U.S. EPR Design Features to Address GSI-191

ANP-10293NP
Revision 4

Technical Report

November 2011

AREVA NP Inc.

Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1	All	Revision 1 incorporates new design bases for the U.S. EPR GSI-191 Design Features. Revision 1 revises ANP-10293 in its entirety.
		Revision 2
2	Appendix F	Added
3	All	Miscellaneous editorial changes
		Revision 3
4	All	Miscellaneous editorial changes
5	3.1.2	Updated debris source term
6	3.2.5	Added section to discuss water holdup in the Reactor Building
7	Appendix A	Updated discussion of conformance for items 1.3.1.1 and 1.3.1.9
8	Appendix B	Added discussion for items 2.d(v) and 2.d(vi)
9	Appendix C	Updated based on latest design input
10	Appendix D	Updated to incorporate IRWST design change
11	Appendix E	Complete revision based on latest test results
12	Appendix F	Complete revision
13	Appendix G	Added to discuss Ex-Vessel downstream effect
		Revision 4
14	All	Miscellaneous editorial changes
15	Main Body	Clarified discussion on upstream effects
16	Main Body	Added discussion about Retaining Basket Tightness Device
17	Main Body	Added discussion about the IRWST gutter system
18	Appendix A	Revised section to reflect Downstream Effects testing
19	Appendix B	Revised section to reflect Downstream Effects testing
20	Appendix C	Revised discussion on debris components and latent debris source term
21	Appendix D	Updated chemical debris amounts
22	Appendix E	Added clarifying statements regarding test configuration and bases
23	Appendix F	Complete revision – updated to reflect latest Downstream Effects testing
24	Appendix G	Complete revision

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Nomenclature

Acronym	**Definition**
BWR	Boiling Water Reactor
CSS	Containment Spray System
ECCS	Emergency Core Cooling System
FME	Foreign Material Exclusion
FPPS	Fuel Pool Purification System
GL	Generic Letter
GSI	Generic Safety Issue
HELB	High Energy Line Break
IRWST	In-Containment Refueling Water Storage Tank
LBLOCA	Large Break Loss of Coolant Accident
LHSI	Low Head Safety Injection
LOCA	Loss Of Coolant Accident
LWR	Light Water Reactor
MHSI	Medium Head Safety Injection
NPSH	Net Positive Suction Head
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
RG	Regulatory Guide
RMI	Reflective Metal Insulation
TSP	Tri-Sodium Phosphate
ZOI	Zone Of Influence

1.0 INTRODUCTION

This report describes the U.S. EPR™ design with respect to Generic Safety Issue (GSI) 191. GSI-191 is concerned with the potential for post-accident debris blockage that could interfere with the capability of the recirculation mode of the emergency core cooling system (ECCS) during long-term reactor core cooling. NRC Regulatory Guide (RG) 1.82 (Reference 1) describes acceptable methods and guidelines for evaluating the adequacy of plant design features and ECCS performance, including a framework for licensees to develop, demonstrate, and implement a comprehensive resolution to GSI-191. Nuclear Energy Institute (NEI) 04-07 (Reference 3) provides methodology and guidance for addressing and resolving GSI-191 issues. This report assesses the U.S. EPR design with respect to RG 1.82, NEI 04-07, and the related generic letter (GL), 2004-02 (Reference 2).

Specifically, this report:

1. Describes the design features of the U.S. EPR that limit the impact of post-accident debris accumulation on ECCS sump performance.
2. Describes the U.S. EPR debris source and generation.
3. Describes the chemical effects and head loss testing associated with debris transport.
4. Presents the supporting bases for the U.S. EPR design relative to GSI-191.
5. Presents an overview of related regulations and guidance.
6. Provides a review of RG 1.82 and GL 2004-02 conformance.

The U.S. EPR sump design is robust with respect to post-accident debris accumulation and ECCS recirculation sump strainer blockage because of the following features:

1. The U.S. EPR will have limited post-accident debris relative to current light water reactors (LWR). Reactor coolant system (RCS) piping and components will be insulated with reflective metal insulation (RMI). There will be no fibrous or micro-porous insulation and no calcium-silicate insulation used on the RCS.

2. The three-tiered debris retention design of the U.S. EPR ECCS recirculation system, including the safety injection system (SIS) and the in-containment refueling water storage tank (IRWST), is an effective solution to post-accident ECCS pump strainer clogging. The combination of weirs, trash racks, and retaining baskets are effective in retaining most of the debris, while also preventing a hold-up of inventory away from the containment sump, per NEI 04-07 guidance. As a result, very little debris will reach the ECCS strainers. The ECCS strainers have large screen surface areas to accommodate the small amount of debris that will reach them.

The U.S. EPR design conforms to the applicable RG 1.82 requirements as detailed in Table A.1 of Appendix A.

The features of the U.S. EPR that mitigate the risk of post-accident debris clogging the ECCS strainers are:

- A general layout of the plant that reduces the zone of influence (ZOI).
- The absence of a containment spray system (CSS) for design basis accident mitigation that would contribute to debris transport.
- Judicious selection of insulating materials. The insulated piping within the ZOI will be RMI. (ZOI = 2D)
- Multiple barriers that significantly limit the amount of post-accident debris from reaching the ECCS strainers without a hold-up, which would prevent water from reaching the sump due to debris buildup:
  - Weirs around the heavy floor openings that promote settling of debris.

- Trash racks above the heavy floor openings to prevent large debris from being transported to the IRWST.
- Retaining baskets below the heavy floor openings that capture the remaining debris contained in weir overflow.
- Large volume and large area IRWST that results in relatively low flow velocities, which permits settling of the debris.
- Large surface area ECCS strainers with small screen mesh sized to minimize debris bypass that may potentially affect any downstream clogging of fuel or critical equipment.

The U.S. EPR sump system design has been validated by a comprehensive testing program which demonstrated:

- Retention capacity and effectiveness of the retaining baskets.
- Strainer retention capacity and large margins relative to the head losses across the strainers, for a given volume of debris.

In summary, this report concludes that the U.S. EPR reactor design provides an innovative and comprehensive solution to post-accident debris blockage that addresses the concerns of GSI-191 and incorporating the guidance of NEI 04-07. The U.S. EPR design conforms to RG 1.82 as detailed in Table A.1 of Appendix A.

2.0 U.S. EPR DESIGN FEATURES

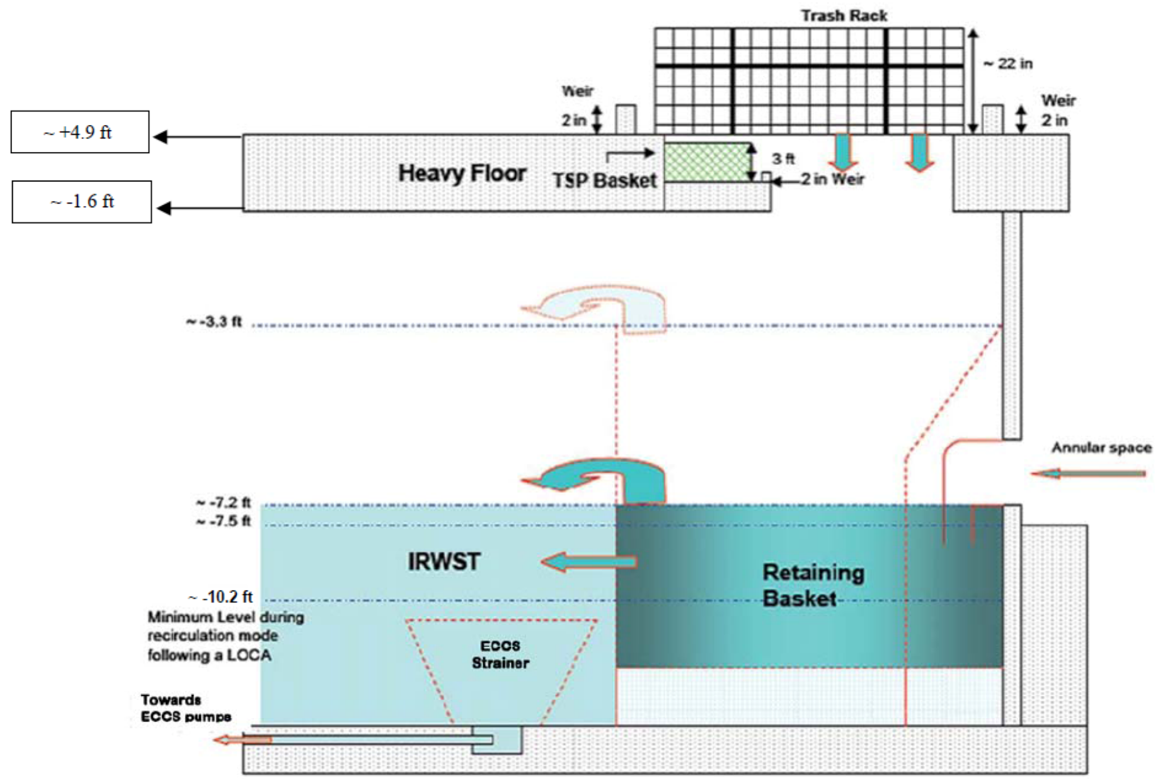
2.1 *IRWST*

A key feature of the U.S. EPR design important to resolving post-accident debris blockage is the IRWST. The IRWST is functionally equivalent to the external refueling water storage tank found in the current fleet of PWRs. The IRWST contains a large volume of borated water that is monitored for a homogeneous concentration, level, and temperature. The IRWST serves as a water source, heat sink, and return reservoir for ECCS. The IRWST is an open pool within a partly immersed building structure. The walls of the IRWST have an austenitic stainless steel liner covering the immersed region of the building structure. The liner prevents interaction of the boric acid and concrete structure and provides water tightness. Locating the IRWST inside containment and immediately below the RCS loop vaults permits integrating design features that collectively represent an effective solution for preventing post-accident debris blockage and ECCS sump clogging.

2.2 *Defense-in-Depth Strategy*

The U.S. EPR design takes advantage of the in-containment physical arrangement to develop a tiered “defense-in-depth” strategy against ECCS sump suction clogging without preventing sufficient inventory from reaching the sump due to post-accident debris accumulation as shown in Figure 2-1. The return water discharged from a loss of coolant accident (LOCA) drains to the containment heavy floor and flows to the IRWST.

Figure 2-1 U.S. EPR ECCS Sump Blockage Mitigation Design Features



This tiered "defense-in-depth" strategy includes:

- A large area, low flow velocity region in each of the four RCS loop vaults that promotes debris settling.
- A set of four protective weir/trash rack structures to retain large debris in the RCS loop vault.
  - The weir (curb) is approximately 2 inches high, to facilitate water pooling and debris settling in the RCS loop vault areas.
  - The trash rack is a 4x4 inch heavy-duty screen that fully encompasses the floor opening and prevents large debris from entering the retaining basket below.

- Four retaining baskets in the IRWST. Each retaining basket is located under each weir/trash rack port to catch and retain any small debris that is carried through the trash racks by ECCS recirculation flow.
- Large area, low flow velocity region within the IRWST promotes settling of fine debris that passes through the retaining baskets.
- Four large surface area three-dimensional flat screen sump strainers in the IRWST, each protecting one of the four ECCS pump suction sumps located in the floor of the IRWST.

Additional features associated with these barriers that contribute to the overall effectiveness of the system include:

- Retaining basket area sized to overlap trash rack portal area so that ECCS recirculation flow falls within the retaining basket.
- An approximately 1.6 ft gap between the top of the retaining basket and the bottom of the heavy floor permits the double compartment retaining basket to overflow into the IRWST should the retaining basket be filled with debris. The single compartment retaining baskets overflow into the annular space as the basket fills.
- Retaining basket screen mesh size is equivalent to the strainer screen mesh size; both are sized to minimize fine debris that may bypass the strainer and obstruct downstream clearances in the ECCS flow path.
- Inverted side screens on the sump suction strainers to promote gravitational release of debris beds in low flow or no flow conditions.
- Retaining baskets and ECCS strainers sized so that each set is sufficient to accommodate the anticipated debris load resulting from the worst-case LOCA.
- RCS insulation materials selected to minimize the quantity of insulation debris known to be highly deleterious to post-loss of coolant accident (LOCA) ECCS function.

2.3 *Details of the U.S. EPR ECCS Sump Blockage Mitigation Design Features*

Figure 2-2, Figure 2-3, and Figure 2-4 show the locations of the weir/trash rack structures, the retaining baskets, and the sump strainers in relation to the RCS and the IRWST. Figure 2-5 and Figure 2-6, respectively, show the design of the trash rack structure and the sump strainer structure.

Figure 2-2 Elevation View of ECCS Sump Blockage Mitigation Features

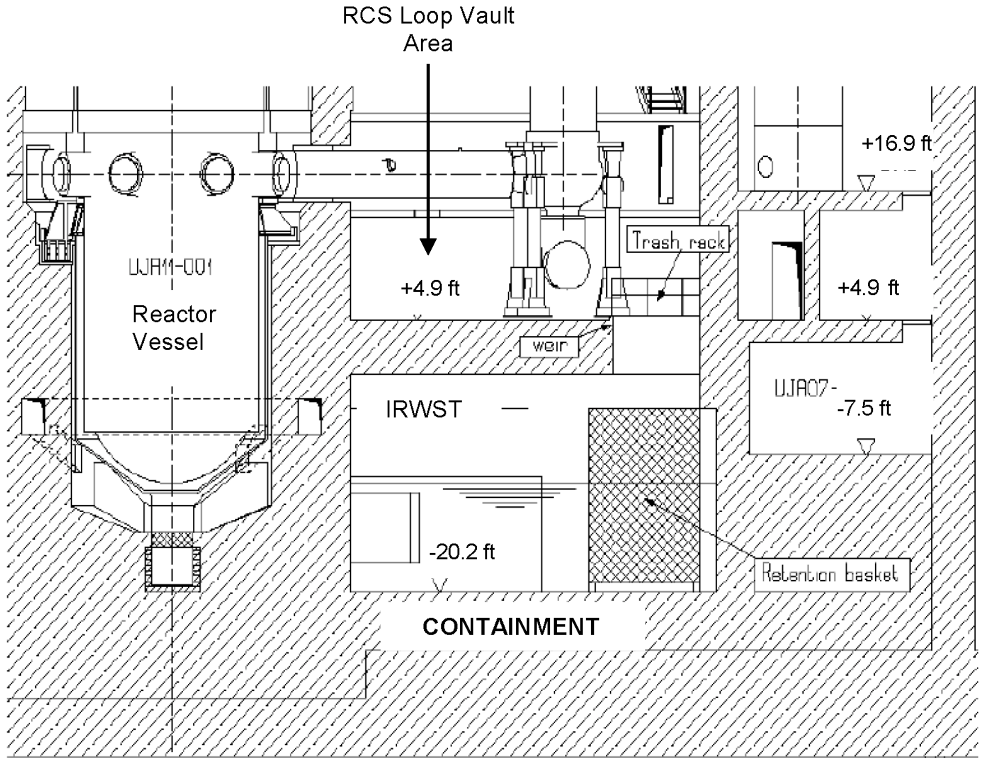


Figure 2-3 IRWST Cut-away View

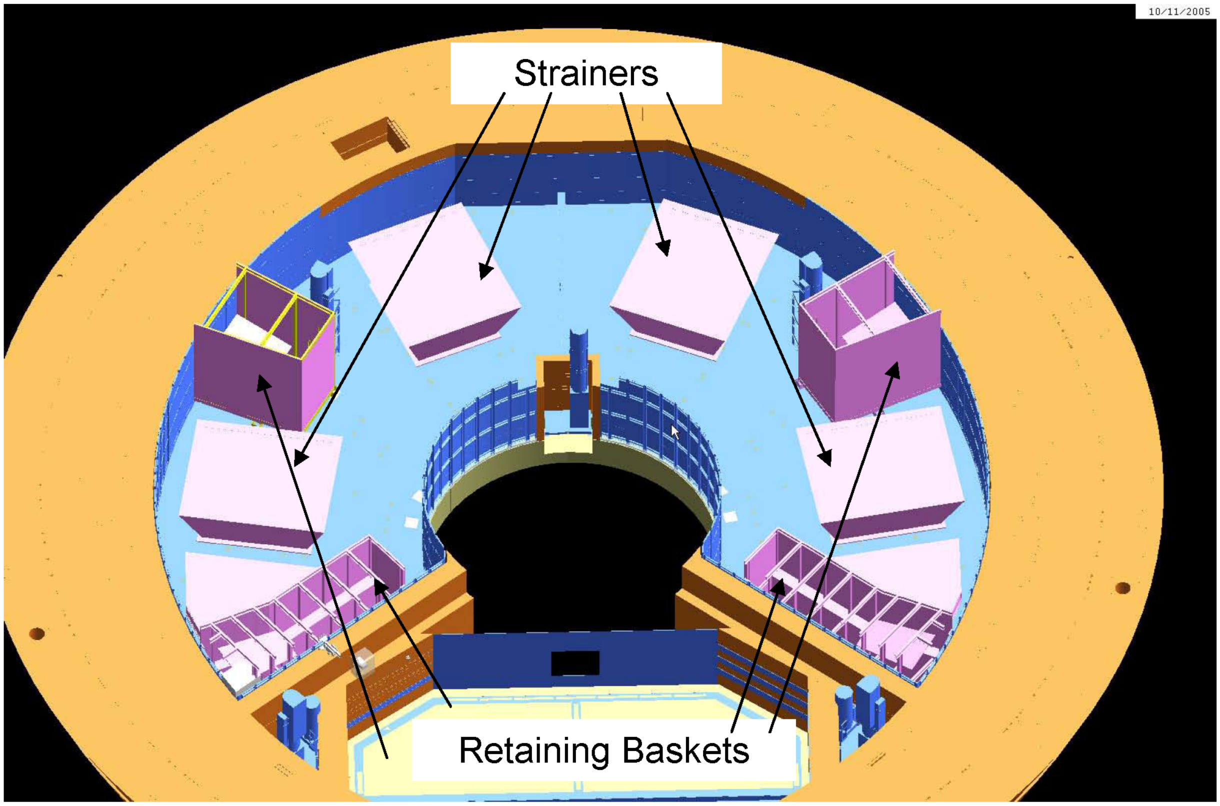


Figure 2-4 Weir and Trash Rack Locations Above the Heavy Floor

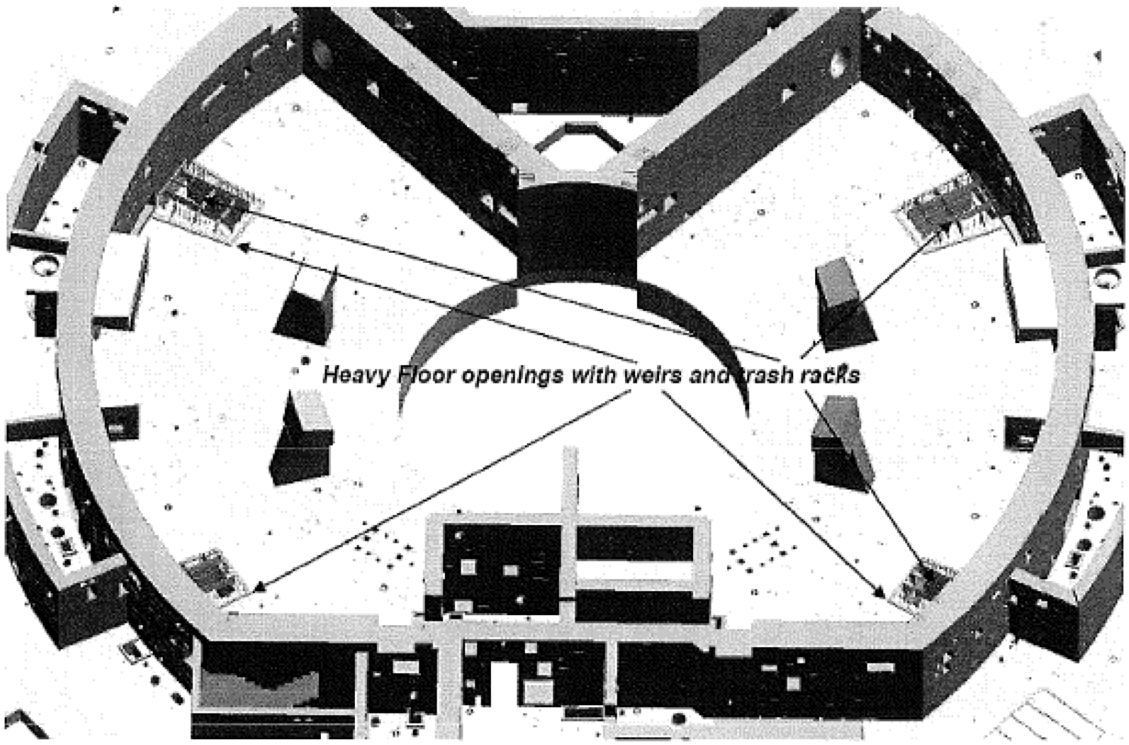


Figure 2-5 ECCS Trash Rack Structure (typical of 4)

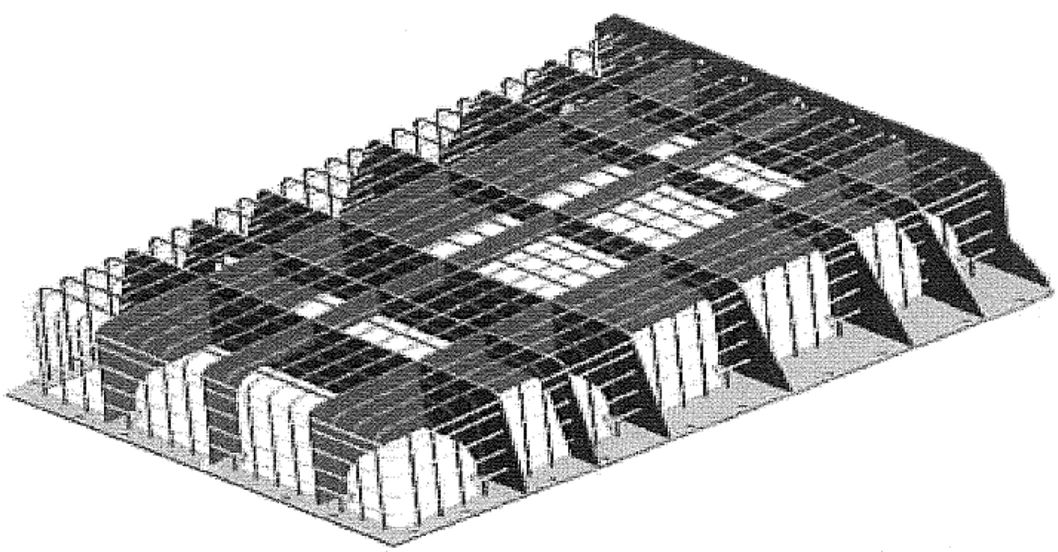
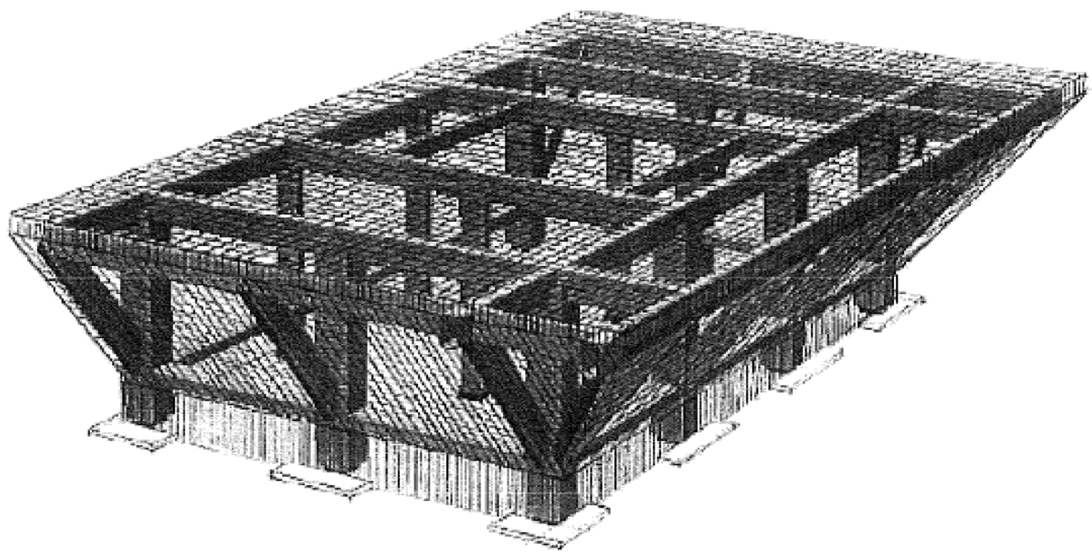


Figure 2-6 ECCS Sump Strainer Structure (typical of 4)



2.3.1 *Weirs and Trash Racks*

There are four openings in the RCS loop area “heavy” floor that open to the IRWST below. Each opening is approximately 50 ft^2 in area and is protected by a weir and trash rack assembly. The weir is a 2-inch high concrete curb around the perimeter of the floor opening that permits pooling of LOCA return water and promotes debris settling in the RCS loop vault area. The trash rack is a box-like mesh structure approximately 22 inches tall that consists of a 4x4 inch rigid metal grid that envelopes the floor opening. Each of the floor openings is aligned with the retaining basket located below. In addition to the protection offered by the trash racks, the 6.6 ft depth of the floor openings also provides jet impingement protection by limiting the angle of any jet that could pass through the opening unimpeded.

The weirs and trash racks prevent most of the LOCA-generated debris from passing through the four heavy floor openings to the IRWST below. LOCA-generated debris that passes through each trash rack will fall into a retaining basket.

In conformance with the guidance in NEI 04-07, the debris-settling effect of the weir will prevent medium- and large-sized debris from completely covering the trash rack. Therefore, inventory hold-up due to the trash rack is minimized.

2.3.2 *Retaining Baskets*

A retaining basket is positioned under each of the four heavy floor openings. The retaining baskets collect and retain debris that pass through the trash racks. The retaining baskets are constructed of austenitic stainless steel. The mesh size of the retaining baskets (nominal opening 0.08 x 0.08 inches) is the same size as the down stream ECCS sump strainer mesh size.

The perimeter of the upper portion of the retaining basket extends approximately 1.5 ft beyond the perimeter of the heavy floor opening. This extension prevents debris that passes through the trash racks from bypassing the retaining basket and reaching the sump strainers. There is a gap of approximately 1.6 ft between the top of each basket and the heavy floor to provide a flow path for return water in the event the basket becomes filled with debris. Because the retaining baskets use the IRWST wall to form a portion of the basket boundary, a tightness device is installed to prevent debris from bypassing the strainer at these interface locations. Because the tightness device is a part of the retaining basket, its design requirements, including filtering capability, are the same as those of the retaining basket.

The volume of each retaining basket can accommodate the debris generated from the limiting break. Water level in the basket is self-regulating and increases as the lower portion of the basket becomes filled with debris. Water overflow over the top of the retaining basket would occur after the debris have been captured.

However, prior to overflowing, the single compartment baskets will flood the annular space when the level reaches the annular space weir. This limits the potential level rise in the single compartment baskets. Once the water overflows into the annular space, it is routed to the other baskets and back into the IRWST via openings in the annular space walls. These openings include a gutter (see Section 2.3.4) to route the water into the IRWST. Because of this arrangement, the single compartment will have a surface area that is effectively bypassed from filtering. The unbypassed area for the single compartment basket (≈600 ft^2) is less than the total filtering surface of the entire large compartment of the double compartment basket (minimum 721 ft^2). However, the other single compartment basket will communicate with the other retaining baskets (e.g., the single compartment basket and the two small compartments of the double compartment basket) via the gutter and annular space in the event that the basket clogs. This will effectively increase the available filtering area significantly above the filtering area of the large compartment of the double compartment basket.

Two of the four retaining baskets are split into two compartments: a large one (minimum volume of approximately 1589 ft^3 and minimum surface area of approximately 721 ft^2) dedicated to the flow from the heavy floor, a smaller one (minimum volume of approximately 530 ft^3 and minimum surface area of approximately 269 ft^2) dedicated to the flow from the annular space. The latter compartment is lower and its height is designed to minimize water retention in the annular space. The minimum volume of the two other baskets is approximately 1589 ft^3 each with a minimum surface area of 721 ft^2.

Per NEI 04-07 guidance, each retaining basket qualifies as a possible area of concern, potentially having the capacity to restrict flow to the containment sump. However, a review of the design features explained above (basket sizing and water overflow) shows these features are sufficient to prevent hold-up of inventory.

2.3.3 *IRWST (ECCS) Sump Strainers*

The ECCS sump strainers are arranged above each of their respective sumps. The following aspects are taken into account to size the IRWST strainers:

- Nature of the debris (e.g., fiber, RMI, particulates, paint chips).
- Maximum quantity of debris that can reach one strainer during the recirculation phase after a large break loss of coolant accident (LBLOCA) when considering the effectiveness of the retaining basket.
- A conservative head loss across the strainer of approximately 2.18 psi at 104°F.
- The zone of influence of the break.
- ECCS recirculation flow.
- Maximum head loss across the strainer with consideration of ECCS pump NPSH margin and the mechanical strength of the strainer.
- Ample strainer surface area to prevent excessive strainer head loss.

A conservative approach is used for sizing the ECCS strainer. Based on the above conservative input and assumptions, the minimal design surface area of approximately 690 ft^2 is selected for the ECCS strainer. The installed strainers will have about 10% more surface area (approximately 760 ft^2) to provide additional margin. The strainer sizing has been validated by testing.

The screen filters retain debris to prevent pump/equipment malfunction and clogging of the smallest restrictions in the core. The screen design reflects a flat grid configuration with a nominal opening size of 0.08 x 0.08 inches to limit passage of debris through the strainer.

Strainer testing demonstrated conservatism in the dimensioning of the strainer. Because most of the debris is trapped in the retaining basket, a limited amount of debris will reach the ECCS strainers. The small amount of debris reaching the strainer results in a very small head loss through the strainer.

A review of the unique design features of the sump strainers, such as the angled exterior walls, vortex suppressors & mesh size, and in particular, their sizing, and subsequent testing, demonstrate conformance with NEI 04-07 guidance. The sump strainers will not significantly restrict the flow of liquid upstream of the containment sump.

2.3.4 *Retaining Basket Gutter System*

The lower annular space communicates with the IRWST through seven openings via gutters. These gutters seal off the two areas with a water seal in the IRWST to maintain a two-zone containment. The gutters are attached to the IRWST wall at the openings by anchoring bolts to the IRWST wall. The gutters protrude from the wall approximately 12 inches, and then turn 90° down into the IRWST water to a level of -9.2 ft. The minimum IRWST level during normal operating conditions is -8.5 ft, keeping the annular space separated from the IRWST (see Figure 2-1). The gutters are stainless steel, including the anchoring material.

The IRWST wall openings and associated gutters allow each basket to communicate with the other three baskets through the annular space. In the event that a single compartment basket begins to clog, it overflows into the annular space at the level of the IRWST wall opening. This limits the increase in level in the clogged basket and allows the overflow to be routed to the other three baskets. This overflow is then filtered by the other three baskets. This effectively increases the filtering area for the clogged single compartment basket.

The double compartment baskets are designed to have a flow path into the IRWST at the annular space level via the small compartment. This is designed to alleviate excessive flooding in the annular space from the single compartment baskets. Due to the low fiber source term in the U.S. EPR design, the small compartment of the double retaining basket is unnecessary.

2.4 *RCS Insulation*

The judicious selection of insulating materials for piping and equipment inside containment is important in limiting post-accident debris. The U.S. EPR design approach is to extensively use RMI for the RCS piping and major components, including the reactor vessel, the steam generators, reactor coolant pump casings, and the hot, cold, and crossover legs. Insulated piping in the zone of influence will be insulated with RMI. (ZOI =2D)

3.0 APPLICABLE U.S. EPR DESIGN BASES

The design of the U.S. EPR ECCS recirculation system coupled with the judicious selection of and control of insulating materials and other debris generating material effectively addresses strainer clogging. This conclusion is based on U.S. EPR evaluations and substantiated by physical testing that demonstrates the overall system effectiveness.

The design is such that for the postulated event, the LOCA transported debris will not cause a significant loss of NPSH for the ECCS pumps. This is based on the following assumptions:

1. a conservative LOCA debris estimate developed from the guidance of RG 1.82 Rev. 3 and NEI 04-07.

2. all LOCA related debris is transported to the IRWST and all of this material is deposited into one retaining basket.

These assumptions form the underlying technical basis for the U.S. EPR strainer design.

Results of the strainer test program validate the design of the U.S. EPR ECCS recirculation system.

3.1 *Technical Basis for the ECCS Sump Recirculation Design Features*

The technical basis for the ECCS sump recirculation design features is provided by the studies, summarized below. The results of these studies demonstrate the effectiveness of the sump recirculation design features.

3.1.1 *Debris Transport*

Though the U.S. EPR design incorporates multiple LOCA return flow paths and a tiered defense-in-depth debris retention system, a conservative approach is applied in the debris transport evaluation, in that credit is not taken for all design features. For evaluation purposes all LOCA related debris is assumed to be transported to one heavy floor opening (with weir and trash rack) and is assumed to all enter one retaining basket. No credit is taken for debris settling prior to entering the retaining basket. The debris entering the retaining basket is filtered by the retaining basket screen. Some debris passes through the retaining basket filter and is transported to one strainer where it is filtered. The ECCS strainer head loss is based on the accumulation of debris on the single strainer, as shown by testing.

3.1.2 *Debris Source Term*

A debris generation evaluation was performed to establish the debris source term for the U.S. EPR. The details of this evaluation are documented in Appendix C. The evaluation utilizes the guidance of NRC Regulatory Guidance 1.82 Rev. 3 and information presented in Nuclear Energy Institute (NEI) 04-07. This assessment analyzes seven break locations for a postulated LOCA, tabulates the debris generation totals for each break, and identifies the limiting breaks with respect to the most debris generated. The debris generation totals for the limiting pipe breaks serve as a basis for development of the U.S. EPR sump performance program and validation testing.

The debris source term is based on the maximum amount of debris generated by the limiting breaks. For the U.S. EPR design, seven break locations were evaluated for potential limiting debris loads. The following limiting break is identified for the U.S EPR:

- RCS hot leg 3 at pressurizer surge line connection

The RCS hot leg 3 at the pressurizer surge line connection produces the most RMI debris. This debris amount serves as input to the debris source term. Table 3.1-1 summarizes the total debris source term for the U.S. EPR.

Table 3.1-1 Total Debris Source

Material	Amount
RMI (ft^2)	2119.03
Microtherm® (ft^3)	1.00
Qualified Epoxy Coatings (lb_m)	126.30
Qualified IOZ Coatings (lb_m)	958.70
Unqualified Coatings (lb_m)	250.00
Latent Debris (lb_m)	150.00
Miscellaneous (ft^2)	100.00

The bases and assumptions for the debris types and amounts are explained in Appendix C and serve as input to the U.S. EPR Chemical Effects Evaluation and the U.S. EPR ECCS Strainer Performance Testing as detailed in Appendix D and Appendix E, respectively.

3.1.3 *Chemical Effects*

Generic Letter 2004-02 requests the maximum head loss across the ECCS sump strainers postulated from debris accumulation be evaluated. This evaluation requires assessment of chemical effects. As part of the evaluation of IRWST strainer clogging for the U.S. EPR plant, the chemical effects were evaluated to identify specific compounds and quantities of materials that may precipitate within the containment sump pool following a LOCA. This evaluation is comprised of the following integrated studies:

- Chemical Effects Testing

  Chemical Effects Testing involves testing of simulated post-break conditions to identify chemical effects arising from the interaction of debris materials and buffering agents used to raise the pH of the fluid in the IRWST. The test results provide the data required to calculate the chemical debris generated as a result of a design basis LOCA. The calculation of the chemical debris quantities is performed in the IRWST Sump Chemistry Modeling study.

- IRWST Sump Chemistry Modeling

Using the data and results from Chemical Effects Testing, IRWST Sump Chemistry Modeling calculates and identifies the specific compounds and quantities of materials that may precipitate within the U.S. EPR reactor containment sump pool following a LOCA.

Appendix D details the methodology and results of the U.S. EPR Chemical Effects Evaluation. The results of this evaluation serve as a basis for development and input to the U.S. EPR ECCS Strainer Performance Testing as detailed in Appendix E.

Based on chemical effects studies and ECCS strainer performance testing, the amount of chemical precipitate formation will not result in significant impact to strainer head loss and ECCS operation.

3.1.4 *ECCS Strainer Performance*

ECCS strainer testing was conducted to demonstrate strainer performance following a postulated loss of coolant accident (LOCA). Testing is based on guidance specified in NEI 04-07 Volumes 1 and 2 (Reference 3) and the March 2008 testing guidance (Reference 4). The U.S. EPR Debris Generation Evaluation (Appendix C) and the U.S. EPR Chemical Effects Evaluation (Appendix D) serve as a basis and input to the strainer testing.

ECCS strainer testing conservatively challenged the “defense in depth” design of the U.S. EPR IRWST design by using only one of the four sets of retaining basket/strainer combinations that exist in the IRWST design. Testing determined the strainer head loss based on prototypical water flow and debris mix conditions expected in the U.S. EPR containment following a postulated LOCA. Testing also evaluated strainer response to thin bed conditions, debris transport response, and provided bypass sampling for downstream analysis. A total of five tests were performed. These tests include:

- Debris Transport Test
- Clean Strainer Head Loss Test

- Design Basis Debris Loaded Strainer Head Loss Test
- Fibrous Debris Only Sample Bypass Test
- Debris Loaded Strainer Head Loss Thin Bed Test

ECCS strainer performance testing demonstrated the effective and reliable performance of the U.S. EPR design for GSI-191. The strainer design, complimented by the design mitigation features of the retaining basket, provides an abundance of head loss margin for the ECCS strainer. Testing concludes the strainer head loss is conservatively limited to less than 0.5 feet of water as compared to a strainer design head loss of approximately 5.0 feet. The observed head loss was zero feet because of debris. In addition, testing revealed no thin bed formation on the strainer. Fiber-only bypass testing also yielded acceptable results.

The details of U.S EPR ECCS strainer performance testing are provided in Appendix E.

3.2 *Other Considerations*

3.2.1 *NPSH Assessment*

An NPSH assessment of the ECCS system was performed. Results of this assessment conclude the system will satisfactorily function with the strainer design head loss of approximately 5 feet. Based on the results of strainer testing, the actual strainer head loss for the design basis LOCA is less than 0.5 feet with a water temperature of 120°F. The strainer testing head loss of approximately 1/10th of the design strainer head loss ensures adequate NPSH margin for the ECCS pumps.

3.2.2 *Strainer Vortexing, Submergence, Flashing, and Deaeration Assessment*

Vortexing

An evaluation was performed of the potential for IRWST vortexing using the methodology of ANSI Standard 9.8-1998 (Reference 5), Sections 9.8.6 and 9.8.7. To minimize free surface vortices for the U.S. EPR inlet sump for the low head safety injection (LHSI) and medium head safety injection (MHSI) pumps, the recommendation in ANSI Standard 9.8-1998 was followed, which recommends a minimum submergence of ~50 in. The U.S. EPR-designed submergence is ~147 in., so there is no vortexing potential for the U.S. EPR sump design. The calculated minimum submergence is based on maximum LHSI/MHSI combined flow and higher-than-expected fluid temperature, both of which are conservative and provide additional vortexing margin.

Submergence / Flashing

The strainer height is 7.8 feet. The IRWST minimum level for ECCS pump NPSH is 10.0 feet. This results in a strainer submergence of 2.2 feet under LOCA conditions. The maximum strainer head loss is 0.88 psi at 212°F. This converts to an equivalent head of 2.1 feet of head loss. The strainer submergence level exceeds the associated head loss. If the surface pressure is conservatively assumed at the saturation pressure of the IRWST water temperature, the local static pressure after the strainer will not be less than the saturation pressure, and flashing will not occur across the strainer surface.

During testing, the maximum observed head loss across the strainer is less than 0.5 feet, which provides additional margin to flashing.

Deaeration

The strainer submergence post LOCA is greater than the observed head loss under loss of coolant conditions. Since solubility of gas in water is directly proportional to the fluid pressure, the increase in solubility of air due to the static pressure increase of the water above the strainer is more than enough to compensate for the decrease in solubility of air due to the head loss across the strainer. Therefore, deaeration of fluid will not occur. The design head loss value is a conservative value aimed primarily at minimizing the calculated NPSH for the ECCS pumps, and does not imply deaeration even though it may be greater than the strainer submergence.

3.2.3 *IRWST Cleanliness*

The IRWST serves as a water source, heat sink, and return reservoir and contains a large volume of borated water that is monitored for a homogeneous concentration, level, and temperature. The IRWST is an open pool within a partly immersed building structure. The walls of the IRWST have an austenitic stainless steel liner covering the immersed region of the building structure. The liner prevents interaction of the boric acid and concrete structure and provides water tightness.

During normal operations and refueling, there is the potential for debris to enter the IRWST and settle on its submerged surfaces. This “latent, resident” debris could become re-entrained post-accident. To maintain the cleanliness of the IRWST, the IRWST water inventory and access to the IRWST areas will be controlled and monitored. The fuel pool purification system (FPPS) is utilized to maintain the purity of the IRWST water inventory. IRWST programmatic controls for foreign material exclusion (FME) and tank cleaning will be implemented. A cleanliness control program will limit debris within containment.

3.2.4 *Strainer Mechanical Integrity*

The ECCS strainers are designed to accommodate an approximate 5.0 feet pressure differential. The maximum pressure drop across the strainers is less than 0.5 feet as shown by strainer performance testing. The strainers are Seismic Category I, safety-related components.

3.2.5 *Water Holdup*

The water holdup mass in the Reactor Building is examined during various phases of the LBLOCA transient, including time of blowdown, refill/reflood, post-reflood, peak containment pressure, and half peak containment pressure time. There are different categories analyzed for water holdup, including condensate on walls and ceilings, water retained in steam and droplet phase in the containment atmosphere, and water retained on floors. Water is also retained in a retaining basket assumed to be clogged and in the RCS.

Condensation on vertical walls and ceilings is assumed to be at a uniform film thickness and distribution throughout the Reactor Building. For a LBLOCA, the mass of droplets in the containment atmosphere is only significant early in the transient during blowdown. Steam mass inside the containment atmosphere is evenly distributed throughout the containment free volume and is based on containment vapor partial pressure and saturation temperature.

The mass of retained water on the heavy floor and lower annular area is based on the height of each respective weir plus an additional dynamic head height based on the flow rate onto each floor. The flow on the heavy floor consists of condensation from rooms above the heavy floor and liquid break flow leaving the RCS. Water on the heavy floor returns to the IRWST via the four trash racks.

Wall openings are provided in the SGBD room walls at four locations, two in each wall, to route the surge line break fluid out of the SGBD tank room and onto the heavy floor. During a LBLOCA, water may flow from the heavy floor into the SGBD and PRT rooms. In the water retention analysis, the SGBD and PRT rooms (UJA11018 and UJA11019) are considered to be flooded at the same depth as the heavy floor.

The four openings between the SGBD and PRT rooms and the loop areas are free openings (0.618 $feet^2$ each) (Figure 3-2). The minimum opening height from the floor for each 0.618 $feet^2$ opening is approximately 1.05 feet (Figure 3-3). There are no devices in the openings, allowing bidirectional flow. A 20 inch (1.67 feet) (Figure 3-1) high berm around the SGBD system tank prevents flooding into the compartment below. The two doors leading into the annular regions from room UJA11018 will contain a flooding berm of at least 20 inches (1.67 feet) high to preclude flooding into the annular area. Obstructions to drainage of water such as toe-plates will be specifically designed to allow drainage to the IRWST.

Debris generation is limited to reflective metallic insulation (RMI) and latent debris. There is no fibrous insulation in the ZOI in the U.S. EPR containment design. However, fibrous insulation may be used outside the ZOI.

The maximum level of flooding on the heavy floor and the floors of the SGBD and PRT rooms in the water retention analysis is 0.79 feet, which occurs during blowdown of a LBLOCA. The flooding level for a pressurizer surge line break was not evaluated because the LBLOCA is more limiting for water retention. The maximum level of water retention (0.79 feet) is lower than the level of berms (1.67 feet), and no water will flood out to the annular space or to the room below the SGBD tank room. Door operation in the SGBD tank room is not required to release or contain the water level because the flooding level, 0.79 feet, from the LBLOCA is below the 1.67 feet height of the berms at each door.

Figure 3-1 20" Berm around SGBD Tank

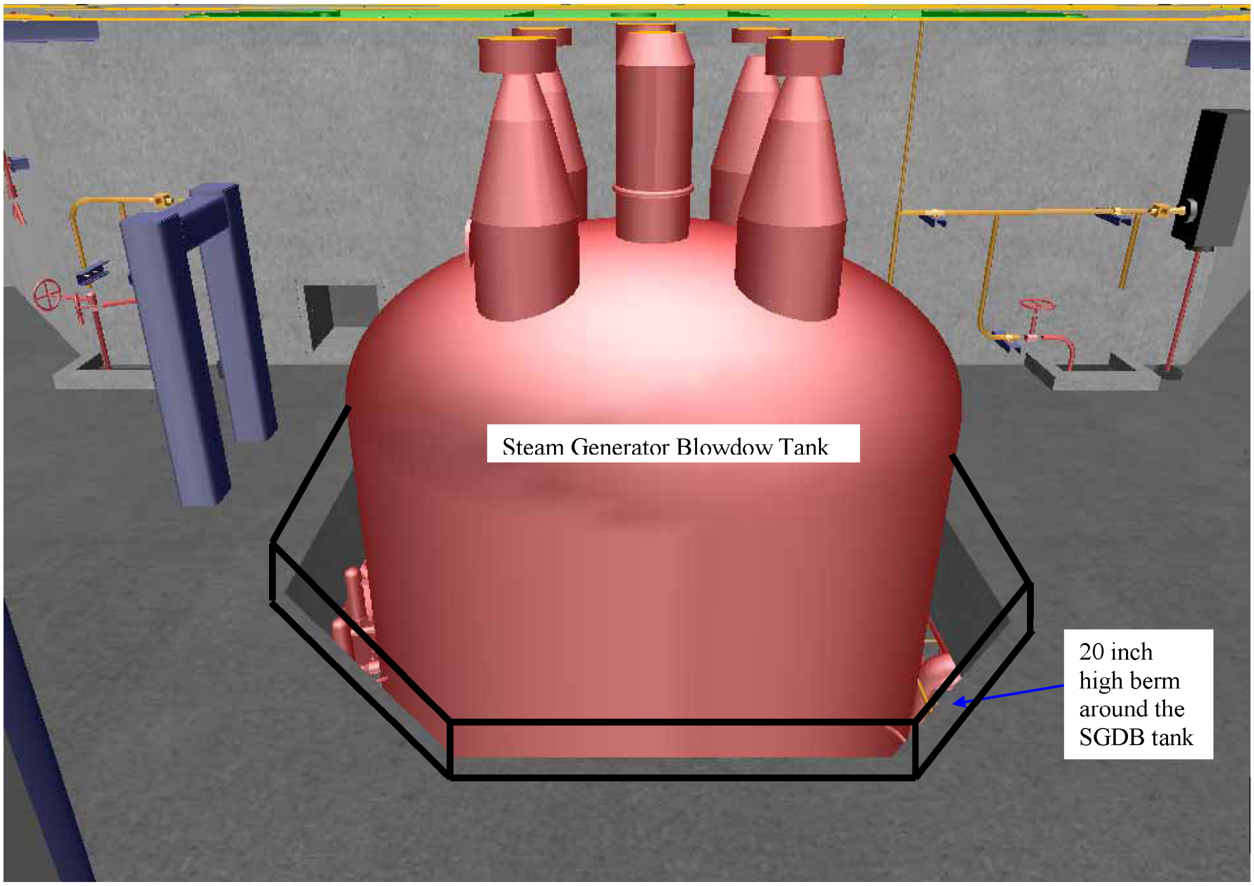


Figure 3-2 Openings that Communicate to the Heavy Floor Area

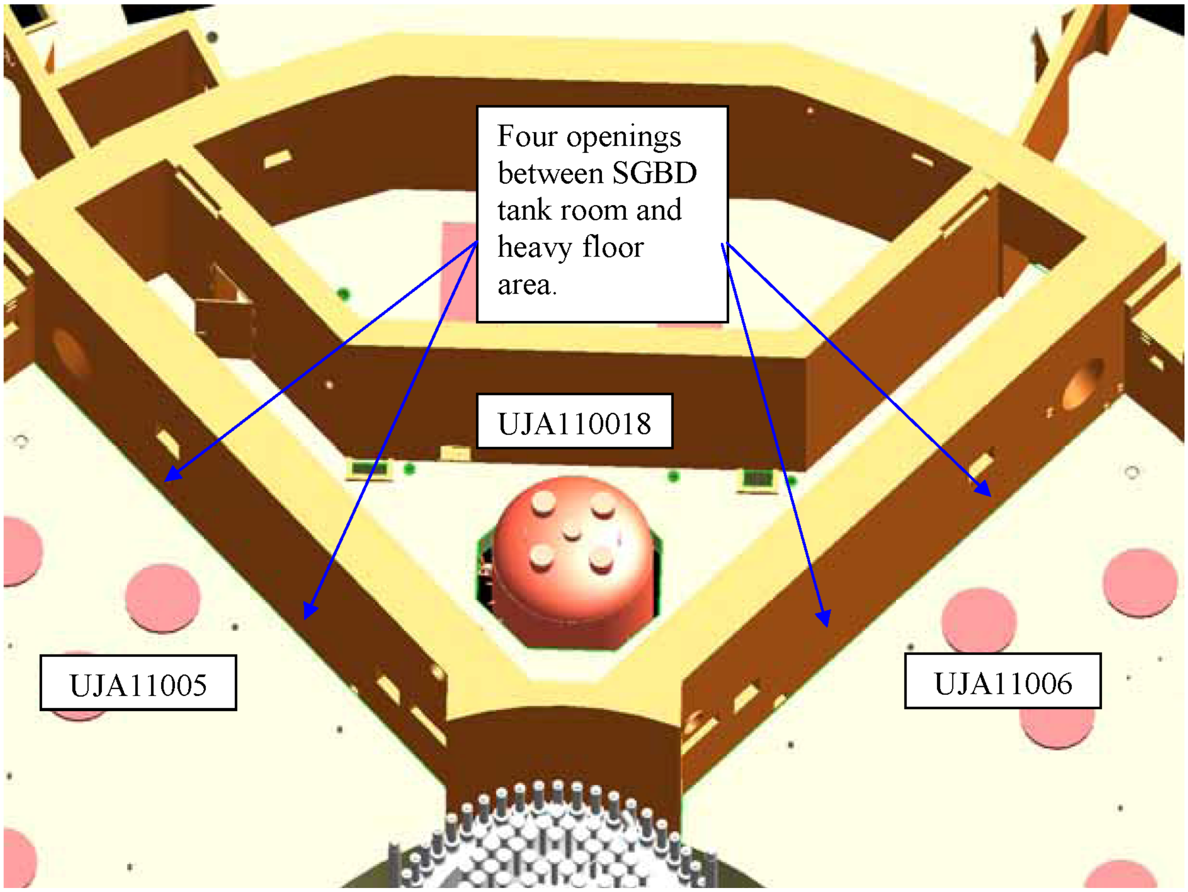
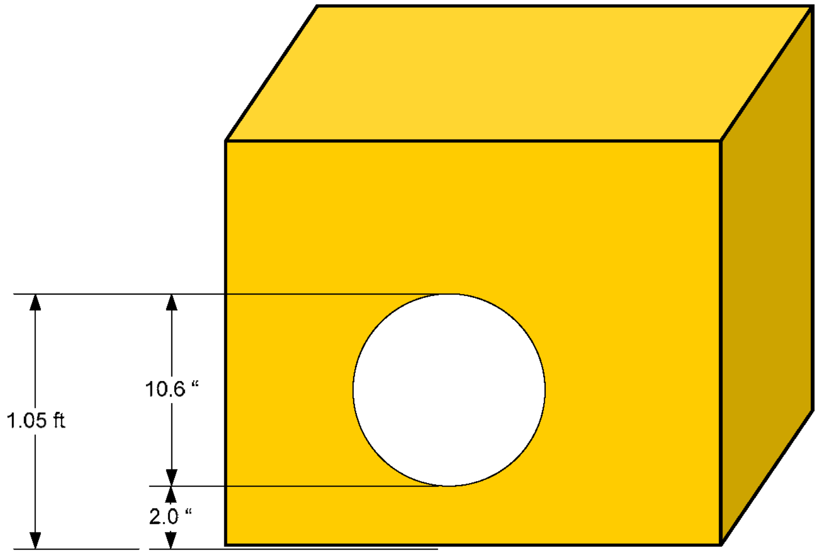


Figure 3-3 Profile of the 4 openings



The flow to the lower annular area consists only of condensation flow, although it is possible for the pressure during blowdown to force water from the IRWST into the lower annular service area. The exact amount of IRWST water that could be displaced depends on different, interrelated factors for each break scenario. The water retention analysis was a worst-case evaluation, assuming that the annular area would instantly fill to the weir height with IRWST liquid. This worst-case scenario only impacts the early phases of the transient.

There are no RCS breaks outside the equipment compartment that can affect the annular area. The only high-energy line breaks that will affect the annular area are a feedwater line break and a main steam line break, but in those cases, ECCS recirculation is not required for event mitigation.

In addition to the heavy floor and the lower annular area, water is retained on the floors of several rooms where condensation will occur but will not return to IRWST. These rooms contain walls or curbs that completely hold up water, or doors that partially hold up water.

The total amount of water holdup is used to calculate the IRWST level for evaluation of NPSH requirements and for the debris distribution evaluation for GSI-191 requirements. The maximum amount of water holdup for a LBLOCA occurs at 29 seconds into the transient. Table 3.2-1 summarizes water holdup in the Reactor Building at 29 seconds. Table 3.2-1 shows that after accounting for the water held up in containment, the IRWST has a margin to ECCS pump NPSH of 79,726 pounds.

Table 3.2-1 Maximum Water Holdup

Time (s)	29
Steam Phase (lbm)	303,391
Droplets (lbm)	39,208
Wall Condensate (lbm)	28,855
Ceiling Condensate (lbm)	26,053
Retention on RB Floors (lbm)	717,968
Retention in Clogged Basket (lbm)	68,064
Re-injected into RCS (lbm)	54,958
Total Mass of Retained Water (lbm)	**1,238,497**
Accumulator Injection (lbm)	-94,683
RCS Inventory (lbm)	-671,504
Total IRWST Water Loss (lbm)	**472,310**
Allowable IRWST Loss (lbm)	552,036
Margin (lbm)	**79,726**

3.2.6 *Upstream Effects*

Section 7.2 of NEI 04-07 provides guidance regarding hold-up of inventory away from the containment sump, possibly depriving the sump of inventory due to post-accident debris accumulation. Section 2.3 of this report discusses how the U.S. EPR tiered "defense-in-depth" strategy conforms to NEI 04-07 guidance. A review of containment drawings was performed and did not reveal any areas of the plant that could be identified as areas of concern regarding water hold-up due to the formation of debris "mounds", such as the narrowing of hallways or passages, with the exception of those identified in Section 3.2.5. Another area to consider for possible hold-up of liquid upstream of the containment sump is the refueling canal drain to lower containment, which was considered in the water holdup evaluation described in Section 3.2.5.

4.0 REGULATORY OVERVIEW

The purpose of this section is to provide a brief overview of the related regulatory issues and an evaluation of the U.S. EPR conformance.

4.1 *Generic Safety Issue 191*

GSI-191, “Assessment of Debris Accumulation on PWR Sump Performance,” was initiated by the NRC in 1996 in response to a number of plant events and subsequent follow-on research regarding the adequacy of ECCS sump designs.

The issue of post-accident debris blockage arising from a LOCA or high energy line break (HELB) for which sump recirculation is required could potentially impact the plant’s ability to demonstrate compliance with General Design Criterion 38, “Containment Heat Removal,” and 10 CFR 50.46 (b) (5) as it relates long term post-LOCA core cooling requirements. The objective of GSI-191 is to prevent post-accident debris blockage that could impede the operation of the emergency core cooling system (ECCS) and the containment spray system (CSS) in the recirculation mode at PWRs during LOCAs or other HELB accidents for which sump recirculation is required.

4.2 *Regulatory Guide 1.82 Rev. 3*

Regulatory Guide 1.82 Rev. 3, “Water Sources for Long-Term Recirculation Cooling Following a Loss-Of-Coolant Accident,” provides guidelines for evaluating the adequacy of the availability of the sump and suppression pool for long-term recirculation cooling following a LOCA.

The primary safety concerns regarding long-term recirculation cooling following a LOCA are:

1. LOCA-generated and pre-LOCA debris materials transported to the debris interceptors (i.e., trash racks, debris screens, suction strainers) resulting in adverse blockage effects.

2. Post-LOCA hydraulic effects, particularly air ingestion.

3. The combined effects of items (1) and (2) on long-term recirculation pumping operability (i.e., NPSH available at the pump inlet).

The above safety concerns extend to the CSS for plants with containment designs where the CSS draws suction from the recirculation sump. In some cases, the CSS would draw from the recirculation sump significantly earlier than would the ECCS. However, the U.S. EPR design basis does not rely on a CSS.

Debris resulting from a LOCA, together with debris that exists before a LOCA, could block the ECCS debris interceptors and result in degradation or loss of NPSH margin. Such debris can be divided into the following categories:

1. Debris that is generated by the LOCA and is transported by blowdown forces (e.g., insulation, paint).

2. Debris that is generated or transported by washdown.

3. Other debris that existed before a LOCA (e.g., corrosion material, sludge in a BWR suppression pool) and that may become suspended in the containment sump or suppression pool.

Debris can be further subdivided as follows:

1. Debris that have a high density and could sink but are still subject to fluid transport if local recirculation flow velocities are high enough.

2. Debris that have an effective specific gravity near 1.0 and tend to remain suspended or sink slowly and will nonetheless be transported by very low velocities or local fluid turbulence phenomena.

3. Debris that will float indefinitely by virtue of low density and will be transported to and possibly through the debris interceptors.

Debris generation, early debris transport, long-term debris transport, and attendant blockage of debris interceptors should be evaluated to show that the ability of the ECCS to provide long-term post-LOCA core cooling is not jeopardized. All potential debris sources should be evaluated, including but not limited to, the fire barrier material, insulation materials (e.g., fibrous, ceramic, and metallic), filters, corrosion material, and paints or coatings.

Regulatory Guide 1.82 provides separate guidance for PWR and BWR plants based on the design features of currently operating reactors. However, advanced PWR or BWR designs may employ design features that this regulatory guide only associates with the opposite reactor design (e.g., an advanced PWR design that employs an IRWST similar to the suppression pool of a current BWR design, or an advanced BWR design that employs a large dry containment similar to a current PWR design).

Therefore, for advanced PWR and BWR designs, the guidance provided in both the PWR and BWR sections of RG 1.82 that is appropriate and consistent with the plant's design features should be considered.

4.3 *RG 1.82 Conformance Assessment*

An assessment of U.S. EPR conformance to RG 1.82 is provided in Appendix A. All 53 PWR-related guidance and five potentially applicable BWR guidance items were reviewed.

4.4 Generic Letter 2004-02

GL 2004-02 was issued to licensees of operating plants requesting that they demonstrate that corrective actions taken to address GSI-191 are adequate.

Additionally, GL 2004-02 requested the licensee provide information to assess the potential impact of debris blockage on emergency recirculation during design basis events.

Table B.1 of Appendix B provides U.S. EPR sump recirculation information as applicable to requested information outlined in GL 2004-02.

5.0 CONCLUSION

The U.S. EPR sump design has advanced and redundant features with respect to post-accident debris accumulation and ECCS recirculation sump strainer blockage. The U.S. EPR's ECCS recirculation system has multiple levels of debris removal and filtration that provide an effective system for preventing LOCA-generated debris from degrading ECCS performance or impeding core cooling. In conformance with NEI 04-07 guidance, an upstream effects evaluation shows there is no threat of the hold-up of inventory, from the IRWST due to debris accumulation. The conclusion is supported by the following information presented in this report:

1. The U.S. EPR has a minimal post-accident debris source term relative to current LWRs. RCS piping and components will be insulated with RMI; there will be no fibrous or micro-porous insulation within the ZOI, and no calcium-silicate insulation within containment.

2. The three-tiered debris retention design of the U.S. EPR ECCS recirculation system prevents post-accident ECCS pump strainer clogging without depriving the IRWST of inventory due to water hold-up from accumulation of post-accident debris. The combination of weirs/trash racks and retaining baskets are effective in retaining most of the debris. As a result, very little debris and sufficient inventory will reach the ECCS strainers. The ECCS strainers have a large screen surface area to accommodate the small amount of debris that will reach them.

3. The U.S. EPR design conforms to the applicable RG 1.82 requirements as detailed in Table A.1 of Appendix A.

4. Test results using a conservative debris source term validate the performance of the U.S. EPR ECCS recirculation system features to prevent sump/strainer clogging.

6.0 REFERENCES

1. USNRC Regulatory Guide 1.82, Rev. 3, “Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident,” November 2003.

2. GL 2004-02, “Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors,” U.S. NRC, September 2004.

3. NEI 04-07, “Pressurized Water Reactor Sump Performance Evaluation Methodology,” Volumes 1 (Methodology) and 2 (Safety Evaluation), December 2004.

4. “NRC Staff Review Guidance Regarding Generic Letter 2004-02 Closure in the Area of Strainer Head Loss and Vortexing,” March 2008.

5. ANSI Standard 9.8-1998, “Pump Intake Design.”

Appendix A
RG 1.82 Conformance Assessment

A.1 Regulatory Guide 1.82

NRC Regulatory Guide (RG) 1.82 describes acceptable methods and guidelines for evaluating the adequacy of plant design features and ECCS performance. RG 1.82 provides a framework for licensees to develop, demonstrate and implement a comprehensive response to GSI-191 resolution.

An assessment of U.S. EPR conformance to RG 1.82 has been performed. All 53 PWR-related guidance and five potentially applicable BWR guidance items were reviewed. The results of this assessment are detailed in Table A.1.

Table A.1 RG-1.82 Conformance Assessment Matrix

RG 1.82 Rev.3	Water Resources for Long Term Recirculation Cooling following a Loss-of-Coolant Accident	
	GUIDANCE	**CONFORMANCE ASSESSMENT**
C.	**REGULATORY POSITION**	
	This section states regulatory positions on design criteria, performance standards, and analysis methods that relate to PWRs (Regulatory Position 1) and BWRs (Regulatory Position 2). As stated in the Introduction to this guide, the purpose of the guidance is to identify information and methods acceptable to the NRC staff for evaluating analytical techniques and implementing regulations related to water sources for long-term cooling of both existing and future reactor systems. The guidance, to a great extent, is generic and it may go beyond the current design of some operating reactor systems.	No response necessary – Introductory Material.
1.	**PRESSURIZED WATER REACTORS**	
1.1	**Features Needed to Minimize the Potential for Loss of NPSH**	
1.1.1	**ECC Sumps, Debris Interceptors, and Debris Screens**	
1.1.1.1	A minimum of two sumps should be provided, each with sufficient capacity to service one of the redundant trains of the ECCS and CSS. Distribution of water sources and containment spray between the sumps should be considered in the calculation of boron concentration in the sumps for evaluating post-LOCA subcriticality and shutdown margins. Typically, these calculations are performed assuming minimum boron concentration and minimum dilution sources. Similar considerations should also be given in the calculation of time for Hot Leg Switchover, which is calculated assuming maximum boron concentration and a minimum of dilution sources.	The U.S. EPR IRWST has 4 sumps, one for each of the 4 ECCS pumps. The IRWST is the sole water source (≈500,000 gallons) for these pumps. Sub-criticality analyses assume minimum boron concentrations while maximum boron concentrations are assumed for hot leg switchover timing. Furthermore, dilution of the IRWST from internal sources has been evaluated. The

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	GUIDANCE	**CONFORMANCE ASSESSMENT**
		risk of dilution is considered negligible because of the amount of dilutent (≈53,000 gallons) required to achieve a significant (i.e., 10%) reduction in boron concentration is unrealistic (i.e., without going undetected).
1.1.1.2	To the extent practical, the redundant sumps should be physically separated by structural barriers from each other and from high-energy piping systems to preclude damage from LOCA, and, if within the design basis, main steam or main feedwater break consequences to the components of both sumps (e.g., trash racks, sump screens, and sump outlets) by whipping pipes or high-velocity jets of water or steam.	The IRWST is a 270° annular tank located in the space bounded by the reactor vessel support structure, the RCS loop area heavy floor (6.6 ft thick), the containment basemat, and the containment annular wall. These boundaries, in particular, the heavy floor, provide significant protection for the ECCS sumps (located on the IRWST floor); thereby precluding any post-LOCA induced damage. Hence, the U.S. EPR design eliminates the need for physically separated sumps.
1.1.1.3	The sumps should be located on the lowest floor elevation in the containment exclusive of the reactor vessel cavity to maximize the pool depth relative to the sump screens. The sump outlets should be protected by appropriately oriented (e.g., at least two vertical or nearly vertical) debris interceptors: (1) a fine inner debris screen and (2) a coarse outer trash rack to prevent large debris from reaching the debris screen. A curb should be provided upstream of the trash racks to prevent high-density debris from being swept along the floor into the sump. To be effective, the height of the curb should be appropriate for the pool flow velocities, as the debris can jump over a curb if the velocities are sufficiently high. Experiments documented in NUREG/CR-6772 and NUREG/CR-6773 have	U.S. EPR design features satisfy this guidance – weir, trash racks, retaining basket and ECCS sump strainer. ECCS sump strainer testing validates design. Also, the ECCS sumps are located on the IRWST floor, which is also the top of the containment basemat. This maximizes the pool depth relative to the sump screens and pump suction.

RG 1.82 Rev.3	Water Resources for Long Term Recirculation Cooling following a Loss-of-Coolant Accident	
	GUIDANCE	**CONFORMANCE ASSESSMENT**
	demonstrated that substantial quantities of settled debris could transport across the sump pool floor to the sump screen by sliding or tumbling.	
1.1.1.4	The floor in the vicinity of the ECC sump should slope gradually downward away from the sump to further retard floor debris transport and reduce the fraction of debris that might reach the sump screen.	NOT APPLICABLE: The U.S. EPR design does not require that the floor in the vicinity of the ECC sumps be sloped away from the sump for the following reasons: The IRWST, due to its isolated location, is not subject to heavy debris loading. The retaining baskets will intercept any debris entering from the loop area above. The ECCS sump screens have a significant amount of surface area and the effect of floor debris will be minimal. The physical attachment of the ECC sump screen to the IRWST floor will also function as a berm. All these features coupled with the very low flow velocities within the IRWST will significantly reduce the amount of floor debris that might reach the screen.
1.1.1.5	All drains from the upper regions of the containment should terminate in such a manner that direct streams of water, which may contain entrained debris, will not directly impinge on the debris interceptors or discharge in close proximity to the sump. The drains and other narrow pathways that connect compartments with	U.S. EPR design meets this guidance. Reactor Building drains that contain retained debris terminate in the retaining baskets, with the exception of a cavity drain line from the reactor cavities to the

RG 1.82 Rev.3	Water Resources for Long Term Recirculation Cooling following a Loss-of-Coolant Accident	
	GUIDANCE	**CONFORMANCE ASSESSMENT**
	potential break locations to the ECC sump should be designed to ensure that they would not become blocked by the debris; this is to ensure that water needed for an adequate NPSH margin could not be held up or diverted from the sump.	IRWST. Following a LOCA, the only water that passes through the cavity drain line to the IRWST is "condensation" from the containment atmosphere. The U.S. EPR design does not take credit for the containment spray system. Therefore, this drain line does not function as a return path for containment spray during a design basis LOCA event. The upstream opening of the cavity drain line is remote from the LOCA debris. The downstream opening of the cavity drain line does not affect the strainer operation. The cavity drain line is not considered a debris supply path to the IRWST water volume.

RG 1.82 Rev.3	Water Resources for Long Term Recirculation Cooling following a Loss-of-Coolant Accident	
	GUIDANCE	**CONFORMANCE ASSESSMENT**
1.1.1.6	The strength of the trash racks should be adequate to protect the debris screens from missiles and other large debris. Trash racks and sump screens should be capable of withstanding the loads imposed by expanding jets, missiles, the accumulation of debris, and pressure differentials caused by post-LOCA blockage under design-basis flow conditions. When evaluating impact from potential expanding jets and missiles, credit for any protection to trash racks and sump screens offered by surrounding structures or credit for remoteness of trash racks and sump screens from potential high energy sources should be justified.	The 6.6 ft thick RCS loop area heavy floor and the heavy duty trash racks that cover the floor openings prevent missiles, large debris, and expanding jets from impacting the retaining baskets or the ECC screens. The floor openings are located on the periphery of the RCS loops, thereby reducing the trash rack profile for a majority of break locations. The trash racks are designed to prevent major debris from falling through the opening into the retaining baskets. The retaining baskets and the ECC sump screens rely on the 6.6 ft thick heavy floor, the trash racks and distance for protection from jet impingement and missiles. Nevertheless, they are designed for the maximum expected debris loading and the corresponding differential pressure.
1.1.1.7	Where consistent with overall sump design and functionality, the top of the debris interceptor structures should be a solid cover plate that is designed to be fully submerged after a LOCA and completion of the ECC injection. The cover plate is intended to provide additional protection to debris interceptor structures from LOCA generated loads. However, the design should also provide means for venting of any air trapped underneath the cover.	NOT APPLICABLE: The recommended guidance is not consistent with the U.S. EPR design. The U.S. EPR trash racks perform the debris intercept function and are located on the RCS loop area floor openings. The trash racks are designed to prevent major debris from falling through the opening

RG 1.82 Rev.3	Water Resources for Long Term Recirculation Cooling following a Loss-of-Coolant Accident	
	GUIDANCE	**CONFORMANCE ASSESSMENT**
		into the retaining baskets. Therefore, a cover plate is not required. As such, the U.S. EPR design does not require venting.
1.1.1.8	The debris interceptors should be designed to withstand the inertial and hydrodynamic effects that are due to vibratory motion of a safe shutdown earthquake (SSE) following a LOCA without loss of structural integrity.	The trash racks, retaining baskets and ECC sump strainers are safety-related components and are designed to meet U.S. EPR Seismic Category I.
1.1.1.9	Materials for debris interceptors and sump screens should be selected to avoid degradation during periods of both inactivity and operation and should have a low sensitivity to such adverse effects as stress-assisted corrosion that may be induced by chemically reactive spray during LOCA conditions.	Materials of construction are consistent with those used in other systems containing borated water. Hence, the trash racks, retaining baskets, ECC sump screens are made of austenitic stainless steel. The acceptability of the material selection for post-LOCA service relative to chemical effects (i.e. sump chemistry) is part of the U.S. EPR design process and design requirements.
1.1.1.10	The debris interceptor structures should include access openings to facilitate inspection of these structures, any vortex suppressors, and the sump outlets.	U.S. EPR design provides access for IRWST component inspections.
1.1.1.11	A sump screen design (i.e., size and shape) should be chosen that will avoid the loss of NPSH from debris blockage during the period that the ECCS is required to operate in order to maintain long-term cooling or maximize the time before loss of NPSH caused by debris blockage when used with an active mitigation system (see Regulatory Position 1.1.4).	U.S. EPR ECCS sump screens are designed such that NPSH is not lost even with maximum debris loading. Their large surface area provides ample filtration area and debris build up is self-limiting on vertical surfaces due to their inverted trapezoidal shape.

RG 1.82 Rev.3	Water Resources for Long Term Recirculation Cooling following a Loss-of-Coolant Accident	
	GUIDANCE	**CONFORMANCE ASSESSMENT**
1.1.1.12	The possibility of debris-clogging flow restrictions downstream of the sump screen should be assessed to ensure adequate long term recirculation cooling, containment cooling, and containment pressure control capabilities. The size of the openings in the sump debris screen should be determined considering the flow restrictions of systems served by the ECCS sump. The potential for long thin slivers passing axially through the sump screen and then reorienting and clogging at any flow restriction downstream should be considered. Consideration should be given to the buildup of debris at downstream locations such as the following: containment spray nozzle openings, HPSI throttle valves, coolant channel openings in the core fuel assemblies, fuel assembly inlet debris screens, ECCS pump seals, bearings, and impeller running clearances. If it is determined that a sump screen with openings small enough to filter out particles of debris that are fine enough to cause damage to ECCS pump seals or bearings would be impractical, it is expected that modifications would be made to ECCS pumps or ECCS pumps would be procured that can operate long term under the probable conditions.	U.S. EPR design has been evaluated for strainer downstream effects. Requirements for downstream components have been identified. In addition, fuel assembly testing has been performed with prototypical debris loadings and the results were acceptable.
1.1.1.13	ECC and containment spray pump suction inlets should be designed to prevent degradation of pump performance through air ingestion and other adverse hydraulic effects (e.g., circulatory flow patterns, high intake head losses).	U.S. EPR design is such that the ECCS sumps are submerged sufficiently to preclude vortex formation and air ingestion. Additionally, sump screens are provided with vortex suppressors to provide an added measure of margin against vortex formation and air ingestion.
1.1.1.14	All drains from the upper regions of the containment building, as well as floor drains, should terminate in such a manner that direct streams of water, which may contain entrained debris, will not discharge downstream of the sump screen, thereby bypassing the sump screen.	The U.S. EPR reactor building drains and similar lines terminate upstream of the sump screen, thereby precluding bypass of the ECCS sump strainers.

RG 1.82 Rev.3	Water Resources for Long Term Recirculation Cooling following a Loss-of-Coolant Accident	
	GUIDANCE	**CONFORMANCE ASSESSMENT**
1.1.1.15	Advanced strainer designs (e.g., stacked disc strainers) have demonstrated capabilities that are not provided by simple flat plate or cone-shaped strainers or screens. For example, these capabilities include built-in debris traps where debris can collect on surfaces while keeping a portion of the screen relatively free of debris. The convoluted structure of such strainer designs increases the total screen area, and these structures tend to prevent the condition referred to as the thin bed effect. It may be desirable to include these capabilities in any new sump strainer/screen designs. The performance characteristics and effectiveness of such designs should be supported by appropriate test data for any particular intended application.	NOT APPLICABLE: The U.S. EPR design employs a simple strainer concept validated by testing.
1.1.2	**Minimizing Debris -** The debris (see Regulatory Position 1.3.2) that could accumulate on the sump screen should be minimized.	No response necessary – Introductory Material
1.1.2.1	Cleanliness programs should be established to clean the containment on a regular basis, and plant procedures should be established for control and removal of foreign materials from the containment.	ADDRESSED BY COL APPLICANT: This is a programmatic requirement. Refer to U.S. EPR FSAR COL Information Item 6.3-1 (Table 1.8-2).
1.1.2.2	Insulation types (e.g., fibrous and calcium silicate) that can be sources of debris that is known to more readily transport to the sump screen and cause higher head losses may be replaced with insulations (e.g., reflective metallic insulation) that transport less readily and cause less severe head losses once deposited onto the sump screen. If insulation is replaced or otherwise removed during maintenance, abatement procedures should be established to avoid generating latent debris in the containment.	NOT APPLICABLE: This item applies to potential insulation replacement after the plant is licensed and is operating. The U.S. EPR design uses RMI for reactor coolant system piping and components. A limited amount of fibrous insulation will be permitted. As described

RG 1.82 Rev.3	Water Resources for Long Term Recirculation Cooling following a Loss-of-Coolant Accident	
	GUIDANCE	**CONFORMANCE ASSESSMENT**
		in 1.1.2.1 above, containment cleanliness is ensured programmatically.
1.1.2.3	To minimize potential debris caused by chemical reaction of the pool water with metals in the containment, exposure of bare metal surfaces (e.g., scaffolding) to containment cooling water through spray impingement or immersion should be minimized either by removal or by chemical-resistant protection (e.g., coatings or jackets).	As part of the U.S EPR GSI-191 program, chemical effects evaluations were evaluated to address the potential impact of chemical reaction with the debris sources.
1.1.3	**Instrumentation -** If relying on operator actions to mitigate the consequences of the accumulation of debris on the ECC sump screens, safety-related instrumentation that provides operators with an indication and audible warning of impending loss of NPSH for ECCS pumps should be available in the control room.	NOT APPLICABLE: U.S. EPR design does not require operator action to backflush ECC sump screens; however, a non-safety-related backflushing system is provided.
1.1.4	**Active Sump Screen System -**An active device or system (see examples in Appendix B) may be provided to prevent the accumulation of debris on a sump screen or to mitigate the consequences of accumulation of debris on a sump screen. An active system should be able to prevent debris that may block restrictions found in the systems served by the ECC pumps from entering the system. The operation of the active component or system should not adversely affect the operation of other ECC components or systems. Performance characteristics of an active sump screen system should be supported by appropriate test data that address head loss performance.	NOT APPLICABLE: The U.S. EPR design does not require operator action to backflush ECC sump screens; however, a non-safety-related backflushing system is provided.
1.1.5	**Inservice Inspection** To ensure the operability and structural integrity of the trash racks and screens, access openings are necessary to permit inspection of the ECC sump structures and outlets. Inservice inspection of racks, screens, vortex suppressors, and sump outlets, including visual examination for evidence of structural degradation or corrosion, should be performed on a	U.S. EPR design provides suitable access to trash racks, retaining baskets and sump screens. Refer to U.S. EPR Technical Specifications Surveillance Requirement 3.5.2.6.

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	regular basis at every refueling period downtime. Inspection of the ECC sump components late in the refueling period will ensure the absence of construction trash in the ECC sump area.	
1.2	**Evaluation of Alternative Water Sources -** To demonstrate that a combination of the features and actions listed above are adequate to ensure long-term cooling and that the five criteria of 10 CFR 50.46(b) will be met following a LOCA, an evaluation using the guidance and assumptions in Regulatory Position 1.3 should be conducted. If a licensee is relying on operator actions to prevent the accumulation of debris on ECC sump screens or to mitigate the consequences of the accumulation of debris on the ECC sump screens, an evaluation should be performed to ensure that the operator has adequate indications, training, time, and system capabilities to perform the necessary actions. If not covered by plant specific emergency operating procedures, procedures should be established to use alternative water sources that will be activated when unacceptable head loss renders the sump inoperable. The valves needed to align the ECCS and containment spray systems (taking suction from the recirculation sumps) with an alternative water source should be periodically inspected and maintained.	NOT APPLICABLE: U.S. EPR design does not require an alternate source of water (i.e., alternate to the water in the IRWST) to meet 10 CFR 50.46 (b) requirements following a LOCA.
1.3	**Evaluation of Long-Term Recirculation Capability -** The following techniques, assumptions, and guidance should be used in a deterministic, plant-specific evaluation to ensure that any implementation of a combination of the features and capabilities listed in Regulatory Position 1.1 are adequate to ensure the availability of a reliable water source for long-term recirculation following a LOCA. The assumptions and guidance listed below can also be used to develop test conditions for sump screens.	Informational Material

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	Evaluation and confirmation of (1) sump hydraulic performance (e.g., geometric effects, air ingestion), (2) debris effects (e.g., debris transport, interceptor blockage, head loss), and (3) the combined impact on NPSH available at the pump inlet should be performed to ensure that long-term recirculation cooling can be accomplished following a LOCA. Such an evaluation should arrive at a determination of NPSH margin calculated at the pump inlet. An assessment should also be made of the susceptibility to debris blockage of the containment drainage flow paths to the recirculation sump; this is to protect against reduction in available NPSH if substantial amounts of water are held up or diverted away from the sump. An assessment should be made of the susceptibility of the flow restrictions in the ECCS and CSS recirculation flow paths downstream of the sump screens and of the recirculation pump seal and bearing assembly design to failure from particulate ingestion and abrasive effects to protect against degradation of long-term recirculation pumping capacity.	
1.3.1	**Net Positive Suction Head of ECCS and Containment Heat Removal Pumps**	
1.3.1.1	ECC and containment heat removal systems should be designed so that sufficient available NPSH is provided to the system pumps, assuming the maximum expected temperature of pumped fluid and no increase in containment pressure from that present prior to the postulated LOCA. (See Regulatory Position 1.3.1.2.) For sump pools with temperatures less than 212°F, it is conservative to assume that the containment pressure equals the vapor pressure of the sump water. This ensures that credit is not taken for the containment pressurization during the transient. For sub-atmospheric containments, this guidance should apply after the	The U.S. EPR design does not fully conform to Section 1.3.1.1. The containment pressure is assumed to be equal to the initial containment pressure prior to the start of the accident. This fulfills the requirements of RG 1.1 and RG 1.82 that the NPSH available is evaluated without crediting any increase in pressure resulting from accident conditions at low temperatures. This

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	injection phase has terminated. For sub-atmospheric containments, prior to termination of the injection phase, NPSH analyses should include conservative predictions of the containment atmospheric pressure and sump water temperature as a function of time.	approach verifies that sufficient containment pressure is available under accident conditions. For temperatures higher than the initial saturation pressure, the containment pressure is assumed to be equal to the sump fluid vapor pressure.
1.3.1.2	For certain operating PWRs for which the design cannot be practicably altered, conformance with Regulatory Position 1.3.1.1 may not be possible. In these cases, no additional containment pressure should be included in the determination of available NPSH than is necessary to preclude pump cavitation. Calculation of available containment pressure and sump water temperature as a function of time should underestimate the expected containment pressure and overestimate the sump water temperature when determining available NPSH for this situation.	NOT APPLICABLE U.S. EPR design conforms to Regulatory Position 1.3.1.1 with the exception noted above.
1.3.1.3	For certain operating reactors for which the design cannot be practicably altered, if credit is taken for operation of an ECCS or containment heat removal pump in cavitation, prototypical pump tests should be performed along with post-test examination of the pump to demonstrate that pump performance will not be degraded and that the pump continues to meet all the performance criteria assumed in the safety analyses. The time period in the safety analyses during which the pump may be assumed to operate while cavitating should not be longer than the time for which the performance tests demonstrate that the pump meets performance criteria.	NOT APPLICABLE U.S. EPR design precludes ECCS pump operation in cavitation.
1.3.1.4	The decay and residual heat produced following accident initiation should be included in the determination of the water temperature. The uncertainty in the determination of the decay heat should be included in this calculation. The residual heat should be calculated	U.S. EPR design calculations for sump water temperature include decay heat (with margin) and all residual heat sources.

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	with margin	
1.3.1.5	The hot channel (i.e., fluid) correction factor specified in ANSI/HI 1.1-1.5-1994 should not be used in determining the margin between the available and required NPSH for ECCS and containment heat removal system pumps.	The assessment of available NPSH for the U.S. EPR ECCS pumps conservatively does not use the hot fluid correction factor specified in ANSI/HI 1.1-1.5-1994. (This factor permits a reduction in NSPH required).
1.3.1.6	The calculation of available NPSH should minimize the height of water above the pump suction (i.e., the level of water on the containment floor). The calculated height of water on the containment floor should not consider quantities of water that do not contribute to the sump pool (e.g., atmospheric steam, pooled water on floors and in refueling canals, spray droplets and other falling water, etc.). The amount of water in enclosed areas that cannot be readily returned to the sump should not be included in the calculated height of water on the containment floor.	The assessment of available NPSH for the U.S. EPR ECCS pumps is based on the minimum post LBLOCA water level in the IRWST.
1.3.1.7	The calculation of pipe and fitting resistance and the calculation of the nominal screen resistance without blockage by debris should be done in a recognized, defensible method or determined from applicable experimental data.	ECCS performance calculations properly treat pipe and fitting resistance and use a conservative value for ECCS screen resistance based on ECCS strainer testing results.
1.3.1.8	Sump screen flow resistance that is due to blockage by LOCA-generated debris or foreign material in the containment which is transported to the suction intake screens should be determined using Regulatory Position 1.3.4.	The assessment of available NPSH for the ECCS pumps is determined from screen pressure drop based on validation testing and the maximum expected debris loading.
1.3.1.9	Calculation of available NPSH should be performed as a function of time until it is clear that the available NPSH will not decrease further.	An assessment of available NPSH as a function of time was performed.
1.3.2	**Debris Sources and Generation**	

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1.3.2.1	Consistent with the requirements of 10 CFR 50.46, debris generation should be calculated for a number of postulated LOCAs of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated LOCAs are calculated. The level of severity corresponding to each postulated break should be based on the potential head loss incurred across the sump screen. Some PWRs may need recirculation from the sump for licensing basis events other than LOCAs. Therefore, licensees should evaluate the licensing basis and include potential break locations in the main steam and main feedwater lines as well in determining the most limiting conditions for sump operation.	The U.S. EPR design is based on the most penalizing break locations with respect to debris generation. The debris generation evaluation utilizes the guidance of NRC Regulatory Guidance 1.82 Rev.3 and information presented in Nuclear Energy Institute (NEI) 04-07. The U.S. EPR does not require recirculation from the IRWST for non-LOCA events. For the U.S. EPR, ECCS recirculation is not required for main steam or feedwater line breaks.
1.3.2.2	An acceptable method for estimating the amount of debris generated by a postulated LOCA is to use the zone of influence (ZOI). Examples of this approach are provided in NUREG/CR-6224 and Boiling Water Reactor Owners' Group (BWROG) Utility Resolution Guidance (NEDO-32686 and the staff's Safety Evaluation on the BWROG's response to NRC Bulletin 96-03). A representation of the ZOI for commonly used insulation materials is shown in Figure 3.	The ZOI method is used for determining the debris source for the U.S. EPR.
	• The size and shape of the ZOI should be supported by analysis or experiments for the break and potential debris. The size and shape of the ZOI should be consistent with the debris source (e.g., insulation, fire barrier materials, etc.) damage pressures, i.e., the ZOI should extend until the jet pressures decrease below the experimentally determined damage pressures appropriate for the debris source.	The U.S. EPR design uses the methodology presented in Nuclear Energy Institute (NEI) 04-07 for determining the ZOI.
	• The volume of debris contained within the ZOI should be used to estimate the amount of debris generated by a postulated break.	See below.
	• The size distribution of debris created in the ZOI should be	See below.

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	determined by analysis or experiments. • The shock wave generated during the postulated pipe break and the subsequent jet should be the basis for estimating the amount of debris generated and the size or size distribution of the debris generated within the ZOI. Certain types of material used in a small quantity inside the containment can, with adequate justification, be demonstrated to make a marginal contribution to the debris loading for the ECC sump. If debris generation and debris transport data have not been determined experimentally for such material, it may be grouped with another like material existing in large quantities. For example, a small quantity of fibrous filtering material may be grouped with a substantially large quantity of fibrous insulation debris, and the debris generation and transport data for the filter material need not be determined experimentally. However, such analyses are valid only if the small quantity of material treated in this manner does not have a significant effect when combined with other materials (e.g., a small quantity of calcium silicate combined with fibrous debris).	The U.S. EPR uses a conservative approach to determine the amount of debris generated within the ZOI. Specifically, all potential debris material within the ZOI is included in the debris source estimate. This debris then non-mechanistically assumed to be transported to the IRWST. The retaining basket head loss and ECC strainer head loss are determined by testing using this debris source term.
1.3.2.3	A sufficient number of breaks in each high-pressure system that relies on recirculation should be considered to reasonably bound variations in debris generation by the size, quantity, and type of debris. As a minimum, the following postulated break locations should be considered. • Breaks in the reactor coolant system (e.g., hot leg, cold leg, pressurizer surge line) and, depending on the plant licensing basis, main steam and main feedwater lines with the largest amount of potential debris within the postulated ZOI, • Large breaks with two or more different types of debris, including the breaks with the most variety of debris, within the expected ZOI,	The U.S EPR break selection process is based on the guidance of NRC Regulatory Guide 1.82 Rev 3, Section 1.3.2.3.

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	• Breaks in areas with the most direct path to the sump, • Medium and large breaks with the largest potential particulate debris to insulation ratio by weight, and • Breaks that generate an amount of fibrous debris that, after its transport to the sump screen, could form a uniform thin bed that could subsequently filter sufficient particulate debris to create a relatively high head loss referred to as the 'thin-bed effect.' The minimum thickness of fibrous debris needed to form a thin bed has typically been estimated at 1/8 inch thick based on the nominal insulation density (NUREG/CR-6224).	
1.3.2.4	All insulation (e.g., fibrous, calcium silicate, reflective metallic), painted surfaces, fire barrier materials, and fibrous, cloth, plastic, or particulate materials within the ZOI should be considered a debris source. Analytical models or experiments should be used to predict the size of the postulated debris. For breaks postulated in the vicinity of the pressure vessel, the potential for debris generation from the packing materials commonly used in the penetrations and the insulation installed on the pressure vessel should be considered. Particulate debris generated by pipe rupture jets stripping off paint or coatings and eroding concrete at the point of impact should also be considered.	The significant debris generating material within the ZOI has been considered in the developing debris source estimate for the U.S. EPR.
1.3.2.5	The cleanliness of the containment during plant operation should be considered when estimating the amount and type of debris available to block the ECC sump screens. The potential for such material (e.g., thermal insulation other than piping insulation, ropes, fire hoses, wire ties, tape, ventilation system filters, permanent tags or stickers on plant equipment, rust flakes from unpainted steel surfaces, corrosion products, dust and dirt, latent individual fibers)	Latent debris has been considered as part of the total debris source estimate. Control of material used and the overall cleanliness inside containment is a programmatic requirement. Refer to U.S. EPR FSAR COL Information Item 6.3-1 (Table 1.8-2).

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	to impact head loss across the ECC sump screens should also be considered.	
1.3.2.6	In addition to debris generated by jet forces from the pipe rupture, debris created by the resulting containment environment (thermal and chemical) should be considered in the analyses. Examples of this type of debris would be disbondment of coatings in the form of chips and particulates or formation of chemical debris (precipitants) caused by chemical reactions in the pool.	Debris created by the resulting containment environment (thermal and chemical) is considered in the U.S. EPR analyses. Included in these debris types are disbondment of coatings and formation of chemical debris (precipitants).
1.3.2.7	Debris generation that is due to continued degradation of insulation and other debris when subjected to turbulence caused by cascading water flows from upper regions of the containments or near the break overflow region should be considered in the analyses.	All insulation and debris generating material within the ZOI has been conservatively assumed to reach the retaining baskets. Additionally, quantities for latent debris, paint chips, and micro-porous insulating material have been included in the debris source term and are representative of such additional debris contribution from outside of the ZOI.
1.3.3	**Debris Transport**	
1.3.3.1	The calculation of debris quantities transported from debris sources to the sump screen should consider all modes of debris transport, including airborne debris transport, containment spray washdown debris transport, and containment sump pool debris transport. Consideration of the containment pool debris transport should include (1) debris transport during the fill-up phase, as well as during the recirculation phase, (2) the turbulence in the pool caused by the flow of water, water entering the pool from break overflow, and containment spray drainage, and (3) the buoyancy of the debris. Transport analyses of debris should consider: (1) debris that	The assessment of ECCS sump strainer blockage is conservatively bounded by the assumption that all available insulation and debris within the ZOI is transported to the IRWST. Also included in the debris source estimate is an amount of debris representing the contribution from outside the ZOI.

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	would float along the pool surface, (2) debris that would remain suspended due to pool turbulence (e.g., individual fibers and fine particulates), and (3) debris that readily settles to the pool floor.	
1.3.3.2	The debris transport analyses should consider each type of insulation (e.g., fibrous, calcium silicate, reflective metallic) and debris size (e.g., particulates, fibrous fine, large pieces of fibrous insulation). The analyses should also consider the potential for further decomposition of the debris as it is transported to the sump screen.	The assessment of ECCS sump strainer clogging conservatively assumes all debris is non-mechanistically transported to the IRWST.
1.3.3.3	Bulk flow velocity from recirculation operations, LOCA-related hydrodynamic phenomena, and other hydrodynamic forces (e.g., local turbulence effects or pool mixing) should be considered for both debris transport and ECC sump screen velocity computations.	LOCA recirculation flow characteristics for the U.S. EPR™ are considered for assessing both debris transport and ECC sump screen velocity.
1.3.3.4	An acceptable analytical approach to predict debris transport within the sump pool is to use computational fluid dynamics (CFD) simulations in combination with the experimental debris transport data. Examples of this approach are provided in NUREG/CR-6772 and NUREG/CR-6773. Alternative methods for debris transport analyses are also acceptable, provided they are supported by adequate validation of analytical techniques using experimental data to ensure that the debris transport estimates are conservative with respect to the quantities and types of debris transported to the sump screen.	NOT APPLICABLE: Conservative assumptions regarding debris transport have been used; hence, use of CFD is unnecessary.
1.3.3.5	Curbs can be credited for removing heavier debris that has been shown analytically or experimentally to travel by sliding along the containment floor and that cannot be lifted off the floor within the calculated water velocity range.	U.S. EPR design incorporates a weir (curb) that prevents heavier debris from entering the retaining basket. This has been validated by testing.
1.3.3.6	If transported to the sump pool, all debris (e.g., fine fibrous, particulates) that would remain suspended due to pool turbulence should be considered to reach the sump screen.	Debris transported to the IRWST will first encounter the retaining baskets which will remove a majority of the debris. Debris

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		which passes through the retaining baskets will not encounter any turbulence due to IRWST size. This has been demonstrated by testing. Hence, suspended particulates were not directly considered downstream of the retaining basket. Instead, the ECC strainer was conservatively sized based on 2 times the maximum design head loss and the quantity of debris reaching the ECC strainer. U.S. EPR testing was performed in a manner that kept debris exiting the basket suspended. This maximized the debris that could reach the strainer.
1.3.3.7	The time to switch over to sump recirculation and the operation of containment spray should be considered in the evaluation of debris transport to the sump screen.	NOT APPLICABLE: The U.S. EPR design features include an IRWST. As such, the ECCS pumps continuously operate in a recirculation mode post-LOCA.
1.3.3.8	In lieu of performing airborne and containment spray washdown debris transport analyses, it could be assumed that all debris will be transported to the sump pool. In lieu of performing sump pool debris	Conservative assumptions regarding debris transport and quantity of debris have been used in the evaluation of U.S.

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	transport analyses (Regulatory Position 1.3.3.4), it could be assumed that all debris entering the sump pool or originating in the sump will be considered transported to the sump screen when estimating screen debris bed head loss. If it is credible in a plant that all drains leading to the containment sump could become completely blocked, or an inventory holdup in containment could happen together with debris loading on the sump screen, these situations could pose a worse impact on the recirculation sump performance than the assumed situations mentioned above. In this case, these situations should also be assessed.	EPR ECCS sump performance. Furthermore, given the multiple pathways for water to drain to the IRWST, complete blockage of all pathways to the IRWST is considered to be not credible.
1.3.3.9	The effects of floating or buoyant debris on the integrity of the sump screen and on subsequent head loss should be considered. For screens that are not fully submerged or are only shallowly submerged, floating debris could contribute to the debris bed head loss. The head loss due to floating or buoyant debris could be minimized by a design feature to keep buoyant debris from reaching the sump screen	The U.S. EPR design is not affected by floating debris because even with the IRWST at minimum water level, the ECC sumps are significantly submerged.
1.3.4	**Debris Accumulation and Head Loss**	
1.3.4.1	ECC sump screen blockage should be evaluated based on the amount of debris estimated using the assumptions and criteria described in Regulatory Position 1.3.2 and on the debris transported to the ECC sump per Regulatory Position 1.3.3. This volume of debris should be used to estimate the rate of accumulation of debris on the ECC sump screen.	The performance of the U.S. EPR ECC sump strainers is based on conservative assumptions relative to the quantity of debris, ECC flow, and temperature conditions.
1.3.4.2	Consideration of ECC sump screen submergence (full or partial) at the time of switchover to ECCS should be given in calculating the available (wetted) screen area. For plants in which containment heat removal pumps take suction from the ECC sump before switchover to the ECCS, the available NPSH for these pumps should consider the submergence of the sump screens at the time	The performance of the U.S. EPR ECC sump strainers is based on conservative assumptions relative to the quantity of debris, ECC flow, and temperature conditions. The strainer design provides sufficient screen area for acceptable

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	these pumps initiate suction from the ECC sump. Unless otherwise shown analytically or experimentally, debris should be assumed to be uniformly distributed over the available sump screen surface. Debris mass should be calculated based on the amount of debris estimated to reach the ECC sump screen. (See Revision 1 of NUREG-0897, NUREG/CR-3616, and NUREG/CR-6224.)	screen head loss under debris laden conditions. The screen head loss is validated by testing. The U.S. EPR design is such that the ECC sumps remain continuously submerged.
1.3.4.3	For fully submerged sump screens, the NPSH available to the ECC pumps should be determined using the conditions specified in the plant's licensing basis.	The performance of the U.S. EPR ECCS sump strainers is based on conservative assumptions relative to the quantity of debris, ECC flow, and temperature conditions.
1.3.4.4	For partially submerged sumps, NPSH margin may not be the only failure criterion, as discussed in Appendix A. For partially submerged sumps, credit should only be given to the portion of the sump screen that is expected to be submerged, as a function of time. Pump failure should be assumed to occur when the head loss across the sump screen (including only the clean screen head loss and the debris bed head loss) is greater than one-half of the submerged screen height or NPSH margin.	NOT APPLICABLE: The U.S. EPR design is such that the ECC sumps remain continuously submerged.
1.3.4.5	Estimates of head loss caused by debris blockage should be developed from empirical data based on the sump screen design (e.g., surface area and geometry), postulated combinations of debris (i.e., amount, size distribution, type), and approach velocity. Because debris beds that form on sump screens can trap debris that would pass through an unobstructed sump screen opening, any head loss correlation should conservatively account for filtration of particulates by the debris bed, including particulates that would pass through an unobstructed sump screen.	The performance of the U.S. EPR ECC strainers is based upon strainer validation testing. While the testing included a mix of particulates, micro-porous insulating material, paint chips, and glass wool, no relevant thin-bed effects were observed. The U.S. EPR design testing has shown no thin bed developed on the strainer.

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1.3.4.6	Consistent with the requirements of 10 CFR 50.46, head loss should be calculated for the debris beds formed of different combinations of fibers and particulate mixtures (e.g., minimum uniform thin bed of fibers supporting a layer of particulate debris) based on assumptions and criteria described in Regulatory Positions 1.3.2 and 1.3.3.	See response to 1.3.4.5, above.
2.	**BOILING WATER REACTORS** Regulatory Guide 1.82 (top of page 1.82-4) states that for advanced designs, the regulatory positions for both PWRs and BWRs should be considered (as appropriate to the plant's design). The example given, a PWR with an in-containment refueling water storage tank (IRWST) that is similar to the suppression pool in a BWR, is directly relevant to the U.S. EPR design.	The RG 1.82 guidance for BWRs was reviewed for applicability to the U.S. EPR. Most of the BWR guidance items have a similar, if not identical, counterpart item in the PWR guidance. The review did identify five items that are unique to BWRs. These items are assessed for U.S. EPR applicability below.
2.3.1	**Debris Sources and Generation**	
2.3.1.7	The amount of particulates estimated to be in the pool prior to a LOCA should be considered to be the maximum amount of corrosion products (i.e., sludge) expected to be generated since the last time the pool was cleaned. The size distribution and amount of particulates should be based on plant samples.	The amount of particulates contained in the IRWST prior to a LOCA is insignificant. Materials of construction for the IRWST are compatible with contained fluid chemistry; hence, no corrosion products are expected. In addition, the FPPS provides for IRWST cleaning and the tank internals and liner are constructed of austenitic stainless steel. The U.S. EPR design process concludes resident debris material in the IRWST prior to the LBLOCA to be insignificant.
2.3.2	**Debris Transport**	

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2.3.2.2	It should be assumed that LOCA-induced phenomena (i.e., pool swell, chugging, condensation oscillations) will suspend all the debris assumed to be in the suppression pool at the onset of the LOCA.	NOT APPLICABLE: Unlike a BWR suppression pool, the lost coolant does not enter the IRWST through submergence. Hence, phenomena contributing to significant mixing in the IRWST are absent.
2.3.2.3	The concentration of debris in the suppression pool should be calculated based on the amount of debris estimated to reach the suppression pool from the drywell and the amount of debris and foreign materials estimated to be in the suppression pool prior to a postulated break.	Debris transported to the IRWST will first encounter the retaining baskets which will remove a majority of the debris. The amount of particulates contained in the IRWST prior to a LOCA is expected to be insignificant as explained in 2.3.1.7 above. The U.S. EPR design process concludes resident debris material in the IRWST prior to the LBLOCA to be insignificant.
2.3.2.4	Credit should not be taken for debris settling until LOCA-induced turbulence in the suppression pool has ceased. The debris settling rate for the postulated debris should be validated analytically or experimentally.	The U.S. EPR design does not take credit for debris settling. Refer to 1.3.3.6, above.
2.3.3	**Strainer Blockage and Head Loss**	
2.3.3.2	The flow rate through the strainer should be used to estimate the rate of accumulation of debris on the strainer surface.	The combined flow from LHSI and MHSI is used to determine the ECC strainer differential pressure. Because a conservative calculation approach is used, the estimate of rate of debris accumulation on the strainer surface was not determined.

Appendix B
Generic Letter 2004-02 Information Matrix

B.1 GL 2004-02

GL 2004-02 was issued to PWR licensees of operating plants requesting that they demonstrate that corrective actions taken to address GSI-191 are adequate.

Additionally, GL 2004-02 requested the licensee provide information to assess the potential impact of debris blockage on emergency recirculation during design basis events.

Table B.1 provides U.S. EPR sump recirculation information in response to requested information outlined in GL 2004-02.

Table B.1 GL 2004-02 Information Matrix

GL 2004-02	**Potential Impact of Debris Blockage on Emergency Recirculation During design Basis Accidents At Pressurized-Water Reactors**	
	Requested Information	**Observation/Comment**
2.(d)(i)	The minimum available NPSH margin for the ECCS and CSS pumps with an unblocked screen.	The minimum available NPSH margin for the ECCS pumps is detailed in the U.S. EPR Safety Injection Systems Analysis for Design Certification. The U.S. EPR design does not take credit for the CSS.
2.(d)(ii)	The submerged area of the sump screen at this time and the percent of submergence of the sump screen (i.e., partial or full) at the time of switchover to sump recirculation	Switchover is not part of the U.S. EPR design. However, the U.S. EPR design is such that the ECCS sump screens remain completely and continuously submerged. (Refer to Section 3.2)
2.(d)(iii)	The maximum head loss postulated from debris accumulation on the submerged sump screen, and a description of the primary constituents of the debris bed that result in this head loss. In addition to debris generated by jet forces, from the pipe rupture, debris created by the resulting containment environment (thermal and chemical) and CSS washdown should be considered in the analyses. Examples of this type of debris are disbonded coatings in the form of chips and particulates and chemical precipitants caused by chemical reactions in the pool.	Section 3.2 provides the maximum head loss for the ECCS pumps. The performance of the U.S. EPR ECCS strainers is based upon studies and strainer validation testing. The testing included a mix of particulates, micro-porous insulating material, paint chips, latent debris, etc., as defined in the U.S. EPR debris evaluation. Approved coatings will be used.
2.(d)(iv)	The basis for concluding that the water inventory required to ensure adequate ECCS and CSS recirculation would not be held up or diverted by debris blockage at choke points in containment recirculation sump return flowpaths.	The minimum IRWST water level for ECCS recirculation is -10.2 ft. This level considers the initial IRWST water inventory prior to the LOCA event, return water from the LOCA, quantities of water in containment that do not return to the IRWST (pooled water on the containment floor, atmospheric steam, wetted areas, trapped water pockets at various locations). The return flow path to the IRWST is via 4 large heavy floor openings that are each provided with a weir and trash rack.

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	Requested Information	**Observation/Comment**
2.(d)(v)	The basis for concluding that inadequate core or containment cooling would not result due to debris blockage at flow restrictions in the ECCS and CSS flowpaths downstream of the sump screen, (e.g., a HPSI throttle valve, pump bearings and seals, fuel assembly inlet debris screen or containment spray nozzles). The discussion should consider the adequacy of the sump screen's mesh spacing and state the basis for concluding that adverse gaps or breaches are not present on the screen surface.	The valve size in the ECCS flow path ranges from 2 inches (isolation valve in small miniflow line for pump protection) to 16 inches (inlet of ECCS inlet pipe). These sizes are larger than the largest expected debris size (strainer hole size of strainer). The post-LOCA debris will not clog the ECCS valves per NUREG/CR-6902. Vendors for valves, pipes, and orifices will provide tests or evaluations to verify adequate performance during operation with post-LOCA fluid. Testing has been performed to access the impact of debris on the fuel assemblies.
2.(d)(vi)	Verification that close-tolerance subcomponents in pumps, valves and other ECCS and CSS components are not susceptible to plugging or excessive wear due to extended post-accident operation with debris-laden fluids.	Based on the ex-vessel downstream effects evaluation, the following ECCS components will be evaluated to verify post-LOCA operation for a minimum of 30 days: 1. The LHSI and MHSI pumps. 2. The LHSI heat exchanger. The evaluation will address the items identified in Appendix G.
2.(d)(vii)	Verification that the strength of the trash racks is adequate to protect the debris screens from missiles and other large debris. The submittal should also provide verification that the trash racks and sump screens are capable of withstanding the loads imposed by expanding jets, missiles, the accumulation of debris, and pressure differentials caused by post-LOCA blockage under predicted flow conditions.	The 6.6 ft thick RCS loop area heavy floor and the heavy duty trash racks that cover the floor openings prevent missiles, large debris, and expanding jets from impacting the retaining baskets or the ECCS screens. The floor openings are located on the periphery of the RCS loops, thereby reducing the trash rack profile for a majority of break locations. The trash racks are significantly robust to prevent major debris from falling through the opening into the retaining baskets. They are safety-related Seismic Category I components. The retaining baskets and the ECCS sump screens rely on the 6.6 ft thick heavy floor, the trash

GL 2004-02	Potential Impact of Debris Blockage on Emergency Recirculation During design Basis Accidents At Pressurized-Water Reactors	
	Requested Information	**Observation/Comment**
		racks and distance for protection from jet impingement and missiles. Nevertheless, they are designed for the maximum expected debris loading and the corresponding differential pressure. The ECCS sump screen design head loss is approximately 2.2 psi. Based on testing, the maximum differential pressure resulting from debris across the strainer screen is approximately 0 feet of water.
2.(d)(viii)	If an active approach (e.g., backflushing, powered screens) is selected in lieu of or in addition to a passive approach to mitigate the effects of the debris blockage, describe the approach and associated analyses.	The U.S. EPR design does not take credit for an active approach to reduce/eliminate the effects of debris blockage.

Appendix C
Debris Generation Evaluation for the U.S. EPR

C.1 Introduction

Appendix C documents the process and results of the debris generation evaluation for the U.S. EPR. The evaluation utilizes the guidance of NRC Regulatory Guidance 1.82 Rev.3 (Reference 2) and information presented in Nuclear Energy Institute (NEI) 04-07 (Reference 1).

This effort is in response to an ongoing concern by the Nuclear Regulatory Commission (NRC) detailed in Generic Safety Issue 191 (GSI-191). Debris generated by a postulated LOCA or high energy line break (HELB) can be transported to the containment building sump and potentially impede the performance of the Emergency Core Cooling Systems (ECCS) during recirculation.

The analysis determines the quantity of debris released in the containment building by the LOCA or HELB prior to the start of recirculation. The primary debris source is thermal insulation installed on the piping and equipment within containment. Coatings, latent debris, and miscellaneous debris are considered additional elements of the debris load.

The LOCA break is the limiting break that requires long term ECCS recirculation. This assessment analyzes seven break locations for a postulated LOCA, tabulates the debris generation totals, and identifies the limiting pipe breaks with respect to GSI-191 for the U.S. EPR. The debris generation results serve as serve as a basis and input to the Chemical Effects Evaluation (Appendix D) and ECCS Strainer Performance Testing (Appendix E).

C.2 Assumptions

C.2.1 Industry Assumptions

The following industry assumptions are employed to conservatively account for debris generation.

1. Zone of influence (ZOI) determinations based on experimentally observed or conservatively established destruction pressures are assumed to adequately define the spatial volume within which debris is generated.

2. ZOI determinations are based on experimentally observed or conservatively established destruction pressures and are assumed to define the spatial volume within which debris is generated.

3. Qualified coatings outside the ZOI will remain intact (Reference 1).

4. Structural concrete does not contribute to the debris source term. Structural concrete is assumed to be impervious to the effects of a LOCA. This was observed during testing that supported the NRC Staff Review Guidance regarding GL 2004-02, “Closure in the Area of Coatings Evaluation,” March 2008. The quantity of concrete dust generated by the LOCA blast is assumed to be insignificant with respect to the quantity of latent debris present in containment prior to the LOCA.

5. Destruction pressures documented in Table 3-2 of NEI 04-07 Volume 2 (Reference 1) are assumed to be applicable. In cases where Table 3-2 of Volume 2 does not specifically list the debris type of interest, Table 4-1 of NEI 04-07 Volume 1 (Reference 1) is consulted to ascertain the experimentally determined destruction pressure of the debris type. This destruction pressure is then reduced per guidance in Section 3.4.2.2 of NEI 04-07 Volume 2 (Reference 1).

6. Insulation jacketing is assumed to make no significant contribution to the debris generation load. Insulation jacketing is typically made of stainless steel sheet

metal. Knowledge based tests have not identified jacketing as a significant source of debris fines. Larger sizes of jacketing debris are unlikely to transport under typical pool fill or recirculation conditions.

C.2.2 Plant Specific Assumptions

The following plant specific assumptions are applied to this evaluation.

1. Qualified coatings within containment consist mainly of epoxy with an approximate 94 lb_m/ft^3 density. In high temperature areas where epoxy coatings are not practical, inorganic zinc (IOZ) coatings with an approximate 457 lb_m/ft^3 density will be applied in lieu of epoxy coatings. The coating thicknesses are assumed to be 3 mils for IOZ coatings and 12 mils for the epoxy coatings. The use of unqualified coatings within the U.S. EPR containment is not planned. However, for conservatism, 250 lb_m of unqualified coatings is assumed to fail in containment.

2. Miscellaneous debris source materials (tags, tape, labels, etc.) are assumed. An assumed miscellaneous debris amount of 100 ft^2 (tags, tape, labels, etc.) is added to the total debris source term.

3. For determining the volume of insulation on pipe segments (spool pieces), centerline-to-centerline coding of the pipe lengths is used. This practice conservatively adds 5% to 15% more insulation volume to each pipe segment versus using the actual pipe lengths and elbow insulation volumes.

4. Insulation volume for valve and instrument covers is bounded by the conservative insulation volume of the centerline-to-centerline pipe length assumption.

5. Piping with a nominal diameter of one-half inch or less will be insulated with reflective metal insulation (RMI) and contributes an insignificant amount of insulation compared to the overall total debris generated from a postulated LOCA. RMI on one-half inch or less piping is not included in this evaluation.

6. The reflective metal insulation (RMI) thickness and number of foils selected for RCS piping and major equipment are based on vendor proposal information.

7. Within the ZOIs, the plant piping and equipment insulation will consist of stainless steel RMI.

8. The following system piping is assumed to be non-insulated:

    - component cooling water
    - central gas distribution
    - gaseous waste
    - compressed air
    - fuel pool purification
    - fuel handling
    - nuclear sampling
    - drains
    - reactor coolant pump seal injection

C.2.3 Implicit Assumptions

The following conservatisms are incorporated into the debris generation evaluation.

1. No credit is taken for shadowing effects by equipment such as steam generators and reactor coolant pumps.

2. Solid structural barriers such as the primary bioshield are assumed to protect debris source materials on one side from the blast effects emanating from the other side.

3. For the purposes of computing the pipe insulation volume, the pipe outer diameter is assumed to be the inner diameter of the insulation.

4. ZOI sizing is based on the outer diameter of the pipe except for breaks occurring in the RCS hot, cold, and crossover leg piping. The hot, cold, and crossover leg piping has an outer diameter of 36 inches and an inner diameter of 30.71 inches. As a conservative measure, a 31 inch inside diameter will be utilized for the RCS hot, cold, and crossover leg piping ZOI.

C.3 Computer Software

AREVA NP computer software is used for the U.S. EPR debris generation evaluation.

The AREVA NP software program determines the quantity of various insulation materials that reside within a given distance of a specified LOCA or HELB of interest. The output of the program provides the input to the debris generation analysis.

C.4 Technical Approach

C.4.1 Background

The U.S. EPR is a PWR design that incorporates an in-containment refueling water storage tank (IRWST) to achieve design objectives that promote a robust response to accident scenarios. The design uses the IRWST in the ECCS recirculation path following a LOCA. The IRWST is located in the containment, below the four RCS loop vaults. The design takes advantage of this location to develop the following staggered "defense in depth" strategy against ECCS sump suction clogging.

- four protective weir / trash rack structures to retain large debris in the RCS loop vaults.
- four retention baskets in the IRWST under the trash racks to retain small debris carried through the trash racks by ECCS recirculation flow.
- four large surface area ECCS strainers with small screen mesh sized to minimize debris bypass that may potentially impact or clog downstream fuel or critical equipment.

There are four steam generators (SG) each served by a single reactor coolant pump (RCP). The wall structures surrounding the SGs and RCPs within the primary containment walls are symmetrical in design. The pressurizer is connected to loop 3 on the hot leg by a 16 inch surge line and is connected to the cold leg with a 4 inch spray line on the discharge side of the RCP. The U.S. EPR containment building uses RMI as the primary insulation for the RCS loops and major equipment.

C.4.2 Work Scope

The debris generation evaluation utilizes a U.S. EPR-specific three dimensional model of piping and equipment with insulation. Based on modeling information, a debris source inventory database is developed for use as input to debris generation analysis. Several analytical methods are employed to determine the maximum anticipated debris load for selected LOCA break locations. The specific break locations are selected based on industry guidance and impact to ECCS sump screen head loss. The latent and miscellaneous debris present within containment are conservatively estimated and are consistent with current industry practice.

C.4.3 Methodology

This section details the methodology for determining the quantity of insulation debris generated during a LOCA. The methodology complies with NEI 04-07 guidance (Reference 1). The methodologies used to categorize the gross quantities of containment insulation debris by size are explained in the following sections.

C.4.3.1 *Break Location Selection*

To assure that the ECCS can perform its safety functions, the magnitude of the debris load introduced to containment for LOCA breaks must be quantified.

NRC Regulatory Guide 1.82 Rev 3, Section 1.3.2.3 (Reference 2) provides the following guidance:

A sufficient number of breaks in each high-pressure system that relies on recirculation should be considered to reasonably bound variations in debris generation by the size, quantity, and type of debris. As a minimum, the following postulated break locations should be considered.

- Breaks in the reactor coolant system (e.g., hot leg, cold leg, pressurizer surge line) and, depending on the plant licensing basis, main Steam and main feedwater lines with the largest amount of potential debris within the postulated ZOI,
- Large breaks with two or more different types of debris, including the breaks with the most variety of debris, within the expected ZOI,
- Breaks in areas with the most direct path to the sump,
- Medium and large breaks with the largest potential particulate debris to fibrous insulation ratio by weight, and
- Breaks that generate an amount of fibrous debris that, after its transport to the sump screen, could form a uniform thin bed that could subsequently filter sufficient particulate debris to create a relatively high head loss referred to as the 'thin-bed effect.' The minimum thickness of fibrous debris needed to form a thin bed has typically been estimated at 1/8 inch thick based on the nominal insulation density (NUREG/CR-6224) (Reference 3).

Regulatory Guide 1.82 guidance is applied to the U.S. EPR by examining breaks in the RCS piping proximate to major equipment such as the steam generators (Process 1). Since the RCS lines are the largest-bore lines in containment, they result in the largest ZOIs with the greatest quantities of potential debris. The RCS lines also maximize the number of different types of thermal insulation (and other debris sources) that are affected by a break. Break locations centered at connections to the SG nozzles have ZOIs that envelope nearly the entire steam generator as well as the reactor coolant pump(s). Break locations farther from the SG nozzles result in lesser quantities of debris because their ZOIs envelope smaller portions of the steam generators.

Break locations at RCS connections to the reactor vessel (RV) nozzles are also examined. Due to the location inside the primary bioshield, breaks at the RV nozzles do not present the same degree of debris accumulation that is credited for breaks in RCS piping outside the primary bioshield.

Main steam and feedwater lines need only be analyzed as potential break locations in plants where ECCS recirculation is required to mitigate the effects of breaks in these lines. For the U.S. EPR, ECCS recirculation is not required for main steam or feedwater line breaks. Accordingly, main steam and feedwater lines are not analyzed as potential break locations for the U.S. EPR for GSI-191.

The U.S. EPR has four symmetrical loops with the pressurizer surge line connected to loop 3. Since the four loops of the plant are symmetrical, only piping and equipment within loops 3 and 4 are modeled. The limiting break locations are determined to occur in loop 3 which contains the pressurizer surge line connection. Applying the foregoing break selection methodology, the following break locations have been evaluated as potential limiting debris load cases:

Table C.4-1 Pipe Break Selections

Pipe Break	Pipe Break Location
1. RCS hot leg 3	SG3 inlet nozzle
2. RCS cold leg 3	RCP3 outlet nozzle
3. Pressurizer surge line	Hot leg 3 connection
4. Pressurizer surge line	Above cold leg 3
5. RCS crossover leg 3	SG3 outlet nozzle
6. Largest safety injection line	Above the loop 3 trash rack
7. RCS hot leg 3	Pressurizer surge line connection

The pipe break selections of Table C.4-1 fulfill the first four objectives of Regulatory Guide 1.82 Section 1.3.2.3. These selections are also consistent with the selection of break locations discussed in Section 3.3.4 of NEI 04-07 (Reference 1). For primary piping, NEI 04-07 suggests that break locations be evaluated at five-foot intervals along the pipe being considered. This methodology is intended to determine the limiting break location with respect to:

- maximum volume of debris generated and transported to the sump, and
- most limiting combination of debris generated and transported to the sump.

The break selection methodology has been validated and shows conservative results with respect to maximum debris loads and variety of debris types generated for a typical PWR.

C.4.3.2 *Zone of Influence (ZOI)*

With break locations defined, it becomes necessary to determine how much debris is generated by the jet of fluid issuing from the break. This is done by determining the spatial volume about the break in which the expanding jet retains sufficient energy to cause damage to the various debris source materials and summing the quantity of debris source materials that are physically within that spatial volume. This volume is referred to as the ZOI. Modeling the ZOI as a spherical shape is an industry and regulatory accepted approach. An analytical refinement to the calculated ZOI is the methodology used for this analysis in accordance with Section 4.2.2 of NEI 04-07 Volume 2 (Reference 1). This methodology includes a multiple ZOI approach at the specified break location whereby each ZOI spherical radius is dependent on the insulation surrounding the break location.

Modeling the spherical ZOI volume considers the thermodynamic conditions of the fluid released from a given break location and the destruction pressure experimentally observed for selected debris source materials. This approach is consistent with the references identified in Regulatory Guide 1.82 Rev 3 Section 1.3.2.2 (Reference 2) which are based on ANSI/ANS-58.2-1988 “Design Basis for Protection of Light Water Nuclear Power Plants against the Effects of Postulated Pipe Rupture” (Reference 4). ANSI/ANS-58.2-1988 provides an accepted model of the geometry and thermodynamic conditions characterizing the expanding jet downstream of a ruptured pipe. This model is used to determine the isobaric contours of the jet for all of the destruction pressures of interest. The volume enclosed by these contours is then determined by numerical integration. The volume enclosed by a destruction pressure contour of interest defines the volume of the ZOI for debris types of that particular destruction pressure. With the ZOI volume defined, the radial dimension of the ZOI is determined.

Since there are two jets for a double ended guillotine break (DEGB) in RCS piping, the volume calculated for a single jet is doubled and considered to be the volume of the spherical ZOI. The ANSI/ANS-58.2-1988 methodology (Reference 4) considers the critical flow through a given break; this tends to limit the size of the jet that develops for smaller breaks in such a way that when total jet volume is set equal to spherical ZOI volume, the ratio of the spherical ZOI radius to the diameter of the pipe break is constant. AREVA NP independently documents application of this approach to typical PWR conditions. This approach is consistent with the process outlined in Section 3.4.2.1 of NEI 04-07 (Reference 1). Summation of the quantity of debris sources that are within the respective material-specific ZOIs and not shielded from the LOCA blast effects by robust structural barriers determines the total debris generated within the ZOI for that break.

The AREVA NP methodology utilizes ZOIs based on the destruction pressures established for respective debris source materials of interest. The destruction pressures provided in Table 3-2 of NEI 04-07 Volume 2 (Reference 1) are assumed to be applicable. In the cases where Table 3-2 of Volume 2 does not specifically list the debris type of interest, Table 4-1 of NEI 04-07 Volume 1 (Reference 1) is consulted to ascertain the experimentally determined destruction pressure of the debris type. This destruction pressure is then reduced by 40% per guidance in Section 3.4.2.2 of NEI 04-07 Volume 2 (Reference 1).

C.4.3.3 *Piping*

The following steps are involved in processing the piping insulation. Pertinent containment piping is identified based on, but not limited to, insulation types and their location, the location of the trash racks leading to the ECCS sump, the location of the pressurizer, and the postulated break locations. The necessary information pertaining to the pipes of interest is entered into a database for processing. The exact break locations are specified and appropriate ZOIs defined. Finally, the portions of the piping falling within the ZOIs and the corresponding volume of insulation are calculated.

C.4.3.3.1 Data Collection

Compiled piping information and data is obtained from plant drawings. The completed piping database includes the start and end point information of each individual straight leg of insulated pipe including the pipe diameters. Information concerning the type and thickness of insulation installed on each length of pipe is also recorded or conservatively applied, if unknown. This process requires coding each pipe segment by proximity zone. The proximity zone is a pre-defined zone used to indicate its location in containment relative to both potential break locations and robust structural barriers such as walls and floors.

To analyze debris generation for a given break location, all compartments exposed to the break of interest are evaluated and all of the lines in each of theses compartments are included in the input data for processing.

C.4.3.3.2 Data Processing

An AREVA NP methodology is used to calculate the surface area of RMI and the volume of other thermal insulation debris that could be generated during a LOCA inside containment.

Inputs include the pipe break location coordinates, pipe diameters, and the ZOI L/D value for each insulation type of interest. The method uses a series of geometric and conditional arguments to examine each individual line to calculate the quantity of thermal insulation on the line and inside the ZOI. The results provide a tabulation of the quantity of thermal insulation debris generated from the break.

C.4.3.4 *Plant Equipment*

Thermal insulation installed on major plant equipment is a significant portion of the debris generated during a LOCA. This equipment includes SGs, RCPs, and the pressurizer. Insulation surrounding the reactor vessel is not addressed because its location inside the primary bioshield renders it not transportable.

AREVA NP utilizes a developed method to accurately determine the quantity of debris that originates from thermal insulation on major plant equipment. The debris generation result for each piece of equipment that intersects a particular ZOI is added to the debris generation results from piping for that ZOI.

C.4.3.5 *Latent Debris*

This evaluation will use 150 pounds of latent debris. The guidance in NEI 04-07, Volume 2 states that results from plant-specific walkdowns should be used to determine a realistic amount of dust and dirt in containment and to monitor cleanliness metrics that may be necessary following the overall sump-screen blockage vulnerability assessment. The U.S. EPR insulation and cleanliness programs are designed to address GSI-191 issues and limit the potential for debris that may cause sump blockage or debris bypass. The plant will have programs to establish and maintain a plant with a latent debris source term of less than 150 pounds. According to Section 3.5.2.3 of NEI 04-07 Volume 2 (Reference 1), 85 percent of the latent debris is considered particulate, and 15 percent is considered fibrous. This distribution was used for the strainer head loss testing, but this amount of fiber yielded unacceptable results during fuel assembly downstream effects testing. NUREG/CR 6877 evaluated the component parts of the latent debris based on latent debris samples from four nuclear power plants. Reference 5 showed that, on average, approximately 6.8 weight percent of the analyzed latent debris was fiber. Therefore, the latent debris composition was revised to 6.8 percent latent fiber and 93.2 percent latent particulate. This yields a latent fiber amount of 10.2 lbs and a latent particulate amount of 139.8 lbs. These values comprise the design basis distribution for latent debris for the U.S. EPR design.

This change in distribution did not significantly affect the strainer head loss testing. The increase in particulate was 12.3 lbs. This represents a 0.83 percent increase in the amount of particulate. This increase is determined to be negligible relative to the total amount of particulate debris. In addition, significant margin to strainer clogging exists and can accommodate this additional amount.

C.4.3.6 *Miscellaneous Debris*

This evaluation defines miscellaneous debris as debris that is placed inside containment for some operational, maintenance, or engineering purpose. Such debris materials include tape, tags, stickers, adhesive labels used for component identification, fire barrier materials, and a variety of other materials such as rope, fire hoses, ventilation filters, plastic sheeting, etc. Some miscellaneous debris source materials are distinctly two-dimensional with a very thin cross-section (e.g., tape, tags, stickers, labels). This evaluation employs an engineering judgment to provide a practical means of accounting for the potential miscellaneous debris that may be generated by the effects of a postulated LOCA (Assumption C.2.2.3).

C.4.3.7 *Coatings Debris*

Qualified coating amounts are consistent with the guidance outlined in Section 3.4.2.1 of NEI 04-07 Volume 2 (Reference 1). The guidance specifies an L/D value for coatings equal to 10D, or a plant specific analysis may be used to determine the size of the coatings ZOI. Per the latter guidance, testing was conducted to justify reducing the ZOI values for specific types of coatings. Testing demonstrated several coatings that qualified for a ZOI reduction to 4D. The same tests did not show that IOZ coatings could withstand destruction pressures within a 4D ZOI. Therefore, containment IOZ coatings without a topcoat will use a 10D ZOI destruction radius.

The U.S. EPR design will utilize an epoxy topcoat with a 4D ZOI as determined from the testing. The 4D ZOI for epoxy and 10D ZOI for IOZ are used to determine a spherical surface area based on the largest possible pipe break. Section 3.4.3.4 of NEI 04-07

Volume 2 (Reference 1) indicates that plant specific coatings thicknesses must be evaluated. The exact thicknesses of protective coatings in the U.S. EPR design are not yet specified. Therefore, plant specific assumption C.2.2.2 is used to conservatively determine the amount of protective coatings generated from a postulated LOCA. The coating surface area is multiplied by the thickness associated with the qualified coatings to generate the total amount of coatings debris. Though unqualified coatings are not planned within the U.S. EPR containment, a small amount of unqualified coatings are assumed to be present; all of which are assumed to fail.

C.4.3.8 *Additional Debris from Equipment and Major RCS Piping*

The steam generator upper lateral supports are located approximately 43 ft above major RCS piping and require insulation other than RMI. K-wool insulation, or insulation with equivalent destructive pressure, will be used around the steam generator upper lateral supports. Based on Section 3.4.2.2 of NEI 04-07 Volume 2 (Reference 1), K-wool has a ZOI radius of 5.4 times the pipe break diameter. Considering the RCS piping diameter, the ZOI for K-wool generated by a break is 14 ft.

The main RCS piping reaches a high point elevation of 22 ft. Therefore, K-wool insulation at any elevation above 36 ft will not be affected by a main RCS pipe break. Additionally, RCS piping greater than 2 inches does not exist in the area of the steam generator upper lateral supports.

Because the reactor coolant pump support interferes with the crossover leg RMI insulation, an alternate means of insulation at the interference section is required. The approximate volume of the crossover leg interference with the reactor coolant pump support as 0.65 ft^3. Microtherm, or similar microporous insulation, will be installed at this interference point. For conservatism, 1 ft^3 of microtherm insulation will be added to the overall debris source term for all break scenarios.

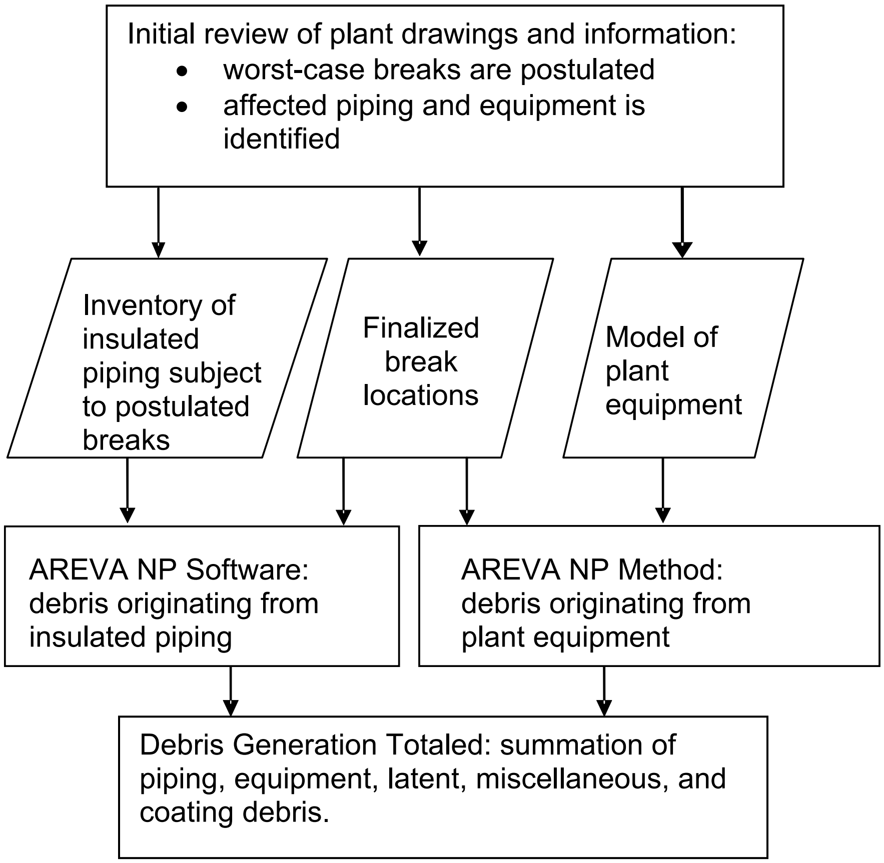
C.4.4 Debris Sizing

Size distribution of generated debris is conservatively estimated based on the guidance in Section 3.4.3 of NEI 04-07 (Reference 1). This guidance employs a two-part distribution of debris sizes for materials generated inside the ZOI of a break. Post-LOCA pool flows have the potential to erode some debris materials and disintegrate other debris materials. Since all fibrous small fines are essentially treated as individual fibers, this evaluation considers the erosion and disintegration of fibrous debris.

C.5 Evaluation Technique

This section details how the technical approach in Section C.4 is implemented for the U.S. EPR debris generation analysis. Figure C.5-1 depicts the process to perform the debris generation analysis.

Figure C.5-1 Debris Generation Analysis Process



C.5.1 Initial Review of Plant Information

Source documentation includes U.S. EPR mechanical and civil layout drawings and containment isometric drawings. When available, the insulation specified by vendor proposals was used to calculate the intended type and amount of insulation. The thickness of the unknown piping insulation is conservatively based on insulation thicknesses of various pipe diameters at other PWR plants.

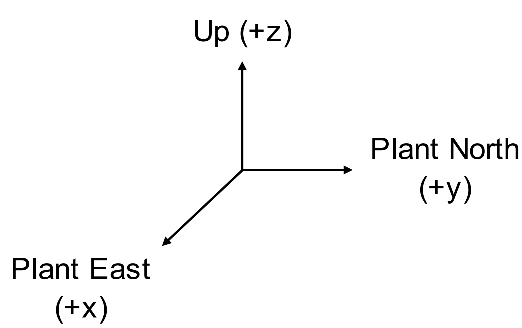
C.5.2 Piping Inventory

A piping inventory database catalogs pertinent information for insulated piping that is potentially affected by the postulated breaks. The piping on the isometric drawings is divided into segments and given a unique identifying descriptor. The pipe segments are defined as a continuous section of pipe going in the same direction with the same diameter and type of insulation.

On each isometric drawing, a starting point is identified in space by a Cartesian coordinate (X, Y, Z format) relative to a spatial reference point. An indication of "N" or "North" on the isometrics, unless otherwise noted, represents plant north and is given a positive "y" axis. Plant east is set as the positive "x" axis, and the "z" axis origin is set at the elevation datum level defined for the U.S. EPR.

Using the Figure C.5-2 Coordinate System, start and end coordinates are determined for each pipe segment, including the lengths of the pipe sections and offset angles as indicated on the isometric drawings.

Figure C.5-2 Pipe Coordinate System



A description of the pipe section, its nominal pipe diameter (or outer diameter for RCS line), insulation type and thickness, number of RMI foils, proximity zone, and other relevant information is collected along with the pipe segment starting and ending coordinates. This information is compiled into a master database and is used as input into the debris generation software tool.

C.5.3 Break Selection Process

The break selection process utilizes the technical approach outlined in Section C.4.3.1 to determine the break locations for the U.S. EPR.

The process postulates break locations that introduce the most critical debris load to the ECCS sump screen. The largest volumes of insulation are located on the steam generators, reactor coolant pumps, pressurizer, and RCS piping within the RCS loop compartments.

The closer the break locations are to the major sources of insulation, the greater the volume of insulation debris generated. The larger the break ZOI, the greater potential to generate insulation debris. The areas affected are directly related to the size of the ruptured pipe. Since the plant is symmetrical in design, the largest potential for debris generation is loop 3 that is connected to the pressurizer. Therefore, loop 3 is used for the break selection process. Because the pressurizer is encased by robust barriers, the pressurizer and piping within the pressurizer zones are not included in the debris generation totals.

Using the technical approach outlined in Section C.4.3.1 combined with large pipes as the source of the LOCA close to the insulated equipment, the break locations are determined. Table C.5-1 provides the basis for each U.S. EPR pipe break selection.

Table C.5-1 Basis for Pipe Break Selections

Pipe Break	Basis for Pipe Break Selection
1. RCS hot leg at SG3 inlet nozzle	a. consistent with NRC RG 1.82 Rev 3 guidance to postulate a hot leg break b. steam generator is a significant potential source of insulation debris and this location is the closest point on the hot leg to the steam generator.
2. RCS cold leg at RCP3 outlet nozzle	a. consistent with NRC RG 1.82 Rev. 3 guidance to postulate a cold leg break
3. Pressurizer surge line at hot leg 3 connection	a. consistent with NRC RG 1.82 Rev 3 guidance to postulate a surge line break b. break has the potential to produce a significant amount of debris because of its proximity to the hot leg and steam generator
4. Pressurizer surge line above cold leg 3	a. consistent with NRC RG 1.82 Rev 3 guidance to postulate a surge line break b. selected as a supplement to Break 3 because of its potential to produce significant debris c. break has the potential to produce significant debris because of its proximity to the cold leg
5. RCS crossover leg 3 at SG3 outlet nozzle	a. analyze at least one break in each of the three legs of the RCS loop b. break has the potential to produce a significant amount of debris because it is a large bore break in close proximity to both the steam generator and the reactor coolant pump
6. Largest safety injection line above the loop 3 trash rack	a. break is the largest bore piping nearest the trash rack with most direct debris path to ECCS sump
7. RCS hot leg 3 at pressurizer surge line connection	a. break has potential to generate significant debris from large bore piping with close proximity to surge line insulation

C.5.4 Piping Insulation Debris

The amount of piping insulation debris is calculated using AREVA NP software. L/D values for the insulation types are determined as discussed in Section 3.4.2.2 of NEI 04-07 Volume 2 (Reference 1). Table C.5-2 provides the L/D values for each insulation type.

Table C.5-2 L/D Values for Each Insulation Type

Insulation Type	Destruction pressure (psig)	ZOI L/D
RMI	114	2.0
K-wool	24	5.4
Jacketed Nukon® with standard bands	6	17.0

Details for the specific pipe breaks are described in Section C.5.3. Pipe break inputs used in this evaluation are provided in Table C.5-3.

Table C.5-3 Pipe Break Inputs

Pipe Break	Approximate Break Coordinates			Broken Pipe Nominal Diameter (inches)
	X	Y	Z	
1. RCS hot leg at SG3 inlet nozzle	31.113	10.348	21.906	31
2. RCS cold leg at RCP3 outlet nozzle	23.520	27.841	18.504	31
3. Pressurizer surge line at hot leg 3 connection	23.445	8.150	21.276	16
4. Pressurizer surge line above cold leg 3	15.420	21.372	30.066	16
5. RCS crossover leg 3 at SG3 outlet nozzle	35.997	17.397	21.073	31
6. Largest safety injection line above the loop 3 trash rack	42.053	22.59	6.877	12
7. RCS hot leg 3 at pressurizer surge line connection	23.445	8.150	18.504	31

Depending on the break location and size of the ZOIs being considered, certain proximity zones may be excluded if they are shielded by a robust barrier or are found to not intersect with the ZOIs of interest.

C.5.5 Plant Equipment Insulation Debris

The insulation installed on the steam generators, reactor coolant pumps, and pressurizer is modeled using an AREVA NP method. This method calculates the volume of insulation on a piece of equipment enveloped by a spherical ZOI.

The following are methods employed to develop geometric models of the insulation installed on plant equipment.

C.5.5.1 *Steam Generator Model*

The U.S. EPR steam generators are insulated with approximately 5 inch thick RMI which has an L/D value of 2 (Table 3-2 of NEI 04-07 Volume 2 {Reference 1}). For conservatism, 6 inch thick RMI is used for this evaluation.

The steam generator is modeled in six distinct sections to accommodate its geometric configuration. Table C.5-4 provides the section descriptions of the steam generator model.

Table C.5-4 Section Descriptions of the Steam Generator Model

Section Number	Description	Top Elevation (feet)	Bottom Elevation (feet)
1	Top of outlet nozzle: modeled as a cylinder with an insulated radius	101.66	98.90
2	SG top bowl: modeled as a half ellipsoid with an insulated major axis	98.90	94.16
3	SG upper straight section: modeled as a cylinder with an insulated radius	94.16	72.50
4	SG tapered middle section: modeled as a truncated cone with an upper insulated radius and a lower insulated radius	72.50	65.50
5	SG lower straight section: modeled as a cylinder with an insulated radius	65.50	27.79
6	SG bottom bowl: modeled as half sphere with an insulated radius	27.79	21.47

The software program for determining plant equipment insulation debris requires the horizontal cross-sections of plant equipment be circular and the insulation along any given cross-section be of uniform thickness. To fulfill this requirement and to introduce added conservatism, the hot leg nozzle and the crossover leg nozzle openings are assumed to be covered with insulation. The inclusion of these additional insulation quantities represents a very small percentage of the total insulation installed on a steam generator and offsets the quantity not specifically included for nozzles and raised covers.

The software program requires the X and Y coordinates corresponding to the vertical centerline of the steam generator. Table C.5-5 provides the centerlines of the steam generators relative to the reactor pressure vessel centerline.

Table C.5-5 Vertical Center Line of Steam Generators

Equipment	X_{center} (feet)	Y_{center} (feet)
SG 1	-35.90	-11.72
SG 2	-35.90	11.72
SG 3	35.90	11.72
SG 4	35.90	-11.72

C.5.5.2 *Reactor Coolant Pump Model*

The U.S. EPR reactor coolant pumps are insulated with approximately 9.5 inch thick RMI which has an L/D value of 2 (Table 3-2 of NEI 04-07 Volume 2 {Reference 1}). For conservatism, 10 inch thick RMI is used for this evaluation.

The insulated portion of the reactor coolant pump is modeled in four distinct sections to accommodate its geometric configuration. Table C.5-6 provides the section descriptions of the reactor coolant pump model.

Table C.5-6 Section Descriptions of the Reactor Coolant Pump Model

Section Number	Description	Top Elevation (feet)	Bottom Elevation (feet)
1	RCP top: modeled as a cylinder with an insulated radius	22.60	21.51
2	RCP upper sides of casing: modeled as a cylinder with an insulated radius	21.51	19.78
3	RCP center sides of casing: modeled as a cylinder with an insulated radius	19.78	17.22
4	RCP lower sides of casing: modeled as a truncated cone with an upper insulated radius and a lower insulated radius	17.22	14.62

The X and Y coordinates corresponding to the vertical centerline of the reactor coolant pump are also required for this analysis. Table C.5-7 provides the centerlines of the reactor coolant pumps relative to the reactor pressure vessel centerline.

Table C.5-7 Vertical Centerline of Reactor Coolant Pumps

Equipment	X_{center} (feet)	Y_{center} (feet)
RCP 1	-27.79	-31.36
RCP 2	-27.79	31.36
RCP 3	27.79	31.36
RCP 4	27.79	-31.36

C.5.5.3 *Pressurizer Model*

The U.S. EPR pressurizer is insulated with approximately 5.5 inch thick RMI which has an L/D value of 2 (Table 3-2 of NEI 04-07 Volume 2 {Reference 1}). For conservatism, a 6 inch RMI thickness is used for this evaluation.

The pressurizer is modeled in five distinct sections to accommodate its geometric configuration. Table C.5-8 provides the section descriptions of the pressurizer model.

Table C.5-8 Section Descriptions of the Pressurizer Model

Section Number	Description	Top Elevation (feet)	Bottom Elevation (feet)
1	PZR top: modeled as cylinder with an insulated radius	85.42	85.10
2	PZR vessel head: modeled as a half sphere with an insulated radius	85.10	80.74
3	PZR sides: modeled as cylinder with an insulated radius	80.74	45.51
4	PZR bottom bowl: modeled as a half sphere with an insulated radius	45.51	41.15
5	PZR bottom: modeled as cylinder with an insulated radius	41.15	39.44

Table C.5-9 provides the centerline of the pressurizer relative to the reactor pressure vessel centerline.

Table C.5-9 Vertical Centerline of Pressurizer

Equipment	X_{center} (feet)	Y_{center} (feet)
Pressurizer	12.24	44.13

C.5.5.4 *Calculation of Equipment Insulation in the ZOI of a Given LOCA Break*

Using the equipment model information provided in Sections C.5.5.1, C.5.5.1, and C.5.5.3, the volume of equipment insulation in the ZOI for a LOCA break is calculated using AREVA developed methodology. The quantities of equipment insulation debris generated for each LOCA break are summarized in Section C.6.

C.5.6 Insulation from Other Sources

Sections C.4.3.5 through C.4.3.7, of this appendix discuss the technical approach for determining the amounts of latent, miscellaneous, and coatings debris.

C.5.6.1 *Latent Debris*

A conservative value of 150 lb_m of latent debris is used for this evaluation. Based on Section C.4.3.5, the breakdown of latent debris into particulate and fibrous matter is as follows and represents the as-tested values:

latent particulate = 150 lb_m x 0.85 = 127.5 lb_m particulate

latent fibrous = 150 lb_m x 0.15 = 22.5 lb_m fibrous

The design basis distribution is as follows:

Latent particulate = 150 lbs x 0.932 = 139.8 lb particulate

Latent fibrous = 150 lbs x 0.068 = 10.2 lb fibrous

C.5.6.2 *Miscellaneous Debris*

100 ft^2 of miscellaneous debris (tags, tape, labels, etc.) are added to the debris total of each break location. Most tags and labels within the U.S. EPR containment will be made of stainless steel.

C.5.6.3 *Coatings*

Qualified coatings amounts are consistent with the guidance of Section 3.4.3.4 of NEI 04-07 (Reference 1). This guidance determines the surface area of the spherical ZOI for qualified coatings and multiplies that area by the thickness associated with each type coating. For the U.S. EPR design, 3 mils of an IOZ primer and 12 mils of an epoxy top coat is assumed per plant specific assumption number 1 (Section C.2.2). Outside the ZOI, qualified coatings are assumed to remain intact. Based on Section C.4.3.7, the qualified coatings debris is calculated using a ZOI radius/break diameter multiplier of 10 for the IOZ coatings and 4 for the epoxy coatings. Based on the above guidance and assumptions, the qualified coatings amounts are determined to be 126.3 lb_m for qualified epoxy coatings and 958.7 lb_m for qualified IOZ coatings. Unqualified coatings are assumed to make up 250 lb_m of the total debris source term per plant specific assumption number 1 (Section C.2.2).

C.5.6.4 *Additional Debris from Equipment and RCS Piping*

K-wool insulation located on the steam generator upper lateral supports is not affected by any break location. Therefore, K-wool is not a source of generated debris. For conservatism, an estimated 1 ft^3 of Microtherm, or similar microporous insulation, is added to all break cases as described in Section C.4.3.8.

C.5.7 Debris Size Breakdown

Table C.5-10 provides the breakdown of debris based on the methodology described in Section C.4.4.

Table C.5-10 Size and Distribution of Debris Within the ZOI

Debris Source Type	Debris Size Distribution	
	Small Fines (%)	Large Pieces (%)
RMI	75	25
Microtherm	100	0

C.6 Results

The U.S. EPR debris generation evaluation utilizes the guidance of RG 1.82 Rev. 3 and information presented in NEI 04-07. The debris generation results are derived from the process detailed in Figure C.5-1.

The results of the debris generation process for each break location are presented in the following subsections. The first table in each subsection details and totals the amount and type of piping and equipment insulation. The second table in each subsection provides the total amount of debris generated from each break location.

As detailed in the following Section C.6 Tables, the generated debris totals for coatings, latent debris, and miscellaneous debris are the same for all break locations. The bounding break location is determined by insulation debris generated from the piping and equipment. Table C.6-14 (Break 7) is the bounding break for RMI generation.

C.6.1 Break 1: RCS Hot Leg at SG3 Inlet Nozzle

Table C.6-1 and Table C.6-2 provide the debris generation results for Break 1.

Table C.6-1 Break 1 Insulation Totals

Insulation Type	RMI (ft^2)	Microtherm (ft^3)
Piping	1078.92	
Steam generator	578.41	
Pressurizer	0	
Reactor Coolant Pump	0	
1/2" Piping		
Other from Equipment		1.00
Total	1657.33	**1.00**

Table C.6-2 Break Debris Generation Totals

Debris Source	Particulate	Small Fines	Large Pieces	Total
RMI (ft^2)	0	1243	414.33	**1657.33**
Microtherm (ft^3)	1.00	0	0	**1.00**
Qualified Epoxy Coatings (lb_m)	126.30	0	0	**126.30**
Qualified IOZ Coatings (lb_m)	958.70	0	0	**958.70**
Unqualified Coatings (lb_m)	250.00	0	0	**250.00**
Latent Debris (lb_m)	127.50	22.50	0	**150.00**
Miscellaneous (ft^2)	0	0	100.00	**100.00**

C.6.2 Break 2: RCS Cold Leg at RCP3 Outlet Nozzle

Table C.6-3 and Table C.6-4 provide the debris generation results for Break 2.

Table C.6-3 Break 2 Insulation Totals

Insulation Type	RMI (ft^2)	Microtherm (ft^3)
Piping	852.16	
Steam Generator	0	
Pressurizer	0	
Reactor Coolant Pump	1109.79	
1/2" Piping		
Other from Equipment		1.00
Total	**1961.95**	**1.00**

Table C.6-4 Break 2 Debris Generation Totals

Debris Source	Particulate	Small Fines	Large Pieces	Total
RMI (ft^2)	0	1471.46	490.49	**1961.95**
Microtherm (ft^3)	1.00	0	0	**1.00**
Qualified Epoxy Coatings (lb_m)	126.30	0	0	**126.30**
Qualified IOZ Coatings (lb_m)	958.70	0	0	**958.70**
Unqualified Coatings (lb_m)	250.00	0	0	**250.00**
Latent Debris (lb_m)	127.50	22.50	0	**150.00**
Miscellaneous (ft^2)	0	0	100.00	**100.00**

C.6.3 Break 3: Pressurizer Surge Line at Hot Leg 3 Connection

Table C.6-5 and Table C.6-6 provide the debris generation results for Break 3.

Table C.6-5 Break 3 Insulation Totals

Insulation Type	RMI (ft^2)	Microtherm (ft^3)
Piping	201.06	
Steam Generator	0	
Pressurizer	0	
Reactor Coolant Pump	0	
1/2" Piping		
Other from Equipment		1.00
Total	**201.06**	**1.00**

Table C.6-6 Break 3 Debris Generation Totals

Debris Source	Particulate	Small Fines	Large Pieces	Total
RMI (ft^2)	0	150.80	50.26	**201.06**
Microtherm (ft^3)	1.00	0	0	**1.00**
Qualified Epoxy Coatings (lb_m)	126.30	0	0	**126.30**
Qualified IOZ Coatings (lb_m)	958.70	0	0	**958.70**
Unqualified Coatings (lb_m)	250.00	0	0	**250.00**
Latent Debris (lb_m)	127.50	22.50	0	**150.00**
Miscellaneous (ft^2)	0	0	100.00	**100.00**

C.6.4 Break 4: Pressurizer Surge Line Above Cold Leg 3

Table C.6-7 and Table C.6-8 provide the debris generation results for Break 4.

Table C.6-7 Break 4 Insulation Totals

Insulation Type	RMI (ft^2)	Microtherm (ft^3)
Piping	400.48	
Steam Generator	0	
Pressurizer	0	
Reactor Coolant Pump	0	
1/2" Piping		
Other from Equipment		1.00
Total	**400.48**	**1.00**

Table C.6-8 Break 4 Debris Generation Totals

Debris Source	Particulate	Small Fines	Large Pieces	Total
RMI (ft^2)	0	300.36	100.120	**400.48**
Microtherm (ft^3)	1.00	0	0	**1.00**
Qualified Epoxy Coatings (lb_m)	126.30	0	0	**126.30**
Qualified IOZ Coatings (lb_m)	958.70	0	0	**958.70**
Unqualified Coatings (lb_m)	250.00	0	0	**250.00**
Latent Debris (lb_m)	127.50	22.50	0	**150.00**
Miscellaneous (ft^2)	0	0	100.00	**100.00**

C.6.5 Break 5: RCS Crossover Leg 3 at SG3 Outlet Nozzle

Table C.6-9 and Table C.6-10 provide the debris generation results for Break 5.

Table C.6-9 Break 5 Insulation Totals

Insulation Type	RMI (ft^2)	Microtherm (ft^3)
Piping	1103.74	
Steam Generator	445.33	
Pressurizer	0	
Reactor Coolant Pump	0	
1/2" Piping		
Other from Equipment		1.00
Total	**1549.07**	**1.00**

Table C.6-10 Break 5 Debris Generation Totals

Debris Source	Particulate	Small Fines	Large Pieces	Total
RMI (ft^2)	0	1144.87	381.62	**1526.49**
Microtherm (ft^3)	1.0	0	0	**1.00**
Qualified Epoxy Coatings (lb_m)	126.30	0	0	**126.30**
Qualified IOZ Coatings (lb_m)	958.70	0	0	**958.70**
Unqualified Coatings (lb_m)	250.00	0	0	**250.00**
Latent Debris (lb_m)	127.50	22.50	0	**150.00**
Miscellaneous (ft^2)	0	0	100.00	**100.00**

C.6.6 Break 6: Largest Safety Injection Line Above the Loop 3 Trash Rack

Table C.6-11 and Table C.6-12 provide the debris generation results for Break 6.

Table C.6-11 Break 6 Insulation Totals

Insulation Type	RMI (ft^2)	Microtherm (ft^3)
Piping	200.69	
Steam Generator	0	
Pressurizer	0	
Reactor Coolant Pump	0	
1/2" Piping		
Other from Equipment		1.00
Total	**200.69**	**1.00**

Table C.6-12 Break 6 Debris Generation Totals

Debris Source	Particulate	Small Fines	Large Pieces	Total
RMI (ft^2)	0	150.52	50.17	200.69
Microtherm (ft^3)	1	0	0	**1.00**
Qualified Epoxy Coatings (lb_m)	126.30	0	0	**126.30**
Qualified IOZ Coatings (lb_m)	958.70	0	0	**958.70**
Unqualified Coatings (lb_m)	250.00	0	0	**250.00**
Latent Debris (lb_m)	127.50	22.50	0	**150.00**
Miscellaneous (ft^2)	0	0	100.00	**100.00**

C.6.7 Break 7: RCS Hot Leg 3 at Pressurizer Surge Line Connection

Break 7 generates the most RMI. Table C.6-13 and Table C.6-14 provide the debris generation results for Break 7.

Table C.6-13 Break 7 Insulation Totals

Insulation Type	RMI (ft^2)	Microtherm (ft^3)
Piping	2119.03	
Steam Generator	0	
Pressurizer	0	
Reactor Coolant Pump	0	
1/2" Piping		
Other from Equipment		1.00
Total	**2119.03**	**40.00**

Table C.6-14 Break 7 Debris Generation Totals

Debris Source	Particulate	Small Fines	Large Pieces	Total
RMI (ft^2)	0	1589.27	529.76	2119.03
Microtherm (ft^3)	1.00	0	0	**1.00**
Qualified Epoxy Coatings (lb_m)	126.30	0	0	**126.30**
Qualified IOZ Coatings (lb_m)	958.70	0	0	**958.70**
Unqualified Coatings (lb_m)	250.00	0	0	**250.00**
Latent Debris (lb_m)	127.50	22.50	0	**150.00**
Miscellaneous (ft^2)	0	0	100.00	**100.00**

C.7 References

1. NEI 04-07, “Pressurized Water Reactor Sump Performance Evaluation Methodology,” Volumes 1 (Methodology) and 2 (Safety Evaluation), December 2004.

2. Regulatory Guide 1.82 Rev 3, “Water Sources for Long-Term Recirculation Cooling following a Loss-Of-Coolant Accident,” November 2003.

3. NUREG/CR-6224, “Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris,” October 1995.

4. ANSI/ANS-58.2-1988, “Design Basis for Protection of Light Water Nuclear Power Plants against the Effects of Postulated Pipe Rupture.”

5. NUREG/CR-6877, “Characterization and Head Loss Testing of Latent Debris from Pressurized-Water-Reactor Containment Buildings,” July 2005.

Appendix D
Chemical Effects Evaluation for the U.S. EPR

D.1 Chemical Effects Evaluation

D.1.1 Background

Appendix D documents the process and results of the chemical effects evaluation for the U.S. EPR to address a concern identified by the Nuclear Regulatory Commission (NRC) regarding Generic Safety Issue 191 (GSI-191). Debris generated by a postulated loss-of-coolant accident (LOCA) or high energy line break (HELB) can be transported to the containment building sump and potentially impede the performance of the Emergency Core Cooling Systems (ECCS) during recirculation.

Generic Letter 2004-02 requests the maximum head loss across the sump strainers postulated from debris accumulation (including chemical effects) be evaluated on a plant specific basis. As part of the evaluation of IRWST strainer clogging for the U.S. EPR plant, a chemical effects evaluation was conducted to identify specific compounds and quantities of materials that may precipitate within the U.S. EPR reactor containment sump pool following a LOCA. This evaluation is comprised of the following integrated studies:

- Chemical Effects Testing
- IRWST Sump Chemistry Modeling

Appendix D documents methodology and results of the chemical effects evaluation. The results of the chemical effects evaluation serve as a basis and input to the ECCS Strainer Performance Testing (Appendix E).

D.2 Chemical Effects Testing

D.2.1 Scope and Objective

The objective of the chemical effects testing is to determine the types and approximate quantities of deposits that form from the reaction of debris materials and buffering chemicals in the IRWST. The results of this testing serve as input to the IRWST Sump Chemistry Modeling (Section D.3). Testing utilized simulated debris materials at a loading that bounds the actual debris loading of the U.S. EPR plant.

The debris materials selected for chemical effects testing include the following:

- Concrete
- Aluminum alloy 1100
- NUKON® silica fiber insulation
- Microtherm microporous insulation
- Latent debris (sand and bentonite)

The debris materials were exposed to borated water at elevated temperature in a recirculating autoclave. Trisodium phosphate was added to the borated water to produce a final room-temperature pH of approximately 7.5 in order to simulate the IRWST fluid conditions.

Due to the chemical composition of the debris materials, the expected precipitates from the test were aluminum oxyhydroxide / aluminum trihydroxide, calcium phosphate, and sodium silicate / sodium aluminum silicate. The test liquid and solid material recovered from the test vessel were analyzed for chemical composition to confirm or refute the presence of these precipitates and attempt to identify other likely precipitate species.

D.2.2 Overview of Testing

The chemical effects testing program was designed to study the interaction of simulated debris material in the IRWST with dissolved chemicals in the leaking reactor coolant.

To accomplish this objective, samples of debris materials were exposed to IRWST chemistry conditions in a temperature-controlled autoclave. The test was conducted over approximately 160 hours (~6.5 days) to study the short-term and moderate-term interactions.

D.2.2.1 *Test Equipment*

The chemical effects testing was performed in the AREVA Chemistry and Materials Center (CMC) process testing autoclave. The autoclave is a stainless steel vessel with a capacity of approximately 7.5 liters that is equipped with four (4) oblong windows for test observation. The autoclave temperature was controlled using a recirculating oil system. Figure D.2-1 provides a schematic of the autoclave system.

Prior to performing the chemical effects test, the autoclave was rinsed with de-ionized water (DI). A sample of the rinse water was analyzed to verify that the autoclave was free from unacceptable contaminants. Table D.2-1 provides a summary of the autoclave pre-test rinse analysis results.

Figure D.2-1 Schematic of the Autoclave System

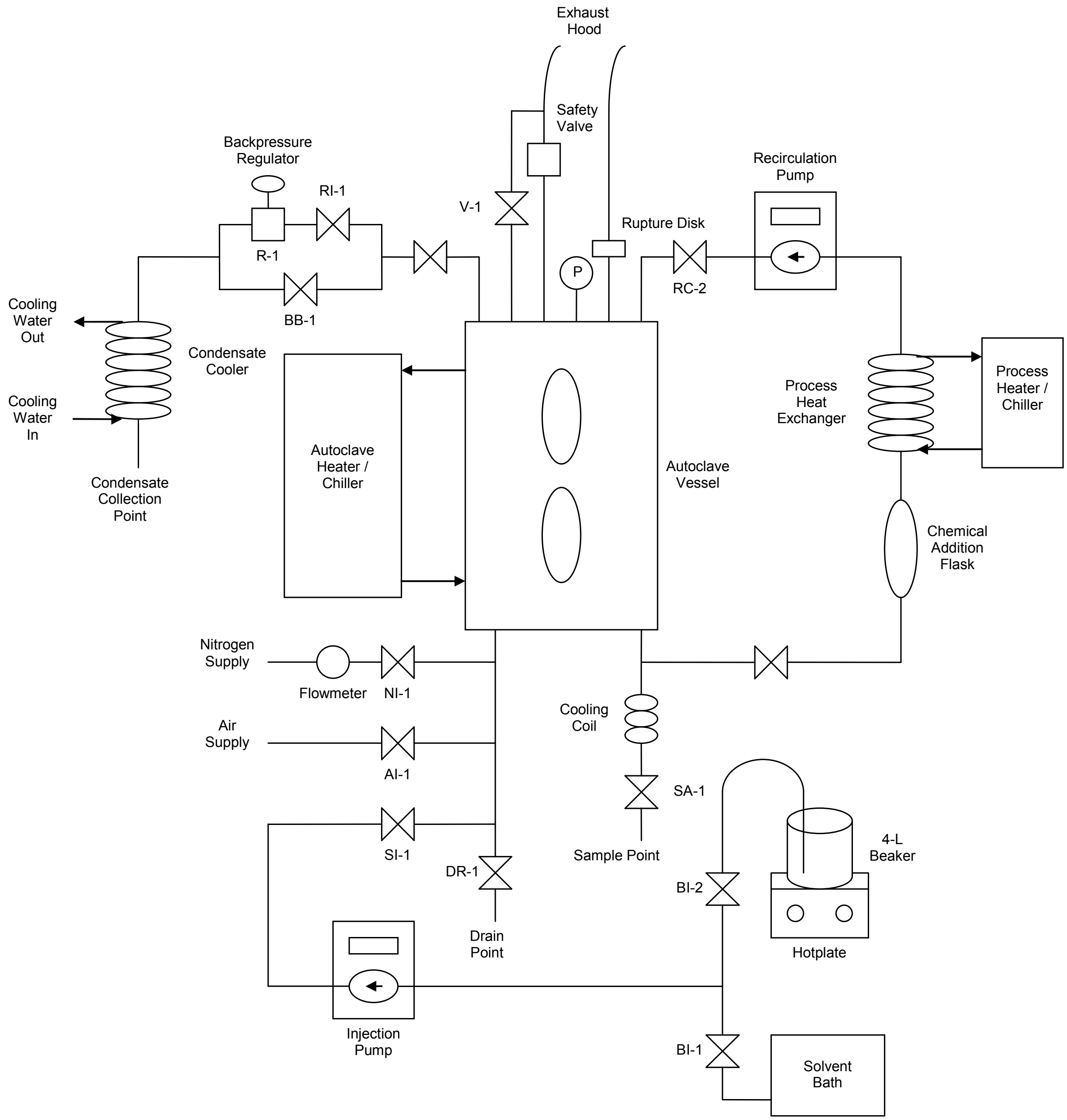


Table D.2-1 Summary of the Autoclave Pre-Test Rinse Analysis Results

Analyte	Concentration Limit	Measured Value
Aluminum	1 ppm	< 1 ppm
Calcium	1 ppm	< 1 ppm
Magnesium	1 ppm	< 1 ppm
Silicon	1 ppm	< 1 ppm
Chloride	5 ppm	0.011 ppm
Sulfate	5 ppm	0.038 ppm
Fluoride	5 ppm	0.010 ppm
Conductivity	10 μS/cm	1 μS/cm

The chemical injection system for the test consisted of a heated bath / tank and a piston injection pump. The system was also equipped with a solvent recirculation loop that drew suction from the bottom of the autoclave and returned it to the top head. The recirculation pump was set to provide one volume turnover approximately every two (2) hours.

D.2.2.2 *Test Procedure*

The autoclave was loaded with debris representative materials as described in Section D.2.3. A solution of boric acid (approximately 2800 ppm boron) was prepared and pre-heated to 120°F prior to injection. A vessel containing approximately 25.28 grams of trisodium phosphate dodecahydrate (TSP) was installed in the solvent circulation line. Once the boric acid solution and autoclave were pre-heated, the solution was injected into the autoclave over approximately 50 minutes. After filling, the system was put on recirculation, allowing the TSP to dissolve and buffer the solution pH over approximately two (2) hours.

The temperature during the test was controlled to simulate the IRWST response to a large-break LOCA (as calculated at the time of the testing) as closely as practicable. Subsequent to the test completion, the IRWST temperature profile was re-calculated, resulting in a more rapid heating and cooling and a slightly higher temperature peak of approximately 250°F versus 230°F. However, the change in the predicted IRWST temperature profile does not affect the validity of the test result because:

1. The time period where the temperature is expected to be above the test temperature is less than 3 hours.

2. The test results are used primarily as a means of validating the method by which AREVA NP predicts chemical releases and precipitation.

Therefore, the usefulness of the test data is not affected by the change in IRWST temperature.

Periodically during the test, samples of the recirculating liquid were collected and analyzed for chemical constituents of the debris materials, particularly calcium, aluminum, and silicon. The autoclave contents were also observed through oblong glass windows to visually determine if precipitation of leached species was occurring. At the conclusion of the test, the final solution drained from the autoclave was filtered and analyzed for chemical constituents. The material collected on the filters and deposits collected from the autoclave internals were analyzed for chemical composition using energy dispersive X-ray spectroscopy.

D.2.3 Debris Loading

D.2.3.1 *Aluminum*

To simulate scaffolding, railing, and other aluminum materials that may be exposed to LOCA water in the U.S. EPR containment building, a single aluminum coupon with a surface area of 2.0 in^2 was included in the test.

The aluminum used for the chemical effects test was Alloy 1100 and procured as commercial grade. After receipt, the aluminum coupon was dedicated as safety related by dimensional and material inspection in accordance with AREVA programs and controls. The elemental composition of the aluminum coupon used in the chemical effects test, as determined by arc-spark optical emission spectroscopy, is provided in Table D.2-2.

Table D.2-2 Elemental Composition of the Aluminum Coupon

Analyte	Concentration
Chromium	< 0.01 %
Manganese	0.01 %
Silicon	0.11 %
Iron	0.47 %
Aluminum	Remainder
Titanium	0.008 %
Copper	0.09 %
Magnesium	0.003 %
Zinc	< 0.01 %
Other – Each	< 0.01 %
Other − Total	< 0.03 %

D.2.3.2 *Concrete*

To simulate the structural concrete that may come into contact with LOCA water, the chemical effects test included a concrete coupon with an exposed surface area of approximately 5.2 in^2. This area corresponds to the entire surface area of the containment building heavy floor being exposed during a design-basis LOCA. Because the heavy floor is coated with epoxy, it is unlikely that full exposure of the heavy floor surface area would occur. However, this condition bounds all possible LOCA conditions.

The concrete coupon was taken from a test cylinder provided by Chaney Enterprises. The concrete mix specified is consistent with structural concrete utilized for the operating Calvert Cliffs Nuclear Power Plant. The concrete was procured as commercial grade. After receipt, the concrete coupon was dedicated as safety related by dimensional and general chemical composition inspection in accordance with AREVA programs and controls.

To dedicate the chemical composition, a sample of the concrete was pulverized, sieved to remove large aggregate stone, ground to analytical fineness (100 mesh size), and analyzed using X-ray diffraction (XRD). To assist in refining the x-ray diffraction pattern, an elemental analysis of the pulverized material was performed using scanning electron microscopy / energy dispersive X-ray spectroscopy (SEM/EDS). Based on the review of the XRD and SEM/EDS analyses and results, the concrete sample was considered acceptable for testing. A summary of the pre-test elemental composition of the pulverized concrete sample is provided in Table D.2-3.

Table D.2-3 Pre-Test EDS Data of Pulverized Concrete Sample

Element	Weight %	Atomic %
O	62.25	77.90
Na	0.13	0.12
Mg	1.61	1.33
Al	1.59	1.18
Si	11.21	8.00
S	0.44	0.28
K	0.46	0.24
Ca	21.07	10.53
Ti	0.12	0.05
Fe	0.81	0.29
Cu	0.29	0.09
Total	**100.00**	N/A

Note that the EDS results were normalized to remove carbon as a constituent of the concrete because the specimen was mounted on carbon tape for the EDS analysis.

D.2.3.3 *NUKON® Insulation*

NUKON® insulation is a glass fiber insulation that is planned for use in areas of the reactor coolant system where reflective metal insulation (RMI) is not practical. The NUKON® material used for chemical effects testing was procured as safety related. The material was supplied as a large woven mat. For the purposes of testing, samples of the insulation were extracted from the mat and heated in air at approximately 600°F for 24 hours in order to decompose the binder on the fibers. After the heat treatment, the fibers were shredded and weighed prior to testing. A total of approximately 0.48 g of heat-treated NUKON® fibers were loaded into the autoclave vessel for testing. Figure D.2-2 and Figure D.2-3 are photographs of the NUKON® material before and after heat treatment. Figure D.2-4 shows an example SEM micrograph of NUKON® fibers prior to testing.

Figure D.2-2 NUKON® Insulation before Heat Treatment

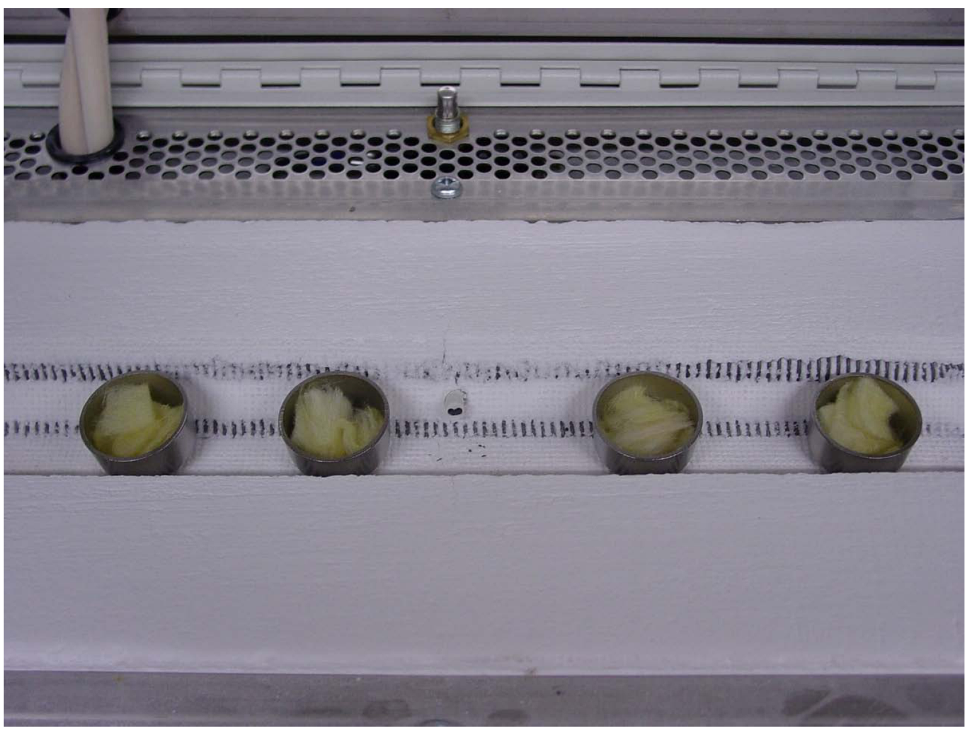
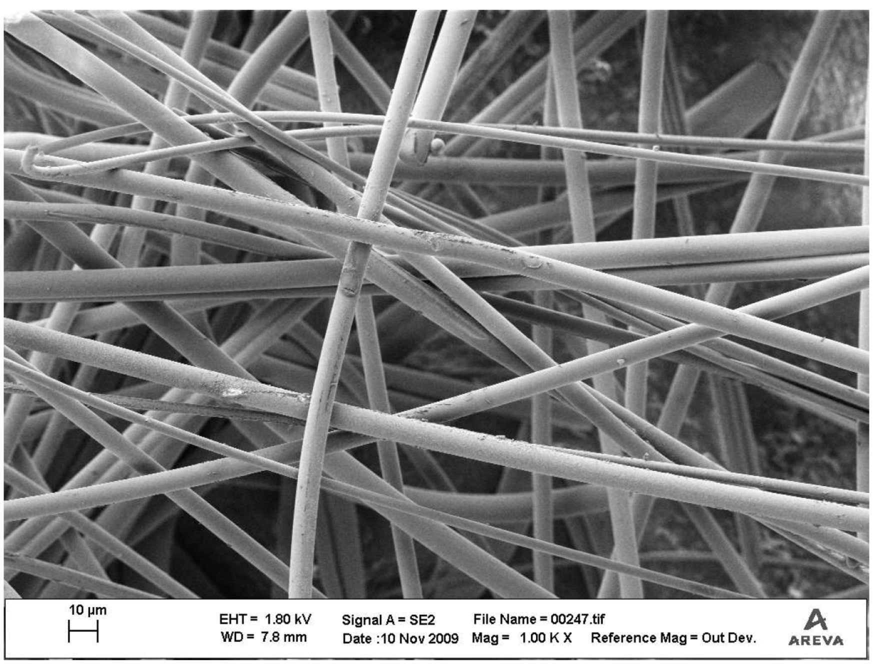


Figure D.2-3 NUKON® Insulation after Heat at 600°F for 24 Hours

Figure D.2-4 SEM Micrograph of NUKON® Fibers before Testing



The test plan called for the inclusion of 0.04 ± .01 g of untreated NUKON® and 0.10 ± 0.01 g of heat-treated NUKON®. However, due to a departure from the test plan when selecting the containers for loading the autoclave, no untreated NUKON® was loaded in the test. Instead, two containers of heat-treated NUKON® fibers, totaling approximately 0.48 g, were loaded into the test vessel. With the exception of increasing the total mass of NUKON® insulation in the test, the use of only heat-treated NUKON® fibers is not expected to significantly affect the test conclusions. NUREG/CR-6873 (Reference 1) states that NUKON® fibrous glass wool insulation is held together with a phenyl formaldehyde resin-based binder, which is about three percent by weight. The binders are applied after fiberization and accumulate on the fibers as droplets. During curing at an elevated temperature, these droplets coat the fiber surface and convert to an insoluble polymer. Although not designed for aggressive acidic or alkaline environments, the binder is expected to be stable in the <250°F, pH 7.2 TSP-buffered solution. NUKON® MSDS notes that the phenolic resin begins to decompose at a temperature of ~400°F. NUREG-1861, Appendix A, Page A-31 states that there is no evidence that this coating impedes corrosion of the underlying fiberglass. Thus, omitting the untreated NUKON® from the test is not expected to affect the test results. However, the deviation in the mass of NUKON® loaded is considered when evaluating the silicon releases from the test.

D.2.3.4 *Microtherm™*

Microtherm microporous insulation is a type of non-RMI insulation planned for use in the U.S. EPR containment. This material is a finely-divided power composed of amorphous silica and titanium dioxide contained in a woven fiber blanket. Approximately 2.6 grams of this material were included in the autoclave testing. Because the woven blanket is likely to tear as a result of a LOCA, a section of the blanket was cut apart and the loose fiber and power were loaded into the autoclave. Optical and SEM micrographs of the pre-test material are shown in Figure D.2-5, Figure D.2-6, and Figure D.2-7. The chemical composition of a sample of Microtherm is provided in Table D.2-4.

Table D.2-4 Elemental Composition of Microtherm Powder by EDS

Element	Weight %	Atomic %
C	25.18	34.28
O	52.88	54.05
F	0.85	0.73
Al	0.12	0.07
Si	15.41	8.97
Ti	5.39	1.84
Fe	0.06	0.02
Cu	0.11	0.03
Totals	100.00	N/A

Figure D.2-5 Optical Micrograph of Microtherm on SEM Sample Stub

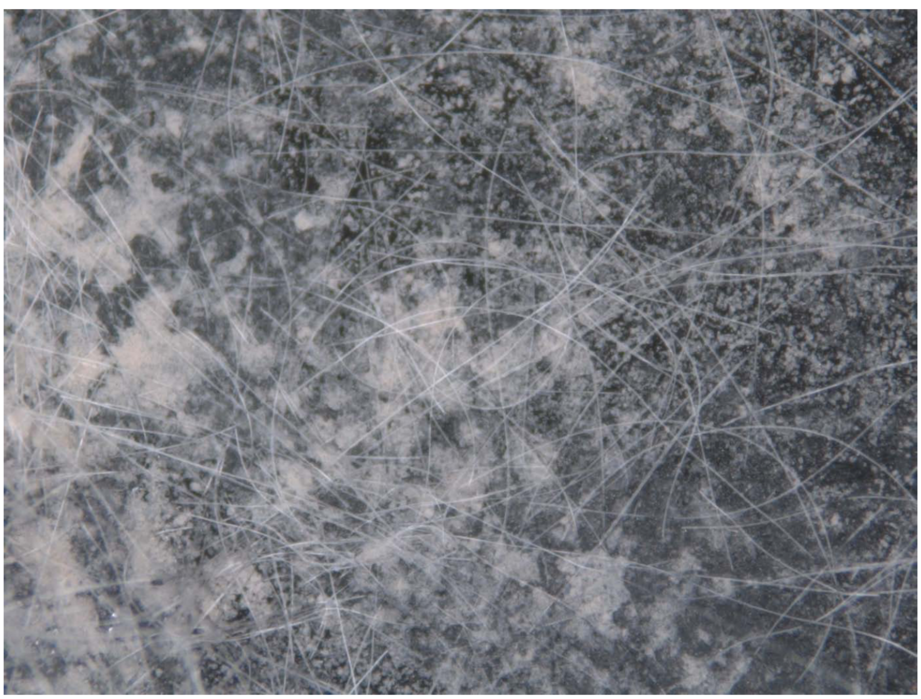


Figure D.2-6 SEM Micrograph of Microtherm Insulation Prior to Testing

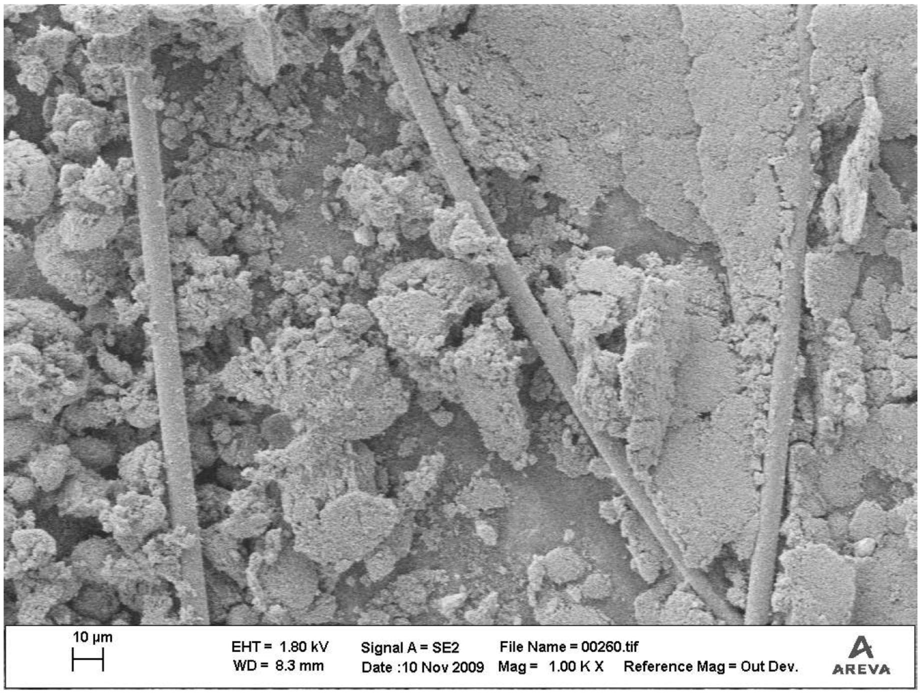
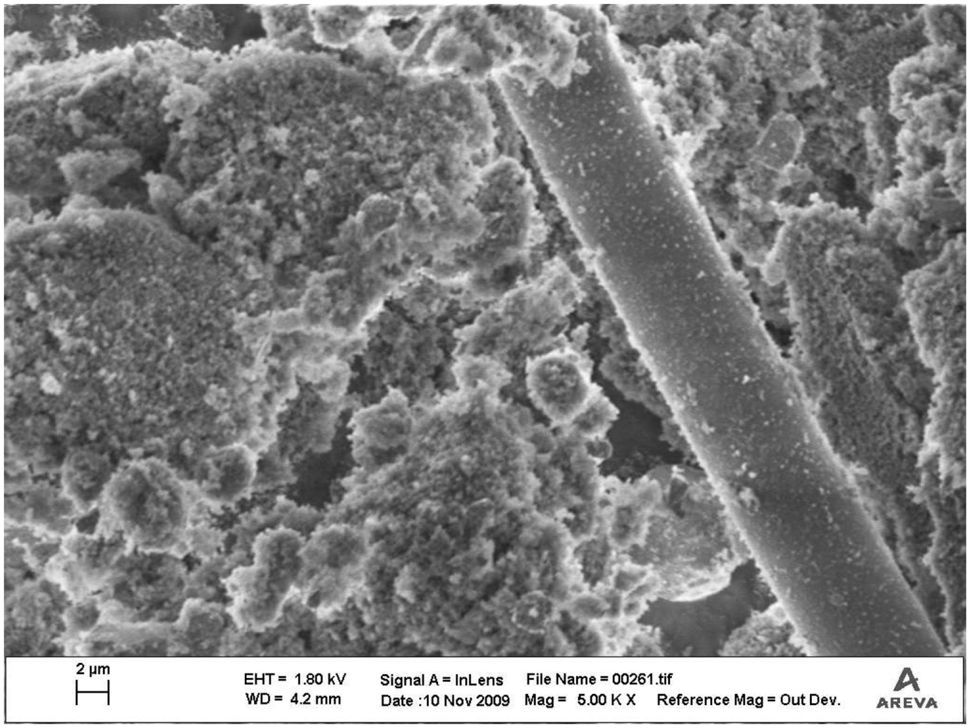
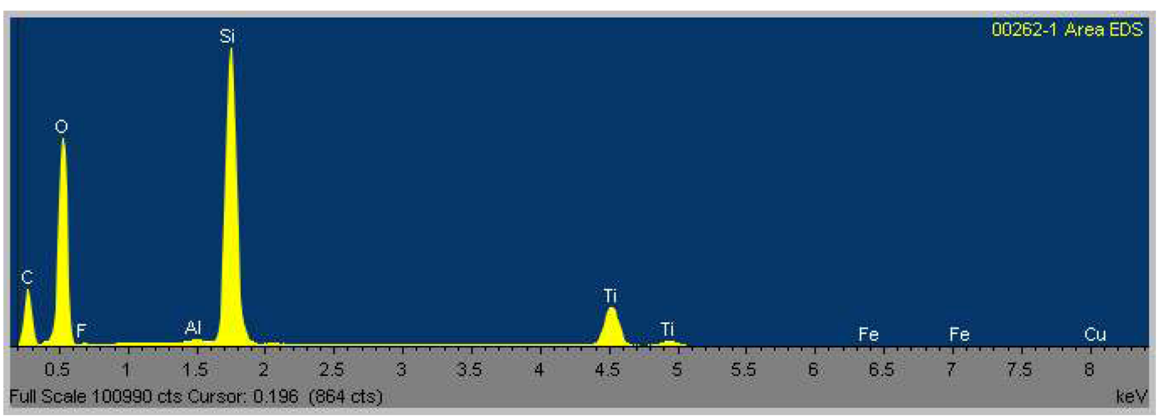


Figure D.2-7 SEM Micrograph and EDS Spectrum of Microtherm Prior to Testing





D.2.3.5 *Latent Debris*

To simulate various sources of latent debris in the containment building, the chemical effects test also included small quantities of sand, sodium-form bentonite powder, and pulverized concrete. These materials were not expected to significantly affect the chemical loading. However, they were included for completeness. The sand and bentonite were procured as commercial grade. Material dedication was not performed on these materials. The concrete was taken from the waste material generated from fabricating the concrete coupon for the test. Approximately 0.54 grams of particulate, split approximately equally between the three components, were loaded into the autoclave test vessel.

D.2.3.6 *Autoclave Loading Summary*

To simulate the IRWST environment following a design-basis LOCA, the chemical effects autoclave was loaded with a variety of potential debris materials. To ensure adequate contact between the debris materials and the test solution, the debris was distributed onto a support structure constructed of stainless steel.

The concrete coupon was attached to a flat plate with a section of lockwire. The five exposed sides of the concrete coupon were sized to provide the appropriate surface area for leaching. Because the aluminum coupon was sized to be exposed on all sides, it was mounted onto the side of the internals using a plastic screw and washers to ensure electrical isolation from the internals.

The Microtherm and latent particulate debris were each distributed onto supports fabricated from 80-mesh stainless steel screen. In order to minimize their distribution into the solution, while still allowing for adequate solution contact, the trays were loosely covered with 40-mesh stainless steel screen. The 40-mesh screen had an open area of approximately 50% to allow for solution contact.

The NUKON® insulation was distributed in the center of the base plate of the internals. The NUKON® was contained in a shallow well supported by a perforated metal screen / plate. Fluid contact in the area is provided by circulation due to the recirculation pump suction being located in the autoclave lower head.

A summary of the autoclave debris loading is provided in Table D.2-5. A photograph of the assembled and debris loaded autoclave internals is provided in Figure D.2-8.

Table D.2-5 Summary of Autoclave Debris Loading

Debris Material	Surface Area (in^2)	Mass (grams)
NUKON® Fibers	−−−	0.4812
Microtherm Insulation	−−−	2.5925
Aluminum Coupon	2.0334	2.4013
Concrete Coupon	5.238	42.5273
Latent Particulate	−−−	0.5388

Figure D.2-8 Assembled Autoclave Internals

D.2.4 Test Results

D.2.4.1 *Test Solution Chemistry*

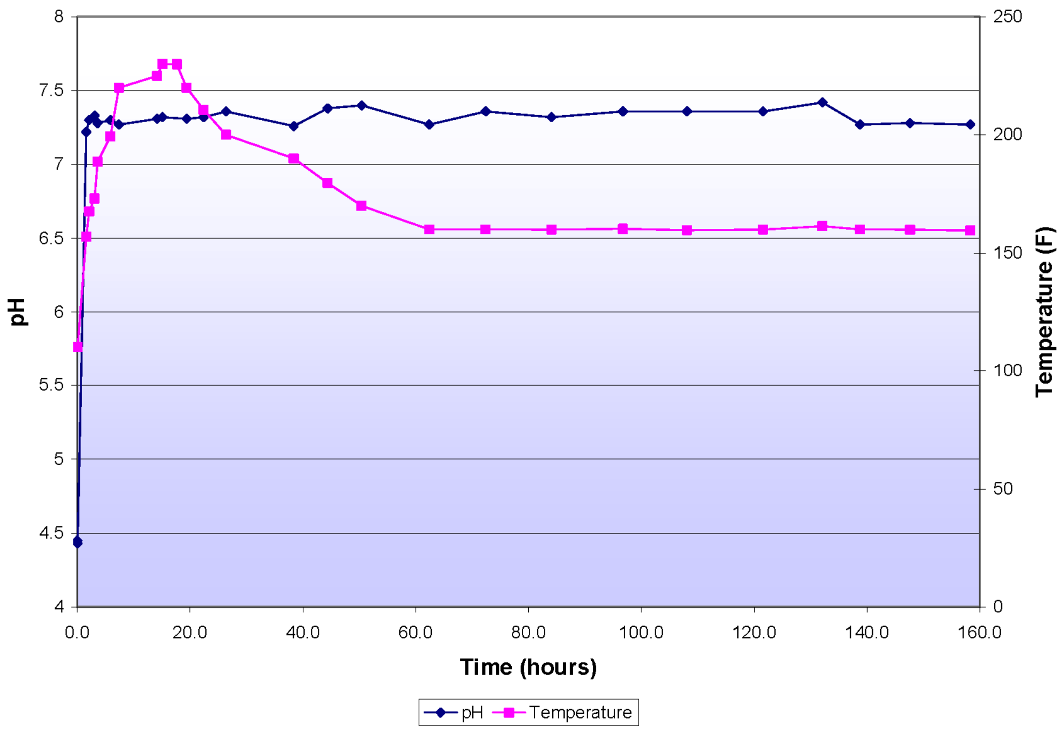
Periodically throughout the test, samples of the recirculating liquid were drawn from the autoclave and analyzed for chemical constituents. These samples indicate the leaching/dissolution of the debris materials with time and temperature. The following sections summarize the analytical results of the solution samples.

D.2.4.1.1 Solution pH

The measured pH of the initial boric acid solution prepared for the test was approximately 4.45. This is consistent with the pH expected from a boric acid solution with a boron concentration of approximately 2,800 ppm. Once recirculation of the solution through the TSP basket commenced, the solution pH began to increase to approximately 7.3 over the next two hours. Thereafter, the solution pH remained constant for the remainder of the test.

A trend for measured pH values and temperatures is provided in Figure D.2-9.

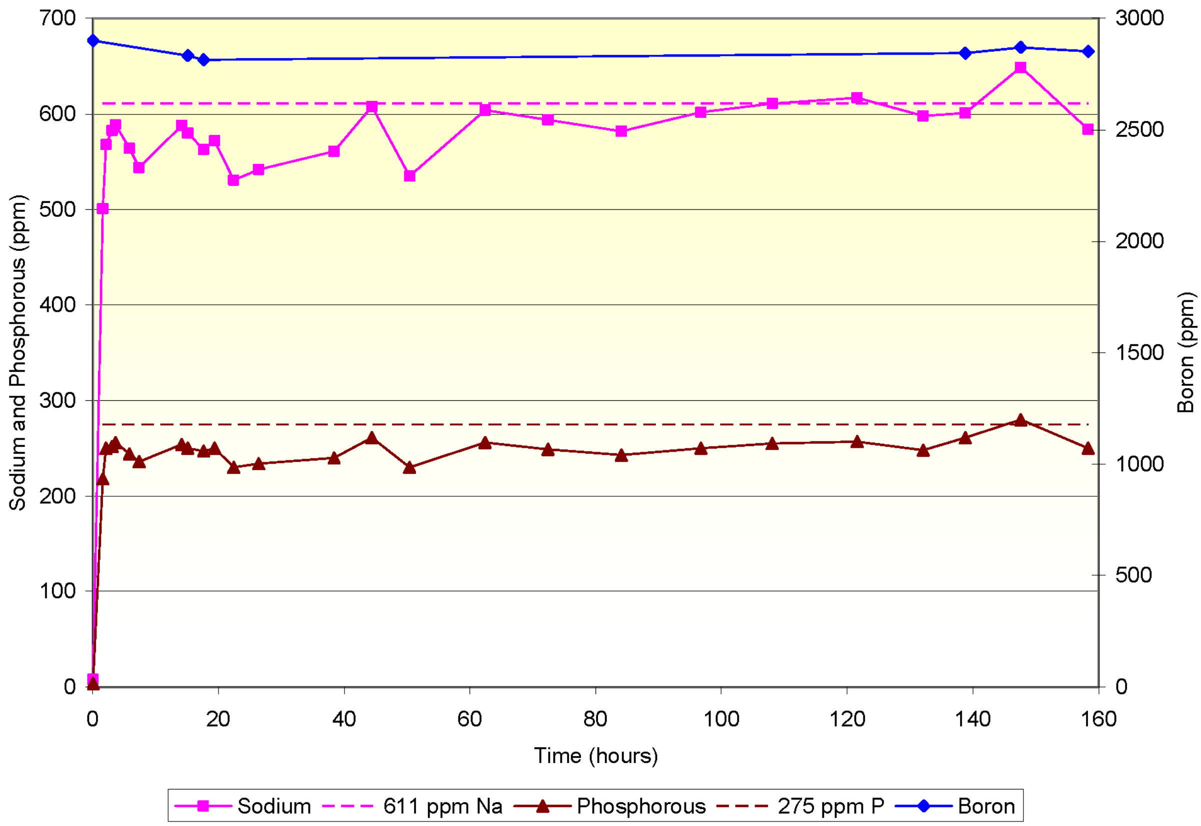
Figure D.2-9 pH and Temperature Trend for Chemical Effects Test



D.2.4.1.2 Boron, Sodium, and Phosphorous

The simulated IRWST solution contained boron, sodium, and phosphorous as additives. The boron was added as boric acid to simulate the shutdown boric acid condition for the U.S. EPR plant. In addition, trisodium phosphate dodecahydrate was added to the test as a pH buffering agent, which resulted in a significant concentration of sodium and phosphorous. As expected, each of the additive species remained relatively constant, after approximately two (2) hours into the test. This constant solution concentration indicates that no whole-scale precipitation of boric acid or sodium phosphate was occurring during the test. Rather, the precipitation quantity will be governed by the materials leached from the debris, although sodium and phosphorous are expected to co-precipitate in small quantities. A summary of the boron, sodium, and phosphorous concentration during the test is provided in Figure D.2-10. Also shown in Figure D.2-10 are the amounts of sodium (611 ppm Na) and phosphate (275 ppm P) added to the autoclave.

Figure D.2-10 Boron, Sodium, and Phosphorous Concentrations during Chemical Effects Test



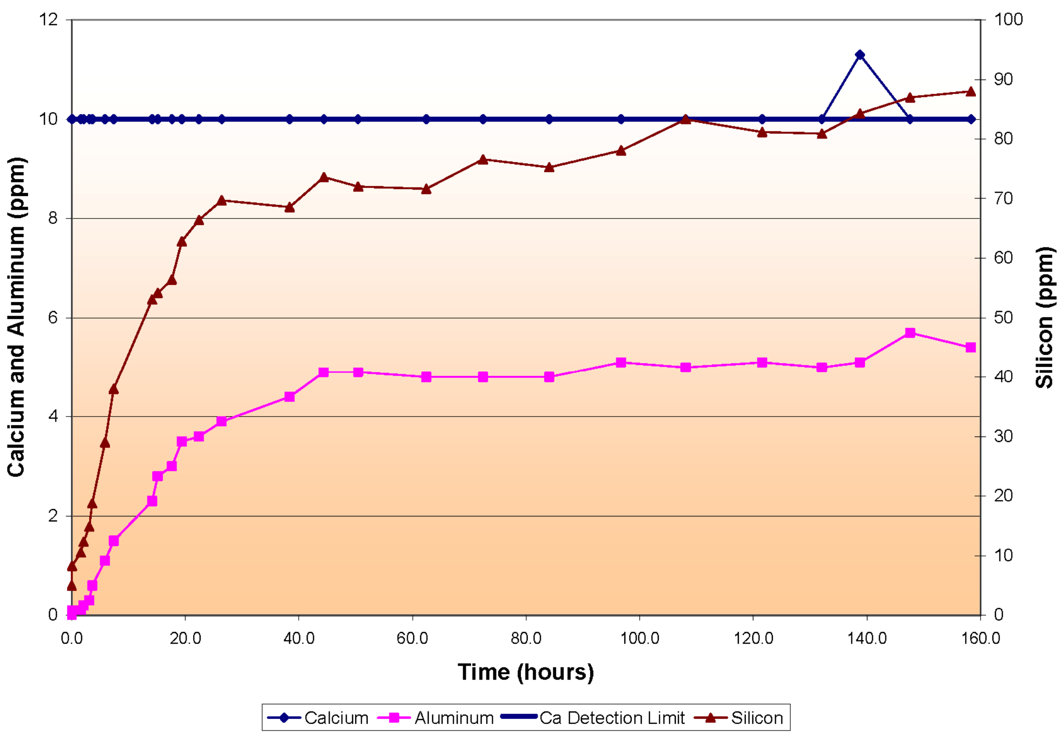
Note that the samples were filtered through 0.45 micron filters during cooling prior to analysis.

D.2.4.1.3 Calcium, Aluminum, and Silicon

Based on industry experience with post-LOCA chemistry conditions, the most likely precipitates in the IRWST conditions are calcium phosphate, aluminum oxyhydroxide / hydroxide, and sodium aluminum silicate. Therefore, the three primary chemical species monitored during the chemical effects test were calcium, aluminum, and silicon.

It was expected that these species would slowly increase in concentration, as they leached from the debris materials, up until the solution saturation point was reached. A graphical summary of the calcium, aluminum, and silicon concentration during the test is provided in Figure D.2-11.

Figure D.2-11 Graphical Summary of Calcium, Aluminum, and Silicon Concentrations during Chemical Effects Test



Note that the samples were filtered through 0.45 micron filters during cooling prior to analysis.

The calcium concentration of the test solution was consistently at or below the detection / quantification limit in the boron matrix, which was approximately 10 ppm (after accounting for dilution to reduce boron quenching of the matrix). Only one data point exceeded 10 ppm, with a solution concentration of 11.3 ppm being measured after approximately 140 hours of exposure. The calcium trend indicates that the material either leached relatively slowly from the debris sources or that the effective solubility limit was somewhat less than 10 ppm.

Both aluminum and silicon behaved more in-line with expectations. However, both species exhibited two distinct release rates. Aluminum and silicon release was rapid during the first 24 hours of the test, followed by a slight increasing trend for the remainder of the 160-hour exposure. The aluminum, in particular, appeared to reach a plateau after approximately 40 hours. The initial rapid release of aluminum into solution is the result of active corrosion of the aluminum coupon prior to the formation of a passive corrosion film. After passivation, the corrosion and release rates of aluminum from the coupon decreased to a low steady-state value.

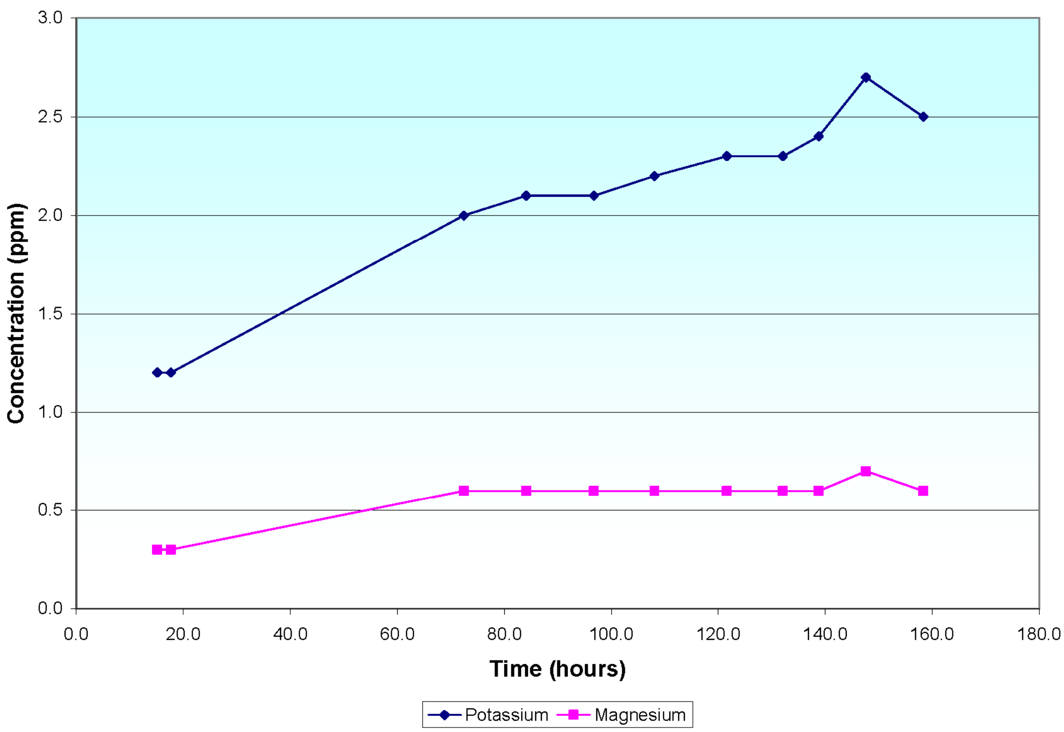
As with aluminum, the silicon concentration of the test solution increased rapidly during approximately the first 24 hours of the test. Afterward, the silicon concentration exhibited a slow upward trend. The most likely source of the rapid initial dissolution of silicon is the Microtherm microporous insulation. The physical form of the Microtherm resulted in an extremely large surface area being exposed to the test solution. In addition, visual examination of the test vessel through the installed windows showed what appeared to be loose Microtherm suspended in the water column. The likely result of these conditions would be a preferential dissolution of the amorphous silica from the Microtherm. Microtherm ceased being a significant silicon source after approximately 24 hours of exposure and the increasing silicon trend for the remainder of the test was the result of slow dissolution of silicon from the NUKON® and concrete debris.

D.2.4.1.4 Potassium and Magnesium

In addition to the major chemical species, the potassium and magnesium concentrations in the test solution were also monitored during the chemical effects test. The primary purpose for monitoring these species was to gather information to interpret solution pH changes should they occur. Because the solution pH remained relatively constant during the test, these data are not expected to be particularly significant.

A modest amount of magnesium was detected in the test solution, presumably present as a trace constituent in the concrete and insulation materials. In addition, a slow, but steady, release of potassium from the debris materials was also detected. However, because of the large excess of sodium present in the solution, the potassium concentration did not affect the solution pH. The potassium and magnesium concentrations are shown in Figure D.2-12.

Figure D.2-12 Potassium and Magnesium Concentration during Chemical Effects Test



D.2.4.2 *Post-Test Specimen Conditions*

D.2.4.2.1 Aluminum

When removed from the autoclave, the aluminum coupon exhibited a dark oxide / deposit film, as shown in Figure D.2-13. Prior to cleaning the oxide film from the coupon, SEM/EDS analysis of the surface was performed. A sample micrograph and EDS spectrum are shown in Figure D.2-14. The EDS spectrum of the coupon showed large aluminum and oxygen peaks, as expected. However, peaks for sodium, silicon, phosphorous, and calcium were also present. These peaks indicate that the coupon film contained traces of precipitates.

Figure D.2-13 Aluminum Coupon after Removal from Autoclave

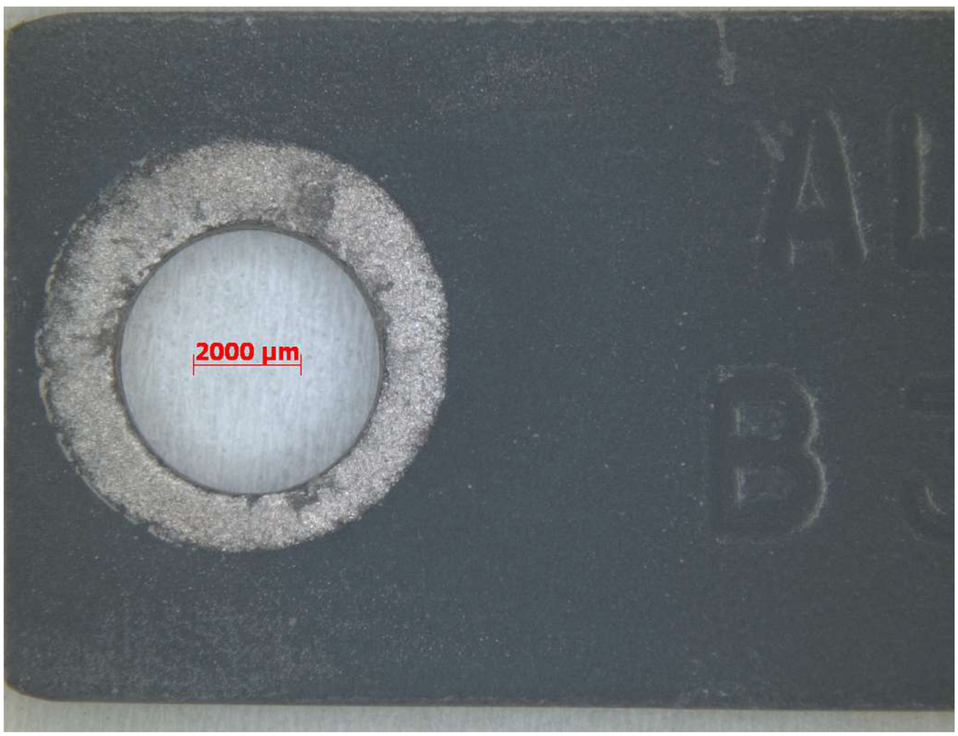
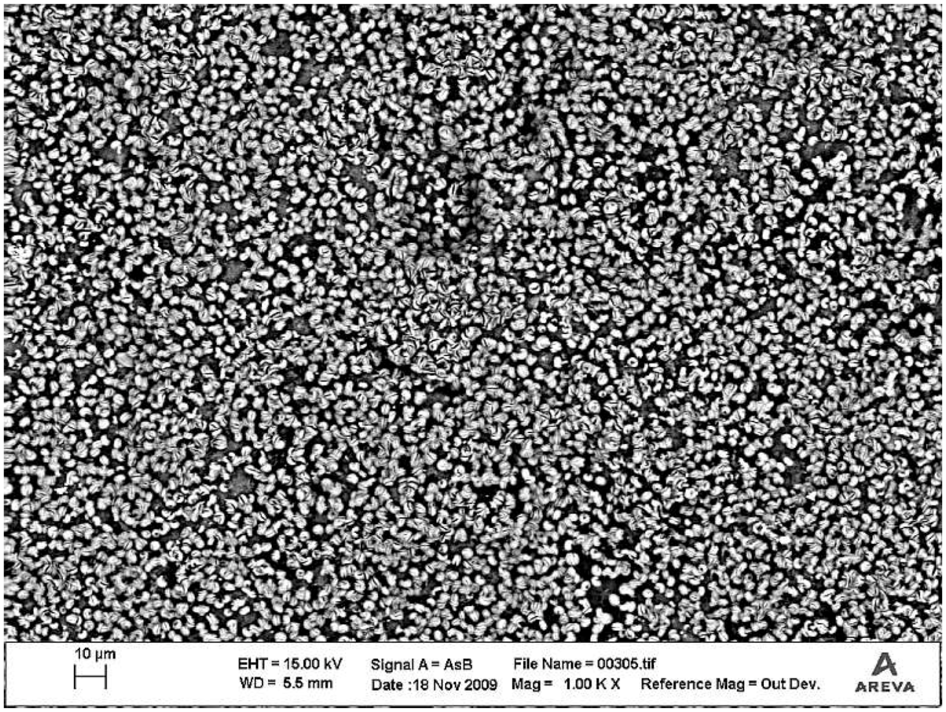
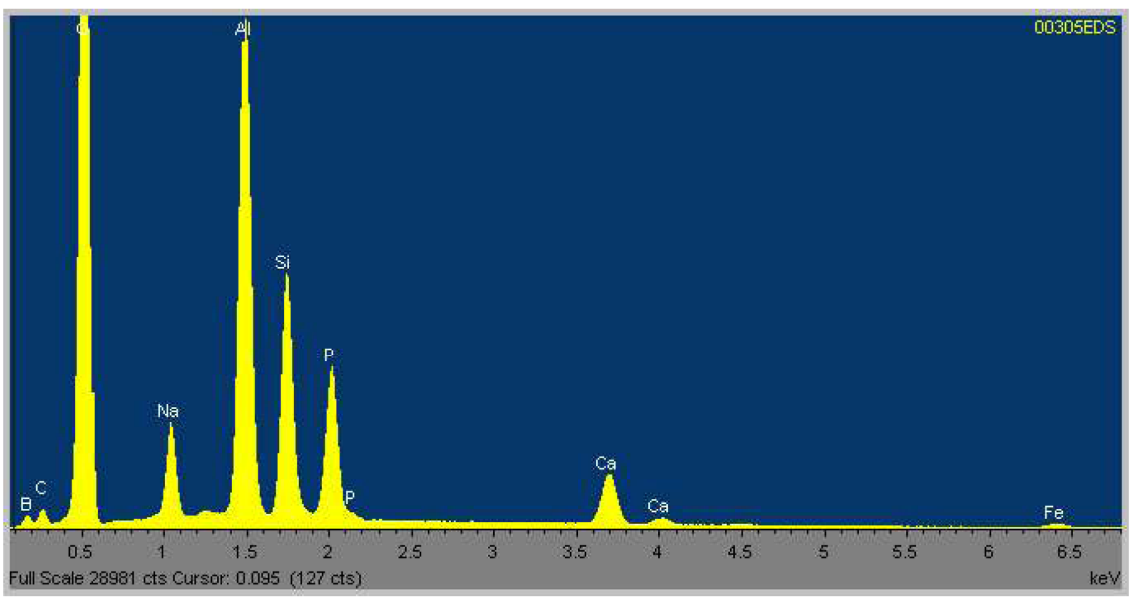


Figure D.2-14 SEM Micrograph and EDS Spectrum of Post-Test Aluminum Coupon prior to Cleaning





After the initial SEM/EDS examination, the aluminum coupon was cleaned by scrubbing with a soft brush and Lava® soap, followed by ultrasonic cleaning in acetone and drying in an oven. The cleaning was successful in removing the deposited material, leaving what appeared to be a passive aluminum oxide surface, as shown in Figure D.2-15. No additional SEM/EDS analyses were performed on the cleaned coupon.

Figure D.2-15 Aluminum Coupon after Cleaning

D.2.4.2.2 Concrete

The concrete coupon removed from the autoclave was scrubbed with a soft brush to remove excess particulate and dried in a vacuum oven prior to examination. Low-magnification examination of the coupon showed that the aggregate phases appeared to be mostly intact. There appeared to be a slight preferential attack of the cement phase. Photographs of the concrete sample after testing are provided in Figure D.2-16 and Figure D.2-17.

Figure D.2-16 Concrete Coupon after Removal From Autoclave

Figure D.2-17 Concrete Coupon after Test

D.2.4.2.3 NUKON®

The NUKON® fibers recovered from the test vessel consisted of a compacted wet mass. After drying, the fibers were examined using optical microscopy and SEM/EDS. Post-test optical examination of the fibers at 100X magnification showed little change in the fibers, as seen in Figure D.2-18. However, the SEM examination showed distinct changes in the fiber characteristics.

The SEM examination of the NUKON® fibers showed the presence of a deposited material coating and often bridging the glass fibers. A close-up SEM micrograph view is shown in Figure D.2-19. At higher magnification, the complete coating of the fibers is apparent, especially in backscattered electron (BSE) images. BSE imaging is sensitive to elemental composition and phase differences, with the difference between the base fibers and outer coating becoming readily apparent. See Figure D.2-20 and Figure D.2-21 for SEM and BSE high-resolution images.

Figure D.2-18 Optical Micrograph of NUKON® Fibers after Test

Figure D.2-19 SEM Micrograph of NUKON® after Testing

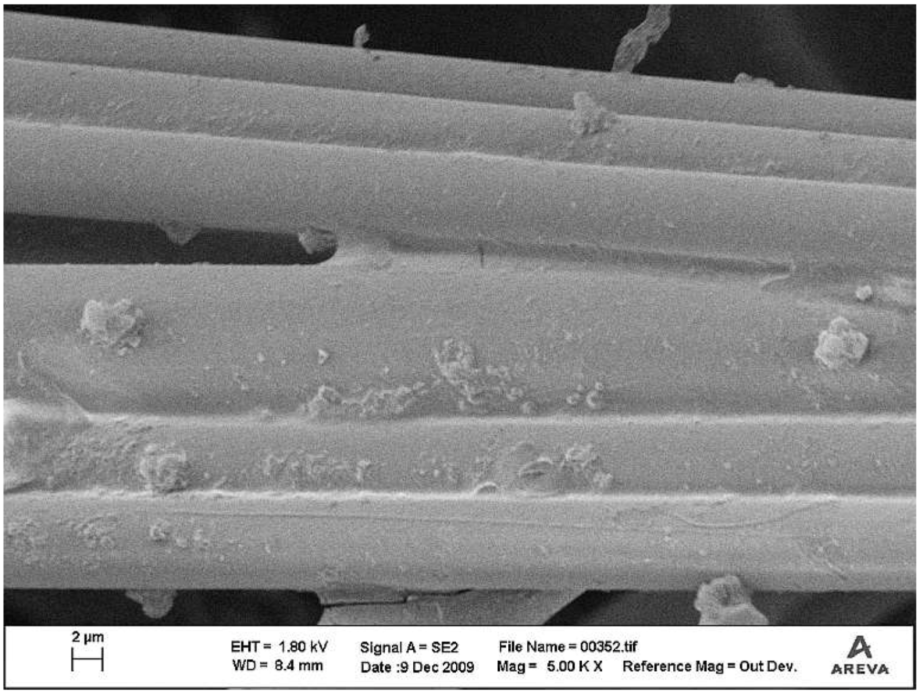


Figure D.2-20 SEM Micrograph of NUKON® Fibers Showing Bridging

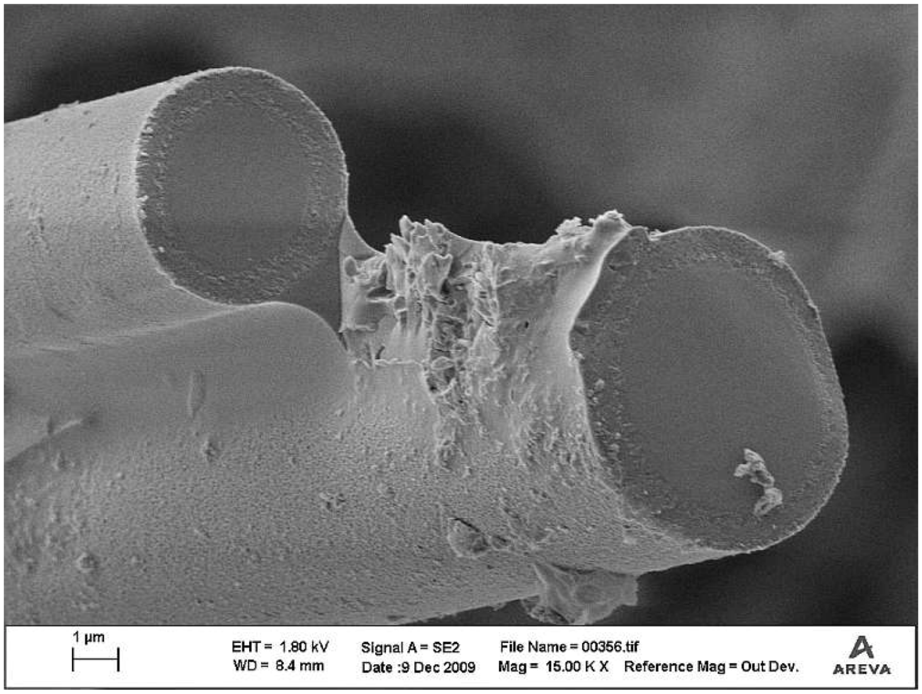
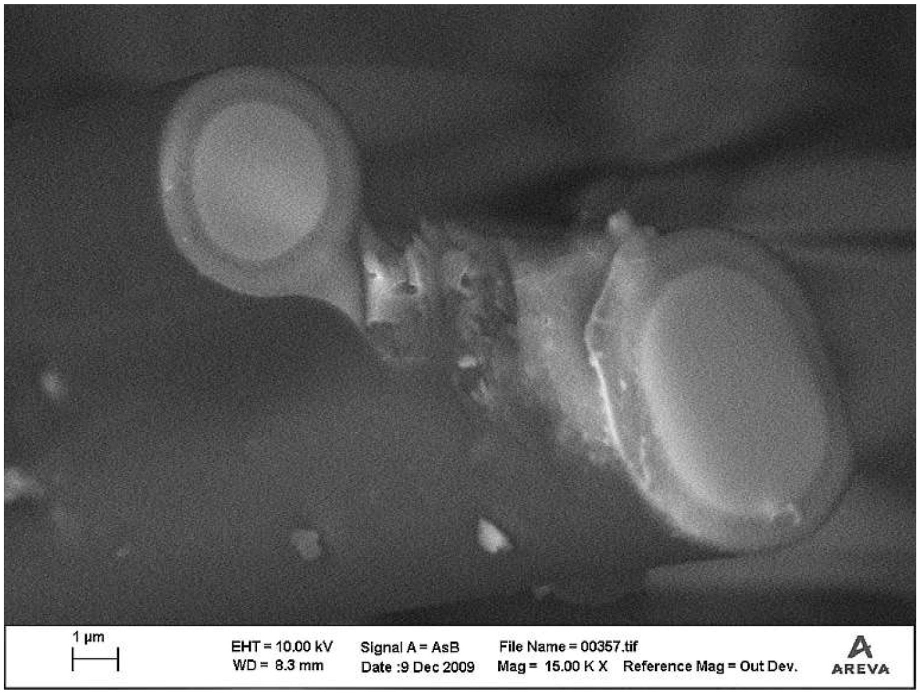


Figure D.2-21 Backscattered Electron Image of NUKON® Fibers after Testing



To characterize the apparent coating on the NUKON® fibers, EDS spectra were collected from a fiber core and coating regions. Due to the electron and x-ray interaction volume, the elemental analysis will not be confined to only these phases. However, these analyses provide a general assessment of the material composition.

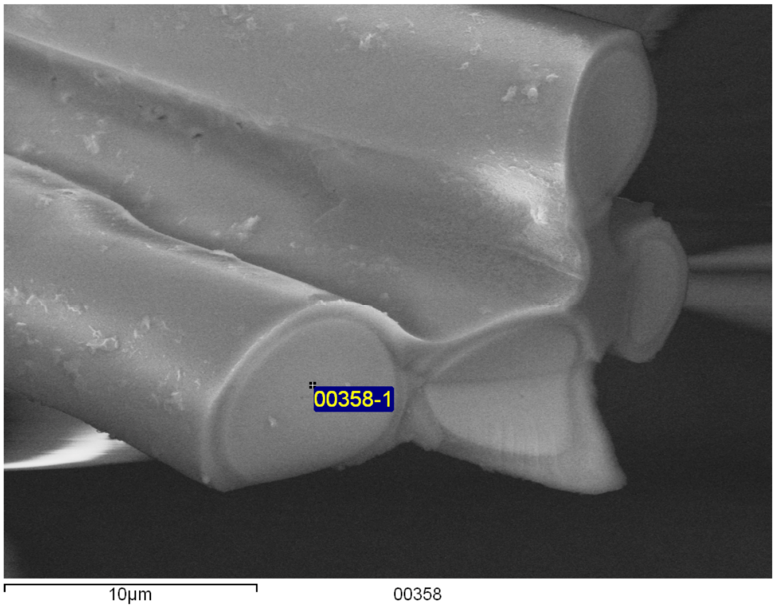
In general, the EDS spectra of the fiber core and coating indicate that the primary component of each is silicon, most likely present as silica. Other elements are also present. A high calcium peak was detected in the center of the fiber. With the exception of calcium, the coating layer tended to show higher concentration of “contaminant” elements such are aluminum, sodium, and phosphorous, indicating that the coating most likely contains or was formed from precipitated materials.

A quantitative EDS summary of the fiber and coating materials is provided in Table D.2-6. Images of the SEM micrographs and EDS spectra are provided in Figure D.2-22and Figure D.2-23.

Table D.2-6 Comparison of NUKON® Post-Test EDS Results

Component	Fiber Core	Fiber Coating
Oxygen	27.19 %	27.19 %
Sodium	0.92 %	2.75 %
Magnesium	0.55 %	---
Aluminum	1.13 %	4.73 %
Silicon	57.77 %	56.56 %
Calcium	18.45 %	3.73 %
Phosphorous	---	5.05 %

Figure D.2-22 NUKON® Fiber Post-Test − EDS Location #1



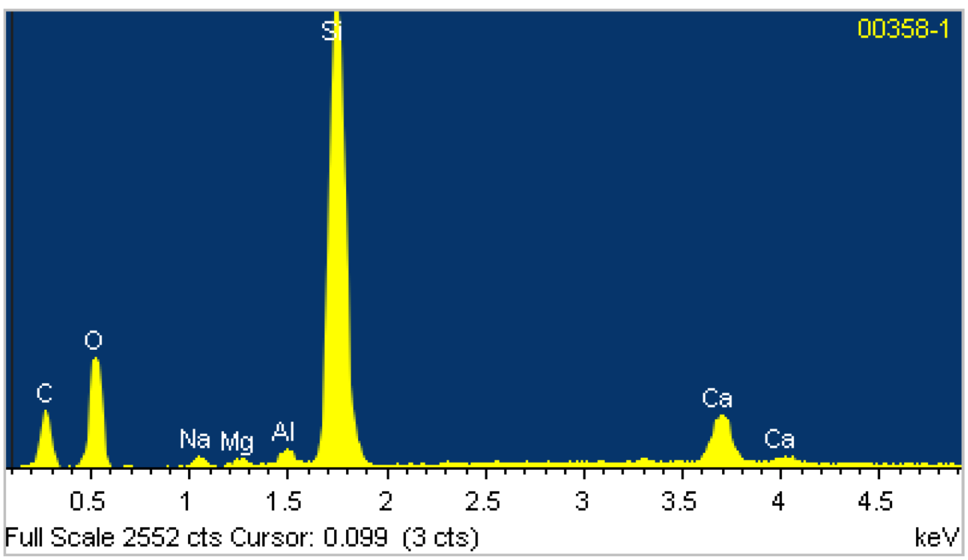


Figure D.2-23 NUKON® Fiber Post-Test – EDS Location #2