

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ENCLOSURE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
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SAFETY EVALUATION REPORT
DIABLO CANYON UNIT 1
NATURAL CIRCULATION, BORON MIXING, AND COOLDOWN TEST
DOCKET NO. 50-275

INTRODUCTION

As part of the seismic evaluation of the postulated Hosgri earthquake in 1978, the licensee committed in the Hosgri Report to perform a natural circulation, boron mixing, and cooldown test (Reference 1). Appendix J to the Hosgri Report provides the scenario and identification of systems and components that would be utilized for natural circulation cooldown to cold shutdown conditions following the postulated SSE. The staff addressed the test in Section 3.2.1 of its Safety Evaluation Report Supplement No. 7 in 1978 (Reference 2). The licensee conducted the test in March 1985 and provided the evaluation and results in a report (proprietary and non-proprietary version) by letter dated March 25, 1986 (Reference 3). The NRC staff has reviewed the report and was assisted in this effort by its consultant, Brookhaven National Laboratory (BNL). NRC staff and BNL met with the licensee and Westinghouse, its consultant, on November 21, 1986 to discuss the preliminary BNL evaluation (Reference 4).

This is the staff's evaluation of the test. The BNL evaluation and results of their studies are included in this evaluation as Enclosure 1.

Branch Technical Position RSB 5-1, "Design Requirements of the Residual Heat Removal (RHR) System", states that test programs for PWRs:

> "shall include tests with supporting analysis to (a) confirm that adequate mixing of borated water added prior to or during cooldown can be achieved under natural circulation conditions and permit estimation of the times required to achieve such mixing, and (b) confirm that the cooldown under natural circulation conditions can be achieved within the limits specified in the emergency operating procedures. Comparison with performance of previously tested plants of similar design may be substituted for these tests."

Therefore, as stated above, the licensee committed to perform a natural circulation, boron mixing, and cooldown test at Diablo Canyon Unit 1.

OBJECTIVES

The objectives of the test were to establish natural circulation conditions using core decay heat, confirm that adequate mixing of borated water added to the reactor coolant system (RCS) prior to cooldown can be achieved under natural circulation conditions, verify that the RCS can be borated to the cold shutdown concentration, maintain hot standby conditions under natural circulation

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conditions for at least 4 hours, determine if cooldown and depressurization of the RCS from normal hot standby to cold shutdown conditions can be accomplished using only safety-grade equipment, obtain reactor vessel head cooldown rates, and verify that adequate water volume is available in the condensate storage tank to cool down the unit.

The acceptance criteria as stated in the test report (Reference 3) was as follows:

(1) The natural circulation evaluation was to verify that RCS natural circulation flow could be established, thereby permitting boron mixing and RCS cooldown/depressurization to RHR system initiation conditions.

(2) The boron mixing evaluation was to demonstrate adequate boron mixing under natural circulation conditions when highly borated water at low temperatures and low flow rates (relative to RCS temperature and flow rate) is injected into the RCS, and to evaluate the time delay associated with boron mixing under these conditions. The acceptance criterion for this phase of the test was that the RCS hot legs (Loops 1 and 4) indicate that the active portions of the RCS were borated such that the boron concentration had increased by 250 ppm or more.

(3) The acceptance criteria for the cooldown portion of the test were to control plant cooldown under natural circulation conditions to be within Technical Specification limits, maintain temperature of all active portions of the RCS uniformly within ±100°F of the core average exit thermocouple temperature, maintain the temperature of the steam generators and reactor vessel upper head to < 450°F when the core average exit thermocouple temperature is 350°F, and assure that the RHR system is capable of cooling down the RCS to cold shutdown conditions.

(4) The acceptance criterion for the upper head bulk water temperature was that a 50°F subcooling margin be maintained during cooldown and depressurization. A 100°F difference between the core average exit temperature and the upper head bulk water temperature was imposed as an administrative limit.

(5) The acceptance criterion for the depressurization portion of the test was that RCS pressure be reduced below RHR system initiation pressure (390 psig).

TEST

The test was performed at Diablo Canyon Nuclear Power Plant, Unit 1 on March 28 and 29, 1985. The reactor was tripped from 100% power and the plant maintained at hot standby. The reactor coolant pumps (RCPs) were operated for the first 3 hours and then tripped. Natural circulation flow was verified and the boron mixing part of the test was then initiated by injecting the contents of the boron injection tank (BIT). The system was maintained at hot standby under natural circulation conditions for approximately 4 hours. Cooldown at a rate of 20°F per hour was initiated using the atmospheric steam dumps (ASDs). The

RCS was then depressurized to RHR initiation conditions. The time for the combined cooldown/depressurization steps was about 13 hours. The RCS was then brought to a cold shutdown condition in about 4 1/2 hours utilizing the RHR system. A test chronology is included in Enclosure 1. The acceptance criteria for the test were met. The test was witnessed by NRC personnel.

It is noted that some non-safety grade systems and components were utilized during the test. These included the letdown system, 3 control rod drive mechanism (CRDM) fans, pressurizer heaters and volume control tank (VCT). The use of the CRDM fans was required to maintain the CRDM temperatures within acceptable limits. However, in the event of loss of offsite power (LOOP) because of the SSE or for other reasons, the fans would not be available during the cooldown. This has a major impact on upper head cooling. The letdown system was used to prevent overfilling the pressurizer since RCP seal injection was maintained during the test. The safety-grade reactor vessel head vent could have been used as an alternate means of letdown but its use could have entailed potential discharge of reactor coolant to the containment. Contraction of the coolant volume during plant cooldown would also tend to mitigate the effects of seal injection. The safety grade refueling water storage tank (RWST) could have been used as an alternate to the VCT but the RWST contains high levels of dissolved oxygen and its use could have resulted in exceeding technical specification oxygen concentration limits which in turn could have resulted in excessive localized corrosion and consequent increased radiation exposures to plant workers.

EVALUATION

In the event of an SSE, the operator would not have normal system capability for RCS pressure control. Pressure reduction could be achieved by the seismically qualified PORVs or, within thermal stress limits, by the auxiliary pressurizer spray. The pressurizer heaters are not seismically qualified, but two of the four heater groups can be manually powered from vital buses. The charging pumps could probably be used to maintain or increase pressure, but this could result in pressurizer overfill. With regard to the delay in tripping the RCPs the licensee stated that this would ensure a more stable condition so that the test could be properly conducted. The delay in the RCP trip allowed RCS temperature to become more uniform, including some reduction in the upper head temperature. The delay also reduced the level of decay heat somewhat. As noted in Enclosure 1, this slightly reduced the natural circulation flow and increased the boron mixing time. It also allowed the upper head temperature to become more uniform.

The Diablo Canyon Plant emergency operating procedures (EOPs) are based on the Westinghouse Owners Group Emergency Response Guidelines (ERGs), which assume the use of normal operation systems. Reference 3 identifies the systems that would be normally used for natural circulation cooldown. It also identifies alternate seismically qualified systems that could be utilized in the event the normal systems are incapacitated, and demonstrates how the necessary functions would be achieved. The effect of CRDM fan unavailability is discussed below. In Reference 3, the licensee also committed to develop alternative operational strategies to provide the operational guidance and technical basis to demonstrate that the Diablo Canyon plant can be taken from normal operating conditions to cold shutdown using only seismically qualified systems.

In support of the staff evaluation of the Diablo Canyon Unit 1 test, the staff consultant Brookhaven National Laboratory (BNL) performed test simulation analyses as reported in a Technical Evaluation Report (TER), included as Enclosure 1. The RELAP5/MOD1 code was utilized. The sequence of events assumed by BNL in the analysis differed somewhat from the test. As noted in Enclosure 1, the purpose of the BNL analysis was not to duplicate the test but to provide the information necessary to assess the impact of the use of non-safety grade equipment during the test. Reasonably good agreement between the test data and analytical results were obtained for RCS natural circulation flow and temperature. Since the BNL analysis did not assume utilization of the pressurizer heaters and the letdown system, it is difficult to compare RCS pressure test data and analytical results.

The largest difference between the test and analytical results were obtained for reactor upper vessel head cooling time. The CRDM fans were operated during the entire test, except for a 2 hour period. The use of the CRDM fans provided adequate cooldown of the upper head. The maximum temperature differential between the RCS and upper head temperature was 40°F. However, the CRDM fans are not safety grade. Since the Diablo Canyon Plant is a T-HOT plant, the upper head temperature is near the RCS hog leg temperature during normal operation because the bypass flow rate between the upper downcomer and the upper head is relatively low. As noted in Reference 5, for T-HOT plants without CRDM fan operation, a waiting period (soak time) is required before the RCS is depressurized to RHR entry conditions. This period is 8 hours for top hat upper support plate plants, which include the Diablo Canyon Plant. The BNL calculations, on the other hand, indicate a required waiting period of about 35 hours. These calculations were done conservatively by dividing the upper head into 4 heat conduction nodes, with the upper head fluid assumed completely stagnant. Conduction was the only mechanism assumed for cooldown, the heat loss from the dome to the containment environment was ignored, and the bypass fluid mixed only with the fluid in the bottom of the upper head. During the test all CRDM fans were turned off for about 100 minutes. The average upper head cooldown rate was estimated to be approximately 6°F per hour, which translates into about a 25 hour hold period. However, the time period for the test without CRDM fans was too short to be conclusive.

Reference 3 states that 126,000 gallons of water from the condensate storage tank (CST) was used as auxiliary feedwater (AFW) makeup for plant cooldown. However, with the CRDM fans unavailable, the BNL calculations conservatively result in a 360,000 gallon secondary water makeup requirement. The Diablo Canyon CST has a volume of 400,000 gallons, of which 178,000 gallons are dedicated for AFWS supply. Additionally, 270,000 gallons of water are maintained in the fire water storage tank for AFWS supply. As stated in the FSAR (Reference 6) the fire water storage tank and the piping between it and the CST are Seismic Category I. The staff concludes that for the Diablo Canyon Plant a sufficient assured water supply is available for plant cooldown via the steam generators even when the CRDM fans are not available.

CONCLUSIONS

Based on the Diablo Canyon Unit 1 test results (Reference 3) and their analyses reported in Enclosure 1, BNL concluded that:

1) The Diablo Canyon Unit 1 test demonstrated that adequate natural circulation was established and the plant was capable of removing the decay heat by natural circulation using only safety-grade equipment.

2) Adequate boron mixing was achieved during natural circulation in the main flow path of the RCS using only safety-grade equipment.

3) The effect of relatively unborated water entering the RCS from the upper head and pressurizer appears to be minimal as long as depressurization is conducted carefully to limit the size of possible void formation.

4) The pressure would rise and reach the PORV actuation pressure without letdown during the boron mixing period.

5) The test adequately demonstrated that the RCS can be cooled to the RHR system initiation temperature while maintaining adequate subcooling during natural circulation using only safety-grade equipment.

6) The test demonstrated that the upper head could be cooled without void formation when the CRDM fans were in operation.

7) The tests results indicate that the upper head cooldown rate without the CRDM fans is about 6°F per hour. This is higher than the conservative BNL calculation based only on conduction heat loss, which estimated a minimum rate of 3°F per hour.

8) The RCS pressure should be maintained about 1200 psia by means of either the pressurizer heaters (if available) or charging during the cooldown period to prevent upper head voiding when the CRDM fans are not in operation.

9) A sufficient supply of safety grade cooling water was available to support the proposed plant cooldown method even if the CRDM fans were not available for the Diablo Canyon Plant.

10) Only one motor-driven AFW pump was sufficient to supply the necessary cooling water throughout the transient.

11) Sufficient ASD valve capacity was available to support the cooldown even when the cooldown rate was assumed to be 50°F per hour.

12) The availability of the pressurizer heaters and letdown system, while not essential, would affect the operational procedures in a major way. The strategy to reduce the upper head cooling time by intentionally forming a void may be difficult to perform without pressurizer heaters.

13) The RCS pressure would increase and stay high, and the PORV may be actuated periodically if the letdown system were not available, due to boron injection and the continuous injection of RCP seal flow. The operation of the auxiliary pressurizer spray normally requires letdown to be in operation to prevent possible thermal stress on the spray nozzle.

References 1 and 3 contain single failure analyses demonstrating redundancy of safety grade systems that would be utilized following a seismic event. BNL has independently verified that adequate cooldown could be accomplished with failure of one AFW pump or ASD. The Diablo Canyon Plant design provides a single RHR drop line with two inlet isolation valves in series. In response to a staff request to provide justification that the probability of mechanical failure of either of the two valves is sufficiently low as to not merit consideration as a single failure, the licensee stated that the combined probability of valve stem failure coincident with the SSE is on the order of 10^{-7} per year (Reference 4). The licensee has also indicated that failure of a power train or valve operator could be mitigated by local operator action (Reference 1).

The staff concludes, therefore, that based upon the licensee's submittals and the BNL analysis, the Diablo Canyon Unit 1 natural circulation, boron mixing and cooldown test adequately demonstrates that the Diablo Canyon Plant systems meet the intent of BTP PSB 5-1 for a class 2 plant.

APPLICABILITY TO OTHER PLANTS

The Diablo Canyon Unit 1 test has been referenced by a number of near-term-operating-license (NTOL) plants and recently licensed Westinghouse plants. Several of these plants have a limited safety grade supply for the AFW system. Also, some plants have different design upper vessel heads which contain much larger volumes of relatively stagnant water. It is, therefore, appropriate to perform more realistic calculations for upper head cooldown with only safety grade systems, in order to provide assurance that each plant in this category has a sufficient volume of safety grade water supply. The staff has, therefore, requested additional information from Westinghouse with regard to the upper head mixing phenomena, convection heat losses, and other pertinent items (Reference 7). If adequate information on these subjects is obtained, BNL could reanalyze upper head cooling in order to obtain more realistic cooldown times. The results of such reanalysis would be documented appropriately. While the staff considers natural circulation cooldown without voids as more desirable, cooldown with voids may be acceptable provided it can be accomplished using only safety grade equipment (including adequate instrumentation), approved procedures, and the operators have adequate training in the use of these procedures. If the use of safety grade head vents is contemplated in order to vent the steam in the upper head and/or enhance upper head mixing, due consideration should be given to the effect of this operation on the integrity of the pressurizer relief tank and the effect of loss of its integrity.

It is the intent of a number of recent licensees and NTOLs to reference the Diablo Canyon Unit 1 test to demonstrate conformance with the testing requirements of BTP RSB 5-1. The staff requires that licensees/applicants referencing the Diablo Canyon Unit 1 test be able to demonstrate thermal and hydraulic similarity of their plants with the Diablo Canyon design. Each plant must also demonstrate that an adequate safety grade water supply is available for secondary makeup during natural circulation cooldown without offsite power. In addition Westinghouse should provide the details of its estimation for the upper head cooling time without the CRDM fans. The BNL analysis and the test data indicate that the cooling period should be substantially longer than the 8 hour hold period estimated by Westinghouse.

In order to facilitate the staff's evaluation of this matter, the BNL report, included as Enclosure 1, includes a sensitivity analysis which identifies plant parameters that may affect application of the test results to other Westinghouse plants, and provides estimates of the sensitivity of the results to these parameters. Table 5.1 of Enclosure 1 shows the sensitivity of the natural circulation flow to these parameters in terms of percent change in natural circulation flow to a 10% change from the Diablo Canyon Unit 1 parameter. However, it should be noted that the "Remark" column of this table is subjective and may vary from plant to plant.

PRINCIPAL CONTRIBUTOR:

R. Mann

REFERENCES

(1) PG&E Report "Seismic Evaluation For Postulated 7.5M Hosgri Earthquake, Units 1 & 2, Diablo Canyon Site", Appendix J "Systems/Equipment For Achieving & Maintaining Hot Standby & Cold Shutdown of Diablo Canyon Units 1 & 2 Following SSE", March 1978.

(2) U.S Nuclear Regulatory Commission, NUREG-0675, "Supplement No. 7 to the Safety Evaluation Report of the Diablo Canyon Nucler Power Station Units 1 and 2", May 1978.

(3) WCAP-11095 (Non-Proprietary), "Natural Circulation, Boron Mixing, and Cooldown Test - Final Post Test Report for Diablo Canyon Power Plant Units 1 and 2, March 1986", Letter DCL 86-078 from J. D. Shiffer (PG&E) to S. A. Varga (NRC) dated March 25, 1986.

WCAP-11096 (Proprietary) - same as above but proprietary

(4) "Meeting Summary - Natural Circulation, Boron Mixing, and Cooldown Test (November 21, 1986)", H. Schierling (NRC), dated December 9, 1986.

(5) Westinghouse Owners Group Emergency Response Guidelines, "Background Information for the Westinghouse Emergency Response Guidelines, ES-0.2, Natural Circulation Cooldown."

(6) Diablo Canyon FSAR Update, Revision 1, September 1985.

(7) "Request for Additional Information Needed to Evaluate Reactor Vessel Upper Head Cooling During Natural Circulation Cooldown", Letter from C. H. Berlinger (NRC) to D. Butterfield (WOG), January 15, 1987.

ENCLOSURES

1. "Technical Evaluation Report for Diablo Canyon Natural Circulation, Boron Mixing, and Cooldown Test", J. H. Jo, K. R. Perkins, and N. Cavlina, Brookhaven National Laboratory Technical Report A-3843, dated December 23, 1986.

ENCLOSURE

TECHNICAL REPORT
A-3843 12-23-86

TECHNICAL EVALUATION REPORT FOR DIABLO CANYON NATURAL CIRCULATION, BORON MIXING, AND COOLDOWN TEST

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Contract No. DE-AC02-76CH00016

TECHNICAL EVALUATION REPORT FOR DIABLO CANYON NATURAL CIRCULATION, BORON MIXING, AND COOLDOWN TEST

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December 1986

Prepared for
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Contract No. DE-AC02-76CH00016
FIN A-3843

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1. INTRODUCTION

While cooling down under natural circulation conditions on June 11, 1980, St. Lucie Unit 1 coolant flashing produced a void in the reactor vessel upper head and forced water into the pressurizer. The reactor was successfully brought to cold shutdown. Based on the NRC review of the event, a multi-plant action item (MPA B-66) was initiated which requires that all PWRs implement procedures and training programs to ensure the capability to deal with such events. In Generic Letter (GL) 81-21, dated May 5, 1981, the licensees were required to provide an assessment of their facility procedures and training program including:

1. a demonstration (e.g., analysis and/or test) that controlled natural circulation cooldown from operating conditions to cold shutdown conditions, conducted in according with plant procedures, would not result in reactor vessel voiding;

2. verification that supplies of "condensate-grade" auxiliary feedwater are sufficient to support plant cooldown methods. (Note: Branch Technical Position RSB 5-1 requires an adequate supply of auxiliary feedwater stored in safety grade systems.)

3. a description of plant training program and the provisions of emergency procedures (e.g., limited cooldown rate, response to rapid change in pressurizer level) that deal with prevention or mitigation of reactor vessel voiding.

It should be noted that at the time GL 81-21 was issued, procedures for natural circulation cooldown with upper head voids were not generally available. Since then, the Westinghouse Owners' Group has issued emergency response guidelines (ERGs) for natural circulation cooldown with voids. While the NRC staff considers natural circulation cooldown without voids as more desirable, cooldown with voids may be acceptable providing it can be accomplished using all safety grade equipment and approved procedures, and operators have adequate training in the use of these procedures.

Additional requirements for pre-operational testing are set forth in the Standard Review Plan under RSB Branch Technical Position (BTP) 5-1. This essentially requires that a Class 2 plant demonstrate that it can be brought from hot standby to cold shutdown under the natural circulation conditions using only systems and functions which are safety grade and with only onsite or offsite (not both) power available and assuming a single failure.

RSB BTP 5-1 also requires that PWR pre-operational and initial startup test programs shall include tests with supporting analyses to (a) confirm that adequate mixing of borated water added prior to or during cooldown can be achieved under natural circulation conditions and permit estimation of the times required to achieve such mixing, and (b) confirm that the cooldown under natural circulation conditions can be achieved within the limits specified in the emergency operating procedures. Comparison with performance of previously tested plants of similar design may be substituted for these tests.

In response to these requirements licensees and vendors have submitted both individual and generic responses to MPA B-66 and they have conducted several boron mixing and natural circulation tests at representative commercial plants. The objective of this project is to assist the NRC staff in evaluating data and supporting analyses obtained from the Boron Mixing and Natural Circulation Tests performed at San Onofre Unit 2, Diablo Canyon Unit 1, and Palo Verde Unit 1.

The present report is primarily concerned with evaluation of the data, analyses, and conclusions submitted by Westinghouse in WCAP-11086 "Diablo Canyon 1 Natural Circulation/Boron Mixing/Cooldown Test Final Post Test Report," in compliance with the design requirement of BTP RSB 5-1 for a Class 2 plant. The Diablo Canyon Power Plant is a 4-loop Westinghouse PWR. Separate reports will be issued for the comparison of the results of the test with the results of previous analyses performed by utilities in their responses to MPA Item B-66, "Natural Circulation Cooldown" for other Westinghouse plants, and for review of the emergency response guidelines for consistency with test findings. Similar reports will also be issued later for the evaluation of the natural circulation, boron mixing and cooldown tests performed at San Onofre

Unit 2 and Palo Verde for the CE Pre-System 80 and CE System 80 plants respectively.

Section 2 of the report summarizes the natural circulation, boron mixing and cooldown test performed at Diablo Canyon Power Plant. Section 3 describes the simulation of the test using the RELAP5/MOD1 Code to provide the analytical basis for the review of test. The nodalization, boundary conditions, assumptions used for the calculation, and its results are discussed. In Section 4, the test results are reviewed on the basis of the simulation results. The test is divided into four stages for review: natural circulation, boron mixing, cooldown and depressurization. Section 5 presents the sensitivity analysis performed to facilitate the application of the test results to other Westinghouse plants. Section 6 summarizes the conclusions and recommendations.

2. TEST DESCRIPTION

A natural circulation, boron mixing and cooldown test was conducted at Diablo Canyon Power Plant Unit 1 on March 28 and 29, 1985.

The test began by manually initiating a turbine trip from 100% power at 2130 hour on March 28. The reactor was shutdown and the plant was maintained in hot standby condition. In about three hours, the natural circulation portion of the test was initiated by manually tripping all RCPs. After verifying the natural circulation condition in about 20 minutes, the boron mixing portion of the test was initiated by injecting the contents of the Boron Injection Tank (BIT) into the RCS and was terminated in about 20 minutes. The flow rate into the reactor system was approximately 150 gpm. The system was maintained at hot standby under natural circulation conditions for more than four hours. The cooldown/depressurization portion of the test was commenced by isolating letdown and cooling down with the atmospheric steam dump (ASD) valves. The cooldown rate was controlled at approximately 20°F/hour. The cooldown/depressurization testing was continued for approximately thirteen hours until residual heat removal (RHR) initiation conditions (350°F, 400 psig) were achieved. The system was finally brought from RHR initiation conditions to cold shutdown conditions in the next four and a half hours by operating the RHR system. The detailed chronology of the significant events and major operator actions performed during the test is shown in Table 2.1.[1]

It is noted that some non-safety grade equipment and systems were used during the test because the operators of the plant did not want to risk damage to some of the equipment for the test. However, unavailability of these systems (in strict adherence to the requirements of RSB Technical Position 5-1) may have significant impact in the plant's performance under actual accident conditions. They were pressurizer heaters, letdown system, and control rod drive mechanism (CRDM) fans. The impact of the potential unavailability of these systems will be assessed in detail in Section 4.

Table 2.1 Chronology of Events and Operator Actions

TIME	EVENT/ACTION
HOT STANDBY (FORCED CIRCULATION)	
2130:	Plant operating at 100% power. Operators initiated the plant trip from 100% power by manually initiating a turbine trip.
2140:	Reactor was shut down and plant was in hot standby conditions. Operators were securing the plant secondary side. Relief valves on the #2 heaters had lifted. Operators were attempting to reseat the reliefs and waiting for the steam generator levels to return to 44% narrow range level.
2150:	Operators have begun their Class 1 equipment alignment per Test Procedure 42.7.
2230:	Operators have attempted to relatch the main turbine to minimize steam leakage on the secondary side.
2300:	Steam generator levels were at 44% narrow range level.
2330:	Main turbine was relatched. Vital power breaker for pressurizer heater 1-3 did not reenergize.
2400:	Vital power breaker for pressurizer heater 1-3 had a blown fuse. Pressurizer heater 1-3 was aligned to vital power.
0015:	All Class 1 equipment was aligned. Total RCP seal injection flow was approximately 50 gpm.
HOT STANDBY (NATURAL CIRCULATION AND BORON MIXING)	
0028:	Operators begin tripping the reactor coolant pumps.
0048:	Natural circulation conditions have been verified.
0052:	Contents of the Boron Injection Tank (BIT) injected into RCS. Flow rate was approximately 150 gpm.

Table 2.1 (Continued)

TIME	EVENT/ACTION
0058:	Power operated relief valve (PORV), PCV-456, opened to relieve excessive pressurizer pressure. PCV-456 actuated nine times from 0058 to 0110 hours.
0111:	Operators established letdown to lower the pressurizer level and minimize PORV actuation.
0113:	Operators terminated BIT injection. RCS boron concentration increased from 890 ppm to 1195 ppm. Continued with the four hour at hot standby stabilization period. RCS temperature was steadily drifting downwards, due to operators trying to maintain the secondary side under hot conditions.
0200:	Operators minimized steam loss on the secondary side by securing 50% of the condenser steam jet ejectors.
0415:	Operators lowered pressurizer level by initiating letdown.
0440:	Operators demonstrated that RCP seal injection flows can be controlled by manually throttling the isolation valve downstream of FCV-128 when using a centrifugal charging pump. After the demonstration, the reciprocating charging pump was placed in service. This would give operators better control of RCP seal injection flow during the remainder of the test, thereby minimizing RCP seal damage due to high seal injection flow.
0450:	Plant has been at hot standby natural circulation conditions for greater than four hours. Operations set VCT makeup control system to provide 2000 ppm makeup to the Volume Control Tank (VCT). This simulated the charging pumps which were aligned to the Refueling Water Storage Tank (RWST).

RCS COOLDOWN/DEPRESSURIZATION TO RHR INITIATION CONDITIONS

TIME	EVENT/ACTION
0450:	Operators isolated letdown and commenced cooldown using the 10% atmospheric steam dumps. Cooldown rate was approximately 20°F/hour.
0533:	Initiated letdown to lower pressurizer level and lower primary/secondary system differential pressure.
0833:	Isolated letdown.
0845:	Secured Control Rod Drive Mechanism (CRDM) fan 1-1.

Table 2.1 (Continued)

TIME	EVENT/ACTION
0957:	Initiated letdown to lower pressurizer level.
1319:	All four loops T_{HOT} less than 350°F. Plant in Mode 4 condition.
1356:	Charging valve 8146 and auxiliary spray bypass valve 8148 open. No appreciable depressurization in the RCS observed.
1402:	Closed charging valve 8146. Depressurization rate was 8.0 psi/min.
1515:	Operators opened PORV PCV-456 to depressurize the RCS and also isolated letdown.

RCS COOLDOWN TO COLD SHUTDOWN CONDITIONS

TIME	EVENT/ACTION
1805:	Operators initiated the RHR system. RHR pump was 1-2 placed in service.
1831:	The remaining CRDM fans were secured.
2015:	Operators .e-energized the CRDM fans (3 only).
2245:	RCS temperature below 200°F. Plant in Mode 5 condition.

3. SIMULATION OF THE TEST

3.1 General Description

The natural circulation, boron mixing and cooldown test performed at Diablo Canyon Power Plant was simulated using the RELAP5/MOD1 Code to provide the analytical basis for the test assessment. The RELAP5/MOD1 Code was selected for the simulation since it has been assessed by many organizations including BNL. Its one-dimensional modeling of the reactor system was considered adequate for this problem since all four loops were symmetric during the transient (test). It is also generally faster (in computing) than the TRAC-PF1 code. This was an important consideration since the total test lasted about 24 hours.

The Diablo Canyon Power Plant is a 4-loop Westinghouse PWR. All four loops including the steam generators were combined into a single loop since they were expected to be symmetric during the transient. Since the detailed modeling of most parts of the RCS, other than upper head (UH) region, was not expected to be important and the transient was expected to be long and slow, an effort was made to minimize the number of nodes used for the calculation in order to reduce the computing time to an acceptable level. The final noding diagram used in the calculation is shown in Figure 3.1. Besides the main reactor coolant system (RCS), pressurizer and steam generators, the bypass flow from the downcomer to the UH to the upper plenum was modeled in detail. The boron injection and the RCP seal injection were also included in the modeling. Heat structures were utilized to represent the metal mass of the fuel, piping, steam generator tubes and other structures. The steam generator secondary model includes the downcomer, boiler region, separator and steam dome. The modeling also included the primary and secondary relief valves. The heat loss through the piping and vessel wall was ignored since it was considered very small compared to the decay heat. However, the ambient heat loss in the pressurizer was included in the modeling to assess its effect on the depressurization rate. Simple control systems for the auxiliary feedwater (AFW) and atmospheric steam dump (ASD) valves were implemented on the basis of level control and cooling rate, respectively. The power was provided by the ANS 5.1

standard decay power table. The cooldown rate was set at 20°F/hour as in the test.

Since the plant was at full power when the test was initiated, the steady state for the hot full power condition was obtained for the simulation. The steady state conditions were mainly based on the information available in the FSAR, augmented by the information directly obtained from Pacific Gas and Electric (PG&E). Special attention was paid to match the pressure drop and flow rate in the various regions of the RCS by adjusting the friction factors in the code input since this information would be important in the assessment of the natural circulation and cooling of the upper head. Table 3.1 presents the comparison between the actual plant data and the final steady state obtained by the calculation. The comparison indicates that the code simulated the actual plant steady state very closely.

The sequence of events for the simulation is summarized in Table 3.2. This sequence of events did not exactly follow those of the test. The purpose of the calculation was not to duplicate the test, but to provide the basic information to assess the impact of the deviation of the test procedures from those of the BTP RSB 5-1 guideline, such as the use of non-safety grade equipment during the test.

3.2 Natural Circulation

The natural circulation phase of the calculation was simulated by tripping the reactor and RCPs at time zero. The turbine stop valve (TSV) and main feedwater isolation valves (MFIV) were closed and the AFW was initiated at the same time as the reactor trip. In the test, the natural circulation was achieved in two stages. Initially the reactor was tripped from full power by a turbine trip to hot shutdown condition with the RCPs still running. The RCS was maintained at this condition for several hours before the RCPs were tripped and hot standby at natural circulation conditions was established. This discrepancy would cause some differences between the test data and calculated results as discussed later.

Figure 3.2 compares the calculated RCS flow by RELAP5 and the pre-test prediction by PG&E. They are essentially identical. The decay heat used in the calculation and pre-test prediction were similar. The ANS decay heat was used for the calculation. It generally represents higher decay heat than in actual transients. Therefore, it was necessary to evaluate the effect of the decay heat on the natural circulation flow rate. The decay heat and natural circulation flow rate was expected to be related by (see Appendix A for the derivation),

$$W = KQ^{1/3} .$$

where W = natural circulation flow rate

Q = decay heat

K = a proportional constant.

This relationship indicates that the natural circulation flow rate is not very sensitive to the decay heat level. To confirm the above relationship, the steady state flow rate was plotted as a function of decay heat as shown in Figure 3.3 along with the results obtained by Westinghouse.[2] They show essentially the same trend, indicating that the adequate natural circulation would be established to remove the decay heat throughout the anticipated transient.

Figures 3.4 and 3.5 show the RCS temperature and pressure calculated by BNL using the RELAP5/MOD1 Code. As expected, the average coolant temperature dropped rapidly at the trip of reactor and pumps, and the pressure also experienced a steep decline due to the shrinkage of the coolant. Once natural circulation was established, the temperature essentially remained constant as the secondary pressure and temperature held constant at its PORV set pressure and its saturation temperature. The test data (Figure 3.6) showed slowly decreasing temperature during this period. This appeared to be due to some steam loss in the secondary side. This slight temperature drop during this period is not expected to have a significant effect on the rest of the transient.

The test pressure (Figure 3.7) was different from the calculated pressure; the calculated pressure showed a steep decline in the beginning due to the shrinkage of the coolant while the test maintained its steady state pressure after a short blip at the plant trip. This was due to the fact that the pressurizer heaters, which were not safety grade equipment, were used in the test during this period, while they were assumed not available in the calculation. However, a similar pressure drop was also shown in the test when the pressurizer heaters were not available in the test briefly (between 24:00 and 24:30 hours, as shown in Figure 3.7). The calculated pressure and pressurizer level showed a slow increase after the initial drop because a small amount of RCP seal injection (20 gpm) was maintained in the calculation as in the test. Letdown was assumed not available in the calculation since it was not safety graded equipment. This continuous injection of additional mass without letdown would eventually cause the opening of the PORV. Although the ambient heat loss in the pressurizer was modelled in the calculation, the pressure drop due to the heat loss was not enough to compensate for the increase of the pressure due to injection of the RCP seal injection. It was estimated that the RCP seal injection would increase the pressurizer level about 10% each hour.

Westinghouse plants may be divided into two groups according to the magnitude of the bypass flow: T_{hot} and T_{cold} plants. For the T_{cold} plant, sufficient bypass flow exists to make the upper head fluid temperature essentially equal to the cold leg temperature. On the other hand, for the T_{hot} plants (including Diablo Canyon), the bypass flow is much smaller. This results in the upper head temperature between the cold leg and the hot leg temperature. This type of plant poses some difficulty in cooling the upper head during the cooldown period and raises a possibility of void formation in the UH region. Thus a T_{hot} plant requires a much more careful study on the coolability of the upper head; this in turn requires an accurate estimation of the bypass flow rate during the natural circulation. The RELAP calculation of the bypass flow rate at natural circulation conditions differed substantially from the results obtained by Westinghouse.[2] In the Westinghouse study, the bypass flow was reversed, flowing from the upper head to the upper downcomer during the natural circulation. The magnitude of the flow was reduced almost proportionately to the main flow from 60 lb/sec (0.15% of the mainflow) at design conditions to approximately 2-3 lb/sec (0.1-0.15% of the main flow) during the natural circulation. However, BNL's calculation using the RELAP/MOD1 Code showed that bypass flow never reversed and substantial bypass flow was maintained despite rapidly decreasing main RCS flow; the flow was reduced from 70 lb/sec (0.2% of the main flow) during the forced flow to 14 lb/sec (1.0% of the main flow) during the natural circulation.

BNL's results appear to be qualitatively correct. The driving force exerted on the bypass flow is the gravity force created by the temperature induced density differences in the RCS loop. As shown in Figure 3.8, there are two buoyancy forces exerted on the flow path AEC acting in opposite directions. One force is created by density differences in the flow path CDA (through steam generator) which forces flow from A to C. The other buoyancy force is created in the flow path ABC (through the core) which forces flow from C to A. In the specific geometry of the Diablo Canyon Power Plant the calculations indicate that the driving force of CDA surpassed that of ABC, thus resulting in the flow from A to C through E. The magnitude of this flow was difficult to confirm by independent calculation, however, since the results are very sensitive to the calculated frictional losses. Based on the calculated bypass flow rate, the upper head fluid would be replaced completely every forty (40) minutes. This relatively large flow and short replacement time would enhance the mixing of fluid in the upper head, thereby promoting cooling and boron mixing in the upper head. However, the mixing of fluid within the upper head region may not be good considering the large amount of guide tube structures in it. The significance of this aspect will be discussed in more detail in Section 4.5.

3.3 Boron Mixing

After the natural circulation was established, the boron was injected. A total of 900 gallons of 21,000 ppm borated water was added to the RCS, using the boron injection tank (BIT). Figure 3.9 shows the boron concentrate calculated by the code as well as the actual test result and the pre-test prediction. Also plotted are the calculated boron concentration in the upper head, when boron was mixed evenly in the upper head. Although the rate of increase of the boron concentration differs somewhat between both analyses and the test, all show a sufficiently rapid rise to insure the adequate mixing of boron in the main flow paths of RCS under natural circulation condition.

Figure 3.9 shows that the increase of the boron concentration was slower in the upper head than in the rest of the RCS. Nevertheless, it also reached the average bulk boron concentration in less than one hour. This was due to relatively large bypass flow fraction into the upper head. It should be noted that the boron concentration in the upper head calculated by the RELAP assumes complete mixing. However, the fluid in the upper head appears to be stratified with little or no mixing as discussed earlier. This suggests that there may be some unborated water in the upper head. A similar concern may be raised about the boron mixing in the pressurizer. This point will be further discussed in the next section.

Both the test and the calculated pressure started increasing rapidly once the boron injection started. It eventually reached the PORV actuation pressure and opened the PORV. This was due to the injection of additional mass into the system without letdown. In the test, the letdown was initiated to minimize PORV actuation at the end of the boron injection period.

3.4 Cooldown

The cooldown was initiated by opening the ASD valve at 12,000 seconds in the simulation. The base calculation was performed with a cooldown rate of 20°F/hour and continuous RCP seal injection as in the test. A simple proportional controller based on the rate of temperature drop was implemented in the calculation. The flow through the ASD valve was calibrated based on its capacity at the normal operating pressure, which was obtained from PG&E. The RCS temperature was approximately 570°F when the cooldown was commenced. Comparison of the test temperature (Figure 3.6) with that of the calculation (Figure 3.4) show that the actual cooldown was very similar to the calculated cooldown. The RCS temperature in the test was approximately 510°F when cooldown was commenced as discussed in the previous section on natural circulation.

The RCS pressure was more difficult to compare since the letdown was used in the test during most of the cooldown period to prevent the water-solid operation of the pressurizer due to continuous operation of the RCP seal injection. The RCS pressure obviously depends on the rate of letdown. The pressure calculated with 20°F/hour cooldown rate, RCP seal injection and no letdown (Fig. 3.5) remained at the PORV actuation pressure almost 4 hours. This was because the volume created by shrinkage of the coolant due to cooldown was less than the increase of coolant volume due to RCP seal injection without letdown. This necessitated the periodic opening of the PORV. The pressure eventually began dropping later as the pressurizer continued to cool.

To assess the impact of the RCP injection, an additional calculation was performed without RCP injection. Figure 3.10 showed the gradual pressure decrease as expected. It showed that pressurizer level was also gradually decreasing and indicated that the pressurizer would eventually empty without further operator actions. In practice, the operators would try to maintain the pressurizer level by operating the charging and letdown systems when available. Figure 3.10 shows the pressure estimated when the pressurizer level was maintained at 50%. The RCS pressure still decreased due to the ambient heat loss in the pressurizer. Figure 3.11 compares the calculated RCS coolant temperature with the saturation temperature corresponding to the RCS pressure and indicates that more than 100°F of subcooling was maintained for the RCS during the cooldown period for both the test and the calculation.

Figures 3.12 and 3.13 give the results of another sensitivity calculation performed with a cooldown rate of 50°F/hour. As expected, the pressure decreased faster than the previous cases even with RCP seal injection since the shrinkage of the coolant was more than the volume of the injected water. During this rapid cooldown, the bulk RCS temperature is adequately subcooled throughout the cooldown, as shown in Figure 3.12.

The upper head fluid temperature calculated by the code (20°F/hour cooldown) is shown in Figure 3.4. The calculations indicate that upper head was cooled at about the same rate as the RCS and, thus, maintained the same margin of subcooling as the RCS. This was due to the fact that a substantial bypass flow was calculated by the code cooling the upper head and mixing with the upper head fluid. (Complete mixing was assumed in the upper head for the calculation but the expected effects of flow stratification are assessed in the next section.) Therefore, cooling of the upper head is expected to be substantially less than that indicated by the calculation.

Other concerns during the cooldown were the capacity of the ASD valves to provide sufficient cooling to maintain the specified cooldown rate, especially during the latter stage of cooldown when the steam generator (SG) pressure was low, as well as the question of the adequacy of the supply of coolant water available in the condensate storage tank (CST). Figure 3.14 shows that the fraction of ASD valve opening during the cooldown period remain less than 70% even near the end of the cooldown period with the high cooldown rate of 50°F/hour. It was less than 50% open when the cooldown rate was 20°F/hour. Figure 3.15 shows the accumulated AFW calculated by the code (not including an allowance for soak time). It should be noted that this represented a conservative (maximum) estimation of the required amount of water since higher decay heat was used in the calculation than in the test. The reactor system used about 120,000 gallons of cooling water until the end of cooldown (about 8 hours with 50°F/hour cooldown). It was estimated that about 150,000 gallons of water would be needed until the end of cooldown with the 20°F/hour cooldown rate (about 14 hours). In the test, about 126,000 gallons of water was used for the entire test (about 24 hours). These are well below the capacity of the CST. However, this did not account for the additional water required during the extended period of cooldown which might be needed to cool the upper head. The calculation also showed that one motor-driven AFW train was sufficient to supply the necessary cooling water throughout the transient.

3.5 Depressurization

Since the pressure and temperature during the depressurization could be readily evaluated without the detailed calculation, the depressurization period of the test was not simulated. Furthermore, there was no non safety grade equipment used during this period in the test.

An approximate equation has been developed to estimate the auxiliary spray water flow rate required to maintain a specified depressurization rate. It was assumed that the pressurizer was at equilibrium state when the auxiliary spray was in operation. The rate equation is:

$$W_{sp} = \frac{V\rho}{T_{pr} - T_{sp}} \left(\frac{dp}{dt}\right) \left(\frac{dTsat}{dp}\right) , \qquad (3.1)$$

where W_{sp} = spray flow rate,

T_{sp} = spray water temperature,

T_{pr} = pressurizer temperature,

V = water volume at the pressurizer,

ρ = density of water at the pressurizer.

The maximum spray water flow rate required during the depressurization for Diablo Canyon to maintain 8 psi/min was estimated to be approximately 40 gpm at the end of depressurization. This was less than the maximum flow rate of 55 gpm. The spray water temperature was assumed to be 100°F and the pressurizer level was assumed to be 60%.

Higher spray water temperature would decrease the depressurization rate and the PORV may be needed at the end of the depressurization period. Note that it was assumed that letdown was to be unavailable. The operation of the auxiliary pressurizer sprayer normally requires letdown to be in operation in order to prevent the thermal stress which might be generated on the charging nozzles.

Table 3.1 Comparison of the RELAP5 Estimated Steady State Conditions with the Plant Steady State.*

Parameters	Plant	RELAP5/MOD1
Power, MW	3338	3338
Pressure, psia	2252.8	2252.8
Hot Leg Temp., °F	608.8	612.1
Cold Leg Temp., °F	544.4	548.0
Coolant Flow, lb/sec	36918	36678
Bypass Flow, lb/sec	77.3**	79.6
Δp Pump, psia	84.0	84.6
Pressurizer Level, %	60.0	61.7
Steam Pressure, psia	805.0	805.0
Steam Temperature, °F	519.0	518.9
Steam Flow, lb/sec	4039	4035.8
SG Water Volume, ft^3	7930	7068.0
Boron Concentration, ppm	890***	890

*The steady state conditions for the plant were taken from the FSAR[5] unless otherwise stated.
**Obtained from PG&E staff.
***Obtained from the Diablo Canyon test report.[1]

Table 3.2 Sequence of Events for the Simulation

Time, sec	Event
0-100	Steady State
100	Plant Trip
	RCP Trip
	TSV Closure
	MFW Closure
	AFW Actuation
5000	Boron Injection
6200	Boron Injection Terminated
12000	ASD Valves Open
	Cooldown Begins

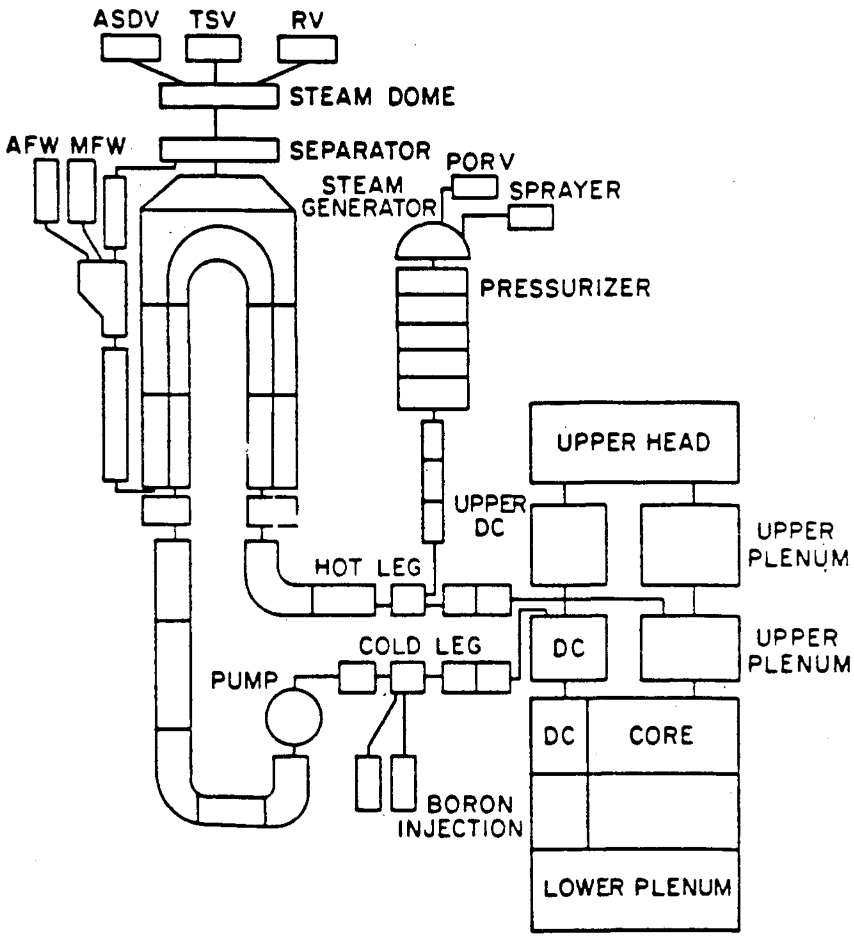

Figure 3.1 RELAP noding diagram for the Diablo Canyon model.

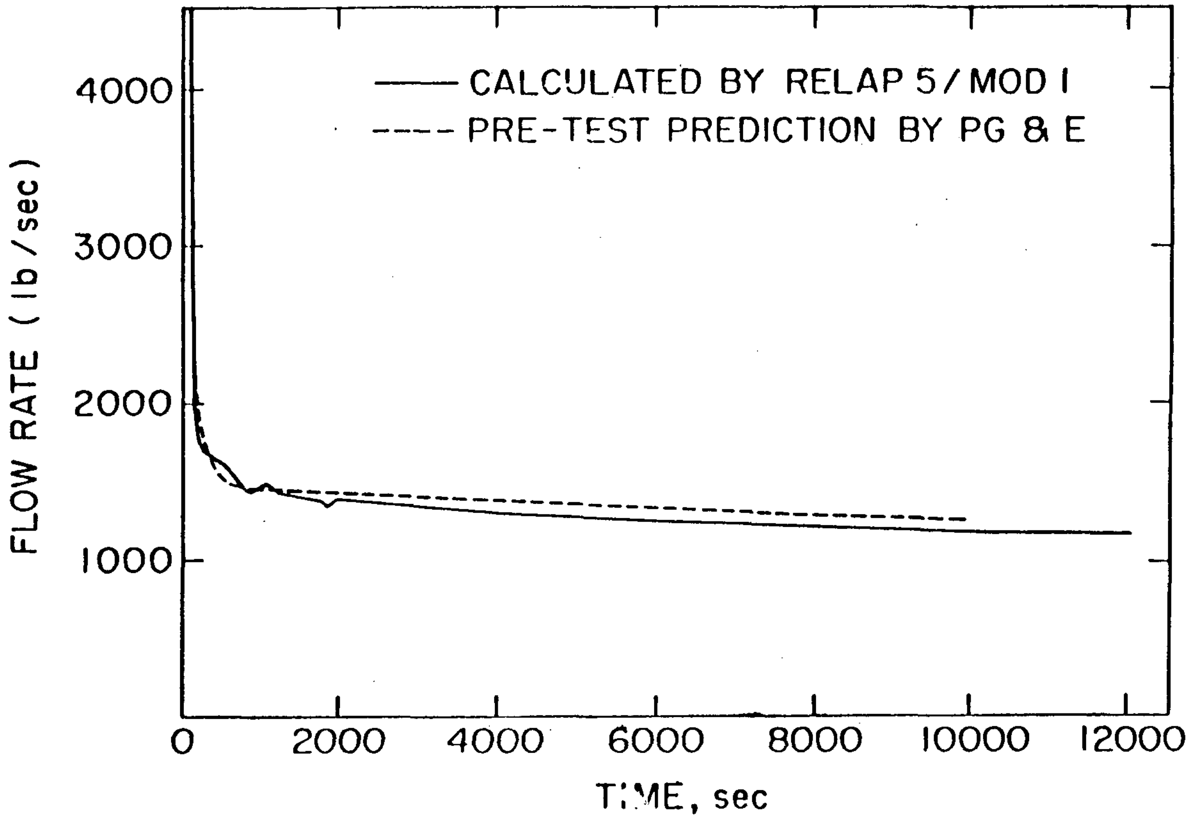

Figure 3.2 RCS flow.

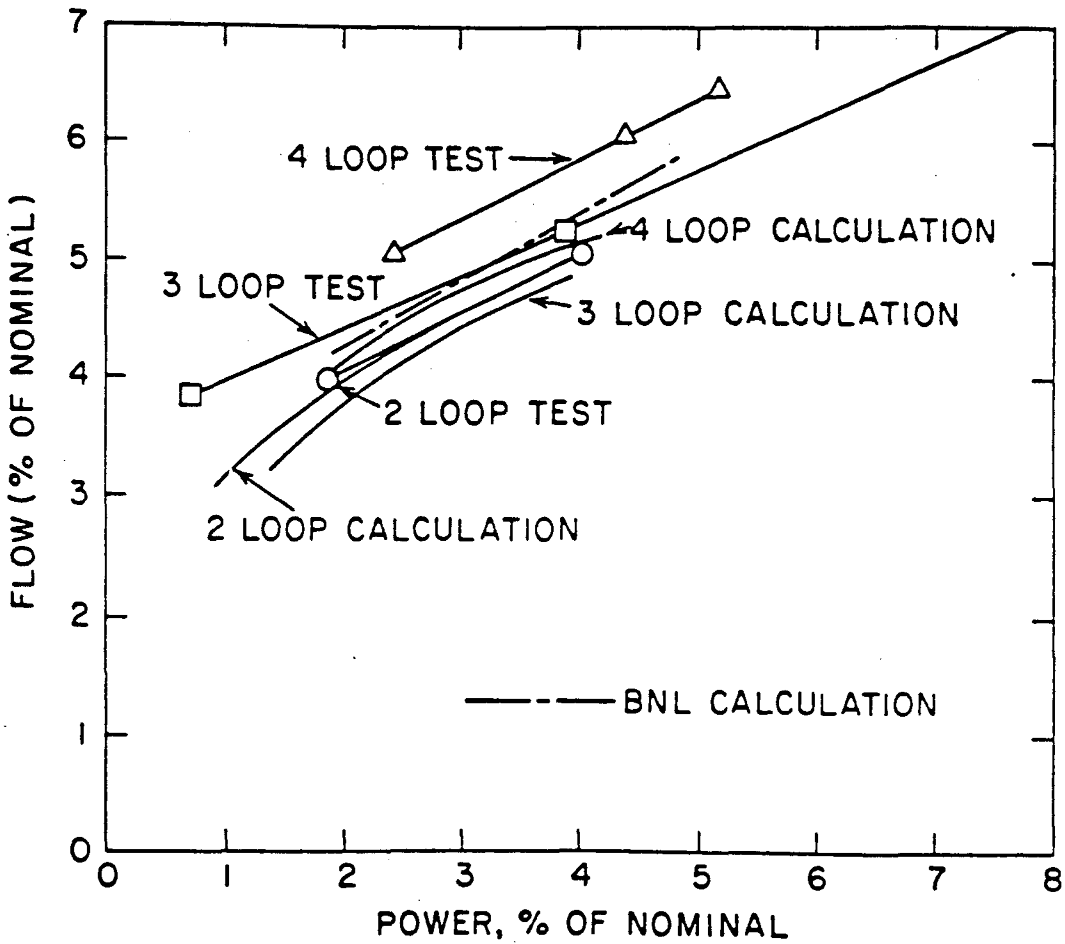

Figure 3.3 Natural circulation flow rate vs. time.

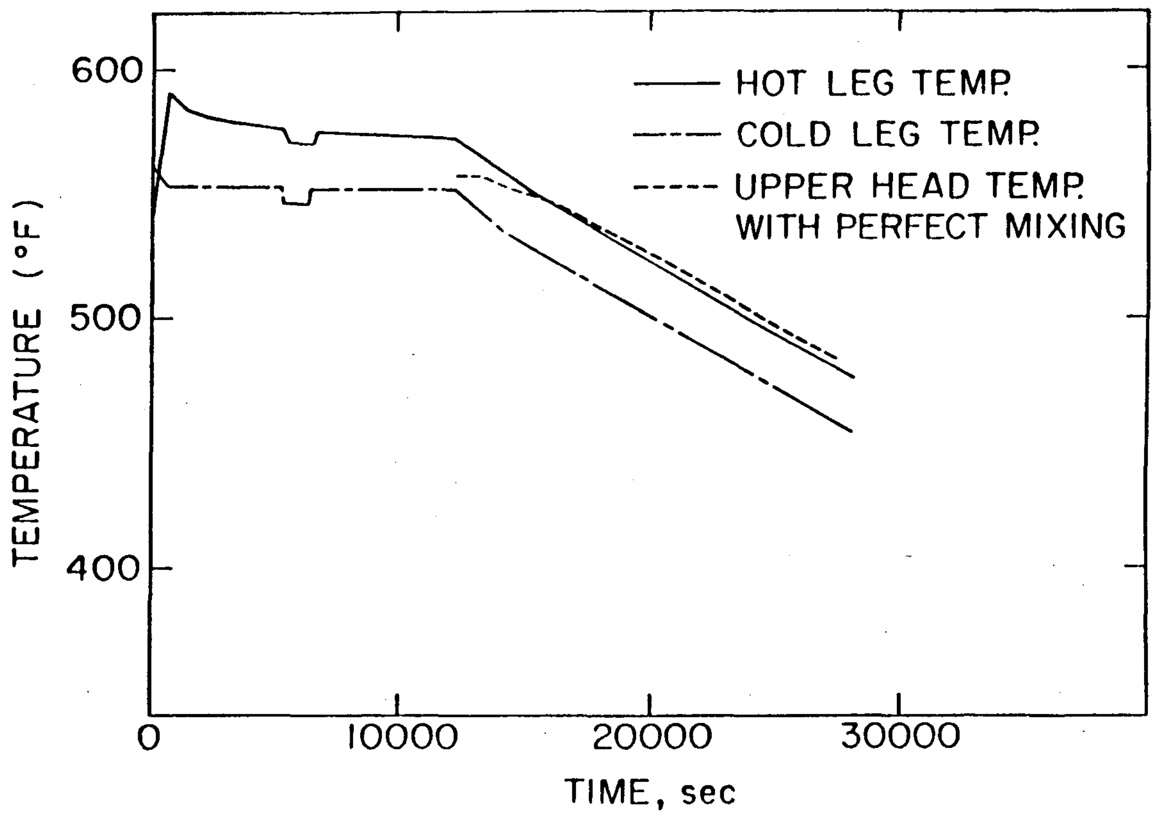

Figure 3.4 The calculated RCS temperature (20°F/hr cooldown).

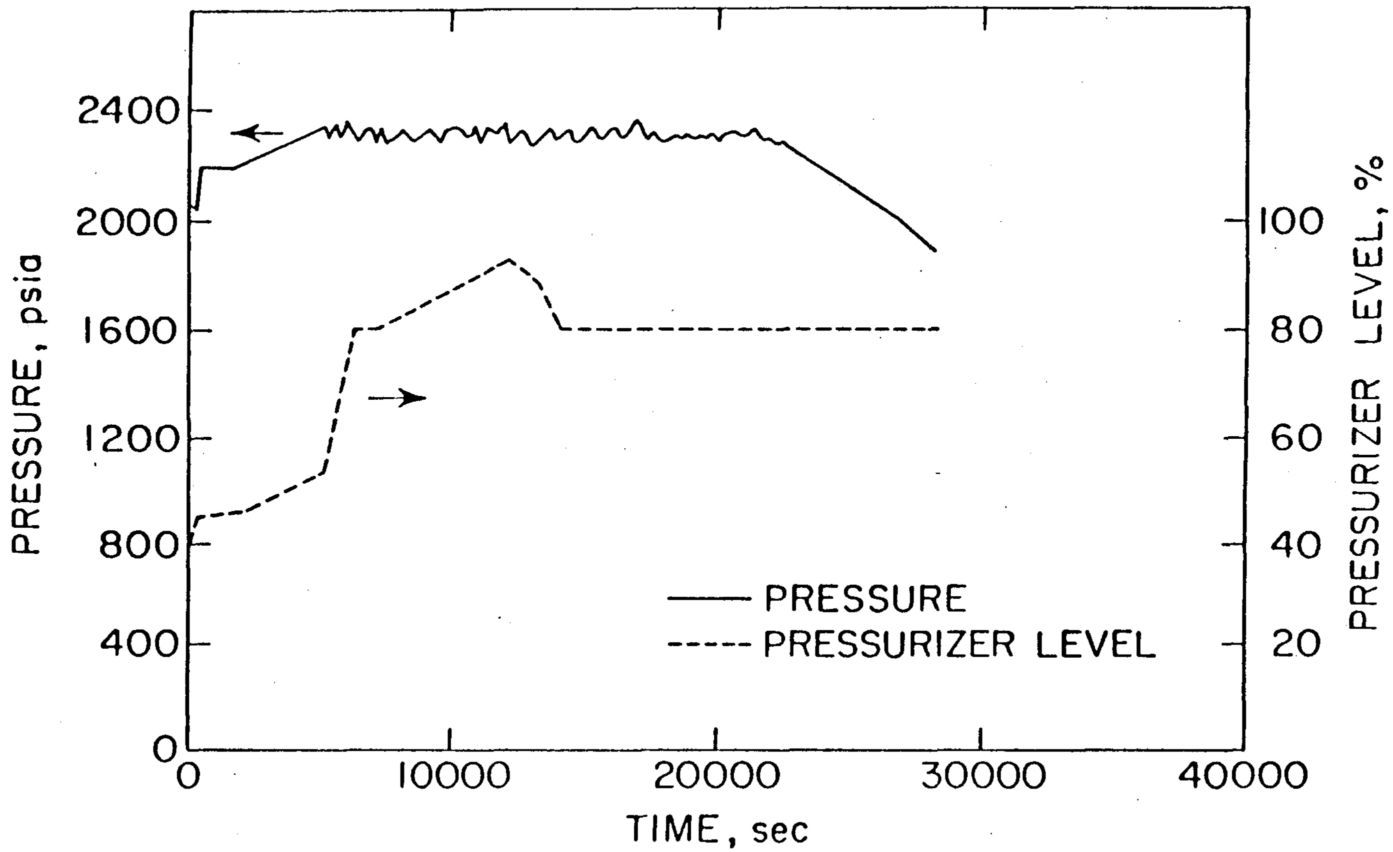

Figure 3.5 RCS pressure and pressurizer level (20°F/hr cooldown).

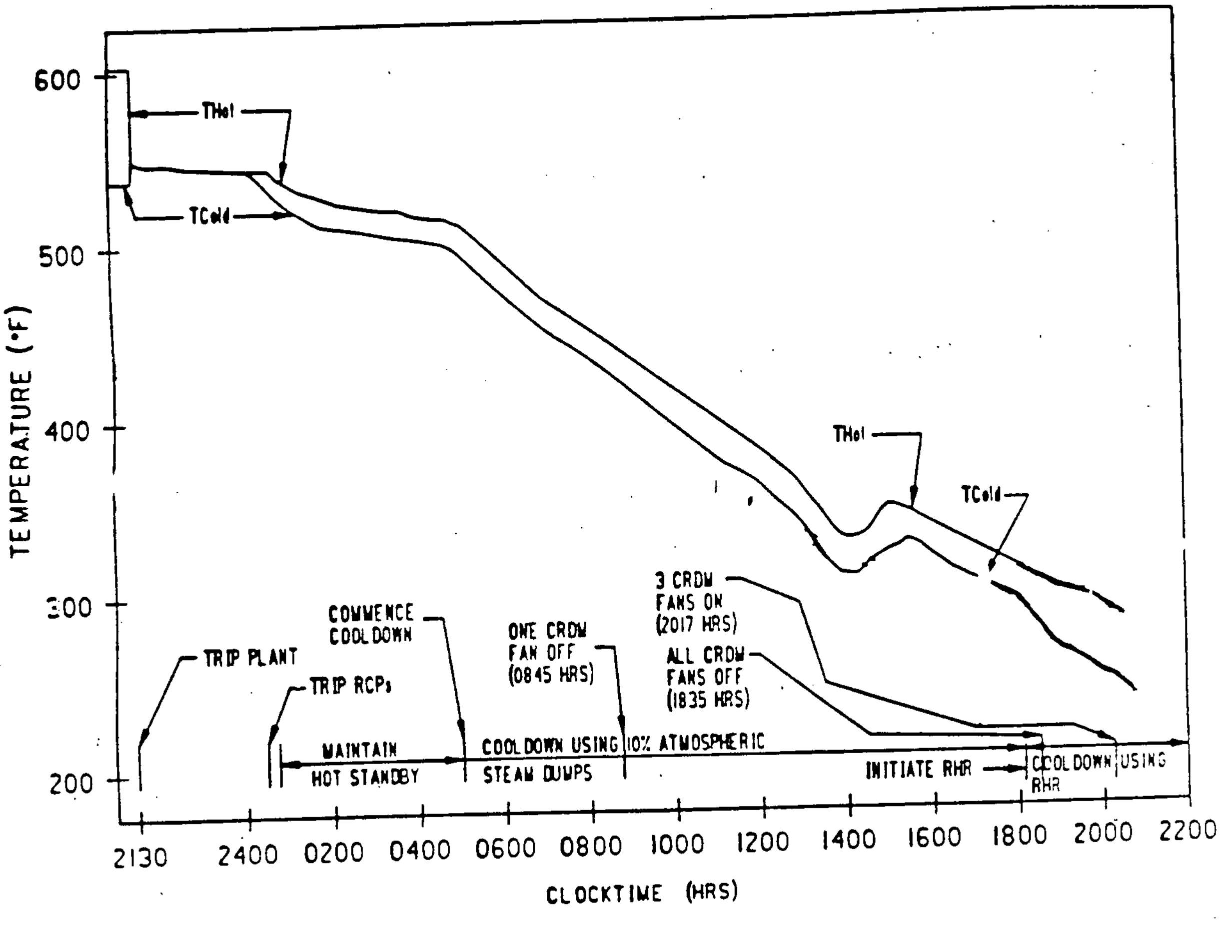

Figure 3.6 RCS temperature for the test.

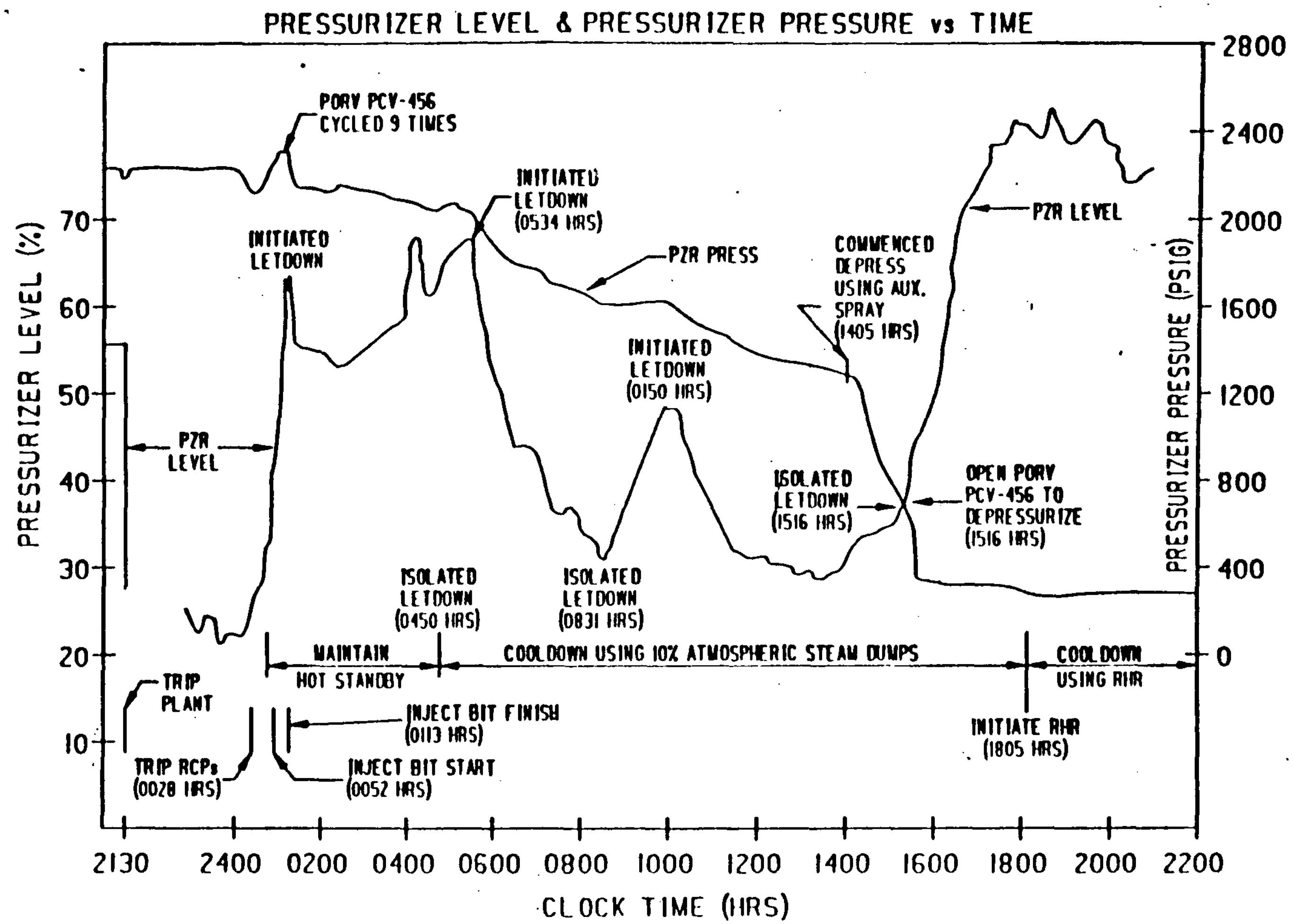

Figure 3.7 Test pressure and pressurizer level.

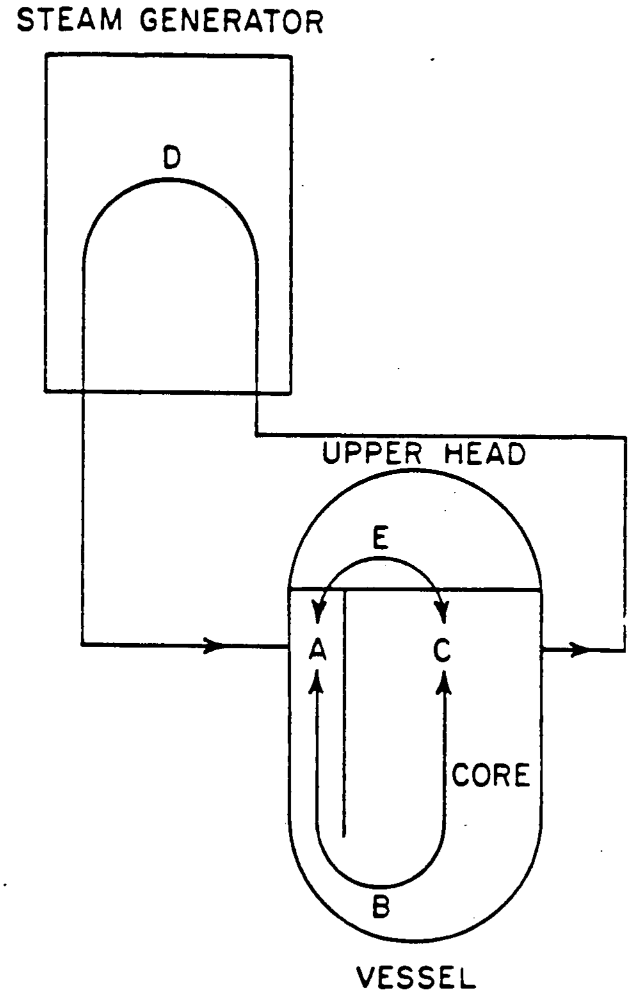

Figure 3.8 Bypass flow.

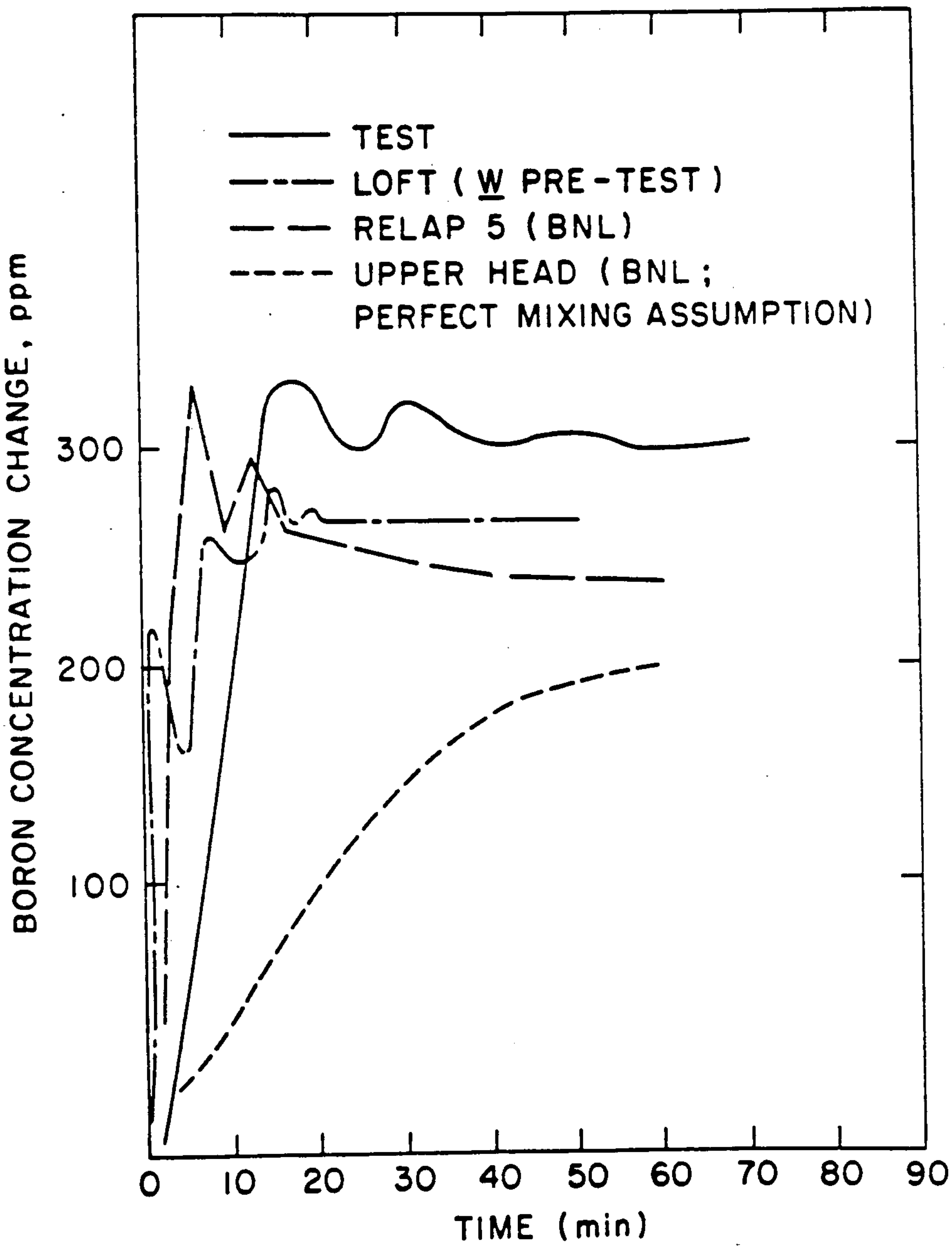

Figure 3.9 Boron concentration.

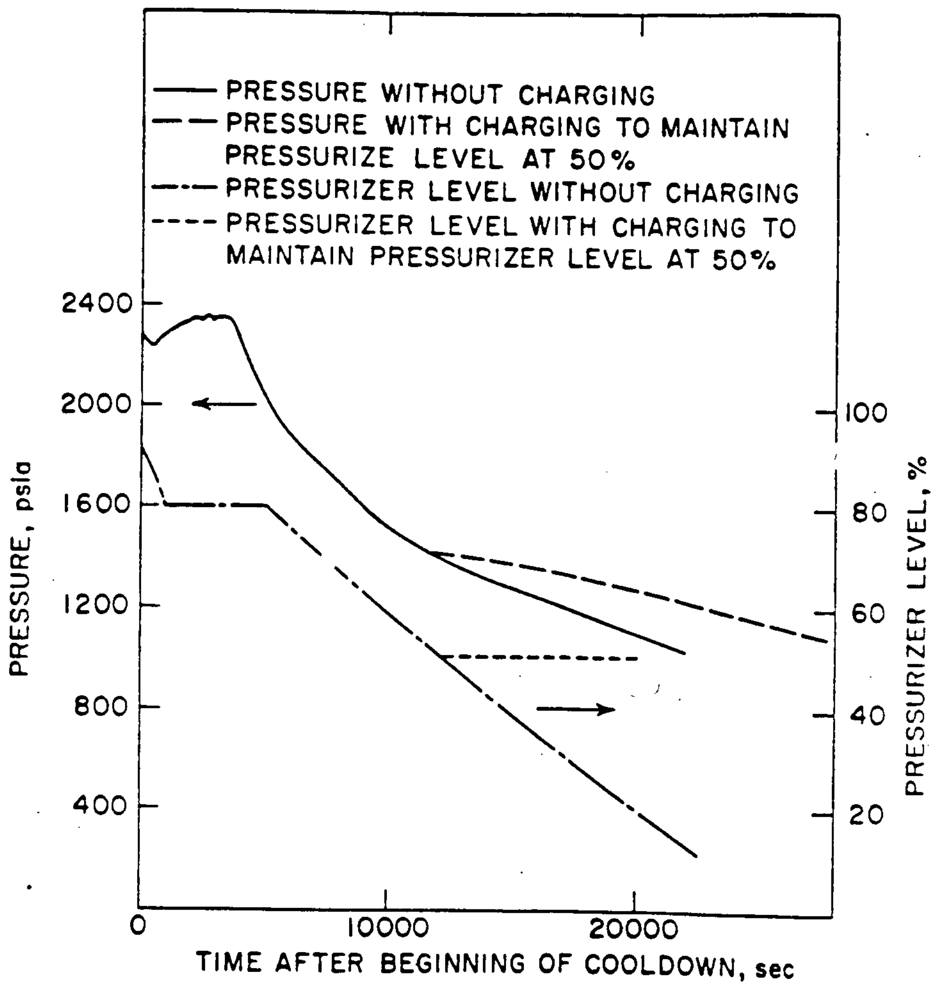

Figure 3.10 RCS pressure and pressurizer level (20°F/hr cooling).

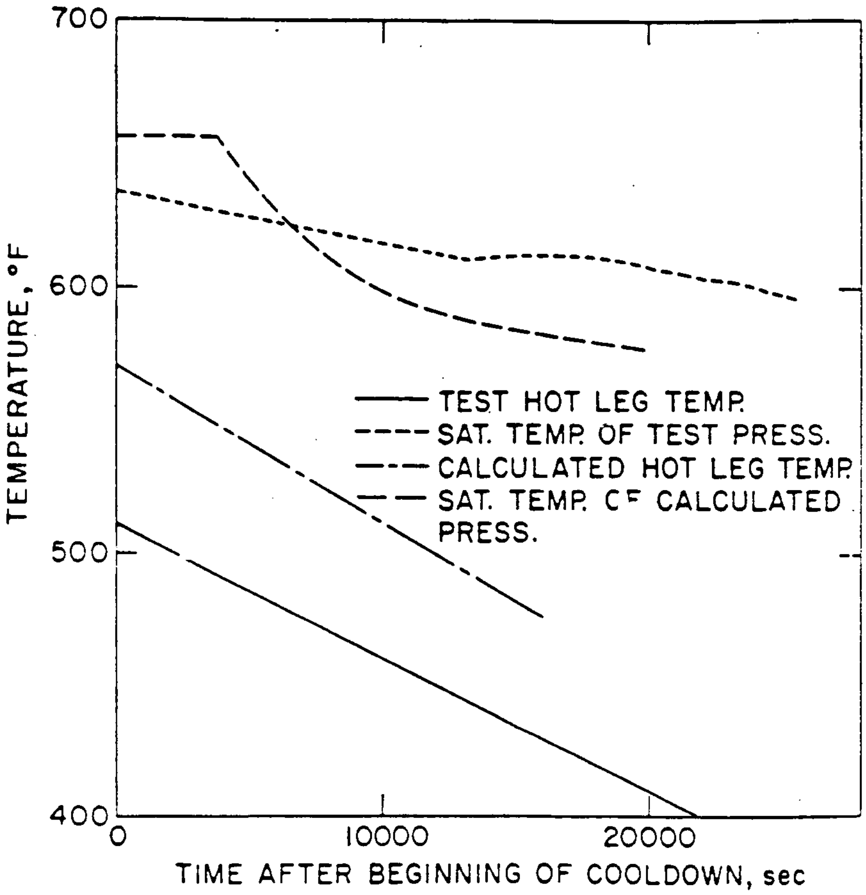

Figure 3.11 Hot leg and saturation temperature of test and calculation (20°F/hr cooldown).

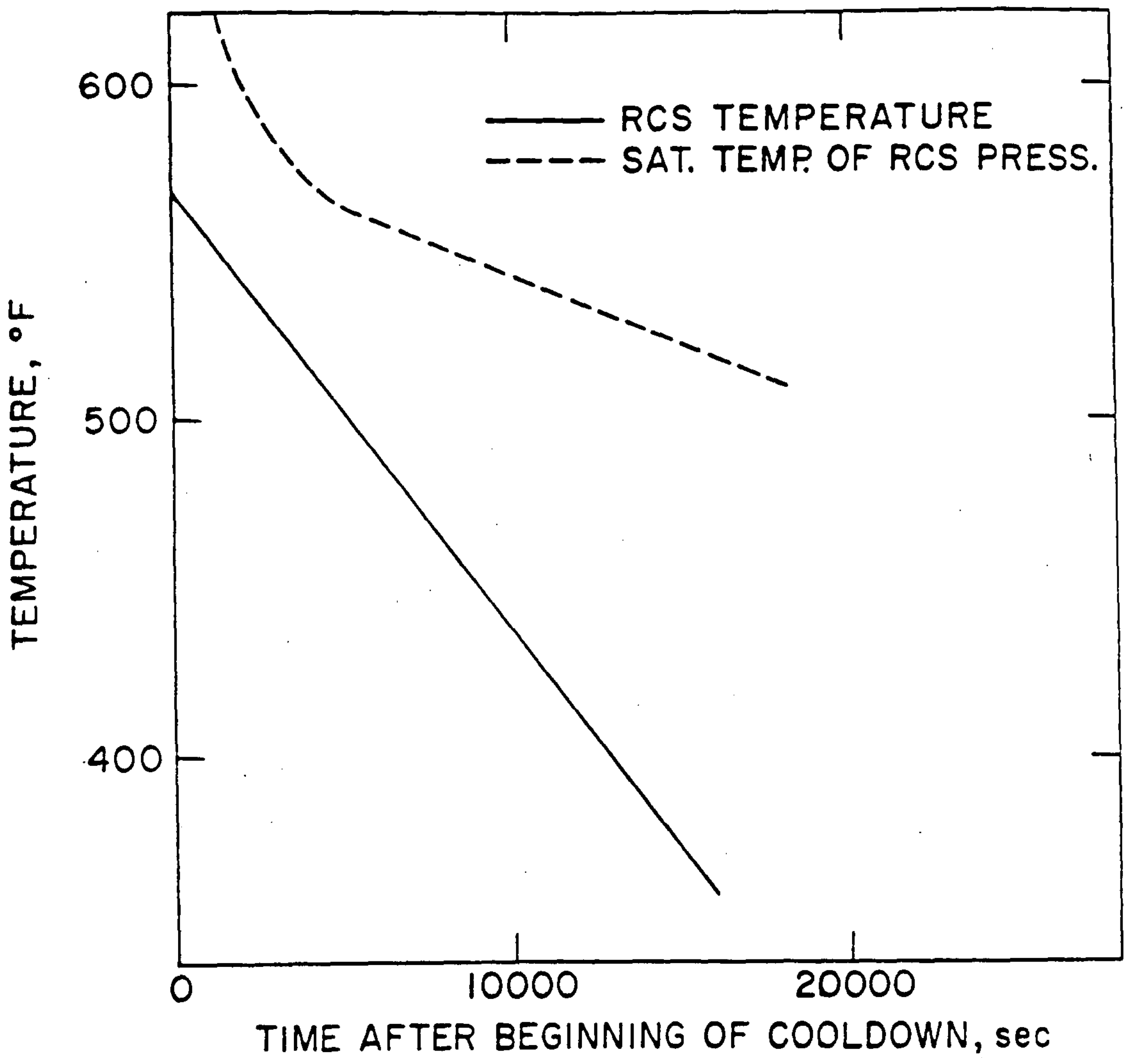

Figure 3.12 RCS temperature and saturation temperature with 50°F/hr cooldown.

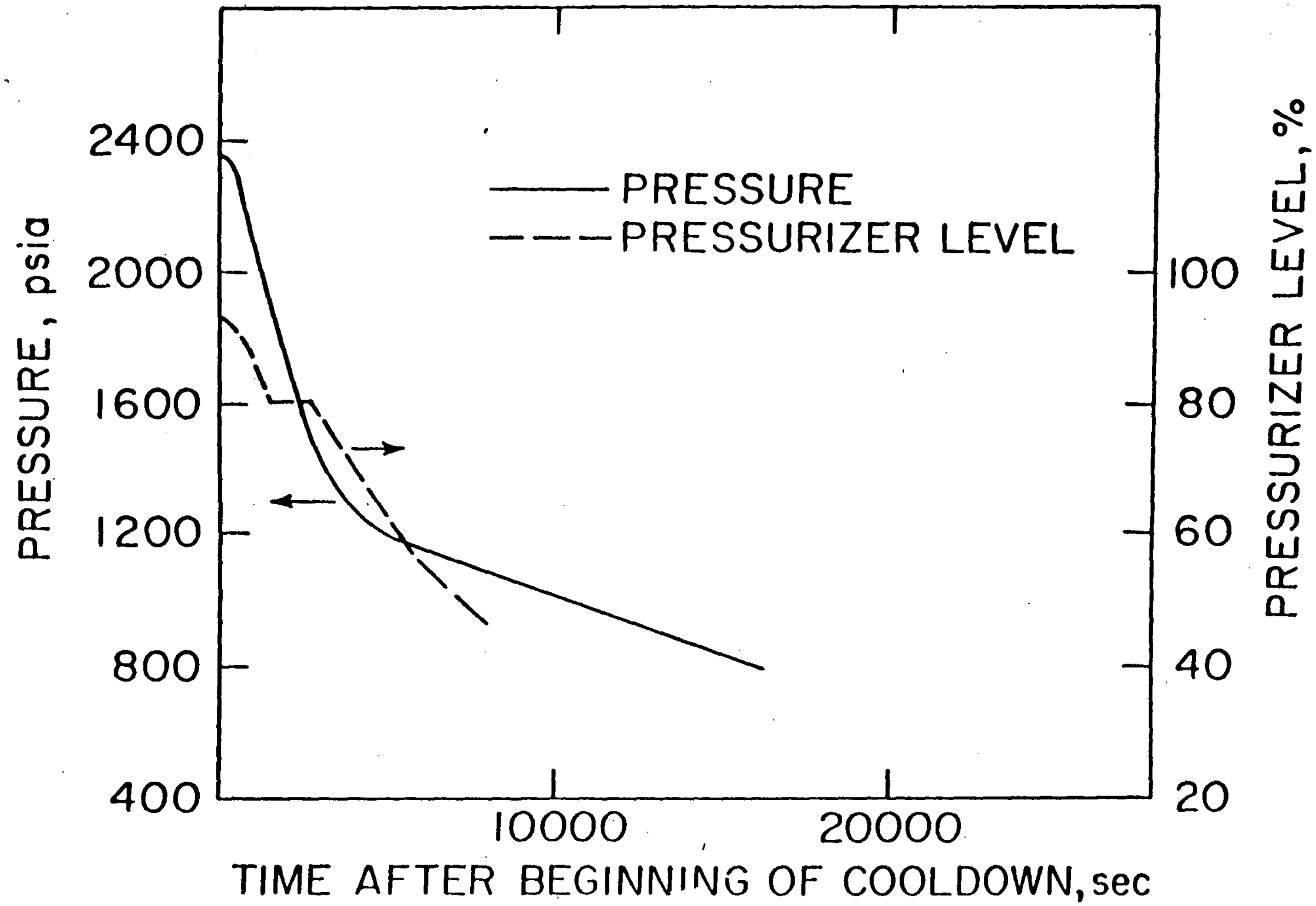

Figure 3.13 RCS pressure and pressurizer level (50°F/hr cooldown).

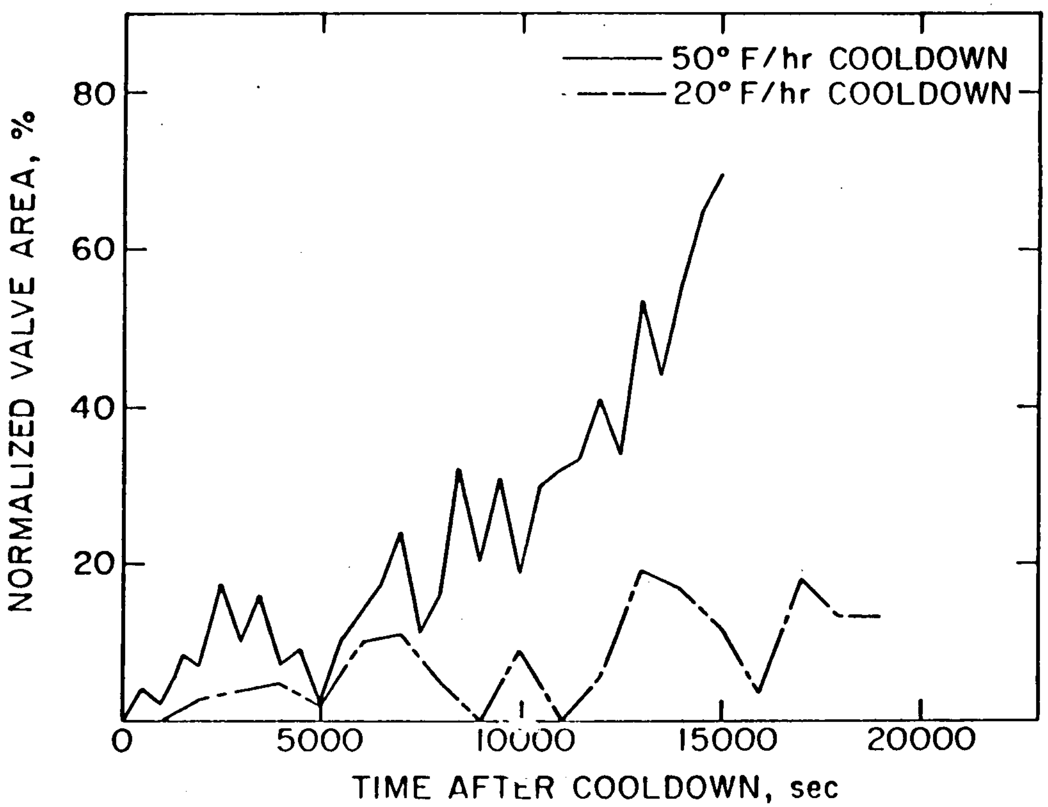

Figure 3.14 Atmospheric steam dump valve opening.

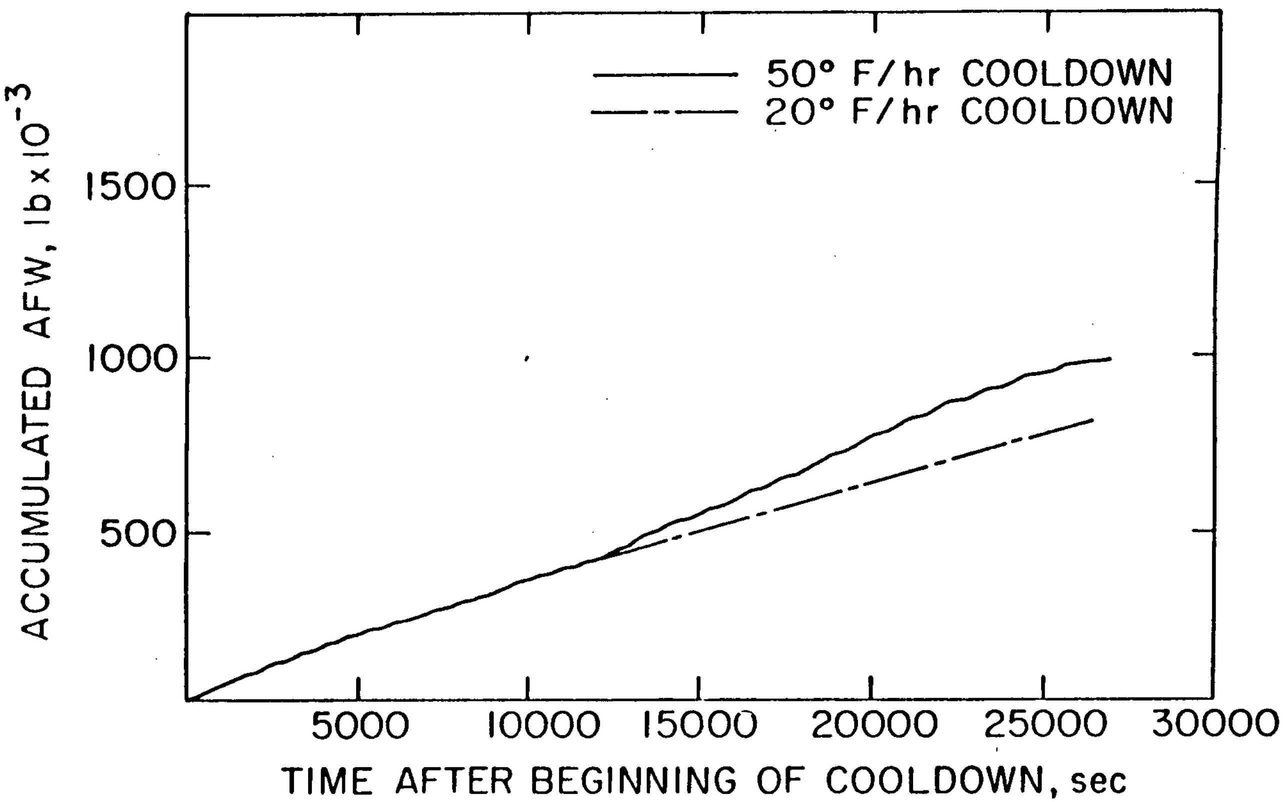

Figure 3.15 Accumulated cooling water.

4. REVIEW OF TEST RESULTS

4.1 Natural Circulation

The natural circulation was achieved in two stages in the test. The plant was tripped from full power by a turbine trip to hot standby conditions with the RCPs still running. The RCS was maintained at this condition for three hours before the RCPs were tripped and hot standby natural circulation was established. Under the accident conditions, the turbine trip and RCP trip would be anticipated to occur simultaneously. The delay in initiating natural circulation reduced the level of decay heat. This slightly reduced the natural circulation flow rate and boron mixing. The delay also allowed the primary system to become more uniform in temperature including some reduction in upper head temperature. This would tend to reduce the likelihood of void formation in the upper head during the natural circulation cooldown.

During the test, both the normal plant control systems and safety grade systems were used to accomplish the boron mixing and the cooldown goals. We would expect the plant procedures to follow an equivalent approach, i.e., the procedure would be as simple and direct as possible using the best available equipment. In those cases where other than safety grade equipment was used it would be demonstrated how the necessary function could be achieved using only safety grade equipment. We believe the Westinghouse test report[1] achieved this goal.

The delay of natural circulation after the plant trip allows some additional cooling of the upper head. This aspect will be discussed in the review of the upper head cooling. During the natural circulation period (including the boron mixing period) in the test, the pressurizer heaters and letdown system were used (neither of which are safety grade). The pressurizer heaters were used to maintain the pressure after the plant trip. The unavailability of the pressurizer heaters would not affect the plant's ability to maintain natural circulation conditions since the natural circulation flow rate would not be affected by the RCS pressure during this period. Use of the pressurizer heaters, however, may necessitate the earlier use of the letdown.

The unavailability of the letdown would affect the system pressure more directly. Since the RCP seal injection would be maintained throughout the natural circulation, this continuous injection of mass (combined with the required boron injection later) without letdown would increase the pressure and eventually open the PORVs. It was estimated that the RCP injection would increase the pressurizer level about 10% each hour. However, this would not directly affect the plant's ability to achieve natural circulations.

Based on the above discussion and results from the previous section, it was concluded that the test in combination with the analysis sufficiently demonstrated the adequacy of natural circulation. Thus, the plant is capable of removing decay heat by the natural circulation with only safety grade equipment.

4.2 Boron Mixing

Both the analysis and test results demonstrated that the rise of the boron concentration in the main flow path of the RCS was sufficiently fast to ensure adequate boron mixing prior to cooldown under natural circulation conditions.

As discussed in Section 3.3, the RELAP calculations predict that a substantial bypass flow into the upper head will occur and the upper head boron concentration will approach that of the main RCS with adequate mixing of the upper head fluid. However, mixing of the fluid in the upper head does not appear to be adequate and the bypass fraction is uncertain. The fluid in some parts of the upper head, especially in the upper region, has the potential to remain stratified considering the large amount of guide tube structures which impede mixing. Similarly, the fluid in the pressurizer may be isolated from the rest of the RCS, if the sprayer is not used. This suggests that the boron mixing in the upper head and pressurizer may be very slow, and the effect of relatively unborated upper head and pressurizer water added to the RCS, particularly during the upper head voiding (if it occurs), should be evaluated. It is not required as part of the BTP RSB 5-1 to demonstrate the mixing of boron in the pressurizer.

The effect of the unborated water entering the RCS would largely depend on the ratio of the flow rate of the incoming water from the upper head or pressurizer relative to the main coolant flow rate during the void formation. In case of the St. Lucie event where void formation in the upper head was observed,[3] it was conservatively estimated that the maximum flow rate from the upper head was less than 50 lb/sec when the pressurizer level increased most rapidly during the depressurization. This was less than 5% of the main coolant flow rate. An even smaller flow rate (about 10 lb/sec) was observed during the natural circulation/cooldown test performed at Palo Verde (a Combustion Engineering PWR) where the formation of a void was intentionally induced.[4] A simple hand calculation based on the assumption that the upper head fluid is in equilibrium during the depressurization indicates that the mass flow rate out of the upper head during void formation would be less than 15 lb/sec for the depressurization rate of 10 psia/min. This means that the fluid leaving the vessel would have been diluted by about 15 ppm at the most if no mixing took place at the upper head. However, this small amount of flow from the upper head would mix with the large amount of fluid in the upper plenum where relatively good mixing could be assumed. Furthermore, this fluid would go through the steam generators where there are thousands of steam generator tubes of slightly different lengths, and large inlet and outlet plena, and would further mix with the main coolant before it entered the core region.

Similarly, the effect of the unborated water entering the RCS from the pressurizer would be negligible during normal cooling/depressurization. But it may pose some problem during the rapid oscillation of the fluid between the pressurizer and the upper head if the emergency procedures do not specify the proper measures for depressurization. This kind of oscillation would occur only after the pressurizer was first filled with water from voiding the upper head. This implies that the water leaving the pressurizer is already mixed with the main coolant and the flow rate would be no more than the flow rate from the upper head as discussed above. The subsequent oscillations would not pose any further problem as far as boron mixing was concerned, because the fluid in the pressurizer (and upper head) would have been mixed with the RCS fluid during the initial phase of oscillation.

Another concern during the boron mixing period of the natural circulation would be the RCS pressure increase due to the injection of additional mass into the system without letdown. It was observed during the Diablo Canyon test that the PORV actuation pressure was reached and a PORV was periodically opened to relieve the pressure. This behavior was reproduced in the calculation as discussed in the previous section. In the test, letdown was initiated in order to lower the pressurizer level and minimize PORV actuation at the end of the boron injection.

It was concluded that:

1. Adequate boron mixing could be achieved during the natural circulation in the main flow paths of the RCS using only safety grade equipment.

2. The effect of relatively unborated water entering the RCS from the upper head and pressurizer would be minimal.

3. The pressure would rise and may reach the PORV actuation pressure without letdown or venting through upper head vents during the boron mixing period. Operators should be prepared for this possibility.

4.3 Cooldown

The Diablo Canyon test and the BNL analysis demonstrate that cooldown of the RCS to RHR system initiating conditions can be accomplished while maintaining the required subcooling during the natural circulation using only safety grade equipment. Although the letdown system was used during the test to prevent filling the pressurizer (and water solid operation) due to continuous RCP seal injection, use of the letdown system was not deemed to be essential during cooldown. However, not using the letdown would maintain the RCS pressure high and actuate the PORV when the cooldown rate was low. Increasing the cooldown rate to 50°F/hour would decrease the pressure throughout the cooldown period and would eliminate the need for PORV operation. Even in the case of the higher cooldown rate, the main RCS maintained the required margin of subcooling. The ASD valve capacity was calculated to be sufficient to maintain the high cooldown rate. Adequate amounts of cooling water was available in the CST to cooldown the RCS. However, additional water may be needed to provide the additional cooldown period needed to cool the upper head. Cooling of the upper head with and without the CRDM fans will be addressed in Section 4.5.

4.4 Depressurization

The test demonstrated that the reactor coolant system could be depressurized to the RHR initiation pressure (400 psig) under the natural circulation conditions using the auxiliary spray and/or pressurizer PORVs. The test also demonstrated that the depressurization can progress to the end of the cooldown period without void formation in the upper head when the cooldown rate was 20°F/hour and the CRDM fans were available to cool the upper head. The following sections (Section 4.5) indicate that the depressurization could progress to the end of cooldown without void formation even with a high cooldown rate of 50°F/hour when the CRDM fans were available.

The Westinghouse Background Information for Emergency Response Guideline ES-0.2[7] estimated that operators should wait about 8 hours after the beginning of cooldown for a Diablo Canyon type plant before proceeding to depressurize if the CRDM fans are not available to provide additional cooling of the upper head. The BNL analysis of cooldown without CRDM fans will be discussed in Section 4.5.

4.5 Reactor Vessel Upper Head Cooling

As discussed earlier, a potential exists for void formation in the upper head during the cooldown/depressurization under natural circulation conditions since the upper head is relatively isolated from the rest of the RCS and its fluid temperature remains higher than the coolant temperature in the main flow paths of the RCS. This will have a major importance to the plant's ability to bring it to cold shutdown conditions under the natural circulation condition.

Several factors influence the cooling of the upper head under natural circulation conditions. They include the following:

a) Heat removal from the upper head into the containment environment through the CRDM and the upper head dome when CRDM fans operate,
b) Amount of bypass into the upper head,
c) Heat conduction from upper head to upper plenum through the guide tube structures,
d) Heat conduction down to the reactor vessel through the upper head dome.

Among these, availability of the CRDM fans appears to be the dominating factor. The CRDM fans, however, are not seismically qualified equipment and no credit can be taken for these under the RSB Technical Position 5-1 assumption. Therefore, the cooling of the upper head will be assessed with and without the CRDM fans.

4.5.1 Cooling with CRDM Fans Operating

According to the Diablo Canyon FSAR,[5] the three operating fans (out of 4) can remove $2.5*10^6$ Btu/hour of heat from the upper head during normal operation. This translates into a cooldown rate of 32°F/hour for the upper head fluid when the upper head fluid temperature is 600°F[2] for a typical 4 loop Westinghouse plant. This cooldown rate was later reduced to 17°F/hour according to revised Westinghouse estimate.[6] Assuming the cooldown rate is approximately proportional to the temperature difference between the upper head and the containment environment (≈100°F), then the cooling rate is given by;

$$\frac{dT}{dt} = -17 \times \frac{T-100}{600-100},$$

This equation indicates that it will take approximately twenty hours for the upper head temperature to reach 350°F, and ten hours to reach 450°F. Ten hours is approximately the time to cool the main coolant to 350°F with 20°F/hour cooldown rate. Figure 4.1 showed the margin of subcooling in the upper head when the CRDM fans were in operation for two different RCS cooldown rates (four hours of natural circulation prior to the cooldown was assumed). It was shown that more than 100°F of subcooling was available when the cooldown rate was 20°F/hour. However, it was less than 50°F with 50°F/hour cooldown rate.

To maintain the 50°F subcooling, the natural circulation prior to the cooldown should be increased to five hours for the 50°F/hour cooldown.

Another concern for the upper head cooling is the degree of mixing. Even if excellent heat transfer occurs at the perimeter of the upper head, some hot spots may remain without good mixing of the fluid. However, since the cooling by the CRDM fans occurs in the upper part of the upper head region, good mixing is expected due to the natural convection (cold fluid above the hot fluid) within the upper head when the CRDM fans are in operation.

4.5.2 Cooling Without CRDM Fans Operating

Without the CRDM fans operating, the cooling of the upper head should depend on other mechanisms. Among the factors listed above, the second mechanism would be a major factor if sufficient bypass flow existed and it mixed well with the upper head fluid. As mentioned in Section 3.4, sufficient bypass flow to cool the upper head is predicted assuming it is well mixed with the upper head fluid. With this assumption, the upper head fluid temperature calculated by the code decreased at about the same rate as the RCS cooling rate with some time lag. However, some part of the upper head, may be stratified and its temperature may remain hot considering the large amount of guide tube structures and the lack of a free convection driving force. Under this circumstance, the only significant mechanism to cool the upper head would be the heat conduction through the guide tube structures and the upper head dome wall down to the upper plenum region.

A simple calculation was performed to estimate the cooling rate of the upper head based on the conduction through these structures. The upper head was divided into four heat conduction nodes, and bypass flow was assumed to mix with the fluid at the bottom part of the upper head. The upper head temperature was 550°F when the cooling began and the cooling rate was 25°F/hour. Figure 4.2 shows the fluid temperature thus calculated at various locations in the upper head; node 1 represented the uppermost part of the upper head. It took approximately 43 hours to reach 450°F after beginning the cooldown. The cooling time was not particularly sensitive to the RCS cooldown rate. The Westinghouse study estimated that the operator should wait about 8 hours to allow upper head cooling once the hot leg temperature reached 350°F.[2] This translated into approximately 16 hours after the beginning of the cooldown, which was about 27 hours shorter than the BNL estimation. It should be noted that several assumptions were made in the BNL calculation, which tend to make the result of the calculation conservative. Specifically, the upper head fluid was completely stagnant, conduction was the only mechanism for cooldown, the heat loss from the dome to the containment environment was ignored, and the bypass fluid mixed only with the fluid in the bottom of the upper head.

In the test, all the CRDM fans were temporarily turned off for about 100 minutes during the cooldown period to evaluate the effect of the CRDM fans and the average upper head cooldown rate was estimated to be approximately 6°F/hour. This translated into about 25 hours to cool the upper head by 150°F. However, it is difficult to extrapolate this result since the time period for this test was short and several factors could influence the results for such a short test. Specifically, cooling from above will cause circulation within the UH region due to buoyancy effects.

Figure 4.3 compares the upper head temperature calculated by BNL with the saturation temperature corresponding to the RCS pressure with 20°F/hour cooldown rate. It showed that the saturation temperature of the RCS pressure may go below the upper head temperature and thus a void may form during the cooldown operation even with a low cooling rate of 20°F/hour without the CRDM fans in operation unless the RCS pressure was maintained by means of either the pressurizer heaters or charging. The pressure would decrease slowly due to RCS cooldown contraction and ambient heat loss in the pressurizer. The rate of pressure drop due to pressurizer heat loss was estimated to be approximately 80 psia/hour.

It is concluded that:

a) The test demonstrated that the reactor vessel upper head cooling could be accomplished without void formation with 20°F/hour cooldown of the RCS when the CRDM fans were in operation.

b) The test results indicated that the upper head cooldown rate was about 6°F/hour for the Diablo Canyon plant. Note that this is slightly above the conservative (no upper head mixing) BNL calculation, but it is considerably above the rate predicted for this type of plant in the Westinghouse Owner's Group estimate.[2]

c) The RCS pressure may go below the saturation pressure of the upper head and thus a void may form during the cooldown operation even with the recommended low cooldown rate of 20°F/hour when the CRDM fans were not in operation.

4.6 Cooling Water and Compressed Air Requirement

Figure 3.15 shows the accumulated AFW calculated to be used during the cooldown operation. Approximately 120,000 gallons of auxiliary feedwater would be used until the end of cooldown when the cooldown rate was 50°F/hour. This included all the sensible heat of the system to bring the RCS from full power to the cold shutdown condition (including the water and metal structures) and the initial eight hours of decay heat. However, the total cooldown operation may last as long as 50 hours to allow time for upper head cooldown when the CRDM fans are not available as discussed in the previous section. Accounting for the additional decay heat during this period, a total of 360,000 gallons of cooling water may be needed, based on the ANS limiting decay heat. This is less than total water available from the condensate storage tank (CST) and other seismic category I sources (a total of 1,170,000 gallons).

It was reported that 126,000 gallons of water was used during the test (during approximately 24 hours) where the CRDM fans were operating. This is fairly consistent with the 120,000 gallons calculated by RELAP but the test duration and decay heat are somewhat different.

Another concern during the natural circulation cooldown is adequate supply of class I compressed air (or nitrogen gas) which is needed to operate the ASD valves. According to the PG&E staff,[8] eight bottles of class I air are installed to the two units at Diablo Canyon for this purpose and these are expected to last about 18 hours. Additionally, 35 bottles of air are stocked on site at all times. This translates into additional 80 hours of supply, which is considerably more than the estimated cooling time even with the most conservative assumptions.

It is concluded that a sufficient supply of safety-grade cooling water and compressed air is available to support the proposed plant cooldown method for Diablo Canyon but other plants with less cooling water and air available than in Diablo Canyon may require a faster cooldown method.

4.7 Effect of Non-Safety Grade Systems Used in the Test

During the test, several non-seismically qualified equipment and systems were used; they were the pressurizer heaters, letdown systems and CRDM fans. The effect of unavailability of this equipment is summarized below.

a) Pressurizer Heaters

The pressurizer heaters are a major part of the RCS pressure control system. They provide the ability to increase the pressure independently of the RCS water inventory and RCS water temperature. During hot standby conditions, the RCS pressure is expected to decrease due to the cooldown contraction of the RCS and the heat loss from the pressurizer as discussed in Section 3.4. It appears that during the cooldown without CRDM fans, the pressurizer heaters may be needed to maintain the RCS pressure above the saturation pressure of the upper head. Even with the CRDM fans in operation, should the pressure fall below the saturation pressure of the fluid temperature of any part of the RCS such as in the upper head, as happened at St. Lucie, the capability to control the resultant void would be limited if the pressurizer heaters are not available. Without the pressurizer heaters, RCS pressure control can still be achieved by operating the safety grade charging system. However, maintaining the elevated pressure using the charging system would increase the pressurizer water level and eventually cause water-solid operation of the pressurizer. Operators should be instructed to prepare for these circumstances and appropriate operating procedures should be included in the Emergency Operating Procedures (EOP) including reduction of the cooldown rate. It should also be mentioned that the strategy to cool the upper head more rapidly by intentionally forming a void would be more difficult without the pressurizer heaters. Some plants have upper head venting capability which could be used with charging flow to form and vent a steam bubble in the upper head.

b) Letdown System

The letdown system provides a direct means to reduce the water inventory. It was used throughout the test to prevent overfilling of the pressurizer (with resultant water-solid operation) since a substantial amount of RCP seal injection was maintained in the test. The RCP injection was estimated to increase the pressurizer level about 10% each hour without letdown. The continuous RCP seal injection without letdown may keep the RCS pressure high and actuate the PORV even during the cooldown if the cooldown rate was low as shown in Figure 3.5. Increasing the cooldown rate above 20°F/hour would eliminate the need for letdown or PORV operation.

Unavailability of the letdown system may also affect the depressurization procedure. The operation of the auxiliary pressurizer sprayer normally requires letdown in operation to prevent the thermal stress which might be generated on the charging nozzles.

c) CRDM Fans

The CRDM fans have a major impact on the cooling of the upper head. With CRDM fans operating, the reactor vessel upper head would be cooled at approximately 20°F per hour. Without them, the cooling time of the RCS would increase by 20-30 hours and about 180,000-240,000 gallons of additional cooling water would be required. It would also increase the possibility of void formation during the cooldown/depressurization period.

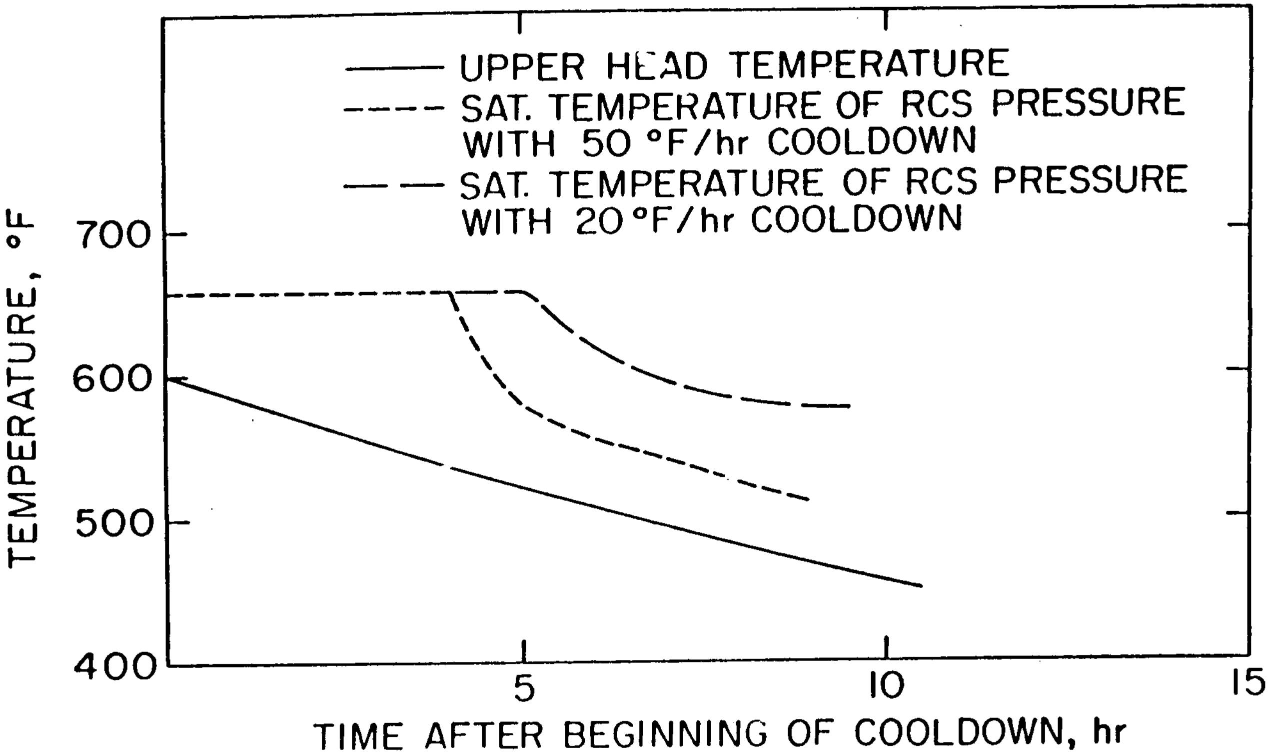

Figure 4.1 Margin of subcooling in the upper head with CRDM fans in operation.

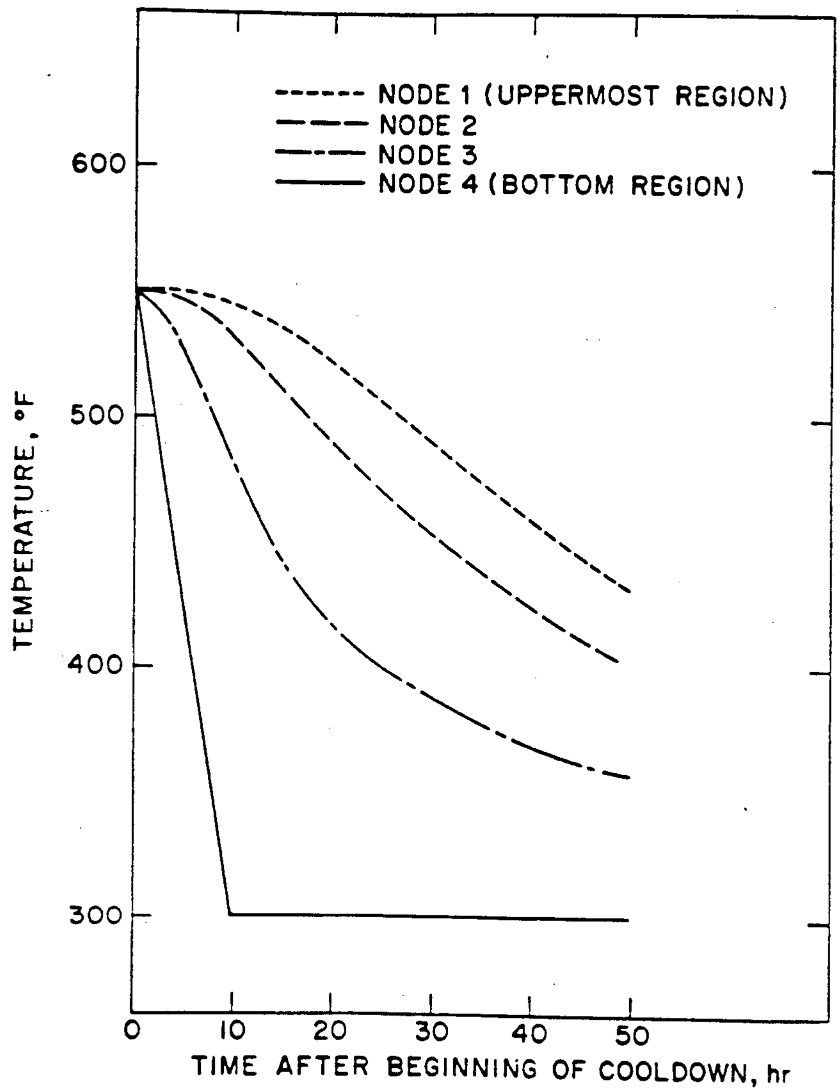

Figure 4.2 Upper head temperature when loss is due to conduction only (25°F/hr cooldown of RCS).

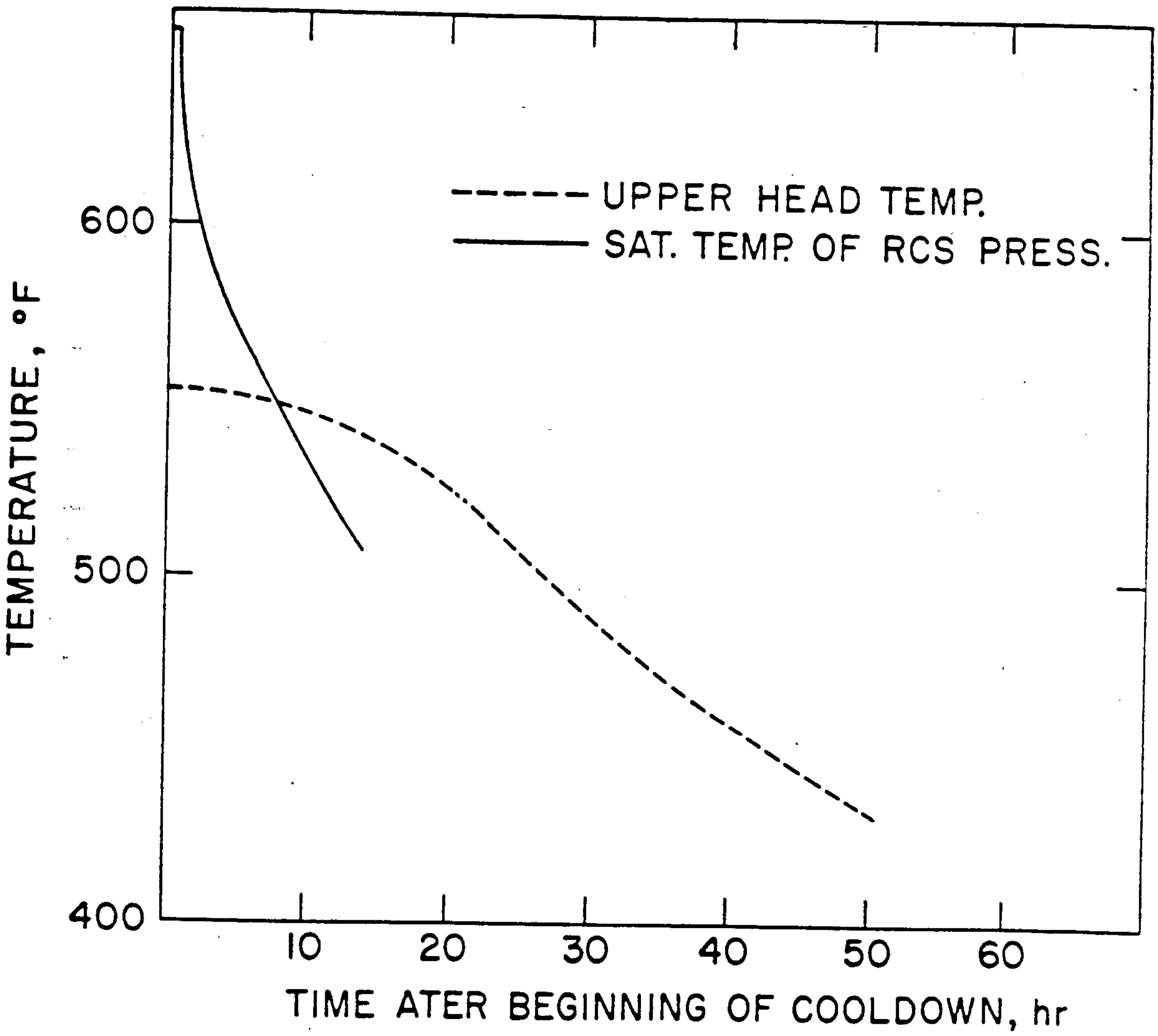

Figure 4.3 Upper head temperature and saturation temperature of RCS pressure with 20°F/hr cooldown.

5. SENSITIVITY ANALYSIS

The results of the natural circulation and cooldown test performed at Diablo Canyon are expected to be referenced by other Westinghouse plants in determining their compliance with BTP RSB 5-1. To facilitate this application, the plant parameters which may affect application of the test results to other Westinghouse plants are identified and the sensitivity of the results to these parameters is estimated for each stage of the test. The results are summarized in Table 5.1. The sensitivity listed is the expected change of the natural circulation conditions for each 10% change of the parameters unless otherwise mentioned.

5.1 Natural Circulation

The parameters which affect the natural circulation flow are:

1. Level of decay heat,
2. Relative elevation of the thermal center steam generators to the thermal center of core, and
3. Coolant flow rate and total pressure drop across the loop during the normal operation.

Equations A.3 and A.6 in the Appendix A shows the approximate relationship between these parameters. Table 5.1 shows the sensitivity of the natural circulation flow to these parameters. It expresses the percent change of natural circulation flow for the 10% change from the Diablo Canyon Plant condition. It indicates that the natural circulation flow rate is generally not sensitive to the variation of most plant conditions. Since the plant's ability to cooldown and to mix boron in the main loop is not significantly affected by slight changes in the natural circulation flow rate, it is concluded that these parameters do not have a major impact the plant's ability to cooldown and mix boron.

5.2 Boron Mixing

The plant's ability to mix boron prior to cooldown mainly depends on the injection rate of boron relative to the total inventory of water in the RCS, as shown in the following equation.

$$\Delta t = \Delta C \frac{V}{G*C} , \qquad (5.1)$$

where Δt = time required to increase the boron concentration of the RCS by ΔC sec.

ΔC = required increase of boron concentration, ppm.

V = RCS volume, ft^3.

G = borated water injection rate, ft^3/sec.

C = concentration of the injected boron, ppm.

Since the time needed for boron injection is much less (order of 1 hour) than the available time prior to the initiation of cooldown (order of 4 hours), minor variation in the boron injection time due to variation of the above parameters will not significantly affect the plant's ability to inject and mix boron. However, each plant should demonstrate that a seismically-qualified boron injection system is available (such as the BIT in the Diablo Canyon plant). It should also be demonstrated that the capacity of the boron source is large enough to sustain the specified flow.

5.3 RCS Cooldown

The plant's ability to cool the RCS at a specified cooldown rate is determined by the capacity of the ASD valves to allow sufficient steam flow to account for the sensible heat and decay heat at the end of the cooldown period when the steam generator pressure is low, and the supply of sufficient cooling water. These are in turn affected by the total amount of water and structural material in the RCS, level of decay heat and the cooldown rate. Table 5.1 shows the sensitivity of the ASD valve opening and the required AFW sensitivity to the parameters affecting the cooldown. (The required AFW amount includes the additional amount of water required to remove the decay heat during the upper head cooldown period when the CRDM fans are not operating. This will be discussed in the next section.) The available capacity of the ASD valve and supply of cooling water for other plants should be compared to the required ASD valve opening and supply of AFW listed in Table 5.1 to determine their adequacy.

5.4 Depressurization

The parameters affecting the depressurization rate are the water inventory at the pressurizer, pressurizer auxiliary spray water temperature and sprayer flow rate according to Equation 3.1. Amount of the ambient heat loss will also affect the demand on the auxiliary pressurizer sprayer.

Table 5.1 summarizes the sensitivity of the depressurization rate to these parameters. If the desired depressurization rate is more than the maximum depressurization rate, manual operation of PORV would be needed to achieve the desired rate.

5.5 Upper Head Cooling

The major parameters affecting the upper head cooling are:

1. Capacity of the CRDM fans when they are in operation,
2. The bypass flow rate to the upper head,
3. Upper head volume,
4. The upper head metal structure mass including the guide tubes, upper head dome and upper head plate.

Operation of the CRDM fans are the dominating factor to determine the upper head cooling rate when they are in operation. For the Diablo Canyon plant, the CRDM fans cooled the upper head at the rate of 17°F/hour when the upper head temperature was 600°F with the CRDM fans. This time would be approximately proportional to the inverse of the fan capacity. The capacity of the CRDM fans at Diablo Canyon was 82,000 ft^3/min (with all four operating).

The bypass flow would have a major impact on the cooling of the upper head if it mixes well in the upper head. However, it was difficult to determine the degree of mixing. The degree of mixing of the bypass flow in the upper head remains a major question for the upper head cooling.

The upper head volume was expected to increase the cooling time roughly in proportion of its size. The Westinghouse analysis[7] of upper head cooling indicates that there are three upper head support plate configurations which critically affect the cooldown rate. Diablo Canyon with a "top hat" support plate was estimated to require only about 8 hours to cool the upper head even without CRDM fans available. Other plants with an "inverted top hat" design would require as much as 32 hours to cool the upper head. This difference in the upper head cooling time was mainly due to the difference in the upper head volume for the different upper plant configurations.

The impact of the amount of the upper head metal structure to the upper head cooling time was more complex; while increasing the amount of guide tube structures, etc. would increase the sensible heat to be removed, it also increases the heat conduction down to the upper plate area. A simple calculation showed that 10% increase of the metal structure decreases the cooling time by about 4%.

5.6 Cooling Water

The required amount of cooling water during the cooldown period was discussed in Section 5.3. Additional cooling water would be needed to remove the decay heat if additional time is required to cooldown the upper head as discussed in Section 4.1. For each additional hour, it was estimated that approximately 5,000 gallons of additional cooling water would be needed. Decay heat level of 0.5% for the 3,300 MW plant during this period was assumed for the estimation. The required water should be linearly adjusted for different decay heat level.

5.7 Summary

Based on Table 5.1, the following plant and operating parameters will be required to apply the results of the natural circulation/boron mixing/cooldown/depressurization test at Diablo Canyon to other Westinghouse plants.

a) Total RCS volume,
b) Upper head volume,
c) Pressurizer water and vapor volume,
d) Steam generator secondary side water volume,

e) Total metal structure mass,

f) Upper head metal structure (detailed geometry of the guide tubes and dome wall will be useful),

g) Elevation difference between the bottom of the core and top of U-tubes in the steam generators,

h) Total pressure drop across the whole loop at 100% power,

i) Pressure drop across the downcomer, core and SG U-tubes, respectively,

j) Ambient heat loss for the entire RCS,

k) Pressurizer ambient heat loss,

l) The coolant flow rate at 100% power,

m) The bypass flow rate from the upper downcomer to the upper head at 100% power (and during the natural circulation if available),

n) Boron injection flow rate and concentration,

o) Desired increase in boron concentration,

p) Boron injection tank capacity,

q) Planned cooldown rate,

r) Planned depressurization rate,

s) Auxiliary pressurizer sprayer water temperature,

t) Max. auxiliary pressurizer sprayer capacity,

u) CRDM fan capacity and number of control rod drives,

v) Auxiliary feedwater pump capacity,

w) Atmospheric steam dump valve capacity,

x) RHR initiation temperature and pressure,

y) Condensate storage tank capacity and other water supply.

Table 5.1 Summary of the Sensitivity Analysis

N.C. Condition To Be Affected	Plant Parameters	Base Condition	Sensitivity	Remark
Natural Circulation Flow		1600-1200 lb/sec		
	Decay Heat	ANS	3.2%	A
	Steady State Coolant Flow	36,918 lb/sec	6.5%	A
	Steady State Pump Δp	84 psia	-3.1%	A
	Elevation Change Between Core and SG	58.3 ft	3.2%	A
Bypass Flow		13 lb/sec		
	Steady State Bypass Flow	77 lb/sec	10%	B+
	Δp Across the DC, Core, SG	8.9/24.6/31.4	*	B
Boron Injection Time		Less than 1 hour		
	Injection Flow Rate	150 gpm	-10%	B+
	Boron Conc. of Inj. Flow	21,000 ppm	-10%	B+
	Desired Conc. Change	300 ppm	10%	B+
	RCS Volume	12,080 ft^3	10%	A
	Boron Injection Tank Cap.	3000 gallon	--	B+
Maxium ASD Valve Opening		70%		
	Cooldown Rate	50°F/hr	5.5%	B
	Decay Heat	ANS	4.5%	C
	Total Water Volume (Primary & Secondary)	20,010 ft^3	4%	B
	Total Metal Structure	3.08×10^6 lb	1.2%	B
	Capacity of ASDV	1.53×10^6 lb/hr at 775 psig	-10%	B

Table 5.1 (Continued)

N.C. Condition To Be Affected	Plant Parameters	Base Condition	Sensitivity	Remark
Maxium Required Auxiliary Pressurizer Sprayer Flow Rate		40 gpm		
	Depressurization Rate	8 psia/min	-10%	B
	Spray Water Temperature	100°F	+25%	B
	Pressurizer Water Volume	900 ft^3	-10%	B
	Pressurizer Ambient Heat Loss	130 kW	-2%	A
	Max. Aux. Pressurizer Sprayer Capacity	55 gal/min	--	B
Upper Head Cooling Time With CRDM Fans Without CRDM Fans		 10 hours 43 hours		
	CRDM Fan Capacity	82,000 ft^3/min	-10%	B
	Bypass Flow	13 lb/sec	*	**
	Upper Head Water Volume	471.7 ft^3	6%	B
	Upper Head Metal Structure (Guide Tubes and Dome Wall)	235,000 lb	-4%	B
Cooling Water		360,000 gallon		
	Decay Heat	ANS	8%	C
	Total System Water Vol.	20,010 ft^3	0.8%	A
	Total Metal Structure	3.08×10^6 lb	0.3%	A
	Upper Head Cooling Time	43 hours	6%	C
	Condensate Storage Tank Capacity	400,000 gallon	--	B
	Other Water Supply	--	--	B

A - Results are not sensitive to these parameters.
B - Results are sensitive to these parameters.
B^+ - Results are not sensitive to these parameters, but these parameters can have major changes from plant to plant.
C - These parameters are estimated or assumed by the calculation.
* - Difficult to determine without detailed calculation or uncertain.
** - For each 100°F increase of the sprayer water temperature.

6. SUMMARY AND CONCLUSION

The natural circulation/boron mixing/cooldown test performed at Diablo Canyon in compliance with the design requirement of BTP PSB 5-1 for a class 2 plant was reviewed. Based on the test results and analyses, it was concluded that

1) The test sufficiently demonstrated that adequate natural circulation was established and the plant was capable of removing the decay heat by the natural circulation using only safety-grade equipment,

2) Adequate boron mixing could be achieved by the natural circulation in the main flow path of the RCS using only safety-grade equipment,

3) The effect of relatively unborated water entering the RCS from the upper head and pressurizer appears to be minimal as long as depressurization is conducted carefully to limit the size of possible void formation.

4) The pressure would rise and reach the PORV actuation pressure without letdown during the boron mixing period,

5) The test adequately demonstrated that it could cool the main RCS to the RHR system initiation temperature while maintaining adequate subcooling during the natural circulation using only safety-grade equipment.

6) The test demonstrated that the upper head could be cooled without void formation when the CRDM fans were in operation,

7) The test results indicate that the upper head cooldown rate without the CRDM fans is about 6°F per hour. This is higher than the conservative BNL calculation (accounting only for conduction heat loss) which estimated a minimum rate of 3°F/hour.

8) The RCS pressure should be maintained above 1200 psia by means of either the pressurizer heaters (if available) or charging during the cooldown period to avoid the void formation in the upper head when the CRDM fans were not in operation.

9) Sufficient supply of safety grade cooling water was available to support the proposed plant cooldown method even if the CRDM fans were not available for the Diablo Canyon plant but the worst case requirements (360,000 gallons) may not be available at all plants.

10) Only one motor-driven AFW pump was sufficient to supply the necessary cooling water throughout the transient.

11) Sufficient ASD valve capacity was available to support the cooldown even when the cooldown rate was 50°F/hour.

12) The availability of the pressurizer heaters and letdown system, while not essential, would affect the operational procedures in a major way. The strategy to reduce the upper head cooling time by intentionally forming void may be difficult to perform without pressurizer heaters. Some plants appear to have the capability to control voiding by charging and venting through reactor vessel head vents.

13) The RCS pressure would increase and stay high, and the PORV may be actuated periodically if the letdown system was not available, due to the boron injection and the continuous injection of RCP seal flow. The operation of the auxiliary pressurizer sprayer normally requires letdown to be in operation to prevent the possible thermal stress on the charging nozzles.

14) It is recommended that Westinghouse provide the details of its estimation for the upper head cooling time without the CRDM fans. (The BNL analysis and the test data indicate that the cooling period should be substantially longer than the 8 hours estimated by Westinghouse).

15) BNL concludes that the test demonstrates compliance with the requirements of the BTP RSB 5-1 for Diablo Canyon.

7. REFERENCES

1. "Diablo Canyon Units 1 and 2 Natural Circulation/Boron Mixing/Cooldown Test Final Post Test Report," WCAP 11086, March 1986.

2. "Forwards Description, Assumptions and Results of Study to Ascertain Potential for Void Formation in Westinghouse Designed NSSS's During Natural Circulations Cooldown/Depressurization Transients," Westinghouse OG-57, April 1981.

3. "Summary of Meeting with FP&L and Combustion Engineering Regarding St. Lucie Unit No. 1 Cooldown on Natural Circulation," A Letter by Chris C. Nelson, NRC, June 25, 1980, Docket No. 50-335.

4. "Palo Verde Trip Report - Boron Mixing and Natural Circulation Test," A Letter by C.Y. Liang and E.F. Branagan, Jr., NRC, February 26, 1986.

5. "Final Safety Analysis Report, Diablo Canyon 1 & 2," Pacific Gas and Electric Company, Docket No. 275/323, 1984.

6. Private Communication with A. Cheung of Westinghouse, October 1986.

7. "Backgroung Information for Westinghouse Owner's Group Emergency Response Guideline, EX-0.2, Natural Circulation Cooldown," HP-Rev. 1, September 1, 1983.

8. Private Communication with Tom Libf of PG&E, December 1986.

Appendix A

NATURAL CIRCULATION FLOW

The single phase momentum equation states

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial}{\partial z}(\rho v^2) = -\frac{\partial p}{\partial z} - g_z\rho - C_f\rho v^2 ,$$

where $C_f = \frac{f}{2d} + K$.

The nomenclature is consistent with standard thermal/hydraulics notation.

For the steady state,

$$\frac{\partial(\rho v)}{\partial t} = 0$$

Therefore,

$$\frac{d}{dz}(\rho v^2) = -\frac{dp}{dz} - g_z\rho - C_f\rho v^2$$

The equation above can be applied to the natural circulation condition since it is slow and thus can be assumed to be pseudo steady state.

Integrating over the loop

$$\oint \frac{d}{dz}(\rho v^2)\,dz = -\oint \frac{dp}{dz}\,dz - \oint g_z\rho dz - \oint C_f\rho v^2 dz$$

Since $\oint \frac{d}{dz}(\rho v^2)\,dz = 0$,

$$\oint \frac{dp}{dz}\,dz = -\Delta p_{pump} ,$$

and $W = \rho v A$,

$$\Delta p_{pump} - \oint g_z \rho dz - \oint C_f \frac{W^2}{\rho A^2} dz = 0 .$$

Since W = constant for a (pseudo) steady state

$$\Delta p_{pump} - \sum_i (g_z \rho \ell)_i - W^2 \sum_i (C_f \frac{\ell}{\rho A^2})_i = 0 \quad (A.1)$$

For the natural circulatione, $\Delta p_{pump} = 0$.

$$W_{nc}^2 = \frac{-\sum_i (g_z \rho \ell)_i}{\sum (C_f \frac{\ell}{<\rho> A^2})_i} \approx \frac{g \Delta Z_{elev} (\rho_{cold} - \rho_{hot})}{\sum (C_f \frac{\ell}{<\rho> A^2})_i} \quad (A.2)$$

$$\approx \frac{g \Delta Z_{elev}}{F_{nc}} (- \frac{\partial \rho}{\partial T}) (T_{hot} - T_{cold})$$

$$= K_1 (T_{cold} - T_{hot}) = K_1 \Delta T ,$$

where ΔZ_{elev} = Elevation difference between the core and steam generator.

From the energy equation

$$Q_{decay} = W_{nc} \Delta h_{core} = W_{nc} c_p (T_{hot} - T_{cold})$$

$$= W_{nc} c_p \Delta T$$

eliminating ΔT from the above two equations

$$W_{nc}{}^3 = K_2 Q_{decay} . \quad (A.3)$$

Or eliminating W_{nc},

$$Q^2 = K_3 \Delta T^3 . \quad (A.4)$$

For the forced circulation with pump, Equation (A.1) becomes

$$\Delta p_{pump} \approx W_{nc}^2 \sum (C_f \frac{\ell}{\rho A})_i = W_{fc}^2 F_{fc} , \qquad (A.5)$$

since

$$\sum_i (g_z \rho \ell)_i << \Delta p_{pump}$$

Equation (A.3) indicates

$$W_{nc}^3 \alpha \frac{1}{F_{nc}} ,$$

and Equation (A.5) indicates

$$F_{fc} \alpha \frac{\Delta p}{W_{fc}^2}$$

F_{nc} and F_{fc} are mainly functions of the geometry of the loop and weak functions of their respective velocities.

Since under steady state conditions the buoyancy force is balanced by the frictional resistance,

$$W_{nc}^3 \alpha \frac{W_{fc}^2}{\Delta p} \qquad (A.6)$$