Evaluation of NuScale Post ECCS Actuation Boron Dilution Events

Revision 1.

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DISCLAIMER:

This report was written by the author to provide the detailed evidences in support of the Non-Concurrence Form 757 preparation regarding the latest approval of NuScale design changes related to boron dilution. The technical evaluation and conclusion only represent author's personal view points with the information available to the author at this point. In addition, all the information in this report is considered sensitive proprietary and export-control information.

Executive Summary

NuScale has recently developed the new ECCS system design changes to address ACRS's comments from the full committee meeting on February 18, 2020. Although NuScale's latest new design changes can reduce the boron dilution in the downcomer and the core region prior to the ECCS actuation, they have no significant impacts on the boron transport and event progression following the ECCS actuation. During the ACRS full committee meeting on June 3, 2020, the committee raised the concerns about NuScale post ECCS actuation operations and the activation of non-safety injection systems. The author, coordinated with staff members from reactor system branch, PRA and RES, evaluated possible event scenarios. It is author's view that the reactor could reach fuel failure and prompt criticality condition for a wide range of initial conditions. The CDF could be between 0.33E-4 to 0.33E-6 without any other new design changes or analyses to justify otherwise.

Following these findings, the author became deeply concerned about NuScale's process of handling boron dilution phenomenon in its design process. In its condition report CR-0220-69077, NuScale found the apparent cause that the boron dilution phenomenon was missed [[ ]]. Along this line, the author found that NuScale's overall approach missed the interrelated parts of the design and analyses associated with the boron dilution phenomenon. The weakness started from the PIRT process. It then cascaded through the event characterization, the event tree development, the PRA analyses, the LOCA spectrum analysis, the post ECCS actuation boron transport analyses and the core neutronics design evaluation. As the result, for the post ECCS actuation operation, the current design basis analyses missed the most limiting return to power transients which would cause significant core damage with an unacceptable frequency and risk.

This report first briefly describes the unique NuScale RCS water volume distribution characterization and its core boron dilution vulnerability to the system disturbances during the post ECCS actuation scenarios. It then documents author's concerns about the event characterization and the event tree development, along with the boron dilution progression with no other system intervention and the related modeling. For all three potential non-safety system actuation events after ECCS actuation, the author provides a summary of the qualitative and quantitative core damage evaluation results including the core damage frequency for each case.

Based on event analysis and the identified modelling deficiencies associated with the core post ECCS boron dilution analysis, the author believes that the NuScale reactor will most likely experience core damage during the anticipated non-safety injection system actuation or even in the case without operator actions due to prolonged volatility induced boron loss. Therefore, the latest NuScale design changes are not adequate. Additional design changes are needed from NuScale to avoid the catastrophic core damage during the post ECCS actuation operations and improve the safety margin.

Background:

On June 3, 2020, NuScale presented its latest ECCS actuation set points and riser hole design changes to the ACRS full committee. Because the latest design changes did not address the boron dilution scenarios during the operator follow-up actions after ECCS actuation, ACRS was concerned that NuScale has not analyzed the potential return to power scenarios resulting from operator actions after ECCS actuation.

ACRS Concerns:

After ECCS actuation, the DHRS and CNV will generate fresh condensate resulting in diluted water in the downcomer and the lower plenum. The operator can have the following three options to restore the reactor to its normal shutdown condition.

1. If the operator has the CVCS available and starts to inject the cold water into the riser, the cold water will shrink the riser void fraction and cause a surge of diluted water from lower plenum and downcomer into the core. The resulting consequence could be the return to power. In addition, if the CVCS was in the dilution mode of operation prior to the event, the discharge line initially contains fresh water. The cold and fresh water injection on top of the core could make the return to power worse.
2. If the operator has the Pressurizer Spray available and start to inject the cold water into the pressurizer spray, the cold water will depressurize the RCS and cause the riser fluid flashing and void fraction increase. The resulting consequence could be the surge of diluted water into the core and return to power.
3. If the operator initiates the Containment Flood and Drain System, the injection at 100 gpm rate could also push a slug of diluted water into the core.

One ACRS member considered NuScale design as being incomplete and has a very high risk.

Staff Evaluation

In response to ACRS comments, the author began to look into these transients and became concerned about the consequences of these events. Starting from here, the author began a systematic evaluation of areas which are potentially impacted by the boron dilution phenomenon. These areas under evaluation are listed below:

1. Phenomenon Identification and Ranking Table;
2. System Vulnerability and Sensitivity to System Disturbances;
3. Event Trees and Events Involving System Disturbances;
4. Design Basis Events and Long-Term Cooling With and Without Non-safety System Operations;

5. Beyond Design Basis Events and Shutdown Operation.

Based on these evaluations, the effectiveness and the limitations of the latest design changes are evaluated and the need for further design improvement is identified.

Technical Evaluation

Phenomenon Identification and Ranking Table

Although NuScale's PIRT in 2008 [[ ]], its 2015 PIRT [[ ]]. By then, the framework of analyses and design has already been developed and it was too late to alter. In addition, the phenomenon was not evaluated until NuScale worked on the response to RAI 8930 and the latest design changes. The current NuScale's status related to boron dilution is that the source of the diluted water during DHRS extended cooling and LOCA have been identified from the condensation in the steam generator region and in the containment. Additional fresh water injection could come from CVCS system injection (Figure 1) as the fresh water residue could remain in the CVCS discharge pipe line or with a misalignment of the fresh water source.

The transport phenomenon associated with diluted water slug movement may not have been identified completely. For example, the riser surge and core flow increase could be caused by the injection through spray or the lower riser injection nozzle during the post ECCS actuation operation. Other transport phenomenon and mechanisms are the manometer type of flow oscillation under low pressure and low temperature post ECCS operating conditions. NuScale, however, has not identified these transport mechanisms as the potential core dilution contributors nor evaluated the consequence of this type of flow instability. Figure 2 shows the deficiencies of the analyses and the design effort from a bird's eye view. Because of these gaps, it is considered unacceptable.

System Vulnerability and Sensitivity to System Disturbances

As it is shown in Figure 3, NuScale module has a very unique fluid volume distribution. From the perspective of maintaining core collapsed water level during ECCS operation, there is an ample margin. For boron transport, after the ECCS actuation, the downcomer and lower plenum becomes diluted quickly. The system becomes an "unstable" boron distribution pattern with a relatively small core fluid volume and [[ ]] more fresh or diluted water in the lower plenum, downcomer and the containment ready to move into the core. Any system disturbances, such as non-safety system injections, manometer type of oscillation or flow instability may have a good chance to turn the unstable steady state into a transient with a large amount of fresh water getting into the core.

After the ECCS actuation, the system pressure quickly drops to atmospheric pressure range due to the condensation in the containment and the steam generator. A manometer type of natural circulation boiling system under low pressure and low flow condition can be unstable.

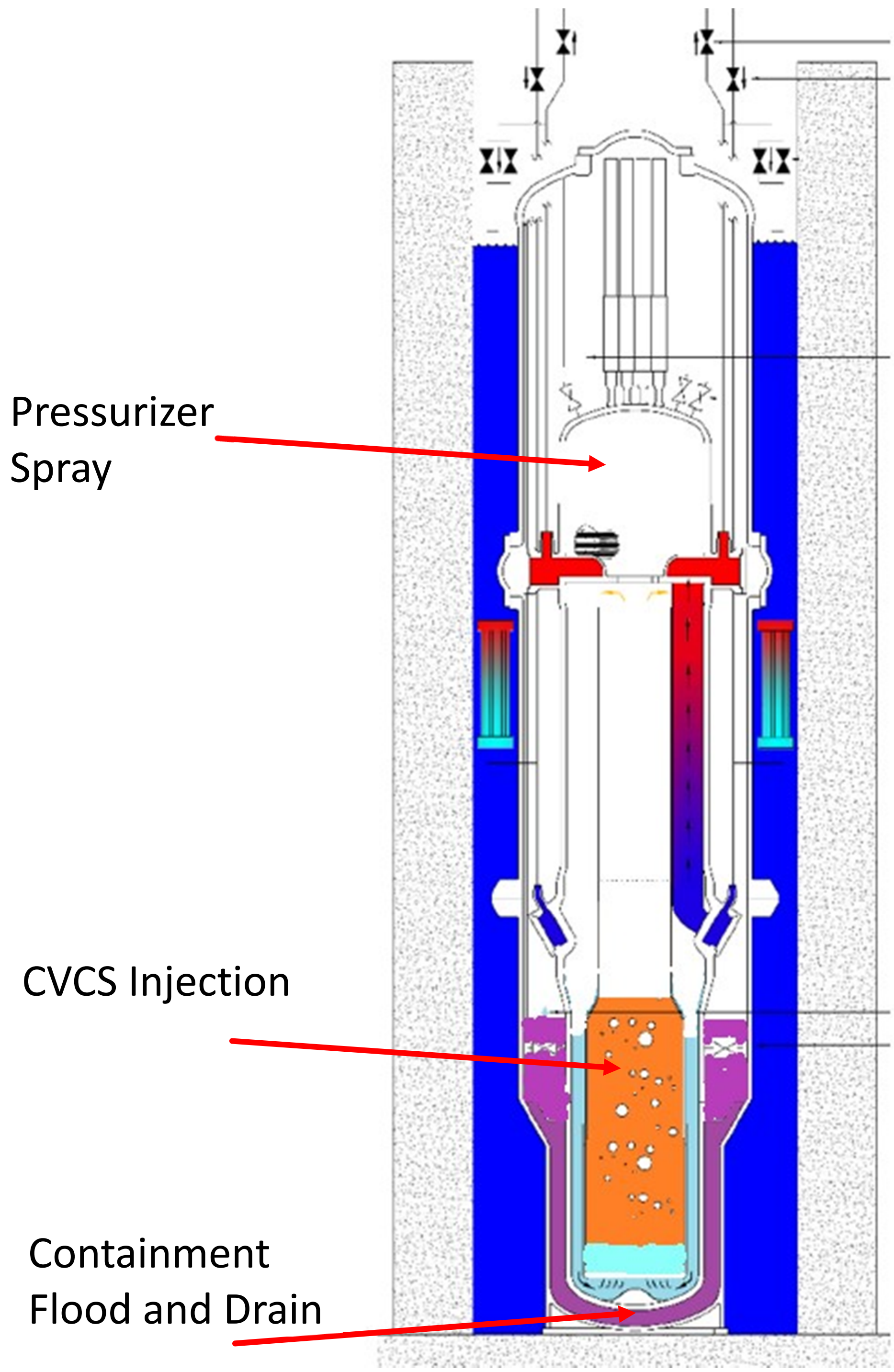

Figure 1. NPM module under post ECCS actuation condition and non-safety injection points.

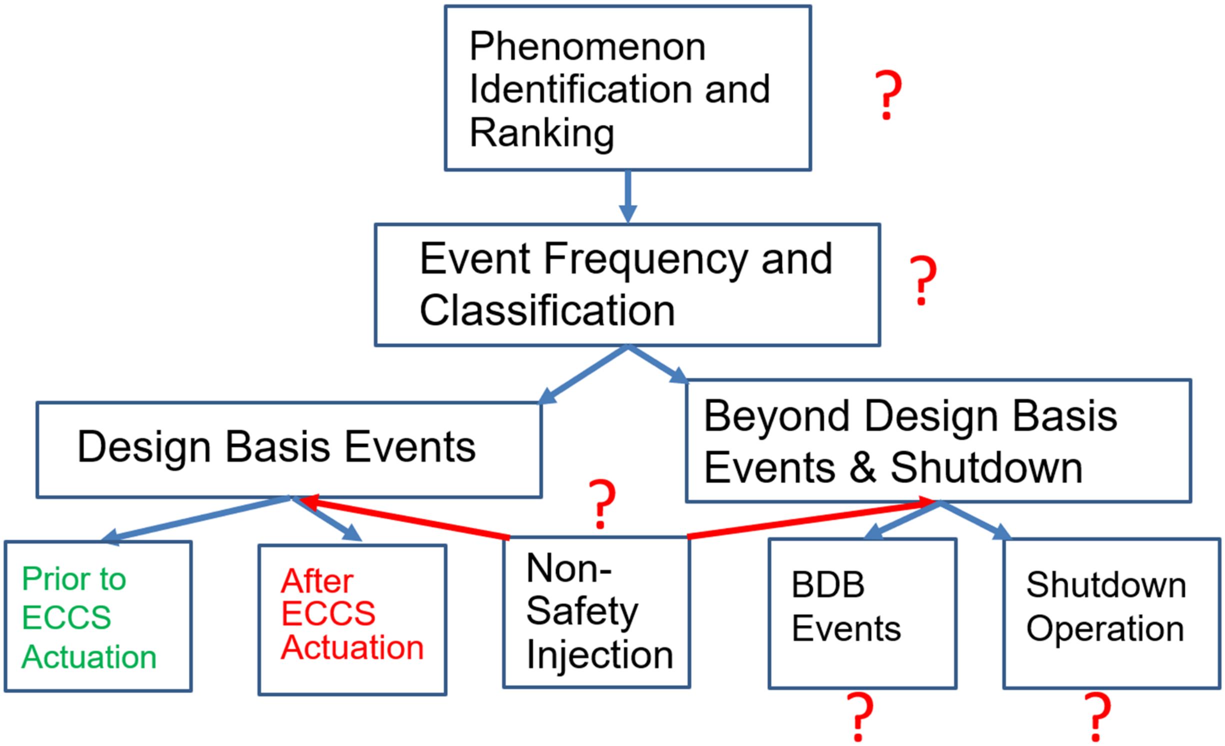

Figure 2. Gaps of NuScale Design and Analyses Related to Boron Dilution Phenomenon

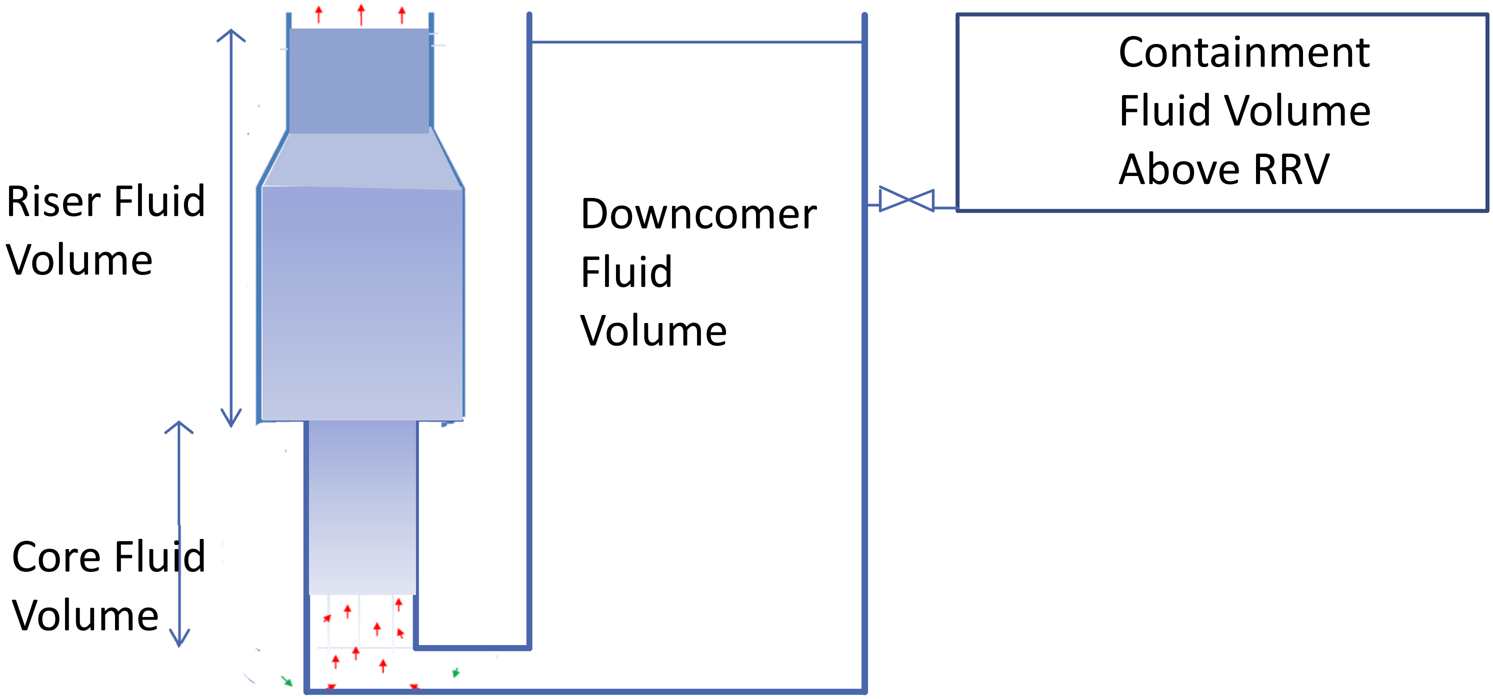

Figure 3. NPM Post ECCS actuation Fluid Volume and Boron Concentration Distribution.

Event Trees and Events Involving System Disturbances

Because the initial PIRT process missed the boron dilution phenomenon, the event classification in FSAR Section 15.0.0.6.3 (Engineered Safety Features Characteristics), Section 15.0.0.6.4 (Required Operator Actions) do not currently include any consideration of CVCS injection through spray and the riser, or, the containment flooding and drain system operation. Without considering boron dilution phenomenon, these classifications were considered adequate and complete as NuScale reactor has ample water inventory to remove decay heat during the post ECCS operation. Once the boron dilution phenomenon is considered, the actuation of non-safety injection systems play an important role in the event progression following any accidents or AOOs which lead to the ECCS actuation. Unfortunately, NuScale FSAR 15.0.0 missed this part of the event classification.

During the course of evaluating small leakage case with a break size smaller than the LOCA lower bound break size, the staff was concerned that the downcomer water level could drop below the riser hole elevation and the downcomer boron concentration could be lower than the core critical boron concentration. NuScale took a position that the CVCS can be available for operator to inject boron from risk informed perspective as the break size is outside of the LOCA spectrum. Because of this position, the staff relaxed the review requirements on the leakage boron dilution analyses although staff's confirmatory analysis showed the possibility of riser hole uncovery.

However, if the injection from these non-safety systems can be part of the event progression or credited by NuScale, the evaluation of these system operation should be part of Chapter 15 design basis accident analyses. Unfortunately, the inclusion of these non-safety system injections and their performance evaluation were missed from NuScale's FSAR and any submittals. In particular, their adverse impacts on ECCS performance have not been analyzed. This is considered unacceptable.

<u>Design Basis Long-Term Cooling Without Actuation of Non-Safety Systems</u>

For the post ECCS actuation scenarios up to 72 hours, the NuScale's response to RAI 8930 documented its boron dilution analyses. As shown in Figure 2, several hours after ECCS actuation, most of the boric acid in the downcomer, water volume above RRV in the containment and the lower plenum has been flushed to the core and lower riser water volume. The boron concentration in these volumes is close to zero. The difficult question is how much of the mixing is between the lower riser and the core. NuScale's methodology assumed that [[ ]]. Therefore, according to them, there would not be any dilution in the core region. The staff performed sensitivity studies on the mixing between the core and the lower riser by dividing the core and lower riser into two separate volumes. The author assumed 95% of the boil off fluid mass coming back from the lower riser fluid volume with high boron concentration. The result shown the reactor becomes critical with one stuck rod within about 9 hours and with all rods in about 20 hours. This type of uncertainty was indeed not tolerable as there was no relevant experimental data to justify NuScale's [[ ]] assumption. From author's view, there should be mixing between the core and the lower riser fluid volume. However, the [[ ]] assumption is non-conservative.

1. Diluted Non-Boiling Length Determination

In response to author's concern, NuScale identified one VVER boron precipitation test in October 2019. According to NuScale, the test shown lower boron concentration below the elevation of the boiling length of the VERA test facility. Since then, NuScale has been assuming that anything below the boiling length has [[ ]] for its criticality margin assessment. Although this approach is better than the [[ ]] assumption, the author examined the relevant VERRA test report and found the results may not be conservative either.

The Finish VEERA test facility was designed to measure boric acid concentration distribution during the VVER (PWR) boron precipitation scenario. Figure 4 shows the test facility and a simple relevance drawing of the facility. VERRA test facility has a 12 ft bundle with only about 0.1 meter of water on top of the bundle. NuScale has 10 ft water above the core with a core height of 6 ft. Because of this mismatch, the author expects that NuScale has longer diluted non-boiling region than what was measured in VERA. Therefore, the use of VERA test data to determine the NuScale non-boiling length is non-conservative

2. Non-Applicable Volatility Correlation

Volatility plays a gradually significant role with a time span beyond 10 hours. As shown in Figure 5, NuScale adopted a German correlation developed for BWR ATWS SLC injection scenario. The heated section has a height of 12 ft and the mass flow rate is close to 100 times more than NuScale boil off rate. Not only the test was not scalable to NuScale condition, but also the correlation predicted much lower value than both WAPD data and 1999 Chemical Thermo-dynamic Journal data by a factor of 2.0 (Figure 6). The staff also performed sensitivity analyses and predicted the return to power within 72 hours once other volatility correlations are used.

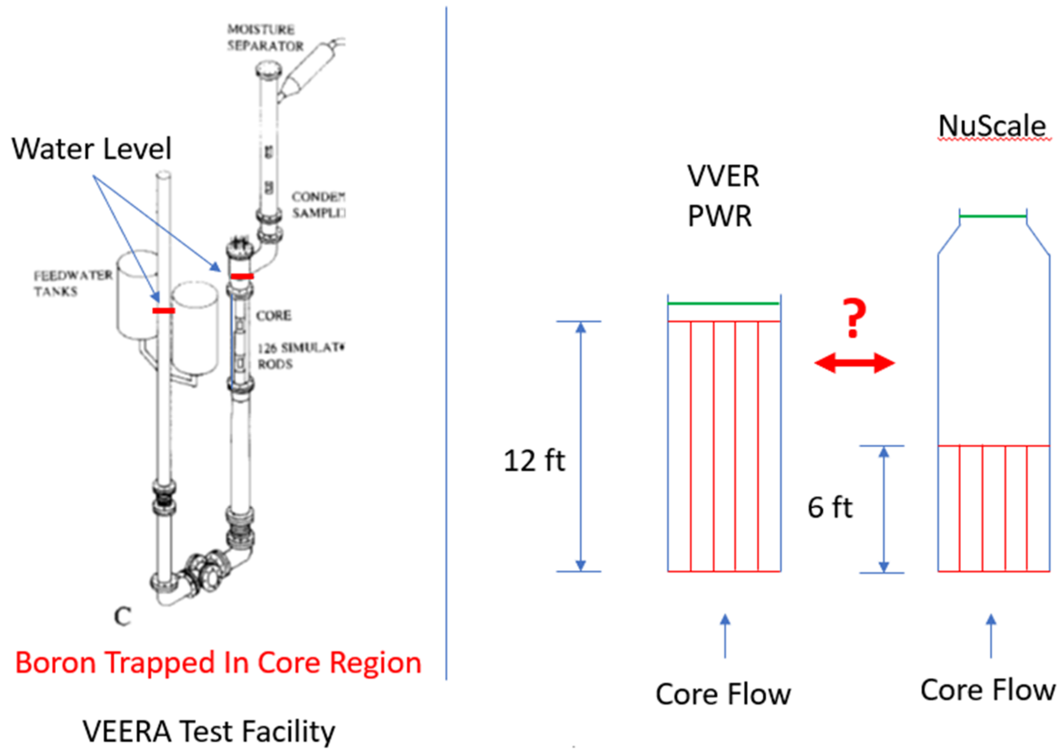

Figure 4. VERRA Test Facility and Its Relevance to NuScale Boiling Length Calculation

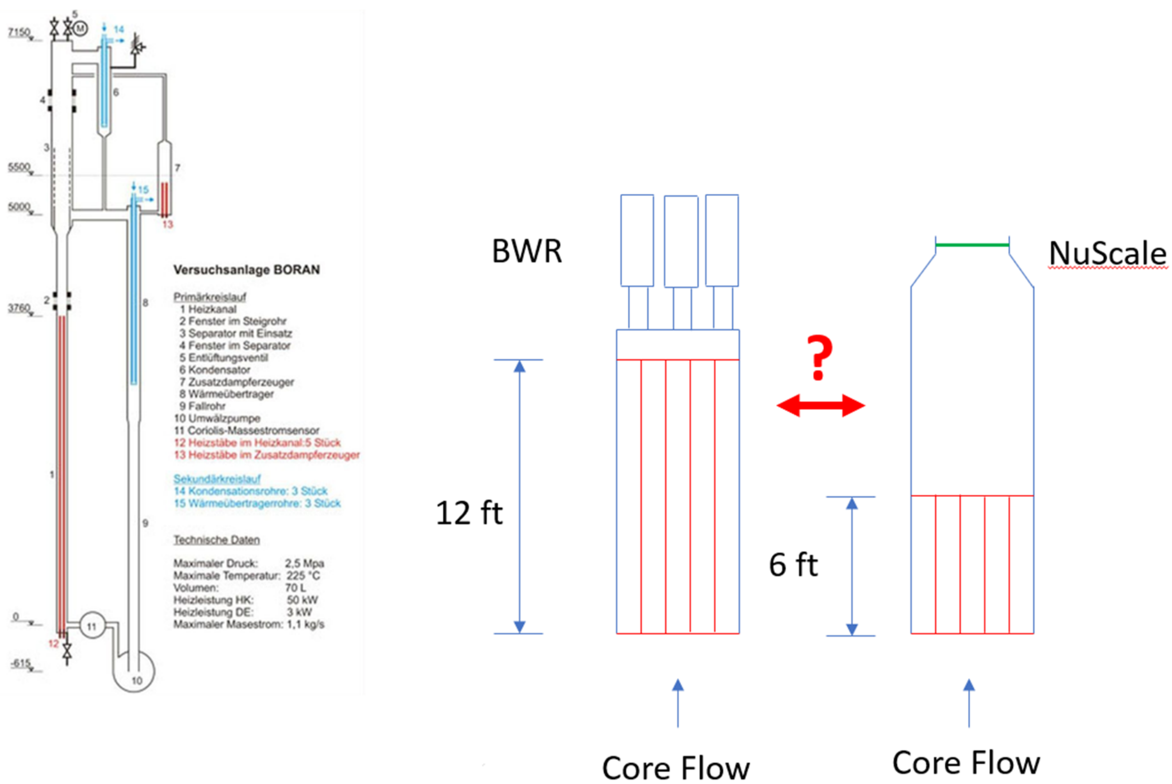

Figure 5. German Boron Volatility Test Facility For BWR ATWS Application

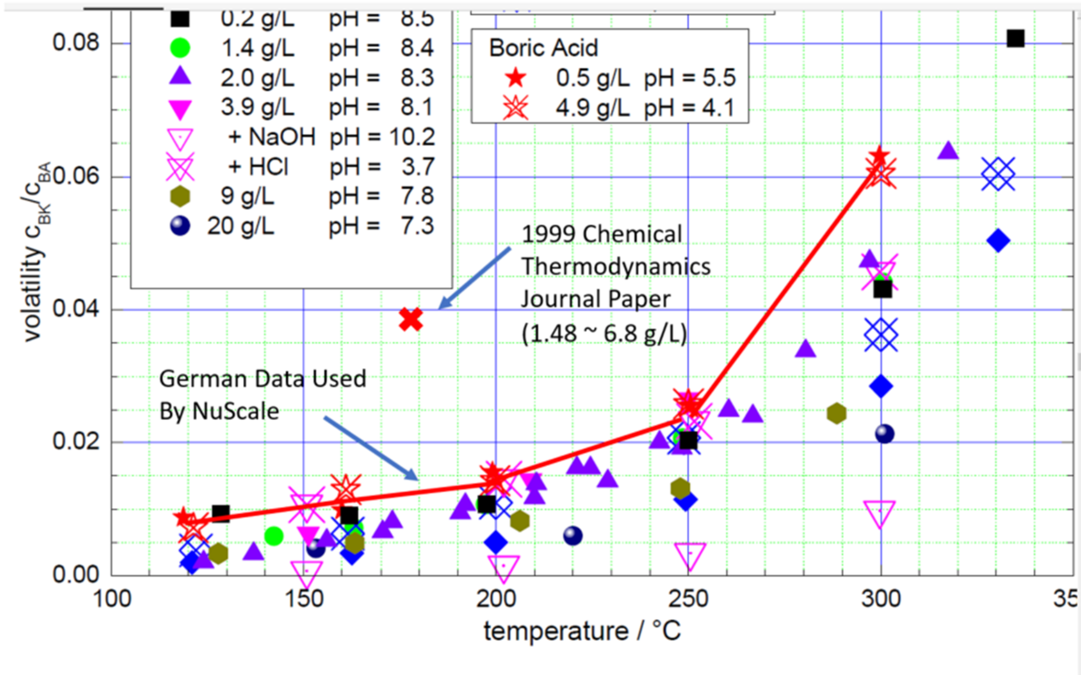

Figure 6. Comparison of German Volatility Correlation With Other Test Data.

Although NuScale's analysis has some other conservatisms, both the volatility correlation and the non-boiling length calculation are considered non-conservative. The overall conservatism can hardly be proved with two major uncertainties from NuScale's approach. Therefore, the author does not believe that we have reasonable assurance to approve NuScale's boron dilution analysis and their claim that there is no return to power as long as there is boron in the RCS.

<u>Design Basis Long-Term Cooling With Non-safety Injection System Operations</u>

As a follow-up of ACRS's comments on June 3, 2020, the author and several staff performed back-to-envelope hand calculations and NRELAP5 analysis using NuScale's NPM model. The analysis assumed a large CVCS line break and the non-safety injection system is actuated one hour after the ECCS actuation to see the feasibility of a surge of colder water into the core. If it is feasible to have a surge, the actuation of these systems later are expected to have similar consequencs. The preliminary initial results are summarized below for these three scenarios.

A. Pressurizer Spray Case

The operator could actuate CVCS to inject cold water through the pressurizer spray. The cold spray water would condense the steam in the pressurizer and cause a surge of diluted water into the core. The results shown that the cold spray water depressurizes the RCS steam space and causes a period of diluted water surge into the core for more than 100 seconds. Within less than 60 seconds after the spray injection is initiated, the entire core is replaced with the downcomer diluted water. Depending on the time of the operator action, the downcomer water concentration could be even lower than the critical boron concentration with all rods in. Combined with the void collapse, the cold and diluted spray water introduces a large amount of reactivity (~$21) within a short period of time (less than 60 seconds). The core is expected to fail due to the quick insertion of a large amount of reactivity. The staff is still reviewing these preliminary calculations results.

B. Containment Flooding And Drain Case

The containment flooding and drain injection occurs at the bottom of the containment. The injection rate at 100 gpm rate could also raise the containment level and push a slug of diluted water into the core before the borated water front reaches the core. A hand calculation shows that the entire core could be replaced with diluted downcomer water within about 15 minutes. Due to boron dilution, a large amount of reactivity ($21) would be injected into the core within 15 minutes. The reactivity inserted is more than enough to return the reactor to power with all rods inserted, which has not been analyzed before.

C. CVCS Injection Case

The injected CVCS cold water into the riser will shrink the riser void fraction and may cause a surge of diluted water from lower plenum and downcomer into the core. A RES preliminary hand calculation indicates the certainty of the occurrence of this phenomenon. In addition, staff confirmatory analysis using NRELAP5 code indicates significant manometer type of oscillation after the injection and the surge of diluted water into the core. This may cause a return to power with or without a stuck rod. Additional studies need to be done to evaluate the consequences.

These preliminary initial scoping analysis results revealed the possibility of return to power with or without a stuck control rod. The amount of reactivity introduced into the core due to boron dilution can be so large that the core damage is expected. Therefore, the adverse impact of actuating these non-safety injection systems have not been analyzed by NuScale at all as part of its ECCS long term cooling analysis. Therefore, the current FSAR Chapter 15.0.5 and ECCS Section 6.3 should not be approved.

CDF Estimate For Adverse Impact of Non-Safety Injection System Actuation

NuScale's unique ECCS design triggers its actuation following many AOO events in addition to LOCA and other accidents. For example, an inadvertent opening of an RRV is an AOO, which can trigger the ECCS actuation. A discharge line LOCA has an event frequency of 1.0E-3. Therefore, the ECCS actuation has at least an occurring frequency of 1.0E-3. Only one third of cycle has sufficient boron to be diluted and cause an all-rod-in return to power condition with a potential power surge, which has a frequency of 0.33. The frequency of the operator error to actuate the non-safety injection system is estimated to be 1.0E-2 and 1.0E-3. Therefore, if the return to power happens due to boron dilution with all rods in and causes severe core damage as the result of operator actions, the CDF could be in the range of 0.33E-6 ~ 0.33E-4.

Beyond Design Basis Events and Recovery Capabilities

The author was made aware recently that all the Chapter 19 PRA event trees and event sequence have not covered the potential adverse impact of non-safety injection system actuation and the related boron dilution phenomenon. If these adverse impacts are considered, the overall risk profile is expected to change.

It has been claimed by NuScale that the actuation of these non-safety injection system should be part of post ECCS recovery operation governed by EOPs which will be developed by COL applicants. On the contrary, when NuScale requested staff's relaxation of review requirements on small leakage case following GDC 33 exemption, they claimed that operator can take action to mitigate the downcomer dilution. These two claims are not consistent. In addition, all the recovery operations should not result in a scenario with return to power with all rods in. If they do, these recovery scenarios should be treated as an extension of an AOO or a design basis accident in Chapter 15. The current design can most likely result in core damage once these non-safety injections are actuated early on during a fuel cycle. Therefore, the author is not sure whether NuScale has a reasonable recovery capability at all.

Although GDC 27 exemption allows the reactor to return to power with one stuck rod, a return to power with all rods in is never allowed.

Regulatory Implications

It is author's view that the current version of FSAR should not be approved. Specifically, these FSAR sections are listed below with a summarized rational for non-approvals.

Section 15.0.0.6.3 and 15.0.0.6.4

-- Missed the classification of non-safety injection systems.
(Non-compliance with 10CFR 50.46 ECCS rule)

Section 15.0.5

-- Used a non-conservative volatility correlation and non-applicable boiling length test data

-- Missed the analysis of adverse impact of non-safety injection systems.
(The most limiting return to power case has not been identified. Non-compliance with GDC 27 and its exemption acceptance criteria.)

Section 15.6.5

--As the result of Section 15.0.5, the long term cooling conclusion is no longer valid.

Section 6.3 ECCS Design

--As the result of Chapter 15 deficiencies, the ECCS design is incomplete.

The latest NuScale design changes have improved the boron mixing prior to the ECCS actuation. However, additional design modifications are needed for NuScale to mitigate post ECCS actuation boron dilution and demonstrate that the system capabilities to bring the system back to normal with no adverse impacts on the core cooling.

Possible Design Modifications

Once NuScale recognizes the significant deficiencies of its design to handle boron dilution with those non-safety injection system and the current ECCS post actuation settings, there are always many design options for NuScale to consider. The current NuScale innovative passive design features allows the development of a passive boron addition system as a natural extension of its passive design features. All the existing analyses and design efforts can be fully utilized with minimum changes. NuScale staff has learned a lot about boron dilution and transport during the past several years. They have developed a good knowledge base and expertise to quickly supplement the design with a new boron dilution mitigation device.

Schedule Impact

If NuScale makes right design choices, they can supplement with additional design changes and obtain the NRC approval within the current NRC DCD review schedule.

Conclusion:

The latest NuScale design changes significantly improves the boron mixing prior to the ECCS actuation. However, NuScale has not analyzed the adverse impact of non-safety injection system actuations. The current system design has questionable capabilities to bring the reactor back to normal after the ECCS actuation. If any one of these non-safety injection systems is being activated, the reactor may experience diluted water surge into the core and a power excursion with a CDF estimated to be between 0.33E-4 and 0.33E-6. Therefore, the author decided to non-concur SER section 15.0.0.6.3, 15.0.0.6.4, 15.0.5, 15.6.5 and 6.3.