



December 18, 2008

U.S. Nuclear Regulatory Commission  
Attention: Document Control Desk  
One White Flint North  
11555 Rockville Pike  
Rockville, MD 20852-2378

Serial No. 08-0740  
NLOS/GAW R0  
Docket Nos. 50-336/423  
License Nos. DPR-65  
NPF-49

**DOMINION NUCLEAR CONNECTICUT, INC.**  
**MILLSTONE POWER STATION UNITS 2 AND 3**  
**NOTICE OF COMPLETION OF ACTIVITIES RELATED TO NRC GENERIC LETTER**  
**2004-02, POTENTIAL IMPACT OF DEBRIS BLOCKAGE ON EMERGENCY**  
**RECIRCULATION DURING DESIGN BASIS ACCIDENTS AT PRESSURIZED-WATER**  
**REACTORS**

Dominion Nuclear Connecticut, Inc. (DNC) has completed the corrective actions associated with Nuclear Regulatory Commission (NRC) Generic Letter (GL) 2004-02<sup>(1)</sup> at Millstone Power Station, Units 2 and 3 (MPS2 and MPS3). The GL requested information requiring an evaluation of the emergency core cooling system (ECCS) and containment spray system (CSS) recirculation functions. The GL required the completion of corrective actions by December 31, 2007, necessary to ensure system function. The request was based on identified potential susceptibility of the pressurized water reactor (PWR) recirculation sump screens to debris blockage during design basis accidents requiring recirculation operation of ECCS or CSS, and on the potential for additional adverse effects due to debris blockage of flowpaths necessary for ECCS and CSS recirculation and containment drainage.

DNC provided the initial response to the GL in a letter dated September 1, 2005<sup>(2)</sup> that committed to completion of corrective actions by December 31, 2007. DNC requested changes to the MPS3 Operating License on September 15, 2005<sup>(3)</sup> to modify initiation of the MPS3 recirculation spray (RSS). On September 20, 2006,<sup>(4)</sup> the NRC approved the requested MPS3 change as Amendment 233 to the Operating License. Subsequently, DNC completed the installation of the hardware associated with passive strainers to substantially increase the available strainer surface area during the winter 2006 MPS2

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- (1) NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized Water Reactors," September 13, 2004.
- (2) DNC letter 05-212, Millstone Power Station Units 2 and 3 Response to NRC Generic Letter 2004-02, September 1, 2005 (ADAMS Accession No. ML052500378)
- (3) DNC letter 05-357, "Millstone Power Station Unit 3 Proposed Technical Specifications Change, Recirculation Spray System," September 15, 2005, (ADAMS Accession No. ML052580387)
- (4) NRC letter, Millstone Power Station Unit No. 3, Issuance of Amendment Re: Recirculation Spray System (TAC No. MC8327)," September 20, 2006, (ADAMS Accession No. ML062220160)

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refueling outage 16 and spring 2007 MPS3 refueling outage 11. The modified initiation of RSS in accordance with MPS3 Amendment 233 was installed during MPS3 refueling outage 11. Additionally, by NRC letter dated September 18, 2007,<sup>(5)</sup> issuance of MPS2 Amendment 300 and MPS3 Amendment 240 provided for use of generic terminology for ECCS containment sump strainers. DNC then requested an extension of the schedule for the remaining regulatory commitments in a DNC letter dated November 15, 2007.<sup>(6)</sup> The outstanding design requirements required resolution of downstream effects analysis and chemical effects testing at MPS2 and MPS3. NRC letter dated December 13, 2007<sup>(7)</sup> approved the schedule extension to May 31, 2008. DNC letter dated February 29, 2008<sup>(8)</sup> submitted requested information, consistent with industry and NRC staff guidance on final licensee responses to the GL. DNC letters dated May 21<sup>(9)</sup> and May 22, 2008<sup>(10)</sup> requested further extension of the schedule. NRC letter dated May 29, 2008 approved the schedule extension to June 30, 2008.<sup>(11)</sup> NRC letter dated July 1, 2008<sup>(12)</sup> approved the schedule extension to complete the remaining design and licensing basis corrective actions by September 30, 2008. On September 25, 2008, DNC completed the MPS2 and MPS3 implementation of associated regulatory commitments and the actions necessary for compliance with the requirements discussed in the GL.

Attachments 1 and 2 to this letter provide updated information about downstream effects analysis and chemical effects testing. On December 17, 2008,<sup>(13)</sup> NRC staff forwarded a request for additional information (RAI) that included several questions regarding DNC actions in response to the GL. DNC is currently developing the information requested by the NRC and will provide the requested response consistent with the schedule specified in the RAI.

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- <sup>(5)</sup> NRC letter, "Issuance of Amendments re: Technical Specification Change Request for use of Generic Terminology for Emergency Core Cooling Systems Containment Sump Strainers, (TAC Nos. MD2943 and MD2944)," September 18, 2007, ADAMS Accession No. ML072290132
- <sup>(6)</sup> DNC letter 07-0660, "Request for Extension of Completion Dates for Corrective Actions," November 15, 2007, ADAMS Accession No. ML073190553
- <sup>(7)</sup> NRC letter, "Request for Extension of Completion Dates for Generic Letter 2004-02 Corrective Actions (TAC Nos. MC4691, MC4694, MC4695, MC4696, MC4697, MC4722 and MC4723)," December 13, 2007, ADAMS Accession No. ML073450594
- <sup>(8)</sup> DNC letter 07-0797, "Supplemental Information of Corrective Actions in Response to NRC Generic Letter 2004-02," February 29, 2008, ADAMS Accession No. ML080650561
- <sup>(9)</sup> DNC letter 08-0275, "Request for Extension of Completion Dates for Corrective Actions," May 21, 2008, Accession No. ML081420793
- <sup>(10)</sup> DNC letter 08-0275A, "Request for Interim Extension of Completion Dates for Corrective Actions," May 22, 2008, ADAMS Accession No. ML081430612
- <sup>(11)</sup> NRC letter, "Request for Extension of Completion Dates for Generic Letter 2004-02 Corrective Actions (TAC Nos. MC4691, MC4694, MC4695, MC4696, MC4697, MC4722 and MC4723)," May 29, 2008, ADAMS Accession No. ML081490572
- <sup>(12)</sup> NRC letter, "Request for Extension of Completion dates for Generic Letter 2004-02 Corrective Actions (TAC Nos. MC4691, MC4695, MC4695, MC4696, MC4697, MC4722 and MC4723)," July 1, 2008, ADAMS Accession No. ML 081830247
- <sup>(13)</sup> NRC letter, "Request for Additional Information Regarding GL 2004-02 (TAC Nos. MC4694 and MC4695)," December 17, 2008, ADAMS Accession No. ML 083230469

Please contact Mr. Geoffrey A. Wertz at (804) 273-3572 if you have any questions or require additional information.

Sincerely,

  
J. Alan Price  
Vice President – Nuclear Engineering

Commitments made in this letter: None

Attachments:

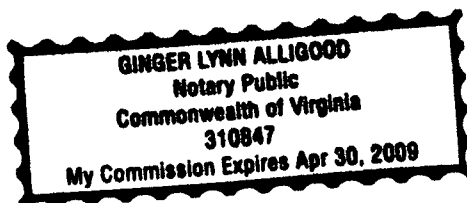
1. Updated Information About Downstream Effects Analysis and Chemical Effects Testing for Millstone Power Station Unit 2
2. Updated Information About Downstream Effects Analysis and Chemical Effects Testing for Millstone Power Station Unit 3

COMMONWEALTH OF VIRGINIA     )  
  )  
COUNTY OF HENRICO            )

The foregoing document was acknowledged before me, in and for the County and Commonwealth aforesaid, today by J. Alan Price, who is Vice President – Nuclear Engineering of Dominion Nuclear Connecticut, Inc. He has affirmed before me that he is duly authorized to execute and file the foregoing document in behalf of that company, and that the statements in the document are true to the best of his knowledge and belief.

Acknowledged before me this 18th day of December, 2008.

My Commission Expires: 4/30/2009



  
Notary Public

cc: U. S. Nuclear Regulatory Commission  
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**ATTACHMENT 1**

**UPDATED INFORMATION ABOUT DOWNSTREAM EFFECTS ANALYSIS AND  
CHEMICAL EFFECTS TESTING FOR MILLSTONE POWER STATION UNIT 2**

**DOMINION NUCLEAR CONNECTICUT, INC.  
MILLSTONE POWER STATION UNIT 2**

**UPDATED INFORMATION ABOUT DOWNSTREAM EFFECTS ANALYSIS AND CHEMICAL  
EFFECTS TESTING FOR MILLSTONE POWER STATION UNIT 2**

**1.0 BACKGROUND:**

By Dominion Nuclear Connecticut, Inc. (DNC) letter dated February 29, 2008, Serial No. 07-0797, (ADAMS Accession No. ML080650561), DNC provided the supplemental response to Generic Letter (GL) 2004-02, for Millstone Power Station Units 2 and 3 (MPS2 and MPS3). This attachment updates information that was previously provided concerning downstream effects analysis and chemical effects testing for MPS2. Accordingly, the balance of this attachment provides the following items:

- 1.C CONSERVATISMS
- 3.M DOWNSTREAM EFFECTS – COMPONENTS AND SYSTEMS,
- 3.N DOWNSTREAM EFFECTS – FUEL AND VESSEL, and
- 3.O CHEMICAL EFFECTS.

**1.C CONSERVATISMS:**

Detailed analyses of debris generation and transport ensure that a bounding quantity and a limiting mix of debris are assumed at the Emergency Core Cooling System (ECCS) containment sump strainer. Using the results of the analyses, conservative head loss testing was performed to determine worst-case strainer head loss and downstream effects analysis. Chemical effects bench-top tests conservatively demonstrate the solubility and behaviors of precipitates, and applicability of industry data on the dissolution and precipitation tests of station-specific conditions and materials. Reduced-scale testing was performed with the Atomic Energy of Canada, Limited (AECL) Test Rig 33 and Multi-loop Test Rig 89. The reduced-scale testing established the influence of chemical products on head loss across the strainer surfaces by simulating plant specific chemical environment present in the water of the containment sump after a Loss-of-Coolant-Accident (LOCA). These analyses rely upon the conservatisms discussed in the balance of this section.

1. Test evaluations demonstrate that a fully formed thin-bed of debris takes significant time (hours) to form and is dependent on unsetting debris throughout the test tank. Consequently, a worst-case thin-bed of debris will be difficult to form and will not form until several hours after sump recirculation can be initiated. Significant debris settling and significant sump water subcooling occurs during the formation of a debris-bed so additional NPSH margin is present for chemical effects head loss.
2. The debris load in head loss testing was taken from the debris transport calculation, which credits no particulate settling.
3. Debris introduction procedures in chemical effects testing resulted in minimum near-field settling and conservatively high head losses.
4. Debris introduction was accomplished in a carefully controlled manner to result in the highest possible head loss. Particulate was introduced initially, which was followed by discrete fiber additions after the particulate debris was fully circulated.

5. Only fines of fibrous debris were used in head loss testing, as if all the fibrous debris erosion occurred at recirculation start.
6. The test tank was periodically stirred in the Rig 89 testing and continuously stirred in the Rig 33 testing. However, local areas of turbulence that may exist in any post-LOCA containment sump water are expected to be limited to certain portions of sump water volume. Consequently, much of the sump water will be quiet and have near zero velocity.
7. Particulate settling in head loss testing was conservatively minimized through use of a lower density walnut shell particulate as a surrogate for the higher density epoxy coating particulate that may be present in post-LOCA sump water.
8. Downstream wear analysis used the Large Break LOCA particulate load to determine abrasive and erosive wear. This is a conservative particulate loading, in view of the following.
  - Much of the particulate included in analysis is unqualified coating that is outside the break zone of influence (ZOI). This unqualified coating is assumed to potentially dislodge due to exposure to the containment environment. However, an exposure based mechanism to dislodgement, if it occurs at all, is likely only after many hours and days.
  - The low velocity of the sump water column and the significant number of surfaces throughout containment promote significant settling of particulate in containment. Settled coating will not be drawn through the ECCS strainer since the strainer sits approximately seven inches above the containment floor. Additionally, qualified coating postulated to fail in the presence of the ZOI is not buoyant in the sump water column.
  - The capture of particulate in the debris-bed on the strainer does not occur in this analysis, maximizing effects of downstream wear.
9. Conservatively, the base concrete dissolution is assumed uninhibited by the presence of tri-sodium phosphate (TSP), even though bench scale test solutions demonstrate inhibition of concrete degradation at containment sump water pH levels. Consequently, calculations of the amount of calcium to be added to the test tank for head loss tests were conservative.
10. The amount of aluminum and associated test results concerning its release into the simulated post-LOCA sump water through corrosion of aluminum surfaces was conservative based upon several conditions:
  - Aluminum corrosion amounts were calculated at high pH to favor corrosion, and aluminum precipitation was evaluated at low pH to favor precipitation.
  - Testing with a lower pH favors precipitation. Testing using Rig 89 was with pH 7 to encourage aluminum compound precipitation, even as actual pH in sump water is approximated as pH 8 and a minimum Technical Specifications is at pH 7.

- Rig 89 testing was evaluated conservatively with low short-term acceptance criteria, along with the maximum aluminum concentration of the sump water that exists only after 30 days.
- Analysis conservatively does not account for the possible inhibitory effect of silicate, phosphate or other species on aluminum corrosion.
- The rate of corrosion is maximized by analysis that does not assume development of passive films, e.g., no aluminum oxides remain on aluminum surfaces. Passive films can otherwise be used to decrease the corrosion rate by a factor of the exposure time. Consequently, having no aluminum oxides remain on aluminum surfaces so all aluminum released by corrosion enters the solution is conservative.
- All aluminum not submerged in containment is considered by analysis to be exposed to containment sprays and therefore available for corrosion. However, some of the aluminum sources in containment, such as the out-of-core detector holders, may not be subject to a continuous containment spray and would not contribute to the total aluminum concentration in the containment pool.
- All aluminum released into the solution is assumed to transport to the debris-bed instead of plating out on the multiple surfaces throughout containment. During bench-top testing, aluminum plated out on glass beakers and during reduced scale testing, aluminum plated out on fiber. It is reasonable to expect that a portion of the aluminum ions released into solution will plate out on some of the multiple surfaces in containment prior to arriving at the debris-bed on the strainer.
- Chemical effects test evaluations conservatively neglect the effect of the presence of oxygen in the sump water. Corrosion rate of aluminum in aerated pH 10 alkaline water can be a factor of two lower than when the rate is measured in nitrogen-deaerated water. This data is in NUREG/CR-6873, "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191," (Jain et al. April 2005).

### 3.M. DOWNSTREAM EFFECTS—COMPONENTS AND SYSTEMS:

No design or operational changes were made as a result of downstream effects analysis.

DNC uses methodology for downstream effects analysis that is consistent with Pressurized Water Reactor Owner's Group (PWROG) Technical Report (TR), WCAP-16406-P, Revision 1, "Evaluation of Downstream Sump Debris Effects in Support of GSI [Generic Safety Issue]-191," and the NRC limitations and conditions described in the NRC Safety Evaluation regarding the performance of this analysis, dated December 20, 2007, (ADAMS Accession No. ML073520295).

Downstream component clogging was previously described in the supplement to GL 2004-02 response by DNC letter dated February 29, 2008, Serial No. 07-0797, (ADAMS Accession No. ML080650561).



This update of downstream effects analysis includes the following:

- Wear in the high pressure safety injection (HPSI), low pressure safety injection (LPSI), and containment spray (CS) pumps, manually throttled valves, motor operated valves, orifices, and heat exchangers. The evaluation of the wear effects on the performance of these components is also evaluated.
- Evaluation of the downstream instrumentation, including temperature indicators, pressure indicators, and flow indicators for potential blockage due to the presence of debris.

Debris from the LOCA may pass the containment sump strainer and enter the CS and ECCS, causing abrasion and erosion on the surfaces of components. A wear model was developed per the WCAP-16406-P, Revision 1 to assess the amount of wear in CS and ECCS components based on the initial debris concentration in the pumped fluid, the debris concentration depletion, the hardness of the wear surfaces, and the mission time.

#### Abrasive Wear Model:

Abrasive wear in the close running clearances may result from free-flowing abrasive wear or packing type abrasive wear as described by the Archard model. WCAP-16406-P, Revision 1, provides for consideration of these two abrasive wear model types:

- free flow, and
- packing (or Archard's).

The principal differences between the Archard wear model and the free-flowing abrasive wear model are:

- The wear associated with the Archard model is single-sided. The debris packing adheres to the stationary surface (wear rings), and wear only the rotating surface (impeller hub). The free-flowing abrasion model wears both the rotating and the stationary surfaces individually at rates determined by the fluid debris concentration and the hardness of the wear surfaces.
- The wear rate of Archard's model is constant. Once the packing is established, debris depletion on the bulk fluid does not affect the rate of wear. For the free-flowing abrasive wear model, the rate of wear is a direct result of the debris concentration in the fluid at any time during the pump duty cycle. Both models are considered valid because both will reasonably predict abrasive wear in close tolerance components. The wear predictions from both models match the results from field testing that support the WCAP-16406-P, Revision 1. The Archard model can also be adjusted to reflect changes in debris concentration.

### Erosive Wear Model:

Erosive wear is the result of particles impinging on a component surface, or edge, causing material to be removed from that surface due to momentum effects. This type of wear is noticed in components with high velocity flows such as throttling valves, orifices, heat exchangers, tubes and pump components.

### Pumps:

The abrasive and erosive wear of a pump's internal subcomponents resulting from pumping debris-laden water will cause an increase in the flow clearances of the pump. For abrasive wear of close-tolerance subcomponents such as wear rings, both Archard's and free flowing abrasive wear were considered and the wear which produced the maximum wear was conservatively used.

The increase in flow clearances is evaluated for impact on hydraulic performance of the pump. A second issue associated with wear is the potential for changing system resistance curve due to wear of components such as valves and orifices. The results indicate that all valves, plate orifices, multi-stage orifices, and containment spray nozzles pass the criteria in the WCAP-16406 Revision 1 and therefore, the effect on system flow rates is negligible.

Hydraulic performance and mechanical dynamic performance of each ECCS pump is found acceptable because the total abrasive and erosive wear of small clearance areas on the ECCS pumps is less than the wear allowance in the original equipment design, and are therefore, acceptable. Thus, the hydraulic performance of the ECCS pumps will not be impaired due to abrasive and erosive wears of pump subcomponents while pumping debris-laden water for 30 days post-LOCA.

### Pump Mechanical Seal Wear:

WCAP-16406-P, Revision 1 calls attention in particular to the mechanical shaft seal assembly and its functionality with debris laden fluid. Westinghouse pump testing referenced in WCAP-16406-P, Revision 1 has been used as a basis for demonstrating mechanical shaft seal assembly performance. The results of this testing suggest that no failure is expected of seals due to debris ingestion within the defined mission time for the ECCS and CS pumps.

MPS2 site-specific evaluation of pump seal performance with debris laden fluid includes:

- pump seal injection/leak-off rates with respect to fluid velocity and suspension of debris in fluid,
- pump seal critical clearances and materials with respect to debris entering into critical clearances, and an
- annular orifice calculation to determine the change in flow rate through the pump seal packages during the mission time.

These analyses use debris loading data from MPS2 and indicate that debris is not expected to cause mechanical seal leakage in excess of acceptable limits. The technical basis for the conclusion includes the following considerations:

- The debris is too large to pass through the primary seal and cause wear.
- The amount of the debris that can be expected drawn into the seal injection line is limited by flow velocities, and whatever debris that does get introduced will not settle in the mechanical seal region.
- If it is assumed that wear and failure of the primary seal could occur, the disaster (safety) bushing would wear a negligible amount in 30 minutes, and the leakage rate of the pump would be kept to an acceptable limit until the leakage could be isolated and another train of ECCS or CS could be started.
- It was shown that the gap due to wear of the disaster bushing would increase the leakage rate by a maximum of 0.26%. This percent of increase will remain the same and is a negligible change.

For these reasons, the downstream effects analysis show that debris would not be expected to cause excessive seal leakage or mechanical seal failure in these pumps.

#### Heat Exchangers:

The actual wall thickness of the heat exchangers minus the tube wall thickness lost to erosion is greater than the minimum wall thickness required to withstand the internal tube design pressure. Therefore, the heat exchanger tubes have sufficient wall thickness to withstand the erosive effect of the debris-laden water for a period of 30 days post-LOCA.

#### Other components:

The manually throttled valves, plate orifices, multi-stage orifices, and containment spray nozzles in the recirculation flow path pass the criteria set forth per WCAP-16406-P, Revision 1 and therefore, the calculated wear will have an insignificant effect on the system flow. No further evaluation is required. No piston check valves are required to close during recirculation so no further evaluation is required.

#### Instrumentation:

The instrumentation is mounted either on the top or side of the piping and is not susceptible to failure due to plugging. The velocity of the fluid as well as the orientation of the instrument in the pipe will allow the debris to continue flowing beyond the instrumentation. Therefore, the identified instrumentation will not be adversely affected by debris in the recirculation flow path.

### **3.N. DOWNSTREAM EFFECTS—FUEL AND VESSEL:**

DNC completed a LOCA Deposition Analysis Model (LOCADM) to quantify the maximum expected deposition of chemical precipitates on the MPS2 fuel and the resultant maximum clad temperature. The results show that the maximum clad temperature is a monotonically decreasing function of time from a maximum of approximately 360°F at the start of recirculation to 178°F at the end of 30 days. The maximum temperature is well below the acceptance criterion of 800°F. The scale buildup starts at recirculation and reaches a maximum of 650 microns (25.6 mils) at the end of 30 days. This takes into account the potential for strainer bypass. This is well below the acceptance criteria of

1270 microns (50 mils). The results are essentially the same as shown in Figure 5-3 of the WCAP-16793-NP, Revision 0, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," dated February 4, 2008. Thus, the conclusions of the WCAP-16793-NP for the fuel and vessel analysis are applicable to MPS2 and demonstrate acceptable long-term core cooling in the presence of core deposits.

Although this analysis to date has incorporated conditions and limitations imposed on use of WCAP-16793-NP, the initial NRC comments provided for this technical report have been withdrawn and the WCAP is currently in revision. The source of the revision is understood to be related to the fuel blockage analysis, not the fuel deposit methodology. Upon issuance of revised guidance, and the anticipated Regulatory Issue Summary to inform the industry of the NRC staff's expectations and plans regarding resolution of this remaining aspect of GSI-191, DNC assumes that the existing analysis for MPS2 will remain bounding of plant conditions and limitations on LOCADM use in a final Safety Evaluation (SE) for WCAP-16793-NP. Should this assumption be demonstrated to be invalidated by the ongoing industry actions on this issue, in accordance with the station corrective action program, DNC would take the appropriate corrective action to update the analysis and the design basis, accordingly.

### 3.O. CHEMICAL EFFECTS:

Methodology for chemical effects testing and evaluations have used the observations of Integrated Chemical Effects Tests (ICET), and the Westinghouse Owners Group document WCAP-16530-NP, Revision 0, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," Laine et al. (2006), and various NRC sponsored research presented at public meetings or posted on the NRC website. The balance of this section provides an update to the supplement for MPS2. Chemical effects bench-top tests conservatively demonstrate the solubility and behaviors of precipitates, and applicability of industry data on the dissolution and precipitation tests of station-specific conditions and materials. Reduced-scale testing was performed with the AECL Multi-loop Test Rig 89. The reduced-scale testing established the influence of chemical products on head loss across the strainer surfaces by simulating plant specific chemical environment present in the water of the containment sump after a LOCA. These analyses rely upon the evaluation methodology and conservatism discussed in the balance of this section.

#### Potential for Clean Strainer Surface Area:

MPS2 chemical effects head loss testing was conducted at the Chalk River Ontario Laboratories run by AECL. It is expected that due to debris settling and very low pool velocities that much of the debris at MPS2 will not reach the strainer. For any small break LOCA, much more debris could be expected to not reach the strainer. The strainer construction at MPS2 has two legs of strainer modules that stretch out and away from each other, beginning from a common enclosure. This effectively places much of the debris from any particular break nearer one of the two strainer legs and thus more likely to be drawn to one strainer leg over the other when recirculation flow begins. Additionally, due to the significant open floor area (covered only by grating) in the steam generator cubicles, many of the possible break locations are above a portion of the strainer and break flow in these areas would keep the portion of the strainer below the break clear of debris. Despite these factors which encourage the existence of open strainer surface

area, no credit is taken for open strainer surface area in the evaluation of head loss due to chemical effects.

Debris-bed Formation:

The worst-case debris-bed for MPS2 has consistently been the formation of a thin-bed. Extensive testing prior to addition of chemical precipitants has determined the thin-bed fiber thickness is nominally 1/8 inch. Since the fibrous and particulate debris mixtures for MPS2 are essentially the same for any of the limiting break locations, the break which produces the maximum particulate load produces the worst-case head loss when an approximately 1/8 inch thick fibrous bed is deliberately formed following the addition of particulate. The same break which produces the worst-case head loss in the absence of chemical effects is expected to produce the worst-case head loss with chemical precipitants added to the debris-bed. Debris-bed formation for the chemical effects testing followed the same procedure as for previous head loss testing to ensure the worst-case debris-bed was formed (i.e. head loss was highest). All of the particulate was added to the test tank which contained borated water with trisodium phosphate (TSP,  $\text{Na}_3\text{PO}_4$ ) and lithium hydroxide (LiOH) to simulate the post-LOCA sump water. Once the particulate was well distributed throughout the test tank water, fiber debris was added. Fibrous debris was prepared consistent with previous head loss tests in order to ensure individual fiber separation and maximum head loss. Fibrous debris was added in two increments, each of which had enough fiber to form a 1/16 inch thick fiber bed. These additions were spaced 30 minutes apart to allow sufficient time for the previous addition to pack onto the strainer and begin collecting particulate debris. Since the nominal thin-bed thickness for MPS2 was determined to be 1/8 inch, no further fiber additions were made. No chemical additions to this debris-bed were made until after the head loss had stabilized.

Plant Specific Materials and Buffers:

Potentially reactive materials included in the MPS2 containment have been listed in Table O-1 of the supplement previously provided by DNC letter Serial No. 07-0797, dated February 29, 2008, (ADAMS Accession No. ML080650561). Table O-1 is updated below to remove zinc and show a more realistic (but still conservative) total for bare concrete. Zinc is no longer included in this table because there is no evidence that zinc reacts to form any significant chemical precipitant affecting debris-bed head loss.

The pH buffer at MPS2 is TSP which contributes phosphate ions to the post-LOCA sump water. Degradation of bare concrete due to contact with sprays or being submerged in post-LOCA water potentially contributes calcium to the sump water. Together, the calcium and phosphate are thought to potentially form an insoluble calcium phosphate which could contribute to debris-bed head loss. The revised amounts of reactive material are shown in Table O-1.

Table O-1: Surface Areas of Materials Subjected to Containment Spray and Submergence

Material	Surface Area Submerged (ft <sup>2</sup> )	Surface Area Exposed to Containment Spray (ft <sup>2</sup> ) (does not include submerged material)
Aluminum	24	1876
Carbon Steel (uncoated)	500	0
Concrete (uncoated)	400	925
Fibrous Insulation (NUKON™)	1400 ft <sup>3</sup> a	0
Mineral Fiber Insulation	297 ft <sup>3</sup> a	0
Mineral Wool Insulation	159 ft <sup>3</sup> a	0

Note a: This entry is a total volume of fibers dislodged from piping and equipment.

The worst-case pH profile is slightly altered from the original submittal in that the pH still peaks at about 8.3, but is likely to drift down to about 8.2 in the worst (high pH) case which promotes maximum corrosion of aluminum. Sump water temperature and containment air temperature profiles are unchanged from the original supplemental response.

#### Approach to Determine Chemical Source Term:

Chemical effects testing consisted of chemical effects assessment, bench-top testing and reduced-scale tests. The chemical effects assessment has been previously described in the DNC supplement. Bench-top testing was conducted to gain an understanding of the chemistry to be expected in reduced-scale testing. Reduced-scale testing was conducted to determine the debris-bed head loss in the presence of expected chemical precipitants. Details of the bench-top testing and the reduced scale testing are described in the balance of this section.

#### Chemical Species Formation:

The assessment performed prior to chemical effects testing is an extensive review to determine the chemical species likely to be formed in the containment sump water post-accident. The assessment concludes that corrosion of aluminum could lead to formation of aluminum hydroxide or oxyhydroxide precipitates but that formation of these precipitates is unlikely at MPS2 due to the low aluminum concentrations expected to be added into the sump water. Degradation of concrete and fibrous insulation in the containment sump water could lead to the release of small amounts of calcium into the sump water and this calcium may combine with the phosphate produced by the TSP buffer to form an insoluble calcium phosphate.

The conclusions of the chemical effects assessment are:

- Calcium phosphates are not expected to precipitate from the MPS2 post-LOCA sump water. However, a limited number of bench-top tests were run to assess the risk of calcium phosphate precipitation.

- The calculations show that the unsubmerged aluminum (Al) is the largest contributor of Al released into the sump water, while the contribution from submerged aluminum surfaces is a factor of 10 smaller. The predicted aluminum concentrations in the sump water resulting from release from the submerged and sprayed aluminum surfaces are 0.4 and 4.4 mg/L, respectively.

The total aluminum concentration in the post-LOCA sump water is predicted to be 4.8 mg/L, well below the solubility limits for aluminum hydroxide. Since the predicted dissolved aluminum concentration does not exceed the solubility of amorphous aluminum hydroxide, aluminum hydroxide precipitation is not expected. However, to be conservative, bench-top testing was performed to;

- Experimentally determine whether aluminum hydroxide will precipitate under MPS2 conditions,
- Characterize any resulting precipitates, and
- Develop a method to produce precipitates for reduced scale testing should such testing be required.

Chemical effects head loss testing, showed that all of the aluminum added to the tank plated out or precipitated, most on the debris-bed. This test result makes the aluminum solubility argument moot.

#### Bench-top Testing:

Bench-top testing was performed to support the strainer chemical effects testing.

The bench-top testing consisted of the following tasks:

- Calcium dissolution and Calcium Phosphate precipitation testing
- Precipitation testing of Aluminum Hydroxide
- Determination of dependence of Walnut Shell (paint surrogate) properties on chemistry

#### Calcium Dissolution and Precipitation Testing:

Bench-top tests using debris materials specific to MPS2 were conducted to determine the amount of calcium released from concrete and insulation materials (dissolution tests). For MPS2, a clean concrete coupon, Nukon fiber, mineral fiber and mineral wool were placed in each of four 5-liter flasks containing 4L of a solution of 1500 mg/L Boron with pH of 5, 6, 7, and 8, respectively. Temperature of the fluid in the flasks was 90°C. A magnetic stirrer was used in each of the flasks. The masses of insulation material and surface area of concrete coupon were calculated based on the expected amounts of these materials in the containment sump water post-LOCA. The concrete coupon size was determined based on a conservative and bounding estimate of bare concrete which could exist in containment. The dissolution tests duration was 30 days.

Dissolution test results, in the absence of TSP:

- The pH of the solutions which started at pH 5 and 6 increased while the pH of the solutions which started at 7 and 8 were relatively stable. This is likely due to the dissolution of the concrete which produces a salt ( $\text{CaSiO}_3$ ) of a strong base ( $\text{Ca(OH)}_2$ ) and a weak acid ( $\text{H}_4\text{SiO}_4$ ).
- The concrete coupons fully dissolved in the pH 5 and 6 solutions and were significantly degraded in the pH 7 and 8 solutions.
- The major species in solution at the end of 30 days are calcium (Ca), silicon (Si), and sodium (Na) with minor amounts of potassium (K) and magnesium (Mg) detected. Concentrations of sodium are due to the use of sodium hydroxide (NaOH) to adjust the pH.
- Calcium concentrations were significantly higher in the pH 5 solution (503 mg/L) than in the pH 7 (126 mg/L) or the pH 8 solution (70 mg/L). The pH 7 and 8 solutions are more representative of the long-term pH in the containment sump water since the minimum pH is 7.1 and the realistic maximum is calculated to be approximately 8.3.

Identical tests were run with the only difference being that TSP (at the expected 30 day concentration) was added to the flasks along with the insulation materials, concrete, and borated water. The most striking aspect of the tests with TSP is the apparent inhibition of concrete dissolution which occurred with TSP present. The presence of TSP was expected to cause precipitation of calcium phosphate, leading to either;

- lower concentrations of calcium in solution and increasing the dissolution of concrete and insulation, or
- calcium phosphate on surfaces inhibiting further release of calcium.

However, though lower concentrations of calcium in solution were observed with TSP present, dissolution of concrete did not occur, (e.g., weight change of all the concrete coupons was much less than 1% at all four pH values). Calcium concentration without TSP at pH 7 after 30 days was 126 mg/L as compared to the test with TSP at pH 7 after 30 days which yielded a calcium concentration of <10 mg/L.

To conservatively predict calcium release, the data from the MPS2-specific bench-top tests were used to determine the amount of calcium to be added to the test tank for the reduced scale tests, which are discussed later. Results obtained using these data are somewhat lower than results reported in WCAP-16530 [Lane et al., 2006]; however, powdered concrete with a surface area far in excess of that seen in containment was used in the WCAP testing which would lead to higher calcium concentrations.

The concentration of calcium to be added to the Rig 89 test tank was conservatively determined from the results of the bench-top testing, which determined the dissolution of concrete and fibrous insulation in the post-LOCA solution in the absence of TSP. The results of the bench-top tests showed that TSP may tend to inhibit the dissolution of concrete and thus the calcium concentration used in Rig 89 is significantly conservative.



Calcium dissolution in these bench-top tests followed first order kinetics and so can be described:

$$C(t) = C^{\infty}(1-\exp(-kt))$$

Where  $C(t)$  and  $C^{\infty}$  are the dissolved calcium concentrations at time  $t$  and time infinity and  $k$  is the first order dissolution rate constant.

Table O-2 lists the values of  $C^{\infty}$  and  $k$  obtained by fitting the measured calcium concentrations in the four dissolution tests.

Table O-2: Calcium Concentration Factors

Parameter	pH 5	pH 6	pH 7	pH 8
$C^{\infty}$ (mg/L)	529	380	117	69
$k$ (1/hr)	0.0052	0.0055	0.0072	0.0066
$r$ (g/m <sup>2</sup> x hr)	2.4	1.7	0.54	0.32

In general calcium dissolution increased at lower pH values. The release rate ( $r$ ) for the pH 7 test (lowest pH allowed in containment) was used in the following equation to determine the maximum calcium concentration post-LOCA after 30 days:

$$C_{30d} = r * \text{Concrete surface area} * 30\text{days} * 24 \text{ hr/day/sump volume}$$

Using a concrete surface area of 1325 ft<sup>2</sup> (from Table O-1), a minimum sump volume of 41,800 ft<sup>3</sup>,  $r$  value from above table at pH 7 (0.54), and a conversion factor of 0.3048 m/ft, this equation yields a calcium concentration of 40.4 g/m<sup>3</sup> (or 40.4 mg/L), which was used for the Rig 89 testing.

To characterize calcium phosphate precipitation under MPS2 sump water chemistry conditions, the solutions remaining at the end of the dissolution tests conducted without TSP at pH 5, 6, 7 and 8 were mixed with TSP solutions at the same pH, and at temperatures of 25, 50, 60 and 80°C for precipitation tests. Precipitation was visually observed in some samples and quantified using turbidity measurements. Table O-3 summarizes the results of the visual observations and turbidity measurements of the test solutions for the precipitation tests. Turbidity measurements above 6 FTU<sup>(1)</sup> were considered to indicate a positive detection of precipitate, though the precipitate may not have been visually observable. In each test above room temperature, the turbidity was measured at temperature and at room temperature. No difference in the two readings was noted. Precipitation was observed at pH 6, 7 and 8 at all temperatures studied. This behavior is expected because the dissolved calcium and phosphate concentrations in the solutions are supersaturated relative to the known solubility of hydroxyapatite. The results are as expected since the solubility of hydroxyapatite decreases as the temperature increases and shows a minimum around 50-60°C.

<sup>(1)</sup> FTU = 1 NTU. The NTU (Nephelometric Turbidity Unit) is reserved for turbidity measured using a nephelometer, which measures light reflected at 90 degrees from the source beam. Measurements were made using a spectrophotometer, which measures light transmitted through 180 degrees, and are therefore listed as FTU (Formazin Turbidity Unit).

Table O-3: Summary of Precipitation Behavior as Determined by Visual Observation and Turbidity Measurements in the Calcium Precipitation Tests

Temperature (°C)	pH 5		pH 6		pH 7		pH 8	
	Visual	Turbidity	Visual	Turbidity	Visual	Turbidity	Visual	Turbidity
25	N	N	P	P	P	P	P	P
50	N	N	P	P	P	P	P	P
60	N	P	P	P	P	P	P	P
80	N	P	P	P	P	P	P	P

P - Precipitation Observed

N - No Precipitation Observed

The solubility of calcium phosphate is lowest at pH values around 7 and temperatures below 100°C. The MPS2 test results are consistent with these observations.

Both WCAP-16530 and the Integrated Chemical Effects Tests (ICET) show that in the absence of added calcium silicate insulation (MPS2 debris-bed has no calcium silicate), the amounts of calcium released from fiberglass insulation are insufficient to result in significant precipitation of calcium phosphate. Additionally, leachate produced from Nukon insulation (typical of what exists in MPS2 containment) amounts were similar to, or less than amounts found by, WCAP testing. Thus, calcium from fiberglass insulation is not a significant source for the post-LOCA containment sump water.

The following conclusions can be drawn from the data on calcium release and precipitation under MPS2 sump water conditions:

1. Calcium release from concrete and other debris followed first order kinetics,  $C(t) = C_{\infty}(1 - \exp(-kt))$ .
2. Concrete dissolution increased as the pH decreased in borated water.
3. The presence of TSP in the test solutions inhibited concrete dissolution.
4. The presence of TSP in the test solutions decreased the measured calcium concentration, due to inhibition of concrete dissolution and precipitation of calcium phosphate.
5. The degree of calcium phosphate precipitation increased as the pH increased.
6. The degree of calcium phosphate precipitation increased as the temperature increased.

The bench-top testing shows that there is a potential for calcium phosphate precipitation for MPS2.

### Aluminum Precipitation:

At pH 7, the data suggest that no precipitation will occur at aluminum concentrations less than about 12 ppm. Aluminum solubility has also been investigated by Argonne National Laboratory (ANL). The report by C.B. Bahn, et al, "Technical Letter Report on Evaluation of Long-term Aluminum Solubility in Borated Water Following a LOCA," dated February 28, 2008, (ADAMS Accession No. ML082330153) reports on solubility tests conducted at aluminum concentrations ranging from 40-98 ppm and pH from 7.0 to 8.5 in borated water solutions. These solutions were subjected to a heating and cooling regimen to simulate the heating and cooling that would occur in post-LOCA sump water as it was recirculated between a heat exchanger (for cooling) and the reactor core (for heating). Sodium aluminate was used in these tests; sodium aluminate was also used in the AECL bench-top and reduced scale testing. As shown in Table 1 of that report, with a total aluminum concentration of 40 ppm, no precipitation was observed upon cooling the solutions from 200°F to 80°F at pH values above 7.5. The report also suggests that the solubility limit at pH 7.0 is less than 40 ppm even at 200°F. This value of 40 ppm bounds the bench-top test results reported by AECL (summarized above) and bounds the maximum concentration of aluminum in the MPS2 post-LOCA sump water of approximately 5 ppm. No precipitation of aluminum hydroxide species is expected in the MPS2 post-LOCA sump water.

AECL conducted bench-top tests to determine aluminum solubility under the worst-case conditions expected in the post-LOCA sump water. The sump water chemistry conditions which are expected to exist after 30 days were used for determination of aluminum precipitation. These chemistry conditions are considered the most conservative since after 30 days, the temperature of the sump water has decreased to a stable, low value, and the dissolved aluminum concentration has reached its maximum value. For additional conservatism, a pH of 7.0 (at 25°C) was used since this is lower than the actual pH which will exist and is the required minimum pH per the MPS2 Technical Specifications. The bench-top tests for aluminum precipitation were conducted in three flasks. One of the flasks was maintained at 150°F, and one at room temperature. The third flask was a blank which had no insulation debris added to facilitate detection of precipitation in the "warm" and "room temperature" flasks. All three of the flasks contained borated water to which was added sodium aluminate. The required mass of insulation debris was added to the warm and room temperature flasks. The solutions were stirred slowly with a magnetic stirrer and once the pH was adjusted to the target value, the solutions were allowed to stand for 30 days. The pH was nearly constant throughout the 30 days. No precipitation was observed from these tests conducted with MPS2 specific boric acid, aluminum concentrations, and insulation masses. The maximum concentration of aluminum expected in the MPS2 containment is approximately 5 ppm and these tests were conducted with a concentration of 4 ppm aluminum. The difference does not invalidate the test result based on the finding by AECL that the precipitation/no precipitation zone is at approximately 12 ppm aluminum.

The available data on Al solubility in borated water is summarized in the recent ANL report by C.B. Bahn, et al., "Technical Letter Report on Evaluation of Head Loss by Products of Aluminum Alloy Corrosion," dated August 11, 2008, (ADAMS Accession No. ML082330153). The results of the Dominion-AECL bench-top test are within the precipitation region determined in ANL tests (without distinguishing flocculated and non-flocculated precipitation). Most of the bench-top test data points lie within the non-flocculated region, as expected since the bench-top tests were taken only to the onset

of precipitation, where the concentration of particles would be low and less likely to show flocculation.

As discussed below, the Rig 89 testing showed that no aluminum remained in solution even at the low levels of aluminum expected in the MPS2 containment. Thus the testing showed that aluminum hydroxide solubility is not a factor in the post-LOCA sump environment at MPS2.

The concentration of aluminum to be added to the test rig was conservatively determined by determining the maximum aluminum corrosion which could occur in the containment post-LOCA without considering any inhibitory effects. AECL determined the overall aluminum corrosion rate at a given temperature and pH using ICET and other literature data to be:

$$\text{Corrosion rate (T)} = 9.2 \cdot 2 \times 10^7 \cdot \exp(-6301.1 \times (1/T (^{\circ}\text{K})))$$

$$\text{Corrosion rate (pH)} = 3 \times 10^{-7} \times \exp(1.3947 \times \text{pH})$$

The total aluminum (Al) release rate determined by AECL is given by:

$$\text{Al release rate} = \text{corrosion rate (T)} \times \text{corrosion Rate (pH)}$$

or

$$\text{Release Rate (mg/m}^2\text{·s)} = 9.2 \cdot 2 \times 10^7 \cdot \exp(-6301.1/T) \cdot 3 \times 10^{-7} \cdot \exp(1.3947 \cdot \text{pH})$$

The average corrosion rate over the time interval was then calculated assuming a linear change in corrosion rate over that interval. The aluminum release was then calculated using:

$$\text{Al Release over Interval} = \text{Corrosion Rate} \times \text{Interval length} \times \text{Al Surface Area}$$

The highest expected pH in the MPS2 containment post-LOCA (pH=8.3) was used in the calculation of aluminum corrosion. The total amount of aluminum created was calculated as 4.8 ppm.

#### Testing for Walnut shell Dissolution and Alteration:

Walnut shell powder is used in the debris head loss tests to simulate qualified and unqualified coating which is conservatively anticipated to be broken into very small particulate sizes (nominally 10 $\mu$ m) and transported to the strainer post-LOCA. Tests were carried out as part of the bench-top testing to determine if exposure to chemicals would dissolve or alter the walnut shell particulate.

Particle size and dissolution tests carried out to characterize the effects of exposure of walnut shells to borated water containing sodium aluminate showed no obvious change on particle size distribution or particle morphology. Measurements of the total organic carbon in the test solution gave inconsistent results with respect to the amount of walnut shell dissolution, while measurements of the weight change suggested a maximum weight loss of 12%. No significant effect from walnut shell dissolution or weight change is expected to impact the results of the Rig 89 tests.

### Reduced Scale Testing:

Reduced scale testing was conducted for MPS2 to determine the debris-bed head loss with a conservative amount of potential chemical precipitants added to the debris. The amounts of chemicals added were determined based on plant conditions and the chemical effects assessment which determined the debris source term. The Rig 89 test results are more prototypical of containment and are the relevant test results for determining maximum debris-bed head loss at MPS2.

### Test Description:

The chemical effects tests were performed using the newly constructed multi-loop test rig, Rig 89. Rig 89 is a multi-loop facility designed and constructed to support the schedule for conducting six Dominion head loss tests with chemicals simultaneously instead of conducting these in series using the existing Rig 33 facility. The loop was filled with solutions of chemicals based on MPS2 specific plant conditions and pH requirements. Loop filling was via the debris addition tank and the header tank. A vent valve on top of the debris addition tank was used to eliminate air pockets within the loop. The loop was filled to approximately half the height of the header tank to allow water expansion during the heating process and to accommodate chemical additions over time. The loop was heated to 60°C (140°F) and cooled to 40°C (104°F) while circulating at 17 gal/min to remove dissolved air. The loop was operated for at least 20 minutes at the test flow rate and temperature before debris addition. Chemical addition to the test tank occurred after a fiber and particulate thin-bed was formed and had developed a stable head loss. Chemicals were added in increments throughout the test to simulate the gradual corrosion of aluminum and degradation of concrete.

Approximately ten gallons of water were removed from the debris addition tank through a drain valve located at the bottom of the tank while the tank was isolated from the loop. The water was used to prepare the debris addition for each test. The sprayed slurry of debris was returned into the debris addition tank. The debris addition tank isolation valve was then opened to slowly meter out debris. Additions of debris were done slowly (over at least 10 minutes per addition) and with throttled valves to ensure that debris deposition on the strainer surface was as uniform as possible, thus promoting the highest achievable head loss. The full particulate debris load for each test was added at the start of the test, and then additions of fibrous debris were made in 1/16 in. (1.6 mm) theoretical bed thickness increments. The theoretical bed thickness is defined as the uncompressed fiber volume divided by the test module surface area. The first fiber addition (1/16 in. (1.6 mm)) was made 30 minutes (enough time for debris preparation) after the addition of the particulate debris. The second fiber addition (an additional 1/16 in. (1.6 mm)) was made 30 minutes after the first addition. The thin-bed thickness for MPS2 is nominally 1/8 inch as established in previous debris-bed testing. Debris-bed stabilization occurred relatively quickly in the Rig 89 testing because of a very short tank turnover time. After the debris-bed was formed and the pressure drop stabilized (changed by less than 5% or 0.01 psi, whichever was greater), and exhibiting no general steadily increasing trend within 25 minutes, chemicals were added into the loop through the chemical injection points. Chemical addition was accomplished in small batches over the course of the test to simulate gradual corrosion of aluminum and degradation of concrete and insulation fiber. The effects of calcium and aluminum precipitate formation on strainer debris-bed head loss were evaluated by adding calcium chloride and sodium aluminate to the test rig in the already established chemical environment of TSP, boric acid, and lithium hydroxide at

pH 7. The amount of calcium chloride to be added was calculated from a concrete dissolution rate obtained from bench-top testing in boric acid solution at pH 7 (without TSP) as described above. The amount of sodium aluminate to be added was calculated from a corrosion rate model. Both calculations ignored the inhibitory effect of TSP and were extremely conservative. Bench-top test results discussed above showed that concrete coupons exposed for 30 days to a solution of boric acid and TSP at pH 7 had no significant mass change, indicating that the dissolution rate employed was extremely conservative. Likewise, the results published in WCAP-16785-P, "Evaluation of Additional Inputs to the WCAP-16530-NP Chemical Model", indicate that phosphate inhibits aluminum release by a factor of 3-4 between pH 8 and 9.

The test was run for > 70 days to observe the head loss change due to any precipitate formation after chemical additions. A 30-mL grab sample was taken every day for each test using the drain valve at the bottom of the debris addition tank. Some of the water samples were sent for elemental analysis using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). The remaining samples were kept for possible future use. A 50-mL grab sample was taken twice a week for each test for possible microbial analysis. At the end of each test a debris-bed sample was taken for analysis by Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Spectroscopy (EDX).

The test termination criteria were:

1. Little or no precipitate forms in 30 days; aluminum concentrations remain at the specified value.
2. Precipitate forms and the head loss exceeds the allowable debris-bed head loss for MPS2 or the available test rig margin.
3. Precipitate forms but criterion 2 is not met. Aluminum will be added to the test loop to maintain the specified concentration until the mass of aluminum added reaches the maximum mass of aluminum that should be added. The maximum mass of aluminum is based on the consideration that, per unit of strainer area, more precipitate would be formed in a sump strainer than in a test strainer because of the volume to strainer surface ratio difference. The test tank volume is 8.1 ft<sup>3</sup>. The minimum sump volume is 41,800 ft<sup>3</sup> and the scaled volume is 42.7 ft<sup>3</sup> based on the debris-scaling factor of 979.1 used for the test. The ratio of the scaled volume to the actual test loop volume is 5.3 (i.e. 42.7/8.1).

Head loss test results are summarized in the table and figures below. The head loss values reported in this table are the peak head loss values measured during the day listed.

TABLE O-4: TEST M2-C1 CHEMICAL ADDITIONS AND HEAD LOSS VALUE

Day (Events)	Masses of Chemical Additions					Concentration of Calcium and Al				Head Loss (psi)
	CaCl <sub>2</sub> (g)	NaAlO <sub>2</sub> (g) <sup>a</sup>	B(OH) <sub>3</sub> (g)	TSP (g)	NaOH (g)	[Ca] <sub>calc</sub> (mg/L) <sup>c</sup>	[Ca] <sub>ICP</sub> (mg/L) <sup>d</sup>	[Al] <sub>calc</sub> (mg/L) <sup>c</sup>	[Al] <sub>ICP</sub> (mg/L) <sup>d</sup>	
Environment	/	/	2030	1105	/	/	/	/	/	0
Debris-bed	/	/	/	/	/	/	/	/	/	0.26
0 (1 <sup>st</sup> )	7.3	2.79	8.82	/	40.6	11.46	11.2	3.19	bd	0.66
3 (2 <sup>nd</sup> )	4.34	/	8.74	/	0.15	18.27	15.5	3.19	bd	0.65
6 (3 <sup>rd</sup> )	2.6	/	8.81	/	0.12	22.35	17.8	3.19	bd	0.69
9 (4 <sup>th</sup> )	1.55	/	4.4	/	0.1	24.78	19.1	3.19	bd	0.68
12 (5 <sup>th</sup> )	0.92	/	4.4	/	0.1	26.23	21.1	3.19	bd	0.69
15 (6 <sup>th</sup> )	0.55	/	2.2	/	0.1	27.09	21.2	3.19	bd	0.68
18 (7 <sup>th</sup> )	0.33	/	2.2	/	0.11	27.61	22.8	3.19	bd	0.69
21 (8 <sup>th</sup> )	0.2	/	0.88	/	0.11	27.92	22.0	3.19	bd	0.69
24 (9 <sup>th</sup> )	0.12	/	0.88	/	0.1	28.11	22.4	3.19	bd	0.7
27 (10 <sup>th</sup> )	0.07	/	0.88	/	0.11	28.22	21.1	3.19	bd	0.7
59 (11 <sup>th</sup> )	/	2.62	30.4	16.5	/	28.22	18.6	6.19	bd	0.98
61 (12 <sup>th</sup> )	/	2.62	30.4	16.5	/	28.22	/	9.18	bd	1.04
63 (13 <sup>th</sup> )	/	2.62	30.4	16.5	/	28.22	13.4	12.18	bd	1.01
65 (14 <sup>th</sup> )	/	2.62	30.4	16.5	/	28.22	12.0	15.17	bd	1
67 (15 <sup>th</sup> )	/	2.62	30.4	16.5	/	28.22	/	18.17	bd	0.93
69 (16 <sup>th</sup> )	/	2.62	30.4	16.5	/	28.22	9.1	21.17	bd	1
71 (17 <sup>th</sup> )	/	2.62	30.4	16.5	/	28.22	/	24.16	bd	0.98
72 (18 <sup>th</sup> )	4.35	/	8.81	/	0.1	35.05	/	24.16	bd	0.87
73 (19 <sup>th</sup> )	4.35	/	8.81	/	0.1	41.88	25.7	24.16	bd	0.86
75 (20 <sup>th</sup> )	8.7	/	17.62	/	0.19	55.53	/	24.16	bd	0.86
76 (21 <sup>st</sup> )	4.35	/	8.81	/	0.1	62.36	/	24.16	bd	0.86
77 (22 <sup>nd</sup> )	4.35	/	8.81	/	0.1	69.19	28.0	24.16	bd	0.87
Total:	44.08	21.13								

Notes:

- 0.035 g of LiOH was added on the day of establishing the *Chemical Environment* (May 4).
- Sodium aluminate is a hygroscopic substance. Analysis results indicate that the sodium aluminate contained 27.3 wt% Al on Day 22 (June 6), shortly after the 8<sup>th</sup> chemical addition *Event*. A value of 26.3% was used for calculations.
- Concentration was calculated from the mass added.
- Concentration was measured by ICP-AES.
- bd denotes that signal was below the detection limit of 0.4 mg/L Al.

Figure O-1 exhibits the debris-bed head loss in Rig 89 prior to chemical addition.

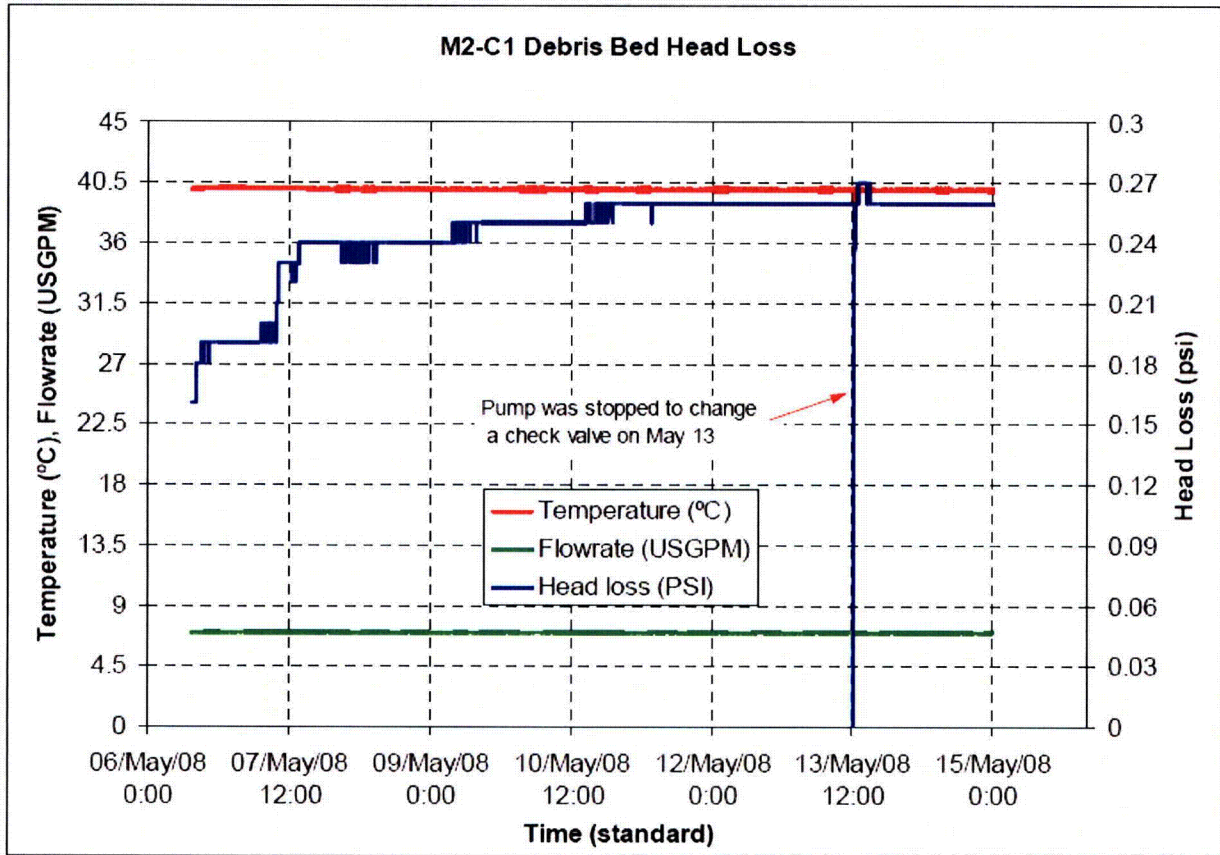


FIGURE O-1: DEBRIS-BED HEAD LOSS VERSUS TIME FOR TEST M2-C1



Figure O-2 exhibits the head loss trace as a function of time for the Rig 89 test (blue line), measured calcium concentration (black line), measured aluminum concentration (maroon line), and all of the calcium additions.

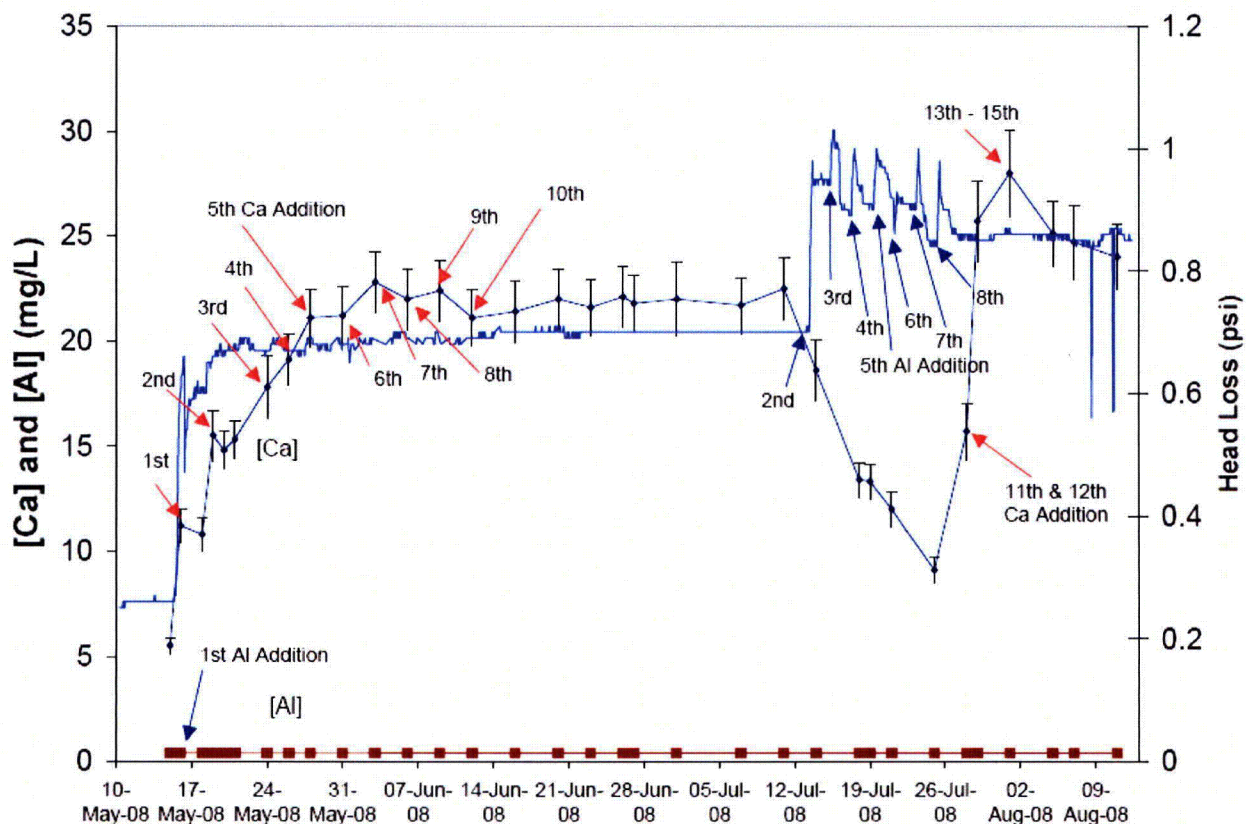


FIGURE O-2: HEAD LOSS TRACE AND MEASURED CALCIUM AND ALUMINUM ADDITIONS FOR M2-C1

Figure O-3 exhibits the debris-bed head loss that was recorded during the initial calcium and aluminum additions in Rig 89.

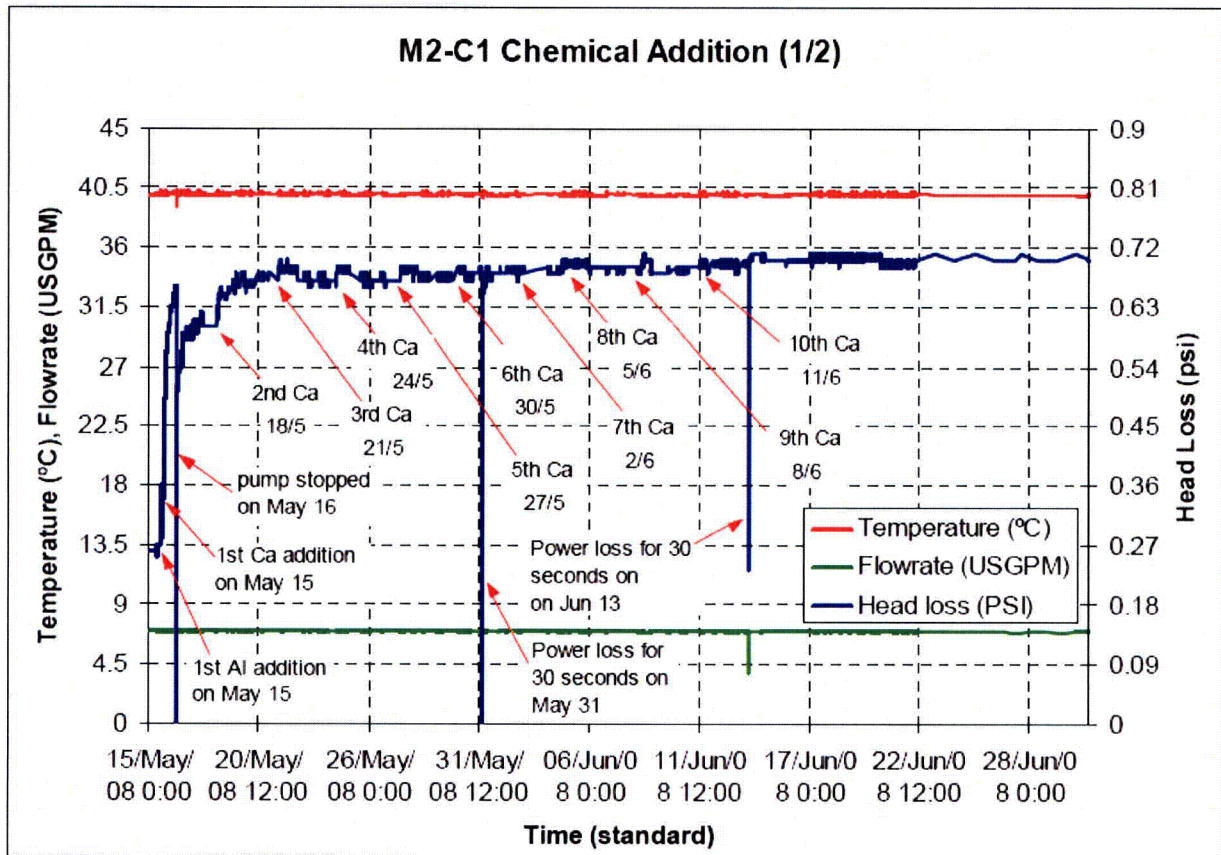


FIGURE O-3: HEAD LOSS ACROSS THE MPS2 STRAINER DURING THE INITIAL CALCIUM AND ALUMINUM ADDITIONS

Figure O-4 exhibits the impact on head loss during the final calcium and aluminum additions during the Rig 89 test.

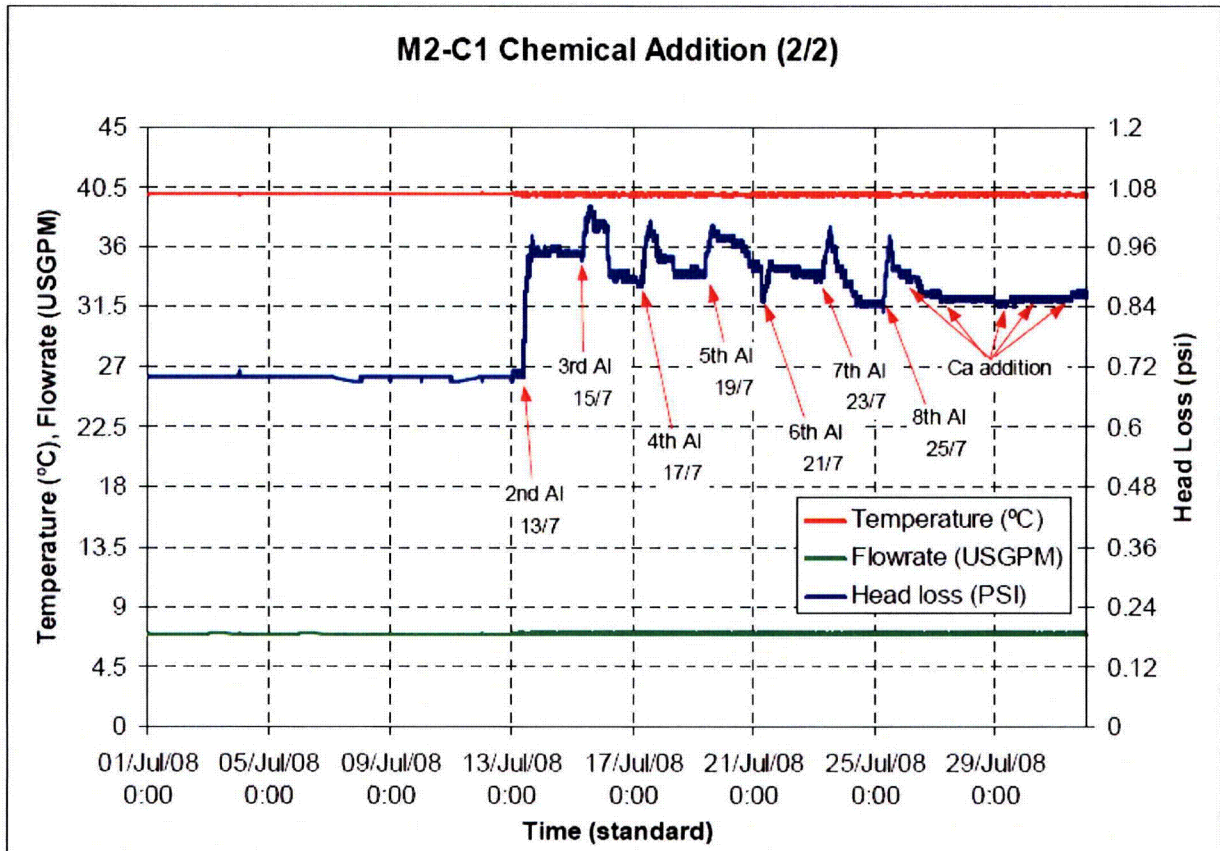


FIGURE O-4: HEAD LOSS ACROSS THE MPS2 STRAINER DURING THE FINAL ALUMINUM AND CALCIUM ADDITIONS

#### Test Results Discussion:

The test rig was filled with deionized water solution with boric acid, TSP and lithium hydroxide added in amounts representative of post-LOCA sump water. The pH of this solution was 7.93 at 20.5°C. To ensure conservatism in aluminum hydroxide precipitation, the pH was lowered (using nitric acid) to 7.10 (at 22°C) which is the conservatively calculated minimum pH of the post-LOCA sump water. Aluminum hydroxide precipitation is more likely at lower pH values. The temperature of the solution was maintained at 40°C for the duration of the test. Following filling of the test rig, particulate debris and then fiber debris was added to the test tank as described above. A total of 15 calcium chloride additions and 8 sodium aluminate additions were made over the course of the test. Once the debris-bed was established, the first aluminum and calcium additions were made as listed in Table O-4. These additions combined with the second calcium addition raised the head loss to about 0.7 psi. The next nine additions of calcium had no apparent effect on the debris-bed head loss. Throughout the test, aluminum concentration remained below the detection limit, indicating that all of the aluminum had either precipitated in solution or precipitated on surfaces ("plated-out") such as the debris-bed. As no visible precipitate was noted in the test tank, it was concluded that the aluminum plated-out on the debris-



bed. In the containment, since the aluminum sources are significantly separated from the sump strainer, it is likely that the aluminum will plate out on multiple surfaces throughout containment and much of the aluminum that is released by corrosion may never reach the strainer debris-bed. This effect was not credited in the test tank and adds further support to the conservatism of the Rig 89 test. Since the solution volume to strainer area is smaller in the Rig 89 test loops than in the containment sumps, aluminum additions were continued to match the predicted aluminum loading per unit strainer area. The final seven aluminum additions increased the head loss as listed in Table O-4. The second aluminum addition caused the head loss to increase above the acceptance criteria but the head loss subsequently drifted down and remained above the acceptance criteria for only a few days. Once the aluminum additions were complete, the final five calcium additions were made with no significant impact on the head loss. At the conclusion of the test, a sample of the debris-bed was sent for analysis by SEM/EDX. The results showed the presence of Ca, Al and P on the surfaces of the fibers and particles in the debris-bed. This is consistent with the precipitation of calcium phosphate and aluminum phosphate on the debris surfaces (plating out).

Once all chemical additions were complete, the debris-bed was checked for boreholes by lowering flow rate, allowing head loss to stabilize, and then restoring flow rate to the original value. Presence of boreholes would have been indicated by little or no change in head loss as the flow rate was reduced. However, head loss responded as expected in that head loss remained proportional to velocity squared during the flow changes (flow sweeps). Following the first set of flow sweeps, loop temperature was gradually cooled from 40°C to 21°C to quantify the impact of viscosity on head loss. Flow sweeps were performed at 21°C to check again for the presence of boreholes in the debris-bed.

The flow sweep tests revealed that head loss is very nearly proportional to velocity squared. Furthermore, the temperature reduction test revealed an almost immeasurable viscosity effect on head loss. These results suggest that turbulent flow exists across the debris-bed and that flow across the strainer is restricted.

In the MPS2 test, calcium chloride additions, when not tied with sodium aluminate additions, did not cause increases in head loss. The one exception was the second calcium addition, which may have caused a head loss jump from 0.60 to 0.69 psi. However, prior to the pump stoppage that occurred two days before this addition, the head loss had reached 0.66 psi following the initial calcium chloride and sodium aluminate additions on Day 0. The second calcium chloride addition may simply have aided the head loss recovery by increasing the ionic strength and accelerating the precipitation of aluminum phosphate.

Sodium aluminate additions, on the other hand, invariably increased head loss, if only temporarily in some cases. After the second aluminum addition, the head loss exceeded the short-term allowable debris-bed head loss, but not permanently. Subsequent aluminum additions resulted in head loss peaks, followed by lower stabilized head loss values. The data suggest that there is a limit to the effect of aluminum on head loss. The test ended at 0.85 psi, just short of the short-term allowable debris-bed head loss of 0.90 psi.

A calculation error resulted in slightly less aluminum being added to the test rig than would bound the total aluminum concentration which could occur post-LOCA in the MPS2 sump water. Application of the re-calculated aluminum concentration would have required an

extra 1½ aluminum additions to the test rig. The data suggest that a head loss limit was reached and that further additions of aluminum would not have increased head loss. Nonetheless, the test was still conservative; if a factor of 2 is used for corrosion inhibition by phosphates, then the tests added at least 65% more aluminum than was required.

As seen in Table O-4, the head loss exceeded the short-term acceptance criteria for a relatively short period of time during the Rig 89 test by approximately 15% (1.04 psi versus the acceptance criteria of 0.9 psi). Based on the test data, the maximum debris-bed head loss did not occur until well after the chemical additions had begun. The additions of sodium aluminate appear to have caused the head loss increase after the thin-bed was formed. The following significant margins and conservatisms in the testing ensure that exceeding the short-term head loss acceptance criteria by approximately 15% due to compounds formed by free aluminum ions in solution is inconsequential.

- Maximum sump pool water temperature is less than 200°F and exists at 7370 seconds (approximately 2 hours) after the accident. This is significantly before aluminum corrosion could release significant amounts of aluminum ions into solution. The vapor pressure of the water at 200°F is 11.5 psia as compared to the vapor pressure of water at the lowest possible containment pressure (14.2 psia) which is conservatively assumed to exist at the start of the accident. This provides approximately 2.5 psi of additional head loss margin which far exceeds the difference between the maximum debris-bed head loss and the acceptance criteria (approximately 1.04-0.9 or 0.14 psi). Sump water temperature continues to drop as time passes after the accident, adding additional margin due to subcooling. This particular subcooling margin is not necessary to explain the acceptability of the head loss result of 1.04 psi since the chemical precipitants take many hours and days to form and additional subcooling of the sump water far below 200°F will have occurred. However, this margin illustrates the impact of subcooling sump water on margin to head loss acceptance criteria. This margin provides assurance that the differences seen in the Rig 89 head loss prior to chemical addition and the Rig 33 head loss (no chemicals) have no consequential impact on ECCS pump NPSH margin post-accident.
- Aluminum corrosion due to sprayed or submerged aluminum is expected to add aluminum ions into solution relatively slowly. Corrosion rates in the literature vary widely but higher pH and the presence of boric acid tend to promote greater aluminum corrosion. Only a small fraction (approximately 4%) of the total aluminum surface area is submerged and the remainder must be impacted by the containment sprays in order to experience significant corrosion. Aluminum added into the solution during the testing was added in discrete amounts as highly soluble sodium aluminate to conservatively put aluminum ions in solution and promote precipitation. Aluminum corrosion, insulation breakdown (leaching of aluminum and calcium), and concrete degradation (producing calcium) all take significant time, thus making the addition of chemicals into the sump water a long-term issue which is unlikely to impact the debris-bed head loss until at least several hours or days after the accident.
- ICET testing showed that aluminum corrosion can be inhibited by the presence of phosphates and silicates. No credit was taken for this corrosion inhibition effect in calculating the amounts of aluminum to be added to the Rig 89 test loop.

- Head loss acceptance criteria is calculated for maximum ECCS pump flow lineup which only occurs in an ECCS pump lineup which supplies both hot and cold leg injection in order to prevent boron precipitation. Simultaneous hot and cold leg injection is initiated no sooner than 8 hours post-accident. The maximum flow rate in that mode (equal to the tested flow rate for all head loss testing) is 6800 gpm. The maximum flow rate prior to initiation of simultaneous hot and cold leg injection is approximately 5000 gpm or about 75% of the maximum ECCS flow rate. A lower flow rate for the first 8 hours of the accident will result in lower head losses across a fully formed debris-bed and thus more margin to the acceptance criteria. This lower flowrate will also promote settling of debris which is unlikely to be lifted back into solution and drawn to the debris-bed even if a higher flowrate is initiated 8 hours after the accident.

A recent ANL report by C.B. Bahn, et al "Technical Letter Report on Evaluation of Head Loss by Products of Aluminum Alloy Corrosion," August 11, 2008, ADAMS Accession No. ML082330143) reported head loss test results using aluminum metal coupons instead of a surrogate such as aluminum nitrate (or sodium aluminate as used in AECL-Dominion testing) to produce aluminum ions in a post-LOCA environment. The ANL testing found that the use of aluminum metal produces intermetallic particles which tend to promote aluminum compound precipitation prior to the point predicted by aluminum hydroxide solubility. Aluminum hydroxide precipitant creates a head loss in a fiber bed in the ANL vertical test loop. Additional head loss could be created by the addition of the intermetallic particles to the debris-bed. Use of aluminum nitrate or sodium aluminate to simulate corroded aluminum would not produce intermetallic particles. Additional precipitation of aluminum compounds due to the presence of intermetallic particles is consistent with the results of the MPS2 test, in which all of the aluminum added to the test tank came out of solution by plating out onto debris-bed surfaces, rendering any argument about aluminum compound solubility moot. The additional head loss due to the intermetallic particles also does not significantly impact the MPS2 test results since the small amount of intermetallic particles that may be formed and transported to the existing debris-bed will have little impact on head loss due to the presence of a very conservative particulate load from coatings (qualified and unqualified) and latent debris.

The ICET data on aluminum corrosion is potentially non-conservative since the lid of the test tank was insulated and the unsubmerged aluminum coupons did not have a lot of condensation dripping on them and thus the corrosion of the unsubmerged Al coupons is likely somewhat non-conservative. However, the Al release predicted using the WCAP and AECL release models are very similar and significantly overpredict the measured Al release in the ICET 5 test, as shown in Figure O-5.

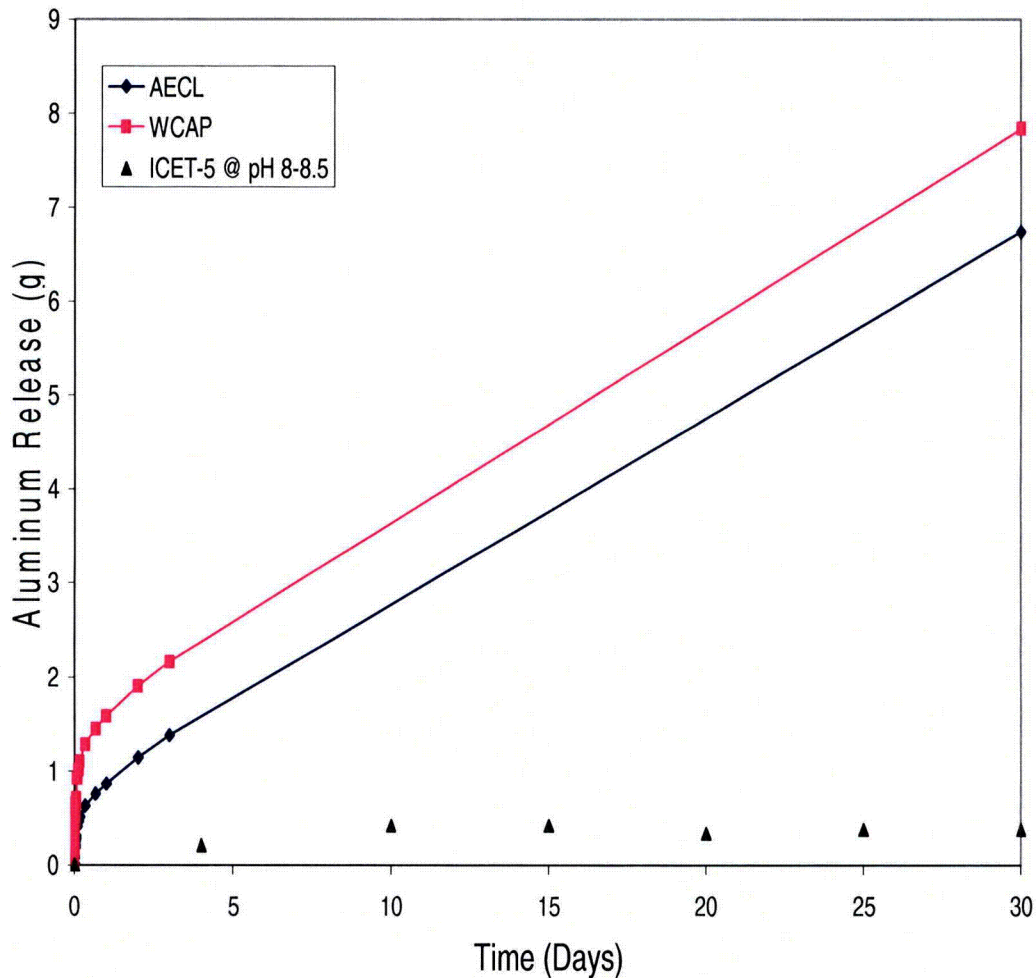


FIGURE O-5: PREDICTED ALUMINUM RELEASE PER SQUARE FOOT OF SUBMERGED ALUMINUM AT A LONG-TERM SUMP PH OF 8.5

Comparison of Test Results With and Without Chemical Effects:

Several reduced scale tests and large scale tests were run in a separate test rig (Rig 33) to determine debris-bed head loss with no added chemicals. These tests for MPS2 were run in early 2006 for strainer sizing prior to chemical effects testing and provided a debris-bed only worst case (thin-bed) head loss. The debris-only head loss in Rig 33 was higher than the debris only head loss in Rig 89 (prior to addition of chemical precipitants).

Significant similarities between the Rig 33 and Rig 89 tests included:

- The same scaling methodology was used for both Rig 33 and Rig 89 tests.

- Test debris amount and flow rate were scaled from specific plant parameters by the ratio of modeled strainer area to test strainer area.
- Fibrous and particulate debris additions were done to maximize thin-bed head loss by adding the particulate first and then adding the fiber in discrete amounts calculated to provide a uniform 1/16" bed on the strainer.
- The test temperature for both rigs was 40°C (104°F).
- The modeled strainer area for both rigs was 5620 ft<sup>2</sup>.

Significant differences included:

- Rig 89 used deionized water with MPS2-specific post-LOCA concentrations of TSP, Boron Acid, and Lithium Hydroxide while Rig 33 used Ottawa River water with known particulate and with no chemical treatment.
- A continuous stirrer was used in Rig 33 to maintain as much debris as possible in suspension while Rig 89 had occasional stirring of the bottom of the tank. Continuous stirring of the tank water is not prototypical of containment where much of the containment pool is expected to be quiescent.
- Rig 89 testing included addition of chemicals and sufficient time for precipitants to form after the fiber and particulate debris-bed had formed and head loss was stable whereas Rig 33 testing included no chemicals.
- Rig 89 particulate load was approximately half of the Rig 33 particulate load due to a recalculation of the expected amount of qualified coating debris based on a 5 times the diameter of the pipe break (5D) ZOI. The exception to this is that the particulate bypass test, M2-31, performed in the Rig 33 tank, used the same reduced particulate load as the Rig 89 test.

A brief summary description of the test results follows with the explanation of why the head loss differences existed.

#### Rig 33 Description:

MPS2 sump strainer reduced-scale thin-bed tests were conducted in Rig 33 to determine total strainer surface area. The Rig 33 reduced scale tests, conducted without chemicals, provided the basis for the final strainer area and fin pitch (distance between the fins). All reduced scale tests without chemical effects were run in open tanks using Ottawa River water to simulate the post-LOCA sump water. No TSP or boron was added to the test tank.

The test facility consisted of a 90 in. (2.3 m) diameter open plastic tank and a test module assembly. The test module assembly included one central fin and two half fins attached to the header. The test module assembly was positioned on the floor of the tank and was attached to a piping system leading to a pump below the tank. The pump discharge piping exit was located behind the fin/header assembly. The last piece of discharging piping was positioned on the tank floor along the tank wall and pointed to the right hand side. A variable speed electric stirrer was used in the thin-bed tests to suspend particulate and



fibrous debris. Thoroughly mixed debris was slowly added into the test tank at a location close to the stirrer. The use of a stirrer reduced debris settlement on the tank floor. Because of the shape of the tank and the flushing of the returning water, a counter-clockwise flow was maintained in the test tank during the test. In the thin-bed testing, stainless steel baffle plates were arranged around the test module to ensure that the turbulent flow eddies generated by the tank flow did not enter between the fins, possibly disturbing the bed formation. Debris addition was performed to maximize the head loss of the debris-bed. Particulate was added to the tank first and then fiber was added in increments calculated to cover the strainer in 1/16" thick fibrous debris-bed. These fibrous debris additions were spaced apart to allow maximum particulate capture and to determine how many were required to form the thin-bed with the highest head loss. The peak thin-bed head loss values in the reduced scale (Rig 33) testing were determined to be 0.81 psi and 0.68 psi. The predicted head loss using the NUREG/CR-6224 [G. Zigler et al., 1995] correlation was 1.3 psi.

The debris composition and debris quantities were the same for both of the reported Rig 33 tests.

#### Rig 89 Description:

Sump strainer chemical effects tests were conducted in the Rig 89 test loop to determine the influence of chemical precipitates on the worst-case debris-bed head loss. MPS2-specific chemicals were added into the test loop after the formation of the debris-bed. Each test loop includes a 16 in. x 16 in. x 36 in. strainer box and a 12 in. diameter x 18 in. long cylindrical debris addition tank. A header tank located 15 ft above floor level was connected to the test loop to accommodate extra fluid from debris addition or thermal expansion and to control the loop pressure. The loop was capable of producing flow rates from 1 to 20 gpm (1.5 L/s). Flow rates were controlled via a variable frequency drive and a magnetic flow meter. Two half fins were installed inside the strainer box with a pitch distance the same as installed in MPS2. For MPS2 testing, the fins and strainer boxes were horizontally oriented to simulate the installed module. No baffle plates were installed in Rig 89 tests. Water flow could enter the test strainer from the front, the top and the bottom of the fins.

The difference between the Rig 33 debris-bed head loss and the Rig 89 debris-bed head loss without chemicals is primarily due to two factors.

The first, and most significant factor, is that the particulate load for the Rig 89 test was just over half of the particulate load used for the Rig 33 tests due to the adoption of a 5D ZOI for coatings. The strainer area, developed from the Rig 33 tests, used particulate debris generation calculated using a 10D ZOI. Adoption of the 5D ZOI based on Westinghouse WCAP 16568-P was done after strainer sizing was complete. As expected, reducing the particulate debris directly impacted thin-bed head losses.

The second factor is that the Rig 33 tests were run using Ottawa River water whereas the Rig 89 test was conducted using deionized water. Though not measured for the MPS2 tests, the Ottawa River water particulate levels measured for later reduced scale tests run for Dominion plants suggest that river particulate levels are likely to have caused significant increased head loss in the Rig 33 tests over what would be observed in containment post-LOCA.

The following table presents test results from the two Rig 33 tests used for strainer sizing, the Rig 89 test prior to addition of calcium or aluminum compounds, and the NUREG/CR-6224 predicted head loss for comparison.

TABLE O-5: SUMMARY OF RIG 33 AND RIG 89 TEST RESULTS

Test	NUREG/CR-6224 (psi)	Rig 89 (psi)	Rig 33 (psi)
M2-22	1.3	--	0.81
M2-27	1.3	--	0.68
M2-C1	0.6	0.26	--

The reduction in particulate between the Rig 33 and Rig 89 tests for MPS2 caused an approximately 46% reduction in the NUREG predicted head loss (1.3 to 0.6) as seen in Table O-5. The average Rig 33 head loss reported in the Table O-5 is 0.75 psi. The Rig 89 head loss (without chemicals) is 0.26 psi or approximately 35% of the Rig 33 average value.

Most of the reduced head loss in the Rig 89 test (prior to chemical addition) can be attributed to a lower particulate load. However, a potentially significant portion of this reduction is due to use of the deionized water in the Rig 89 test which is far more prototypical of the RCS fluid than is the Ottawa River water used in the Rig 33 testing.

A particulate bypass test (M2-31) was run for MPS2 in Rig 33 using the same particulate load as used in the Rig 89 tests. This test was unique in Rig 33 because it was the only one which used the reduced particulate load and because it was conducted to determine whether the presence of latent fiber alone could trap particulate in the debris-bed. The test used the same flowrate, temperature, and scaled strainer area as was used for tests M2-22 and M2-27 documented in Table O-5. For test M2-31, all of the particulate was added first, prior to any fiber additions, the same as other Rig 33 tests. Four fiber additions were made. The four fiber additions were calculated to provide a 1/32, 1/64, 1/16, and 1/16 inch fiber bed respectively. The total fiber bed thickness was just over the 1/8-inch thin-bed thickness. A thin-bed was formed and the peak head loss was 0.052 psi, significantly below any of the other Rig 33 tests (which were done with a larger particulate load) and significantly above the Rig 89 test which was done with the same particulate load and a slightly smaller (1/8 inch total) fiber load. This test result further supports the conservatism of the Rig 89 test result.

Uncertainty exists both in the ability of the NUREG/CR-6224 correlation to predict the behavior of the debris-bed with very small particulate and in the repeatability of the test results which is nominally 25%. However, this uncertainty is overcome by the long-term margin for head loss at MPS2. Short term allowable debris-bed head loss for MPS2 is 0.9 psi. However, this head loss acceptance criterion is for a containment sump water temperature of 99°C (210°F). The sump water temperature cools relatively quickly post accident due to the action of the safety-related fan coolers and containment spray which is cooled in a heat exchanger prior to being sprayed into containment after recirculation pump start. The maximum temperature of the containment sump water is less than 200°F by approximately two hours post-LOCA for the limiting large-break LOCA. This temperature reduction adds significant margin due to subcooling (approximately 2.5 psi) to

the allowable debris-bed head loss before a cohesive debris-bed is likely to have formed and long before chemical precipitants begin to potentially affect debris-bed head loss. This margin overwhelms any uncertainty in the actual debris-bed head loss without chemical precipitants.

#### Precipitate Generation—Chemical Injection into Loop:

Precipitates were generated in the Rig 89 test tank as described above by adding sodium aluminate and calcium chloride to the test tank which already had a stable worst-case particulate and fiber debris-bed and which already contained TSP and boric acid to simulate the post-LOCA sump water.

The pH used for the test was near the lowest allowable in containment (7.0) which promotes precipitation of aluminum hydroxides.

The temperature of the test tank was maintained at 40°C which would also promote precipitation of aluminum hydroxides. Additionally, the temperature of the test tank was lowered to 21°C at the end of the test to determine if additional precipitation would occur and whether there was any impact on head loss from increased water viscosity at lower temperatures. Since no aluminum remained in solution throughout the test as seen in Table O-4 and since calcium phosphate precipitation is relatively insensitive to temperature in the tested range, no additional precipitation was expected and none occurred.

#### Head Loss Testing Without Near-Field Settlement:

No near-field settlement is credited in the MPS2 testing. The Rig 89 testing resulted in 56% of the debris attaching to the fins on the test module. Periodic stirring using the installed magnetic stirrer was done to maximize the amount of debris reaching the strainer surface. The remaining debris settled in the bottom of the test tank. Quantification of this debris was done by volume measurement (in buckets) when the tank was cleaned out following testing. No estimate or quantification was done to determine the separate amounts of particulate and fiber which settled on the test tank floor. The percentage of debris attached to the fins was similar to that seen in the reduced scale testing conducted in Rig 33 where for test M2-22, 67% of the debris attached to the fins and for test M2-27, 58% of the debris attached to the fins. A magnetic brush was used intermittently in the Rig 89 test to re-suspend settled debris. In the Rig 33 tests, the continuous stirring and periodic floor sweeping led to somewhat more debris attaching to the fins.

The conservatism of the Rig 89 test results relative to the containment was demonstrated by the following factors:

- The test tank size for Rig 89 is a 16-in x 16-in x 36-in stainless box. No significant debris transport was needed for debris to reach the strainer surface. Debris transport distance in the test tank was essentially zero whereas in containment, due to the large footprint of the strainer, debris transport distances to at least one leg of the strainer are expected to be substantially greater than this test tank size.

- Walnut shell particulate (used as the surrogate for epoxy) has a density of approximately  $80 \text{ lb/ft}^3$  as compared to the higher density of epoxy ( $94 \text{ lb/ft}^3$ ). Thus, epoxy is more likely to settle than the particulate surrogate used in testing.
- Turbulence created by the break will serve to maintain heavier debris in solution only in a small region local to the break waterfall. This turbulence will not significantly impact approach velocity or the amount of debris entrained in the water column near much of the strainer surface area due to the large strainer footprint.
- Much of the small particulate debris created by the break blowdown will be directed upwards in containment and will settle on myriad surfaces throughout containment and only slowly, if at all, be washed to the containment floor by containment sprays.
- A significant portion of the particulate expected to be generated is from unqualified coatings which are postulated to be dislodged from components throughout containment by temperature and humidity in containment post-LOCA. Degradation of these unqualified coatings will take significant time (hours, and probably days) and thus the amount of particulate in the debris-bed (and in the test tank) is quite conservative. Additionally, all of the unqualified coating is postulated to fail as small, transportable particulate when in reality, much of the failure is far more likely to occur as large pieces which will not transport.
- The strainer in containment sits approximately 7 inches above the containment floor. Thus, any particulate which slides along the floor with the sump water motion is unlikely to reach the strainer surface.

**ATTACHMENT 2**

**UPDATED INFORMATION ABOUT DOWNSTREAM EFFECTS ANALYSIS AND  
CHEMICAL EFFECTS TESTING FOR MILLSTONE POWER STATION UNIT 3**

**DOMINION NUCLEAR CONNECTICUT, INC.  
MILLSTONE POWER STATION UNIT 3**

## **UPDATED INFORMATION ABOUT DOWNSTREAM EFFECTS ANALYSIS AND CHEMICAL EFFECTS TESTING FOR MILLSTONE POWER STATION UNIT 3**

### **1.0 BACKGROUND:**

By Dominion Nuclear Connecticut, Inc. (DNC) letter dated February 29, 2008, (Serial No. 07-0797, ADAMS Accession No. ML080650561), DNC provided the supplemental response to Generic Letter (GL) 2004-02, for Millstone Power Station Units 2 and 3 (MPS2 and MPS3). This attachment updates information that was previously provided concerning downstream effects analysis and chemical effects testing for MPS3. Accordingly, the balance of this attachment provides the following items:

- 1.C CONSERVATISMS
- 3.M DOWNSTREAM EFFECTS – COMPONENTS AND SYSTEMS,
- 3.N DOWNSTREAM EFFECTS – FUEL AND VESSEL, and
- 3.O CHEMICAL EFFECTS.

### **1.C CONSERVATISMS:**

Detailed analyses of debris generation and transport ensure that a bounding quantity and a limiting mix of debris are assumed at the Emergency Core Cooling System (ECCS) containment sump strainer. Using the results of the analyses, conservative head loss testing was performed to determine worst-case strainer head loss and downstream effects. Chemical effects bench-top tests conservatively demonstrate the solubility and behaviors of precipitates, and applicability of industry data on the dissolution and precipitation tests of station-specific conditions and materials. Reduced-scale testing was performed with the Atomic Energy of Canada, Limited (AECL) Test Rig 33 and Multi-loop Test Rig 89. The reduced-scale testing established the influence of chemical products on head loss across the strainer surfaces by simulating plant specific chemical environment present in the water of the containment sump after a Loss-of-Coolant-Accident (LOCA). These analyses rely upon the conservatisms discussed in the balance of this section.

1. Test evaluations demonstrate that a fully formed thin-bed of debris takes significant time (hours) to form and is dependent on unsettling debris throughout the test tank. Consequently, a worst-case thin-bed of debris will be difficult to form and will not form until several hours after sump recirculation can be initiated. Significant debris settling and significant sump water subcooling occurs during the formation of a debris-bed so additional NPSH margin is present for chemical effects head loss.
2. The debris load in head loss testing was taken from the debris transport calculation, which credits no particulate settling.
3. Debris introduction procedures in chemical effects testing resulted in minimum near-field settling and conservatively high head losses.

4. Debris introduction was accomplished in a carefully controlled manner to result in the highest possible head loss. Particulate was introduced initially, which was followed by discrete fiber additions after the particulate debris was fully circulated.
5. Only fines of fibrous debris were used in head loss testing, conservatively simulating fibrous debris erosion occurring at recirculation start.
6. The test tank was periodically stirred in the Rig 89 testing and continuously stirred in the Rig 33 testing. However, local areas of turbulence that may exist in any post-LOCA containment sump water are expected to be limited to certain portions of sump water volume. Consequently, much of the sump water will be quiet and have near zero velocity.
7. Particulate settling in head loss testing was conservatively minimized through use of a lower density walnut shell particulate as a surrogate for the higher density epoxy coating particulate that may be present in post-LOCA sump water.
8. Downstream wear analysis used the Large Break LOCA particulate load to determine abrasive and erosive wear. This is a conservative particulate loading, in view of the following.
  - Much of the particulate included in analysis is unqualified coating that is outside the break zone of influence (ZOI). This unqualified coating is assumed to potentially dislodge due to exposure to the containment environment. However, an exposure based mechanism to dislodgement, if it occurs at all, is likely only after many hours and days.
  - The low velocity of the sump water column and the significant number of surfaces throughout containment promote significant settling of particulate in containment. Settled coating will not be drawn through the ECCS strainer since the strainer sits approximately seven inches above the containment floor. Additionally, qualified coating postulated to fail in the presence of the zone of influence (ZOI) is not buoyant in the sump water column.
  - The capture of particulate in the debris-bed on the strainer does not occur in this analysis, maximizing effects of downstream wear.
9. Conservatively, the base concrete dissolution is assumed uninhibited by the presence of tri-sodium phosphate (TSP), even though bench scale test solutions demonstrate inhibition of concrete degradation at containment sump water pH levels. Consequently, calculations of the amount of calcium to be added to the test tank for head loss tests were conservative.
10. The amount of aluminum and associated test results concerning its release into the simulated post-LOCA sump water through corrosion of aluminum surfaces was conservative based upon several conditions:
  - Aluminum corrosion amounts were calculated at high pH which favors corrosion, and aluminum precipitation was done at low pH which favors precipitation.

- Testing with a lower pH favors precipitation. Testing using Rig 89 was with pH 7 to encourage aluminum compound precipitation, even as actual pH in sump water is approximated as pH 8 and a minimum Technical Specifications is at pH 7.
- Rig 89 testing was evaluated conservatively with low short-term acceptance criteria, along with the maximum aluminum concentration of the sump water that exists only after 30 days.
- Analysis conservatively does not account for the possible inhibitory effect of silicate, phosphate or other species on aluminum corrosion.
- The rate of corrosion is maximized by analysis that does not assume development of passive films, e.g., no aluminum oxides remain on aluminum surfaces. Passive films can otherwise be used to decrease the corrosion rate by a factor of the exposure time. Consequently, having no aluminum oxides remain on aluminum surfaces so all aluminum released by corrosion enters the solution is conservative.
- All aluminum not submerged in containment is considered by analysis to be exposed to containment sprays and therefore available for corrosion. However, some of the aluminum sources in containment, such as the out-of-core detector holders, may not be subject to a continuous containment spray and would not contribute to the total aluminum concentration in the containment pool.
- All aluminum released into the solution is assumed to transport to the debris-bed instead of plating out on the multiple surfaces throughout containment. During bench-top testing, aluminum plated out on glass beakers and during reduced scale testing, aluminum plated out on fiber. It is reasonable to expect that a portion of the aluminum ions released into solution will plate out on some of the multiple surfaces in containment prior to arriving at the debris-bed on the strainer.
- Chemical effects test evaluations conservatively neglect the effect of the presence of oxygen in the sump water. Corrosion rate of aluminum in aerated pH 10 alkaline water can be a factor of two lower than when the rate is measured in nitrogen-deaerated water. This data is in NUREG/CR-6873, "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191," (Jain et al. April 2005).

### 3.M DOWNSTREAM EFFECTS—COMPONENTS AND SYSTEMS:

No design or operational changes were made as a result of downstream effects analysis.

DNC uses methodology for downstream effects analysis that is consistent with Pressurized Water Reactor Owner's Group (PWROG) Technical Report (TR), WCAP-16406-P, Revision 1, "Evaluation of Downstream Sump Debris Effects in Support of GSI [Generic Safety Issue]-191," and the NRC limitations and conditions described in the NRC Safety Evaluation regarding the performance of this analysis, dated December 20, 2007, (ADAMS Accession No. ML073520295).



Downstream component clogging was previously described in the supplement to GL 2004-02 response by DNC letter dated February 29, 2008, Serial No. 07-0797, (ADAMS Accession No. ML080650561).

This update of downstream effects analysis includes the following:

- Wear in the Safety Injection (SI), Charging (CHS), and Recirculation Spray (RSS) pumps, manually throttled valves, motor operated valves, orifices, and heat exchangers. The evaluation of the wear effects on the performance of these components is also evaluated.
- Evaluation of the downstream instrumentation, including temperature indicators, pressure indicators, and flow indicators for potential blockage due to the presence of debris.

Debris from the LOCA may pass the containment sump strainer and enter the RSS and ECCS, causing abrasion and erosion on the surfaces of components. A wear model was developed per the WCAP-16406-P, Revision 1 to assess the amount of wear in RSS and ECCS components based on the initial debris concentration in the pumped fluid, the debris concentration depletion, the hardness of the wear surfaces, and the mission time.

#### Abrasive Wear Model:

Abrasive wear in the close running clearances may result from free-flowing abrasive wear or packing type abrasive wear, as described by the Archard model. WCAP-16406-P, Revision 1, provides for consideration of these two abrasive wear model types:

- free flow, and
- packing (or Archard's).

The principal differences between the Archard wear model and the free-flowing abrasive wear model are:

- The wear associated with the Archard model is single-sided. The debris packing adheres to the stationary surface (wear rings), and wear only the rotating surface (impeller hub). The free-flowing abrasion model wears both the rotating and the stationary surfaces individually at rates determined by the fluid debris concentration and the hardness of the wear surfaces.
- The wear rate of Archard's model is constant. Once the packing is established, debris depletion on the bulk fluid does not affect the rate of wear. For the free-flowing abrasive wear model, the rate of wear is a direct result of the debris concentration in the fluid at any time during the pump duty cycle. Both models are considered valid because both will reasonably predict abrasive wear in close tolerance components. The wear predictions from both models match the results from field testing that support the WCAP-16406-P, Revision 1. The Archard model can also be adjusted to reflect changes in debris concentration.

### Erosive Wear Model:

Erosive wear is the result of particles impinging on a component surface, or edge, causing material to be removed from that surface due to momentum effects. This type of wear is noticed in components with high velocity flows such as throttling valves, orifices, heat exchangers, tubes and pump components.

### Pumps:

The abrasive and erosive wear of a pump's internal subcomponents resulting from pumping debris-laden water will cause an increase in the flow clearances of the pump. For abrasive wear of close-tolerance subcomponents such as wear rings, both Archard's and free flowing abrasive wear were considered and the wear which produced the maximum wear was conservatively used.

The increase in flow clearances is evaluated for impact on hydraulic performance of the pump. A second issue associated with wear is the potential for changing system resistance curve due to wear of components such as valves and orifices. The results indicate that all valves, plate orifices, multi-stage orifices, and containment spray nozzles pass the criteria in the WCAP-16406 Revision 1 and therefore, the effect on system flow rates is negligible.

Hydraulic performance and mechanical dynamic performance of each ECCS pump is found acceptable because the total abrasive and erosive wear of small clearance areas on the ECCS pumps is less than the wear allowance in the original equipment design, and are therefore, acceptable. Thus, the hydraulic performance of the ECCS pumps will not be impaired due to abrasive and erosive wears of pump subcomponents while pumping debris-laden water for 30 days post-LOCA.

### Pump Mechanical Seal Wear:

WCAP-16406-P, Revision 1 calls attention in particular to the mechanical shaft seal assembly and its functionality with debris laden fluid. Westinghouse pump testing referenced in WCAP-16406-P, Revision 1 has been used as a basis for demonstrating mechanical shaft seal assembly performance. The results of this testing suggest that no failure is expected of seals due to debris ingestion within the defined mission time for the ECCS and CS pumps.

MPS3 site-specific evaluation of pump seal performance with debris laden fluid includes;

- pump seal injection/leak-off rates with respect to fluid velocity and suspension of debris in fluid,
- pump seal critical clearances and materials with respect to debris entering into critical clearances, and an
- annular orifice calculation to determine the change in flow rate through the pump seal packages during the mission time.

These analyses use debris loading data from MPS3 and indicate that debris is not expected to cause mechanical seal leakage in excess of acceptable limits. The technical basis for the conclusion includes the following considerations:

- The debris is too large to pass through the primary seal and cause wear.
- The amount of the debris that can be expected drawn into the seal injection line is limited by flow velocities, and whatever debris that does get introduced will not settle in the mechanical seal region.
- If it is assumed that wear and failure of the primary seal could occur, the disaster (safety) bushing would wear a negligible amount in 30 minutes, and the leakage rate of the pump would be kept to an acceptable limit until the leakage could be isolated and another train of ECCS or CS could be started.
- It was shown that the gap due to wear of the disaster bushing would increase the leakage rate by a maximum of 0.26%. This percent of increase will remain the same and is a negligible change.

For these reasons, the downstream effects analysis show that debris would not be expected to cause excessive seal leakage or mechanical seal failure in these pumps.

#### Heat Exchangers:

The actual wall thickness of the heat exchangers minus the tube wall thickness lost to erosion is greater than the minimum wall thickness required to withstand the internal tube design pressure. Therefore, the heat exchanger tubes have sufficient wall thickness to withstand the erosive effect of the debris-laden water for a period of 30 days post-LOCA.

#### Other components:

The manually throttled valves, plate orifices, multi-stage orifices, and containment spray nozzles in the recirculation flow path pass the criteria set forth per WCAP-16406-P, Revision 1 and therefore, the calculated wear will have an insignificant effect on the system flow. No further evaluation is required. No piston check valves are required to close during recirculation so no further evaluation is required.

#### Instrumentation:

The instrumentation is mounted either on the top or side of the piping and is not susceptible to failure due to plugging. The velocity of the fluid as well as the orientation of the instrument in the pipe will allow the debris to continue flowing beyond the instrumentation. Therefore, the identified instrumentation will not be adversely affected by debris in the recirculation flow path.

### 3.N. DOWNSTREAM EFFECTS—FUEL AND VESSEL:

DNC completed a LOCA Deposition Analysis Model (LOCADM) to quantify the maximum expected deposition of chemical precipitates on the MPS3 fuel and the resultant maximum clad temperature. The results show that the maximum clad temperature is a monotonically decreasing function of time from a maximum of approximately 337°F at the start of recirculation to 131°F at the end of 30 days. The maximum temperature is well below the acceptance criterion of 800°F. The scale buildup starts at recirculation and reaches a maximum of 38 microns at the end of 30 days. This takes into account the potential for strainer bypass. This is well below the acceptance criteria of 1270 microns

(50 mils). The results are essentially the same as shown in Figure 5-3 of WCAP-16793-NP, Revision 0, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," dated February 4, 2008. Thus, the conclusions of the WCAP-16793-NP for the fuel and vessel analysis are applicable to MPS3 and demonstrate acceptable long-term core cooling in the presence of core deposits.

Although this analysis to date has incorporated conditions and limitations imposed on use of WCAP-16793-NP, the initial NRC comments provided for this technical report have been withdrawn and the WCAP is currently in revision. The source of the revision is understood to be related to the fuel blockage analysis, not the fuel deposit methodology. Upon issuance of revised guidance, and the anticipated Regulatory Issue Summary to inform the industry of the NRC staff's expectations and plans regarding resolution of this remaining aspect of GSI-191, DNC assumes that the existing analysis for MPS3 will remain bounding of plant conditions and limitations on LOCADM use in a final Safety Evaluation (SE) for WCAP-16793-NP. Should this assumption be demonstrated to be invalidated by the ongoing industry actions on this issue, in accordance with the station corrective action program, DNC would take the appropriate corrective action to update the analysis and the design basis, accordingly.

### 3.O CHEMICAL EFFECTS:

Methodology for chemical effects testing and evaluations have used observations of Integrated Chemical Effects Tests (ICET), and the Westinghouse Owners Group document WCAP-16530-NP, Revision 0, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," Laine et al. (2006), and various NRC sponsored research presented at public meetings or posted on the NRC website. The balance of this section provides an update to the supplement for MPS3. Chemical effects bench-top tests conservatively demonstrate the solubility and behaviors of precipitates, and applicability of industry data on the dissolution and precipitation tests of station-specific conditions and materials. Reduced-scale testing was performed with the AECL Test Rig 33 and Multi-loop Test Rig 89. The reduced-scale testing established the influence of chemical products on head loss across the strainer surfaces by simulating plant specific chemical environment present in the water of the containment sump after a LOCA. These analyses rely upon the evaluation methodology and conservatisms discussed in the balance of this section.

#### Potential for Clean Strainer Surface Area:

MPS3 chemical effects head loss testing was conducted at the Chalk River Ontario Laboratories run by AECL. It is expected that due to debris settling and very low pool velocities that much of the debris at MPS3 will not reach the strainer. For any small break LOCA, much more debris could be expected to not reach the strainer. The strainer construction at MPS3 has 17 modules spanning a significant arc of the containment basement annulus, and has approximately half of the strainer directly over the sump pit and the other half over a channel which flows to the sump pit. Thus, debris from any particular break will more likely to be drawn to the portion of the strainer over the sump pit due to lower flow losses when recirculation flow begins. Despite these factors that encourage the existence of open strainer surface area, no credit is taken for open strainer surface area in the evaluation of head loss due to chemical effects.

#### Debris-bed Formation:

The worst-case debris-bed for MPS3 has consistently been the formation of a thin-bed. Extensive testing prior to addition of chemical precipitants has determined the thin-bed fiber thickness is nominally 1/4 inch. Since the fibrous and particulate debris mixtures for MPS3 are essentially the same for any of the limiting break locations, the break which produces the maximum particulate load produces the worst-case head loss when an approximately 1/4 inch thick fibrous bed is deliberately formed following the addition of particulate. The same break which produces the worst-case head loss in the absence of chemical effects is expected to produce the worst-case head loss with chemical precipitants added to the debris-bed. Debris-bed formation for the chemical effects testing followed the same procedure as for previous head loss testing to ensure the worst-case debris-bed was formed (i.e. head loss was highest). All of the particulate was added to the test tank which contained borated water with trisodium phosphate (TSP,  $\text{Na}_3\text{PO}_4$ ) and lithium hydroxide (LiOH) to simulate the post-LOCA sump water. Once the particulate was well distributed throughout the test tank water, fiber debris was added. Fibrous debris was prepared consistent with previous head loss tests in order to ensure individual fiber separation and maximum head loss. Fibrous debris was added in two increments, each of which had enough fiber to form a 1/16 inch thick fiber bed. These additions were spaced 30 minutes apart to allow sufficient time for the previous addition to pack onto the strainer and begin collecting particulate debris. Since the nominal thin-bed thickness for MPS3 was determined to be 1/4 inch, no further fiber additions were made. No chemical additions to this debris-bed were made until after the head loss had stabilized.

#### Plant Specific Materials and Buffers:

Potentially reactive materials included in the MPS3 containment have been listed in Table O-1 of the supplement previously provided by DNC letter Serial No. 07-0797, dated February 29, 2008, (ADAMS Accession No. ML080650561). Table O-1 is updated below to remove zinc and show a more realistic total for bare concrete. Zinc is no longer included in this table because there is no evidence that zinc reacts to form any significant chemical precipitant affecting debris-bed head loss.

The pH buffer at MPS3 is TSP which contributes phosphate ions to the post-LOCA sump water. Degradation of bare concrete due to contact with sprays or being submerged in post-LOCA water potentially contributes calcium to the sump water. Together, the calcium and phosphate are thought to potentially form an insoluble calcium phosphate which could contribute to debris-bed head loss. The revised amounts of reactive material are shown in Table O-1 below.

Table O-1: Surface Areas of Materials Subjected to Containment Spray and Submergence

Material	Surface Area Submerged (ft <sup>2</sup> )	Surface Area Exposed to Containment Spray (ft <sup>2</sup> ) (does not include submerged material)
Aluminum	120	1080
Carbon Steel (uncoated)	1000	0
Concrete (uncoated)	100	408
Fibrous Insulation (Transco Thermal Wrap and some NUKON™)	1390 ft <sup>3</sup> a	0
Microtherm	1.1 ft <sup>3</sup> a	0

Note a: This entry is a total volume of fibers dislodged from piping and equipment.

The worst-case pH profile is slightly altered from the original submittal in that the pH still peaks at about 8.5, but is likely to drift down only to about 8.1 in the worst (high pH) case which promotes maximum corrosion of aluminum. Sump water temperature and containment air temperature profiles are unchanged from the original supplemental response.

#### Approach to Determine Chemical Source Term:

Chemical effects testing consisted of chemical effects assessment, bench-top testing and reduced-scale tests. The chemical effects assessment has been previously described in the DNC supplement. Bench-top testing was conducted to gain an understanding of the chemistry to be expected in reduced-scale testing. Reduced-scale testing was conducted to determine the debris-bed head loss in the presence of expected chemical precipitants. Details of the bench-top testing and the reduced scale testing are described in the balance of this section.

#### Chemical Species Formation:

The assessment performed an extensive review to determine the chemical species likely to be formed in the containment sump water post-accident. The assessment concludes that corrosion of aluminum could lead to formation of aluminum hydroxide or oxyhydroxide precipitates but that formation of these precipitates is unlikely at MPS3 due to the low aluminum concentrations expected in the sump water. Degradation of concrete and fibrous insulation in the containment sump water could lead to the release of small amounts of calcium into the sump water and this calcium may combine with the phosphate produced by the TSP buffer to form an insoluble calcium phosphate.

The conclusions of the chemical effects assessment are:

- Calcium phosphates are not expected to precipitate from the MPS3 post-LOCA sump water. However, a limited number of bench-top tests were run to assess the risk of calcium phosphate precipitation.

- The calculations show that the unsubmerged aluminum (Al) is the largest contributor of Al released into the sump water, while the contribution from submerged aluminum surfaces is much smaller. The predicted aluminum concentrations in the sump water resulting from release from the submerged and sprayed aluminum surfaces are 0.4 and 1.4 mg/L, respectively.

The total aluminum concentration in the post-LOCA sump water is predicted to be 1.8 mg/L, well below the solubility limits for aluminum hydroxide. Since the predicted dissolved aluminum concentration does not exceed the solubility of amorphous aluminum hydroxide, aluminum hydroxide precipitation is not expected. However, to be conservative, bench-top testing was performed to;

- Experimentally determine whether aluminum hydroxide will precipitate under MPS3 conditions,
- Characterize any resulting precipitates, and
- Develop a method to produce precipitates for reduced scale testing should such testing be required.

Chemical effects head loss testing showed that all of the aluminum added to the tank plated out or precipitated, most on the debris-bed. This test result makes the aluminum solubility argument moot.

#### Bench-top Testing:

Bench-top testing was performed to support the strainer chemical effects testing.

The bench-top testing consisted of the following tasks:

- Calcium dissolution and Calcium Phosphate precipitation testing
- Precipitation testing of Aluminum Hydroxide
- Determination of dependence of Walnut Shell (paint surrogate) properties on chemistry

#### Calcium Dissolution and Precipitation Testing:

Bench-top tests using debris materials specific to MPS3 were conducted to determine the amount of calcium released from concrete and insulation materials. For MPS3, a clean concrete coupon, Transco Thermal Wrap fiber and microtherm were placed in each of four 5-liter flasks containing 4L of a solution of 1500 mg/L Boron with pH of 5, 6, 7, and 8, respectively. Temperature of the fluid in the flasks was 90°C. A magnetic stirrer was used in each of the flasks. The masses of insulation material and surface area of concrete coupon were calculated based on the expected amounts of these materials in the containment sump water post-LOCA. The concrete coupon size was determined based on a conservative and bounding estimate of bare concrete which could exist in containment. The dissolution tests duration was 30 days.

Dissolution test results in the absence of TSP:

- The pH of the solutions which started at pH 5 and 6 increased while the pH of the solutions which started at 7 and 8 were relatively stable. This is likely due to the dissolution of the concrete which produces a salt ( $\text{CaSiO}_3$ ) of a strong base ( $\text{Ca(OH)}_2$ ) and a weak acid ( $\text{H}_4\text{SiO}_4$ ).
- The concrete coupons fully dissolved in the pH 5 and 6 solutions and were significantly degraded in the pH 7 and 8 solutions.
- The major species in solution at the end of 30 days are calcium (Ca), silicon (Si), and sodium (Na) with minor amounts of potassium (K) and magnesium (Mg) detected. Concentrations of sodium are due to the use of NaOH to adjust the pH.
- Calcium concentration was somewhat higher in the pH 5 solution (87 mg/L) than in the pH 7 (78 mg/L) or the pH 8 solution (70 mg/L). The pH 7 and 8 solutions are more representative of the long-term pH in the containment sump water since the minimum pH is 7.1 and the maximum is calculated to be approximately 8.5.

Identical tests were run with the only difference being that TSP (at the expected 30 day concentration) was added to the flasks along with the insulation materials, concrete, and borated water. The most striking aspect of the tests with TSP is the apparent inhibition of concrete dissolution which occurred with TSP present. The presence of TSP was expected to cause precipitation of calcium phosphate, leading to either;

- lower concentrations of calcium in solution and increasing the dissolution of concrete and insulation, or
- calcium phosphate on surfaces inhibiting further release of calcium.

However, though lower concentrations of calcium in solution were observed with TSP present, dissolution of concrete did not occur. Calcium concentration without TSP at pH 7 after 30 days was 78 mg/L as compared to the test with TSP at pH 7 after 30 days which yielded a calcium concentration of 2.2 mg/L.

To conservatively predict calcium release, the data from the MPS3-specific bench-top tests were used to determine the amount of calcium to be added to the test tank for the reduced scale tests, which are discussed later. Results obtained using these data are somewhat lower than results reported in WCAP-16530 [Lane et al., 2006]; however, powdered concrete with a surface area far in excess of that seen in containment was used in the WCAP testing which would lead to higher calcium concentrations.

The concentration of calcium to be added to the Rig 89 test tank was conservatively determined from the results of the bench-top testing, which determined the dissolution of concrete and fibrous insulation in the post-LOCA solution in the absence of TSP. The results of the bench-top tests showed that TSP inhibited the dissolution of concrete and thus the calcium concentration used in Rig 89 is significantly conservative. Calcium dissolution in these bench-top tests followed first order kinetics and so can be described by the following equation:



$$C(t) = C^{\infty}(1 - \exp(-kt))$$

Where  $C(t)$  and  $C^{\infty}$  are the dissolved calcium concentrations at time  $t$  and time infinity and  $k$  is the first order dissolution rate constant.

Table O-2 lists the values of  $C^{\infty}$  and  $k$  obtained by fitting the measured calcium concentrations in the four dissolution tests.

Table O-2: Calcium Concentration Factors

Parameter	pH 5	pH 6	pH 7	pH 8
$C^{\infty}$ (mg/L)	82	77	103	68
$k$ (1/hr)	0.017	0.0049	0.0029	0.0034
$r$ (g/m <sup>2</sup> x hr)	1.8	1.6	1.96	1.4

In general calcium dissolution increased at lower pH values. The release rate ( $r$ ) for the pH 7 test (lowest pH allowed in containment) was used in the following equation to determine the concentration post-LOCA after 30 days:

$$C_{30d} = r * \text{Concrete surface area} * 30\text{days} * 24 \text{ hr/day/sump volume}$$

Using a concrete surface area of 508 ft<sup>2</sup> (from Table O-1), a minimum sump volume of 160,000 ft<sup>3</sup>,  $r$  value from above table at pH 7 (1.96), and a conversion factor of 0.3048 m/ft, this equation yields a calcium concentration of 14.7 g/m<sup>3</sup> (or 14.7 mg/L), which was used for the Rig 89 testing.

To characterize calcium phosphate precipitation under MPS3 sump water chemistry conditions, the solutions remaining at the end of the dissolution tests conducted without TSP at pH 5, 6, 7 and 8 were mixed with TSP solutions at the same pH, and at temperatures of 25, 50, 60 and 80°C. Precipitation was visually observed in some samples and quantified using turbidity measurements. Table O-3 summarizes the results of the visual observations and turbidity measurements of the test solutions for the precipitation tests. Turbidity measurements above 6 FTU<sup>(1)</sup> were considered to indicate a positive detection of precipitate, though the precipitate may not have been visually observable. In each test above room temperature, the turbidity was measured at temperature and at room temperature. No difference in the two readings was noted. Precipitation was visually observed at pH 7 and 8 at all temperatures studied, at pH 5 and 6 at 80°C. This behavior is expected because the dissolved calcium and phosphate concentrations in the solutions are supersaturated relative to the known solubility of hydroxyapatite. The results are as expected since the solubility of hydroxyapatite decreases as the temperature increases and shows a minimum around 50-60°C.

<sup>(1)</sup> FTU = 1 NTU. The NTU (Nephelometric Turbidity Unit) is reserved for turbidity measured using a nephelometer, which measures light reflected at 90 degrees from the source beam. Measurements were made using a spectrophotometer, which measures light transmitted through 180 degrees, and are therefore listed as FTU (Formazin Turbidity Unit).

Table O-3: Summary of Precipitation Behavior as Determined by Visual Observation and Turbidity Measurements in the Calcium Precipitation Tests

Temperature (°C)	pH 5		pH 6		pH 7		pH 8	
	Visual	Turbidity	Visual	Turbidity	Visual	Turbidity	Visual	Turbidity
25	N	N	N	N	N/P <sup>a</sup>	P	N/P <sup>b</sup>	P
50	N	N	N	P	P	P	P	P
60	N	N	N	P	P	P	P	P
80	P	P	P	P	P	P	P	P
P Precipitation observed								
N No Precipitation Observed								
<sup>a</sup> Precipitation observed on day 7								
<sup>b</sup> Precipitation observed after 1 hour								

The solubility of calcium phosphate is lowest at pH values around 7 and temperatures below 100°C. The MPS3 test results are consistent with these observations.

Both WCAP-16530 and the Integrated Chemical Effects Tests (ICET) show that in the absence of added calcium silicate insulation (MPS3 debris-bed has no calcium silicate) the amounts of calcium released from fiberglass insulation are insufficient to result in significant precipitation of calcium phosphate. Additionally, leachate produced from Nukon insulation (similar to the Transco fiberglass in MPS3 containment) amounts were similar to, or less than amounts found by, WCAP testing. Thus, calcium from fiberglass insulation is not a significant source for the post-LOCA containment sump water.

The following conclusions can be drawn from the data on calcium release and precipitation under MPS3 sump water conditions:

1. Calcium release from concrete and other debris followed first order kinetics,  $C(t) = C_{\infty}(1 - \exp(-kt))$ .
2. Concrete dissolution increased as the pH decreased in borated water.
3. The presence of TSP in the test solutions inhibited concrete dissolution.
4. The presence of TSP in the test solutions decreased the measured calcium concentration, due to inhibition of concrete dissolution and precipitation of calcium phosphate.
5. The degree of calcium phosphate precipitation increased as the pH increased.
6. The degree of calcium phosphate precipitation increased as the temperature increased.

The bench-top testing shows that there is a potential for calcium phosphate precipitation for MPS3.

### Aluminum Precipitation:

At pH 7, the data suggest that no precipitation will occur at aluminum concentrations less than about 12 ppm. These data can be used to define target aluminum concentrations in the post-LOCA sump water that can be used to refine post-LOCA pH and temperature evolutions and containment aluminum inventories.

Aluminum solubility has also been investigated by Argonne National Laboratory (ANL). The report by C.B. Bahn, et al "Technical Letter Report on Evaluation of Long-term Aluminum Solubility in Borated Water Following a LOCA," dated February 28, 2008, (ADAMS Accession No. ML082330153) reports on solubility tests conducted at aluminum concentrations ranging from 40-98 ppm and pH from 7.0-8.5 in borated water solutions. These solutions were subjected to a heating and cooling regimen to simulate the heating and cooling that would occur in post-LOCA sump water as it was recirculated between a heat exchanger (for cooling) and the reactor core (for heating). Sodium aluminate was used in these tests; sodium aluminate was also used in the AECL bench-top and reduced scale testing. As shown in Table 1 of that report, with a total aluminum concentration of 40 ppm, no precipitation was observed upon cooling the solutions from 200°F to 80°F at pH values above 7.5. The report also suggests that the solubility limit at pH 7.0 is less than 40 ppm even at 200°F. This value of 40 ppm bounds the bench-top test results reported by AECL (summarized above) and bounds the maximum concentration of aluminum in the MPS3 post-LOCA sump water of approximately 2 ppm. No precipitation of aluminum hydroxide species is expected in the MPS3 post-LOCA sump water.

AECL conducted bench-top tests to determine aluminum solubility under the worst-case conditions expected in the post-LOCA sump water. The sump water chemistry conditions which are expected to exist after 30 days were used for determination of aluminum precipitation. These chemistry conditions are considered the most conservative since after 30 days, the temperature of the sump water has decreased to a stable, low value, and the dissolved aluminum concentration has reached its maximum value. For additional conservatism, a pH of 7.0 (at 25°C) was used since this is lower than the actual pH which will exist and is the required minimum pH per the MPS3 Technical Specifications. The bench-top tests for aluminum precipitation were conducted in three flasks. One of the flasks was maintained at 150°F, and one at room temperature. The third flask was a blank which had no insulation debris added to facilitate detection of precipitation in the "warm" and "room temperature" flasks. All three of the flasks contained borated water to which was added sodium aluminate. The required mass of insulation debris was added to the warm and room temperature flasks. The solutions were stirred slowly with a magnetic stirrer and once the pH was adjusted to the target value, the solutions were allowed to stand for 30 days. The pH was nearly constant throughout the 30 days. No precipitation was observed from these tests conducted with MPS3 specific boric acid and aluminum concentrations and insulation masses. The maximum concentration of aluminum expected in the MPS3 containment is approximately 2 ppm and these tests were conducted with a concentration of 4 ppm aluminum which is well below the AECL-determined precipitation/no precipitation zone of approximately 12 ppm aluminum.

The available data on Al solubility in borated water is summarized in the recent ANL report by C.B. Bahn, et al. "Technical Letter Report on Evaluation of Head Loss by Products of Aluminum Alloy Corrosion," dated August 11, 2008, (ADAMS Accession No. ML082330153). The results of the Dominion-AECL bench-top test are within the precipitation region determined in the ANL tests (without distinguishing flocculated and

non-flocculated precipitation). Most of the bench-top test data points lie within the non-flocculated region, as expected since the bench-top tests were taken only to the onset of precipitation, where the concentration of particles would be low and less likely to show flocculation.

As discussed below, the Rig 89 testing showed that no aluminum remained in solution even at the low levels of aluminum expected in the MPS3 containment. Thus the testing showed that aluminum hydroxide solubility is not a factor in the post-LOCA sump environment at MPS3.

The concentration of aluminum to be added to the test rig was conservatively determined by determining the maximum aluminum corrosion which could occur in the containment post-LOCA without considering any inhibitory effects. AECL determined the overall aluminum corrosion rate at a given temperature and pH using ICET and other literature data to be:

$$\text{Corrosion rate (T)} = 9.2 \times 2 \times 10^7 \times \exp(-6301.1 \times (1/T (^{\circ}\text{K})))$$

$$\text{Corrosion rate (pH)} = 3 \times 10^{-7} \times \exp(1.3947 \times \text{pH})$$

The total aluminum (Al) release rate determined by AECL is given by:

$$\text{Al release rate} = \text{corrosion rate (T)} \times \text{corrosion Rate (pH)}$$

or

$$\text{Release Rate (mg/m}^2\text{-s)} = 9.2 \cdot 2 \times 10^7 \cdot \exp(-6301.1/T) \cdot 3 \times 10^{-7} \cdot \exp(1.3947 \cdot \text{pH})$$

The average corrosion rate over the time interval was then calculated assuming a linear change in corrosion rate over that interval. The aluminum release was then calculated using:

$$\text{Al Release over Interval} = \text{Corrosion Rate} \times \text{Interval length} \times \text{Al Surface Area}$$

The highest expected pH in the MPS3 containment post-LOCA (pH=8.5) was used in the calculation of aluminum corrosion. The total amount of aluminum created was calculated as 1.8 ppm.

#### Testing for Walnut Shell Dissolution and Alteration:

Walnut shell powder is used in the debris head loss tests to simulate epoxy coating which is conservatively anticipated to be broken into very small particulate sizes (nominally 10 $\mu$ m) post-LOCA. Tests were carried out as part of the bench-top testing to determine if exposure to chemicals would dissolve or alter the walnut shell particulate.

Particle size and dissolution tests carried out to characterize the effects of exposure of walnut shells to borated water containing sodium aluminate showed no obvious change on particle size distribution or particle morphology. Measurements of the total organic carbon in the test solution gave inconsistent results with respect to the amount of walnut shell dissolution, while measurements of the weight change suggested a maximum weight loss of 12%. No significant effect from walnut shell dissolution or weight change is expected to impact the results of the Rig 89 tests.

### Reduced Scale Testing:

Reduced scale testing was conducted for MPS3 to determine the debris-bed head loss with a conservative amount of potential chemical precipitants added to the debris. The amounts of chemicals added were determined based on plant conditions and the chemical effects assessment which determined the debris source term. The Rig 89 test results are more prototypical of containment and are the relevant test results for determining maximum debris-bed head loss at MPS3.

### Test Description:

The chemical effects tests were performed using the newly constructed multi-loop test rig (Rig 89). Rig 89 is a multi-loop facility designed and constructed to support the schedule for conducting six Dominion head loss tests with chemicals simultaneously instead of conducting these in series using the existing Rig 33 facility. The loop was filled with solutions of chemicals based on MPS3 specific plant conditions and pH requirements. Loop filling was via the debris addition tank and the header tank. A vent valve on top of the debris addition tank was used to eliminate air pockets within the loop. The loop was filled to approximately half the height of the header tank to allow water expansion during the heating process and to accommodate chemical additions over time. The loop was heated to 60°C (140°F) and cooled to 40°C (104°F) while circulating at 17 gal/min to remove dissolved air. The loop was operated for at least 20 minutes at the test flow rate and temperature before debris addition. Chemical addition to the test tank occurred after a fiber and particulate thin-bed was formed and had developed a stable head loss. Chemicals were added in increments throughout the test to simulate the gradual corrosion of aluminum and degradation of concrete.

Approximately ten gallons of water were removed from the debris addition tank through a drain valve located at the bottom of the tank while the tank was isolated from the loop. The water was used to prepare the debris addition for each test. The sprayed slurry of debris was returned into the debris addition tank. The debris addition tank isolation valve was then opened to slowly meter out debris. Additions of debris were done slowly (over at least 10 minutes per addition) and with throttled valves to ensure that debris deposition on the strainer surface was as uniform as possible, thus promoting the highest achievable head loss. The full particulate debris load for each test was added at the start of the test, and then additions of fibrous debris were made in 1/16 in. (1.6 mm) theoretical bed thickness increments. The theoretical bed thickness is defined as the uncompressed fiber volume divided by the test module surface area. The first fiber addition (1/16 in. (1.6 mm)) was made 30 minutes (enough time for debris preparation) after the addition of the particulate debris. The second fiber addition (an additional 1/16 in. (1.6 mm)) was made 30 minutes after the first addition. The thin-bed thickness for MPS3 is nominally 1/4 inch as established in previous debris-bed testing. The final two debris additions were made one at a time after head loss had stabilized following the previous fiber addition. After the debris-bed was formed and the pressure drop stabilized (changed by less than 5% or 0.01 psi, whichever was greater), and exhibiting no general steadily increasing trend within 25 minutes, chemicals were added into the loop through the chemical injection points. The effects of calcium and aluminum precipitate formation on strainer debris-bed head loss were evaluated by adding calcium chloride and sodium aluminate to the test rig in the already established chemical environment of TSP, boric acid, and lithium hydroxide at pH 7. The amount of calcium chloride to be added was calculated from a concrete dissolution rate obtained from bench-top testing in boric acid solution at pH 7 (without

TSP) as described above. The amount of sodium aluminate to be added was calculated from a corrosion rate model. Both calculations ignored the inhibitory effect of TSP and were extremely conservative. Bench-top test results discussed above showed that concrete coupons exposed for 30 days to a solution of boric acid and TSP at pH 7 had no significant mass change, indicating that the dissolution rate employed was extremely conservative. Likewise, the results published in WCAP-16785-P, "Evaluation of Additional Inputs to the WCAP-16530-NP Chemical Model," indicate that phosphate inhibits aluminum release by a factor of 3-4 between pH 8 and 9.

The test was run for > 50 days to observe the head loss change due to any precipitate formation after chemical additions. A 30-mL grab sample was taken every day for each test using the drain valve at the bottom of the debris addition tank. Some of the water samples were sent for elemental analysis using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). The remaining samples were kept for possible future use. A 50-mL grab sample was taken twice a week for each test for possible microbial analysis. At the end of each test a debris-bed sample was taken for analysis by Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray Spectroscopy (EDX).

The termination criteria used for the tests were:

1. Little or no precipitate forms in 30 days; aluminum concentrations remain at the specified value.
2. Precipitate forms and the head loss exceeds the allowable debris-bed head loss for MPS3 or the available test rig margin.
3. Precipitate forms but criterion 2 is not met. Aluminum will be added to the test loop to maintain the specified concentration until the mass of aluminum added reaches the maximum mass of aluminum that should be added. The maximum mass of aluminum is based on the consideration that, per unit of strainer area, more precipitate would be formed in a sump strainer than in a test strainer because of the volume to strainer surface ratio difference. The test tank volume is 8.1 ft<sup>3</sup>. The minimum sump volume is 160,000 ft<sup>3</sup> and the scaled volume is 214.1 ft<sup>3</sup> based on the debris-scaling factor of 747.4 used for the test. The ratio of the scaled volume to the actual test loop volume is 26.4 (i.e. 214.1/8.1).

Head loss test results are summarized in the table and figures below. The head loss values reported in this table are the peak head loss values measured during the day listed.

TABLE O-4: TEST M3-C1 CHEMICAL ADDITIONS AND HEAD LOSS VALUE

Day (Events)	Masses of Chemical Additions					Concentration of Calcium and Al				Head Loss (psi)
	CaCl <sub>2</sub> (g)	NaAlO <sub>2</sub> (g)a	B(OH) <sub>3</sub> (g)	TSP (g)	NaOH (g)	[Ca] <sub>calc</sub> (mg/L)c	[Ca] <sub>ICP</sub> (mg/L)d	[Al] <sub>calc</sub> (mg/L)c	[Al] <sub>ICP</sub> (mg/L)d	
Environment	/	/	3348	1520	/	/	/	/	/	0
Debris-bed	/	/	/	/	/	/	/	/	/	0.43
0 (1 <sup>st</sup> )	1.8	2.79	14.57	/	64.6	2.83	7.5	3.19	1.4	0.63
3 (2 <sup>nd</sup> )	1.4	/	14.56	/	0.11	5.02	9.2	3.19	0.4	0.74
6 (3 <sup>rd</sup> )	1.1	/	14.56	/	0.11	6.75	10.7	3.19	bd	0.74
9 (4 <sup>th</sup> )	0.86	/	7.28	/	0.5	8.10	11.3	3.19	bd	0.75
12 (5 <sup>th</sup> )	0.67	/	7.28	/	7	9.15	12.2	3.19	bd	0.76
15 (6 <sup>th</sup> )	0.52	/	3.64	/	0.5	9.97	/	3.19	bd	0.79
18 (7 <sup>th</sup> )	0.41	/	3.64	/	0.17	10.61	14.0	3.19	bd	0.77
21 (8 <sup>th</sup> )	0.32	/	1.46	/	0.13	11.11	14.5	3.19	bd	0.77
24 (9 <sup>th</sup> )	0.25	/	1.46	/	0.13	11.50	14.6	3.19	bd	0.79
25 (10 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.50	11.9	6.19	bd	1.14
31 (11 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.50	10.5	9.18	bd	1.61
34 (12 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.50	8.5	12.18	bd	2
36 (13 <sup>th</sup> )	0.2	/	1.46	/	0.11	11.82	/	12.18	bd	1.52
38 (14 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.82	/	15.17	bd	1.85
39 (15 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.82	6.1	18.17	bd	1.88
40 (16 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.82	/	21.17	bd	1.9
41 (17 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.82	/	24.16	bd	1.9
42 (18 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.82	3.7	27.16	bd	1.86
43 (19 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.82	/	30.15	bd	2.07
44 (20 <sup>th</sup> )	/	2.62	50.2	22.8	/	11.82	3.2	33.15	0.5	2.17
47 (21 <sup>st</sup> )	/	3.25	62.5	28.4	/	11.82	2.8	36.87	0.6	1.96
48 (22 <sup>nd</sup> )	3.77	/	29.11	/	0.2	17.74	/	36.87	bd	1.96
49 (23 <sup>rd</sup> )	3.77	/	29.11	/	0.2	23.65	7.3	36.87	bd	1.95
52 (24 <sup>th</sup> )	3.77	/	29.11	/	0.2	29.57	/	36.87	bd	1.93
53 (25 <sup>th</sup> )	3.77	/	29.11	/	0.2	35.49	12.8	36.87	bd	1.96
Total:	22.61	32.24								

Notes:

- 0.016 g of LiOH was added on the day of establishing the *Chemical Environment* (May 10<sup>th</sup>).
- Sodium aluminate is a hygroscopic substance. Analysis results indicate that the sodium aluminate used contained 27.3 wt% Al on Day 5 (June 6), shortly after the 2<sup>nd</sup> chemical additional *Event*. A value of 26.3% was used for calculations.
- Concentration was calculated from the mass added.
- Concentration was measured by ICP-AES.
- bd denotes that signal was below the detection limit of 0.4 mg/L Al.

Figure O-1 below shows the debris-bed head loss in Rig 89 prior to chemical addition.

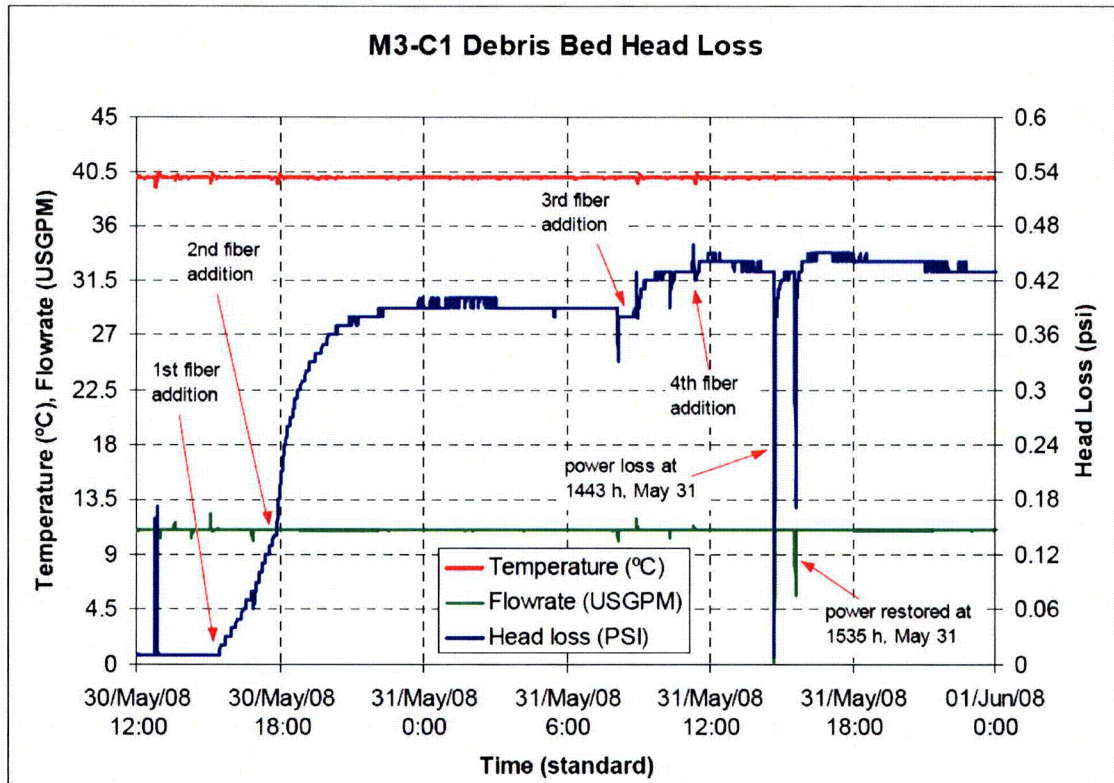


FIGURE O-1: DEBRIS-BED HEAD LOSS VERSUS TIME FOR MPS3 RIG 89 TEST



Figure O-2 below shows the head loss trace over time for the Rig 89 test (blue line), measured calcium concentration (black line), measured aluminum concentration (maroon line), and all of the calcium and aluminum additions.

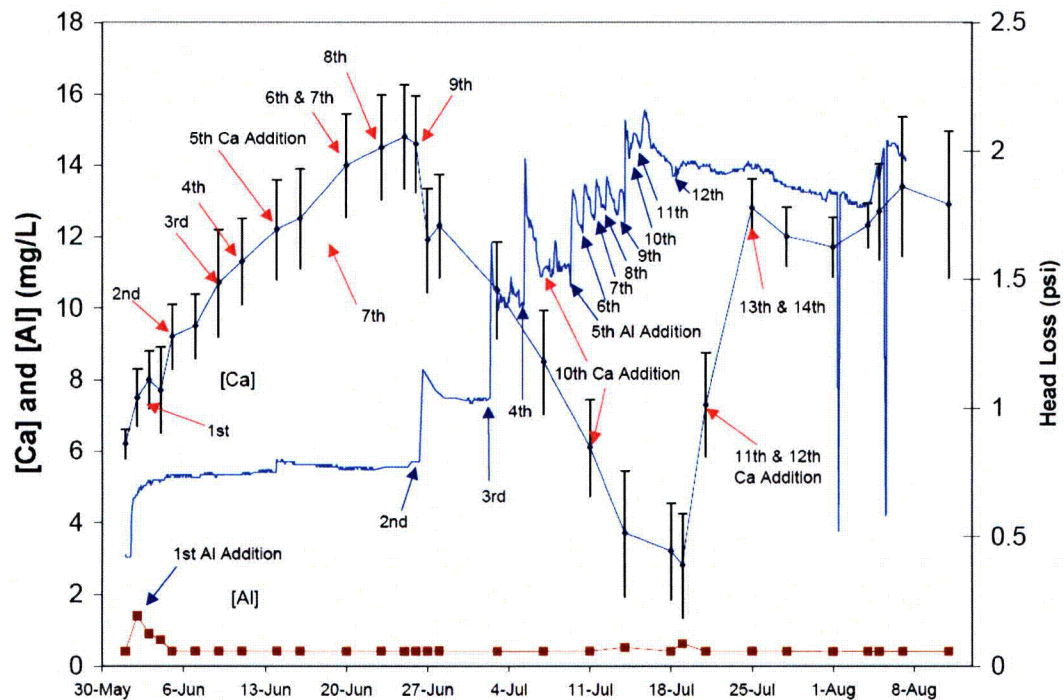


FIGURE O-2: HEAD LOSS TRACE AND MEASURED CALCIUM AND ALUMINUM CONCENTRATIONS FOR MPS3 TEST

Figure O-3 below shows the debris-bed head loss recorded during the initial calcium and aluminum additions in Rig 89.

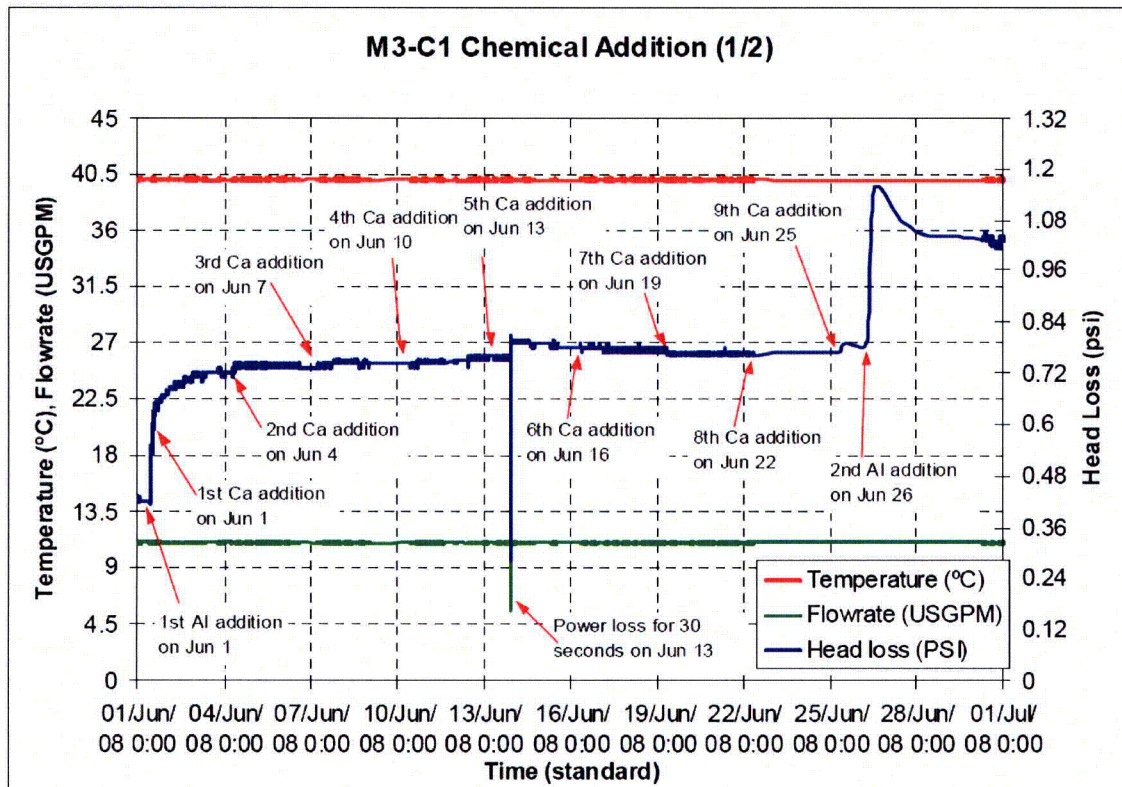


FIGURE O-3: HEAD LOSS ACROSS THE MPS3 STRAINER DURING THE INITIAL CALCIUM AND ALUMINUM ADDITIONS



Figure O-4 shows the impact on head loss during the final calcium and aluminum additions during the Rig 89 test.

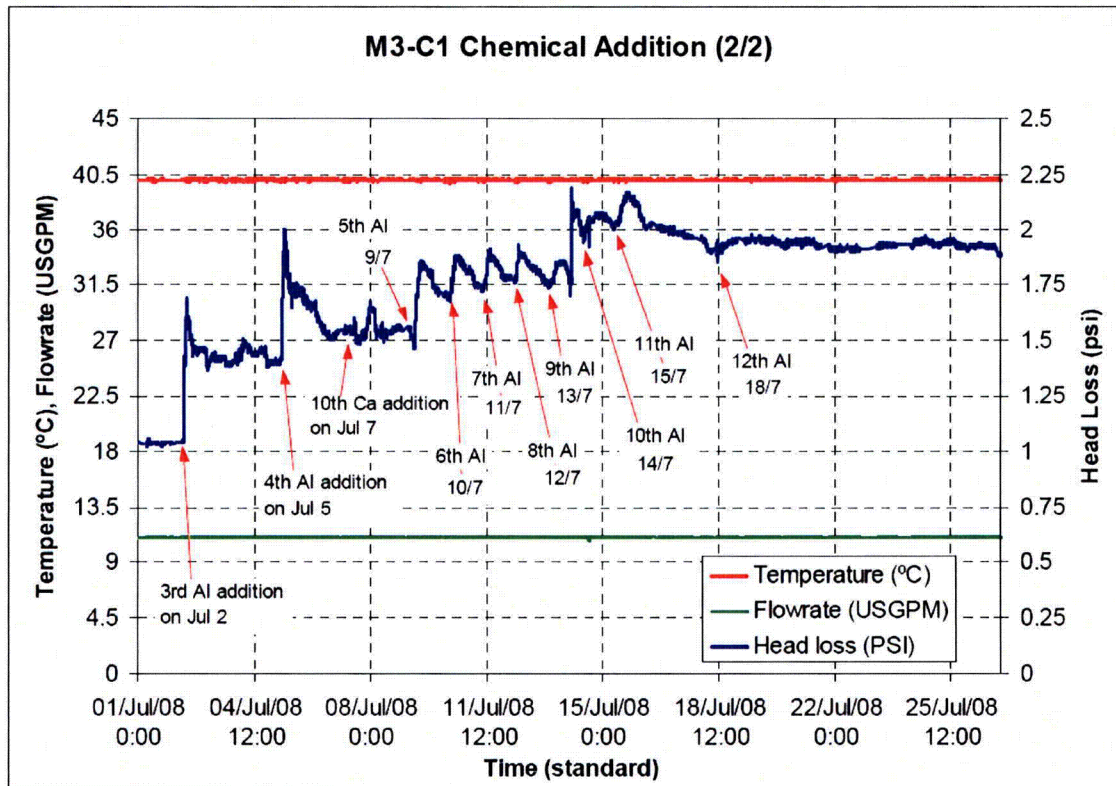


FIGURE O-4: HEAD LOSS ACROSS THE MPS3 STRAINER DURING FINAL ALUMINUM AND CALCIUM ADDITIONS

#### Test Results Discussion:

The test rig was filled with deionized water solution with boric acid, TSP and lithium hydroxide added in amounts representative of post-LOCA sump water. The pH of this solution was 6.97 at 22.5°C. Conservatism in aluminum hydroxide precipitation is assured since the pH is below 7 (at 22.5°C) which is the conservatively calculated minimum pH of the post-LOCA sump water. Aluminum hydroxide precipitation is more likely at lower pH values. The temperature of the solution was maintained at 40°C for the duration of the test. Following filling of the test rig, particulate debris and then fiber debris was added to the test tank as described above. A total of 14 calcium chloride additions and 12 sodium aluminate additions were made over the course of the test. Once the debris-bed was established, the first aluminum and calcium additions were made as listed in Table O-4. These additions combined with the second calcium addition raised the head loss to about 0.74 psi. The debris-bed head loss increased slowly to 0.79 psi during the next seven additions of calcium. Throughout the test, aluminum concentration remained near or below the detection limit, indicating that the aluminum had either precipitated in solution or precipitated on surfaces ("plated-out") such as the debris-bed. As no visible precipitate was noted in the test tank, it was concluded that the aluminum plated-out on the debris-bed. In the containment, since the aluminum sources are significantly separated from the sump strainer, it is likely that the aluminum will plate out on multiple surfaces throughout containment and much of the aluminum that is released by corrosion may never reach the

strainer debris-bed. This effect was not credited in the test tank and adds further support to the conservatism of the Rig 89 test. Since the solution volume to strainer area is smaller in the Rig 89 test loops than in the containment sumps, aluminum additions were continued to match the predicted aluminum loading per unit strainer area. Aluminum additions increased the head loss as listed in Table O-4. The peak head loss of the test occurred after the eleventh aluminum addition and the head loss subsequently drifted down. Once the aluminum additions were complete, the final four calcium additions were made with no significant impact on the head loss.

At the conclusion of the test, a sample of the debris-bed was sent for analysis by SEM/EDX. The results showed the presence of Ca, Al and P on the surfaces of the fibers and particles in the debris-bed. This is consistent with the precipitation of calcium phosphate and aluminum phosphate on the debris surfaces (plating out).

Once all chemical additions were complete, the debris-bed was checked for boreholes by lowering flow rate, allowing head loss to stabilize, and then restoring flow rate to the original value. Presence of boreholes would have been indicated by little or no change in head loss as the flow rate was reduced. The head loss responded quickly to changes in flow rate and head loss changes were found to be reversible. Following the flow sweeps, loop temperature was gradually cooled from 40°C to 21°C to quantify the impact of viscosity on head loss. The reduction in temperature increased the head loss from 1.82 psi to 2.02 psi. The kinematic viscosity of the test solution was measured and found to be  $0.70 \pm 0.01$  at 40°C and  $1.03 \pm 0.04$  at 21°C. The observed increase in head loss upon cooling was likely due to the increase in viscosity. The head loss increase is proportional to the change in the viscosity of the test solution to the power of 0.27. Flow sweeps were performed at 21°C to check again for the presence of boreholes in the debris-bed.

The flow sweep tests revealed that head loss is very nearly proportional to velocity squared. Furthermore, the temperature reduction test revealed an almost immeasurable viscosity effect on head loss. These results suggest that turbulent flow exists across the debris-bed and that flow across the strainer is restricted.

In the MPS3 test, calcium chloride additions, when not tied with sodium aluminate additions, did not cause increases in head loss. Sodium aluminate additions, on the other hand, invariably increased head loss. The one exception was the 12<sup>th</sup> aluminum addition, which arguably did not increase head loss because a head loss plateau had been established. Aluminum additions resulted in head loss peaks, followed by lower stabilized head loss values. The data suggest that there is a limit to the effect of aluminum on head loss. The test ended at 1.96 psi, well below the allowable debris-bed head loss of 5.1 psi.

A calculation error resulted in slightly less aluminum being added to the test rig than would bound the total aluminum concentration which could occur post-LOCA in the MPS3 sump water. Application of the re-calculated aluminum concentration given in would have required an extra 3½ aluminum additions to the test rig. The data suggest that a head loss limit was reached and that further additions of aluminum would not have increased head loss. Nonetheless, the test was still conservative; if a factor of 2 is used for corrosion inhibition by phosphates, then the tests added at least 65% more aluminum than was required.

A recent ANL report by C.B. Bahn, et al, "Technical Letter Report on Evaluation of Head Loss by Products of Aluminum Alloy Corrosion," dated August 11, 2008, (ADAMS

Accession No. ML082330153) reported head loss test results using aluminum metal coupons instead of a surrogate such as aluminum nitrate (or sodium aluminate as used in AECL-Dominion testing) to produce aluminum ions in a post-LOCA environment. The ANL testing found that the use of aluminum metal produces intermetallic particles which tend to promote aluminum compound precipitation prior to the point predicted by aluminum hydroxide solubility. Aluminum hydroxide precipitant creates a head loss in a fiber bed in the ANL vertical test loop. Additional head loss could be created by the addition of the intermetallic particles to the debris-bed. Use of aluminum nitrate or sodium aluminate to simulate corroded aluminum would not produce intermetallic particles. Additional precipitation of aluminum compounds due to the presence of intermetallic particles is consistent with the results of the MPS3 test in which all of the aluminum added to the test tank came out of solution by plating out onto debris-bed surfaces, rendering any argument about aluminum compound solubility moot. The additional head loss due to the intermetallic particles also does not significantly impact the MPS3 test results since the small amount of intermetallic particles that may be formed and transported to the existing debris-bed will have little impact on head loss due to the presence of a very conservative particulate load from coatings (qualified and unqualified) and latent debris.

ICET data on aluminum corrosion is potentially non-conservative since the lid of the test tank was insulated and the unsubmerged aluminum coupons did not have a lot of condensation dripping on them and thus the corrosion of the unsubmerged Al coupons is likely somewhat non-conservative. However, the aluminum release predicted using the WCAP and AECL release models are very similar and significantly overpredict the measured aluminum release in the ICET 5 test, as shown in Figure O-5.

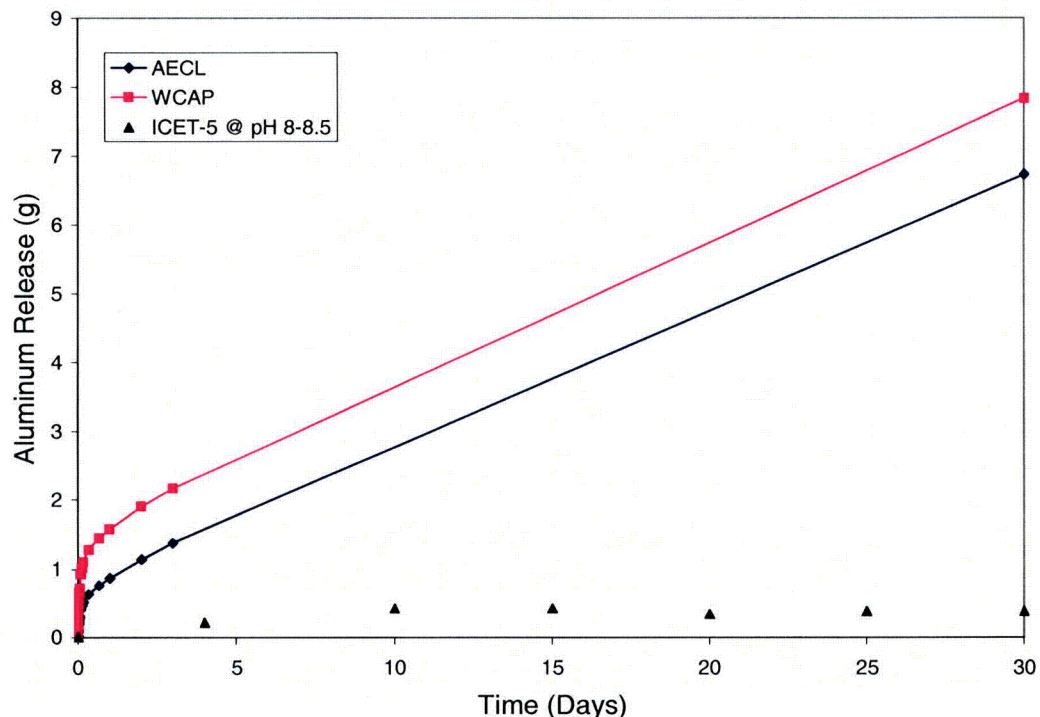


FIGURE O-5: PREDICTED ALUMINUM RELEASE PER SQUARE FOOT OF SUBMERGED ALUMINUM AT A LONG-TERM SUMP PH OF 8.5



### Comparison of Test Results With and Without Chemical Effects

Several reduced scale tests and large scale tests were run in a separate test rig (Rig 33) to determine debris-bed head loss with no added chemicals. These tests for MPS3 were run in September, October, and November of 2006 for strainer sizing prior to chemical effects testing and provided a debris-bed only worst case (thin-bed) head loss. The debris-only head loss in Rig 33 was higher than the debris only head loss in Rig 89 (prior to addition of chemical precipitants).

Significant similarities between the Rig 33 and Rig 89 tests included:

- The same scaling methodology was used for both Rig 33 and Rig 89 tests.
- Test debris amount and flow rate were scaled from specific plant parameters by the ratio of modeled strainer area to test strainer area.
- Fibrous and particulate debris additions were done to maximize thin-bed head loss by adding the particulate first and then adding the fiber in discrete amounts calculated to provide a uniform 1/16" bed on the strainer.
- The test temperature for both rigs was 40°C (104°F).
- The modeled strainer area for both rigs was 4290 ft<sup>2</sup>.

Significant differences included:

- Rig 89 used deionized water with MPS3-specific post-LOCA concentrations of TSP, Boron, and Lithium Hydroxide while Rig 33 used Ottawa River water with known particulate and no TSP, Boron, or Lithium Hydroxide.
- A continuous stirrer was used in Rig 33 to maintain as much debris as possible in suspension while Rig 89 had occasional stirring of the bottom of the tank. Continuous stirring of the tank water is not prototypical of containment where much of the containment pool is expected to be quiescent.
- Rig 89 testing included addition of chemicals and sufficient time for precipitants to form after the fiber and particulate debris-bed had formed and head loss was stable whereas Rig 33 testing included no chemicals.
- Rig 89 particulate load was approximately 10% lower than the Rig 33 particulate load due to a refinement of the expected amount of qualified coating debris.

A brief summary description of the test results follows with the explanation of why the head loss differences existed.

### Rig 33 Description:

MPS3 sump strainer reduced-scale thin-bed tests were conducted in Rig 33 to determine total strainer surface area. The reduced scale tests conducted without chemicals provided the basis for the final strainer area and fin pitch (distance between the fins). All reduced

scale tests without chemical effects were run in open tanks using Ottawa River water to simulate the post-LOCA sump water. No TSP or boron was added to the test tank.

The test facility consisted of a 90 in. (2.3 m) diameter open plastic tank and a test module assembly. The test module assembly included one central fin and two half fins vertically mounted on the header. The test module assembly was positioned on the floor of the tank and was attached to a piping system leading to a pump below the tank. The pump discharge piping exit was located behind the fin/header assembly. The last piece of discharging piping was positioned on the tank floor along the tank wall and pointed to the right hand side. A variable speed electric stirrer was used in the thin-bed tests to suspend particulate and fibrous debris. Thoroughly mixed debris was slowly added into the test tank at a location close to the stirrer. The use of a stirrer reduced debris settlement on the tank floor. Because of the shape of the tank and the flushing of the returning water, a counter-clockwise flow was maintained in the test tank during the test. In the thin-bed testing, stainless steel baffle plates were arranged around the test module to ensure that the turbulent flow eddies generated by the tank flow did not enter between the fins, possibly disturbing the bed formation. Debris addition was performed to maximize the head loss of the debris-bed. Particulate was added to the tank first and then fiber was added in increments calculated to cover the strainer in 1/16" thick fibrous debris-bed. These fibrous debris additions were spaced apart to allow maximum particulate capture and to determine how many were required to form the thin-bed with the highest head loss. The peak thin-bed head loss values in the Rig 33 reduced scale testing were determined to be 5.1 psi (test M3-2) and 3.6 psi (test M3-16). The predicted head loss using the NUREG/CR-6224 [G. Zigler et al., 1995] correlation was 4.6 psi.

The debris composition and debris quantities were the same for both of the reported Rig 33 tests.

#### Rig 89 Description:

Sump strainer chemical effects tests were conducted in the Rig 89 test loop to determine the influence of chemical precipitates on the worst-case debris-bed head loss. MPS3-specific chemicals were added into the test loop after the formation of the debris-bed. Each test loop includes a 16 in. x 16 in. x 36 in. strainer box and a 12 in. diameter x 18 in. long cylindrical debris addition tank. A header tank located 15 ft above floor level was connected to the test loop to accommodate extra fluid from debris addition or thermal expansion and to control the loop pressure. The loop was capable of producing flow rates from 1 to 20 gpm (1.5 L/s). Flow rates were controlled via a variable frequency drive and a magnetic flow meter. Two half fins were installed inside the strainer box with a pitch distance the same as installed in MPS3. For MPS3 testing, the fins and strainer boxes were vertically oriented to simulate the installed module. No baffle plates were installed in Rig 89 tests. Water flow could enter the test strainer from the front, the top and the bottom of the fins.

The difference between the Rig 33 debris-bed head loss and the Rig 89 debris-bed head loss without chemicals is primarily due to two factors.

The first factor is that the Rig 33 tests were run using Ottawa River water whereas the Rig 89 test was conducted using deionized water. Ottawa River water has both significantly more particulate than deionized water and has biological activity due to the presence of decaying organisms. This contributed to a higher head loss in the Rig 33

tests than was observed in the Rig 89 test prior to chemical addition. During the Rig 33 test program, two different methods of tank cleaning and filtration were used to eliminate the impacts of biological activity and river water particulate. Development of the second method was done after the first method did not adequately eliminate the river water particulate and biological activity. In Test M3-2, nitric acid was added into the test tank after the tank was filled with water. Before the debris addition, the test water was neutralized with sodium hydroxide. No filtration treatment was used for Test M3-2 before debris addition. In Test M3-16, Javex bleach, containing 5.25% sodium hypochlorite, was added into the test tank to maintain the chlorine concentration above 10 ppm during the subsequent heating and filtering process. The two-stage water filtration was used to remove suspended solids before debris addition. A water sample was collected during Test M3-16 after the heating and filtering process for total suspended solids (TSS) analysis. A deionized water sample was also sent for TSS analysis for Rig 89 tests. The TSS levels are shown in Table O-5 below.

TABLE O-5: TOTAL SUSPENDED SOLIDS OF TEST WATER

Test	TSS (mg/L)	
	Standard <sup>1</sup>	Fine <sup>2</sup>
M3-2	0.6	N/A
M3-16	1	3.0
M3-C1	<0.2	2.0

Notes: 1) Standard TSS was measured by drawing the water sample through a 1.5- $\mu$ m-pore Misa filter.  
2) Fine TSS was measured by drawing the water sample through a 0.1- $\mu$ m-pore filter.

TSS results for the service water sample taken on Sept. 1, 2006 were used as a reference for Test M3-2, which was started on Sept. 9, 2006. Both the inherent TSS and the test rig volume were much higher in Rig 33 than in Rig 89. The number of test water-borne particles in Rig 33 test was 33 times more than in the Rig 89 test, while the test strainer area was only 9.1 times greater. Small size particles (< 1  $\mu$ m) could greatly increase the existing debris-bed head loss by blocking the debris-bed pores. The deionized water used in the Rig 89 tests was much more prototypical of the RCS fluid than was the Ottawa River water used in the Rig 33 tests.

The second significant factor for differences between the Rig 33 and Rig 89 tests is the submergence level above the strainer fin. The Rig 33 test tank used a submergence of between 6 and 8 inches. This submergence level simulates the submergence of the strainer in containment at the start of the RSS pumps. At RSS pump start, just over half of the RWST water has been put into containment. Over the next approximately three hours, the remainder of the usable RWST water is sprayed into containment via the Quench Spray (QSS) pumps. This additional water produces a strainer submergence of at least 4 feet. Debris-bed formation will take far longer than three hours based on results from the extensive test program in both Rig 33 tests. With a submergence of only 6-8 inches and a full debris-bed head loss, air evolution in Rig 33 tests contributed to a much higher head loss than would exist in the absence of the air. The head tank on the Rig 89 test tank adequately simulated the existence of several feet of water above the strainer which suppressed air evolution from the debris-bed. Late in the Rig 89 test, the head tank was



disconnected and the resulting water level above the test tank was approximately 4 feet which corresponds to the minimum expected water level in containment after the QSS pumps stop spraying RWST water into containment. No air evolution occurred. Formation of the debris-bed in containment will largely occur with at least four feet of water over the strainer which will adequately suppress air evolution.

A test was run for MPS3 with deionized water and chemicals in the Rig 33 test tank prior to testing in the Rig 89 tank. This test resulted in significant air evolution as evidenced by rapid rises and falls in debris-bed head loss. The peak head loss in this test was approximately 6.8 psi which is well in excess of the maximum debris-bed head loss of 2.2 psi seen in Rig 89.

Another factor which produces a lower head loss for the Rig 89 test is that the particulate load for the Rig 89 test was approximately 10% less than the particulate load used for the September-November 2006 Rig 33 tests.

Table O-6 presents test results from the two Rig 33 tests used for strainer sizing, the Rig 89 test prior to addition of calcium or aluminum compounds, and the NUREG/CR-6224 predicted head loss for comparison.

TABLE O-6: SUMMARY OF RIG 33 AND RIG 89 TEST RESULTS

Test	NUREG/CR-6224 (psi)	Peak Head Loss prior to chemicals (psi)	Peak Head Loss after chemical addition (psi)
M3-2	4.6	5.1	5.1
M3-16	4.6	3.6	3.6
M3-C1	4.2	0.45	2.2

Uncertainty exists both in the ability of the NUREG/CR-6224 correlation to predict the behavior of the debris-bed with very small particulate and in the repeatability of the test results which is nominally 25%. Maximum debris-bed head loss for MPS3 is 2.2 psi per the Rig 89 test result which was performed at a water temperature of 104°F. The water saturation temperature for the minimum containment pressure (10.4 psia) at MPS3 is 195°F. At the higher temperature, the debris-bed head loss is expected to be less due to a drop in water viscosity.

Since the previous supplemental response of February 29, 2008, the margin to RSS pump suction line flashing has been recalculated. This was done as a result of the planned power uprate for MPS3. The margin to suction line flashing for MPS3 (which is more limiting than the NPSH margin) is 10 inches for a LBLOCA and 2 inches for a SBLOCA at RSS pump start. This margin is calculated with minimum strainer submergence which occurs just after RSS pump start and (very conservatively) a worst-case debris-bed head loss. At any temperature below saturation, subcooling of the sump water adds significantly to the NPSH and flashing margin. The sump water temperature cools relatively quickly post accident due to the cooling of the containment sump water in a heat exchanger prior to being sprayed into containment after recirculation pump start. The maximum temperature of the containment sump water is less than 185°F (vapor pressure of 8.4 psia) by three hours post-LOCA for the limiting large-break LOCA. This temperature reduction adds margin due to subcooling (approximately 2 psi) to the allowable debris-bed head loss before a cohesive debris-bed is likely to have formed and long before chemical

precipitants begin to potentially affect debris-bed head loss. With additional strainer submergence after QSS pumps stop spraying RWST water into containment, this margin is increased by approximately 4 feet (or 1.7 psi using the density of water at 185F). The combination of minimum additional submergence margin (1.7 psi) and minimum subcooling margin (2 psi) yields a total margin of 3.7 psi. Further subcooling of the sump water adds additional margin to RSS pump suction line flashing. Other conservatisms documented in the beginning of this letter further assure that any uncertainty in test result repeatability is not significant and does not compromise reasonable assurance of long-term core cooling post-accident.

#### Precipitate Generation—Chemical Injection into Loop:

Precipitates were generated in the Rig 89 test tank as described above by adding sodium aluminate and calcium chloride to the test tank which already had a stable worst-case particulate and fiber debris-bed and which already contained TSP and boric acid to simulate the post-LOCA sump water.

The pH used for the test was near the lowest allowable in containment (7.0) which promotes precipitation of aluminum hydroxides.

The temperature of the test tank was maintained at 40°C which would also promote precipitation of aluminum hydroxides. Additionally, the temperature of the test tank was lowered to 21°C at the end of the test to determine if additional precipitation would occur and whether there was any impact on head loss from increased water viscosity at lower temperatures. Since no aluminum remained in solution throughout the test as seen in Table O-4 and since calcium phosphate precipitation is relatively insensitive to temperature in the tested range, no additional precipitation was expected and none occurred.

#### Head Loss Testing Without Near-Field Settlement:

No near-field settlement is credited in the MPS3 testing. The Rig 89 testing resulted in 55% of the debris attaching to the fins on the test module. Periodic stirring using the installed magnetic stirrer was done to maximize the amount of debris reaching the strainer surface. The remaining debris settled in the bottom of the test tank. Quantification of this debris was done by volume measurement (in buckets) when the tank was cleaned out following testing. No estimate or quantification was done to determine the separate amounts of particulate and fiber which settled on the test tank floor. The percentage of debris attached to the fins was smaller than that seen in the reduced scale testing conducted in Rig 33 where for test M3-2, 84% of the debris attached to the fins and for test M3-16, 72% of the debris attached to the fins. A magnetic brush was used intermittently in the Rig 89 test to re-suspend settled debris. In the Rig 33 tests, the continuous stirring and periodic floor sweeping led to more debris attaching to the fins.

The conservatism of the Rig 89 test results relative to the containment was demonstrated by the following factors:

- The test tank size for Rig 89 is a 16-in x 16-in x 36-in stainless box. No significant debris transport was needed for debris to reach the strainer surface. Debris transport distance in the test tank was essentially zero whereas in

containment, due to the large footprint of the strainer and the displacement of the strainer from the loop rooms, debris transport distances are many feet.

- Walnut shell particulate (used as the surrogate for epoxy) has a density of approximately 80 lb/ft<sup>3</sup> as compared to the higher density of epoxy (94 lb/ft<sup>3</sup>). Thus, epoxy is more likely to settle than the particulate surrogate used in testing.
- Very low velocities in the test tank and similarly low velocities in containment will promote debris (especially particulate) settling.
- Turbulence created by the break will serve to maintain heavier debris in solution only in a small region local to the break waterfall. This turbulence will not significantly impact approach velocity or the amount of debris entrained in the water column near the strainer surface area due to the large strainer footprint and remote position of the strainer.
- Much of the small particulate debris created by the break blowdown will be directed upwards in containment and will settle on myriad surfaces throughout containment and only slowly, if at all, be washed to the containment floor by containment sprays.
- A significant portion of the particulate expected to be generated is from unqualified coatings which are postulated to be dislodged from components throughout containment by temperature and humidity in containment post-LOCA. Degradation of these unqualified coatings will take significant time (hours, and probably days) and thus the amount of particulate in the debris-bed (and in the test tank) is quite conservative. Additionally, all of the unqualified coating is postulated to fail as small, transportable particulate when in reality, much of the failure is far more likely to occur as large pieces which will not transport.
- The strainer in containment sits approximately 7 inches above the containment floor. Thus, any particulate which slides along the floor with the sump water motion is unlikely to reach the strainer surface.