May 23, 2013

OG-13-205

Document Control Desk
U. S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Attention: Mr. Stewart Bailey – Chief, Safety Issues Resolution Branch
Division of Safety Systems
Office of Nuclear Reactor Regulation

Subject: PWR Owners Group
**NRC Technical Concerns Regarding Boric Acid Precipitation in the Presence of In-Vessel Fibrous Debris and the Consequential Effects on Long-Term Core Cooling (PWROG PA-SEE-1090 and PA-SEE-1072)**

References:

Dear Mr. Bailey:

In consideration of discussions between the Pressurized Water Reactor Owners Group (PWROG) and NRC staff during a public meeting on April 4, 2013, the PWROG believes that it is mutually desireable to state its interpretation of the NRC staff’s boric acid precipitation (BAP) concerns as related to closure of the overall GSI-191 issue. The following is offered as the problem statement:

The NRC aproval of WCAP-16793-NP Revision 2 stipulated that consideration of the effects of in-vessel debris on long term core cooling following a loss of coolant accident will include the effects associated with boric acid precipitation. Testing and analyses intended to demonstrate the adequacy of long term core cooling will address the localized coolant flow and mixing of boric acid
solutions. This is an inter-disciplinary approach in order to fully understand the phenomena.

The resequencing of the GSI-191 and boric acid programs needs to consider the timing and effects of the debris and chemicals to determine the debris bed development versus time, the impact of the debris bed on the core inlet flow, and the impact of the alternate core flow paths on the local flow mixing as it relates to BAP.

The PWROG would like to ensure that this problem statement clearly reflects the central issues associated with boric acid precipitation as it relates to closure of GSI-191. Attachment 1 to this letter presents the PWROG’s technical justification for resequencing the BAP and GSI-191 issues. We believe that this provides reasonable assurance that post-LOCA debris, if acceptable from a GSI-191 perspective, would not present a safety issue with regards to its impact on BAP.

Understanding that PIRT data results relative to BAP and debris would also be helpful, it is prudent to point out the previous BAP PIRTs (References 1 and 2) and clarify that the current GSI-191 PIRT team (which is addressing debris and including information from previous GSI-191 testing) is considering some important BAP inputs as well. The draft of this PIRT is scheduled to be completed by end of June 2013. The PWROG will share the results of this PIRT with the NRC once finalized. A follow-on PIRT to specifically focus on debris impacts on BAP is also planned as part of the future BAP activities, but not until GSI-191 testing is complete to provide new and additional testing information to advance the state of knowledge.

The PWROG would like the opportunity to have an informal 1-day meeting at Westinghouse’s Cranberry offices in June to discuss the problem statement, the justification, PIRTs, potential use of computational flow dynamics analysis tools, and other BAP topics that your reviewers might have. We hope to use this meeting to bring any remaining concerns regarding separating the BAP and GSI-191 licensing to an expeditious resolution.

Correspondence related to this transmittal, including requests for additional information, should be addressed to:

Mr. W. Anthony Nowinowski, Program Manager  
PWR Owners Group, Program Management Office  
Westinghouse Electric Company LLC  
Suite 380, 1000 Westinghouse Drive  
Cranberry Township, Pennsylvania 16066

If you have any questions, please do not hesitate to contact me at (205) 992-7037 or Mr. W. Anthony Nowinowski at (412) 374-6855.

Sincerely,
Jack Stringfellow, Chairman  
PWR Owners Group
Attachments:  (1) Pressurized Water Reactor Owners Group (PWROG) White Paper
Technical Basis for Separation of GSI-191 In-Vessel Effects and Boric Acid Precipitation.

cc:  PWROG Management Committee
     PWROG SEE Subcommittee
     PWROG LSC Subcommittee
     PWROG PMO

     J. D. Andrachek – Westinghouse
     M. K. Barnett - Westinghouse
     T. D. Croyle – Westinghouse
     J. A. Gresham – Westinghouse
     D. C. Kovacic – Westinghouse
     J. T. Maruschak – Westinghouse
     F. Gartland – AREVA NP
     R. Schomaker – AREVA NP
ATTACHMENT 1
INTRODUCTION

Methodologies that demonstrate post-loss-of-coolant-accident (post-LOCA) long-term core cooling (LTCC) have gained considerable regulatory attention recently. For example, extended power uprate (EPU) license amendment requests have provided the Nuclear Regulatory Commission (NRC) the opportunity to challenge some of the common approaches, assumptions and simplifications related to the methods that demonstrate adequate boric acid precipitation control (BAPC). The entire US pressurized water reactor (PWR) fleet uses boron as a reactivity control method and therefore all US PWRs are subject to concerns regarding potential BAP in the reactor vessel under certain post-LOCA scenarios. The common approach for demonstrating adequate BAPC in a post-LOCA scenario uses simplified methods with conservative boundary conditions and assumptions. These methods are used with limiting scenarios in calculations that determine the appropriate time at which operator action must be taken to initiate an active core dilution flow path or alternately, to show that BAP will not occur.

The pending closure of Generic Safety Issue-191 (GSI-191) has provided another opportunity for the NRC to review the methodologies used for BAP calculations. In July 2012, the NRC staff issued SECY-12-0093 (Reference 1) to the commission identifying a scenario where large amounts of in-vessel debris may affect the timing of BAP. The concern is that the buildup of fibrous debris in the reactor vessel may inhibit mixing and mass transport between the core and the lower plenum region of the vessel. This scenario, if it were to occur, could lead to boron precipitation before BAPC measures are in place. In the analyses that support current plant operation, precipitation timing is based on uninhibited mixing and mass transport between the core and lower plenum. Interruption of these mixing and mass transport processes could invalidate the adequacy of operator action timing in the emergency operator procedures to control precipitation. Therefore, in order to adequately address LTCC, the NRC staff may ask licensees to show that the buildup of chemicals, particulates, and fibrous material in the core will not inhibit adequate water from entering the core, but to also show that the plant’s current BAPC measures adequately prevent boron precipitation.

In the Safety Evaluation (SE) to WCAP-16793-NP Revision 2, debris-related BAP issues were integrated into the overall resolution of GSI-191. Plants with less than 15 grams of fibrous debris reaching the core per fuel assembly (15 g/FA) would not need to address BAP issues due to insufficient debris quantities, but those seeking higher limits would need to integrate BAP into their resolution plan.

In the December 14, 2012 Staff Requirements Memo (SRM) responding to SECY-12-0093, the NRC Commissioners stated the following:

“The agency has dealt with GSI-191 for many years and resolving this matter has proven to be an extraordinarily complex and, at times, frustrating process. Part of the reason for this frustration is a decision made quite some time ago to continually expand the definition of the issue to capture concerns that are related to but in some cases quite different from the original sump-clogging challenge. As part of its efforts to
improve the Generic Issues Program as described on page 8 of SECY-12-0105, “Summary of Activities Related to the Generic Issues Program,” the staff should consider the need to definitively scope, investigate, act upon, and close a technical issue. In its next annual status report to the Commission on the Generic Issues Program, the staff should discuss the actions taken to assure that future generic issues are and remain well-defined and avoid the mission creep experienced by GSI-191.

Based on this perspective, the PWROG believes that it would be prudent to resequence BAP and GSI-191 to allow focused and timely closure of GSI-191 while still planning to address debris-related impacts on BAP in the larger BAP program. Allowing these programs, and in particular, the associated test programs, to be in series rather than in parallel would eliminate some excess conservatism from BAP testing, close GSI-191 faster, and better utilize industry resources (including both people and funds) to focus on solving one issue at a time rather than being split between the two. Additionally, it would allow individual plants and the PWROG to focus some of its 2013 and 2014 funds on other critical plant issues that may have more significant effects on overall plant health, operation, and safety.

In order to provide a technical basis for the resequencing of BAP and GSI-191, an evaluation of conservatisms contained in the BAPC methodology is completed. The evaluation is made against a typical Westinghouse 3 loop PWR analysis of record (AOR) hot leg switchover (HLSO) time which was reanalyzed for an EPU using approved “interim” methods. A review of other PWR AOR HLSO analyses was performed and it was deemed that the evaluation made against the Westinghouse 3 loop PWR also applies to other Westinghouse- and CE-designs for the purposes of demonstrating reasonable assurance that BAP concerns will not require the debris limits established for the closure of GSI-191 to be reduced. The evaluation is not directly applicable to the B&W-design due to differences in the analytical methods however the overall conclusions are applicable to the B&W-design. It is also noted that the BAPC methodologies applied to B&W-designs do not credit the lower plenum as part of their mixing volume. Therefore, the NRC’s primary concern is not applicable to B&W BAPC analyses.

For the B&W plants, the blockage at the core inlet will reduce the mixing volume used in the boron precipitation calculations by the volume between the inlet to the baffle and the first row of “LOCA holes”, a reduction of about 65 cubic feet. This decrease in mixing volume is more than compensated by reducing the conservatism in the decay heat model used and using nominal values for the boron concentration in the BWST, accumulator & primary system. Preliminary calculations for a sample plant indicate that with the reduction of mixing volume of 65 cubic feet and using the 1971 Decay Heat model, the time required for measures to preclude boron precipitation increases above the AOR value. Using nominal values for boron concentration in the BWST tank, accumulator and primary system, would lead to further increase in the time to boron precipitation.

Following the evaluation of the BAPC methodology, an assessment of the safety significance of the potential for BAP following a postulated LOCA is made that further bolsters the argument that BAP concerns do not need to be completed concurrently with the resolution of GSI-191. The conclusions from this assessment are applicable to all US PWRs.
For typical plant designs (Westinghouse 2-loop Upper Plenum Injection (UPI) plants excluded), the limiting scenario for boric acid precipitation is a large cold leg (pump discharge) break where the downcomer is eventually filled and the excess SI flows out the break. The SI flow into the core region is largely limited to that quantity boiled off in the core to remove the decay heat. The steam generated in the core travels around the intact hot leg(s) (or through the internals Reactor Vessel Vent Valves (RVVVs) in the B&W-designed plants) to exit the break. Boric acid left behind accumulates in the core region and the boric acid concentration in the core region increases. The calculated rate of increase in boric acid concentration in the core region after a LOCA is directly affected by the assumed liquid volume and mixing assumptions. During this time, the core and upper plenum are filled with a two-phase mixture whose liquid content is dependent on the degree of voiding in the core and upper plenum region. The degree of voiding is a function of the core decay heat and Reactor Coolant System (RCS) pressure, and the pressure drop around the loop (or through the RVVVs) as it affects the hydrostatic balance between the downcomer head and the collapsed liquid level in the core. At low RCS pressures and high decay heat levels, the boiling in the core is vigorous, and the volume of liquid in the core region is smaller. As the decay heat drops off, the boiling becomes less vigorous and more liquid is retained in the core region.

Westinghouse US 2-loop plants differ from typical PWR designs in that they utilize low pressure upper plenum safety injection (or UPI). For these plants, the limiting large break LOCA boric acid precipitation scenario is a hot leg break where the cold leg high pressure SI may be terminated at or prior to sump recirculation. This scenario is relevant only with the very conservative assumption that all UPI flow in excess of core boil-off bypasses the core region and flows directly out the break (i.e., no mixing in the core and upper plenum).

For Westinghouse-designed and CE-designed plants, boric acid precipitation calculations determine the appropriate time to switch to some or all the ECCS sump recirculation flow to the hot leg or to otherwise show that boric acid precipitation will not occur. For B&W-designed plants, boric acid precipitation calculations are used to justify plant-specific active boric acid dilution methods or limitations on the dilution methods (e.g., plant specific auxiliary pressurizer spray flows, protection of the sump screens, prevention of potential water-hammer scenarios in the decay heat piping, challenges to Net Positive Suction Head (NPSH) limits for Low Pressure Injection (LPI) pumps, hot and cold fluid mixing limits, prevention of boric acid precipitation inside the decay heat cooler, etc.).

Current Post-LOCA boric acid analysis methodologies do not consider the effects of GSI-191 in-vessel debris. The current analysis methods assume that the coolant entering the reactor vessel is free of any debris constituents. Further, the analyses do not account for any effects that in-vessel debris may have on the mixing, mass transport, or precipitation phenomena associated with BAP.

EVALUATION OF BORIC ACID PRECIPITATION CONTROL METHODOLOGY CONSERVATISMS

This section presents the results of the evaluation performed to quantify some of the conservatisms contained in the BAPC methodology to demonstrate that if a debris bed were to form at the core inlet, under large cold leg break conditions, sufficient margin exists such that a
plant remains in compliance with regulations and their design basis. The evaluation assumes that sufficient coolant can reach the core such that decay heat removal is not challenged. In other words, after the debris bed forms, coolant can penetrate upward through the debris bed but boron cannot penetrate downward through the bed.

The HLSO time for a Westinghouse 3 loop PWR that recently underwent an EPU is 6.5 hours based on a solubility limit of 29.27 wt%. The HLSO time for this plant was calculated using a more sophisticated method than the current standard methods in order to address NRC concerns regarding some of the simplifying assumptions in the standard methodology. The key NRC concerns addressed by the HLSO analysis are related to the decay heat modeled, mixing volume assumptions, voiding in the mixing volume, and solubility limit.

The AOR was performed using the 1971 ANS standard for infinite operating time with 20% added uncertainty consistent with the requirements of 10CFR50 Appendix K.

The method for calculating the effective mixing volume utilizes the modified form of Yeh’s void fraction correlation (Reference 2) to calculate the void fraction in the core. Using this correlation, the core average void fraction will be calculated at various points in time which is then used to calculate the time varying effective mixing volume.

Other key differences relative to the standard methodology are:

- Specifically accounting for core and upper plenum (UP) voiding
- Crediting up to 50% of the lower plenum (LP) in the mixing volume. This only applies once the core/UP H$_3$BO$_3$ concentration is at least 8.5 wt% higher than the concentration in the LP (Reference 3).
- A H$_3$BO$_3$ solubility limit of 29.27 wt% (Reference 4)

The NRC has stated concerns related to the effect of in-vessel debris on the BAPC analyses. Specifically, the NRC is concerned that if a debris bed forms at the core inlet following a postulated large cold leg break the communication between the core and the lower plenum may be lost such that the effective mixing volume is reduced and BAP could occur before the established HLSO time.

In order to address this concern, an evaluation is performed to demonstrate that sufficient margin contained in the approved BAPC methodology offsets the loss of lower plenum volume that is credited when determining the HLSO time. To accomplish this task, a BAPC analysis is performed in which the lower plenum volume is not credited. Then, a realistic analysis is performed in a stepwise manner such that the available margin can be quantified for the predicted HLSO times. The areas to be investigated include:

- Decay Heat Model
- Mixing Volume Assumptions
- RWST and Accumulator Volumes and Boric Acid Concentrations
- Solubility Limit
- Inlet Subcooling
- Inception Time for Core-to-Lower Plenum Exchange

The following test cases are run using SKBOR Version 10.0T4 in order to quantify the change to HLSO time. Note Case 1 is a rerun of the AOR case using this newer version of SKBOR.
Case 1: Rerun of AOR
The inputs used for this case are consistent with the AOR. The HLSO time calculated using SKBOR Version 10.0T4 compares well with the AOR result. The HLSO time is provided in Table 1.

Case 2: AOR Case Run without Lower Plenum Volume
This case is run using the same inputs as the AOR case but without the lower plenum volume. The calculated HLSO time is shown in Table 1 and is significantly lower than the AOR HLSO time.

Case 3: Nominal Decay Heat Model
This case is the same as Case 2 only Appendix K decay heat is replaced with the 1971 ANS finite with no uncertainty. The HLSO time for this case is shown in Table 1.

Case 4: Increased Upper Plenum Mixing Volume
This case builds on Case 3 and includes the upper plenum mixing volume up to the centerline of the hot leg which is an additional 116 cubic feet. This volume is assumed to have a void fraction equal to the core exit void fraction calculated by SKBOR as a function of time. In reality, the mixture level will vary as a function of time due to pressure drop variations through the loop. This analysis assumes that the average mixture level is at the hot leg centerline. The HLSO time for this case is shown in Table 1.

Case 5: Addition of Barrel/Baffle Volume
This case builds off of Case 4 and includes the barrel/baffle region volume which is 188.7 cubic feet. The MHI BACCHUS tests showed that the barrel/baffle volume can be credited as part of the effective mixing volume for upflow-design plants. The tests showed that the boron concentration in the barrel/baffle was slightly less than that in the core region and the buildup of boron is delayed relative to the core. The BACCHUS tests did not consider the effects of debris, however, the flow path between the top of the barrel/baffle and the core periphery will remain open which is a viable flow path for boron to enter the barrel/baffle volume. Plants with pressure relief holes have additional flow paths that allow communication between the core and barrel/baffle region. This analysis credits half of the barrel/baffle mixing volume making the additional mixing volume 94.4 cubic feet. Only half of the volume is credited to account for the boron concentration gradient between the barrel/baffle and the core as well as any voids that may exist in the barrel/baffle volume. The HLSO time for this case is shown in Table 1.

Case 6: Addition of Thimble Tube Volume
This case builds of Case 5 and includes the thimble tube volumes. The credited thimble tube volume assumes all rods in (ARI) following the postulated LOCA. A 50% average void fraction is assumed in the thimble tube volumes for the entire transient. This value was selected based on the observation that the core average void fraction is around 45% six hours into the transient. The HLSO time for this case is shown in Table 1.

Case 7: Nominal Input Values
This case builds off of Case 6 and uses nominal input values for the RWST and accumulator liquid volumes and boric acid concentrations. The HLSO time for this case is shown in Table 1.

Case 8: Increase in Solubility at Pressures above Atmospheric Pressure
This case builds off of Case 7 and uses a containment pressure of 20 psia and a solubility limit of 32 wt% boric acid. At containment pressures above atmospheric, the boiling temperature of the
boric acid and water solution increases and the solubility limit increases correspondingly. For an assumed containment pressure of 20 psia, the boiling point of pure water is 228°F and the boiling point of a boric acid and water solution is even higher. As indicated in Reference 4, the solubility limit of a 228°F boric acid and water solution is >32 wt%. The HLSO time for this case is shown in Table 1.

Review of Table 1 indicates that sufficient margin exists in the approved BAPC methodology such that if a debris bed were to form under large cold leg break conditions and inhibit exchange flow between the core and lower plenum, the licensed HLSO time remains valid. This evaluation assumes that coolant can enter the core such that decay heat removal is not challenged.

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Description</th>
<th>HLSO Time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AOR</td>
<td>6.51</td>
</tr>
<tr>
<td>2</td>
<td>Case 1 with no lower plenum credit</td>
<td>1.96</td>
</tr>
<tr>
<td>3</td>
<td>Case 2 with 1971 ANS finite decay heat model</td>
<td>3.25</td>
</tr>
<tr>
<td>4</td>
<td>Case 3 with two-phase mixture to hot leg centerline</td>
<td>3.93</td>
</tr>
<tr>
<td>5</td>
<td>Case 4 with barrel/baffle volume considered as part of mixing volume</td>
<td>5.44</td>
</tr>
<tr>
<td>6</td>
<td>Case 5 with thimble tube volumes considered as part of mixing volumes</td>
<td>5.88</td>
</tr>
<tr>
<td>7</td>
<td>Case 6 with nominal RWST and accumulator volumes and boric acid concentrations</td>
<td>6.28</td>
</tr>
<tr>
<td>8</td>
<td>Case 7 with 20 psia containment pressure and 32 wt% solubility limit</td>
<td>7.49</td>
</tr>
</tbody>
</table>

Additional Margin not Considered in the Realistic Analysis

All plants in the US PWR fleet utilize alkaline additives (i.e. TSP, NaOH, or sodium tetraborate) to control the pH of the water in the containment sump after a LOCA. Containment sump pH control additives increase the boric acid solubility limit by increasing the ionized fraction of boric acid solution. Few US PWR fleet post-LOCA boric acid precipitation analyses credit the increased solubility limit that may results from containment sump pH additives. One analysis that has credited the effects of trisodium phosphate (TSP) is the Waterford 3 Extended Power Uprate Long Term Cooling analysis, discussed in Reference 5. Reference 5 cites tests indicating a boric acid solubility limit of >36 wt% for a solution of water, boric acid, and TSP undergoing boiling at saturation under atmospheric pressure conditions. Recently, RAI (Request for Additional Information) responses for a long term cooling analysis under NRC review (Reference 6), cites testing that shows a boric acid solubility limit of >48 wt% for a solution of water, boric acid, and NaOH undergoing boiling at saturation under atmospheric pressure conditions. Also, the solubility limit for a solution of water, boric acid, and sodium tetraborate is greater than that of boric acid alone by at least 7 wt% (Reference 7). The amount of solubility
increase will depend on the pH of the coolant. However, since all pH control additives will increase the ionized fraction of boric acid, all of the pH control additives would be expected to increase the boric acid solubility of the solution. This expectation is supported by the preliminary chemistry testing of boric acid, water, and sump pH buffering agents performed for the PWROG.

Crediting safety injection (SI) subcooling would provide additional margin to the HLSO time. If subcooled liquid enters the core region, the boil-off rate is reduced and the core average void fraction will also be reduced thus increasing the effective mixing volume used to determine the build-up of boric acid within the reactor vessel. Subcooled SI sensitivities have been performed and summarized in Reference 8 that assume an SI temperature of 65°F. The sensitivity study credited the reduction in boil-off but neglected the subcooling effect on core voiding. The results are as expected. The reduced core boil-off due to the lower enthalpy reduces the rate at which boric acid builds up in the mixing volume. The results show a reduction of approximately 3.2 wt% boric acid 6 hours into the transient; however, the effect would be greater if subcooling had been factored into the void fraction calculations.

INCEPTION OF CORE-TO-LOWER PLENUM BORON TRANSPORT

A model for boric acid transport between the reactor core and lower plenum is implemented in a developmental version of the computer program SKBOR. A two-region model is used to predict the boric acid concentrations in the core and lower plenum by assuming liquid-density-gradient-gravity-driven exchange flow through the lower core plate. Each region is assumed to be well mixed and therefore, the boric acid concentration and temperature in each region is assumed to be uniformly distributed throughout. The core is assumed to be at saturation temperature while the lower plenum can be either saturated or subcooled, depending on the user specified initial condition.

Inception of boric acid transport is determined by two factors. First, the density gradient between the core and lower plenum due to solute concentration differences must overcome the density gradient caused by the temperature difference between the core and lower plenum if subcooling exists in the lower plenum region. Second, since there is upflow through the reactor vessel due to the makeup of liquid boil-off, the buoyancy driven exchange flow in the downward direction must be larger than the boil-off flow rate in the upward direction such that the downward flow can penetrate through the lower core plate and into the lower plenum. By modeling the inception in this fashion, both the effects of subcooling in the lower plenum and upward liquid kinetic energy due to the makeup of boil-off are accounted for.

The volumetric flow of make-up water through the lower plenum and into the core is \( Q_{\text{boil}} \) (ft\(^3\)/s) and the source concentration (weight fraction) of boric acid into the lower plenum from the sump is denoted by the symbol \( M_0 \). The quantity of interest is the concentration of boric acid in the core, \( M_2 \) as a function of time, \( t \) within the core region. In order to predict this concentration, the following simplifying assumptions are made:

1. The lower plenum and core regions are well mixed and the boric acid concentration and temperature profiles within these regions are spatially uniform.
2. The lower core plate represents the only resistance to buoyancy-driven transport between the core and lower plenum.
3. The Boussinesq approximation is invoked such that the variation of liquid density with liquid temperature and solute concentration appears only in the buoyancy terms and all
other terms that contain density are represented with an effective density which is defined as the average density between the core and lower plenum.

4. The water in the core instantaneously rises to saturation temperature and remains there throughout the transient.

5. The volumetric coefficient of thermal expansion of water, $\beta$ and the boric acid expansion coefficient, $k$ are known.

The boil-off flow, $Q_{\text{boil}}$ through the vessel is essentially an externally supplied flow that passes through the lower core plate and carries boric acid into the core region. Initially, the boric acid concentration in the core increases with time at a rate directly proportional to $Q_{\text{boil}}$. However when the boric acid in the core becomes sufficiently concentrated, the density of the core solution exceeds that of the solution in the lower plenum. This density difference induces a buoyancy-driven, countercurrent down-flow of the heavier core liquid and consequential up-flow of the lighter liquid through the openings in the lower core plate.

Model Equations

In accordance with the assumptions presented in the previous section, the following linear expression for the density difference, $\Delta \rho_{12}$ between the liquid in the lower plenum (region 1) and the reactor core (region 2) can be written as:

$$\Delta \rho_{12} = \rho \beta (T_1 - T_{\text{sat}}) + \rho k (M_2 - M_1)$$

(1)

where $T$ and $M$ refer to the temperature and boric acid weight fraction, respectively. $\rho$ is the effective constant density of the liquid solution in the vessel and is defined as the average between the lower plenum and core densities:

$$\rho = \frac{(\rho_1 + \rho_2)}{2}$$

(2)

The term $Q_{\text{boil}}$ represents the net upward flow through the lower core plate required for make-up due to boil-off of liquid in the core region. It is the difference between the actual upward flow through the plate, $Q_{12}$ and the buoyancy-driven downward flow from the core to the lower plenum, $Q_{BF}$. A volumetric flow balance across the lower core plate requires that:

$$Q_{\text{boil}} = Q_{12} - Q_{BF}$$

(3)

Strictly speaking, the countercurrent flow occurs within each opening (hole) in the lower core plate. Denoting $N_{12}$ as the number of holes in the plate and assuming that each hole in the plate has the same diameter, $Q_{\text{boil}}/N_{12}$ may be regarded as an externally imposed, upward forced flow opposite to the downward buoyant flow, $Q_{BF}/N_{12}$ in each opening. This is the flow pattern that was studied experimentally by Epstein and Kenton (Reference 9). In these experiments, the downward buoyancy-driven component $Q_{BF}/N_{12}$ in the presence of an imposed upward flow $Q_{\text{boil}}$ within an opening in a horizontal partition that separates two unstably stratified fluids was measured and a correlation was developed for the downward buoyancy-driven component, $Q_{BF}$ that is a function of the purely buoyancy-driven, countercurrent exchange flow, $Q_{cc}$.

The purely buoyancy-driven, countercurrent exchange flow, $Q_{cc}$ is the exchange flow through an opening without the presence of an externally imposed upward flow. Epstein (Reference 10) has provided an empirical correlation for the purely buoyancy-driven, countercurrent exchange flow.
Q_{cc} in the form of a Froude number versus the aspect ratio of the opening. With these two correlations, an expression for Q_{BF} can be obtained and Q_{12} becomes the only unknown in Eq. 3.

The time histories of the solute concentrations, M_i and the temperatures, T_i in each region are given transient solute mass and liquid energy balances. Applying the correlations for Q_{BF} along with Eq. 3, the transient mass and liquid energy balances can be simplified to form a set of nonlinear equations that are functions of T_i, M_i, Q_{BF}, Q_{boil} which can be solved numerically for a set of given initial and boundary conditions.

The model has been benchmarked against an MHI BACCHUS test. The BACCHUS boron concentration data measured in the core and lower plenum was volume average in order to compare with the two-region model results and the model power was adjusted such that the initial boil-off rate matched that recorded during the test. The two-region model predictions compare well with the BACCHUS test data.

**Inception Criteria**

In view of Eq. 1, when $\Delta \rho_{12} \leq 0$ the system is stably stratified and the buoyancy driven back flow, Q_{BF} is zero, that is:

$$Q_{BF} = Q_{cc} = 0 \quad \text{when } \Delta \rho_{12} \leq 0 \quad (4)$$

Also, when the destabilizing density difference, $\Delta \rho_{12}$ is positive but small, the buoyancy driven back flow is not large enough to penetrate the upward makeup flow, Q_{boil} through the core plate and the net downward transport rate is again zero:

$$Q_{BF} = 0 \quad \text{when } q_{12} \leq Q_{boil} \quad (5)$$

Eqs. 4 and 5 define the inception criteria for the transport of higher concentration boric acid from the core to lower plenum. If the liquid in the lower plenum is not subcooled then, $\Delta \rho_{12} \geq 0$ and Eq. 5 is the only criterion that has to be met and transport between the core and lower plenum will occur sooner in the transient. If subcooling exists in the lower plenum, $\Delta \rho_{12} \leq 0$ and the concentration gradient between the core and lower plenum will have to overcome the oppositely opposing temperature gradient in addition to Eq. 5 and inception will occur later in the transient.

**Plant Simulation**

Using the Westinghouse 3 loop PWR plant model used in the previous section, an analysis using the boron transport model is performed. This analysis is performed using inputs consistent with the AOR. The analysis assumes a lower plenum fluid temperature of 130°F and credits the entire lower plenum volume. The large subcooling results in a larger concentration gradient between the core and lower plenum at the inception time which in turn delays the onset of exchange flow. Results show that the inception to buoyancy-driven transport from the core to the lower plenum occurs within 1000 seconds (0.28 hours) when the concentration gradient between the core and lower plenum is roughly 8.5 wt% boric acid. This result is consistent with observations from the MHI BACCHUS tests which indicated an approximate 8.5 wt% concentration gradient at the inception time. A comparison of this run to the AOR case is provided in Figure 1. As the figure shows, the core boric acid concentration from the prediction using the core-to-lower plenum boron transport model initially increases at a faster rate compared to the AOR case because the
effective mixing volume is smaller. After the inception time, the core concentration build-up rate slows as the lower plenum concentration begins to increase. Just after 10,000 seconds, the core boric acid concentration predicted with the boron transport model crosses the AOR case and remains below it for the rest of the transient. The lower plenum concentration trend follows the core concentration but remains roughly 8.5 wt% lower for the remainder of the transient. The HLSO time predicted using the boron transport model is 8.32 hours which is almost 2 hours longer than the AOR case.

Since the communication between the core and lower plenum begins before a highly resistive debris bed is expected to form, some credit can be taken for the lower plenum volume. In addition, when the core boric acid concentration becomes high enough to overcome the temperature gradient between the core and lower plenum as well as the upward force generated by the upward makeup flow the system becomes unstable. This instability may generate oscillations in the flow field around the core inlet which could serve to breakup or prevent a debris bed from forming. It is shown in Figure 2 that the magnitude of the countercurrent exchange flow between the core and lower plenum overcomes that required to replace boil-off within the first 10,000 seconds of the transient. Given that the countercurrent exchange flow is greater than the upward flow required to replace boil-off, it can be postulated that the exchange flow would breakup any existing debris bed or prevent one from forming.
Figure 1: Predicted Boric Acid Concentration from AOR Compared to Results from the Core-to-Lower Plenum Boron Transport Model
Figure 2: Boil-off Rate Compared to the Core-to-Lower Plenum Exchange Flow Rate Predicted by the Boron Transport Model
EVALUATION OF BORIC ACID PRECIPITATION CONTROL FOLLOWING A POSTULATED LARGE HOT LEG BREAK LOCA

It has been postulated that core inlet blockage caused by the ingestion of debris into the ECCS under large hot leg break conditions can lead to a situation in which boric acid precipitation is a concern. Without the influence of debris, large hot leg breaks are not limiting with regard to boric acid precipitation when cold leg safety injection is present because a dilution flow exists through the core that effectively flushes boron from the reactor vessel. However, the formation of a debris bed at the core inlet has the potential to increase the flow resistance such that flow through the core is limited and boric acid concentrations in the reactor vessel may increase. The potential issue described above can be mitigated by showing that flow through the reactor core is maintained in excess of that required to remove decay heat (boil-off) such that liquid carryover out the hot leg break delays the concentration build-up of boric acid in the reactor vessel such that the calculated HLSO time remains bounding.

In order to quantify the fraction of addition flow necessary to preclude boric acid precipitation before the timing of BAP control measures are implemented, a simple analysis is performed that considers liquid carryover out the hot leg break.

The major assumptions used in this analysis are as follows:

- The transient begins 100 seconds after the LOCA event and assumes that a highly resistive debris bed is present at that time such that the lower plenum volume is not credited as part of the boron mixing volume.
- The initial reactor core boron concentration is equal to the sump mixed mean concentration. The mixed mean concentration is determined by taking all the possible sources of liquid in containment (i.e. RWST, accumulators, RCS, and BIT) and assuming that they are homogenously mixed within the associated control volumes (reactor vessel and sump).
- The effective mixing volume used to track the boric acid concentration build-up considers core voiding and a two-phase mixture to the bottom of the hot leg. Lower plenum volume is not credited as part of the mixing volume.
- Flow into the reactor core is in excess of boil-off. Flow into the core is assumed to occur through the highly resistive debris bed, or through flow that bypasses the core inlet via alternate flow paths or through some combination of both. Regardless of the flow path, liquid in excess of boil-off is reaching the reactor core.
- Liquid in the effective mixing volume is assumed to be well mixed such that the boric acid concentration is uniform in the mixing volume.

Results from the analysis described above indicate that as little as 5% liquid carryover out of the hot leg break is sufficient to preclude boric acid precipitation well past any currently established hot leg switchover time as shown in Figure 3. Assuming 5% liquid carryover indicates that flow into the core must be, at minimum, 5% in excess of boil-off for this result to hold because any reduction in core flow would result in a reduction in two-phase mixture level which would reduce the liquid carryover out of the vessel and result in a faster build-up of boric acid in the reactor vessel.

In order to demonstrate that boric acid precipitation is not a concern under a large hot leg break scenario with core blockage, it needs to be shown that flow in excess of boil-off reaches the core...
and that the entire core volume remains completely mixed. These two items will be addressed as part of the current GSI-191 deterministic resolution program.

**Figure 3: Core Boric Acid Concentration with Liquid Carryover out of the Hot Leg Break**
ASSESSMENT OF THE SAFETY SIGNIFICANCE OF THE POTENTIAL FOR BORIC ACID PRECIPITATION IN THE REACTOR VESSEL AFTER A LOCA

The purpose of this section is to discuss the overall safety significance of the potential for BAP in the reactor vessel after a LOCA. This discussion supplements the evaluations presented earlier and provides defense-in-depth for support of current plant safe operation. The risk of BAP is the effect on core cooling and the potential for core damage that may result from an incidence of post-LOCA BAP. With this perspective in mind, the BAP concerns cited in Reference 1 do not represent a significant safety concern for the following reasons:

- There is low probability of a large break LOCA (LBLOCA) where conditions leading to significant boric acid accumulation may be encountered.

- If some of the transient behavior is incorporated into BAPC analyses, there would be a beneficial effect on the results. These include: liquid entrainment around the loop early in the transient, boron carryover in the steam, containment overpressure, and mixing in regions outside the core, upper plenum and portions of the lower plenum. Modeling realistic subcooling for lower plenum fluid would provide significant benefits in terms of reduced boil-off rates and core voiding. Given the size of the steam generators and the reduced steam flow rates through the RCS post-LOCA, it would take substantial depositions of boron to have any significant effect on pressure in the upper plenum, and boron deposited in the steam generator would not be available to precipitate in the core.

- If best estimate or realistic assumptions are used, the predicted BAP time would be significantly longer than designated emergency operating procedure (EOP) action times that address BAP concerns. The most significant realistic assumptions are best estimate decay heat, nominal boron concentrations and water source volume assumptions, some level of liquid entrainment out of the core early in the transient, and an increased solubility limit due to the presence of buffering agents.

- Observations from a test facility representative of a typical Westinghouse 3-loop PWR indicate that BAP would not occur for at least 24 hours after a LBLOCA (Reference 3). This indicates a boric acid buildup well below that calculated with the methodology in question.

- In the event that BAP should occur, it is unlikely that core cooling would be compromised as long as the core remains subcritical.
  - It is expected that boric acid would tend to plate out on the colder structures, accumulate in the lower plenum, or would collect at the top of liquid mixture level. This tendency was noted in tests documented in Reference 11.
  - Any boric acid precipitate would go back into solution once the core dilution flow is initiated.
  - The ultimate ability of boric acid to insulate the fuel rods is limited since orthoboric acid precipitate has a melting point of 340°F.
It would take significant boric acid precipitate to totally block water from getting to the core. For example, for a typical Westinghouse 3-loop PWR, if all of the boric acid in the expected decay heat core boil-off were to precipitate 4 hours after the LOCA, the total precipitate for the next 4 hours would displace less than 58 cubic feet, or less that 5% of the total free volume of the core and lower plenum.

CONCLUSION

The technical discussion in this paper demonstrates that there is reasonable assurance of protection of the public health and safety, and the PWROG should be allowed to methodically approach the necessary testing and development of methodologies to support the evaluation of BAPC without being included in the resolution of GSI-191. The evaluation performed demonstrates that if a debris bed does form at the core inlet following a large cold break such that communication between the core and lower plenum is lost, sufficient margin exists in the methodology and assumptions to prevent the boron concentration in the reactor vessel from exceeding the solubility limit prior to currently licensed HLSO times. The assessment of safety significance of the potential BAP in the reactor vessel following a LOCA provides defense-in-depth for support of current plant safe operation and further bolsters the argument that BAP can be separated from the resolution of GSI-191.

REFERENCES


