

ANP-10288NP Revision 1

U.S. EPR Post-LOCA Boron Precipitation and Boron Dilution Technical Report

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ABSTRACT

This technical report provides an evaluation of two phenomena that potentially occur following loss of coolant accidents (LOCA) in the U.S. EPR:

- Boron precipitation
- Boron dilution during a small-break LOCA (SBLOCA)

Boron Precipitation

During the pool boiling phase that follows the initial mitigation of all but the smallest LOCAs, boron could concentrate in the reactor core region if countermeasures are not taken. If the concentration of boron reaches the solubility limit, boron precipitates out of solution and potentially causes coolant channel blockage. The design of the U.S. EPR provides the operator with two actions that prevent the concentration of boron from reaching the solubility limit:

- Continue the initial automatic cooldown of the steam generators (SGs) at 90°F/h to cool and depressurize the reactor coolant system (RCS) for small breaks.
 This allows the low-head safety injection (LHSI) system to refill the RCS and establish natural circulation if the break is small enough.
- Redirect part of the LHSI to the RCS hot leg. The simultaneous injection into both hot and cold legs limits the boron concentration in the core, regardless of break location, and prevents the concentration of boron when the breaks are too large to establish natural circulation.

This evaluation demonstrates that these measures are adequate to prevent boron precipitation.

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Boron Dilution

Generic Safety Issue 185 (GSI 185) identified a concern for potential recriticality following an SBLOCA because of the accumulation of de-borated water in the reactor coolant pump suction piping due to the condensation of steam in the steam generator tubes during reflux boiling. It is postulated that when RCS circulation restarts, this deborated water moves into the core, thus reducing the boron concentration below the minimum required to prevent core recriticality. This report presents test data from the PKL integral test facility, results from CFD analysis of a representative EPR, and an analysis for the U.S. EPR, which demonstrate that the safety injection is able to reborate the water before it reaches the core inlet when natural circulation restarts. Thus, recriticality is precluded.

Record of Revisions

		Change	
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Number	Date	Page	Description and Justification
0	11/07		Original issue
1	1/10	Abstract	Editorial clarifications
		Nomenclature	Added acronyms needed from new text
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		Section 3.1	Modified to focus on the key conclusions of the PKL tests. Modified to include PKL III F1.1 test results.
		Section 3.2	Added section for the CFD analyses
		Section 3.3, Table 3-1, Table 3-2, & Table 3-3.	Added editorial clarification and added results from an additional neutronics analysis
		Section 4.0	Added reference 6

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Nomenclature

Acronym	Definition
CFD	Computational Fluid Dynamics
EBS	Extra Borating System
ECCS	Emergency Core Cooling System
GSI	Generic Safety Issue
IRWST	In-Containment Refueling Water Storage Tank
LBLOCA	Large Break Loss of Coolant Accident
LHSI	Low Head Safety Injection
LOCA	Loss of Coolant Accident
MHSI	Medium Head Safety Injection
MSRT	Main Steam Relief Train
PCT	Peak Cladding Temperature
PWR	Pressure Water Reactor
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHRS	Residual Heat Removal System
SBLOCA	Small Break Loss of Coolant Accident
SI	Safety Injection
SG	Steam Generator
TSP	Trisodium Phosphate

1.0 INTRODUCTION

The reactor coolant system (RCS) contains boric acid at a concentration that maintains the core subcritical with all but the most reactive rod inserted in the core following a loss of coolant accident (LOCA). The required boron concentration varies with time during an operating cycle. The boric acid may concentrate in the core region during the long-term pool boiling phase of a LOCA, potentially reaching the point where it precipitates causing coolant channel blockage. Because the boric acid concentrates slowly, the operator has time to act to prevent precipitation.

For a small-break LOCA (SBLOCA), the operator prevents excessive boron concentration in the core region by establishing natural circulation. Natural circulation is achieved by cooling the RCS with the steam generators (SGs) to reduce pressure so that the medium head safety injection (MHSI) and low-head safety injection (LHSI) pumps can refill the primary loops. For a large-break LOCA (LBLOCA), the operator prevents excessive boron concentration in the core region by diverting a portion of the LHSI to the hot leg. Delivery of emergency core cooling system (ECCS) water to the core from both the hot legs and cold legs eliminates the potential for boric acid precipitation during an LBLOCA, regardless of break location.

Generic Safety Issue 185 (GSI 185) identified a concern for potential recriticality during a SBLOCA because of the accumulation of de-borated water in the reactor coolant pump (RCP) suction piping due to the condensation of steam in the SG tubes during reflux boiling. It is postulated that when circulation restarts, this de-borated water moves into the core and reduces the boron concentration below the minimum required to prevent core recriticality. Test data and analysis demonstrate that natural circulation is established, and the water is re-borated by safety injection before it reaches the core.

2.0 BORON PRECIPITATION

2.1 *Introduction*

Boron concentrates in the core region during the continued pool boiling that follows the initial recovery phase of a LOCA. Boron precipitates when its concentration exceeds the solubility limit. The U.S. EPR incorporates two design features that limit boric acid concentration in the core and other regions of the RCS to levels that will not precipitate:

- Main steam relief trains (MSRTs). The MSRTs depressurize the SGs during an SBLOCA, which cools and depressurizes the RCS, increases safety injection flow, and establishes natural circulation. A partial cooldown is initiated automatically on a safety injection signal. This action depressurizes the SGs to 870 psia at a rate corresponding to 180°F/h. Operator action is credited to continue the partial cooldown of the SGs at 90°F/h.
- LHSI capability. LHSI capability allows the operator to redirect a portion of the flow to the residual heat removal system (RHRS) letdown line nozzles on the respective hot legs. This action prevents the concentration of boron, regardless of break location.

S-RELAP5 analyses are performed to evaluate the plant thermal-hydraulic behavior during the post-LOCA period that is potentially susceptible to boron precipitation. Bounding calculations based on these analyses demonstrate that boron concentrations remain within solubility limits.

2.2 Small-Break LOCA

SBLOCA events are evaluated using the approved S-RELAP5-based methodology described in the Codes and Methods Applicability Report for the U.S. EPR (Reference 1).

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2.2.1 Small Breaks that Establish Single-Phase Natural Circulation

For break sizes up to 4-inch diameter, two trains of ECCS can refill the RCS and establish natural circulation within four hours. This capability limits the period of pool boiling to less than three hours. The 2-inch diameter break size case is representative of this range of break sizes. Figure 2-1 compares RCS and SG secondary-side pressures. This figure shows the automatic partial cooldown at 180°F/h, followed by the operator initiated cooldown at 90°F/h starting at 1800 seconds. Primary system pressure increases at 9500 seconds, when the LHSI refills and pressurizes the RCS.

Core outlet void fraction for this case (Figure 2-2) increases to 40 percent in 1500 seconds, then slowly increases to 45 percent at 7500 seconds, at which time the LHSI starts to refill the core and active coolant loops. As natural circulation restarts, core outlet void fraction drops to zero. The collapsed liquid level in the hot assembly (Figure 2-3) is approximately 9 feet at 1500 seconds. It fluctuates near this level until 7500 seconds, when two-phase natural circulation begins. The liquid level then increases to cover the core at approximately 9000 seconds.

Figure 2-4, the plot of RCP flow, shows that natural circulation stops at 1500 seconds and two-phase circulation starts at 7500 seconds. Single-phase flow is established at 10,000 seconds. Figure 2-5 shows core inlet flows. The pressurizer liquid level (Figure 2-6) decreases quickly at accident initiation. It recovers at approximately 9600 seconds.

2.2.2 The 6.5 inch Small Break

The limiting peak cladding temperature (PCT) SBLOCA break size, 6.5 inches, was analyzed assuming redirection of a majority of the LHSI to the hot leg and continued cooldown of the steam generators at 90 °F/h at 1800 seconds. As a result of the LHSI redirection, a hot leg injection flow pattern develops that returns the LHSI flow from the loops receiving hot leg injection to the upper plenum and down the peripheral regions of the core. This upper plenum and core flow behavior is similar to that observed in test facilities with hot leg injection, such as the Slab Core Test Facility, the Cylindrical Core

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Test Facility, and the Upper Plenum Core Test Facility. Figure 2-7 shows the reversal of the redirected flow in loops one and four into the upper plenum, which makes additional coolant available to the core concentrating region. Figure 2-8 shows that the hot leg injected water continues to flow from the upper plenum, further reversing the fuel assembly flow in the peripheral region of the core. Some of the downflow continues down through the lower plenum to the lower head region (Figure 2-9). Thus, the hot leg injection is effective at penetrating the core, thereby reducing the boron concentration in the core region and preventing precipitation of boron in the core and RCS. At 7000 seconds into the event, the continued cooldown of the steam generators has not caused the secondary side pressure to reach the point where the steam generator one secondary pressure, Figure 2-10, and the restart of natural circulation has not occurred.

2.2.3 Small Breaks Larger than 6.5 inch

Small breaks larger than about 6.5-inch diameter are too large for two trains of LHSI and MHSI to refill the loops and establish natural circulation. These breaks remain in a pool boiling configuration similar to that of large break LOCA, but they retain more water in the core concentrating region than the LBLOCA. Therefore, for boron precipitation, the larger SBLOCAs are bounded by the evaluation of LBLOCA.

2.3 Large-Break LOCA

2.3.1 Cold-Leg Breaks

LBLOCA events are evaluated using the realistic LOCA methodology described in the U.S. EPR Realistic Large Break Loss of Coolant Accident Topical Report (Reference 2). Sensitivity studies, such as those used to evaluate boron precipitation, are performed deterministically using the same S-RELAP5 modeling approach.

The post-LOCA phenomena associated with boron concentration in the core is independent of break size once the break is too large for the LHSI to refill the loops. A 4.1 ft² LBLOCA is evaluated as representative of the effect of hot leg injection for this class of breaks. The analysis assumes that at 2000 seconds the operator continues the

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partial cooldown of the SGs at 90F/hour and switches to hot leg injection. While the hot leg injection design redirects at least 75 percent of the LHSI to the hot-leg RHRS nozzles, the analysis conservatively assumes that the switch redirects only 50 percent.

Figure 2-11 presents a plot of integrated mass flow from the upper plenum to one of the hot legs receiving LHSI water. Integrated flow is presented to more clearly identify the net change in flow. The transition from a positive slope to a negative slope at 2100 seconds indicates that water is entering the reactor vessel upper plenum from the hot leg. Although the core continues to boil and the inner regions have positive flow, the peripheral region of the core experiences liquid downflow. Figure 2-12, the integrated mass flow from the outlet of the peripheral core region to the upper plenum, shows that flow out of the peripheral core region reverses soon after flow enters the upper plenum from the hot leg at 2100 seconds.

Figure 2-13, the integrated mass flow from the average core region to the upper plenum, shows flow through this region generally remains positive throughout the transient. Figure 2-14, integrated mass flow from the lower plenum to the average core region, shows flow rate increases after initiation of LHSI hot-leg injection. Figure 2-15, integrated mass flow from the lower plenum to the peripheral core region, shows little flow until after the initiation of LHSI hot-leg injection, when the flow rate becomes strongly negative. Figures 2-11 through 2-14 demonstrate that the hot-leg injection produces mixing within the core region as cool water falls along the peripheral fuel assemblies and rises through the remainder of the core.

Figure 2-16, integrated mass flow from reactor vessel lower head to the lower plenum, shows reverse flow of approximately 250 lb_m/s following the initiation of LHSI hot-leg injection. The flow rate at this location indicates the coolant mass entering or exiting the core; it demonstrates that the hot-leg injection purges the core region. This purge removes concentrated boric acid solution that accumulated before the initiation of hot-leg injection.

2.3.2 Hot-Leg Breaks

For a large break in a hot leg, the MHSI and remaining portion of LHSI that is injected into the cold legs after the switch to hot leg injection is sufficient to flush the core coolant toward the break. This injection is sufficient to prevent the concentration of boron in the core. The LHSI injected into the intact hot legs also is available to the core to prevent boron concentration.

2.4 Boron Concentration Analysis

This section establishes the allowable solubility limit for boron and determines the time available to terminate the concentrating process by either establishing natural circulation for SBLOCA or initiating hot-leg LHSI injection for LBLOCA.

For conservatism, the analysis does not credit the following:

2.4.1 Boron Solubility Limit

2.4.2 Boron Concentration Equation

The concentration of boron in the core region as a function of time is calculated using the following equation:

The bases for the terms are described in the following sections.

2.4.3 Injected Boron Concentration (CI)

The U.S. EPR uses a minimum of 37 percent enriched B-10 boron for all sources of borated water. The maximum mixed boron concentration that is injected during the post-LOCA period is determined by combining the following sources of borated water:

Using the above information, the maximum injected boron concentration is calculated to be:

$$C = \frac{\left[(2590 \text{ ft}^3 x 7300 \text{ } ppm) + (4944 \text{ } ft^3 + 66,886 \text{ } ft^3 x 1900 \text{ } ppm + (12,105 \text{ } ft^3 x 955 \text{ } ppm)\right]}{(2590 \text{ } ft^3 + 4944 \text{ } ft^3 + 66,886 \text{ } ft^3 + 12,105 \text{ } ft^3)}$$

= 1929 ppm

2.4.4 Core Mixing Volume (V)

Tables 2-2 and 2-3 show the volumes of liquid available in the core for mixing with injected boron for an SBLOCA and an LBLOCA, respectively. The five sub-regions comprising the liquid volume of the concentrating region (core region, lower support plate to heated core, upper plenum to the bottom of the hot legs, heavy reflector, and guide tubes) are included because of the recirculation flow pattern which develops in the core following a LOCA. The values are based on S-RELAP5 results for the 6.5-inch diameter small break presented in Section 2.2.2 at 1700 seconds and a 4.7 ft² LBLOCA case at the end of the PCT transient, respectively. The 4.7 ft² LBLOCA is the limiting break size from the RLBLOCA analyses and is different from the analysis used to evaluate the effectiveness of the hot leg injection.

Region	Volume (ft3)	Void Fraction SBLOCA*	Liquid Volume (ft3)
	975.8	0.404	581.6
	127.5	0.0	127.5
	403.2	0.512	196.8
	37.8	0.097	34.1
	98.4	0.177	81.0
– Totals	1643	_	1021

.Table 2-2—Core Mixing Volume for SBLOCA at 1700 Seconds

* Note: The void fractions are representative void fractions for each of the five sub-regions. Liquid volumes within the detailed nodal model of the sub-region are determined and then void fractions representative of that liquid volume within a sub-region are calculated.

Region	Volume (ft ³)	LBLOCA Void Fraction*	Liquid Volume (ft ³)
	975.8	0.635	356.2
	127.5	0	127.5
	363.5	0.992	2.9
	37.8	0.633	13.9
	93.4	0.552	41.8
Totals	1598	-	542

Table 2-3—Core Mixing Volume for LBLOCA

* Note: The void fractions are representative void fractions for each of the five sub-regions. Liquid volumes within the detailed nodal model of the sub-region are determined and then void fractions representative of that liquid volume within a sub-region are calculated.

2.4.5 Steaming Rate (SR)

For the LBLOCA and SBLOCA evaluations, the decay heat is treated as a timedependent function based on the ANS 1971 draft decay heat standard ANS 5.1-1971 (Reference 3) with a 20 percent uncertainty added. The evaporation rate can therefore be calculated as a function of time. The model is based on the evaporation of saturated water at 212°F, a density of 59.81 lb_m/ft³, and a latent heat of evaporation of 970.30 BTU/lb_m. No sensible energy is included, even though the water makeup from the IRWST is subcooled. This evaluation assumes that the boiling and concentrating phase starts at the decay heat power level at reactor trip; no credit is taken for the continued natural circulation during the SBLOCA transient.

2.4.6 Time-Dependent Calculation of Boron Concentration

2.4.6.1 Small-Break LOCA

The time-dependent concentration of boron in the core region is determined by advancing the boron concentration equation in Section 2.4.2 with time. For the 6.5-inch diameter SBLOCA case, the core region boron concentration is calculated to be

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approximately 14,100 ppm at 3600 seconds (Figure 2-19). This value is well below the 38,500 ppm mixing solubility limit for boron precipitation at 212°F.

2.4.6.2 Large-Break LOCA

For LBLOCAs, the core region boron concentration is calculated to be approximately 24,900 ppm at 3600 seconds (Figure 2-19), when the operator would switch to hot leg injection, thereby redirecting the majority of the LHSI flow to the hot legs. This reverses net flow through the reactor vessel. The operator initiates hot-leg injection before the solubility limit is reached (about 6800 seconds). The concentration of boron in the core quickly decreases to about 3000 ppm and then gradually decreases to the maximum mixed value of 1929 ppm calculated in Section 2.4.3.

2.4.7 Boron Precipitation Conclusions

The design of the U.S. EPR reactor is adequate to prevent the precipitation of boron in the core or elsewhere in the RCS for the entire spectrum of SBLOCA and LBLOCA. For large breaks, the operator has approximately two hours to initiate LHSI hot-leg injection in order to terminate the concentration process. For breaks small enough to refill and establish natural circulation, the manually initiated depressurization of the SGs at 30 minutes following the automatic partial cooldown is adequate to establish this circulation before the boron solubility limit is reached. For the larger SBLOCAs, the concentration of boron in the core as a function of time is bounded by that of the LBLOCA. Thus, the time to redirect the LHSI injection to the hot leg based on the LBLOCA is conservative for the larger small breaks.

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Figure 2-1— Pressurizer Pressure and Steam Generator Pressure



Figure 2-2—Core Exit Node Void Fraction



Figure 2-3—Hot Fuel Assembly Collapsed Liquid Level



Figure 2-4—Inlet Flow Rate at the Reactor Coolant Pumps



Figure 2-5—Core Inlet Flows









Figure 2-7—Integrated Flow from Upper Plenum to the Hot Legs for 6.5-inch Break

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Figure 2-8—Integrated Flow from the Core Regions to the Upper Plenum Regions for 6.5-inch Break

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Figure 2-9—Integrated Flow from the Lower from the Lower Head to the Lower Plenum for the 6.5-inch Break



Figure 2-10— Pressurizer Pressure and Loop One Steam Generator Secondary Pressure for the 6.5-inch Break



Figure 2-11—Upper Plenum to Hot-leg Flow for a Loop Receiving Hot-leg Injection, 2.0 ft² Break



Figure 2-12—Peripheral Core Region Flow to Upper Plenum, 2.0 ft² Break



Figure 2-13—Average Core Region Flow to the Upper Plenum, 2.0 ft² Break







Figure 2-14—Lower Plenum Flow to Average Core Region, 2.0 ft² Break



Figure 2-15—Lower Plenum Flow to the Peripheral Core Region, 2.0 ${\rm ft}^2$ Break



Figure 2-16—Lower Head Flow to the Lower Plenum, 2.0 ft² Break

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Figure 2-19—Time Dependent Boron Concentration

3.0 BORON DILUTION

3.1 *Introduction*

GSI 185 identified a concern for potential recriticality during an SBLOCA because of the accumulation of de-borated water in the RCP suction piping due to the condensation of steam in the SG tubes during reflux boiling. A narrow range of break sizes, between approximately 0.5-inch diameter and 2.0-inch diameter (Reference 4), is potentially susceptible to the accumulation of de-borated water. Below that range, the breaks are too small to interrupt natural circulation before the automatic partial cooldown of the SGs cools and depressurizes the RCS sufficiently for the MHSI to offset the break flow and refill the primary system. Since natural circulation continues, de-borated water does not accumulate. Above the 0.5- to 2.0-inch break range, the break is large enough to depressurize the RCS to low pressure faster than the secondary side pressure is reduced by the partial cooldown. The secondary side is a heat source to the RCS, and de-borated water does not accumulate.

For breaks that are within the range of susceptibility, natural circulation is interrupted and boiling in the core and condensation in the SGs to remove decay heat occurs. Because boric acid is not as volatile as water at these conditions, boron is concentrated within the reactor vessel core region, and de-borated water can collect in the suction piping of the reactor coolant loops. The de-borated water eventually accumulates to fill the RCP suction piping and then flows to the reactor vessel at the rate of condensation along with the safety injection water. As long as the de-borated water is returned to the reactor vessel at the rate of condensation or is lost out the break, the reactor core boron concentration does not decrease below the critical value needed to maintain subcriticality. However, should an RCP be restarted or the plant return to natural circulation, the boron concentration in the core could be reduced substantially. The restart of an RCP is precluded by procedure during an SBLOCA.

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The first of the sections that follow presents the results of integral facility tests at the PKL test facility that demonstrate natural circulation restarts, enabling re-boration of the water before it reaches the core inlet. In addition, the results of computational fluid dynamic analyses of a representative EPR are presented in the second section. These are followed by a description of the applicable boron criticality limits. Finally, analyses are presented of three bounding scenarios that confirm boron criticality limits are not violated.

3.2 PKL Tests

Tests were performed at AREVA's PKL test facility in Erlangen, Germany, to evaluate boron dilution effects during SBLOCA in four-loop large pressure water reactors (PWR); Two sets of tests were performed: the E series and the F1.1 test. PKL is a full-elevation, four-loop, 1/145-scale integral test facility. It simulates a 1300 MWe PWR. The two major conclusions from these tests at the PKL facility are:

- Prior to the restart of continuous natural circulation, there will be intermittent twophase natural circulation that re-borates any slug that has developed.
- Natural circulation starts in one loop even though symmetric conditions were simulated to induce simultaneous restarts. The start of two-phase natural circulation in the second loop was delayed approximately 10 minutes.

The tests show that two intermediary flow regimes precede restart of a stagnant loop to continuous single-phase natural circulation. The first transition period is composed of refill and intermittent two-phase flow in the SG. With the intermittent two-phase natural circulation, water carried over the U-tubes from the hot leg and backflow from the pumps add boron to the liquid in the SG outlet plenum and RCP suction piping loop seal. Depending on the rate of SG cooldown and the safety injection flow, the period of this intermittent flow can last over an hour. During this period of intermittent flow, the flow rate in the cold leg is low enough that de-borated water displaced to the reactor vessel is borated adequately by ECCS injection.

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The second transition period is characterized by continuous two-phase natural circulation flow. This flow indicates the end state of refill and intermittent flow and continues until single-phase natural circulation is established. The duration of this phase is up to ten minutes. The flow rate resulting from this period of circulation can peak to twice that of single-phase natural circulation; however, on average the two-phase flow, due to the oscillating fluid dynamics, is about equal to that of the single-phase flow. The initial moments of this period of circulation present the greatest potential for recriticality.

The tests demonstrate that the primary parameters for quantifying the boron concentration at the core inlet are the volume of the de-borated water, the rate that it flows toward the core, its boron concentration, the intermittent circulation as the loop refills, the boron concentration in the safety injection to the cold legs, and the boron concentration of the fluid in the downcomer and lower head/lower plenum regions.

The maximum volume of de-borated water that can accumulate is determined by the primary system geometry. For the U.S. EPR RCS, this is small (171 ft³ per loop) because it only includes the volume of coolant in the RCP suction piping up to the elevation of the RCS pump spillover (refer to Figure 3-1). It does not include the SG outlet plenum because it is above this spillover elevation. The volume of de-borated coolant flowing to the reactor vessel downcomer also depends on the number of loops that experience two-phase circulation at the same time. The tests performed at PKL with identical conditions in all four loops demonstrated that circulation starts in one loop and that the impetus is reduced for circulation to start in other loops when the first loop returns to natural circulation. In all cases, flow in other loops is delayed by several minutes.

The PKL test had a larger slug at a very low concentration, scaled to approximately 388 ft³ and 50 ppm. However, the volume of the slug was conservatively maximized to fill the entire PKL loop seal, and a large part of the slug generation had to be accomplished in a conditioning phase at a constant pressure. The results of the PKL tests provide confirmation of the phenomena associated with SBLOCA reflux boiling

and the restart of natural circulation. They also provide realistic boundary conditions for assessing this boron dilution event for the U.S. EPR.

3.3 CFD Analyses

Several "local" computational fluid dynamics (CFD) analyses were performed for a representative EPR. The analyses are termed "local" because the RCS modeling was limited to the four cold legs, the reactor vessel downcomer, and the lower plenum (i.e., up to core inlet). The analyses used the STAR-CD CFD code to assess the mixing between the de-borated water of the moving slug; the highly borated water of the safety injection (SI) system and extra borating system (EBS); and the borated water in the cold leg, downcomer, and lower plenum. The minimum boron concentrations at the core inlet, which would result if a slug of water with a highly reduced boron concentration was sent to the core at the restart of natural circulation, were calculated by the CFD used to evaluate regarding the return to criticality. The boundary conditions for that CFD analyses were based on the PKL test and by a system analysis. The system analysis was performed from the beginning of a LOCA until the restart of natural circulation to determine the times of restart and RCS conditions, such as temperature and pressure. The PKL test results were used to define the volume of the slug, the slug flow rate profile at the restart of natural circulation, and the initial boron concentrations in the slug.

Two cases (Case 3 and Case 4) from the CFD analyses were selected as representative of the mixing that occurs. These cases are based on the natural circulation peak flow from the PKL tests and closely match the restart flow rates seen in the U.S. EPR S-RELAP5 analyses performed in support of the boron dilution evaluation.

The loop flow assumptions used in Case 3 and Case 4 are:

- Cold Leg 1 EBS injection
- Cold Leg 2 Both medium head safety injection (MHSI) and EBS injection
- Cold Leg 3 Broken loop; neither in-flow nor out-flow

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• Cold Leg 4 – Restart of natural circulation; both MHSI and EBS injection

Case 3 assumes complete mixing of the MHSI and EBS fluid with the slug at the entrance to the downcomer. In contrast, Case 4 assumes stratified flow in the cold leg by using separated inlets to the downcomer for the slug and for the MHSI and EBS flow. For each case, three sets of slug volumes and boron concentrations were analyzed, as shown in Table 3-1. Set-1 is the analysis based on the volume and concentration of the slug generated in the PKL test. Two additional, more conservative sets of volume/boron concentration combinations, Set-2 and Set-3, were also evaluated. In both these sets two slugs were sent to the core. The first slug was from the downward area of the SG tubes simulating condensate in the SG downside tubes, SG outlet plenum, and crossover pipe for a slug volume of 639 ft³. In Set 2, this first slug had a concentration of 50 ppm, while in Set 3 it had a concentration of 400 ppm. The second slug was from the upward area simulating condensate in the SG upside tubes and SG inlet plenum, for a volume of 480 ft³. In both Set 2 and Set 3, the boron concentration of the second slug was 685 ppm. The CFD analysis results are provided in Table 3-2. Although Case 3 and Case 4 had opposing assumptions regarding the mixing of the slug with the SI and EBS flow in the cold leq, the difference in the boron concentrations at the core inlet for Case 3 and Case 4 is small.

The representative reactor used in the CFD analysis has the same geometry as the U.S. EPR and therefore, the results from these CFD analyses can (with an evaluation of the differences in the safety injection boron concentrations) are applicable. A key difference between the U.S. EPR design and the representative reactor is the boron concentrations in the in-containment refueling water storage tank (IRWST), the accumulators, and the EBS tanks. The equivalent boron concentration as natural boron in the U.S. EPR reactor is higher than that used in the CFD analyses (see Table 3-3). Additionally, the volume/concentrations sets had slug sizes significantly larger than the volume of the crossover pipe, which was shown in the S-RELAP5 analyses not to be completely full prior to the refill stage. As shown in Table 3-2, even with large slug volumes and system boron concentrations lower than those used in the U.S. EPR

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reactor, the CFD results show there is mixing in the reactor vessel sufficient to raise the minimum boron concentration at the core inlet above that which is required for maintaining a 1 percent core shutdown margin when completely filled at the critical concentration. Thus, the CFD analyses provide additional supporting evidence to show that U.S. EPR natural circulation restart will not make the core critical.

		Set 1, 1 Slug Simulating PKL	Set 2, 2 Slugs Sent to the Core	Set 3, 2 Slugs Sent to the Core
	Mixing Assumption at Downcomer Inlet	Slug Volume and Concentration	Slug Volume and Concentration	Slug Volume and Concentration
Case 3	Fully Mixed	388 ft ³ @ 50 ppm	639 ft ³ @ 50 ppm 480 ft ³ @ 685 ppm	639 ft ³ @ 400 ppm 480 ft ³ @ 685 ppm
Case 4	Stratified	388 ft ³ @ 50 ppm	639 ft ³ @ 50 ppm 480 ft ³ @ 685 ppm	639 ft ³ @ 400 ppm 480 ft ³ @ 685 ppm

Table 3-1— CFD Case Description

Table 3-2— Evaluation of the Minimum Boron Concentration at theCore Inlet

Slugs Volume and Concentration	Minimum Boron Concentration at Core Inlet, Cold Leg Mixed Case 3, ppm	Minimum Boron Concentration at Core Inlet, Separated Inlets Case 4, ppm	Required Boron Concentration for U.S. EPR Full Core, No Xenon in the Core, 1% Shutdown Margin, ppm
Set 1 388ft ³ @ 50 ppm	2043	2454	1519
Set 2 639/480 ft ³ @ 50/685 ppm	2001	1987	1519
Set 3 639/480 ft ³ @ 400/685 ppm	2075	2102	1519

Table 3-3— Representative EPR and U.S. EPR Comparison

	Slug Size (ft ³)	IRWST Boron Concentration (ppm)	EBS Tank Concentration (ppm)
Representative EPR CFD	Set 1: 388 Set 2*: 639 and 480 Set 3*: 639 and 480	2700	11,750
U.S. EPR Design	Maximum Deborate Volume: 216	3235	13,335

* Set 2 and Set 3 simulate sending two slugs to the core

3.4 Boron Criticality Limit

The minimum concentration of boron in the core to maintain subcriticality depends on the time in the fuel cycle because PWR cores contain excess reactivity to achieve criticality over the entire fuel cycle. Boron compensates for this excess reactivity. PWR core designs use boric acid dissolved in the coolant, and burnable poison in some fuel

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rods, to offset the excess reactivity. Therefore, boron concentrations are highest early in the fuel cycle.

Xenon-135 is a strong neutron absorber that helps to maintain the core subcriticality. Its negative worth peaks at about eight hours after reactor trip, after which it steadily decreases and reaches its initial equilibrium value at 24 hours. Because the SBLOCA event is mitigated within this period, the assessment of the boron dilution event conservatively assumes that the xenon-135 remains at its equilibrium value throughout the event.

For additional conservatism, it is assumed that the most reactive control rod assembly is stuck out of the core. The resulting minimum boron concentration for the U.S. EPR reactor is calculated to be the equivalent of 905 ppm of natural boron assuming equilibrium xenon in the core. Applying a 100 ppm uncertainty raises the minimum critical boron concentration to the equivalent of 1005 ppm of natural boron.

3.5 Analysis of Bounding Scenarios

Three bounding natural circulation restart scenarios are evaluated to determine potential boron dilution and recriticality. As initial conditions, they assume the maximum volume of de-borated water has accumulated in the RCP suction piping. For conservatism, the volume is assumed to be 125 percent of the physical volume (1.25 x 171 ft³ ≈215 ft³) and the concentration is 50 ppm of natural boron, the minimum observed in PKL tests. Credit is taken for the injection of borated MHSI water from two of four trains, one of which is located in the broken loop. Credit also is taken for two EBS trains, which also inject into all of the cold legs. No credit is taken for accumulators and LHSI. The results of the evaluation of three bounding natural circulation restart scenarios are as follows:

 Intermittent natural circulation starts simultaneously in all four loops. Once it restarts, it continues long enough to displace and effectively re-borate the coolant in the RCP suction piping.

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In this scenario, the intermittent circulation displaces the de-borated liquid from the RCP suction piping gradually before continuous circulation is established. This condition allows the MHSI and EBS to re-borate the water in the reactor vessel downcomer and lower plenum before reaching the core inlet. Assuming conservatively that the intermittent circulation begins simultaneously in all four loops, the minimum core entry boron concentration is maintained above 1500 ppm, well above the minimum of 1005 ppm that causes criticality with equilibrium xenon in the core. The margin in the boron concentration of 495 ppm is more than that required to maintain the core one percent subcritical.

 Intermittent natural circulation starts in three loops and continues long enough to effectively re-borate the coolant in their sections of RCP suction piping. This action is followed by the restart of natural circulation in the remaining loop.

The start of circulation in three loops is calculated to reduce the average boron concentration in the downcomer and lower head/lower plenum region to 1700 ppm before the start of circulation in the remaining loop. When this condition occurs, it introduces a slug of liquid at 50 ppm boron concentration. To evaluate this scenario, a CFD calculation was performed for the cold leg, reactor vessel downcomer, and lower head/lower plenum region of a representative EPR. The assumption of a slug of 388 ft³, more than twice the actual maximum volume for U.S. EPR potential de-borated accumulation, demonstrates that the boron concentration in the fluid entering the core would be reduced by approximately 450 ppm. This change would result in an inlet core concentration of approximately 1250 ppm. This is above the minimum concentration margin of 245 ppm is adequate to maintain the core one percent subcritical.

3. Without prior circulation, continuous circulation abruptly restarts in one loop.

This scenario is bounded by Scenario 2 because the concentration of boron in the reactor vessel is not reduced before flow restarts in one loop.

3.6 Boron Dilution Conclusions

The minimum boron concentration at the core inlet is above the threshold necessary to maintain the core subcritical. Therefore, the concern for recriticality due to the accumulation of de-borated water during an SBLOCA as described in GSI 185 is mitigated in the U.S. EPR design.



Figure 3-1—Reactor Coolant Pump Suction Pipe Geometry

4.0 **REFERENCES**

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