North Anna Power Station Audit Report
Corrective Actions for Generic Letter 2004-02: Chemical Effects

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) staff performed sample audits of nine licensees' corrective actions for Generic Letter (GL) 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors," dated September 13, 2004. The purpose of the audits was to help verify that licensees have resolved the concerns in GL 2004-02. Audit candidates were selected based on a sampling basis related to reactor type, containment type, strainer vendor, NRC regional office, and sump replacement analytical contractor. North Anna Power Station (NAPS, Dominion, the licensee), was included in these nine audits, and the NRC staff evaluated the new sump design, associated analyses, and testing for NAPS, Unit No. 2, in July 2007. The NAPS audit report is available in the Agencywide Document Access and Management System (ADAMS), Accession No. ML072740400 (Reference 1). Since the licensees' chemical effects evaluations were in progress during the nine earlier audits, the NRC staff was not able to reach a conclusion about the adequacy of chemical effects evaluations for the 69 U.S. operating pressurized-water reactors (PWRs). Therefore, the NRC staff determined that it would be appropriate to perform additional limited scope audits focusing on chemical effects.

In general, the chemical effects audits will consider the chemical effects evaluation guidance document process flow sheet (see Figure 1, ADAMS Accession No. ML080380214, Reference 2) as a useful guide for the audit scope. The NRC staff is interested in the licensee's overall strategy for evaluation and accommodation of chemical effects, including why the licensee thinks chemical effects have been addressed in a representative or conservative manner. Specific topics of interest to the NRC staff include:

- Plant-specific debris mix (non-chemical)
- Plant-specific debris bed formation (non-chemical)
- Plant-specific sump fluid conditions (pH, buffer chemicals, temperature profile)
- Method used to calculate the plant-specific chemical precipitate load
- Supplemental testing (e.g., bench top tests) used as part of the chemical effects evaluation.
- Any assumptions used to reduce the predicted plant-specific precipitate load
- Integrated (with chemical effects) head loss test protocol and any open generic issues related to the vendor's test protocol
- Precipitate generation method for integrated head loss testing
- Settlement of chemical debris during head loss testing
- Integrated head loss test plot(s)
- Test termination and head loss extrapolation, if applicable
- Data analysis

NAPS was selected as one of the plants for a chemical effects audit since it is a representative plant for the chemical effects evaluation approach performed by Atomic Energy of Canada Limited (AECL). The NRC staff and an NRC contractor visited Dominion's Innsbrook facility from November 12-14, 2008, to perform the chemical effects audit. Prior to the on-site portion of the audit, the NRC staff reviewed relevant documents related to chemical effects bench testing and integrated head loss test results for NAPS.

Enclosure

The NRC staff and an NRC contractor also had the benefit of a preceding visit to AECL's Chalk River facility during May 5-9, 2008, to observe integrated chemical effects head loss testing for the Dominion plants, including NAPS. A trip report summarizing observations from the NRC staff's visit to Chalk River is provided in Appendix I (Reference 3) to this audit report.

Table 1 lists key NRC staff, licensee personnel, and contractors, identifying attendance during the November 2008, chemical effects audit meetings at Dominion's Innsbrook facility.

Table 1: NAPS GSI-191 Chemical Effects Audit Participation

Name	Organization	11-12-08 Entrance Meeting	11-14-08 Exit Meeting
Michael Henig	Dominion	X	X
Christopher Burks	Dominion	X	X
David Rhodes	AECL	X	X
David Guzonas	AECL	X	X
Richard Redmond	Dominion	X	X
Mike Sekulic	Dominion	X	X
Addison Hall	Dominion	X	X
Robert Litman	NRC consultant	X	X
Allen Hiser	NRC		X
Paul Klein	NRC	X	X
John Lehning	NRC	X	X
Matthew Yoder	NRC	X	X
Harry Blake	Dominion		X
Bob MacMeccan	Dominion	X	X
Bill Corbin	Dominion	X	X
Thomas Shaub	Dominion	X	X
Eric Hendrixson	Dominion		By phone
Mike Whalen	Dominion		By phone
Megan Sharrow	Dominion		By phone
Thomas Jones	Dominion		X
Martin Legg	Dominion	X	
Mike Rezendes	Dominion	X	
Gary Nayler	Dominion	X	
Allen Price	Dominion	X	
Mark Sartain	Dominion	X	
Delbert Horn	Dominion	X	
Donnie Harrison	NRC		By phone

2.0 OVERALL CHEMICAL EFFECTS APPROACH

The licensee evaluated potential plant-specific chemical effects by considering possible interactions between the materials in containment and the projected post-loss-of cooling accident (LOCA) environment. NAPS Unit Nos. 1 and 2 both control the post-LOCA pH by adding sodium hydroxide (NaOH) to the recirculation spray. A range of post-LOCA pool pH values were calculated using a Monte Carlo analysis methodology (95 percent confidence value) considering the volumes of fluids, concentrations of NaOH, etc. Post-LOCA temperature profiles were determined using the GOTHIC Code.

Given the postulated NAPS plant-specific conditions, the post-LOCA chemical source term was determined using a combination of analysis and experiments. Based on the available test data for aluminum corrosion in alkaline, borated waters, AECL developed an aluminum corrosion relationship as a function of pH and temperature. The total dissolved aluminum in a post-LOCA sump pool at NAPS was calculated using the AECL model. Bench testing was performed in simulated plant-specific post-LOCA sump pool environments at the AECL Chalk River facility. One of the bench testing objectives was to determine the point where aluminum hydroxide would precipitate over a range of parameters of interest for the Dominion plants, including NAPS. Initially, aluminum was added to the bench tests at a high pH value, and the solution was titrated to lower pH until the onset of precipitation. After determining the pH for the onset of precipitation with this technique, longer-term (30-day) follow-on tests were performed with test solutions one pH unit higher to evaluate aluminum solubility for a time period that is more representative of an emergency core cooling system mission time.

The initial goal of the bench test program for NAPS was to show that no precipitation would occur in the projected plant-specific post-LOCA environment. Since the bench test results indicated precipitation could occur, the licensee concluded that additional chemical effects testing was needed. Therefore, Dominion performed integrated chemical effects head loss testing for NAPS at the AECL Chalk River facility. In particular, a multi-loop test facility identified as Rig 89 was fabricated to perform these tests. Design and operation of the Rig 89 test loops are discussed in further detail in Section 3.1, “AECL Test Facilities.”

The NAPS Rig 89 integrated chemical effects tests were performed in a simulated post-LOCA pool environment containing representative amounts of boron and scaled amounts of plant-specific debris. Test loop pH was adjusted to a representative value using NaOH. The test loop temperature was held constant at 104°F (40°C). Plant-specific particulate debris quantities and the quantity of fiber needed to develop a thin bed were added in increments to the test loop. After a stable baseline head loss was established across the test strainer section, sodium aluminate was added in small batches with the objective of having the dissolved aluminum concentration in the Rig 89 test loop equal the predicted plant-specific calculated dissolved aluminum concentration. Since the Rig 89 loop aluminum addition is scaled according to the post-LOCA pool concentration (instead of scaling the aluminum precipitate mass to the strainer area), precipitation of an aluminum compound during the test could result in a non-conservative dissolved aluminum concentration in the test loop. Therefore, if dissolved aluminum measurements indicate precipitation of an aluminum-containing compound occurred during the test, more sodium aluminate is added to the test loop, up to an amount that would represent the maximum amount of aluminum precipitate mass per strainer area for the plant.

The total head loss measured in the Rig 89 test loop represents the plant-specific, integrated head loss across the sump strainer for plant debris and chemical effects.

3.0 INTEGRATED HEAD LOSS

As part of the chemical effects audit for NAPS, the NRC staff performed a review of the non-chemical portion of the debris bed head loss testing methodology and results. The head loss from the non-chemical debris is pertinent to the chemical effects audit because the filtration and accumulation of precipitate in the debris bed, and hence the resultant overall head loss impact attributed to chemical effects, depends upon the formation of a prototypical non-chemical debris bed.

An NRC staff review of the head loss testing conducted for NAPS prior to the NRC staff's audit for GL 2004-02 corrective actions in July 2007, was documented in the NRC staff's audit report (Reference 1). Considering this earlier review, the NRC staff's head loss review for the chemical effects audit focused primarily upon systematic differences that had been observed for similar non-chemical debris loadings in two different AECL head loss test rigs used for testing Dominion PWRs. These systematic differences in head loss were first identified during the NRC staff's trip to observe chemical effects head loss testing at AECL in May 2008 (Reference 3), see Appendix I.

3.1 AECL TEST FACILITIES

Head loss tests for NAPS were performed by AECL in two different head loss test rigs. The earlier tests for NAPS were performed in the reduced-scale tank (Rig 33, see Figure 1), and did not include chemical precipitates. The final tests for NAPS were performed in the multi-loop test facility (Rig 89, see Figure 2), and were longer-term tests that included the modeling of chemical precipitation and the measurement of the head loss impact of the precipitates that accumulated in the debris bed.

Figure 1: Reduced-Scale Test Tank (Rig 33)

Figure 2: Multi-Loop Test Rig 89 (1 of 6 Loops)

The reduced-scale test tank is a cylindrical tank approximately 7.5 ft. in diameter and 5 ft. high. The test fluid was service water supplied by the Ottawa River that had been filtered and chlorinated by AECL. The test fluid was maintained at a temperature of 104°F (40°C). Debris was typically added to the tank from buckets near a mechanical stirrer used to discourage debris settling. Debris settling was further discouraged through the positioning of the pump discharge line, which induced turbulence along the tank floor. Baffles were positioned around the strainer to prevent the induced turbulence from disrupting the formation of a uniform debris bed.

In early 2008, the multi-loop test rig was constructed so that head loss testing for several Dominion PWRs (NAPS Unit Nos. 1 and 2, Surry Power Station, Unit Nos. 1 and 2, and Millstone Power Station, Units 2 and 3) could be performed in parallel. Each of the six loops of the multi-loop test rig consists primarily of a 16-inch by 16-inch by 36-inch box housing the test strainer, a 12-inch-diameter by 18-inch-long cylindrical debris addition tank, a pump, and associated piping, components, and instrumentation. The test fluid was deionized water maintained at 104 °F. Debris was added to the debris addition tank, where it was stirred with a mechanical stirrer until a valve was opened that would allow the debris to transport down to the box housing the test strainer. Prior to adding chemical precipitates to the multi-loop test rigs, the non-chemical debris bed head losses were allowed to stabilize.

A comparison of selected parameters for the two test rigs is provided in the table below. Note that the reduced-scale tank test protocol underwent revisions during the course of the NAPS testing, and that the table below is intended to reflect the revised procedure used for the (non-chemical) design case tests.

Table 2: Comparison of Selected Test Rig Parameters

Parameter	Reduced-Scale Tank (Rig 33)	Multi-Loop Rig (Rig 89)
Test Fluid	Filtered and chlorinated water from Ottawa River	Deionized water
Test Fluid Volume (L)	5000	230
Temperature (°F)	104	104
pH	Not controlled	7.0
Test Strainer Area (ft^2)		
RS[1] Strainer	9.4	5.74
LHSI[2] Strainer	16.9	5.74

[1] Recirculation spray
[2] Low-head safety injection

3.2 SAFETY SYSTEMS DRAWING SUCTION FROM CONTAINMENT SUMP

NAPS, Unit Nos. 1 and 2 are both Westinghouse 3-loop PWRs with subatmospheric containment designs. During the recirculation phase of a design-basis accident, low-head safety injection (LHSI) pumps and recirculation spray (RS) pumps draw suction from the containment recirculation sump. The RS system provides long-term containment heat removal by passing sump water through a heat exchanger and then spraying it into the containment atmosphere. The NRC staff recently approved a license amendment to change the start signal for the RS pumps to the coincidence of signals for high-high containment pressure and a wide-range refueling water storage tank (RWST) level of 60 percent. The LHSI pumps provide low-pressure, high-flow-rate cooling to the reactor core and are aligned to the containment sump when the RWST reaches its low-low level setpoint.

At NAPS, each unit has a single recirculation sump that provides the common suction for the LHSI pumps and the RS pumps of both trains. A photograph showing a section of the AECL Finned Strainers™ installed at NAPS is provided below as Figure 3. In the photograph, the upper fins of the strainer belong to the LHSI system and the lower fins belong to the RS system. Separate strainers are provided for the RS and LHSI systems because the RS pumps begin drawing water from the containment sump significantly earlier than the LHSI pumps. This design allows the RS pumps to take suction through strainer fins that are fully submerged for the reduced water level conditions at the time the RS pumps are actuated, while also allowing the upper strainer fins used by the LHSI pumps to take advantage of the increased water level available at the time their suction is switched to the sump.

Figure 3: A Section of North Anna's Containment Sump Strainers

3.3 OBSERVED SYSTEMATIC NON-CHEMICAL HEAD LOSS DIFFERENCES

As mentioned above, systematic differences in non-chemical debris bed head loss were observed between tests conducted for NAPS in the reduced-scale tank rig and the multi-loop test rig. The strainer design case head loss results for similar debris loadings in the reduced-scale tank and the multi-loop rig (prior to the introduction of chemical precipitates) are shown in the table below.

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Table 3: Comparison of Head Loss Test Results at 104 °F (Reference 4)

Strainer	Reduced-Scale Tank Head Loss (ft)	Multi-Loop Rig Head Loss (ft)	Ratio (Multi-Loop / Reduced-Scale)
RS	4.8 3.2	0.69	0.14 0.22
LHSI	3.2 3.0	1.7	0.53 0.57

The LHSI measured head loss in the single multi-loop rig test was slightly more than half of the measured head loss values for the two tests conducted in the reduced-scale tank. The discrepancy was even more significant for the RS strainers, for which the head loss measured in the multi-loop rig test was only 14 - 22 percent of the value measured in the reduced-scale tank tests.

As noted in Appendix I, similar systematic differences in non-chemical debris bed head loss were also observed for other Dominion PWRs, for which a similar series of tests had been conducted. These other plants' head loss results were beyond the scope of the NAPS chemical effects audit, and the NRC staff's conclusions in this report are not intended to be applied to these plants directly. However, due to the similarity of the strainer testing methodologies, some results for other Dominion PWRs were reviewed as part of this audit in order to gain insights into the evaluation of the NAPS head loss testing results.

The licensee presented several possible reasons to explain the systematic differences in measured debris bed head loss between the reduced-scale tank and multi-loop test rig for the Dominion PWRs. The possible reasons included the following:

- The potential for filtration of fine particulate from the Ottawa River suspended in the service water used as the test fluid in the reduced-scale tank.
- The potential for biological growth in the debris bed due to organisms from the Ottawa River suspended in the service water used for the reduced-scale tests.
- The potential for excessive deaeration across the debris bed due to the inability to model prototypically the full strainer submergence for some plant configurations in the reduced-scale tank.

These reasons are discussed in further detail below as pertaining to the observed differences in the head loss tests conducted for NAPS.

3.3.1 Ottawa River Particulate

AECL observed that, even after being filtered, the service water taken from the Ottawa River that was used for the reduced-scale tank tests contained fine suspended particulate. The licensee hypothesized that this suspended particulate was filtered out in the debris beds formed in the reduced-scale tank, resulting in a significant head loss impact that was not prototypical of the plant condition. The multi-loop test rig used deionized water as the test fluid to minimize the potential influence of suspended impurities on the test results.

The service water used for the reduced-scale tests for NAPS had been successively filtered through 200-μm and 10-μm filter bags prior to the initiation of the test. After being filtered, measurements of the remaining suspended particulate were made and compared to similar measurements made for the multi-loop rig tests. An example of the total suspended solids (TSS) measurements for tests conducted for the RS strainers is shown below in Table 4.

Table 4: Example of Total Suspended Solids Measurements (Reference 4)

Test Rig	TSS (mg/L)	
	Standard (1.5-μm filter)	Fine (0.1-μm filter)
Reduced-Scale Tank	3	5
	2	6
Multi-Loop Test Rig	< 0.2	2
	< 0.2	2

From the quantities of fine particulate measured to be present in the test fluid, the licensee calculated the total mass of the fine particulate and a particle number based upon the assumption of a 0.2-μm particle size (Reference 3). Based on this assumption, the licensee stated that the number of silt particles from the Ottawa River was several orders of magnitude larger than the number of walnut shell particles added to the test to simulate failed coating and other sources of particulate debris. The licensee further compared the impact of the fine river particulate to that from Microtherm insulation debris, which was added to one of the early head loss tests for NAPS and resulted in a rapid head loss increase (the licensee subsequently replaced the Microtherm in question with a different insulation, Reference 1).

After reviewing the licensee's analysis of the Ottawa River silt that is summarized above, the NRC staff concluded that the presence of this fine particulate did not provide an adequate basis to explain the discrepancy between the head loss results in the reduced-scale tank and multi-loop test rig. In particular, many assumptions made in the licensee's calculations appeared to significantly overestimate the impact of the river water particulate. The primary factors leading to the NRC staff's conclusion are as follows:

- The licensee had not performed head loss testing to directly examine the effect of the river particulate in the absence of other variables. Without such testing, the influence of river particulate could not be reliably estimated. Also, in the analytical calculation of the significance of the river particulate, the licensee had not validated many important assumptions that had substantial uncertainty associated with them, the most significant of which are elaborated upon below.

- The licensee assumed that the river particulate was uniformly 0.2 μm in diameter. In actuality, the NRC staff expected that much of the fine particulate would be distributed more evenly in an approximate range of 0.1 - 1.5 μm. Images AECL took of several samples of river particulate that had been analyzed with a scanning electron microscope confirmed the NRC staff's expectation; however, this information had not been considered in the estimation of the significance of the river particulate. Assuming complete or essentially complete filtration (as the licensee did), head loss correlations would predict that a more even particulate size distribution with a larger average size would lead to a reduced impact on head loss compared to the licensee's assumptions.

- The licensee assumed that debris beds would be capable of effectively filtering 0.2-μm particulate. The NRC staff expected that much of the 0.2-μm particulate would actually be capable of repeatedly passing through the pores in the debris beds. Had the debris beds formed by AECL been capable of effectively filtering 0.2-μm particulate, the NRC staff expected that the measured debris bed head losses would have been significantly in excess of the values shown in Table 3.

- The mass of Microtherm added to the early test where the significant head loss increase occurred was approximately 2.4 lbm; whereas, the mass of river particulate present in the reduced-scale test tank typically ranged from approximately 0.06–0.08 lbm. Due to the substantial difference in mass, the NRC staff considered it very unlikely that the river particulate could have a similar effect to that observed for Microtherm. Furthermore, the NRC staff noted that microporous insulations such as Microtherm have been shown to be more effective at increasing debris bed head loss than equal masses of other typical particulate sources.

- The licensee stated that, with an assumed particulate size of 0.2 μm, the quantity of silt particles was 3 to 4 orders of magnitude greater than the number of 10-μm walnut shell flour particles added to the NAPS tests. The NRC staff noted again that, on a mass basis, the river particulate was essentially negligible (0.06–0.08 lbm), whereas the walnut shell flour masses ranged from approximately 1.3–8.8 lbm. Although the number of particles was computed to be greater for the river silt (based on the licensee's assumptions evaluated above), the NRC staff noted that the number of 0.2-μm pores in the debris bed may exceed the number of 10-μm pores by a similar factor or more. The NRC staff considered it very unlikely that the minute quantity of river silt suspended in the test fluid had a significant effect on the final head loss relative to the walnut shell flour.

3.3.2 Biological Fouling

The head loss tests performed by AECL in the reduced-scale tank typically lasted several days to a week. The licensee attributed part of the long-term head loss increase experienced in these reduced-scale tests to the growth of organisms in the debris bed which slowly reduced the bed porosity and hence resulted in a gradual increase in measured head loss. The origin of the biological organisms was thought to be the service water from the Ottawa River, and the licensee considered the biological fouling phenomenon to be closely associated with the river silt discussed above. The licensee considered this biological growth to be non-prototypical of the plant and, in the multi-loop test rig used deionized water as the test fluid and disinfected the debris used for bed formation to preclude the potential influence of biological growth on these tests.

In order to mitigate the potential head loss impact due to biological growth in the reduced-scale tank tests, the licensee added bleach to the test tank to achieve an initial chlorine concentration over 10 ppm during the heating and filtering of the test fluid prior to the start of testing. However, most debris bed samples taken following the completion of head loss testing still showed evidence of some biological growth. Based on a comparison to shorter strainer pass-through tests that had lasted roughly 6 - 8 hours and did not show evidence of biological growth, the licensee suspected that the biological growth had predominately occurred after the chlorination had lost its potency (e.g., after 24 hours).

After reviewing the licensee's analysis of biological fouling that is summarized above, the NRC staff concluded that the growth of biological organisms in the debris bed did not provide an adequate basis to explain the discrepancy between the head loss results in the reduced-scale tank and multi-loop test rig. The primary factors leading to the NRC staff's conclusion are as follows:

- The licensee had not performed head loss testing to directly examine the effect of biological fouling in the absence of other variables. Without such testing, the influence of biological fouling could not be reliably established.

- The NRC staff's examination of the licensee's head loss versus time traces for the reduced-scale testing showed that the most significant part of the head loss increases appeared to be fairly rapid, as opposed to the gradual increases that would be expected from biological fouling. In other cases, gradual increases appeared more consistent with the filtration of particulate from the test fluid following the addition of debris to the test rig, with a leveling of the head loss as the filtration process was completed. The NRC staff could not conclude that the head loss versus time traces indicated a significant impact from biological fouling.

- No metric had been developed to determine what quantity of biological fouling was necessary to contribute significantly to the measured strainer head loss.

- After being filtered and chlorinated, it was unclear that the service water used for the AECL reduced-scale tests was fundamentally different than the tap water used for head loss testing by other strainer vendors. The NRC staff considered it possible that a similar degree of biological growth to that experienced at AECL may occur in other test vendor's debris beds during long-term tests, but without being considered a significant contributor to the measured head loss.

3.3.3 Deaeration Across the Debris Bed

The submergence of the test strainer in the reduced-scale tank was not modeled prototypically for all head loss tests conducted for the Dominion plants. As a result, the licensee noted that the effect of deaeration resulting from the test fluid undergoing a pressure drop at the debris bed would be more severe for the test condition than for the plant condition. In addition, the containment pressure credited in NAPS's net positive suction head (NPSH) margin analysis would also reduce the potential for deaeration to occur for the plant condition.

Two effects of deaeration in the reduced-scale tank tests were noted by the licensee during the audit: (1) deaeration as the test fluid passes through the debris bed that increases the differential pressure due to the two-phase flow through the debris bed porous medium and (2) the accumulation of air in the fins of the test strainer that creates an imbalance in the static head of water across the strainer, thereby increasing the differential pressure across the strainer. The licensee performed air accumulation calculations for a number of reduced-scale tests and concluded that the effect of air accumulation for the NAPS tests was minor (e.g., 25-30 percent). However, for several tests conducted in the reduced-scale tank for other Dominion PWRs, air was considered to have had a significant impact, and the presence of air downstream of the strainer was observable through a transparent section of piping.

After reviewing the licensee's analysis of deaeration that is summarized above, the NRC staff agreed with the licensee's assessment that the effect of air accumulation on the NAPS tests was likely minor, and potentially somewhat less than predicted by the licensee. The primary factors leading to the NRC staff's conclusion are as follows:

- Although conservative means exist for determining the deaeration the test fluid would experience after undergoing a pressure drop across the debris bed (e.g., Henry's Law), the dynamics of air accumulation inside a strainer volume is not considered amenable to accurate prediction. The licensee stated that calculations indicated that air bubbles larger than a critical size (e.g., on the order of tenths of millimeters, but which ultimately depends on the orientation of the strainer fins) would move to the tops of the strainer fin channels, whereas smaller bubbles would be entrained in the flow toward the pump. Some of the calculations performed by the licensee estimated significant voiding in the strainer fins, to the point of assuming almost the entire fin was filled with air. Yet without being able to evaluate such complex effects as the dynamics of bubble coalescence, the rates at which air bubbles would enter and leave air pockets as a function of the size of the pockets, and the impact of the strainer and suction line geometry on the transport and accumulation of air, the quantity of air that accumulates in the strainer fins cannot be reliably calculated. As a result, the NRC staff could not determine that the licensee's estimates of the differential pressure effect due to the accumulation of air inside the strainer were reliable. Furthermore, the licensee had not adequately demonstrated that air would not fill the fins of the strainer under plant conditions in a manner similar to that for the test strainer.

- Regarding the effect of deaeration increasing the differential pressure from the flow through the debris bed porous medium, the NRC staff expected that this phenomenon would not be significant until a certain head loss threshold (related to the submergence of the test strainer) was exceeded. However, some reduced-scale test results displayed potential symptoms of air effects only at relatively large head losses (e.g., 8 - 10 feet), whereas other tests displayed fairly similar symptoms at head losses that were less than the strainer submergence. Based on the interactions during the audit concerning these results, the licensee did not appear to have identified a threshold for air effects that could consistently explain the range of behaviors observed in the head loss test results.

- In addition, as described in Appendix I, the NRC staff performed confirmatory deaeration calculations for several cases for different Dominion PWRs using the deaeration model in the NUREG/CR-6224 Correlation Software Package (Reference 3). These calculations suggested that the void fraction downstream of the strainer for the test conditions in the reduced-scale tank typically should not have been excessive, particularly for conditions applicable to NAPS.

3.4 ADDITIONAL AUDIT ISSUES

The licensee assumed that the non-chemical debris loading for the LHSI strainers at NAPS would be 50 percent of the RS strainers' loading. The NRC staff reviewed the report from the July 2007, audit of NAPS and determined that this debris loading was accepted by the NRC staff at that time based upon information from the licensee that the maximum flow percentage through the LHSI strainers assuming at least two RS pumps in operation would be 46 percent (Reference 1). During the November 2008, chemical effects audit of NAPS, the licensee showed the NRC staff reviewer a copy of the plant procedures that directed that at least two RS pumps remain in operation post-LOCA to support the debris-distribution assumptions made in the sump performance analysis.

However, based upon calculations received by the NRC staff during the chemical effects audit, the NRC staff observed that the LHSI strainer could draw up to 62 percent of the total recirculation flow (and debris), even with two RS pumps operating, rather than the maximum of 46 percent that had been assumed by the licensee in July 2007. Because this issue was not directly related to chemical effects and the time available to discuss issues with the licensee during the onsite portion of the audit was limited, the NRC staff deferred this question to the RAI process on the GL 2004-02 supplemental responses.

3.5 CHEMICAL EFFECTS HEAD LOSS TEST RESULTS

Once the non-chemical debris beds in the multi-loop test rig had reached a suitably stable head loss value, AECL proceeded to introduce chemical debris in batches over an extended period of time. The total duration of the multi-loop rig tests was roughly three months. The results of the multi-loop rig tests for the NAPS RS and LHSI strainers are provided in the table below. The first value provides the stabilized head loss for the non-chemical debris, and the second value provides the final head loss measured after the completion of the chemical effects portion of the testing.

Table 5: Multi-Loop Test Rig Results for NAPS at 104 °F

System	Non-Chemical Debris Bed Head Loss (ft)	Final Head Loss (ft)
RS	0.69	6.0
LHSI	1.7	6.7

Based on the Rig 89 test results, the licensee recognized that reducing the aluminum inventory in containment would be necessary to ensure the conservatism of the limiting aluminum concentration assumed for the post-LOCA sump pool. Therefore, aluminum ladders were removed from the NAPS containment. Since aluminum is an important contributor to chemical effects at NAPS, the NRC staff was interested in comparing the predicted plant-specific aluminum release between the AECL method and the WCAP-16530-NP spreadsheet. The licensee provided a comparison of aluminum release for the two different methods as a function of pH. For a pH of 8.5, which was used to calculate the NAPS aluminum release, the AECL method predicted a slightly higher aluminum release than the WCAP method.

3.6 ANALYTICAL CONSERVATISMS

Taking into account the considerations discussed above, the NRC staff did not agree that the licensee had developed a sufficient technical basis to fully address the observed differences in the non-chemical debris bed head loss results for similar debris loadings added to the reduced-scale tank and the multi-loop test rig. Therefore, the NRC staff suggested that the licensee document significant conservatisms that were incorporated into the strainer performance analysis that could potentially mitigate the uncertainties associated with the differences in the measured head losses between the two test rigs.

Near the end of the onsite audit, the licensee provided the NRC staff a five-page list of conservatisms that were incorporated in the sump performance analysis. The conservatisms covered a range of different aspects of the strainer performance analysis, including the following:

- Debris generation
- Debris transport
- Latent debris
- Chemical effects
- Downstream effects
- Head loss testing
- Pump net positive suction head

After reviewing the list of conservatisms, the NRC staff concluded that the licensee had incorporated significant conservatism in many areas of the sump strainer performance analysis. Some of the conservatisms that the NRC staff considered to be particularly significant included the following:

- Conservative zones of influence from Nuclear Energy Institute 2004-07, "Pressurized -Water Reactor Sump Performance Evaluation Method," were used to estimate debris generation.
- Full transport was assumed for miscellaneous debris materials, which resulted in a sacrificial strainer area of 150 ft^2.
- Conservative debris transport fractions were assumed for all debris types, with 100 percent transport assumed for most debris types.
- All failed coatings were assumed to be in the form of fine particulate debris.
- The head loss testing protocol prepared the fibrous debris into a relatively fine size distribution, whereas the plant debris distribution also included small and large debris pieces.
- Conservative debris sequencing was used for the thin bed tests.
- The calculated post-LOCA pool equilibrium pH for NAPS is 8. Plant specific aluminum release was calculated at a pH of 8.5, and the Rig 89 multi-loop rig tests were performed at a pH of 7. These values provide for a conservative amount of aluminum release and a conservative amount of aluminum precipitation in the test loop relative to that projected for the plant-specific environment.
- The licensee has added margin into their calculations for plant-specific aluminum.
- No credit was taken for long-term subcooling of the sump fluid in the calculation of pump NPSH.

The NRC staff's review of the licensee's list of conservatisms resulted in increased confidence that the uncertainties associated with the differences in reduced-scale tank and multi-loop test rig head loss results were bounded. However, due to the difficulty in quantifying the conservatism inherent in these assumptions, the NRC staff initially considered the difference in the head loss results between the two test rigs to be a draft open item at the conclusion of the onsite audit.

To address this draft open item, the licensee provided additional information to the NRC staff directly following the onsite portion of the chemical effects audit to quantify the long-term increase in NPSH margin resulting from the decreasing temperature of the sump fluid as a design-basis LOCA progresses. The additional information is summarized in the table below.

Table 6: Short-Term and Long-Term NPSH Margin Values at 104 °F

System	Short-Term Debris Bed Head Loss Acceptance Criterion (ft)	Long-Term NPSH Margin to Offset Debris Bed Head Loss (ft)
RS	6.3	> 25
LHSI	7.5	12.5

The short-term debris bed head loss acceptance criterion bounds the non-chemical debris head loss results for both the reduced-scale tank and the multi-loop test rig (see Table 3). The short-term acceptance criterion similarly bounds the multi-loop rig final results with chemical effects, although the NRC staff considers the final multi-loop test rig results to be affected by uncertainties associated with the formation of the non-chemical debris beds. The additional long-term NPSH margin for the RS and LHSI pumps shown in Table 6, however, provides confidence that uncertainties associated with debris bed formation and the subsequent impact of chemical precipitates are bounded by the available margins. Based on information provided by the licensee, the long-term margins shown above would be present soon after the switchover to sump recirculation (e.g., within 2 or 3 hours). Based on the existing knowledge developed from chemical effects testing, aluminum-containing precipitates are not expected to occur immediately after a LOCA, since there is a time dependency associated with aluminum corrosion in the post-LOCA environment, and the elevated pool temperatures immediately following a LOCA favor the aluminum remaining in solution rather than immediately forming a precipitate. As a result, by the time the peak chemical effects head loss occurs, the NRC staff expects that the additional long-term margin will be available to ensure functionality of the RS and LHSI pumps. Furthermore, test data generated at the Argonne National Laboratory (Reference 5) indicates that, for a constant aluminum concentration, the NAPS multi-loop tests performed at a pH of 7 would be expected to have significantly more aluminum hydroxide precipitate compared to a test pH of 8 that would be more representative of the projected post-LOCA pool pH.

Therefore, based on the discussion above, the NRC staff determined that the uncertainties associated with debris bed formation in the multi-loop test rig, which may have affected the final debris bed head losses with chemical precipitates, were adequately addressed by the conservatisms associated with additional NPSH margin gained in a relatively short time after the initiation of containment sump recirculation, as well as the other conservatisms in the licensee's sump performance analysis that were reviewed by the NRC staff.

3.7 HEAD LOSS SUMMARY

The licensee concluded that the influences of river particulate, biological fouling, and deaeration were sufficient to explain the increased head loss of the reduced-scale tests relative to the multi-loop rig tests prior to the addition of chemicals. The licensee further concluded that, because these phenomena were not expected to be present in the plant containment pool, the multi-loop rig tests were more representative of the plant condition than the reduced-scale tank test.

Based upon the discussion above, the NRC staff does not concur with the licensee's conclusions. A definitive cause of the head loss difference between the two head loss rigs could not be identified during the chemical effects audit or the NRC staff's earlier trip to Chalk River to observe head loss testing in May 2008. The NRC staff expected, however, that a significant part of the systematic difference in head loss could be attributed to differences in the debris preparation, addition, transport, and accumulation on the test strainers in the two test rigs. These differences are described further in Appendix I (Reference 3). The NRC staff considered the debris preparation, addition, and accumulation for the reduced-scale tank to be more prototypical of the plant condition than the multi-loop rig. Although the NRC staff did recognize that the influences of river particulate, biological fouling, and deaeration likely affected the measured head losses in the reduced scale test tank, based on the information provided by the licensee, the NRC staff did not conclude that they were of primary importance for the NAPS test conditions.

4.0 CONCLUSIONS

After considering the significant conservatisms incorporated into the licensee's sump performance analysis, the NRC staff concludes that the uncertainties associated with the formation of debris beds in the multi-loop test rig are bounded. As a result, the draft open item discussed with the licensee during the onsite portion of the chemical effects audit is resolved, and the NRC staff's chemical effects audit of NAPS is complete with no open items or requests for additional information.

5.0 REFERENCES

1. U.S. NRC Audit Report, "North Anna Power Station Corrective Actions for Generic Letter 2004-02," November 15, 2007, ADAMS Accession No. ML072740400.

2. "U.S. NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Plant-Specific Chemical Effect Evaluations," March 2008, ADAMS Accession No. ML080380214.

3. U.S. NRC, Appendix I (Attached), "Report of the NRC Staff's Visit to Chalk River, Canada, to Observe Integrated Chemical Effects Head Loss Testing Performed for Pressurized-Water Reactors Operated by Dominion."

4. AECL, "Discussion of the Results of Head Loss Tests Conducted in Rigs 89 and 33, GnP-34325-AR-001, Revision 0, October 2008.

5. Argonne National Laboratory Technical Letter Report on Evaluation of Long-Term Aluminum Solubility in Borated Water, ADAMS Accession Number ML081550540.

APPENDIX I

REPORT OF THE NUCLEAR REGULATORY COMMISSION STAFF'S VISIT TO CHALK RIVER, CANADA, TO OBSERVE INTEGRATED CHEMICAL EFFECTS HEAD LOSS TESTING PERFORMED FOR PRESSURIZED-WATER REACTORS OPERATED BY DOMINION

Travel Dates: May 5 - 9, 2008

Travelers: John Lehning, Reactor Systems Engineer, NRC/DSS/SSIB
Paul Klein, Senior Materials Engineer, NRC/DCI/CSGB
Robert Litman, NRC Contractor

Location: Chalk River Laboratories
Chalk River, Ontario
Canada

Organizations: Dominion Energy (Dominion)
Atomic Energy of Canada, Limited (AECL)

Sensitivity: Non-Sensitive

Background/Purpose

In response to Generic Letter 2004-02 (GL 2004-02), "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized- Water Reactors," pressurized-water reactor (PWR) licensees are evaluating the performance of their containment recirculation sumps and making any plant modifications necessary to achieve regulatory compliance according to approved mechanistic sump performance criteria.

Atomic Energy of Canada, Limited (AECL), is one of five vendors supplying replacement sump strainers to U.S. PWRs in support of their GL 2004-02 resolution activities. In the U.S. market, AECL supplied replacement sump strainers to 7 PWR units, including Millstone Power Station, Units 2 and 3 (Millstone), Surry Power Station, Unit Nos. 1 and 2 (Surry), and North Anna Power Station, Unit Nos. 1 and 2 (NAPS), which are all operated by Dominion. AECL also supplied replacement sump strainers to Virgil C. Summer Nuclear Station, which is operated by South Carolina Electric and Gas. AECL became involved with sump strainer performance issues in the mid-1990s and has since completed the design and testing of sump strainers for reactors located in Canada and abroad.

Prior to the NRC staff's May 2008, trip to Chalk River, the NRC staff understood that AECL had already completed non-chemical testing for its client PWR licensees in the United States. However, the chemical effects testing protocol had not been developed by the time of the NRC staff's previous trip to observe head loss testing at Chalk River in June 2006, or by the time of the NRC staff's audit of NAPS Power Station corrective actions for GL 2004-02 in July 2007.

In late 2007 and early 2008, the NRC staff held several discussions with Dominion and AECL concerning their plan for completing chemical effects testing. The NRC staff's primary objective was to ensure that technically adequate testing would be completed by Dominion on a schedule commensurate with the overall plan for completion of the GL 2004-02 review activities. To ensure that the chemical effects testing would be completed in a timely manner, Dominion and AECL constructed a new multi-loop test rig that would allow chemical effects head loss testing for its PWRs to be performed in parallel and developed procedures for performing tests in this new rig. Dominion invited the NRC staff to observe this testing.

The chemical effects testing protocol developed by AECL that was used for the Dominion test program was different than the approaches ultimately used by many other test vendors, which were typically based on the WCAP-16530-NP methodology. Therefore, the purpose of the NRC staff's trip to Chalk River in May 2008 was to observe chemical effects head loss testing in the recently constructed multi-loop test rig and to discuss the bench-top testing results used to justify the chemical effects head loss testing procedure.

Desired Outcome

The NRC staff's trip was intended to support the NRC staff's resolution of issues associated with Generic Safety Issue 191 (GSI-191), "Assessment of Debris Accumulation on PWR Sump Performance," for several PWRs operated by Dominion. In particular, the NRC staff's observations of Dominion's chemical effects head loss testing at the AECL test facilities support evaluations of the licensee's supplemental responses to GL 2004-02 in the areas of strainer head loss and chemical effects. The trip benefits the resolution and closure of GSI-191 by presenting an opportunity for the NRC staff to observe the execution of AECL's chemical effects head loss testing procedures and to discuss with AECL personnel the bench-top chemical testing results and other information that form the basis for the procedures developed by AECL.

Results Achieved

The NRC staff fulfilled the essential trip mission described above. Specific accomplishments include the following:

(1) Obtaining and reviewing the test plan for the AECL/Dominion multi-loop integrated head loss testing including chemicals,
(2) Observing the preparation and addition processes for particulate and fibrous debris for one loop of the multi-loop test rig,
(3) Observing a demonstration of the planned chemical addition process for the multi-loop test rig,
(4) Observing four multi-loop chemical head loss tests and one reduced-scale chemical head loss test that were in progress during the NRC staff's trip,
(5) Observing the laboratories, test equipment, and some test materials used to perform the bench-top chemistry experiments that AECL used to develop its chemical head loss testing methodology, and
(6) Discussion of results achieved from the bench-top chemical testing used to justify the chemical effects head loss test procedures.

Summary of Trip

The main focus of the NRC staff's trip was to observe the chemical effects head loss testing being performed in the new multi-loop test rig at AECL's Chalk River Laboratories. The construction of the multi-loop test rig was motivated by Dominion's objective of conducting head loss testing in parallel for Millstone, Surry, and NAPS in order to complete activities associated with GL 2004-02 on a schedule consistent with the NRC staff's plan for closure of GSI-191. The multi-loop test rig consists of six individual test loops, which is a sufficient number to perform simultaneous testing of the strainers for Millstone, Surry, and NAPS. Currently, the Dominion PWRs mentioned above are the only plants that have completed chemical head loss testing in the multi-loop test rig using the AECL test protocol. However, it remains possible that additional U.S. or foreign plants could seek to perform similar testing at AECL in the future.

Overall, the NRC staff was impressed with the quality of the multi-loop test rig, particularly in light of the compressed schedule for its design and construction. An example of one of the multi-loop test rig loops is shown below in Figure 1, with the key features labeled. The NRC staff also noted that the AECL and Dominion personnel present at the test site appeared to have a high level of expertise concerning strainer testing and that the test facility and test procedure appeared to have been designed with an awareness of many NRC staff comments previously made concerning test setups and procedures used by other strainer vendors.

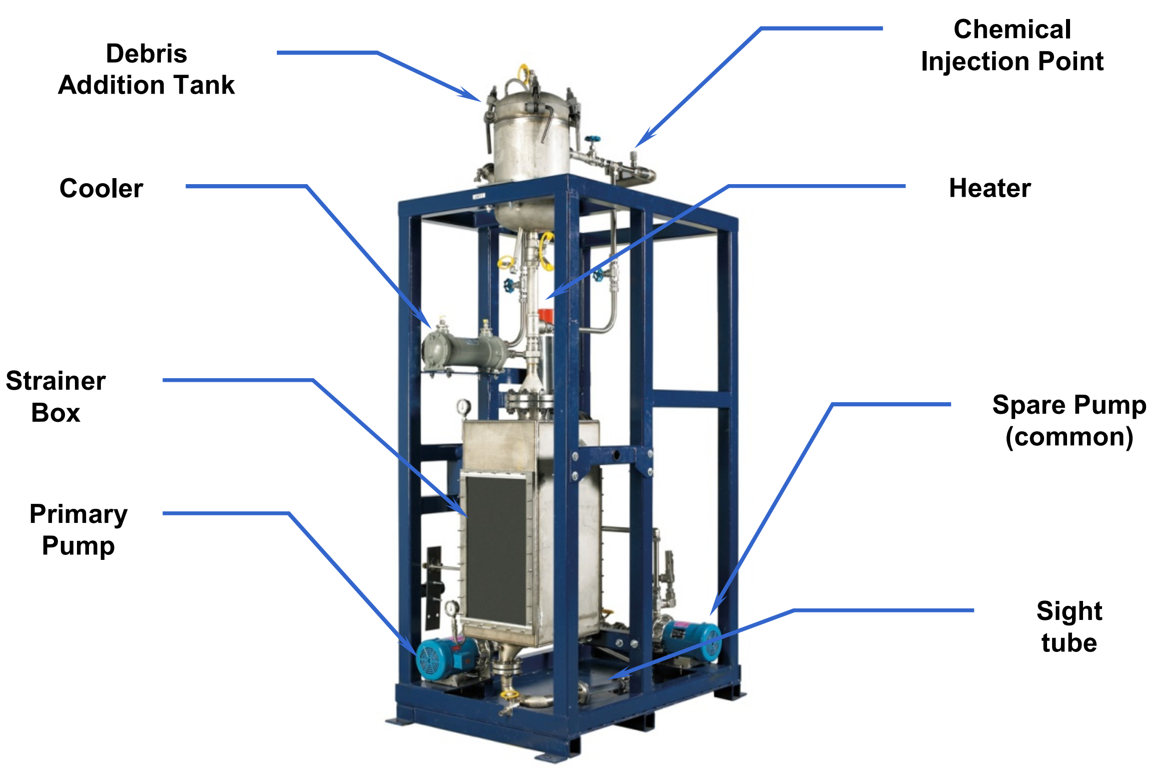

Figure 1: Multi-Loop Test Rig (1 of 6 Loops)

Key Head Loss Testing Observations

Based on observing the testing in progress during the trip to Chalk River, as well as discussions with licensee and vendor personnel, the NRC staff made several observations concerning the head loss testing performed by AECL for Dominion PWRs. The most significant NRC staff observation was that, prior to the chemical additions, the head losses for the debris beds formed in the multi-loop test rig were significantly lower than the head losses for previous non-chemical head loss testing with similar debris loadings conducted in AECL's reduced-scale test rig. Comparisons of head loss results from selected tests for the six strainer design cases considered in the testing are shown in Table 7 below (Reference 5). Note that, although multiple tests were conducted for a number of cases, the NRC staff considered that the selection of alternate data points for comparison would not affect the overall conclusion that the multi-loop rig test results were systematically lower than results for similar cases conducted in the reduced-scale test tank. Since the multi-loop rig testing was in its early stages at the time of the NRC staff's trip to Chalk River, the data in the table below was based on post-trip teleconferences mentioned below and information obtained during the NAPS chemical effects audit.

Table 7: Comparison of Head Loss Results in the Reduced-Scale and Multi-Loop Test Rigs

Strainer	Reduced-Scale Head Loss (ft)	Multi-Loop Rig Pre-Chemical Head Loss (ft)	Head Loss Ratio (Multi-Loop / Reduced-Scale)
Surry – Recirculation Spray	0.90	0.60	0.67 *
Surry – Low-Head Safety Injection	1.2	0.25	0.21
NAPS – Recirculation Spray	4.8	0.69	0.14
NAPS – Low-Head Safety Injection	3.2	1.7	0.53
Millstone 2	1.9	0.60	0.32 **
Millstone 3	15.6	1.0	0.064

* Note that the reduced-scale result shown for the Surry recirculation spray strainer was based on a homogeneous debris addition sequence. Higher head losses (e.g., 2–3 ft) in other reduced-scale tests had been achieved for similar loadings by adding the particulate prior to the fibrous debris, although the vendor and licensee believe these tests may have been more sensitive to biological fouling.

** Due to reductions in the plant debris loading following reduced-scale tank testing, the Millstone 2 multi-loop rig pre-chemical head loss was predicted to be only approximately 0.46 of the reduced-scale test value using the NUREG/CR-6224 correlation.

Due to the observation during the NRC staff's visit that the measured head loss for the NAPS recirculation spray strainer test in the multi-loop rig was spuriously low, the licensee decided to shut down this test loop prematurely so that the same test could be repeated to provide additional head loss data for the multi-loop test rig prior to the addition of chemicals. (Note that the Millstone 3 strainer test had not yet begun at this time.) Following the NRC staff's visit to Chalk River, the NAPS recirculation spray test was restarted and a new debris bed was formed. The licensee subsequently informed the NRC staff that a pre-chemical debris bed head loss was achieved similar to that of the initial test that was terminated prematurely.

The licensee suggested that a significant part of the systematic differences in measured head loss could be attributed to the presence of fine particulate and biological matter in the service water used for the reduced-scale testing, and that the accumulation of these contaminants on the debris beds formed in the reduced-scale tank led to significantly higher head losses relative to the multi-loop rig testing, which used deionized water (Reference 5). The licensee stated that, because the plant coolant is generated from deionized water, the fine particulate and biological matter in the AECL service water (ultimately derived from the Ottawa River) were not prototypical of the expected plant condition in this regard. Another cause of the discrepancy suggested by the licensee was deaeration and air accumulation in the fins of the test strainers used in the reduced-scale tank (Reference 5). The licensee considered deaeration to be particularly significant for the Millstone 3 reduced-scale tank tests.

Based upon the preliminary information available during the May 2008 trip to Chalk River, the NRC staff concluded that the licensee's hypotheses explaining the lower head loss values in the multi-loop test rig were not supported by a documented technical basis and recommended that the issue be discussed further after the completion of the multi-loop tests so that the licensee could perform additional comparative analysis.

In an effort to understand the basis for the systematic discrepancy noted above between the head loss results for the multi-loop test rig and the reduced-scale test tank, the NRC staff subsequently reviewed the steps in the licensee's test procedure for the multi-loop test rig based on observations made during the trip to Chalk River. (Previous reviews of the corresponding procedure used by AECL to conduct head loss testing in the reduced-scale tank are available in an NRC staff trip report from June 2006 (Reference 1) and in the NRC staff's GL 2004-02 audit for NAPS in July 2007, Reference 2).

- The debris loadings used for the multi-loop tests were typically thin bed cases, since these tests were shown to be the most limiting condition for previously completed non-chemical testing. In the AECL thin bed test protocol, the addition of particulate was performed first, followed by the addition of batches of fibrous debris. The target thin bed thickness, which AECL chose based on previous testing experience, was typically 1/4-inch.

- The debris preparation procedures appeared adequate in general. Particulate and fibrous debris were mixed up in separate batches, and the concentration of the prepared debris slurries appeared appropriate. The fluid used to generate the test slurries was taken from the test loops, however, and since the particulate was added to the test loops first, the test fluid used to generate the fiber slurries contained suspended particulate debris. Therefore, the addition sequence for particulate and fibrous debris was not considered by the NRC staff to be purely heterogeneous. The fibrous debris prepared by AECL for the tests observed by the NRC staff appeared to be sufficiently fine. Photographs of the prepared debris slurries were taken, although there did not appear to be objective acceptance criteria to ensure adequate fibrous debris preparation. A thin layer of the prepared fibrous debris typically floated in a mat on the surface of the barrel used to mix the debris slurry, as shown in Figure 2, below.

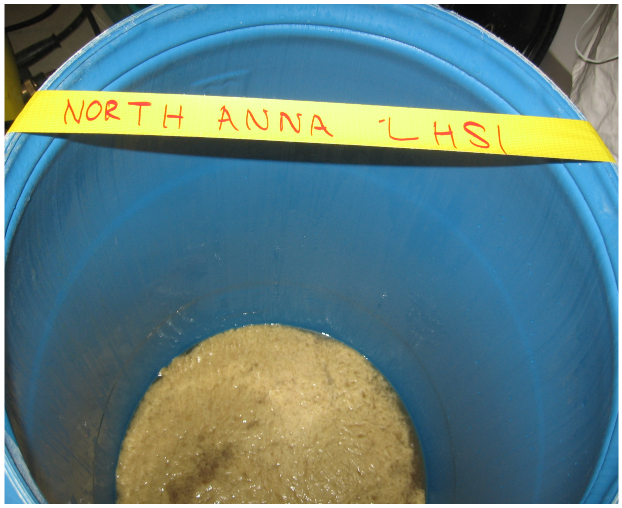

Figure 2: Prepared Fibrous Debris Slurry for a Multi-Loop Rig Test

- Debris slurries were poured into the multi-loop test rigs' debris addition tanks (see Figure 1 above). AECL test technicians prepared and transferred debris carefully and thoroughly. Once a slurry was poured into the debris addition tank, shown in Figure 3 below, the debris addition tank was closed, and valves were manipulated to allow debris to transport from the debris addition tank into the strainer box (Figure 1). AECL test technicians attempted to open the valves on the multi-loop test rig slowly so that the fibrous debris would gradually be transferred from the debris addition tank to the strainer box. It was unclear to the NRC staff how gradual the transport process between the debris addition tank and the strainer box was in practice, however, since visual observation was prevented by solid tank walls and piping, as well as the opaqueness of the test fluid behind the strainer box observation window. Since the flow of debris to the strainer box was due, not only to flow, but also to gravity, it is not clear whether a significant part of the fibrous debris transport occurred only after the valve to the strainer box had been opened past a critical value (e.g., transport occurring as a slug of fiber rather than a fine slurry). A layer of floating fiber was typically present on the surface of the debris addition tank after the debris slurry was added, as shown in Figure 3.

Figure 3: Debris Slurry Poured Into Debris Addition Tank

- A stirrer was installed inside the debris addition tank to keep the debris slurry from agglomerating prior to its arrival into the strainer box, as shown in Figure 4, below. The NRC staff observed that, when the debris addition tank was reopened after debris addition was thought to be complete, some small agglomerations of fibrous fines would occasionally remain on the surface of the debris addition tank. This fiber was subsequently broken up by AECL test technicians, and the debris addition tank was closed and restirred, allowing additional opportunity for the floating fibers to transport down to the strainer box. AECL test technicians ensured that the fibrous debris from the previous batch was transferred to the strainer box prior to adding the next batch of debris to the debris addition tank.

Figure 4: Debris Addition Tank Stirrer

- Once sufficient fiber had been added to the test tank, filtration of the suspended particulate occurred and the opacity of the water was reduced. The NRC staff could eventually observe in several of the strainer boxes that the flow pattern appeared to result in a fairly uniform debris loading on the test strainers, as evidenced below by Figure 5. For a number of the test loops, the NRC staff also observed that the flow in the strainer box was sufficient to keep the majority of the test debris in motion.

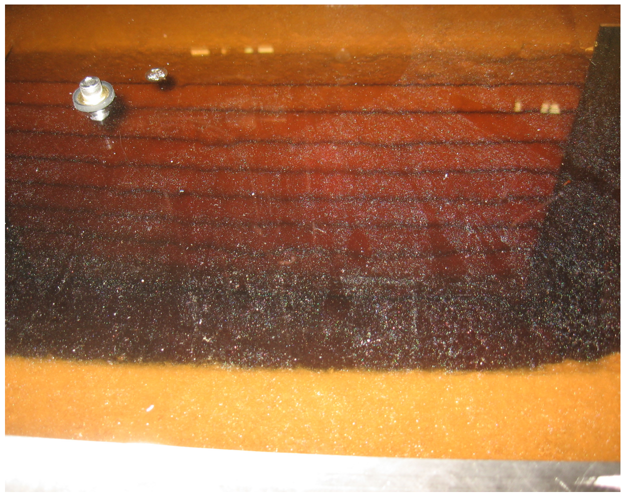

Figure 5: Debris Bed Formed in Multi-Loop Test

- The NRC staff observed that the AECL test technicians used magnetic brushes to stir debris that initially settled on the strainer box floor, as opposed to transporting to the test strainer module inside the strainer box. A photograph of settled debris on the floor of one of the strainer boxes is shown below in Figure 6. Settling appeared to be more significant for the test loops that had smaller gaps between the strainer fins and lower recirculation flow rates. However, after the test technicians finished using brushes to stir the settled debris, the NRC staff did not consider the small quantities of debris remaining on the strainer box floor to be of significance for any of the observed tests.

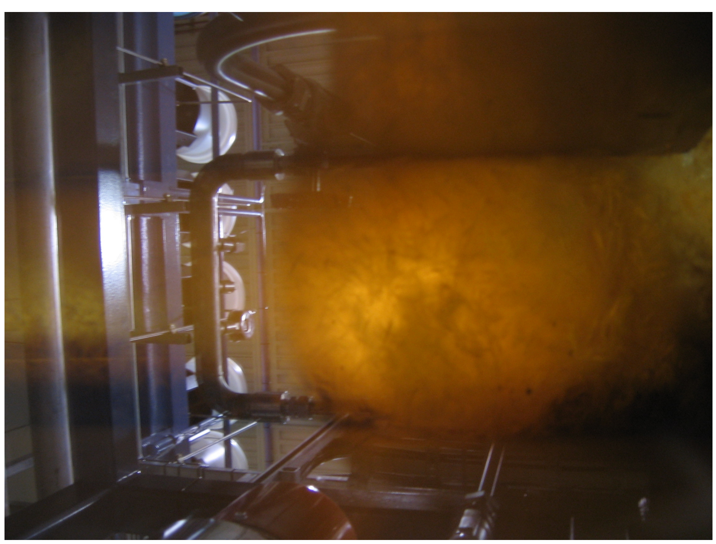

Figure 6: Fibrous Debris Settled in a Strainer Box

- Following the addition of a batch of fibrous debris, the floors of the strainer boxes were typically brushed to re-suspend settled debris. The NRC staff observed that, in some cases, the head loss increase following the brushing of the tank was comparable to or greater than the increase associated with the fibrous debris addition itself. This observation indicated that a significant amount of the debris entering the strainer box likely first settled onto the strainer box floor and then was subsequently brushed back into suspension and drawn onto the strainer by the flow through the loop. The NRC staff noted three possible effects of this transport sequence:

  - First, the transport of part of the fibrous debris to the floor of the strainer box resulted in a splitting of each fibrous debris batch into two sub-batches, with the first sub-batch likely having an increased fraction of the finest debris fragments.
  - Second, the intermediate step of settling part of the fibrous debris onto the strainer box floor prior to its arrival on the strainer could have provided an opportunity for fine debris to agglomerate into debris pieces of increased size. However, the NRC staff did not directly observe agglomeration of this debris, and it can be seen above in Figure 6 that the small clumps of fibrous debris that settled on the tank floor apparently remained relatively loose and fluffy.
  - Third, the NRC staff also observed that a small quantity of the particulate debris remained on the strainer box floor after the addition of several batches of fiber had clarified the test fluid. The cyclical re-suspension of this settled particulate when the strainer box floor was brushed following the addition of batches of fibrous debris appeared to be equivalent to an addition sequence wherein a portion of the particulate loading was added to the debris bed in a staggered pattern with batches of fiber.

- AECL test technicians implemented rigorous practices to ensure sterilization of the test loop, the test fluid, and the debris added to the loop. For example, buckets used for debris preparation were wiped with a bleach solution and then rinsed with deionized water. Debris added to the test loop was autoclaved for a time and temperature considered sufficient to eliminate sources of biological growth (although it can be inferred from the floating fibers seen in Figure 2 and Figure 3 that the autoclave temperature was not sufficiently high to completely remove the fibrous binder). Such steps, which have not been observed at other strainer vendor test facilities, were motivated by AECL's observations during reduced-scale tank tests that biological growth during long-duration tests (e.g., multiple days) may have non-prototypically contributed to the increase in measured head loss (Reference 3).

- Several power outages were observed to have occurred during the extended test runs in the multi-loop test rig. In discussions with the licensee near the conclusion of the multi-loop rig test runs, the licensee stated that the head losses for the affected test loops had returned to approximately the same level after power was restored.

- Head tanks were installed on the multi-loop rig test loops to increase the static head of water above the surfaces of the test strainers in an effort to prevent deaeration across the debris beds. As shown below in Figure 7, the six head tanks were essentially large buckets located one floor above the multi-loop test rig, each connected to a test loop via piping. The NRC staff did not perform a detailed review of the submergence level modeled for each test loop. However, it appeared that the enhanced submergence provided by the head tanks may have exceeded the actual plant strainers' submergence levels in some cases.

Figure 7: Multi-Loop Rig Head Tank Arrangement

From these observations discussed above, the NRC staff could not conclusively identify the step or steps in the multi-loop rig test procedures that were responsible for the significant differences between the measured head losses in the multi-loop test rig and the reduced-scale test tank. Based on the information available, the NRC staff considered several observations made concerning the test procedure as potentially contributing to the difference, including: (1) the use of test fluid with suspended particulate to prepare fibrous debris slurries, (2) the formation of matted layers of floating fiberglass during debris preparation and insertion into the debris addition tank, (3) the uncertainty as to whether slugs of fibrous debris could transport out of the debris addition tank and into the strainer box, and (4) the potential for staggered debris addition sequences and/or debris agglomeration to result from debris temporarily settling on the floor of the strainer box and later being brushed back into suspension. However, as noted above, the NRC staff did not have evidence that any of these observations resulted in deficiencies in the AECL testing in the multi-loop rig. Additional sensitivity testing with variations in the test procedure would be necessary to identify conclusively whether aspects of the test protocol or test geometry were responsible for the observed differences in measured head loss between the multi-loop test rig and the reduced-scale test tank.

As discussed in the NRC staff's report for the NAPS chemical effects audit (Reference 3), the NRC staff did not agree that the licensee had sufficient basis to demonstrate that the differences in measured head losses for NAPS were primarily the result of conditions in the reduced-scale tank test setup the licensee considered non-prototypical, namely silt particulate from the Ottawa River, the presence of biological fouling, and the effects of deaeration and air accumulation inside the test module. Based on the similarity of the head loss test procedures used for all of the Dominion PWRs that tested at AECL, discussions with licensee and vendor personnel during the trip to Chalk River, and information incidentally reviewed for these plants during the

NAPS chemical effects audit, the NRC staff expected that a similar conclusion would likely hold for Millstone and Surry as well. However, as discussed below, the reduced-scale testing for Millstone 3 appeared to have experienced significantly more deaeration than the other tests.

A second significant observation associated with testing at AECL was the presence of anomalous results in the plots of measured head loss versus time for reduced-scale tests for several Dominion plants. In one non-chemical head loss test performed for Surry, the head loss steeply increased following the addition of the final two batches of fibrous debris to the test tank, and then unexpectedly ramped downward. In a chemical head loss test performed for Millstone 3, the head loss trace oscillated unpredictably throughout the test and also demonstrated a decreasing trend as the quantity of dissolved calcium added to the test rig was increased. This decreasing head loss trend was unexpected because the calcium added to the test tank was expected to react with the phosphate dissolved in the test fluid to form calcium phosphate precipitate, thereby increasing the head loss. Despite the decreasing head loss trend, the measured head loss for the Millstone 3 test exceeded the test acceptance criterion. The licensee attributed these testing anomalies to the release of dissolved air that had accumulated under the debris bed during the test and, therefore, did not consider the test results valid. It was not clear to the NRC staff that all of the observed anomalies during the tests could be attributed to air effects or were non-representative of the plant condition. In particular, since a large head loss (relative to the strainer submergence) is first necessary to generate significant deaeration, it appeared to the NRC staff that a substantial part of the head loss in the Millstone 3 reduced-scale test could not be attributed to deaeration.

The licensee did not consider the reduced-scale tests as strainer design qualification tests, and as such, focused its efforts primarily on the multi-loop test program. However, the NRC staff briefly discussed with licensee and vendor personnel the potential for deaeration in the reduced-scale tank testing. During the NRC staff's visit to Chalk River, the chemical test for Millstone 3 in the reduced-scale test tank was ongoing, and the NRC staff observed the presence of air bubbles in a clear section of piping on the test pump suction line. However, licensee and vendor personnel had not yet had an opportunity to perform calculations to determine the expected void fraction downstream of the test strainer that was considered to be a significant contributor to the measured head loss for that test.

Following the trip to Chalk River, the NRC staff briefly analyzed the Millstone 3 test conditions in the reduced-scale tank using the deaeration model in the NUREG/CR-6224 Correlation and Deaeration Software Package in order to estimate the magnitude of the downstream void fraction. Based on the fluid conditions, minimum strainer submergence, strainer head loss, and other parameters that were considered representative for the Millstone 3 reduced-scale tank test referred to above in Table 7, the NRC staff estimated that the void fraction that occurred through the test debris bed likely remained below an approximate peak value of 1.75 percent and likely was closer to 1 percent for much of the test. In two earlier Millstone 3 tests in the reduced-scale tank that the licensee also considered to have been influenced significantly by deaeration effects, the NRC staff estimated that the void fraction had been on the order of 1 percent or less. Based on subsequent discussions of the deaeration model with AECL personnel during the NAPS chemical effects audit, it was realized that the results calculated by the NRC staff should be considered upper bound values, since the deaeration model in the NUREG/CR-6224 software package appears to model the strainer as a horizontal flat plate and the NRC staff calculation used the minimum submergence rather than a strainer-averaged value.

The NRC staff estimated that a more representative average submergence value may have decreased the void fractions calculated above by several tenths of a percent.

The NRC staff noted that air ingestion is discussed in Regulatory Guide (RG) 1.82, which recommends that a 2 percent limit be imposed on air ingestion in the pump suction line for the purpose of ensuring adequate pumping performance. As described in NUREG-0897, Revision 1, and NUREG/CR-2792, this limit was derived based on testing that measured the degradation of pump head as a function of ingested air at the pump suction. Thus, the specification of the 2 percent recommended air ingestion limit did not account for the impacts on net positive suction head margin resulting from two-phase flow through a debris bed or the accumulation of air inside the strainer resulting in an imbalance in the static head across the strainer surface. Based upon the experience from the Millstone 3 test above, the 2 percent limit of RG 1.82 may not be sufficiently stringent to address all of the means through which air may affect sump performance. The licensee indicated that the Millstone 3 test conditions evaluated are not representative of the plant condition, because the reduced-scale tank could not accommodate the full strainer submergence for the plant condition. Based on a calculation using an increased submergence the licensee stated would exist for the plant strainer prior to the onset of the peak strainer head loss, the NRC staff expected that a significant reduction in the calculated downstream void fraction would occur. In light of the discussion above, the NRC staff concluded that the upcoming revision to RG 1.82 should address the additional means by which air could adversely impact strainer performance that appeared to be present during the Millstone 3 testing.

Considering the anomalous results mentioned above that were observed in the traces of head loss versus time for some of the AECL tests performed for Dominion PWRs, the NRC staff questioned whether differential pressure phenomena had resulted in the disruption of the debris beds. In addition to performing a visual scan of the post-test debris bed to identify bore holes or other bed disruptions, the NRC staff considered it beneficial to use other means to demonstrate conclusively that temperature-based scaling of test head loss results to the plant condition is justified, particularly when unexpected behavior is observed in a test. The NRC staff noted that carefully performed flow sweeps or other means could be used to test the head loss response of the debris bed to a change in hydraulic conditions.

<u>Key Chemical Effects Observations</u>

Most of the NRC staff's observations during the trip to Chalk River focused upon non-chemical aspects of the multi-loop rig test procedures because most of these tests had not progressed to the point of chemical addition at that time. However, on the afternoon prior to the NRC staff's departure from Chalk River, the licensee performed a chemical addition in one of the multi-loop rig test loops. The test loop to which the chemical addition was performed was that for the NAPS recirculation spray strainer that the licensee subsequently planned to restart with a new debris bed, as mentioned above. The NRC staff observed that the licensee prepared the chemical solution by draining fluid from the test loop and mixing in sodium hydroxide flakes and sodium aluminate powder. The resulting chemical solution was subsequently metered into the test loop over a half-hour period using a cylinder/piston device that resembled an oversized syringe, as shown below in Figure 8. The chemical injection did not have an obvious impact on the test head loss, which was expected because the quantity of aluminum added to the test loop was relatively small. The licensee stated that the chemical addition protocol observed by the

NRC staff was for demonstration purposes only, and that the procedure for chemical addition in the formal design-basis tests had not been finalized.

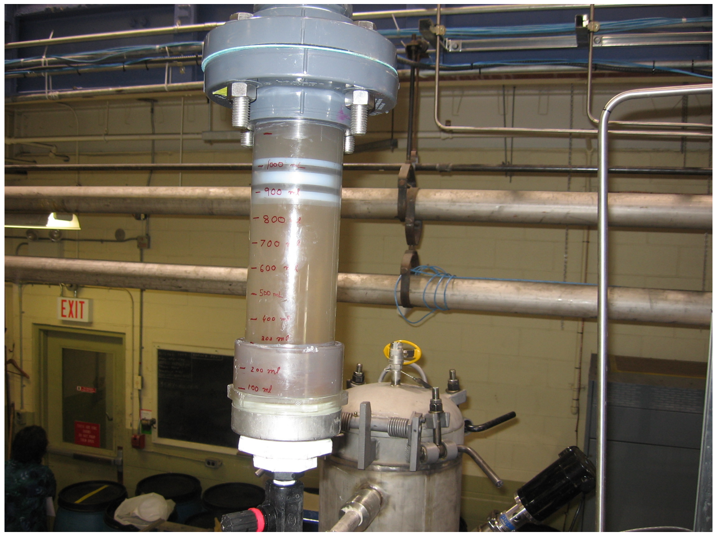

Figure 8: Injection of Chemicals into a Multi-Loop Rig Test Loop

When designing the multi-loop test rig, the licensee realized that simultaneously scaling quantities of chemicals to both the test fluid volume and the test strainer area was not feasible. Specifically, because the ratio of the test strainer area to the test fluid volume in the multi-loop rig is much larger than the corresponding ratio for the plant, adding an amount of dissolved chemicals that would create a representative test fluid condition for modeling precipitation reactions would not lead to the generation of a sufficient quantity of precipitate when scaled to the test strainer area. The NRC staff and licensee discussed how the multi-loop test protocol would compensate for this scaling issue. Although a finalized chemical addition procedure had not been developed by the licensee at the time, the licensee stated that, if indications of precipitation were observed in a given test loop, additional dissolved chemicals would be added to maintain a representative chemical concentration in the test fluid. The licensee further stated that the test fluid would be periodically monitored for evidence of precipitation and that additional chemicals would be added to maintain a representative chemical concentration in the test fluid until an appropriate quantity scaled to the test strainer area had been added to the test loop.

Licensee personnel also described efforts to reduce the calculated quantity of dissolved aluminum in the post-accident sump fluid for Surry and NAPS. The licensee planned to reconsider existing containment analyses to determine whether the potential for reduced containment temperature and pH conditions could lower the aluminum concentration in the post-accident sump fluid into the range of 10 ppm. The licensee also noted that some aluminum equipment, such as ladders, could be removed from these plants' containment buildings if necessary.

Post-Trip Interactions

Due to the extended duration of the AECL multi-loop chemical effects head loss tests, the NRC staff could not observe the execution of all key steps of the test procedure and critical aspects of the testing, such as the behavior of the measured head loss when significant quantities of chemicals were added to the test loops. Therefore, the NRC staff held two follow-on phone calls with Dominion and AECL to discuss the results of the multi-loop rig testing, on June 25, 2008, and August 6, 2008. The date of the first call was selected based on the expectation that the multi-loop tests would be completed within roughly 30 days from the start of the addition of chemicals. However, all six of the test loops were still running into the month of August, and a second phone call was arranged for August 6, 2008, when the multi-loop tests were essentially complete. Key points discussed in these teleconferences have been incorporated into the foregoing discussion.

Conclusions

As described above, during the May 2008, trip to Chalk River Laboratories, the NRC staff identified several issues concerning the testing performed at AECL for Dominion PWRs which were not adequately understood. The primary issues identified included the systematic discrepancy between the head loss results for similar debris loadings in the reduced-scale tank and the multi-loop test rig and anomalous behavior in some of the reduced-scale tank tests. Based on the evaluation of these issues during the NAPS chemical effects audit, the NRC staff considers these issues to be resolved for NAPS. These issues will be considered for Millstone and Surry during the review of their generic letter supplemental responses and dispositioned appropriately at that time.

Notwithstanding the issues discussed above, the NRC staff found the licensee and vendor personnel present during the trip to the Chalk River Laboratories to be highly knowledgeable regarding head loss testing and strainer performance in general. The NRC staff was further impressed with the thoroughness and attention to detail of the AECL engineers and test technicians. Finally, the NRC staff also noted that the licensee and vendor had both expended considerable effort in constructing a high-quality multi-loop test rig on a compressed schedule in order to complete the chemical effects head loss testing in a timely manner.

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Attachment I: List of People Contacted

Name	Organization	Title
Addison Hall	Dominion	Lead, Strainer Testing
Martin Legg	Dominion	Engineer
Michael Henig	Dominion	Project Manager, GSI-191
Dave Guzonas	AECL	Senior Scientist
Dave Rhodes	AECL	Principal Engineer
Qingwu Cheng	AECL	Testing Engineer
Jason Deadman	AECL	Design Engineer
Shelly Maves	AECL	Project Manager
Walter Hahn	AECL	Project Manager