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EVALUATION OF NATURAL CIRCULATION COOLDOWN TESTS PERFORMED AT DIABLO CANYON, SAN ONOFRE, AND PALO VERDE NUCLEAR POWER PLANTS*

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ABSTRACT

The natural circulation cooldown tests performed at Diablo Canyon, San Onofre, and Palo Verde nuclear power plants were evaluated for the compliance with the U.S. Nuclear Regulatory Commission design requirements. BNL concluded that these tests combined with the supporting analyses demonstrated the natural circulation, boron mixing, and cooldown capability of these plants.

INTRODUCTION

While cooling down under natural circulation conditions on June 11, 1980, the St. Lucie Unit 1 primary system coolant flashed and produced a void in the reactor vessel upper head which forced water into the pressurizer. The reactor was successfully brought to cold shutdown and later analysis indicated that core cooling was never lost. However, based on the U.S. Nuclear Regulatory Commission (NRC) review of the event, a multi-plant action item (MPA B-66) was initiated which required that all pressurized water reactors (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 accordance with plant procedures, would not result in reactor vessel voiding, and
2. verification that supplies of condensate-grade auxiliary feedwater are sufficient to support plant cooldown methods.

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 Owner's Group has issued emergency response guidelines for natural circulation cooldown with voids and Combustion Engineering (C-E) has issued an analysis supporting similar procedures. 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 Branch Technical Position (BTP) RSB 5-1. This essentially requires that a Class 2[a] 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.

BTP RSB 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 using only safety-grade equipment 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

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[a] BTP RSB 5-1 divides plants into three classes for the purpose of implementing the requirements for plant heat removal capability for compliance with its position. The classification was based on the date when construction permit or preliminary design approval applications were docketed and/or an operating license was issue. Recommended implementation for a Class 2 plant is specified in the position letter.

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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 have conducted several natural circulation test at representative commercial plants. These tests were performed at Diablo Canyon Unit 1 for Westinghouse plants,[1] San Onofre Unit 2 for C-E Pre-System 80 plants,[2] and Palo Verde Unit 1 for C-E System 80 plants.[3]

The natural circulation cooldown test procedures at the Palo Verde Nuclear Generating Station (PVNGS) were substantially different from those at the Diablo Canyon Power Plant (DCPP) and the San Onofre Nuclear Generating Station (SONGS). In the natural circulation test conducted at the DCPP and SONGS, the test procedures were designed to demonstrate that the plants could be cooled down to the residual heat removal (RHR) system initiation conditions under natural circulation without forming steam bubbles in the upper head. Therefore, the commencement of depressurization was delayed until the upper head was finally cooled below the saturation temperature of the RHR initiation pressure (approximately 232°C (450°F) for both plants) following the cooldown of the main reactor coolant system (RCS) to the RHR initiation temperature. However, a C-E study[4] indicated that this delay of depressurization to avoid forming steam bubbles in the upper head was estimated to be too long for a System 80 plant to complete cooldown within the available seismic Category I condensate supply due to the large size of the upper head of a System 80 design. Therefore, the procedures employed by the PVNGS to demonstrate its compliance with BTP RSB 5-1 involved intentionally forming steam bubbles in the upper head and subsequently venting them by using the reactor vessel gas vent system.

The specific items addressed by these natural circulation cooldown tests included a demonstration of the ability to mix boron under natural circulation, an evaluation of reactor vessel upper head (RVUH) cooldown rates, an assessment of the adequacy of the seismic Category I condensate supply and an evaluation of the adequacy of the safety grade nitrogen supply for the atmospheric dump values (ADV). The purpose of this paper was to evaluate the test data, the supporting analyses, and the conclusions submitted in the test reports.

DESCRIPTION OF THE TESTS

Natural circulation cooldown tests were conducted at the Diablo Canyon Power Plant Unit 1[1] on March 28 and 29, 1985, at the San Onofre Nuclear Generating Station Unit 2[2] on July 27, 1983, and at the Palo Verde Nuclear Generating Station[3] Unit 1 on July 24 and 25, 1986, to demonstrate the capability of their respective plants to mix boron and cooldown under the natural circulation conditions in compliance with the BTP RSB 5-1 requirements.

All of the plants were operating at full or near-full power when the tests began. The natural circulation portion of the tests were initiated by the reactor coolant pump (RCP) trip; however, at the DCPP and PVNGS, the turbine trip and reactor trip preceded the RCP trip. After establishing natural circulation, the boron injection and mixing experiment was conducted using the charging pumps. The required amount of boron was added to the RCS in about 20-40 minutes. In all three tests, the complete mixing of boron in the RCS was verified within two hours after initiation of boron injection. The RCS's were maintained at hot-standby under natural circulation for more than four hours before initiation of cooldown as required by BTP RSB 5-1.

The cooldown portion of the tests was commenced by modulating the ADV's. At the SONGS and PVNGS, the cooldown rate was approximately 27.8°C/hour (50°F/hour) and the cooldown was completed in slightly greater than 4 hours. At the DCPP, the cooldown rate was controlled at about 11.1°C/hour (20°F/hour) and it took slightly more than 8 hours for the RCS to reach the RHR initiation temperature.

At the completion of the cooldown to the RHR entry temperature, depressurization was commenced using the auxiliary pressurizer spray system to achieve the final RHR entry condition. At the DCPP and SONGS, the depressurization was performed without bubble formations in the upper head. However, as discussed above, steam bubble formation was observed during depressurization at the PVNGS. When the void was detected in the upper head, the depressurization was secured and the reactor vessel head vent valve was opened to collapse the void. The cycle of depressurization and head vent opening was repeated to reach the RHR entry pressure since the RCS pressure was still too high to enter the RHR system at the end of the first cycle.

It took about 15 hours at the DCPP and PVNGS, and about 20 hours at the SONGS to reach the RHR entry condition after the RCP trips. Once the RHR initiation condition was achieved, the RCS cooldown was continued by operating the RHR system and the systems were finally brought to cold shutdown conditions at the DCPP and PVNGS. However, at the SONGS the natural circulation cooldown test was terminated by restarting one of the RCPs.

Although the NRC required cooldown capability using only safety-grade equipment, some non safety-grade equipment and systems were used plants did not want to risk damage to any of the equipment for the tests. However, unavailability of these systems may have significant impact on the plant's performance under the strict BTP RSB 5-1 conditions. The significant exceptions to the safety grade specifications were operation of the pressurizer heaters, letdown system, and control rod drive mechanism (CRDM) fans. The impact of the potential unavailability of these systems will be assessed later.

REVIEW OF THE TESTS AND ANALYSES

To evaluate the natural circulation tests conducted at the DCPP and SONGS, the natural circulation cooldown transients from the full power to the RHR initiation conditions under the strict BTP RSB 5-1 scenario were simulated at Brookhaven National Laboratory (BNL) using the RELAP5/MOD1[5] code. The simulation included boron injection and cooldown/depressurization under the natural circulation. To assess the impact of the deviation of the test procedures from those of the BTP RSB 5-1 guidelines, only safety-grade equipment, systems and components were assumed to be in operation. A similar simulation was performed for a System 80 C-E PWR by C-E using its long-term cooling (LTC) code,[6] which applies to the natural circulation test at the PVNGS. Results from these simulations were used in the evaluation of the three natural circulation cooldown tests.

The tests were divided into four stages: natural circulation, boron mixing, cooldown and depressurization. Additionally, cooling of the reactor vessel upper head, cooling water requirements for the cooldown operation and the effect of non safety-grade systems used in the tests will be discussed in detail.

1) Natural Circulation

In all three tests, stable natural circulation was established within 20 minutes of the RCP trips. Sufficient loop flow existed to remove the decay heat in the tests without the water temperature increase between the inlet and outlet of the vessel exceeding that of full power operations. The test RCS flow was slightly lower than that obtained in the calculations under the BTP RSB 5-1 conditions since the actual decay heat in the tests was less than that used in the calculations. The analyses confirmed that sufficient natural circulation flow would exist to remove the decay heat, and the water temperature increase in the vessel would not exceed that of normal operation even when the maximum decay heat was applied. This conclusion was supported by several separate natural circulation tests performed under steady state conditions for the Westinghouse[7] and C-E PWRs.[8]

At the beginning of the natural circulation test, the hot leg temperature of the RCS declined rapidly immediately after the reactor trip in all three tests as expected. Once natural circulation was established, RCS temperature essentially remained stable during the hot standby period. The RCS pressure and pressurizer level in the tests did not match those predicted by the calculation because they were affected by the operation of some of the non safety-grade equipment such as the pressurizer heaters and letdown. However, the natural circulation flow was not affected by the RCS pressure during this period and, thus, unavailability of these systems would not affect the plants' ability to establish natural circulation and remove the decay heat.

2) Boron Mixing

The boron mixing experiment was conducted in all three natural circulation tests using charging pumps prior to the cooldown test. Complete boron mixing in the RCS loops was noted within two hours by manual sampling and boronometer readings. These tests and the analyses indicated that delivery and mixing of borated water to the RCS was adequate and the increase in boron concentration in the main flow path of the RCS would be very rapid under natural circulation conditions.

However, the coolant in the upper head region of the vessel was expected to remain nearly stagnant under the BTP RSB 5-1 conditions since the bypass flow into the upper head is substantially lower than that under the forced circulation and no significant mixing mechanisms exist when the CRDM cooling fans are not in operation. The CRDM fans not only contribute to cooling of the upper head, but also help to mix the upper head fluid with the bypass flow by creating natural convection. Similarly, the fluid in the pressurizer may be isolated from the rest of the RCS if the sprays are not in operation. This suggests that the boron mixing in the upper head and pressurizer may be very slow. This relatively unborated water from the upper head and pressurizer has the potential to dilute the boron concentration in the core when it is forced back into the main RCS during upper head voiding. However, the maximum expected boron dilution was estimated to be less than 5% based on analyses and data available from the St. Lucie event[9] and the Palo Verde natural circulation test.[3]

Another concern during boron mixing under natural circulation is the pressurizer water level increase due to the injection of additional mass into the system without letdown. The letdown system is not safety-grade and thus can not be credited in the BTP RSB 5-1 scenario. In all three tests, letdown was in operation during the boron injection period. This letdown flow helped to limit the increase of the pressurizer level and pressure. Without letdown, it was estimated that boron injection would increase the pressurizer level by about 20-40% at the PVNGS and SONGS. Since the pressurizer level would decrease to about 30% due to liquid contraction during the early phase of natural circulation before boron injection, the additional water due to boron injection can be accommodated in the pressurizer. This indicates that boron injection can be conducted prior to cooldown without overfilling the pressurizer even when letdown is not available at these plants. Unavailability of letdown was a more serious problem at the DCPP, since it required small but continuous RCP seal injection flow which introduced additional water into the RCS. A separate analysis indicated that the pressure would eventually reach the power operated safety valve (PORV) actuation pressure during the boron injection period. It was observed that the PORV was periodically opened during boron injection before initiating letdown in the DCPP natural circulation test. To limit the pressurizer level or pressure increase during the boron injection period, part of the boron injection could be delayed and performed concurrently with the cooldown. Contraction of the water volume would provide space to accommodate the additional water due to boron injection limiting the increase of pressurizer level.

3) Cooldown of the RCS

In all three tests, the RCS was maintained at hot standby at least four hours before initiating the cooldown as required by BTP RSB 5-1. The cooldown was conducted by using the ADVs in these tests. The tests and analyses demonstrated that cooldown of the main flow paths of the RCS (excluding the upper head cooling) to the RHR entry temperature can be accomplished while maintaining the required subcooling during natural circulation using only safety-grade equipment. At the DCPP the letdown system was used during the cooldown period to prevent filling the pressurizer due to continuous RCP seal injection. Although use of the letdown system does not appear to be essential during this period, not using the letdown would keep the RCS pressure high and actuate the PORV when the cooldown rate was low. Increasing the cooldown rate to 27.8°C/hour (50°F/hour) would decrease the pressure throughout the cooldown period and would eliminate the need for PORV operation. Operation of charging was necessary to maintain the pressurizer level and prevent a rapid pressure drop during cooldown for the C-E plants. Sufficient charging capacity was available at these plants. At SONGS, the RCS pressure was estimated to decrease to 8 MPascal (1160 psia) when the pressurizer level was maintained at 50% due to the heat loss from the pressurizer to the containment. However, fluid in the main flow paths of the RCS loops maintained the required margin of subcooling during the cooldown period. Void formation in the upper head was not detected during cooldown in any of these tests although the pressure continued to decrease due to contraction of the liquid and ambient heat loss from the pressurizer at SONGS and PVNGS. However, the C-E analysis[6] indicates that upper head void formation could occur during the cooldown period at the PVNGS since the size of the upper head is bigger than that of SONGS and thus cooling of the upper head is slower at the PVNGS. The upper head cooling will be discussed in more detail later.

The ADV capacity was calculated to be sufficient to maintain the cooldown rate of 27.8°C/hour (50°F/hour) for all these plants. The main steamlines at these plants are designed so that steam can be released from both steam generators using only one ADV should one of the two ADVs become inoperable due to a single failure. This design makes it possible to maintain symmetric cooldown even if one ADV is not available, although at a lower cooldown rate.

4) Depressurization

The tests demonstrated that the reactor coolant systems could be depressurized to the RHR initiation pressure under the natural circulation conditions using the auxiliary spray. However, letdown which is not safety-grade, was in operation during the depressurization to maintain the pressurizer level in these tests. With no letdown available, the pressurizer level was estimated to increase by about 40% due to the operation of auxiliary sprays to depressurize the RCS to the RHR entry condition at the SONGS. The pressurizer level would increase even more at the DCPP without using letdown due to the continuous RCP seal injection. It may be necessary to use the PORV and/or head vent valve to depressurize, especially near the end of depressurization at these plants under the BTP RSB 5-1 scenario.

The tests also demonstrated that the depressurization can progress immediately after the cooldown without void formation in the upper head at these plants when the CRDM fans are available to cool the upper head. However, the CRDM fans are not safety-grade and thus cannot be credited under the BTP RSB 5-1 conditions.

For the PVNGS, a C-E study[6] indicated that the hold period before depressurization to avoid forming steam bubbles in the upper head was too long for a System 80 plant to complete cooldown within the available seismic Category I condensate supply. Therefore the procedures employed during PVNGS natural circulation test opted to depressurize immediately after cooldown without a holding period, thus, allowing a void to form in the upper head. During the PVNGS test, the steam void was formed about two hours after initiation of depressurization and was subsequently collapsed by increasing the charging flow with the reactor vessel head vent valves open. This procedure forced coolant into the upper head and cooled the head below the saturation temperature (230°C) of the RHR entry pressure.

The PVNGS test demonstrated that the RCS could be depressurized to the SCS initiation pressure (27.6 bar = 400 psia) in about four hours using the auxiliary spray and head vent valves under natural circulation conditions. However, the letdown system and the CRDM cooling fans (non-safety grade equipment) were in operation during cooldown and depressurization. Even with letdown in operation, the pressurizer level increased to 75% during the period of void formation. Without letdown, the pressurizer may have filled. To avoid overfilling the pressurizer when the letdown system is not available, the size of the void formation may have to be limited. Several cycles of voiding and venting may have to be repeated to achieve sufficient upper head cooling. The use of several void cycles would not significantly affect the total cooling time.

Another strategy to mitigate possible water-solid operation of the pressurizer during depressurization when letdown is not available, is to induce upper head voiding during the cooldown period rather than during the depressurization period. Analyses[4] indicated that steam voids could form in the upper head during cooldown if the pressurizer level was kept at 33% and the RCS pressure was allowed to decrease due to heat loss from the pressurizer. The pressure was estimated to decrease at the rate of approximately 0.14 bar/min (2 psi/min) under this condition. The pressurizer level increase would be less because contraction of the RCS liquid during cooldown would provide space for the displaced water from the upper head. The analysis indicated that the pressurizer level increase would be less than 15%. Therefore, it may be preferable to allow the upper head void formation to occur during the cooldown period rather than during the depressurization period. This strategy would minimize the impact of the unavailability of the letdown system.

5) Reactor Vessel Upper Head Cooling

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, a potential exists for void formation in the upper head during the cooldown/depressurization under natural circulation conditions. This is a major concern regarding the plant's ability to achieve cold shutdown conditions under natural circulation.

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 and degree of its mixing in the upper head,

c) Heat conduction from upper head to upper plenum through the guide tube structures and the upper head dome.

Among these, availability of the CRDM fans is the dominating factor. It appears that operation of the CRDM fans provides a mixing mechanism of bypass flow by creating natural convection within the upper head (cold fluid above the warmer fluid) in addition to directly removing heat from the upper head. The tests at the DCPP and SONGS where the CRDM fans were in operation, demonstrated that depressurization could proceed within two hours of completion of the cooldown of the main flow paths of the RCS loops. These translate into a 10-15°C/hour cooldown of the upper head. The CRDM fans, however, are not seismically qualified equipment and no credit can be taken for these under the BTP RSB 5-1 assumption. Without the CRDM fans available, the cooling of the upper head would depend on the other mechanisms. Among the factors listed above, the second mechanism would be a major factor if sufficient bypass flow exists and it is mixed well in the upper head region.

Analyses[4,7] indicated that substantial bypass flow to the upper head existed under natural circulation for all three plants. They also indicated that if this bypass flow mixed completely with the upper head fluid, cooling of the upper head would be sufficiently fast so that the upper head temperature would reach the saturation temperature (about 232°C = 450°F) of the RHR entry pressure (about 2.4 MPascal = 350 psia) before the hot leg temperature of the main RCS would reach the RHR entry temperature (about 177°C = 350°F). However, mixing of the bypass flow in the upper head may not be good considering the large amount of guide tube structures within the upper head and the lack of any identifiable mixing mechanism, when the CRDM fans are not in operation. This suggests that the fluid in some parts of the upper head, especially in the upper region, has the potential to remain thermally stratified and depressurization may not proceed immediately after the cooldown of the main RCS to avoid bubble formation in the upper head.

Under this circumstance, the only significant mechanism to cool the upper head would be heat conduction, through the guide tube structures and the upper head dome wall, to the cooler region of the upper plenum. A simple calculation was performed to estimate the cooling rate of the upper head based on the conduction through these structures for the DCPP and SONGS. The upper head was divided into three heat conduction nodes and bypass flow was assumed to mix with the fluid at the bottom part of the upper head. The results showed that it took approximately 40 hours for the uppermost part of the upper head to reach 232°C (450°F) after beginning the cooldown. The upper head cooling time was not particularly sensitive to the RCS cooldown rate. Several simplifying and conservative assumptions were made in this calculation. Specifically: The upper head fluid was completely stagnant. Conduction was the only mechanism for cooling. Heat conduction was assumed to be one-dimensional and the metal properties such as thermal conductivity and specific heat were assumed to be constant. 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. A similar study performed by C-E[4] estimated this time to be approximately 15.5 hours after the start of cooldown for a plant of SONGS type. (The FSAR of St. Lucie Unit 2[10] estimated this time to be 25.7 hours using more conservative assumptions.) The substantial differences in these predictions appeared to be caused by different assumptions regarding the uniformity of the temperature in the upper head. The C-E study assumed a uniform upper head temperature while the BNL study calculated a sharp temperature gradient as a result of assuming stagnation of the fluid within the upper head. It should be noted that these were scoping calculations and more studies would be needed to obtain an accurate prediction of the upper head cooling rate.

This long upper head cooling time (estimated to be about 55 hours for the PVNGS according to the C-E analysis[4]) is the major reason that the PVNGS decided to cool the upper head by intentionally creating a steam bubble in the upper head.

The numerical simulations showed that the margin of subcooling in the upper head disappeared during the cooldown without the CRDM cooling fans in operation, when the pressurizer level was maintained below 50%. A slight margin of subcooling was maintained only when the pressurizer level was kept at 60%. This would not leave sufficient room in the pressurizer for the auxiliary spray water to avoid water solid operation of the pressurizer, since it was estimated that without letdown the pressurizer level would increase by about 40% to depressurize the RCS to the RHR entry pressure (24 bars = 376 psia) using auxiliary sprays. The margin of subcooling would further deteriorate if the upper head cooling is further delayed. The pressure control in this situation would pose a major difficulty and a strategy to form steam bubbles to cool the upper head fluid may have to be considered in order to meet the BTP RSB 5-1 requirement.

6) Cooling Water and Compressed Nitrogen Gas Requirement

BTP RSB 5-1 requires that the seismic Category I water supply for the auxiliary feedwater system for a PWR has sufficient inventory to bring the RCS to the RHR entry conditions based on the longest cooldown time. Approximately 450-530 m^3 (120,000-140,000 gallons) of auxiliary feedwater was used during the DCPP and SONGS tests. This included the water to remove 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 to remove the decay heat. However, the total cooldown operation may last as long as 40-50 hours including the hold time (time needed for the upper head fluid to cool down to the saturation temperature of the RHR entry pressure) when the CRDM fans are not available. Furthermore, the decay heat during the tests were substantially lower than the maximum decay heat expected during the life span of these plants. Accounting for the additional decay heat and the prolonged cooldown period, a total of 1320 m^3 (350,000 gallons) of cooling water was calculated to be needed based on the ANS limiting decay heat. This is approximately equal to the safety grade water available at SONGS from the condensate storage tank and other sources (1300 m^3 = 344,000 gallons).[2] At the DCPP, more than 3780 m^3 (one million gallons) of water is available from the condensate storage tank and other seismic Category I sources.[1]

The PVNGS did not need a long hold period for upper head cooling, since it decided to cool the upper head by intentionally forming steam bubbles in the upper head and subsequently venting them by using the reactor vessel gas vent system. The Palo Verde test took about 15 hours and about 635 m^3 (168,000 gallons) of cooling water. Adjusted for the maximum decay heat, it was estimated that it would take about 905 m^3 (239,000 gallons) of cooling water under the BTP RSB guidelines. This is substantially less than 1135 m^3 (300,000 gallons) which is the minimum condensate storage tank available volume required by the PVNGS Technical Specifications.

The test data and analyses also indicated that one motor-driven AFW train could supply sufficient cooling water even when the feedwater demand was at its maximum for all three plants.

Another concern during the natural circulation cooldown is the capability to operate the ADVs. Adequate supply of class I nitrogen or air should be secured on site to operate the ADVs unless there are other available means of operating them. According to the PG&E staff, eight bottles of class I air are installed at the two units at Diablo Canyon for this purpose and these are expected to last about 18 hours.[11] Additionally, 35 bottles of air are stocked on site at all times. This translates into an additional 80 hours of supply, which is considerably more than the estimated cooling time even with the most conservative assumptions. For the SONGS, it was observed during the test that the average rate of nitrogen usage was about 0.43 MPascal/hour (62 psi/hour) and C-E estimated that a fully charged nitrogen accumulator would last about 17.7 hours at that rate of usage. It appears that the supply of nitrogen from the accumulators is not sufficient to last the long hold time for the upper head cooling. However, the ADVs at SONGS are manually operable and it was demonstrated during the test that manual local control via manual handwheels was possible in the event that the nitrogen supply should become depleted. At the PVNGS, the test data indicated that the capacity of the nitrogen accumulator system was sufficient to supply nitrogen for 14 hours and 20 minutes based on the most conservative estimation of the consumption rate and accumulator capacity. This exceeded the maximum estimated BTP RSB 5-1 scenario duration of 13.3 hours. The ADVs at the PVNGS are also equipped with manual handwheels as at the SONGS.

7) Effect of Non Safety-Grade Systems Used in the Test

During the tests, several non-safety grade equipment and systems were used; they were the pressurizer heaters, letdown systems and CRDM fans. Unavailability of some of these systems may have a significant impact on the plant's performance under the strict BTP RSB 5-1 scenario. The effect of unavailability of these systems is summarized in this section.

(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.

In all three tests, the pressurizer heaters were available for the initial plant response immediately following the plant trip. Availability of the pressurizer heaters during the initial period allows for more precise pressure control during the thermal transient following RCP trip, but the heaters do not appear to be essential. In fact, it may be desirable to allow the pressure to slowly decrease prior to boron injection, since boron injection would increase the pressurizer level and the RCS pressure, and may necessitate opening of the safety valves or vent valve if the letdown system is not available.

During the cooldown period, the RCS pressure is expected to decrease due to the contraction of the RCS water and the ambient heat loss from the pressurizer. The pressurizer heaters were continuously available during the SONGS test to maintain the RCS pressure at the normal operating pressure until depressurization. They were also used occasionally at the DCPP. Without the pressurizer heaters, any necessary increase in the RCS pressure would be accomplished with the safety-grade charging system. However, maintaining pressure using the charging system for a prolonged period would not be desirable, since it would increase the pressurizer water level and may eventually cause water-solid operation of the pressurizer.

At the PVNGS, the heaters were not used after the plant was stabilized. Since the cooldown procedures at PVNGS involve intentionally inducing void formation in the upper head, it is not necessary to maintain RCS pressure control and the pressurizer heaters are not needed. Therefore, unavailability of the pressurizer heaters would not have a significant impact on the natural circulation cooldown at PVNGS.

(b) Letdown

The letdown system provides a direct means to reduce the water inventory in the RCS. Unavailability of the letdown system may complicate the pressurizer level and pressure control under the BTP RSB 5-1 scenario since both available safety grade pressure control system (charging and auxiliary pressurizer spray) increase the water inventory in the RCS.

There are two periods when availability of letdown could be particularly important. During the boron injection period, letdown helps to limit the increase of the pressurizer level when a substantial amount of borated water is injected into the system. Without letdown, the pressurizer level would have increased by about 20-40%. Since the pressurizer level would have decreased prior to boron injection due to the liquid contraction during the early phase of natural circulation, the water added during the boron injection period could be accommodated in the pressurizer. However, because charging is sometimes used immediately after the reactor trip to maintain the pressurizer level, the pressurizer level may be too high to accommodate the additional water. If the pressurizer level was already high prior to boron injection for some reason, part or all of the boron injection could be performed concurrently with the cooldown transient. There would be enough space in the pressurizer due to the contraction of water to accommodate the boron injection water.

Unavailability of the letdown system may also affect the depressurization procedures. The operation of the auxiliary pressurizer sprays increases the pressurizer level significantly. It may be necessary to use the head vent valve or PORV instead of the auxiliary pressurizer spray, especially near the end of depressurization. This would slow down depressurization and result in somewhat longer depressurization time.

In the DCPP, unavailability of the letdown would affect the cooldown procedures even more significantly since a substantial amount of RCP seal injection should be maintained even during the natural circulation.

When a steam void is formed in the upper head, it displaces water into the pressurizer from the upper head. If the void formation occurs during the depressurization period as in the PVNGS test, the combined flow from the auxiliary pressurizer spray and the upper head increase the pressurizer level by more than 50%. In the test, letdown was used to reduce the pressurizer level just prior to void formation to ensure that the pressurizer could accommodate the displaced water from the upper head. Without letdown, high pressurizer level would result. If control of the pressurizer level and the pressure should become difficult, the size of the void may have to be limited and several cycles of voiding and venting would have to be performed to achieve the upper head cooling. The use of several voiding cycles instead of a single cycle would not appear to significantly affect the total cooling time.

According to the C-E analysis,[6] void formation could occur during the cooldown period at the PVNGS if the RCS pressure was allowed to decrease during the cooldown without charging due to the combined effect of the pressurizer ambient heat loss and RCS liquid contraction. Under this circumstance, the pressurizer level increase would be much less because contraction of the liquid during the cooldown would provide room for the displaced water. The analysis indicated that the pressurizer level increase would be less than 15%. Therefore, it may be preferable to allow the upper head void formation to occur during the cooldown period rather than during the depressurization period when the letdown system is not available.

(c) CRDM Cooling Fans

The CRDM cooling fans contribute significantly to the upper head cooling. Unavailability of the CEDM fans could increase the upper head cooling time considerably and a substantial amount of additional cooling water would be required if the cooling is to be completed without void formation. In fact, this prolonged upper head cooling time, when the fans are not available is the main reason why PVNGS chose the strategy to intentionally induce the void formation in the upper head. However, once the strategy to cool the upper head by void formation is taken, the cooling effect of the CRDM cooling fans is less important and unavailability of the fans would not have a major effect on the cooldown procedures.

SUMMARY AND CONCLUSION

The natural circulation cooldown tests which were performed at Diablo Canyon Unit 1, SONGS Unit 2 and PVNGS Unit 1 to demonstrate their compliance with the design requirement of BTP RSB 5-1 for a Class 2 plant were reviewed. Based on the test results and analyses, it is concluded that:

1) The tests demonstrated that adequate natural circulation was established and the plants were capable of removing the decay heat by natural circulation using only safety-grade equipment.
2) Adequate boron mixing could be achieved in less than one hour by natural circulation within the main flow path of the RCS using only safety-grade equipment.
3) Relatively unborated water entering the RCS from the upper head and pressurizer will not have a significant effect on criticality 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 during the boron injection period without letdown at the DCPP.
5) Boron injection may be conducted prior to cooldown without filling up the pressurizer even when letdown is not available at the SONGS and PVNGS. However, it may be desirable to allow the pressurizer level to decrease prior to boron injection to provide space to accommodate the additional water from boron injection.
6) The tests demonstrated that natural circulation heat removal could cool the main flow paths of the RCS to the RHR initiation temperature while maintaining adequate subcooling using only safety-grade equipment.
7) The tests demonstrated that the upper head could be cooled without void formation and the RHR entry conditions can be achieved within 15 hours, when the CRDM fans were in operation.
8) It would take considerably longer to cool the upper head and achieve the RHR initiation condition without upper head voiding if the CRDM fans are not available. The estimated cooling time for the upper head without the CRDM fans varied widely depending on the assumptions regarding mixing of upper head fluid. Calculations indicated that it could be as long as 40 hours at the DCPP and SONGS.
9) It would take about 11.5 hours to achieve the RHR initiation conditions under the BTP RSB 5-11 scenario if upper head void formation is allowed to occur at the PVNGS.

10) Upper head voiding can occur either during cooldown or during depressurization depending on the operation of the CRDM cooling fans, letdown and charging at the PVNGS. The duration of the cooldown transient and the cooling water usage are not significantly affected by the timing of upper head voiding. It appears to be preferable to allow voiding to occur during cooldown rather than during depressurization. This strategy would minimize the impact of the possible unavailability of the letdown system.

11) The test demonstrated that the RCS could be depressurized to the RHR initiation pressure under natural circulation using the auxiliary spray if the letdown system is available. However, if the letdown system is not available, the pressurizer could become full and it may be necessary to use the PORV or the reactor vessel head vent valve to depressurize.

12) A sufficient supply of safety grade cooling water is available in the condensate storage tank to support the proposed plant cooldown methods at all three plants even if the CRDM fans were not available.

13) Only one (of two) motor-driven AFW pumps was sufficient to supply the necessary cooling water throughout the transient.

14) Sufficient ADV capacity was available to support the cooldown even at high cooldown rates. Failure of one of two ADVs would not affect the plants' ability to cooldown.

15) An adequate supply of safety-grade nitrogen or air to control the ADVs is available for the duration of cooldown at the DCPP and PVNGS. An additional supply of safety-grade nitrogen gas is desirable at the SONGS for the prolonged cooldown period.

16) The strategy for pressure control should be very carefully planned when pressurizer heaters and letdown are not available. Both of the available safety-grade pressure control systems (charging and auxiliary spray) require injection of additional water into the system. Without letdown this may result in overfilling of the pressurizer. Occasional use of the PORV and/or head vent valve may be preferable to extended auxiliary spray operation.

17) The natural circulation cooldown tests, combined with the supporting analysis, demonstrated that the plants meet the BTP RSB 5-1 requirements for a Class 2 plant with respect to the natural circulation, boron mixing, safety-grade condensate water supply and capability to operate the ADVs.

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