UNIQUE CHALLENGES IN MAKING A REGULATORY DECISION REGARDING THE COMBINED EFFECTS OF BORIC ACID PRECIPITATION AND GSI-191

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ABSTRACT

Long Term Core Cooling (LTCC) is defined as maintaining the temperature of the core at an acceptably low value while removing decay heat for an extended period of time. It begins after the core has been reflooded following a Loss-Of-Coolant Accident (LOCA) and continues until the plant is sustained in a cold shutdown condition. Debris accumulation, on the recirculation strainers or in the core, following a LOCA could potentially challenge a nuclear power plant's capability to provide adequate LTCC. In addition, boric acid, already present in the core, as well as that injected from Emergency Core Cooling Systems (ECCSs) may precipitate due to boiloff potentially causing an interference with LTCC.

The effect of debris on LTCC is a challenging topic. It requires consideration of debris accumulation on the recirculation strainers and in the reactor vessel, and debris effects on Boric Acid Precipitation (BAP). The challenging nature of this issue has resulted in difficulty establishing regulatory guidance on resolution of the issue. Research testing done in the past has resulted in an inconclusive basis for regulatory decisions. Additional research testing, as well as computational studies are essential tools in making a final regulatory decision regarding the combined effects of BAP and Generic Safety Issue 191.

KEYWORDS

GSI-191, BAP, debris accumulation, recirculation strainers, LTCC

1. INTRODUCTION

The performance of ECCS strainers in currently operating Pressurized Water Reactors (PWRs) was recognized decades ago as an important regulatory and safety issue. The transport and accumulation of debris in containment following a LOCA could impede the operation of ECCS and potentially challenge LTCC. Boron is present in every PWR in the form of boric acid as a means for reactivity control. Boric acid can concentrate and precipitate due to boiloff and collect in the reactor vessel interfering with Emergency Core Cooling (ECC) injection and LTCC. Maintaining sufficient water addition to exceed boiloff and preventing BAP are necessary to accomplish LTCC.

The effect on long term core cooling when considering both debris accumulation on the recirculation strainers and in the reactor vessel, and BAP is a challenging topic. The challenging nature of this issue has resulted in difficulty making a regulatory decision. Past research testing has resulted in an inconclusive basis for regulatory decisions. Additional research and computational studies are essential tools in making a final regulatory decision regarding how the effects of BAP will be treated with respect to GSI-191.

Another challenging aspect of GSI-191 is the effect of chemicals introduced with the initiation of sump recirculation. This is discussed in reference documents [1], [2], but will not be specifically addressed in this paper.

2. GENERIC SAFETY ISSUE 191

The containment sump and ECCS strainers are part of safety systems in both Boiling Water Reactors (BWRs) and PWRs. Every nuclear power plant in the United States is required by Title 10 of the *Code of Federal Regulations* Section 50.46 (10 CFR 50.46) to have an ECCS that is capable of mitigating Design-Basis-Accidents (DBAs). Generic Safety Issue (GSI)-191 was established to determine if the transport and accumulation of debris following a LOCA would impede the operation of the ECCS in operating PWRs and BWRs. Assessing the risk of the ECCS and Containment Spray System (CSS) pumps in PWRs experiencing a debris-induced loss of the Net Positive Suction Head (NPSH) margin during sump recirculation is the primary objective of the U.S. Nuclear Regulatory Commissions (NRCs) technical assessment of GSI-191 [3].

2.1. History of GSI-191

The performance of ECCS strainers in currently operating BWRs and PWRs was recognized decades ago as an important regulatory and safety issue. The issue was considered resolved for both reactor types in the early 1990’s. In the late 1990’s, testing and other evaluations indicated that the issue should be re-evaluated for PWRs. This led to the issue being formally added to the Generic Issues program at the U.S. Nuclear Regulatory Commission (NRC) and was designated GSI-191, “Assessment of Debris Accumulation on PWR Sump Performance” in 1996.

When the issue was re-evaluated, licensees were led to significantly increase strainer sizes and make other plant modifications along with other compensatory measures. The ability of the larger strainers to adequately meet the design requirements was verified through testing and evaluation. In 2004, the NRC staff issued a Generic Letter [4] requesting that each licensee of an operating PWRs in the United States perform an evaluation of the ECCS and containment spray system recirculation functions based on the identified potential susceptibility of PWR components to debris blockage during DBAs with emphasis on recirculation sump screens. A plant-specific evaluation for each response to the Generic Letter is in the review stages.

2.2. Thermal-hydraulic Aspects of GSI-191

The transport and accumulation of debris in containment following a LOCA will impede the operation of the ECCS in operating PWRs. If a LOCA were to occur within the containment of a PWR, thermal insulation and other materials in the vicinity of the break will be damaged and dislodged. A fraction of this material would be transported to the recirculation sump and accumulate on the strainer. The debris that accumulates on the sump screen forms a bed that acts as a filter. Excessive head loss across this debris bed could exceed the NPSH margin of the ECCS or containment spray pumps. Excessive head loss can impede or prevent the flow of water into the core. If the flow of water into the core after a LOCA is impeded or prevented, the ability to maintain the temperature of the core at an acceptably low value for an extended period of time is diminished and the ability of the plant to provide adequate long term core cooling would be challenged. [5]

For postulated cold leg breaks (Figure 1), the ECCS liquid injected into the intact cold legs or downcomer provides liquid to the core to make up for boiloff. The ECCS liquid keeps the downcomer full to at least the bottom of the cold leg nozzles; any excess liquid flows out of the broken cold leg and back into the containment sump. The core level is controlled by the manometric balance between the downcomer liquid level, the core level, and Reactor Coolant System (RCS) pressure drop through the loops. The core flow is limited to the flow required to make up for core boiling to remove the decay heat. For postulated cold leg breaks, most ECCS liquid spills directly out of the break location.

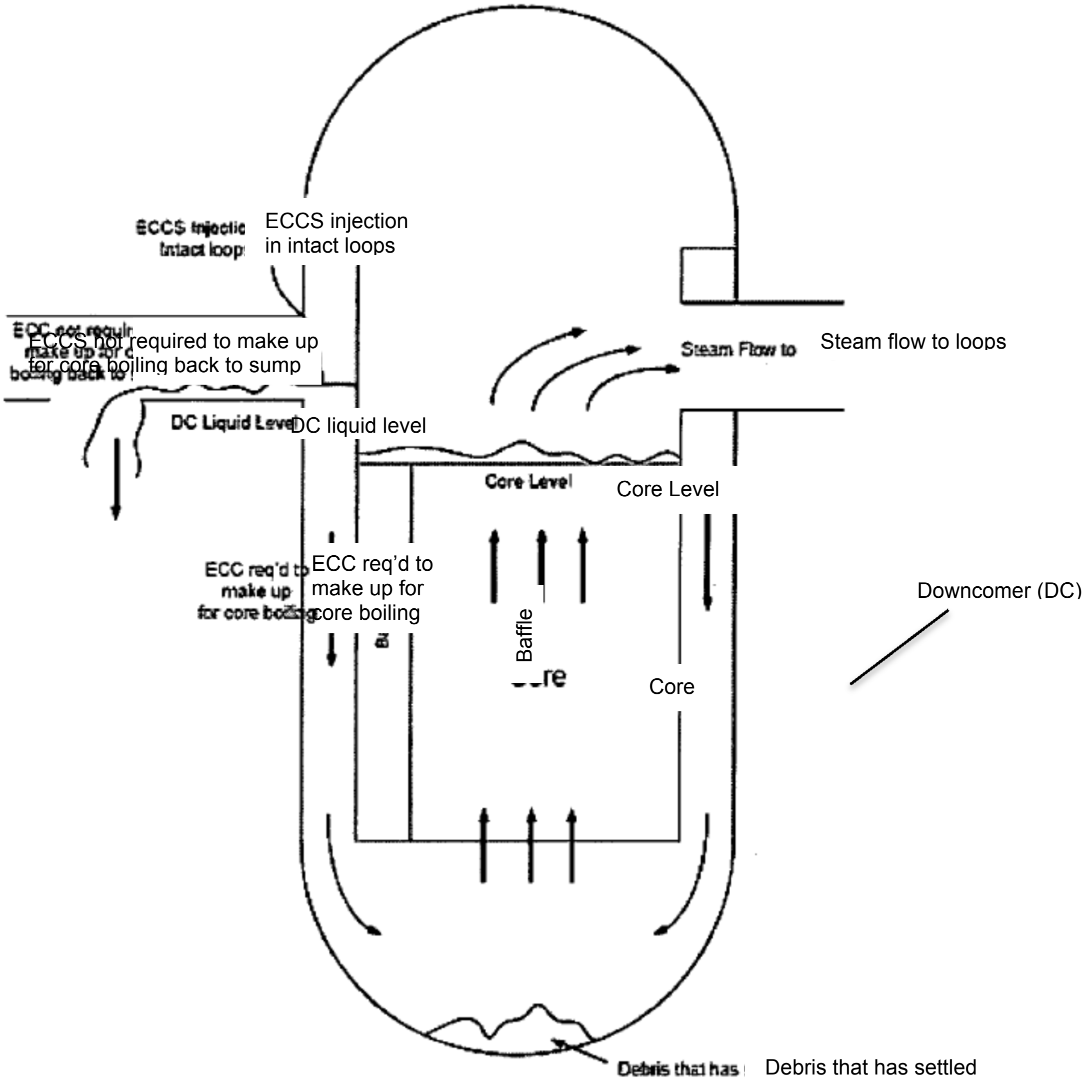

Figure 1: Cold-Leg Break [6]

For a break in the hot leg (Figure 2), the entire ECCS volume must pass through the core to exit the break. The core level will be at least equal to the hot leg nozzle elevation, and the core flow rate will be approximately equal to the ECCS flow rate.

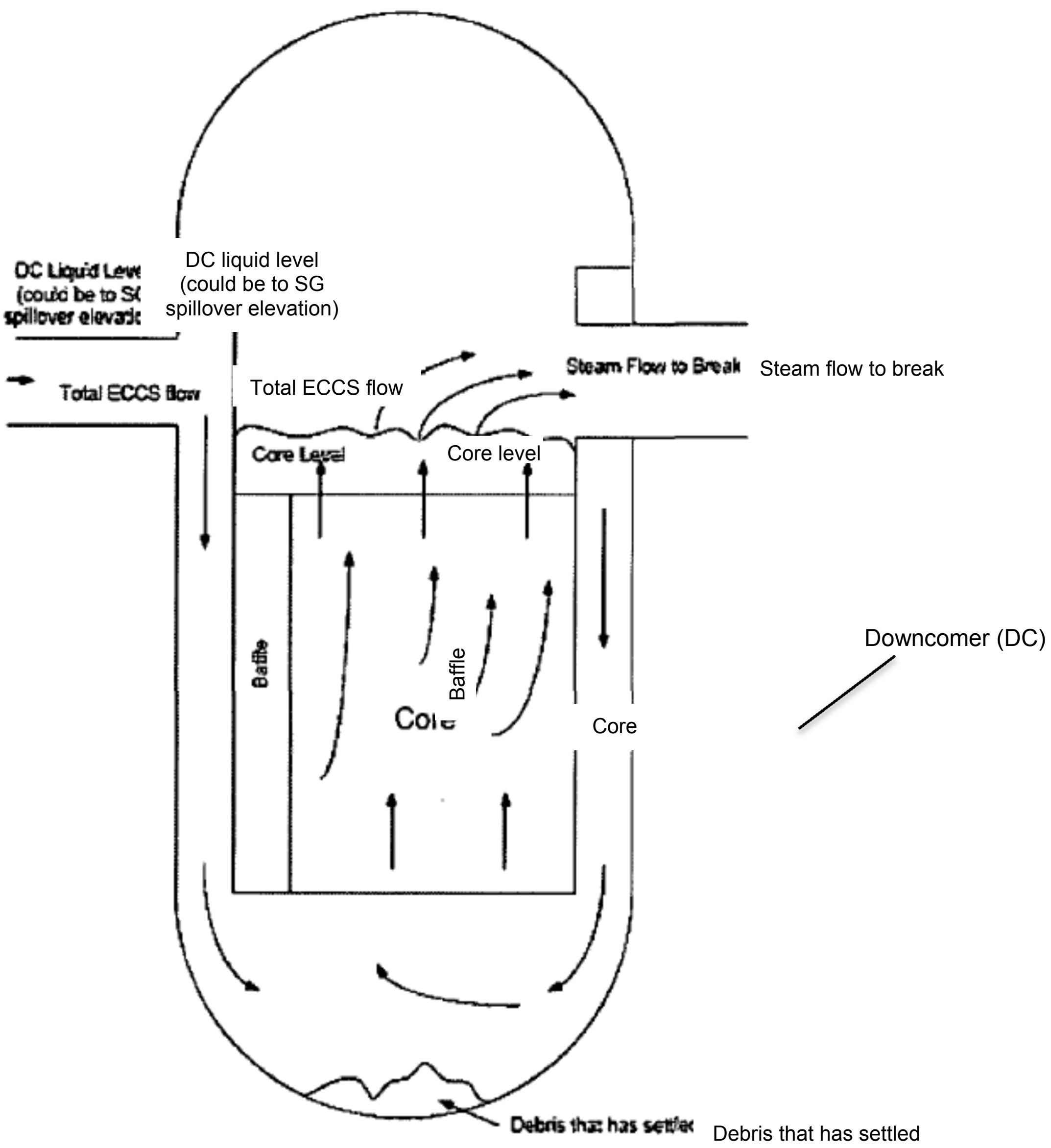

Figure 2: Hot Leg Break [6]

In determining the limiting break with respect to debris buildup the amount of core flow in each type of break is considered. In a hot leg break, all of the ECC injection passes through the core in order to exit out of the break location. For a cold leg break, the only ECC volume that reaches the core is equal to the amount of liquid that has been boiled off of the core. The rest of the ECC volume returns to containment through the break location. Based on this, significantly less debris reaches the reactor vessel lower plenum and core in a cold leg break than in a hot leg break scenario. Therefore, the hot leg break is limiting with respect to debris buildup alone [7].

3. BORIC ACID PRECIPITATION

Boron is present in every PWR in the form of boric acid. Boric acid is used to control reactivity in the reactor. It is present in locations such as the RCS, safety injection tanks, and refueling water storage tank.

Historically, BAP calculations can be used to: (1) determine the appropriate time to switch some of the ECCS sump recirculation flow to the hot leg, (2) show that BAP will not occur, (3) justify boric acid dilution methods. The importance of the accuracy of the calculation to determine the appropriate time to switch some or all of the ECCS sump recirculation flow to hot leg injection is discussed in the next section.

3.1. Thermal-hydraulic Aspects of BAP

During a LOCA, ECC injection enters the reactor vessel containing dissolved boric acid. As boiling occurs in the core, steam exits into the upper plenum leaving boric acid in the reactor vessel. Over time, the concentration of boric acid in the reactor vessel will increase until the solubility limit is reached. Boric acid has the potential to precipitate into a solid formation and collect in the lower regions of the core and possibly into the lower plenum. If BAP were to occur, it could interfere with ECCS injection by blocking the core coolant channels. This could lead to long term core cooling being compromised. In order to assure long term core cooling, operator actions are required as specified at each reactor facility through Emergency Operating Procedures. The specific operator action of concern is the time to switch some of ECCS sump recirculation flow to the hot leg determined by the BAP calculation.

As described in Section 2.2, during a cold leg break, core flow is equal to the boiloff rate. The rest of ECCS injection exits to containment through the break location. Because there is not much core flow in a cold leg break scenario, the boric acid in the coolant remains in the core and does not get flushed out. During a hot leg break, all of the ECCS injection must pass through the core to exit the break preventing any buildup of boric acid in the core. For this reason a cold leg break is the limiting break location with respect to BAP alone.

4. THE COMBINED EFFECTS OF BAP AND DEBRIS ON LONG TERM CORE COOLING

Current post-LOCA boric acid analysis methodologies do not consider the effects of GSI-191 in-vessel debris. These methods assume coolant entering the reactor vessel is free of debris. The analyses do not account for any effects that in-vessel debris may have on the mixing, mass transport, or precipitation phenomena associated with BAP. Both in-vessel debris and BAP should be considered when analyzing post-LOCA situations.

During sump recirculation, the core inlet may become blocked due to the collection of debris on the fuel assembly bottom nozzles and structural spacer grids. This blockage is expected to result in higher resistance to coolant flow at the core inlet, and has the potential to increase the rate at which boric acid builds up in the core leading to much earlier BAPs times than current models calculate. A critical concern is that restricted flow through the lower core plate will reduce mixing with coolant in the lower plenum, and result in an insufficient time for plant operators to realign pumps and prevent BAP. Some extent of mixing with the lower plenum has been credited by most licensees to determine the time required to switch to simultaneous injection in order to preclude precipitation. The precipitation time is used to ensure that operators have adequate time to realign the ECCS to flush concentrated boric acid from the core. As such, it is necessary to determine the extent to which any core blockage by debris interrupts these critical mixing processes between the core and the lower plenum coolant.

5. REGULATORY DECISION MAKING

5.1. Commission Directive through Staff Requirements Memorandum

At the U.S. NRC, the Commission communicates with the NRC staff through a type of letter called a Staff Requirements Memorandum (SRM). In December 2012, the Commission sent SRM-12-0093 [8] to the NRC staff approving the staff's recommendation to allow nuclear power plant licensees the flexibility to choose one of three options to resolve GSI-191. These options were documented in the NRC staff proposal to the Commission in July 2012 [9]. All three options require licensees to demonstrate compliance with 10 CFR 50.46, "Acceptance criteria for ECCSs for light-water nuclear power reactors." The three options are summarized as follows:

Option 1 requires licensees to demonstrate compliance through approved models and test methods. This option is the most clearly defined path for resolution of GSI-191, but could result in extensive plant modifications and occupational dose. Plants that have little debris in containment can use this option relatively easily. There are currently 19 PWRs planning to use Option 1.

Option 2 requires implementation of additional mitigative measures and allows additional time for licensees to resolve issues through further industry testing. This option has an alternative approach to use a risk-informed method to resolve GSI-191. Both deterministic and risk-informed Option 2 methods will reduce the scope of modifications and occupational dose or allow plants to show compliance with greater amounts of problematic materials in the containment. Alternately, some licensees choosing to use this option may have been able to follow Option 1, due to their facilities having relatively low amounts of problematic material, but desire additional margin for their in-vessel debris limits. There are currently 39 PWRs planning to use Option 2.

Option 3 involves separating the regulatory treatment of the sump strainer and in-vessel effects. The ECCS strainers will be evaluated using currently approved models while-in-vessel effects will be addressed using a risk-informed approach. This option is also expected to reduce the scope of modifications and occupational dose. There are currently two PWRs planning to use Option 3.

Plants that have chosen to use Option 1 to resolve GSI-191 are considered to have low amounts of debris in containment available to reach the strainers and potentially block the core. The NRC staff has issued a safety evaluation for review of a licensing topical report that applies to plants that have low amounts if debris [7]. In the safety evaluation the NRC staff notes that "the evaluations conducted in the topical report and the testing did not account for the potential for BAP and that this issue could affect LTCC in some cases. The NRC staff concluded that for a hot-leg-break scenario at a fibrous debris limit of 15 grams per fuel assembly, LTCC would not be challenged because adequate coolant can flow through the core to maintain boric acid concentrations below the saturation limit." For the cold-leg-break or hot-leg break scenarios where the licensee wishes to justify a plant-specific fibrous debris limit boric acid concentration should be considered and may affect LTCC.

It is further stated by the PWRs Owner's Group that "PWRs use boron as a core reactivity control method and are subject to concerns regarding potential post-LOCA BAP in the core. In light of NRC staff and ACRS challenges to the simplified methods commonly used, it has recently become clear that additional insights and new methodologies are needed to answer fundamental questions about boric acid mixing and transport in the RCS and potential precipitation mechanisms that may occur both during the ECCS injection phase and the sump recirculation phase after a LOCA. This will be addressed in a separate PWROG program." [10] It is understood that this work is currently ongoing to determine the combined effects of debris and BAP. Meanwhile, the physical effects of combining debris and BAP are not well understood.

5.2. Too Many Unknowns

The complexity of GSI-191 has made regulatory decision making a challenge. Throughout the numerous years this issue has been part of the Generic Issues program, the required analysis has been expanded to capture concerns that are related to, but in some cases quite different from the original sump-clogging issue [8]. Expanding the issue to include these other concerns has resulted in GSI-191 evaluations having too much uncertainty to allow development of a well-defined evaluation methodology. It has been suggested to remove one variable in order to allow easier resolution of the GSI-191 equation.

An example of a variable that could be removed from the GSI-191 equation is BAP. Consideration has been given to resolve GSI-191 while further BAP testing is being conducted. Once BAP testing is complete, the results can be incorporated into the long-term core cooling evaluation as necessary at that time. Research testing done in the past has resulted in an inconclusive basis for a regulatory decision of this kind. Additional research testing, as well as computational studies are essential tools in making a final regulatory decision regarding the combined effects of BAP and GSI-191.

6. PAST RESEARCH

Various forms of research regarding both BAP and GSI-191 have been conducted in the past. Some of the studies evaluate BAP and others evaluate debris accumulation. Consider these examples a sampling of the research conducted in the past and not an exhaustive list.

6.1. Primary Coolant Test Loop Facility

The Primärkreislauf-Versuchsanlage (PKL-2) test program is investigating safety issues relevant for currently operating PWRs as well as for new PWR design concepts with focus on complex heat transfer mechanisms in the steam generators and boron precipitation processes under postulated accident situations. These issues are being investigated through thermal-hydraulic experiments that will be conducted at the PKL primary coolant test loop facility. One of the eight experiments being conducted as part of this program is related to boron precipitation following a large break LOCA. The results of these experiments are currently not released, but will help to understand boron precipitation following a large break LOCA. Although this research is useful in understanding the risk of boron precipitation in the core or lower plenum, as well as boron mixing, it does not include the effects of debris accumulation.

6.2. Boric Acid Concentrations in a VVER Following a LOCA

A research program was created to define the risk of boron precipitation in the core or lower plenum of a VVER-440 type PWR that would prevent successful core cooling. [11] A facility was built to simulate boron mixing in the lower plenum of the reactor. Experimental results were used to develop a computational model to calculate boric acid concentrations in the reactor following a LOCA. Although this research is useful in understanding the risk of boron precipitation in the core or lower plenum, as well as boron mixing, it does not include the effects of debris accumulation.

6.3. Computational Studies for GSI-191

Computational studies have been conducted to simulate reactor system response during LOCA scenarios under debris-generated core blockage conditions using RELAP5-3D [12]. This study was useful in determining the limiting break sizes and locations under core blockage conditions. Although this research included the effects of a debris-generated core blockage, the effects of boric acid on the model were not simulated.

6.4. Experimental Tests for GSI-191

Industry has done numerous plant-specific tests to support GSI-191. Generic testing to include the effects of debris accumulation on strainers and potentially the core inlet are described in detail in WCAP-16793-NP-A, “Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid” [10]. This testing has created acceptable debris criteria for low fiber plants (Option 1), but does not include the effects of BAP.

7. PRESENT AND FUTURE TESTING AND COMPUTATIONAL STUDIES

There are multiple programs in progress to determine the effect of BAP when in-vessel debris is present at the core inlet. These programs will aid in making a regulatory decision on this issue.

7.1. Industry Testing

The PWR Owner’s Group has done various tests to support closure of GSI-191 [6], [1]. Their GSI-191 program will further include testing to understand the influence of in-vessel debris on boric acid concentration. The objectives of the test are to determine a fibrous limit that does not inhibit mass transport between the core and lower plenum. The mass transport is driven by density gradients that develop due to boron concentration buildup in the core during a cold leg break LOCA.

The test modifies an existing test apparatus constructed for previous GSI-191 testing. The test intends to simulate the post-LOCA density gradient that exists between the core and lower plenum by injecting high density salt solution, which simulates boron buildup in the core post-LOCA. The higher density of the salt solution may have an effect on the debris collection at the core inlet. The test will investigate how this density driven transport mechanism influences the presence of debris at the core inlet and how the debris influences the mixing between the core and lower plenum. Results will be used to help understand the influence of debris and borated solution concentration on lower plenum mixing.

7.2. Research Testing

Experimental tests are planned by the NRC staff through the Office of Nuclear Regulatory Research to identify and establish the impact of core inlet blockage on mixing in the lower plenum and BAP timing. Objectives of the tests include:

a. Providing experimental evidence that boric acid in the core can continue to mix with coolant in the lower plenum for a partially blocked core inlet.

b. Estimating the conditions for which mixing between borated coolant in the core and coolant in the lower plenum becomes limited.

c. Determining the size of the mixing volume in the lower plenum region.

d. Determining if the switch to simultaneous injection successfully flushes the boric acid from the core with core blockage.

e. Providing data suitable for assessment and benchmarking of codes and analytical methods for prediction of boric acid concentration and lower plenum mixing with a blocked core for a range of blockage distributions, fiber thicknesses, and porosities.

The proposed tests are not expected to introduce debris into a test facility. The tests are planned to vary the hydraulic resistance and the distribution of blockage at the core. They will also determine whether borated solution mixes with fluid in the lower plenum and, if so, where the mixing occurs. The experimental results will be used to establish the impact of core inlet blockage on the mixing of boric acid solution within the reactor vessel in order to aid in regulatory decision making for GSI-191.

7.3. Computational Studies

The NRC staff recognizes the limitations of testing relating to boric acid and the introduction of debris at conditions indicative of an operating nuclear power reactor. Introduction of debris or boric acid could have detrimental effects on a test apparatus. Testing at plant conditions such as high pressure and temperature has significant technical challenges as well. While considering these factors, it is desirable to gather the best information possible when determining the combined effects of BAP and GSI-191. In order to do this, the right combination of testing and computational studies is needed. The NRC staff has chosen to explore computational studies to supplement experimental testing.

An analytical study to examine the combined effects of BAP and GSI-191 is currently being conducted using the TRAC/RELAP Advanced Computation Engine (TRACE). TRACE is a best-estimate systems code used for analyzing accident scenarios in light water reactors. TRACE was developed by the NRC and has recently been modified to account for the effects of boron concentration on coolant density and viscosity. Solubility curves for boric acid and sodium pentaborate are available in TRACE to determine if and where boron may precipitate out of solution. The study will simulate a PWR, partially blocked by debris at the core inlet, and determine the variation of boron concentrations throughout the core, vessel and reactor system. Analyses of both hot leg and cold leg large break LOCAs will be performed, with the analysis extended into the period of long term cooling. The analysis will utilize a two dimensional axial and radial mesh in the vessel and will examine transport patterns associated with lower plenum mixing. The results are expected to aid in understanding the transport of boric acid solution with debris present at the core inlet.

A second computational study is being performed using three dimensional computational fluid dynamics. It will investigate the multi-dimensional mixing behavior in a PWR to study BAP in the core following a LOCA. Some cases will simulate a porous layer of fiber between the core and lower plenum to understand mixing of boron into the lower plenum with and without fiber present at the core inlet. The results of this study will assist in understanding the effects of BAP with fiber present at the core inlet using the multi-dimensional mixing behavior in a PWR following a LOCA.

8. CONCLUSIONS

Making a regulatory decision on the combined effects of BAP and GSI-191 is challenging. Testing and computational studies currently being performed, as well as those planned in the future will be useful in making a well-informed regulatory decision. No single piece of research will completely resolve this issue, but together the pieces will make a well-informed regulatory decision possible. The complex history and thermal-hydraulics of both BAP and Generic Safety Issue 191 need to be considered while moving forward with regulatory decisions on this topic.

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REFERENCES

[1] WCAP-16530-NP, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," (2006).

[2] K. J. Howe, L. Mitchell, S.-J. Kim, E. D. Blandford and E. J. Kee, "Corrosion and Solubility in a TSP-Buffered Chemical Environment Following a Loss of Coolant Accident: Part 1 - Aluminum," *Nuclear Engineering and Design,* 2014.

[3] NUREG/CR-7172, "Knowledge Base Report on Emergency Core Cooling Sump Performance in Operating Light Water Reactors," (2014).

[4] GL2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors," (2004).

[5] NUREG/CR-6770, "GSI-191: Thermal-Hydraulic Response of PWR Reactor Coolant System and Containments to Selected Accident Sequences," (2002).

[6] WCAP-17057-NP, "GSI-191 Fuel Assembly Test Report for PWROG," (2009).

[7] WCAP-16793-NP, "Final Safety Evaluation for Pressurized Water Reactor Owners Group Topical Report "Evaluation of Long-Term Cooling Considering Particulate Fibrous and Chemical Debris in the Recirculating Fluid"," (2013).

[8] SRM-12-0093, "Staff Requirements - SECY-12-0093- Closure Options for Generic Safety

Issue - 191, Assesment of Debris Accumulation on Pressurized-Water Reactor Sump Performance," (2012).

[9] SECY-12-0093, "Closure Options for Generic Safety Issue 191, 'Assessment of Debris Accumulation on Pressurized Water Reactor Sump Performance'," (2012).

[10] WCAP-16793-NP-A, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," Rev. 2, (2013).

[11] J. Tuunanen, H. Tuomisto and P. Raussi, "Experimental and Analytical Studies of Boric Acid Concentrations in a VVER-440 Reactor During the Long-term Cooling Period of Loss-of-Coolant Accidents," *Nuclear Engineering and Design,* vol. 148, pp. 217-231, 1994.

[12] R. Vaghetto and Y. A. Hassan, "Study of Debris-Generated Core Blockage Scenarios During Loss of Coolant Accidents Using RELAP-3D," *Nuclear Engineering and Design,* vol. 261, pp. 144-155, 2013.