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Response to RAI 15.3.1 - 1.a.

Tennessee Valley Authority - Watts Bar Nuclear Plant - Unit 2, Docket No. 50-391

WBN Unit 2 Post-LOCA Boric Acid Precipitation Control Analysis

Introduction

The purpose of a Post-LOCA Long Term Cooling Boric Acid Precipitation Control Analysis is to determine the appropriate time to realign sump recirculation to hot leg recirculation in order to flush the core of highly concentrated boric acid. This is referred to as hot leg switchover (HLSO) time (i.e., simultaneous injection).

The injection and sump recirculation ECCS modes are described in Section 6.3 of the Unit 2 FSAR 6.3. Boric acid precipitation during long term cooling is addressed in Section 6.3.2.2 of the Unit 2 FSAR. Operator actions to prevent boric acid precipitation are described in Sections 6.3.2.17 and 15.2.13.2 of the Unit 2 FSAR. The switchover from injection mode to cold leg recirculation mode and the switchover from cold leg recirculation mode to hot leg recirculation mode are described in the Tables 6.3-3 and Table 6.3-3a of the Unit 2 FSAR.

Input Parameters, Assumptions, and Acceptance Criteria

The major inputs to the boric acid precipitation calculation include core power assumptions and assumptions for boron concentrations and water volume/masses for significant contributors to the containment sump. The input parameters used in the WBN Unit 2 boric acid precipitation calculations are given in Table 1 (page E4-3).

The boric acid precipitation calculation model is based on the following assumptions:

- The boric acid concentration in the core region is computed over time with consideration of the effect of core voiding on liquid mixing volume. Voiding is calculated using the Modified Yeh Correlation described in Reference 1.
- The core mixing volume used in the calculations is shown to be conservative with respect to the potential negative effects of loop pressure drop on core mixing volume.
- The liquid mixing volume used in the calculation includes 50% of the lower plenum volume.
- The boric acid concentration limit is the experimentally determined boric acid solubility limit as reported in Reference 2 and summarized in Table 2 (page E4-6). For large breaks and large small breaks, the effect of containment or RCS pressure above atmospheric pressure is not credited and the boric acid solubility limit at 212°F is assumed. For large small breaks where RCS depressurization is not complete or for even smaller small breaks where the RCS might be at elevated pressures at hot leg switchover time, the solubility limit associated with the saturation temperature of water at the associated elevated pressure is credited.
- The decay heat generation rate for both boric acid accumulation and decay heat removal is based on the 1971 American Nuclear Society Standard for an infinite operating time with 20% uncertainty. The assumed core power includes a multiplier to address instrument uncertainty as identified by Section 1.A of 10 CFR 50, Appendix K.
- The effect of containment sump pH additives on increasing the boric acid solubility limit is not credited.

- For SBLOCA scenarios, the analysis does not assume a specific start time for cooldown/depressurization in the emergency procedures, nor does it assume depressurization to some minimum pressure at hot leg switchover time. WBN Unit 2 is designed so that high pressure SI provides hot leg recirculation flow. As such, it is not necessary to depressurize the RCS to get effective core dilution flow. For the purpose of defining expected scenarios, it is expected that operators will begin cooldown/depressurization within 1 hour of the initiation of the event.

- The boric acid concentration of the make-up safety injection water during the injection phase is assumed to be at the Technical Specifications maximum RWST boron concentration. The boric acid concentration of the make-up safety injection water during the sump recirculation phase is a time-based calculated maximum sump boron concentration. The boric acid concentration of the make-up safety injection water during the transition from injection phase to sump recirculation phase is time based calculated average of the safety injection water source (RWST or sump).

- The sump boron concentration is calculated over time using the maximum mass and maximum boron concentrations for significant boron sources, and minimum mass and maximum boron concentrations for significant dilution sources.

- ECCS recirculation flows are evaluated by comparing minimum safety injection pump flows to the flows necessary to provide decay heat removal and core dilution for breaks in either the hot leg or cold leg.

The above methodology meets NRC stated requirements in Reference 3 and is consistent with the interim methodology reported in Reference 4.

The methodology was also consistent with the methodology used to support the recent Unit 1 TPBAR license amendment request and related USNRC SER (References 7, 8 and 9) with one exception; the use of time-based containment sump flood-up calculations and the resulting ECCS flow boron concentrations. Whereas the analysis for Unit 1 assumed that all sump liquid constituents reside in the sump immediately after a LOCA, the analysis for Unit 2 considered specific ice melt and RWST draindown rates to calculate the sump boron concentration over time. The Unit 2 results show a slower rate boric acid buildup as compared to Unit 1 primarily due to the higher RWST and Accumulator boron concentrations assumed in the Unit 1 analysis.

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Table 1

WBN Unit 2 Post-LOCA Long-Term Cooling Analysis Input Values Parameter Value

Analyzed Core Power	3459 MWt
Analyzed Core Power Uncertainty	0.06% (added to core power listed above)
Decay Heat Standard	1971 ANS, Infinite Operation, plus 20% (10 CFR 50, Appendix K)
H_3BO_3 Solubility Limit	27.53 weight percent
RWST Boron Concentration (max)	3300 ppm
RWST Delivered Volume (max)	380,000 gal
RWST Temperature (min)	60°F
Accumulator Boron Conc. (max)	3300 ppm
Accumulator Liquid Volume	1095 ft3 x 4
Accumulator Tank Temperature	40°F
BIT Boron Concentration	3300 ppm
BIT Liquid Volume	900 gal
BIT Tank Temperature	60°F
Ice Bed Boron Concentration*	2000
Ice Bed Mass (min)	2,404,500 lbm
Ice Bed Mass (max)	3,000,000 lbm
RCS Boron Concentration	2000 ppm
RCS Volume	11,683.5 ft3
Mixing Volume (Calculated)	See Tables 1A and 1B.
Mixing Volume Void Fraction	Modified Yeh Correlation
Lower Plenum Volume	Volume 50%
Volume Above Bottom of HL	Not Credited
Lower Plenum Subcooling	Not Credited

* Boron is in the form of Sodium Tetraborate (Na_2B4O_7).

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Table 1A

Vessel/Core Region Boric Acid Mixing Volume (LBLOCA)

Time (sec)	Volume (ft^3)
1000	738.2
2000	784.3
3000	814.1
5000	850.3
10000	895.4
15000	919.8
20000	936.3
30000	958.4
40000	973.7

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Table 1B

Vessel/Core Region Boric Acid Mixing Volume (SBLOCA)

Time (sec)	Volume (ft^3)
1000	888.3
2000	926.2
3000	950.9
5000	981.0
10000	1019.1
15000	1039.9
20000	1055.2
30000	1075.7
40000	1089.7

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Table 2 - Boric Acid Solution Solubility Limit

Temperature, °C (°F)	Solubility g H3BO3/100 g of Solution in H_2O	Temperature, °C (°F)	Solubility g H3BO3/100 g of Solution in H_2O
P = 1 Atmosphere		75 (167)	17.41
0 (32)	2.70	80 (176)	19.06
5 (41)	3.14	85 (185)	21.01
10 (50)	3.51	90 (194)	23.27
15 (59)	4.17	95 (203)	25.22
20 (68)	4.65	100 (212)	27.53
25 (77)	5.43	103.3 (217.9)	29.27
30 (86)	6.34	P = PSAT	
35 (95)	7.19	107.8 (226.0)	31.47
40 (104)	8.17	117.1 (242.8)	36.69
45 (113)	9.32	126.7 (260.1)	42.34
50 (122)	10.23	136.3 (277.3)	48.81
55 (131)	11.54	143.3 (289.9)	54.79
60 (140)	12.97	151.5 (304.7)	62.22
65 (149)	14.42	159.4 (318.9)	70.67
70 (158)	15.75	171 (339.8) = Congruent Melting of H_3BO_3	

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Description of Analyses and Evaluations

The purpose of the boric acid precipitation analysis is to demonstrate that the maximum boric acid concentration in the core remains below the solubility limit, thereby preventing the precipitation of boric acid in the core. If boric acid were to precipitate in the core region, the precipitate might prevent water from remaining in contact with the fuel cladding and, consequently, result in the core temperature not being maintained at an acceptably low value. The boric acid precipitation analysis determines the appropriate time for switching some or all ECCS recirculation flow to the hot leg and verifies that there is sufficient dilution flow through the core to halt and reverse the concentration of the boric acid solution.

Prior to sump recirculation, core cooling is addressed by the Large Break LOCA analysis that demonstrates core reflood with stable and sustained quench and by the small break LOCA analysis that demonstrates core recovery. After an SBLOCA, RCS system will refill, depressurize and eventually enter into shutdown cooling, or will depressurize and remain in sump recirculation indefinitely. With the switch to sump recirculation, long term cooling is addressed by demonstrating that the core remains covered with two-phase mixture in the long term, thereby ensuring that the core temperature is maintained at an acceptably low value. Paragraph (b)(5) of 10 CFR 50.46 is satisfied when the fuel in the core is quenched, the switch from injection to recirculation phases is complete, and the recirculation flow is large enough to match the boil-off rate. ECCS pump availability and specific flow path alignments may reduce ECCS recirculation flow as compared to the flows available during the injection phase. After the switch to hot leg recirculation, core flow sufficient to dilute the core or prevent boric acid buildup, by definition, exceeds core boil-off and therefore provides core cooling.

The Long Term Cooling Analysis described here supports the Post-LOCA Boric Acid Precipitation Control Plan presented in Table 3 (provided in Attachment 7). The flowchart in Figure 2 (provided in Attachment 7) shows the applicability of the calculations to the specific post-LOCA scenarios.

<u>Large Break LOCA</u>

Large breaks (double-ended guillotine down to approximately 1.0 ft^2) will rapidly depressurize to very near containment pressure with no operator action. The 14.7 psia boric acid precipitation calculation models this scenario and calculates the boric acid build-up for the limiting condition of a cold leg break. Dilution and core cooling flows are confirmed for 14.7 psia RCS backpressure. After hot leg switchover, the hot leg injected flow will provide immediate core dilution for a cold leg break. If the break is in the hot leg, injected ECCS flow to the cold leg is sufficient to prevent the buildup of boric acid in the core prior to and after switchover to hot leg recirculation.

Large breaks that lead to rapid RWST draindown represent the limiting case for recirculation flow requirements. For plants that see ECCS flow reductions during recirculation (such as WBN Unit 1 where low head pump flow provides suction to the high head and charging pumps and a portion of its flow may be diverted to containment spray), ECCS flow during sump recirculation is evaluated.

Large Small Break LOCA

Large small breaks (approximately 0.2 - 1.0 ft^2) will depressurize to relatively low pressures (before the potential for boric acid precipitation) with no operator action. The 120 psia boric acid precipitation calculation models this scenario and calculates the boric acid build-up for the limiting condition of a cold leg break. The 120 psia calculations consider less core voiding, a lower h_{fg}, and do not credit SI subcooling to reduce core boil-off. After hot leg switchover, as with large breaks, the hot leg injected flow will provide core dilution for cold leg breaks and cold leg injected flow will prevent buildup of boric acid in the core for hot leg breaks. Dilution and decay heat removal flows are confirmed as adequate at 120 psia RCS backpressure. Core dilution flow will provide effective core cooling.

Small Break LOCA

For small breaks (approximately 0.005 - 0.2 ft^2), emergency procedures will instruct operators to take action to depressurize and cool down the RCS. It is expected that this process will begin within 1 hour after the event. Depressurization to 120 psia (the threshold for boric acid precipitation concerns) may occur before or after hot leg switchover time. In either case, the boric acid buildup at hot leg switchover time is conservatively represented by that calculated for the 120 psia RCS backpressure scenario since this calculation takes no credit for SI subcooling, nor any beneficial effects of the operator action (such as reduced net core boil-off due to condensation in, and resultant reflux from, the steam generators). If 120 psia is reached before hot leg switchover time, the core dilution flow after hot leg switchover, which is confirmed as adequate for 120 psia backpressure, will provide effective core dilution. If at hot leg switchover time, the 120 psia has not been reached, boric acid precipitation will not occur so long as the RCS remains above this pressure since water and boric acid are miscible at the saturation temperature for these pressures. Even if the RCS pressure is above 120 psia at 12 hours after the LOCA with no core dilution flow, the total boric acid in the core will be well below the saturation limit at the corresponding saturation temperature. Furthermore, if after 12 hours with no dilution flow and the RCS depressurized at the maximum cooldown rate allowed by procedure, flushing flow will be established and the core will be diluted prior to reaching the boric acid precipitation point. If subcooled core conditions are reached either before or after hot leg switchover, boric acid precipitation is not a concern since there will be no net boiling in the core. If subcooled core entry conditions are not reached, the operators will continue to depressurize the RCS under controlled conditions. Sump recirculation will continue, decay heat in the core will decrease, and core dilution flow will prevent the buildup of boric acid. Eventually, subcooled core conditions will be reached and the system will be put into shutdown cooling, or it will remain in indefinite recirculation cooling. It is important to note that WBN Unit 2 is designed so that high pressure SI provides hot leg recirculation flow. As such, it is not necessary to depressurize the RCS to get effective core dilution flow.

Very Small Break LOCA

For very small breaks (less than approximately 0.005 ft^2), emergency procedures will instruct operators to take action to depressurize the RCS. Because the break is small, subcooled conditions will be reached prior to depressurization to 120 psia (the threshold for boric acid precipitation concerns). Natural circulation, if lost, will be quickly restored. While in natural circulation, boric acid precipitation is not a concern because the core region will not be stagnant. When subcooled conditions occur, net core boiling will cease and boric acid will not accumulate.

Eventually, the RCS will be depressurized under controlled conditions to shutdown cooling entry conditions, or continued natural circulation and sump recirculation will keep the boric acid from accumulating in the core.

Results

To address large break LOCAs, post-LOCA boric acid precipitation control calculations for 14.7 psia demonstrate that a 3 hour HLSO time to establish simultaneous hot leg and cold leg recirculation will prevent the precipitation of boric acid in the reactor vessel. Figure 3 (provided in Attachment 7) shows the buildup of boric acid versus time and the boric acid solubility limit used for this scenario. Figure 3 also shows the dilution effect of the hot leg injected flow after simultaneous hot leg and cold leg recirculation is established.

To address small break LOCAs, post-LOCA boric acid precipitation control calculations for 120 psia were performed. These calculations show that there is considerable margin to the boric acid solubility limit at the designated switchover time for this scenario. The 120 psia calculations consider less core voiding, a lower h_{fg}, and do not credit SI subcooling to reduce core boil-off. Since the boric acid buildup calculations for this scenario apply to RCS pressures of 30 to 120 psia, the boric acid solubility for the saturation temperature of water at 30 psia was credited. Figure 4 (provided in Attachment 7) shows the buildup of boric acid versus time and the solubility limit appropriate for this scenario. Figure 4 also shows the dilution effect of the hot leg injected flow after simultaneous hot leg and cold leg flow is established.

In the unlikely event that the RCS pressure remains above a saturation pressure of 120 psia (and corresponding saturation temperature) at hot leg switchover time, boric acid precipitation will not occur since the total boric acid in the core will be well below the saturation limit at the elevated pressure saturation temperature. In order to demonstrate the effectiveness of hot leg dilution flow for this scenario, calculations were performed for a hypothetical condition where there would be no hot leg dilution flow for 12 hours. Figure 5 (provided in Attachment 7) shows the boric acid concentration in the core with the RCS at 120 psia for 12 hours assuming no SG heat removal, no dilution flow, and no benefit of reduced steaming due to SI subcooling. At 12 hours, the boric acid concentration is still below the boric acid solubility limit at the saturation temperature at 120 psia. Figure 5 also shows that if hot leg flow is established at 12 hours and the RCS is at saturation and is then cooled (with corresponding depressurization) at a cooldown rate of 100°F/hr, boric acid precipitation will not occur. The resulting hot leg dilution flow maintains the boric acid concentration in the core well below the solubility limit, even as the solubility limit is reduced due to the RCS cooldown. For WBN Unit 2, hot leg dilution flow is provided by the SI pumps which would provide dilution flow at RCS pressures well above 120 psia.

Calculations were performed to support an early switchover to hot leg or simultaneous injection. Two aspects of early switchover were considered: the hot leg entrainment threshold and core cooling. If switchover occurs too early, injected SI in the hot legs might be carried around the loops and might not be available for core cooling and dilution. Entrainment threshold calculations similar to those reported in Reference 5 demonstrated that significant hot leg entrainment would not occur after 63 minutes. Calculations showed that either hot leg or cold leg flows are sufficient to provide core cooling flow at 3 hours after the LOCA.

Assessments were made of the effect of loop pressure drop and downcomer boiling on the core mixing volume by performing calculations similar to those reported to the NRC in References 5 and 6. In all cases, the core region mixing volume assumed in the boric acid buildup calculation was found to be conservatively small in relation to the collapsed liquid volume based on loop pressure drop and available downcomer head.

The effect of the refilling of the pump suction leg loop seals was also assessed by performing calculations similar to those reported to the NRC in References 5 and 6. While the simultaneous complete closure of all four loop seals would depress the core mixture to slightly below that associated with the core mixing volume, the expected duration of the depression would be brief. Brief core mixture level depressions would have the benefit of promoting mixing between the core region and lower plenum by cycling liquid back and forth between the core region, lower plenum and downcomer.

An assessment was made of the effect of boric acid plate-out in the SGs by performing calculations similar to those reported to the NRC in Reference 6. These calculations show that, with 10% entrainment for 1.5 hour, the total boric acid mass entrained would deposit a coating of approximately 0.003 inch over 10 feet of SG tubes. This coating would not significantly increase loop resistance or depress the core mixture level.

An assessment was made concerning the potential for boric acid precipitation at the hot leg injection point or at colder regions of the vessel. A simplified demonstration calculation showed that the mixing of injected SI with the highly borated solution in the reactor vessel would not initiate boric acid precipitation at the injection point. This calculation ignored temperature and boric acid gradients and assumed effective mixing with no differentiation between different mixing mechanisms such as diffusion (thermal or molecular) and density-driven convection within the vessel. The assessment also concluded that the heating of the injected water as it travels to the core region (either from the downcomer or hot leg) and the expected density-driven mixing mechanisms in the vessel would make it unlikely that significant temperature or boric acid gradients would exist. These conclusions were consistent with those reported to the NRC in Reference 6.

Summary and Conclusions

Post-LOCA HLSO calculations were completed for the WBN Unit 2 Completion Project. These calculations demonstrate the acceptability of the planned Unit 2 HLSO time of 3 hours (consistent with Unit 1). Switchover to hot leg recirculation at 3 hours will limit the maximum core region boric acid concentration to 18.59 weight percent allowing for 8.94 weight percent margin to the atmospheric pressure solubility limit of 27.53 weight percent.

The core mass boil-off rates were calculated to be 43.86 lbm/sec (328.7 gpm) for a HLSO time of 3 hours. Hot leg recirculation flows were reviewed and found to be adequate to ensure core cooling and to provide core dilution after HLSO realignment.

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