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RAIO-1119-68093

November 27, 2019

Docket No. 52-048

U.S. Nuclear Regulatory Commission
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Rockville, MD 20852-2738

SUBJECT: NuScale Power, LLC Supplemental Response to NRC Request for Additional Information No. 484 (eRAI No. 8930) on the NuScale Design Certification Application

REFERENCES:
1. U.S. Nuclear Regulatory Commission, "Request for Additional Information No. 484 (eRAI No. 8930)," dated May 29, 2018
2. NuScale Power, LLC Response to NRC "Request for Additional Information No. 484 (eRAI No.8930)," dated September 14, 2018
3. NuScale Power, LLC Supplemental Response to NRC "Request for Additional Information No. 484 (eRAI No. 8930)," dated July 18, 2019

The purpose of this letter is to provide the NuScale Power, LLC (NuScale) supplemental response to the referenced NRC Request for Additional Information (RAI).

The Enclosures to this letter contain NuScale's supplemental response to the following RAI Question from NRC eRAI No. 8930:

- 15-27

Enclosure 1 is the proprietary version of the NuScale Supplemental Response to NRC RAI No. 484 (eRAI No. 8930). NuScale requests that the proprietary version be withheld from public disclosure in accordance with the requirements of 10 CFR § 2.390. The enclosed affidavit (Enclosure 3) supports this request. Enclosure 2 is the nonproprietary version of the NuScale response.

This letter and the enclosed responses make no new regulatory commitments and no revisions to any existing regulatory commitments.

If you have any questions on this response, please contact Matthew Presson at 541-452-7531 or at mpresson@nuscalepower.com.

Sincerely,

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Enclosure 1: NuScale Supplemental Response to NRC Request for Additional Information eRAI No. 8930, proprietary

Enclosure 2: NuScale Supplemental Response to NRC Request for Additional Information eRAI No. 8930, nonproprietary

Enclosure 3: Affidavit of Zackary W. Rad, AF-1119-68094

Enclosure 1:

NuScale Supplemental Response to NRC Request for Additional Information eRAI No. 8930, proprietary

Enclosure 2:

NuScale Supplemental Response to NRC Request for Additional Information eRAI No. 8930, nonproprietary

Response to Request for Additional Information
Docket No. 52-048

eRAI No.: 8930
Date of RAI Issue: 05/29/2018

NRC Question No.: 15-27

Requirements:

Title 10 of the Code of Federal Regulations, Section 50.46, "Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors," requires, in part, that after any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

10 CFR, Part 50, Appendix A, General Design Criterion (GDC) 28—*Reactivity limits* requires that the reactivity control systems be designed with appropriate limits on the potential amount and rate of reactivity increase to ensure that the effects of postulated reactivity accidents can neither (1) result in damage to the reactor coolant pressure boundary greater than limited local yielding nor (2) sufficiently disturb the core, its support structures or other reactor pressure vessel internals to impair significantly the capability to cool the core. These postulated reactivity accidents shall include consideration of rod ejection (unless prevented by positive means), rod dropout, steam line rupture, changes in reactor coolant temperature and pressure, and cold water addition. In addition, Generic Safety Issue (GSI) 185 (Control of Re-criticality Following small break (SB) loss of coolant accidents (LOCAs) addresses scenarios of potential return to criticality following a SB LOCA resulting from insertion of unborated water into a pressurized water reactor (PWR) core.

To meet the requirements mentioned above regarding long-term cooling, the results of the accident analysis should show that for the worst case boron dilution event the capability to cool the core is maintained.

Background:

Page 2 of the applicant's report, "Long-Term Cooling Methodology," TR-0916-51299-P, Revision 0, states that the criterion for the core remaining subcritical (Criterion #5) is "not applicable to the Long-Term Cooling (LTC) condition since no mechanism to push a large volume of diluted water into the core inlet exists, and therefore no credible mechanism for recriticality due to boron dilution exists." However, there are postulated events that could allow the addition of cooler water with diluted boron concentrations from containment to the reactor vessel via the RRVs during the long term cooling phase following any Chapter 15 scenario. For instance, diluted or unborated water can accumulate inside containment due to steaming from the reactor vent valves (RVVs) (which may concentrate boron in the area above the core) when the reactor is being cooled by emergency core cooling system (ECCS) recirculation. The diluted or unborated water accumulating inside containment can also further mix with secondary side unborated water that was introduced into containment after a pipe carrying unborated water ruptered inside containment (see RAI 8744, Question 15.02.08-3). The diluted or unborated water can then make its way back into the reactor pressure vessel, and ultimately, into the core via the RRV ECCS recirculation path. The diluted or unborated water can affect core criticality, potentially leading to recriticality, and thus present a challenge to acceptance criteria.

This RAI is being issued, in part, as a follow-up RAI to RAI 8744, Question 15.02.08-3 after determining that RAI 8744, Question 15.02.08-3 did not provide adequate information to resolve the issue. All together, this RAI will require the applicant to detail and define the methodology used for boron transport inside the reactor pressure vessel and containment vessel after ECCS actuates as well as to present the results in the FSAR of a long-term cooling analysis that show how a bounding boron dilution event affects the criticality and coolability of the core.

The staff asked RAI 8744, Question 15.02.08-3, to require the applicant to determine if core criticality is affected by the introduction of pure, secondary side water into the core after ECCS recirculation begins following a FWLB inside containment. The applicant's response to RAI 8744, Question 15.02.08-3 argues that void fraction due to "high" decay heat limits (or precludes) the return to power evaluated in the LTC analysis. This may be true, but sufficient detail regarding void reactivity vs. dilution reactivity (core generated dilution due to boiling and unborated water pipe break generated dilution) and how these values were determined should be provided. Analysis assumptions (e.g. dilution water volume) and plots of reactivity and, if necessary, core power vs. time are necessary to address this RAI.

Request:

The staff requests the applicant to specify and describe in sufficient detail in the FSAR a methodology used to calculate boron transport during long-term cooling following ECCS actuation after any Chapter 15 event. As part of the description of the methodology, the applicant should appropriately justify the methods, assumptions, and techniques using acceptable validation bases. Furthermore, the staff requests the applicant to provide the results of a long-term cooling analysis that show how a bounding boron dilution event affects the core criticality and coolability. These results should include the quantitative distribution of boron throughout the RCS and containment vessels as a function of time following ECCS actuation. The analysis should consider the most limiting boron dilution volume (e.g. condensate in containment from steaming through the RVVs and from any additional un-borated water already inside containment from breaks in piping carrying un-borated water inside containment). Similarly, the response should include the analysis assumptions and plots of various reactivity effects that determine reactor power to confirm that the core is sub-critical.

NuScale Response:

1. Background

The original response to RAI 8930, question 15-27 was submitted in NuScale correspondence (RAIO-0918-61810, dated September 14, 2018). The first supplement to the original response replaced the original response and addressed issues that were discussed with the staff in subsequent meetings (RAIO-0719-66323, dated July 17, 2019).

This supplemental response rearranges information provided in the previous supplement and includes new information to address specific NRC concerns enumerated after the supplemental response was submitted. Specifically, this supplement revises the previous supplement to:

- Delineate the purpose and scope of the long-term cooling boron distribution evaluation in Sections 1.1, and 1.2 respectively.
- Add a summary comparing the inputs and assumptions of the 72-hour and 7-day evaluations in Table 2-1. This table includes a delineation of the conservative treatment of flowpath modeling and boron volatility and entrainment.
- Add a summary of the boron loss mechanisms for the 72-hour evaluation in Section 2.1.1.3.

- Add a discussion on the applicability of the boron volatility model used in the 72-hour evaluation in Section 2.1.3.
- Add new information for the evaluation for hot region mixing during cold conditions and the possible development of a boron gradient between the core and riser regions and in the core inlet in Section 2.1.4.
- Add results of the 72-hour evaluation as presented in Section 3.1.
- Add a discussion of the seven-day evaluation and results of boron distribution during the long-term cooling period in Sections 2.2 and 3.2.
- Delineate the key conservatisms in the 72-hour evaluation in Section 3.3.

As a result of this response, FSAR 15.0.6 was revised to explain why post-ECCS boron redistribution in the NuScale Power Module (NPM) does not impact the return-to-power analysis presented. Section 6.3.2.5 was also revised to delete reference to any applicable time period beyond 72 hours.

Qualitatively considering boron transport in the NPM, during initial stages of ECCS operation, relatively pure water leaves the reactor pressure vessel (RPV) through the reactor vent valves (RVVs), leaving the boron in the core region. Due to the unique aspects of the NPM emergency core cooling system (ECCS) design, it is not susceptible to large pure water injections similar to a loop seal clearing in a traditional PWR. Regardless of the initial liquid level in the containment prior to ECCS actuation, recirculation of liquid through the reactor recirculation valves (RRVs) does not occur until pressure equalization between the containment vessel (CNV) and the RPV, at which point the recirculation rate is driven by the RCS boil off rate. After ECCS valves open and recirculation is established, liquid from containment enters the reactor pressure vessel through the RRVs, circulates into the core region, and vapor is vented into containment through the reactor vent valves, where it condenses on the containment wall. The boron concentration of liquid in containment may be lower than the boron concentration of liquid in the core/riser region. However, since flow rates from containment into the reactor pressure vessel through the recirculation valves are low and the boron concentration in the core region will tend to increase due to boiling in the core region, no credible means of introducing a large slug of deborated water unmixed into the core region has been identified for the NuScale design. Consequently, the boron mass transport balance will tend toward accumulation of boron in the core region.

For quantitative evaluation of boron transport and distribution, there are two concerns with opposite perspectives: one is boron dilution (under-concentrating boron) and the other is boron precipitation (over-concentrating boron). Therefore, the problem is how to model the boron transport without missing important transport mechanisms, and produce conservative solutions for the boron distributions from different perspectives (i.e., boron dilution and boron precipitation). The purpose and scope of the boron transport and distribution analyses can be represented conceptually as shown in Figure 1-1.

In Figure 1-1, the region bounded between the conservative boron dilution and boron precipitation models (indicated by dashed lines) can be considered as an uncertainty band for the realistic boron transport model (indicated by a solid line). It is likely that the limiting initiating events and conditions are different for the boron dilution and boron precipitation analyses. In the figure, the critical boron concentration and boron solubility limit (indicated by dotted lines) are also included. The boron solubility limit provides the acceptance criteria for boron precipitation analyses. Comparison of the boron dilution analysis result to the critical boron concentration can be used to inform the scope of return to power analyses as discussed further below in Section1.1.

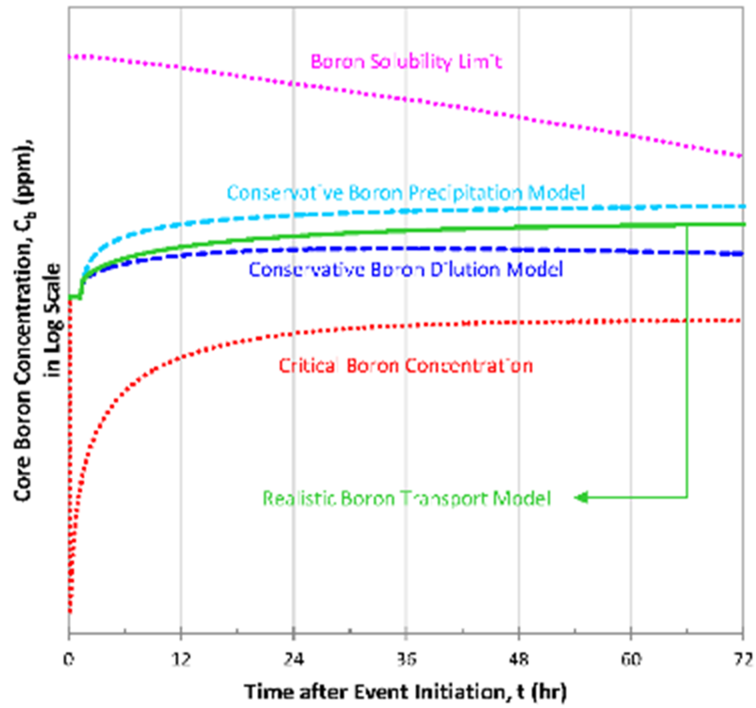

Figure 1-1. Conceptual Boron Transport and Distribution Analysis Results

1.1 Purpose

A systematic analysis approach has been developed for addressing possible boron transport phenomena in the NuScale Power Module (NPM) in order to address and disposition the temporal aspects of boron distribution during ECCS cooling modes. The focus of this discussion is on boron dilution. This bounding transport analysis is performed to quantitatively demonstrate that bulk boron dilution in the NPM is not possible because if there is any boron initially in the RCS, it will tend to accumulate in the core region.

Conceptually for boron dilution analysis, the core region concentration can be compared to the critical concentration. If the core region concentration remains above the critical concentration, then subcriticality is demonstrated and long term cooling analyses demonstrate that adequate cooling is provided to remove decay heat and confirm that SAFDLs are not violated. If the concentration is below the critical concentration then the core is determined to be critical. In the case that the core is critical, return to power analysis is performed to demonstrate that SAFDLs are not violated. The critical boron concentration changes as a function of time in cycle, fluid temperature and density, fission product poisoning, and whether the worst rod stuck out is assumed.

In the NuScale NPM long-term cooling analyses described in TR-0916-51299 (Reference [11]), it is demonstrated that core cooling is provided to remove decay and residual heat from the core. This is demonstrated by, first, showing that the liquid level in the RPV remains above the top of active fuel and, second, that the boron concentration in the core region remains below the solubility limit; demonstrating that the boron concentration remains below the solubility limit supports the conclusion that coolable geometry is maintained. For the NuScale design, long term shutdown capability is defined as the amount of reactivity by which the reactor is subcritical or would be subcritical from its present condition assuming all control rod assemblies are fully inserted and the RCS is cooled to equilibrium conditions. However, given an unmitigated cooldown after reactor trip at late-in-cycle RCS boron conditions and assuming the highest worth control rod is stuck out of the core, it is possible that return to power could occur due to the slow decay of xenon. The NPM return to power analysis summarized in the FSAR Section 15.0.6 provides a conservative characterization of the equilibrium power and corresponding critical heat flux ratio, should a return to power occur. The return to power analysis demonstrates that acceptance criteria including SAFDLs for anticipated operational occurrences are not exceeded. In the return to power analysis it is assumed that the initial boron concentration in the RCS is present in the core region; with this assumption, considering changes in reactivity feedback over the cycle operation, the limiting conditions for the return to power analyses are near end of cycle.

Therefore, quantitative evaluation of boron transport during ECCS cooling is performed to demonstrate that, even absent any injection of additional boron to the module through CVCS or other system, there is no net dilution of the core region during the timeframes of interest. Analyses for 3 days and for 7 days are performed:

- The conservative 3 day analysis results support the conclusion that the conservative time in cycle to evaluate a loss of shutdown margin due to moderator overcooling is end of cycle.
- The 7 day analysis is performed to demonstrate that during this timeframe, even without boron addition, there is no bulk dilution of the core region. This supports the conclusion that CVCS or other system(s) are not classified as RTNSS in the NPM design.

1.2 Scope

In the NPM design the ECCS valves are designed to open following a high containment liquid level signal, indicating a breach in the RCS pressure boundary resulting in transfer of primary coolant from the RCS to containment. The ECCS valves are also designed to fail-safe to the open position if a loss of power to the valve actuators is postulated. The NPM design does not include or require safety-related power supplies. Therefore, in the context of deterministic Chapter 15 loss of power assumptions, a postulated non-LOCA event in which loss of normal AC and DC power supplies is assumed will transition to ECCS cooling.

With respect to evaluation of boron redistribution and potential for core boron dilution during ECCS cooling, three events are considered as these represent the scope of NPM events mitigated by ECCS cooling either due to breach in the RCS or due to assumed loss of normal AC and DC power supply:

- Liquid space primary coolant release due to inadvertent opening of one reactor recirculation valve
- Vapor space primary coolant release due to inadvertent opening of one reactor vent valve
- Break of reactor component cooling water pipe inside containment with assumed loss of normal AC and DC power leading to ECCS actuation

There are two post-event timeframes of interest in the boron transport analysis:

- The 3 day (72 hour) window following event initiation where conservative boron transport analysis is performed, consistent with the design basis analysis timeframe applied in the NPM design for other Chapter 15 event analysis
- The 7 day (168 hour) window following event initiation. The 7 day window is evaluated in order to confirm that boron addition to the NPM from nonsafety-related systems such as CVCS is not required during this extended timeframe. This supports the conclusion that the CVCS or other system(s) are not classified as RTNSS in the NPM design. The 7 day window is beyond the 72 hour mission time for conservative Chapter 15 event analysis; therefore, more realistic boron transport assumptions are used in the 7 day analysis. The use of more realistic boron transport assumptions in the 7 day analysis also provides a quantification of the additional conservatism in the 3 day analysis.

In the 3 day analyses performed, a high initial boron concentration is assumed. As shown in Section 3.1, the concentration in the core region increases from the initial concentration and remains above the initial concentration at the end of the analysis. Therefore, the conclusion of the analysis that there is no bulk dilution of the core region is applicable to initial boron concentrations at different times in cycle. This is also confirmed in the 7 day analysis where different initial boron concentrations reflecting beginning, middle, and end of cycle conditions are evaluated. Therefore, the conservative time in cycle to evaluate a loss of shutdown margin due to moderator overcooling is end of cycle. The 3 day and 7 day analyses performed demonstrate that there is no bulk dilution in the core region, even absent boron addition to the RCS from active systems.

2. Boron Transport Analysis Methodology

In this section the boron transport analysis methodology is described. First, the conservative 3 day analysis approach is summarized. The conservative 3 day analysis approach is based on a control volume analysis approach. {{

}}[2(a),(c)]

Where applicable, NRELAP5 results are used to calculate fluid transport, and appropriate conservatisms are applied in the boron concentration values and boron transport terms used to conservatively evaluate the boron concentration of the RCS hot region. In addition to the NRELAP5 fluid transport results, the boron transport analysis includes consideration of liquid entrainment through the RVVs and volatility of boron in steam vented through RVVs. In discussion of the conservative 3 day analysis approach, subsections provide more detailed information on the following methodology aspects:

- Summary of control volume approach, boron transport between control volumes and summary of boron loss mechanisms

- Scope of initiating events analyzed

- Applicability of boron volatility calculation

- Mixing in the RCS hot region. The potential for a significant gradient in boron concentration is evaluated using first principles approaches, considering available experimental data, quantitatively evaluating the reactivity impact of a lower core region gradient, and by quantifying conservatism in the analysis results.

- Summary of key conservatisms

Then, the analysis methodology for the 7 day analysis is described by summarizing key differences between the 7 day and 3 day analysis. Table 2-1 provides a high level summary of the 3 day and 7 day analysis approaches.

Table 2-1. Summary of 3 Day Conservative and 7 Day Boron Dilution Transport Inputs and Assumptions

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2.1 Conservative Boron Transport Methodology for 3 Day Analysis

2.1.1 Summary of Methodology

This section summarizes the methodology for simplified analyses of the boron transport and distribution in the reactor coolant system (RCS) and the containment vessel (CNV) of the NuScale Power Module (NPM). The methodology is based on a control volume analysis approach using NRELAP5 calculation results, as applicable, with conservative treatment of boron transport between control volumes and conservative treatment of boron transport loss terms. {{

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2.1.1.1 Control Volume Approach

During the LTC period with the ECCS recirculation, for either LOCA or non-LOCA initiating events, the reactor coolant will be nearly stagnant except for the inter-system water flows between the RCS and CNV through the reactor vent valves (RVVs) and reactor recirculation valves (RRVs). Considering the paths for water transport between the RCS and CNV, phase change phenomena affecting boron distribution in the RCS, and the buoyancy driven internal circulation expected in the module, as conceptually shown in Figure 2-1, it is concluded that {{

}}2(a),(c)

2.1.1.2 Boron Transport between Control Volumes

In the NuScale 3 day boron dilution analysis, the thermal-hydraulic conditions (including the water inventory and flow distributions) are obtained from NRELAP5 transient calculation results, except for entrained liquid in the RVVs. The conservation equations governing the boron transport in the RCS and CNV of the NPM are formulated based on a control volume analysis approach considering possible boron transport paths for design-basis loss-of-coolant accident (LOCA) and non-LOCA initiating events followed by the emergency core cooling system (ECCS) actuation. The governing equations for the boron transport model are written for each region, accounting for the time dependent rate of change of the boron mass in the region and the rate of boron mass transport by advection between the region and the other regions. For each of the volumes, a general form of the boron transport equation was developed based on conservation of boron mass in each control volume and the identified transport mechanisms. {{

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The boron dilution analysis model is formulated in such a way that the boron concentration in the core is minimized by maximizing the boron transport out of the core and minimizing the boron transport into the core. As part of this approach, the NRELAP5 calculations are biased for maximum temperature (see discussion in the long term cooling technical report (TR-0916-51299 (Reference [11]). Section 2.1.3.2 provides additional discussion and sensitivity analysis results to demonstrate the conservatism of formulating the analysis to minimize the boron concentration transported into the core while maximizing the boron transport out of the core, as opposed to formulating the analysis to maximize the boron lost to the system through volatility. Section 2.1.4 provides additional justification of mixing in the RCS hot region, to demonstrate that the assumption of mixing in the RCS hot region is reasonable and there is adequate conservatism applied in the formulation of the boron transport analysis.

For the predominant boron transport paths, the conservatism in the applied boron distribution factors is **highlighted** below.

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2.1.1.3 Summary of Boron Loss Mechanisms

As described above, in the 3 day boron dilution analysis the following mechanisms are assumed to remove boron from system, conservatively reducing the boron available to transport into the RCS hot region over time:

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  }}2(a),(c)

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Consideration has been given as to whether local solidification (precipitation or plateout) could occur in the lower riser. Boron plate-out is not expected in the lower riser region due to the following observations:

- WCAP-17047-NP (Reference [7]) outlines various solidification mechanisms which are achieved by either bulk or local super-saturation of the liquid solution. The existing precipitation analysis in the long term cooling technical report (TR-0916-51299 [11]) is sufficiently conservative to conclude any solidification of boron is not possible.

- The 2018 Morozov Journal of Physics paper (Reference [5]) provides a correlation for boron vaporization fraction. The test procedure described in this paper relies on condensing of the volatized boron back into liquid solution to quantify the volatility fraction supporting the conclusion that volatized boron will not actually be a solidification mechanism as conservatively assumed in the limiting analysis. The volatility measurements presented in Reference [1] and Reference [19] similarly relied on condensation of steam to measure the volatilized boron fraction.

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Figure 2-1. Buoyancy Driven Internal Circulations Expected during ECCS Recirculation Phase

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Figure 2-2. Control Volumes Used in Boron Transport and Distribution Analysis Methodology

2.1.2 Initiating Events Analyzed and Identification of Limiting Event

As discussed in Section 1.2, calculations are performed for an inadvertent opening of an RPV valve (IORV) RRV and RVV, in addition to an RCCW line break analysis with assumed loss of AC and DC power. These events are sufficient to address the spectrum of different events in the NPM that are mitigated by ECCS cooling, namely RCS mass release from the liquid region, RCS mass release from the vapor (pressurizer) region, and a non-LOCA type event, with assumed loss of AC and DC power, that initially transports dilute water into the CNV. Due to effects of boron volatility and conservative treatment of the CNV boron concentration, the RRV event without the DHRS activated for a hot reactor condition is identified as the limiting event.

2.1.3 Evaluation of Boron Volatility_

First, the applicability of the selected boron volatility model is justified for the NuScale dilution analysis. Next, the conservatism of biasing the overall transport to minimize hot region concentration is evaluated against an alternate approach which maximizes boron loss due to volatility.

2.1.3.1 Applicability of Boron Volatility Model

In the 3 day analysis vaporization of boric acid is evaluated and volatilized boron is treated as a loss mechanism removing boron from the RCS hot region. Volatilized boron carried with the steam leaving the RCS hot region is conservatively assumed to be lost from the system; therefore, it is assumed that the volatilized boron does not return to solution in liquid upon steam condensation on the CNV wall, to recirculate from the CNV region back into the RCS hot region.

As part of developing the boron dilution transport analysis, a literature survey was performed for data and models evaluating the boron volatility fraction. The Böhlke et al. boron volatility model (Reference [1]) is used with appropriate conservatism, {{

}}2(a),(c) When applied in the NuScale boron transport analysis, the 1.35 coefficient for boric acid is applied, consistent with the expected fluid compound in the NPM. The Böhlke et al. boron volatility fraction predicted by the model is comparable to those obtained from other models and test data, including those presented in Reference [2], except for the WAPD-MRP-49 test data group included in Reference [2] and the Reference [19] volatility data. First, the applicability of the Böhlke et al. model to the NPM is discussed, and then the model is considered in context of other data sets.

The NuScale conditions are fully covered by the applicable ranges for the Böhlke et al. model as summarized in Table BV-1. A schematic of the BORAN facility is presented in Figure BV-1 below. The Bohlke boron volatility correlation (Reference [1]) was developed using data from both an autoclave facility and the BORAN test facility. In the autoclave facility, different boron compounds were tested and this was used to determine appropriate coefficients for the volatility of different compounds. Test data developed from the BORAN facility was used to evaluate the effect of void fraction ranges on volatility. In the autoclave facility, boric acid, sodium-pentaborate, and sodium-tetraborate compounds were tested. When dissolved in water, sodium-pentaborate and sodium-tetraborate dissociate resulting in a complex polyborate equilibria that is dependent on temperature, pH, concentration, and the presence of other ions. The boric acid compound is volatile as it has a neutral charge, while the other compounds are not volatile as they are ions, and volatilizing an ion results in a charge imbalance in the liquid and vapor. This results in different volatility of boric acid when measured against the dissolved boron concentration, and can vary with pH. Therefore, for consistent temperature and pH conditions the difference in volatility for boric acid compared to sodium pentaborate or sodium tetraborate would be consistent. This difference is based on the chemical equilibrium of the compounds. Therefore, the difference in volatility correlated for different compounds from the autoclave facility data can be applied to other geometric configurations.

The NPM and the BORAN facility share similar geometries for the parameters that would impact the volatility fraction. The small differences in boiling height and the water column height are discussed in the dissertation (Reference [9]) to not materially impact the volatility fraction. While the Bohlke boron volatility correlation was developed with test data from varying compounds, when applied in the NuScale boron transport analysis, the coefficient for boric acid is applied consistent with the expected fluid compound in the NPM.

The Bohlke boron volatility correlation (Reference [1]) and PhD dissertation [9] describe the theoretical dependence of the volatility fraction on the interfacial area and contact time between the phases. The BORAN test facility used in developing the correlation did not have the requisite instrumentation to determine the interfacial area and time of contact, and instead used void fraction as the correlating parameter. This suggests that the applicability of the correlation is limited to geometries and conditions that are sufficiently similar to the test facility. The test facility is a 1:1 height scale of a German SWR which is a large BWR. However, the geometry of the NuScale module in ECCS mode is very comparable to the BORAN test facility from which the volatility correlation was developed.

The dimensions of the BORAN test facility and the NuScale reactor during ECCS cooling are listed in Table BV-2 below. Note that the boiling level for the BORAN facility listed is the nominal value, and that the NuScale boiling level listed is based on {{

}}2(a),(c)

Bohlke noted that the vertical distance the bubble traveled affected the boron picked up by the steam bubble, and therefore the volatility fraction. Both the NuScale module and the BORAN test facility have a vertically oriented water column with similar heights, and Bohlke on page 67 of the dissertation notes that increasing the water height from 5.5 to 6.1 m had no distinguishable effects on the volatility fraction. The similar heights and general insensitivity to the parameter in this range suggests that the NuScale module water column height is sufficiently similar to the BORAN test facility and therefore the effect of bubble travel distance on the boron picked up by the steam bubble is accounted for.

Unlike the BORAN test facility, the NuScale module in extended ECCS cooling mode has a very low net liquid velocity in the core and riser, and can be thought of as a nearly stagnant pool. Section 12.3.3 of the Bohlke PhD thesis (Reference [9]) discusses the impact of mass flow rate on the volatility fraction. The conclusion drawn from that section is that the increased turbulent motion at higher mass flow rates tends to break up larger bubbles into smaller bubbles, resulting in significantly higher volatility fractions due to the increase in interfacial area. To better understand the effect of interfacial area on volatility and applicability of the BORAN facility data to the NPM, the two-phase flow regimes at the core exit for the BORAN facility and the limiting NuScale IORV-RRV transient were evaluated. For the BORAN facility the two-phase flow regime was evaluated using the criteria put forth by Liu and Habiki (Reference [10]). For the data reported for the BORAN facility, the flow regime is predicted to be in the cap-turbulent regime. Of the flow regimes considered in this analysis, the bubbly regime has higher interfacial area than cap-bubbly, and cap-bubbly has higher area than cap-turbulent. From inspection of the data given in Table 12-11 of Reference [9], it was also observed that for a given data pair, the data point with the higher mass flux resulted in significantly higher volatility fractions although the data points are in the same flow regime. This conclusion is useful in evaluating the applicability of the correlation to the NPM.

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}}2(a),(c) The results show that for long-term ECCS cooling conditions the flow is expected to be in the cap-turbulent regime, but near the transition criteria for the cap-bubbly regime for some data points. The transition criteria and data points are shown in Figure BV-2.

The cap-turbulent regime is consistent with the BORAN facility data, although the BORAN facility data was near the transition to cap-bubbly flow. However, the mass flux for the NPM is more than two order of magnitude lower than the mass flux in the BORAN test facility. The results form Table 12-9 of Reference [9] demonstrate that approximately doubling the mass flow of the BORAN facility increases the volatility fraction by a factor of 1.2 to 1.8. This was concluded to be due to higher turbulence in the fluid resulting in smaller bulbbles and therefore more interfacial area at higher mass flow rates. In the NPM boron dilution analysis there is no credit taken for lower volatility rates that could be expected due to the lower mass fluxes. {{

}}2(a),(c) Considering the consistency of flow regimes and the higher mass flux in the BORAN facility, and uncertainty accounted for, it is concluded that applying the correlation developed from the BORAN facility to the NPM is conservative.

Treating boron volatility as a loss mechanism is conservative. In experiment procedures used to generate data to develop boron volatility correlations (for example, Reference [1], Reference [5], Reference [19]), the boron volatility fraction is obtained by measuring the boron concentration of condensate, which assumes that all of the volatilized boron is contained in the condensate. Therefore, volatilized boric acid in the NPM carried in steam is realistically expected to condense and be carried with the condensed liquid, and therefore continue to be available for transport in the system. This is a different physical phenomena than boron plating out due to boiling/flashing of entrained liquid droplets on hot surfaces, which can reasonably be considered lost to further transport in the system.

Consideration of Alternate Volatility Models and Volatility Margin Analysis

As part of developing the NuScale boron transport model and identifying the Böhlke et al. boron volatility model as applicable to use, a literature survey was conducted. A summary of the literature survey and evaluated impact of different volatility models is provided below.

EPRI-NP-5558 (Reference [2]) provides a plot presented by Cohen (Reference [3]) compiling various data on the volatility of boric acid with no added alkali (i.e., unbuffered boric acid solution). Digitizing the data presented in the plot and providing additional data from Morozov et al. (Reference [5]) and from Kukuljan et al (Reference [19]) and the predictions from the Glover model (Reference [6]) and the Böhlke et al. model (Reference [1]) gives Figure BV-3 and Figure BV-4 comparing the boron volatility fraction data and models from various sources in log and linear scales, respectively. Figure BV-3 and Figure BV-4 depict the results of the Glover model calculated boron volatility fraction as a function of temperature. {{

}}2(a),(c)

Except for the data from WAPD-MRP-49 (Reference [4]) indicated by the solid pink triangle symbols, and the data from Kukuljan et al (Reference [19]) indicated by solid blue squares, in Figure BV-3 and Figure BV-4, all the boron volatility fraction data are distributed around the green dashed line predicted by the Glover model (1988). The Glover model is almost identical to the blue dotted line predicted by the best-estimate Böhlke et al. model (2008) except for higher temperature conditions, due to the void fraction effect considered by Böhlke et al. The Glover model is below the red solid line predicted by the conservative {{

}}2(a),(c) Böhlke et al. model used in the NuScale boron dilution analysis calculations. The data from WAPD-MRP-49 (1954) show a biased slope of the boron volatility fraction trend with respect to the liquid-phase coolant temperature.

In order to further evaluate the variation seen in the data and applicabilty to the NPM conditions, the conditions used to deveop the data shown in Figure BV-3 and Figure BV-4 are briefly summarized, where available. Further details of the data summarized in EPRI-NP-5558 (Reference [2]), as compiled by Cohen (Reference [3]) are not readily available and are not summarized further.

- The Bohlke et al data (Reference [1] and Reference [9]) was developed from two facilities. An autoclave facility was used to measure the volatlity dependence on temperature, boron concentration, pH, and compound. From Reference [1], the autoclave data was generated for the following ranges: 105-330°C, boron concentrations 0.1 - 20 g/L, pH values 3.5 to 10.2 and for penta borate, tetra borate and boric acid compounds. Reference [9] Figure 5.1 provides a schematic of the autoclave facility; steam samples are drawn from the heated autoclave and are condensed. In addition to the autoclave data, the BORAN facility was used to evaluate the effect of volatility in circulating conditions and particularly to evaluate the effect of void fraction in the two-phase flow. As previously summarized in this response, the BORAN facility was scaled to a German BWR. From Reference [1], the BORAN facility data temperature and pressure limits were 225°C and 2.5 MPa, respectively, and void fractions in two-phase flow from 0-70% were tested.

- The Kukuljan et al (Reference [19]) data was developed for boric acid in an autoclave facility for relatively high temperature saturated conditions from 179-370°C (corresponding to 0.98 MPa - 21 MPa). These experiments were designed to enforce equilibrium condtions between steam and liquid boron concentrations. In this autoclave setup, fluid from the liquid and steam regions was cycled into the opposite regions in order to enforce fully equilibrium conditions before samples were taken from lines used to recirculate the flluid.

- The Glover data and correlation (Reference [6]) are based on geothermal fluid data, developed from analysis of separated steam and water from fluids discharged by wells. Glover also considered available published data from other sources.

- The Morozov et al data (Reference [5]) was developed in a test loop where a prepared solution of boric acid was supplied to the vertically oriented, boiling section with a height of approximately 1m. The generated steam was separated and routed to a condenser from which samples were taken. As described in the paper, the height from the level of the boiling liquid to the line of steam extraction corresponded to the distance from the evaporation surface in a VVER reactor vessel to the lower generatrix of the cold branch of the main circulation pipeline. Testing was carried out at atmospheric pressure conditions.

Since the Reference [19] data was designed to enforce equilibrium conditions, it is concluded that this data reflects the theoretical maximum volatility rate for boric acid as a function of temperature. Figure BV-3 and Figure BV-4 show that the Reference [19] dataset is higher than the other data points, including the best estimate Bohlke curve {{ }}2(a),(c) However, considering the applicability of the Bohlke correlation conditions to the NPM design, the range of available data (particularly at the lower temperature conditions), and the differences betweeen the conditions used to develop the Refernece [19] data and the NPM conditions, it is concluded that bounding the data from WAPD-MRP-49 or Reference [19] is not required to perform a conservative boron dilution analysis for the NPM.

The Reference [19] test data is considered further.

- Test data temperature range. The Reference [19] test data is taken under saturated conditions from 452-643K (179-370°C, or 354-698°F). This corresponds to a saturation pressure range of 0.98 MPa - 21 MPa (142-3045 psia). The NPM is above 180°C only during the first 3 hours of the long term cooling transient. For approximately the first hour the calculated volatility used in the NPM case is close to the volatility from the Reference [19] data, which can be inferred from the high temperature conditions shown on Figure BV-3 and Figure BV-4 below (the points from the Reference [19] dataset in the 180-320°C range are shown on the plot). For hours 1-3 the volatility using the Bohlke correlation using NPM conditions underpredicts the Reference [19] data. The NPM conditions under longer-term recirculation are outside the range of conditions tested in Reference [19]. The NPM volatility calculated with the Bohlke correlation uses {{ }}2(a),(c) The Bohlke correlation uses void fraction as a surrogate factor for vapor/liquid contact time and interfacial area.
- Vapor/Liquid contact time . The contact time between the vapor and liquid phases affects the observed volatility. The BORAN facility quantified the volatility fraction for the phase time contact at that facility. As previously described, the liquid column height, hydraulic diameter and flow regime characteristics of the NPM LTC conditions and the BORAN facility are consistent, and the lower mass fluxes in the NPM would tend to result in less turbulence and bubble breakup, and therefore lower integrated interfacial area and contact time and lower volality, compared to the BORAN facility. The process for measuring volatilized boron in the Reference [19] facility was much different. In

development of the Reference [19] dataset, fluid from the liquid and steam regions was cycled into the opposite regions in order to enforce fully equilibrium conditions before samples were taken. As described in the paper, the steam and liquid were circulated for 3 hours through the sampling loops, which is at least twice the total mixing time. The process of cycling the liquid and steam into the opposite phases in the Reference [19] autoclave facility was different than the autoclave facility used to develop data used in the Bohlke correlation. Considering the different autoclave setups it is concluded that the Bohlke data, particularly at lower temperature conditions, is not likely to reflect equilibrium steam/liquid boron concentrations. While the Reference [19] dataset does not extend to 100°C, this conclusion is consistent with the lower volatility measured at atmospheric conditions in the range of different experiments discussed above; only the Reference [19] setup is known to be designed to enforce equilbribum volatility conditions. Use of the Bohlke correlation remains acceptable for the NPM conditions because the idealized equilibrium conditions reflected in the Reference [19] data are not realistic for the NPM.

- In the NPM design, where vapor is generated in the core and rises to be vented through the RVVs, the vapor contact time is estimated to be on the order of 1 minute {{

  }}[2(a),(c)] compared to the 90-minute equilibrium mixing time estimated for the autoclave conditions. Therefore, the Reference [19] dataset is expected to have a higher volatility rate compared to other datasets and the NPM design, particularly at lower temperatures.

Figure BV-5 shows results from the Bohlke correlation applied for boric acid conditions similar to the Reference [19] solution concentration, at a range of constant void fraction values. As temperature decreases, a higher void fraction is required in the Bohlke correlation to match the Reference [19] data. Qualitatively, this is consistent with physical chemistry reaction rates described by Arrhenius rate equations with exponential dependence on temperature, where, at lower temperatures, a longer time is required to reach equilibrium conditions. At lower temperatures the NPM conditions and Bohlke dataset are expected to be further from the maximum equilibrium volatility conditions, and therefore further from the Reference [19] dataset. While the lowest temperature WAPD-MRP-49 datapoint remains well above the Bohlke correlation prediction, it is also well above the other low temperature data points from diverse, independent data sets shown in Figure BV-3 and Figure BV-4; as information about the WAPD-MRP-49 dataset is not available, the cause of the difference between this ~120°C datapoint and multiple datapoints at 100°C is not considered further. Although Figure BV-5 presents results with the Bohlke correlation over the temperature range from 100°C to 320°C, the BORAN facility data used to develop the void fraction dependence in the correlation was limited to a maximum 225°C. At temperatures above 225°C and with high void fraction values, the Bohlke correlation predicts higher volatility than is measured in the Reference [19] dataset. This is concluded to be due to extrapolation of the correlation under these conditions because concentrations higher than the equilibrium volatility fraction are not physically reasonable.

Therefore, when considering the Reference [19] data and the Bohlke correlation, the Bohlke correlation aligns reasonably with the Reference [19] data given a sufficiently high void fraction that is a surrogate parameter for contact time and interfacial area. When the NPM transient conditions are considered, lower volatility fractions, reflecting conditions that have not reached equilibrium volatility concentrations, are predicted.

Data collected in the BORAN facility demonstrated that in two-phase flow conditions, vapor transport time is not the only factor that affects measured volatility. Data from the BORAN facility demonstrated that higher mass flows, which would result in a shorter vapor transport time, nonetheless, had higher volatility due to the competing effects of bubble size and interfacial area. From the thermal-hydraulic perspective, for a given vapor transport time, the NPM low flow conditions would be expected to result in less bubble break-up and therefore lower interfacial area and less volatility compared to the BORAN facility conditions. The lower volatility effect of lower flow conditions due to interfacial area in the NPM may be partially offset by longer time for vapor-liquid contact that could increase the voltatility. Considering that bubble rise time in the NPM during recirculation is relatively short, on the order of 1 minute, and vapor is continually vented to containment and condensed, rather than recirculated into the liquid region as vapor, it is concluded that the equilibrium volatility conditions measured in the Reference [19] dataset will not exist in the NPM at low temperatures. Therefore, when considering time-integrated vapor/liquid interfacial area in the NPM, the interfacial area effect is expected to dominate the effect of longer transport time. Therefore, it is appropriate to apply the Bohlke correlation to the NPM case, without adjustment or credit for the lower mass flow rates (resulting in a net decrease in volatility), and with adequate conservatism to account for data uncertainty.

- Measurement of volatility data. Reference [19] provides an additional example of measuring volatility from steam by condensing the steam and measuring the boric acid concentration in the condensate. This indicates that no 'lost' boron from steam in the system was expected. Since the sampling loops in the Reference [19] facility had a small (0.5mm) diameter, they would be particularly susceptible to boron blockage in the tubes. If that were to have happened, the facility would not have operated properly.

After considering the available volatility data and correlations, and NPM conditions, it is concluded that calculating volatilized boron in the NPM with the applicable Bohlke correlation and treating the volatilized boron in the NPM entirely as a loss term provides reasonable assurance of conservative treatment regardless of differences observed in various data sets.

Note that for the REWET-II BOR004 test, Reference [18] provides test data for both the core region concentration and the concentration of the condensate sampling tank. While this test was not designed to evaluate boron volatility, the data was considered. From Reference [18] Table 4.1,the BOR004 test did not have a steam separator installed. Reference [18] Section 5.3 discusses the significant impact of boron carried in entrained liquid on the core region concentration in the REWET-II facility. Since the steam separator was not installed in the BOR004 test, the majority of the boron concentration measured in the condensate tank for this test is due to entrained liquid and not volatilized boron. Reference [18] Figure 5.14 shows the condenser concentration for test BOR008 with the steam separator installed; however, core region concentrations for this test are not available. Since the REWET-II tests were designed to study precipitation at atmospheric pressure, it is reasonable to estimate that for test BOR008 the final core region concentration was approximately 27 wt%. From Reference [18] Figure 5.14 the condenser concentration is less than 0.1wt%. Assuming the condenser concentration is entirely due to volatility and with the estimated core region concentration, the estimated volatility fraction is on the order of 0.004. This estimated volatility is relatively consistent with the other datapoints clustered around 100°C in Figure BV-3 and Figure BV-4.

Finally, additional sensitivity calculations were performed with the NPM 3 day analysis results as summarized in Section 3.1 to evaluate margin in the volatility rate.

Table BV-1. Böhlke et al. Boron Volatility Model Applicability to NuScale IORV (RRV) Event

Parameter	Autoclave	BORAN	NuScale ECCS
{{			
			}}2(a),(c)

Table BV-2. Comparison of BORAN Facility and NuScale Module

Parameter	BORAN	NuScale Module in ECCS
{{		
		}}2(a),(c)

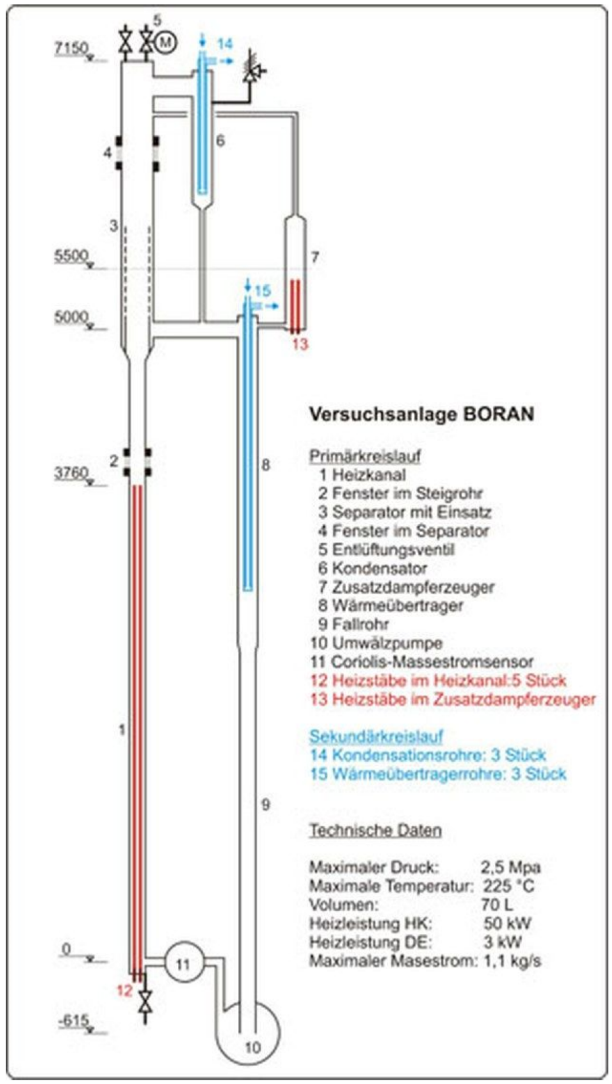

Figure BV-1. BORAN Schematic

{{

}}2(a),(c)

Figure BV-2. BORAN Facility and NPM Flow Regimes

{{

}}2(a),(c)

Figure BV -3. Comparison of Boron Volatility Fraction (in Log Scale) Data and Models from Various Sources

{{

}}2(a),(c)

Figure BV-4. Comparison of Boron Volatility Fraction (in Linear Scale) Data and Models from Various Sources

{{

}}2(a),(c)

Figure BV-5. Comparison of Boron Volatility Fraction (in Log Scale) Reference [19] and Reference [4] Data, and Reference [1] Model at Varying Void Fraction

2.1.3.2 Evaluation of Conservatism in Maximizing Overall Hot Region Dilution vs Maximizing Volatility from Hot Region

The boron dilution analysis model is formulated in such a way that the boron concentration in the core is minimized by maximizing the boron transport out of the core and minimizing the boron transport into the core. An alternate approach is evaluated here to demonstrate the conservatism of formulating the analysis with this approach, as opposed to formulating the analysis to maximize the boron lost to the system through volatility alone.

For each of the three initiating events (inadvertent opening of an RRV, inadvertent opening of an RVV, and RCCWS line break), sensitivity calculations were performed with different assumptions maximizing the volatilized boron loss to see any unfavorable impact on the RCS hot region boron concentration. For these alternative analyses, the following assumptions are made to maximize the volatilized boron loss.

- Assumption 1 {{

}}2(a),(c)

- Assumption 2 {{

}}2(a),(c)

- Assumption 3 (increased boron volatility fraction): {{

}}2(a),(c)

The results of these alternative boron dilution analyses on the boron concentrations and boron masses are presented in Figure BVa-1/Figure BVa-2, Figure BVa-3/Figure BVa-4, and Figure BVa-5/Figure BVa-6 for the IORV (RRV), IORV (RVV), and RCCW line break without DHRS (for all the three events), respectively. The results of the boron dilution analyses using alternate assumptions show more margin to the initial boron concentration, compared to the NuScale approach, for each of the three initiating events. {{

}}2(a),(c) Regardless of the specific initial boron concentration or input to the critical boron concentration, the results in Figure BVa-1/Figure BVa-2, Figure BVa-3/Figure BVa-4, and Figure BVa-5/Figure BVa-6 show that no bulk dilution of the hot region occurs over the 72 hour time frame.

{{

}}2(a),(c)

Figure BVa-1. Boron Concentrations for IORV (RRV) without DHRS for Alternative Analysis Maximizing Volatilized Boron Loss

{{

}}[2(a),(c)]

Figure BVa-2. Boron Masses for IORV (RRV) without DHRS for Alternative Analysis Maximizing Volatilized Boron Loss

{{

}}2(a),(c)

Figure BVa-3. Boron Concentrations for IORV (RVV) without DHRS for Alternative Analysis Maximizing Volatilized Boron Loss

{{

}}2(a),(c)

Figure BVa-4. Boron Masses for IORV (RVV) without DHRS for Alternative Analysis Maximizing Volatilized Boron Loss

{{

}}2(a),(c)

Figure BVa-5. Boron Concentrations for RCCW Line Break without DHRS for Alternative Analysis Maximizing Volatilized Boron Loss

{{

}}2(a),(c)

Figure BVa-6. Boron Masses for RCCW Line Break without DHRS for Alternative Analysis Maximizing Volatilized Boron Loss

2.1.4 Hot Region Mixing and Core Boron Distribution

In the RCS hot region a uniform boron distribution is assumed to calculate the hot region concentration. The total amount of boron available to transport to the RCS hot region is minimized and the boron transported out of the RCS and boron lost to the system are conservatively increased in order to assure a conservatively low RCS hot region concentration. As part of this approach, NRELAP5 calculation are biased for the maximum temperature.

While boiling occurs in the core, boron preferentially accumulates in the boiling region; therefore the realistic boron distribution within the RCS hot region would be expected to be a lower/normally borated region below and above a more highly concentrated region where boiling occurs. In these conditions with boiling in the core region, uniformly mixing the RCS hot region mass over the total liquid in the core and riser region results in a conservatively lower concentration in the core region, compared to the higher concentration due to boiling. Under colder long term temperature conditions, it may be postulated that bulk vapor generation moves from the core into the lower riser region. This may be postulated under conditions where liquid convective heat transfer is sufficient to remove core decay heat, but the water column pressure head in the riser results in vapor generation in the riser as fluid rises from the core and the vapor is vented through the reactor vent valves to containment. The potential for a significant gradient in boron concentration between the core and riser in the hot region is evaluated using first principles approaches and considering available experimental data. The conservatism in the 3 day analysis approach is quantified by evaluation of the total amount of RCS boron mass assumed to be unavailable to transport into the RCS hot region, and by comparison to the 7 day analysis results.

2.1.4.1 Qualitative Engineering Evaluation

During the NPM ECCS long term cooling phase, two-phase or single phase buoyancy-driven natural circulation will be established in the RCS core and riser due to the heat source at the bottom of the region from the core decay heat, and the heat sink at the top of the region as the riser transfers heat to coolant in the downcomer. Similarly, buoyancy-driven natural circulation is expected in the RCS downcomer region, and in containment due to heat transfer from the core and riser region and the reactor pool heat sink outside the containment wall. This is illustrated in Figure 2-1.

Qualitatively, under quiescent conditions, a significant boron concentration in the lower riser near the water level is physically not possible due to the buoyant mixing caused by the Rayleigh-Taylor instability. Furthermore, the buoyancy-induced internal circulation throughout the RCS hot region consisting of the core and lower riser would prevent such a significant non-uniform boron distribution in the lower riser. Both the buoyant mixing induced by the Rayleigh-Taylor instability and the buoyancy-induced internal circulation are supported by the Westinghouse boron mixing/transport and precipitation PIRT (Reference [7]). In the Westinghouse PIRT the unstable fluid density gradients are postulated to be due to axial concentration differences. In the NuScale module, the unstable fluid density gradients are still observed but they are driven by thermal gradients, due to variation in saturated fluid properties at low pressure conditions, as opposed to significant concentration gradients.

2.1.4.2 Mass and Energy Balance Evaluation

{{ }}2(a),(c) mass and energy balance is performed to evaluate a range of postulated flow qualities at the core exit.

The control volume used for the mass and energy balance is shown in Figure MIX-1:

- {{ }}2(a),(c)

Parameters consistent with cold 72 hour ECCS conditions are shown in Table MIX-1 and MIX-2. Note that these conditions are consistent with those justified and used in Section 2.1.4.3.5.

The following parameters are summarized in Table MIX-2:

- {{ }}2(a),(c)

The following assumptions and simplifications are made:

- {{

}}2(a),(c)

- A spectrum of core exit flow qualities are evaluated at the given conditions. The analysis is relatively insensitive to the input conditions and is generally applicable to a wide range of ECCS conditions. The evaluated conditons are reasonably representative to evaluate the long-term quasi-steady conditions following event initiation.

First, the energy balance over the core region is described, assuming steady conditions:

{{

}}2(a),(c)

{{

}}2(a),(c)

The trends of Figure MIX-2 show that the concentration distribution is not very sensitive to the core exit flow quality. This behavior is the result of the equations listed previously, and the way that the exchange flow changes with the core exit flow quality. Figure MIX-3 presents the exchange flow divided by the liquid fraction of the boil-off rate passing from the core into the riser. The equilibrium concentration distribution is a function of the ratio between the net liquid flow rate and the exchange rate. Regardless of what the magnitude is, if that ratio is held constant the same distribution of concentrations would be expected. The results of Figure MIX-3 show that the ratio is relatively unchanged for the range of flow qualities considered, and as expected the distribution of concentrations is nearly constant over the same range.

Table MIX-1. Thermal-Hydraulic Inputs used in Energy Balance Calculations

{{						
						}}2(a),(c)

Table MIX-2. Intermediate Values Calculated in Simplified Heat Balance Analysis

{{					
					}}2(a),(c)

Table MIX-3. Simplified Heat Balance Results - Relative Core and Riser Boron Concentrations for Select Core Exit Flow Qualities

f_b (flow quality)	$\acute{m}_{ex}$ (kg/s)	C_C (core concentration)	C_R (riser concentration)
{{			
			}} 2(a),(c)

{{

}} 2(a),(c)

Figure MIX-1. Control Volume for Mass and Energy Balance

{{

}}2(a),(c)

Figure MIX-2. Boron Concentration Distribution from Energy Balance Analysis

{{

}}2(a),(c)

Figure MIX-3. Mass Exchange Rate Over Net Liquid Mass Flow Rate from Core to Riser as a Function of Flow Quality

2.1.4.3 Evaluation of REWET-II and VEERA Test Results (Core Boron Distribution)

As summarized in Reference [12], Tuunanen et al. used two different test facilities, REWET-II and VEERA, to examine the boric acid concentration distributions in the Loviisa VVER-440 core and lower plenum under post-LOCA long-term cooling conditions. REWET-II and VEERA are full-height, volume scaled models (1:2333 and 1:349, respectively), of the Loviisa reactor. The REWET-II core simulator included 19 heater rods while the VEERA core simulator included 126 heater rods (i.e., one fullscale VVER-440 rod bundle) inside the hexagonal shroud. Examining the REWET-II Test BOR004 and the VEERA Test B11, consistent test conditions were used including:

- Core heating power corresponding to 1.3% of the scaled power (8 kW for REWET-II; 53 kW for VEERA) with a chopped cosine axial power distribution (Reference [13] and Reference [14]);
- boiling allowed in the upper core ;
- atmospheric pressure ;
- feeding coolant flow with very low flow rates to compensate for water loss due to boiling and to keep the water level constant near the top of the core (i.e., coolant flow rate is equal to the steam generation rate in the core);
- feeding boric acid concentration of 2.5 wt.% (i.e., 25000 ppm), which is a high concentration for the purpose of observing boron precipitation.

Tuunanen et al. [12] presented the transient boric acid concentration distributions measured from REWET-II Test BOR004 and VEERA Test B11. The results of similar precipitation tests for both facilities showed starkly different boron distribution behavior. Specifically, the smaller scale REWET-II test BOR004 showed boron stratification in the core and lower plenum. The larger scale VEERA test B11 showed full boron mixing in the core with partial mixing in the lower plenum. A generic scaling evaluation elucidates the differences in the scaling that must be responsible for the differences observed. A review of available literature is used to support the conclusion of the responsible mechanism suggested by the scaling evaluation. Then, NPM conditions during ECCS cooling are quantitatively compared to the applicable boric acid mixing test data, analytically describing subcooled liquid density gradient trends with increasing flow diameter and resulting implications to the reactivity balance.

2.1.4.3.1 REWET-II and VEERA Comparison

Results from the REWET-II BOR004 test and the VEERA B11 test, from Reference [12], are reproduced in Figure V-1 and Figure V-2 below. The results of an additional VEERA test B15, from Reference [15], are included in Figure V-3 below. Figure V-3 presents the concentration gradient in the lower plenum, and includes a single data point for the core concentration. The paragraph preceding the figure in Reference [15] describes how the core is well mixed, providing the basis for representing it with a single data point.

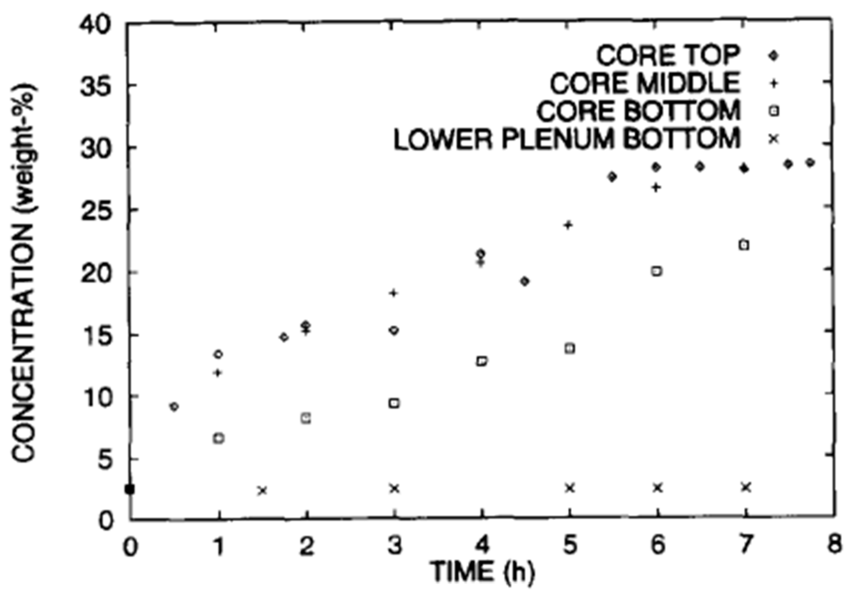

Figure V-1. REWET-II BOR004 Test, Reproduced from Figure 4 of Reference [12]

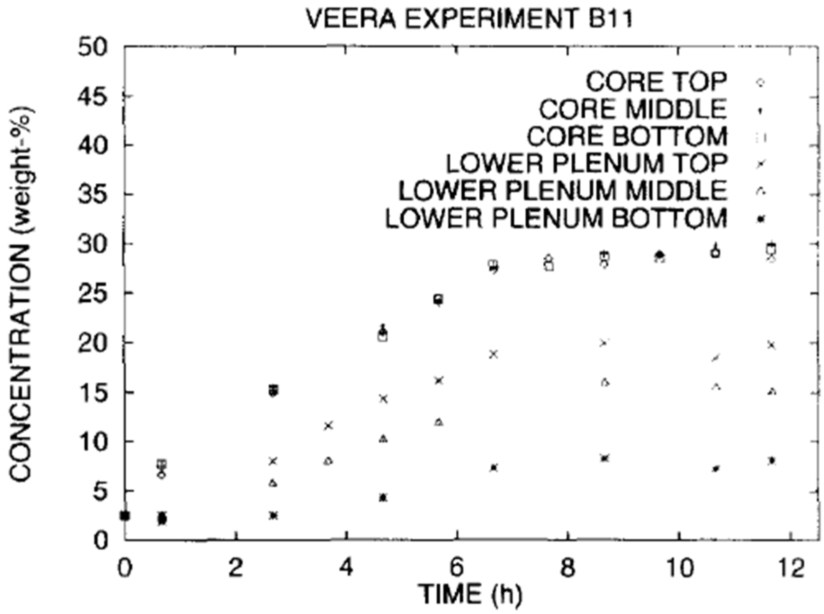

Figure V-2. VEERA B11 Test, Reproduced from Figure 5 of Reference [12]

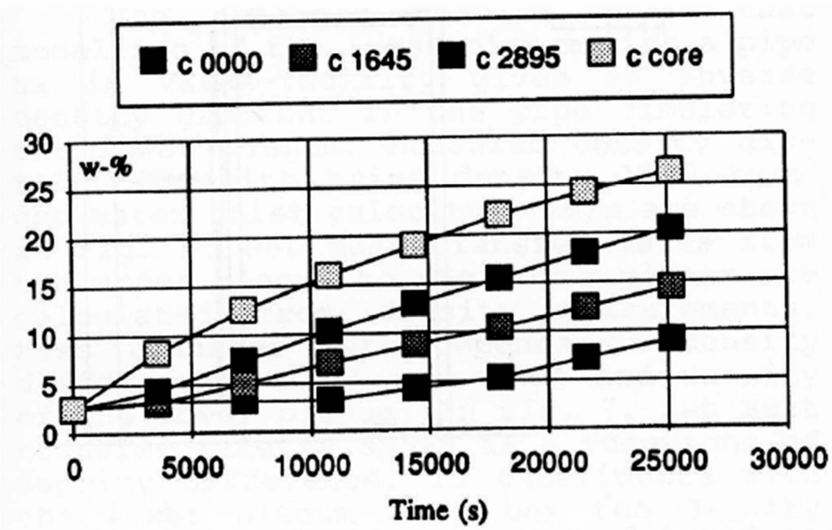

Figure V-3. VEERA B15 Test, Reproduced from Figure 2 of Reference [15]

Note that the legend values c0000, c1645, c2895 refer to the height of the concentration measurement in millimeters from the bottom of the lower plenum.

2.1.4.3.2 REWET-II and VEERA Scaling

The following scaling analysis assumes that REWET-II and VEERA shared a similar thermal property scaling with the prototypic reactor. This means that REWET-II and VEERA share similar thermal-fluid properties, but they may differ by some degree to the actual VVER-440 conditions. This is a reasonable simplifying assumption as both facilities operated with similar temperatures, pressures, and boric acid concentrations. The scaled parameter relationships are given below.

$$\text{Volume} \propto (\text{Length} * \text{Area})$$

$$\text{Area} \propto \text{Diameter}^2$$

$$\text{Power} \propto (\text{Mass flow} * \text{Enthalpy rise})$$

$$\text{Mass Flow} \propto (\text{Density} * \text{Area} * \text{velocity})$$

Using the previously defined power, length, and volume scales with the property similitude, the scale ratio are derived and summarized in Table V-1. Note that the results of the scaling comparison in Table V-1 demonstrate that the mass flux for the VEERA and REWET-II facilities are the same. Given that differences in core density gradients are observed in the facilities suggests that mass flux is not a useful correlating parameter in predicting the presence of density gradients. Next, the difference in expected buoyant mixing flow for the different facility scales is evaluated.

Table V-1. REWET-II and VEERA Scaling

Length	1:1	1:1
Power	1:2333	1:349
Volume	1:2333	1:349
Area	1:2333	1:349
Diameter	1:48.3 ($2333^{1/2}$)	1:18.7 ($349^{1/2}$)
Enthalpy Rise(1)	1:X	1:X
Mass Flow	~1:2333	~1:349
Density(1)	1:Y	1:Y
Velocity	~1:1	~1:1

(1) The test facilities are designed to be similar to the expected long term conditions for the VVER-440. However, this analysis is not interested in quantifying the scaling distortions between the test facilities and the prototypical reactor as it relates to the enthalpy rise or liquid density since the facilities share the same distortions.

2.1.4.3.3 REWET-II and VEERA Exchange Flow

The REWET-II facility observed density and concentration gradients in the core region that were gravitationally unstable. These gradients were not observed in the VEERA tests, and understanding the cause of the density gradients is imperative as it influences the determination of which regions are well mixed in the NuScale reactor. In the absence of other forces, unstable density gradients in fluids result in stabilizing buoyant mixing. In the case of the density gradient observed in the REWET-II facility, it is postulated that the amount of buoyant mixing was limited by the net upward flow from boil off of liquid, and that the buoyant mixing was not limited to the same degree in the VEERA facility. This analysis specifically evaluates equations developed for buoyant mixing between two liquids limited by the forced convection of one liquid. Note that limiting buoyant mixing through forced convection is not unlike the Wallis counter-current flow limitation.

Epstein in 1988 calculated the counter-current exchange flow through a pipe that connected two reservoirs of fluid in a gravitationally unstable configuration (Reference [16]). In 1989 Epstein and Kenton determined the amount of forced convection through the pipe that is required to prevent counter-current exchange flow (Reference [17]). This flow rate was termed the purging or flooding rate. In the same paper, the amount of counter-current exchange flow was quantified as the rate of forced convection approached the purging rate. Figure V-4 presents the relationship identified for counter-current exchange flow, Figure V-5 presents the relation identified for purging flow, and Figure V-6 presents the relation identified for buoyant exchange limited by forced convection. The pertinent equations from the figures are re-arranged below:

$$Q_{cc} = C_1 * (d^5 g\Delta\rho / \bar{\rho})^{1/2}$$

$$q = C2 * (d^5 g\Delta\rho / \bar{\rho})^{1/2}$$

$$Q_u = m/\bar{\rho}$$

$$Q_{BF} = C3 * Q_{cc}$$

In which:

- Q_{CC} is the unimpeded volumetric counter-current flow rate,
- d is the diameter of the tube/core,
- Δρ is the density difference between the reservoirs,
- $\bar{\rho}$ is the average density, g is gravitational acceleration,
- C_1 is determined from the length over diameter value using Figure V-4,
- q is the purging volumetric flow rate,
- C_2 is determined from the length over diameter value using Figure V-5,
- Q_u is the forced convection term equal to the boil-off rate divided by average density,
- C_3 is determined from the forced flow over purging flow value using Figure V-6,
- and Q_{BF} is the buoyant flow accounting for reductions due to forced flow.

Specifically quantifying a single exchange flow in the REWET-II and VEERA test facilities is questionable, because the facilities are heated and the geometry differs from that used by Epstein to develop the relationships between counter-current exchange flow and forced convection flow. Instead, the equations are generically evaluated to identify the expected impacts to the exchange flow for the differences between the REWET-II and VEERA facilities. Table V-2 contains dimensions and representative values for both test facilities, as well as the coefficients derived from the figures using the dimensions. {{

}} 2(a),(c) Figure V-7 clearly demonstrates that for a given fluid density gradient, VEERA results in a significantly larger fraction of exchange flow to advective flow, compared to REWET-II.

If the buoyant exchange flow is considered as a diffusive term, the observed VEERA and REWET-II results are readily explained. The diffusion process smooths gradients, and Figure V-7 shows that VEERA has a larger diffusion term than REWET-II for the same gradient. Effectively, VEERA is a more diffusive test facility, and that behavior is the result of the increase in diameter. Note that this is the same conclusion that the original investigators of the VEERA and REWET-II test programs came to as well (Reference [12]). The trends from Figure V-5 and Figure V-6 indicate that increasing diameter beyond a certain L/D ratio can negatively impact the exchange flow. However, these test facilities have large L/D ratios, and there is no increased diameter size that could reduce the mixing below the current values.

This analysis explains that improved buoyant mixing is the likely mechanism that caused the VEERA facility to be better mixed than the REWET-II facility. In terms of the NPM, the effective diameter for the NuScale core is more than 8 times larger than that of the VEERA facility, and therefore the NuScale core should be at least as well mixed as the VEERA core.

Table V-2 REWET-II and VEERA Buoyant Mixing Parameters

Length	242 cm	242 cm
Power	8 kW	53 kW
Area	13 cm^2	86 cm^2
Effective Diameter	4.07 cm	10.46 cm
Enthalpy Rise(1)	2260 kJ/kg	2260 kJ/kg
Mass Flow	.0035 kg/s	.0230 kg/s
Mass Flux	2.67 kg/m^2-s	2.67 kg/m^2-s
Density(1)	1000 kg/m^3	1000 kg/m^3
L/D	~60	~24
C_1	~0.005	~0.005
C_2	~0.05	~0.05

(1) These are representative values that are appropriate given the known range of conditions.

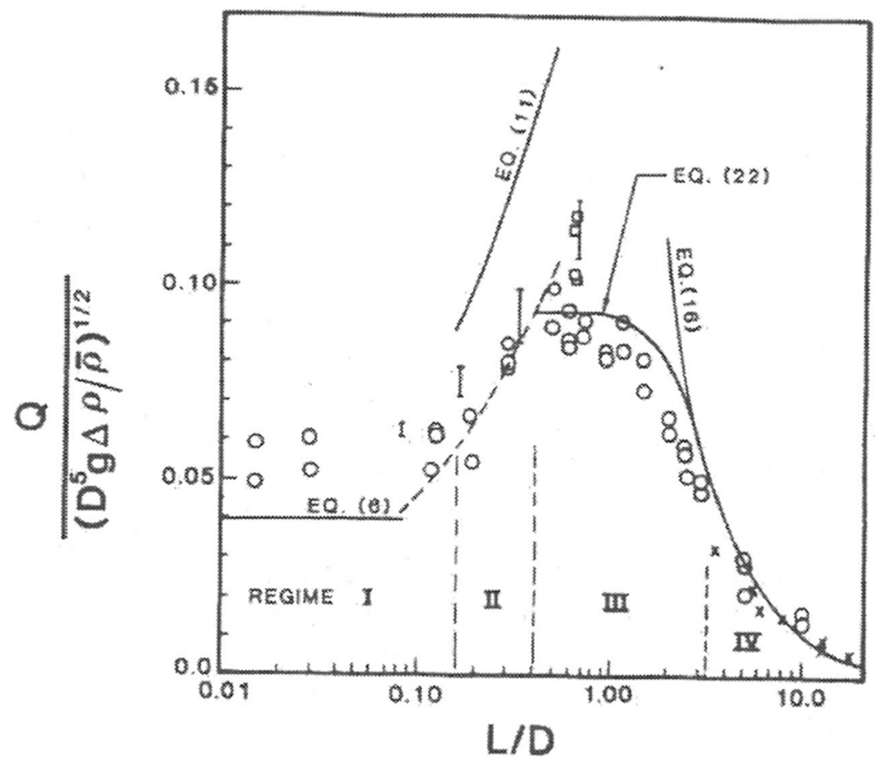

Figure V-4. Counter Current Exchange Flow, Reproduced from Figure 3 of Reference [16]

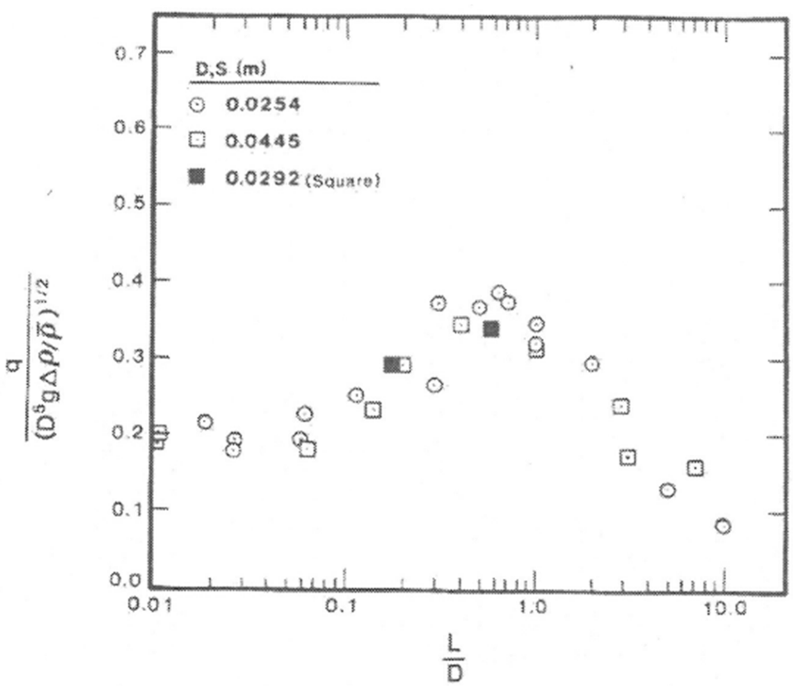

Figure V-5. Purging/Flooding Flow, Reproduced from Figure 4 of Reference [17]

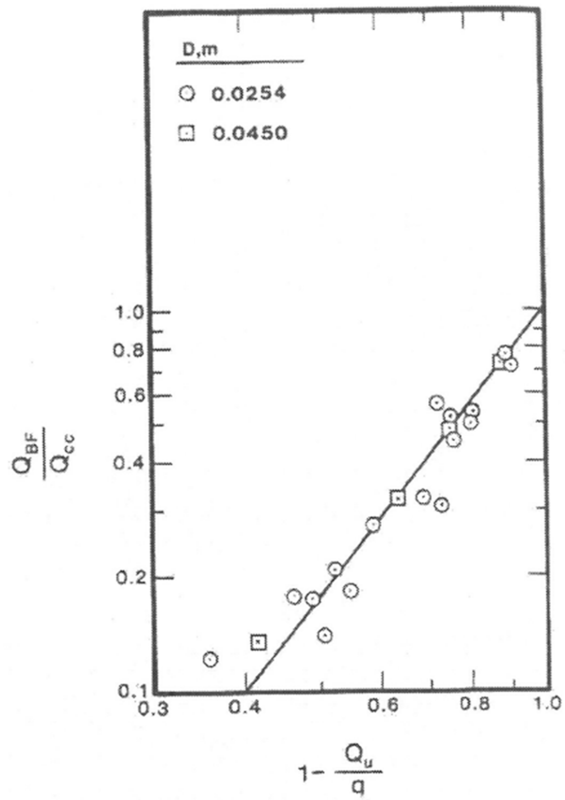

Figure V-6. Buoyant Flow Reduction with Net Flow, Reproduced from Figure 5 of Reference [17]

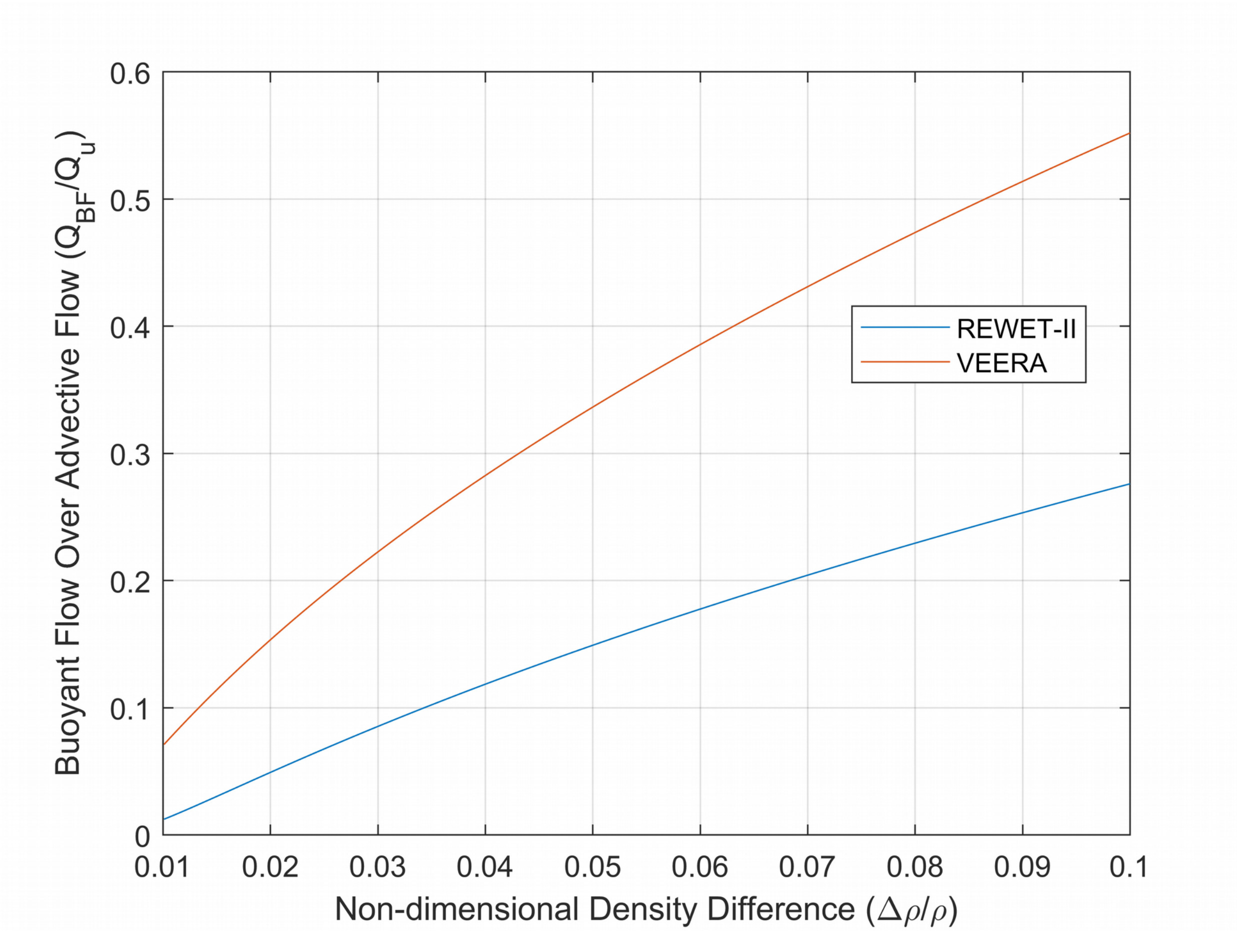

Figure V-7. REWET-II and VEERA, Ratio of Buoyant to Advective Flow Rates

2.1.4.3.4 Evaluation of VEERA Lower Core Flow Quality

As previously discussed, the effective diameter for the NuScale core more than 8 times larger than that of the VEERA facility, and therefore the NuScale core should be at least as well mixed as the VEERA core. For the purposes of subsequent analysis, the VEERA core is considered sufficiently mixed, and no additional mixing needs to be justified or explained for these test results. Figure V-2 showed that for test B11, consistent boron concentrations were measured in the core top, middle, and bottom. Figure V-3 showed that for test B15, the authors justified presenting a single concentration for the core region on the basis that the core region was well mixed.

There is little disagreement that for boiling cores, mixing induced from the generation and upward transport of the vapor phase is the dominant phenomenon. The NuScale position has been that everything above the boiling level has been well mixed. Data from the VEERA facility is evaluated in this context.

The flow quality for VEERA Test B11 at 360 mm, the lowest elevation core concentration data point available, is evaluated using the VEERA facility test dimensions, and thermal-hydraulic parameters provided by the original investigators. {{

}}[2(a),(c)] Values used in this calculation are presented in Table V-3. At this elevation, the measured core concentration is indistinguishable from the other core measurement locations. This is the lowest elevation in the core region for which measured concentration data is available. Based on the calculated quality at this elevation, void generation and associated mixing from subcooled boiling and saturated boiling occur at lower elevations. In the next section, the liquid density gradient in the NPM core region is discussed and the elevation for onset of saturated boiling is calculated.

Table V-3. VEERA Flow Conditions at Lowest Concentration Measurement

Parameter	Value
{{	
	}}2(a),(c)

2.1.4.3.5 Evaluation of NPM Critical Heating Length

First, liquid density and enthalpy axial gradients in the NPM are discussed. Then the 'critical heating length' in the NPM, which is defined as the core inlet distance required to reach fully mixed conditions, is evaluated.

The discussion of the liquid density and enthalpy graidents in the NPM is focused on cold, low pressure conditions because, compared to higher pressure conditions, the cold subatmospheric conditions that can be reached during design basis long term cooling result in higher core inlet subcooling and therefore potentially a larger height of water in the lower core region before well-mixed saturated boiling conditions are reached.

In the NPM, during ECCS cooling, liquid enters the core from the lower plenum with some amount of subcooling and a flow rate roughly equal to the boil-off rate. At low system pressures in the NPM, generally observed at cold bias conditions, relatively small changes in pressure result in significant changes in the saturation temperature. Under these cold, low vapor pressure conditions, the hydrostatic head from the riser water column causes the saturation properties at core inlet to differ appreciably from the saturation properties at the liquid vapor interface in the riser. Since the vapor condenses in the containment at the saturation temperature corresponding to the containment vapor pressure, this results in some degree of core inlet subcooling, as the inlet temperature is roughly the saturation temperature for the system vapor pressure. The local subcooling at the core inlet causes a stable density gradient that does not directly support buoyancy driven exchange flow between the core and lower plenum. Instead, it is anticipated that the fluid enters the core at the boil-off rate, and must be heated until it becomes less dense than the upper core and riser liquid, at which point buoyant mixing would begin.

Figure V-8 shows the liquid density as a function of axial position for the cold bias cases. {{

}}2(a),(c) The axial height of 0 corresponds with the start of active fuel. It is acknowledged that the sub-atmospheric vapor pressure conditions used in Figure V-8 shows a larger density change as a function of the liquid column height compared to the density change that would be observed for more nominal vapor pressure conditions. For the conditions in Figure V-8, {{

}}2(a),(c) If more nominal conditions were considered in the long term cooling analysis, for example, more nominal treatment of pool temperature, the long term equilibrium vapor pressure would be higher. In the case of more nominal vapor pressure conditions, the density gradient shown in Figure V-8 would tend to flatten. For example, consider that the saturated fluid density at 14.5 psia is 959 kg/m^3 and at 22 psia it is 950 kg/m^3, or a difference of 9 kg/m^3. The saturated liquid density gradient would continue to be favorable for buoyant mixing but it would be less extreme than shown in Figure V-8. However, under these conditions the difference between the core inlet temperature and the saturation temperature would correspondingly decrease, compared to the cold conditions used in Figure V-8, and therefore saturated boiling conditions would be reached lower in the core region. Boiling in the core region results in preferentially accumulating boron in the core region and therefore this scenario is less limiting with respect to postulated cold conditions, when considering the potential for a less mixed subcooled core inlet condition.

As discussed further below, {{

}}2(a),(c)The enthalpy rise is evaluated to identify the elevation for the onset of saturated boiling conditions. The region above the critical heating length is demonstrated to be well mixed, but the well-mixed condition indicated from the larger scale VEERA test data under boiling conditions may not extend to the NPM subcooled core inlet region. The length of this region in the NPM is quantified in order to evaluate the impacts of a potential concentration gradient. Figure V-9 presents the calculated liquid enthalpy as a function of axial height. As with the previous figure, 0 corresponds with the start of active fuel. {{

}}2(a),(c)

The critical length is first determined with method below. This is consistent with the approach used to calculate the lower core quality from the VEERA data. {{

}}2(a),(c)

{{

}}2(a),(c)

The relevant parameters and results of the analysis are included in Table V-4. The critical length calculation concludes that, in the absence of exchange flow, the core and riser fluid above the initial {{ }}2(a),(c) of heated length are expected to be uniformly mixed.

The axial liquid density profile shown in Figure V-8, {{

}}2(a),(c) This suggests that buoyant mixing would be prevalent through the entirety of the core and riser region. As discussed above, the density profile in Figure V-8 reflects cold biased, sub-atmospheric conditions; if more nominal long term cooling conditions were considered the density profile would flatten but remain favorable for buoyant mixing. The energy balance results discussed in Section 2.1.4.2 indicate that moving boiling out of the core region results in increased buoyant exchange flow between the core and riser region.

{{

}}[2(a),(c)]

Therefore, further evaluation is performed to examine the reactivity balance implications of a lower boron concentration in the first {{ }}[2(a),(c)] of heated length.

Table V-4. NuScale Cold ECCS Enthalpy Balance Parameters

Parameter	Value
{{	
	}}2(a),(c)

{{

}}2(a),(c)

Figure V-8. NPM Axial Liquid Density Profile for Cold ECCS Conditions

{{

}}2(a),(c)

Figure V-9. NPM Axial Liquid Enthalpy Profile for Cold ECCS Conditions

2.1.4.3.6 Reactivity Balance Implications of Lower Borated Core Inlet Region

In the 3 day analysis method, conservative assumptions were made to the boron transport in order to minimize the boron available to accumulate in the core region, and bound the effect of a gradient developing in the lower core region. In order to quantitatively compare this approach to an approach that explicitly evaluates the reactivity impacts of a lower boron concentration in the lower part of the core region, calculations with MCNP6 were performed. The MCNP6 code solves the integral form of the Boltzmann transport equation by stochastically simulating particle histories and recording aspects of their average behavior. MCNP6 is a general-purpose, continuous-energy, generalized geometry, time-dependent coupled neutron/photon/electron Monte Carlo transport problem. MCNP6 is well suited for solving complicated three-dimensional, time-dependent problems because there are no averaging approximations required in space, energy, and time.

In the MCNP analysis the moderator in the core region is divided by a plane at the specified level, relative to the bottom of the active fuel. The moderator above this plane is modeled as water with high soluble boron concentration while below the plane the moderator has zero or low boron concentration. Isothermal temperature conditions are modeled. The control rods are modeled as fully inserted except the highest worth control rod is assumed stuck out of the core. The fuel isotopic concentration is modeled with no iodine-135 or xenon-135, and equilibrium samarium and promethium. Cycle 4 is modeled as a representative cycle. Beginning of cyle conditions were evaluated because with the higher concentration in the core region the effect of a lower concentration gradient in the lower region of the core is more extreme.

In the 3 day analysis without DHRS operation, the conservative assumption applied to the concentration transported to the core inlet results in effectively trapping a significant boron mass in the RCS cold downcomer/lower plenum region. The results in Figure Res3-1 show that in this case, the concentration in the RCS cold region is calculated to be higher than the concentration in the RCS hot region (the RCS cold region concentration increases from the initial concentration primarily due to flashing during blowdown). With this distribution of boron, there is no adverse concentration gradient that can develop between the RCS hot region and cold region. Therefore, in order to explicitly evaluate a boron concentration gradient in the lower core region, it is necessary to assume that more of the boron in the RCS transports into the RCS hot region. For beginning of cycle core conditions, a mixed RCS hot region concentration of {{ }}2(a),(c) was determined. This value is conservative compared to {{

}}2(a),(c)

{{

}}2(a),(c) Therefore the RCS hot region concentration increases while the RCS cold region concentration decreases, allowing a concentration gradient to develop at the core inlet. The transient concentrations are presented in Figure V-10 and the transient boron masses are presented in Figure V-11. {{

}}2(a),(c)

Table V-5 summarizes inputs for the MCNP analysis, and includes results of the keff value calculated for various postulated deborated front heights. Considering the effect of fluid temperature and potential gradients between a highly borated upper core region and lower borated lower core and lower plenum region, the results demonstrate that the conditions used in the evaluation of the return to power analysis are sufficiently conservative. This conclusion is consistent with the conclusion of the conservative 3 day boron transport analysis. These results demonstrate that the conclusions of the reactivity balance are maintained whether the conservatively calculated mixed core region concentration is considered or whether a more explicit calculation of a boron concentration gradient is considered. This provides a quantitative demonstration that (1) the conservative transport assumptions applied in the 3 day analysis method are sufficient to bound the effect of a gradient developing in the lower core region, and (2) a gradient that may develop during ECCS cooling will not be sufficient to substantively change the reactivity balance in the core region evaluated in the return to power analysis.

Table V-5 Inputs and Results for MCNP Analysis

MCNP Input	
Parameter	**Value**
Core Exposure	Cycle 4 BOC Core
Control Rod Position	ARI-WRSO
Core Power	0.00 MW
Core Inlet Temperature	69 °F
Upper Core Concentration	{{ }}2(a),(c)
Lower Core Concentration	Varied. See below .
Deboration Height	Varied. See below.
Results	
Parameter	**Value**
{{	
	}}2(a),(c)

(1) Uncertainty in the MCNP calculation of keff is {{ }}2(a),(c)

{{

}} 2(a),(c)

Figure V-10. Boron Concentrations for modified RRV opening without DHRS (0-72 hrs)

{{

}}2(a),(c)

Figure V-11. Boron Mass for modified RRV opening without DHRS (0-72 hrs)

2.1.4.4 Conclusions on Hot Region Mixing and Core Boron Distribution Treatment

Qualitatively, single phase or two-phase buoyancy-driven natural circulation is expected to occur due to the heat source and heat sink configuration of the NPM during long term cooling conditions; under quiescent conditions a significant boron concentration increase in the lower riser is not possible due to buoyant mixing caused by the Rayleigh-Taylor instability. Simplified energy balance results indicate that either boiling in the core or hot region mixing would be expected to result in mixing of the core region concentration such that bulk dilution in the corer region does not occur.

The REWET-II and VEERA test configurations were evaluated. The larger area scaling in the VEERA facility is consistent with higher expected buoyant mixing flow rates for the same convective flow rate, compared to the REWET-II facility. Higher buoyant mixing flow in the VEERA facility is consistent with the well-mixed boron concentration results measured in the core region for the VEERA tests, compared to the stratified results in the REWET-II facility. The NPM effective diameter is larger than that of the VEERA facility and therefore is expected to support comparable, or more, buoyant mixing compared to the VEERA facility.

In order to evaluate potential reactivity effects of a lower boron concentration near the core inlet, the VEERA Test B11 was considered in further detail. The flow quality at the elevation of the lowest core region boron concentration measurement, which was shown to be well mixed, was calculated. The low flow quality at the measurement location supported the conclusion that above the onset of boiling in the core is demonstrated to be well mixed. The equivalent elevation in the NPM core where the onset of saturated boiling would occur under {{ }}[2(a),(c)] was calculated to determine the fraction of the core region that may be at a lower boron concentration compared to the higher concentration in the middle and upper core region. The reactivity balance of a deborated lower core region was quantitatively evaluated with MCNP6 to demonstrate that conservative transport assumptions applied in the 3 day analysis method are sufficient to bound the effect of a gradient developing in the lower core region, and a gradient that may develop during ECCS cooling will not be sufficient to substantively change the reactivity balance in the core region evaluated in the return to power analysis.

As discussed in Section 3.3, the results of the 3 day analysis and 7 day analysis were used to quantify the conservatism associated with the boron losses and conservative transport assumptions applied in the 3 day analysis. In the 3 day analysis, only approximately 20% of the boron initially present in the RCS is credited with being able to recirculate into the RCS core and riser region. The more realistic 7 day analysis results show, at 72 hours, that the boron concentration in the RCS core and riser region is 2-3 times the initial concentration.

Considering the qualitative evaluation, the simplified energy balance results, the VEERA test results and explicit evaluation of a concentration gradient at the core inlet, and the conservatism in the 3 day analysis transport assumptions as quantified in the 7 day analysis results at 72 hours, it is concluded that there is reasonable assurance that the NuScale geometry and boron transport will result in boron transport to the core with net accumulation in the core region, and will not support bulk dilution of the core region, or development of a boron concentration gradient sufficient to substantively change the reactivity balance in the core region.

2.1.5 Summary of Key Conservatisms in 3 Day Analysis

For conservative, bounding Chapter 15 safety analyses for 72 hours with the WRSO assumption, the key conservatisms applied to minimize boron transport to the core are discussed below.:

1. The conservatism in the applied boron distribution factors for the predominant boron transport paths is discussed in Section 2.1.1.2. {{

}}2(a),(c)

2. The boron loss mechanisms in the analysis to minimize the core boron concentration are discussed in Section 2.1.1.3.
   a. {{

      }}2(a),(c)
   b. {{

      }}2(a),(c) This can be estimated by inspection of Figure Res3-2.

2.2 Boron Transport Methodology for 7 Day Analysis

The inputs and assumptions used for the 7 day boron dilution analysis is as described in Section 3.1 for the 3 day analysis with differences as summarized in Table 2-1. The most significant changes made in for the 7 day analysis are briefly discussed below.

- The inadvertent opening of an RRV is analyzed as this was the limiting initiating event determined from the 3 day analysis.
- {{ }}2(a),(c)
- {{ }}2(a),(c)
- {{ }}2(a),(c)

- {{

  }}2(a),(c) This can be estimated by inspection of Figure Res7-2.

- Boron volatility is calculated using the Bohlke et al model for boric acid volatility, {{

  }}2(a),(c)

  The volatilized boron is treated as a loss term consistent with the 3 day analysis method. Considering that volatilized boric acid is realistically expected to condense and return to circulation with the condensed liquid, as discussed in Section 2.1.3.1, {{ }}2(a),(c) and treating it as a loss term is considered adequately conservative for the purpose of the 7 day analysis.

- The boron lost to entrainment is negligible and therefore is bounded and removed from the RCS hot region boron mass as a single lumped amount rather than calculated as a function of time.

A spectrum of cases at beginning, middle and end of cycle initial boron concentrations is evaluated, and a spectrum of different containment concentration distribution factors and downcomer concentration distribution factors is evaluated.

3. Transient Results

First, transient results are presented for the 3 day analysis. Then transient results are presented for the 7 day analysis.

3.1 Transient Results - 3 Day Analysis

Transient calculations were developed to evaluate the boron transport and distribution for three different design-basis initiating events, i.e., IORV (RRV), IORV (RVV), and RCCW line break, followed by the ECCS actuation. Among them, the IORV (RRV) initiating event followed by the ECCS actuation without the DHRS activated for a hot reactor condition is the most limiting case.

> **Note:** The case with the DHRS activated is more realistic but less limiting, whereas the case without the DHRS activated is less realistic but more limiting. The more limiting, lower RCS hot region boron concentration, for the case without the DHRS activated is due to {{
>
> }}2(a),(c)

The results of the boron dilution analyses for the three initiating events of the IORV (RRV), IORV (RVV), and RCCW line break are plotted in Figure Res3-1through Figure Res3-4, Figure Res3-5through Figure Res3-8, and Figure Res3-9through Figure Res3-12, respectively. The figures provide results for the boron concentrations, boron masses, boron volatility fraction, and the liquid droplet entrainment vs. boron volatility comparison. The results of the boron dilution analyses show there is no bulk dilution of the RCS hot region concentration, in other words the final RCS hot region boron concentration remains higher than the initial concentration, even for the most limiting case of the IORV (RRV) initiating event followed by the ECCS actuation without the DHRS activated for a hot reactor condition.

{{

}}2(a),(c) Regardless of the specific initial boron concentration or input to the critical boron concentration, the results in Figure Res3-1, Figure Res3-5, and Figure Res3-9 show that no bulk dilution of the hot region occurs over the 72 hour time frame.

Figure Res3-1 and Figure Res3-2 provide the boron concentrations and boron mass distributions, respectively, for the limiting case of the inadvertent RRV opening. Long-term during the ECCS recirculation, the RCS core and riser region concentration decreases slowly because volatilized boron is assumed to be a loss mechanism and it is conservatively assumed that the volatilized boron does not return to solution when the steam condenses in containment, to recirculate back into the RCS. As discussed in Section 2.1.3.1, the nominal volatility calculated by the Bohlke correlation is increased by {{

}}[2(a),(c)] To evaluate margin in the analysis results related to uncertainty in the volatility rate, a sensitivity calculation was performed. In the sensitivity calculation the uncertainty in the volatility calculation was increased from {{

}}[2(a),(c)] The total mass of boron assumed lost due to volatility is small compared to other masses of boron assumed lost or not available to recirculate. As discussed in Section 2.1.3.1, treating volatilized boron as a loss mechanism in the transport analysis is conservative because volatility correlations are developed measuring the boron concentration of condensate; therefore in the NPM design any boron carried in steam is realistically expected to condense and be carried with the condensed liquid, and continue to be available for transport in the system. Even if only half of the volatilized boron were assumed to continue recirculating from the CNV through the downcomer in the RCS hot region, this would ultimately increase the RCS hot region concentration compared to the current calculation results. This provides a quantification of the conservatism in the overall transport analysis used to evaluate the 72 hour boron dilution case, compared to uncertainty in the boron volatility rate.

{{

}}2(a),(c)

Figure Res3-1. Boron Concentrations for IORV (RRV) without DHRS

{{

}}2(a),(c)

Figure Res3-2. Boron Masses for IORV (RRV) without DHRS

{{

}}[2(a),(c)]

Figure Res3-3. Boron Volatility Fraction for IORV (RRV) without DHRS

{{

}}2(a),(c)

Figure Res3-4. Liquid Droplet Entrainment vs. Boron Volatility for IORV (RRV) without DHRS

{{

}}2(a),(c)

Figure Res3-5. Boron Concentrations for IORV (RVV) without DHRS

{{

}}2(a),(c)

Figure Res3-6. Boron Masses for IORV (RVV) without DHRS

{{

}}2(a),(c)

Figure Res3-7. Boron Volatility Fraction for IORV (RVV) without DHRS

{{

}}2(a),(c)

Figure Res3-8. Liquid Droplet Entrainment vs. Boron Volatility for IORV (RVV) without DHRS

{{

}}2(a),(c)

Figure Res3-9. Boron Concentrations for RCCW Line Break without DHRS

{{

}}2(a),(c)

Figure Res3-10. Boron Masses for RCCW Line Break without DHRS

{{

}}[2(a),(c)]

Figure Res3-11. Boron Volatility Fraction for RCCW Line Break without DHRS

{{

}}2(a),(c)

Figure Res3-12. Liquid Droplet Entrainment vs. Boron Volatility for RCCW Line Break without DHRS

3.2 Transient Results - 7 Day Analysis

Table Res7-1 summarizes the spectrum of cases analyzed with the 7 day analysis methodology. For Case 1 (beginning of cycle, nominal containment and downcomer distribution factors), the initial 72 hour boron concentration and masses are shown in Figure Res7-1 and Figure Res7-2, respectively. {{ }}2(a),(c) shown in Figure Res7-3. Tabulated results for this and the remaining cases are provided in Table Res7-2.

As summarized in Section 2.2, for the 7 day analysis {{

}}2(a),(c) This is shown in the 72 hour results in Figure Res7-2.

The results show {{

}}2(a),(c)

Table Res7-1. 7 Day Boron Dilution Analysis Case Spectrum

Case number	Core exposure	Initial RCS boron concentration (ppm)	Containment distribution factor	Downcomer distribution factor
1	{{			
2				
3				
4				
5				
6				}}2(a),(c)

Table Res7-2. 7 Day Boron Dilution Analysis Results

Case number	Initial boron concentration (ppm)	Final boron concentration (ppm)	Maximim boron concentration (ppm)	Time of maximum boron (hr)	Minimum pH
1	{{				
2					
3					
4					
5					
6					}}2(a),(c)

{{

}}2(a),(c)

Figure Res7-1. 7 Day analysis RRV Opening, Case 1, 72 hr. Transient Boron Concentration

{{

}} 2(a),(c)

Figure Res7-2. 7 Day analysis RRV Opening, Case 1, Transient Boron Mass Distribution

{{

}} 2(a),(c)

Figure Res7-3. Case 1 7 Day Boron Concentration

3.3 Quantification of Conservatism in 3 Day Dilution Analysis

Inspection of Figure Reg3-2 shows {{

}}[2(a),(c)] When assuming volatilized boron is a loss mechanism, this leaves approximately 20% of the RCS boron to recirculate to the RCS hot region. Details of these assumed boron loss terms are discussed in Section 2.1.5.

Alternatively, the 7 day analysis concentration results at 72 hours provide a quantification of the conservatism in the 3 day analysis with respect to the overall mass of boron in the core region and the core region concentration. While the 3 day analysis results at 72 hours show a relatively small increase in boron concentration relative to the initial concentration (for example, see Figure Res3-1 final concentration approximately 15% above the initial), the 7 day analysis results show that at 72 hours the concentration is 2-3 times the initial concentration. The 7 day analysis results also demonstrate that {{

}}[2(a),(c)]

4. Summary and Conclusions

- A summary of the conservative 3-day bounding boron dilution analysis methodology and more realistic 7-day boron dilution analysis methodology are provided.
- The boron dilution analysis using the NuScale approach, to minimize the boron transport to the core, demonstrate that the RCS hot region does not experience bulk boron dilution over the course of 72 hours, even for the most limiting case of the IORV (RRV) initiating event followed by the ECCS actuation without the DHRS activated for a hot reactor condition.
- Evaluation of alternate assumptions, to maximize the volatilized boron loss, results in high RCS hot region concentrations, compared to the NuScale approach, for each of the three initiating events of the IORV (RRV), IORV (RVV), and RCCW line break.
- The results of the 7 day analysis, at 72 hours (Figure Res7-1, more than {{ }}[2(a),(c)]), compared to the 3 day analysis results (Figure Res3-1,approximately {{ }}[2(a),(c)]), demonstrate the conservatism in the 3 day analysis results. As summarized in Section 3.3, the conservatism in the 3 day analysis results is primarily due to the treatment of boron transport from the CNV and cold region into the RCS hot region, and the assumed loss of boron from the system during the RCS blowdown into the CNV, and the assumed loss of volatilized boron. In the 3 day analysis, the assumed loss of boron from the system during

the RCS blowdown into the CNV results in loss of {{

}}2(a),(c)

- Considering the qualitative evaluation of mixing in the core and riser region, the simplified energy balance results, the VEERA test results and explicit evaluation of a concentration gradient at the core inlet, and the conservatism in the 3 day analysis transport assumptions as quantified in the 7 day analysis results at 72 hours, it is concluded that there is reasonable assurance that the NuScale geometry and boron transport will result in boron transport to the core with net accumulation in the core region, and will not support bulk dilution of the core region, or development of a boron concentration gradient sufficient to substantively changes the reactivity balance in the core region.
- The 7 day analysis results demonstrate that boron accumulates in the RCS hot region and the RCS hot region concentration remains above the initial concentration, even assuming some initial boron transported into the CNV during blowdown does not continue to recirculate, and treating volatilized boron as a loss mechanism. In the 7 day analysis, the assumed loss of boron from the system during the RCS blowdown into the CNV results in loss of {{ }}2(a),(c) No credit for any boron addition from nonsafety-related systems is assumed. The results of this analysis supports the conclusion that the CVCS or other system(s) are not classified as RTNSS in the NPM design.

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Impact on DCA:

The FSAR has been revised as described in the response above and as shown in the markup provided with this response.

assemblies are designed for an internal pressure and temperature of 2100 psia and 650 degrees F, respectively.

The RRVs and actuators are designed for a minimum neutron exposure of 2.5E17 neutrons/cm^2. Neutron exposure of the RVVs is negligible due to their distance from the core beltline region.

During reactor shutdown and post-LOCA events, the surfaces of ECCS components in the CNV are exposed to borated water. Eliminating or minimizing chloride levels and maintaining low levels of oxygen in the water reduces the potential for stress corrosion-cracking. The post-LOCA coolant is reactor coolant that satisfies RCS chemistry criteria. Water chemistry during shutdown conditions is controlled to preclude stress corrosion-cracking initiation using water treatment methods that are consistent with the spent fuel pool chemistry recommended in the Electric Power Research Institute Primary Water Chemistry Guidelines.

6.3.2.5 System Reliability

RAI 15-27S2

The ECCS is designed to function by transferring heat from the reactor coolant to the UHS through the CNV. The ECCS does not require operator action or support from nonsafety-related systems for continued operation and is capable of post-accident ~~extended~~ long-term cooling of the core ~~for at least 30 days~~.

Reliability of the ECCS is provided by redundant valves remotely and separately actuated by two divisions of the ESFAS function of the MPS. The ECCS valves and actuators are assigned to separate divisions for instrumentation and electric power. One RVV is designed for actuation by either division of ESFAS by redundant trip valves controlled by separate divisions of instrumentation and electric power.

The ECCS main valves do not rely on power or nonsafety-related systems for actuation (i.e., opening the valves) because they are capable of actuation on stored energy. Following actuation, the valves do not require a subsequent change of state or the availability of power to continue to perform their intended safety functions.

No single active or passive failure prevents ECCS initiation or the capability of the system from performing its core cooling or LTOP safety function. The effect and consequences of single failures are discussed in Section 6.3.3 and are provided in Table 6.3-3.

RAI 06.03-6S1

The ECCS main valves are not susceptible to water hammer. The system consists of five main valves attached to the RPV. The system design includes no pumps or piping which precludes the susceptibility to water hammer mechanisms. The ECCS actuator lines and trip reset valves are also not susceptible to water hammer. The design and operation of the ECCS valve actuator lines and trip reset valves precludes susceptibility to water hammer mechanisms.

In the unlikely event of a return to power, shutdown with margin for stuck rods is not required to demonstrate adequate fuel protection. Fuel is protected through physical processes inherent to the NuScale design that control reactivity and limit power compared to a design in which shutdown is required to limit power production to protect fuel integrity. In the NPM design, additional protection is provided by limiting power and passively removing heat. The means for limiting the power produced if the reactor does not remain shut down is dependent on the heat removal system used.

RAI 15-1, RAI 15-6S1, RAI 15-11

15.0.6.1 Identification of Causes and Accident Description

Design basis events are analyzed with an assumed highest worth control rod stuck fully withdrawn in order to evaluate the immediate shutdown capability of the negative reactivity insertion due to a reactor trip with the control rods inserting into the core, consistent with GDC 26 (See Section 3.1). In the event of an extended cooldown, when the RCS is at low boron concentrations and the CVCS is unavailable to add boron, it may be possible to cool the core to the point of reestablishing some level of critical neutron power if the most reactive control rod stuck out is assumed. This potential overcooling could cause a unique reactivity event similar to a steam line break for traditional multi-loop PWRs. Therefore, this event is specifically evaluated for specified acceptable fuel design limits (SAFDLs).

RAI 15-27S2

Boron distribution is an important consideration in the determination of the consequences of a return to power during extended passive cooling conditions. Under emergency core cooling conditions, boron will preferentially redistribute to the core and riser region of the NPM due to the boiling and condensing heat removal design of the ECCS. Over time, the boron concentration of the water recirculating to the core from the containment vessel will be at lower concentrations than the bulk core region and could be below the bulk critical boron concentration. Analysis of these conditions was performed separately from the overcooling return to power evaluation and included the following considerations:

RAI 15-27S2

- Conservative treatment of potential boron solidification mechanisms due to flashing and entrainment during the ECCS depressurization phase.
- Conservative treatment of the total mass of boron available to recirculate to the core including potential for CNV concentration gradients due to thermal stratification and conservative downcomer mixing to bound potential three dimensional effects. The potential for significant boron concentration gradients to develop in the core region was evaluated to justify adequate conservatism.
- Conservative treatment of potential boron lost due to entrainment and volatility during the long term ECCS cooling phase.

RAI 15-27S2

The analysis included consideration of all design basis events which could progress to ECCS cooling with specific evaluation of the inadvertent ECCS valve opening events as well as other piping breaks where pure water could be introduced into containment prior to ECCS cooling being established. These cases were analyzed for 72 hours. The results showed that the bulk core boron concentrations remained above the initial concentration which supports the conservative analysis of the return to power at end of cycle conditions where the initial boron concentration is minimal.

RAI 15-1, RAI 15-6S1

The purpose of this analysis is to evaluate the thermal hydraulic and core neutronic response of the NPM for an extended overcooling return to power. This analysis is intended to provide a generic bounding evaluation of the extended cooling that could result following any DBE, therefore AOO acceptance criteria and conservative analysis assumptions are applied. The limiting return to power event occurs when operating conditions are biased to maximize initial core fission product poisons which gradually decay resulting in reactivity insertion. The timing of this reactivity insertion occurs well after equilibrium DHRS or ECCS passive cooling modes will have been established following an initial transient and reactor trip. Therefore, analysis of the return to power is limited to the equilibrium thermal hydraulic and neutronic conditions with appropriate biases and conservatisms to ensure a conservative CHF analysis is performed.

15.0.6.2 Sequence of Events and Systems Operation

RAI 15-1, RAI 15-6S1

For the overcooling return to power event, it is assumed that a reactor trip occurs at end of cycle (EOC) with the most reactive control rod stuck out of the core. The decay of xenon slowly adds positive reactivity during the cooldown. The subsequent cooldown is left unmitigated and boron addition does not occur. While there are simple operational means for mitigating the extended cooldown and thereby eliminating the need for boron addition, operator action is not credited for either mitigating the cooldown or adding boron, consistent with Section 15.0.0.6.4.

RAI 15-1

15.0.6.3 Thermal Hydraulic and Critical Heat Flux Analyses

15.0.6.3.1 Evaluation Models

RAI 15-6, RAI 15-6S1

The overcooling return to power analysis is performed using the following analysis procedure:

RAI 15-6S1

- The core average RCS temperature is determined using the long term cooling statepoint analysis approach described in the LTC technical report.
- The worst rod stuck out, EOC critical power level is determined using the SIMULATE5 core physic analysis model.
- CHF margin is evaluated using the zero flow CHF correlation described in the LOCA EM topical report.

RAI 15-1, RAI 15-6, RAI 15-6S1

Enclosure 3:

Affidavit of Zackary W. Rad, AF-1119-68094

NuScale Power, LLC
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www.nuscalepower.com

NuScale Power, LLC

AFFIDAVIT of Zackary W. Rad

I, Zackary W. Rad, state as follows:

1. I am the Director, Regulatory Affairs of NuScale Power, LLC (NuScale), and as such, I have been specifically delegated the function of reviewing the information described in this Affidavit that NuScale seeks to have withheld from public disclosure, and am authorized to apply for its withholding on behalf of NuScale.
2. I am knowledgeable of the criteria and procedures used by NuScale in designating information as a trade secret, privileged, or as confidential commercial or financial information. This request to withhold information from public disclosure is driven by one or more of the following:
    a. The information requested to be withheld reveals distinguishing aspects of a process (or component, structure, tool, method, etc.) whose use by NuScale competitors, without a license from NuScale, would constitute a competitive economic disadvantage to NuScale.
    b. The information requested to be withheld consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), and the application of the data secures a competitive economic advantage, as described more fully in paragraph 3 of this Affidavit.
    c. Use by a competitor of the information requested to be withheld would reduce the competitor's expenditure of resources, or improve its competitive position, in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product.
    d. The information requested to be withheld reveals cost or price information, production capabilities, budget levels, or commercial strategies of NuScale.
    e. The information requested to be withheld consists of patentable ideas.
3. Public disclosure of the information sought to be withheld is likely to cause substantial harm to NuScale's competitive position and foreclose or reduce the availability of profit-making opportunities. The accompanying Request for Additional Information response reveals distinguishing aspects about the method by which NuScale develops its long term cooling analysis.

    NuScale has performed significant research and evaluation to develop a basis for this method and has invested significant resources, including the expenditure of a considerable sum of money.

    The precise financial value of the information is difficult to quantify, but it is a key element of the design basis for a NuScale plant and, therefore, has substantial value to NuScale.

    If the information were disclosed to the public, NuScale's competitors would have access to the information without purchasing the right to use it or having been required to undertake a similar expenditure of resources. Such disclosure would constitute a misappropriation of NuScale's intellectual property, and would deprive NuScale of the opportunity to exercise its competitive advantage to seek an adequate return on its investment.

4. The information sought to be withheld is in the enclosed response to NRC Request for Additional Information No. 484, eRAI 8930. The enclosure contains the designation "Proprietary" at the top of each page containing proprietary information. The information considered by NuScale to be proprietary is identified within double braces, "{{ }}" in the document.
5. The basis for proposing that the information be withheld is that NuScale treats the information as a trade secret, privileged, or as confidential commercial or financial information. NuScale relies upon the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC § 552(b)(4), as well as exemptions applicable to the NRC under 10 CFR §§ 2.390(a)(4) and 9.17(a)(4).
6. Pursuant to the provisions set forth in 10 CFR § 2.390(b)(4), the following is provided for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld:
    a. The information sought to be withheld is owned and has been held in confidence by NuScale.
    b. The information is of a sort customarily held in confidence by NuScale and, to the best of my knowledge and belief, consistently has been held in confidence by NuScale. The procedure for approval of external release of such information typically requires review by the staff manager, project manager, chief technology officer or other equivalent authority, or the manager of the cognizant marketing function (or his delegate), for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside NuScale are limited to regulatory bodies, customers and potential customers and their agents, suppliers, licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or contractual agreements to maintain confidentiality.
    c. The information is being transmitted to and received by the NRC in confidence.
    d. No public disclosure of the information has been made, and it is not available in public sources. All disclosures to third parties, including any required transmittals to NRC, have been made, or must be made, pursuant to regulatory provisions or contractual agreements that provide for maintenance of the information in confidence.
    e. Public disclosure of the information is likely to cause substantial harm to the competitive position of NuScale, taking into account the value of the information to NuScale, the amount of effort and money expended by NuScale in developing the information, and the difficulty others would have in acquiring or duplicating the information. The information sought to be withheld is part of NuScale's technology that provides NuScale with a competitive advantage over other firms in the industry. NuScale has invested significant human and financial capital in developing this technology and NuScale believes it would be difficult for others to duplicate the technology without access to the information sought to be withheld.

I declare under penalty of perjury that the foregoing is true and correct. Executed on November 27, 2019.

Zackary W. Rad