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Revision 0

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APP-GW-GSR-012

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AP1000 In-Containment Cables and Non-Metallic Insulation Debris Integrated Assessment

Westinghouse

WCAP-17938-NP
Revision 0

APP-GW-GSR-012

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LIST OF ACRONYMS, ABREVIATIONS, and TRADE MARKS

Al ....Aluminum

AP1000® ....Registered trademark of Westinghouse Electric Company LLC

CL ....Cold leg

DCD..............................Design Control Document

DVI ....Direct vessel injection

EQ ....Equipment qualification

GL ....Generic letter

GSI-191.........................Generic safety issue 191

HL ....Hot leg

Type I ....Upper neutron shield; [ ][a,c]

Type II..........................Upper neutron shield; [ ][a,c]

Type III.........................Upper neutron shield; [ ][a,c]

LV ....Low voltage

LOCA............................Loss-of-coolant accident

MV ....Medium voltage

MRI ....Metal reflective insulation

NMI ....Non-metallic insulation

NTS ....National Technical Services

NRC ....Nuclear Regulatory Commission

PWR..............................Pressurized Water Reactor

PWROG........................Pressurized Water Reactor Owners Group

Si ....Silicon

SS ....Stainless steel

STC ....Westinghouse Science and Technology Center

RCP ....Reactor coolant pump

RVIS..............................Reactor Vessel Insulation System

UNS ....Upper Neutron Shield

ZOI ....Zone of influence

ZOI_r ....Zone of influence radius

EXECUTIVE SUMMARY

The **AP1000**®[1] plant safety evaluation addressing Generic Safety Issue (GSI)-191, "Assessment of Debris Accumulation on PWR Sumps Performance" (Reference 1), and Generic Letter (GL) 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors" (Reference 2), states that zero fibrous debris will be generated during a loss of coolant accident (LOCA). This determination is documented in the licensing basis in subsection 6.3.2.2.7.1 of the design control document (DCD) which states that "a LOCA in the **AP1000** does not generate fibrous debris due to damage to insulation or other materials included in the **AP1000** design." The design of the **AP1000 plant** includes some cabling in close proximity to high energy lines such that they may be directly impinged upon by a postulated LOCA jet. Additionally, the **AP1000** design includes reactor vessel insulation system neutron shield blocks (heretofore referred to as 'neutron shield blocks') surrounding the reactor pressure vessel (RPV) that contain encapsulated fibrous material [ ]^{a,c} and encapsulated neutron shield material [ ]^{a,c} that are designed to be a suitable equivalent to metal reflective insulation (MRI). The results and the conclusions of the neutron shield block and cable test programs are applicable to **AP1000** plants as stated in Section 1.2. This report documents that the neutron shield blocks are a suitable equivalent to metal reflective insulation (MRI), the radius of the zone of influence (ZOI) for cables is 4D, and that the ZOI determination methodology is appropriate for use in GSI-191 debris source term analyses.

CABLES

To assess the potential of cable being directly impinged upon by a LOCA jet and becoming a GSI-191 debris source, Westinghouse completed a cable jet impingement test program at National Technical Systems (NTS, formerly Wyle Laboratories) in Huntsville Alabama. Cable jet impingement testing was performed since a material zone of influence radius (ZOIr) did not exist for cables or their constituent components. Establishment of a cable ZOI enabled Westinghouse to address potential debris from cables with respect to the **AP1000** plant licensing basis requirements.

The cable jet impingement test program utilized **AP1000** plant cables. Jet impingement tests were performed on both fresh and aged cables at LOCA conditions representative of the **AP1000** plant. The aged cables were subjected to conditions that bound 60 years of **AP1000** plant operation.

The test program was developed and undertaken with the following objectives:

- To assess the performance of cable materials under postulated large-break LOCA jet conditions
- To identify the onset of damage when the cable are exposed to postulated large-break LOCA jet conditions
- To establish a cable ZOI based on the onset of incipient damage

1. **AP1000** is a registered trademark of Westinghouse Electric Company LLC, its affiliates and/or its subsidiaries in the United States of America and may be registered in other countries throughout the world. All rights reserved. Unauthorized use is strictly prohibited.

In total, 10 cable tests were performed meeting all requirements for a valid test. The results of the cable tests showed that:

- The threshold for incipient damage from the blowdown jet was [ ][a,b,c] for all cable types where D is the equivalent inner diameter as defined by the debris generation break size assessment
- All cables remained undamaged from the blowdown jet at [ ][a,b,c]

The **AP1000** plant cable jet impingement test program identified the material-specific performance of the **AP1000** plant cables and identified where the onset of damage occurs when the cables are exposed to representative LOCA conditions.

The cable jet impingement tests clearly show the transition between:

- [ ][a,b,c] – Significant cable damage and small fines debris production due to jet impingement
- [ ][a,b,c] – The onset of incipient damage due to jet impingement
- [ ][a,b,c] – No cable damage and no debris production due to jet impingement

Based on the results of the cable jet impingement test program a ZOI of 4D (4 equivalent inner diameters as defined by the debris generation break size assessment) is conservatively applied to **AP1000** plant in-containment cables that may be directly impinged upon by a LOCA jet.

NEUTRON SHIELD BLOCKS

To ensure that neutron shield blocks meet the definition of a suitable equivalent insulation, Westinghouse developed a test program that included both jet impingement and submergence testing of neutron shield blocks. The results of the testing program led to changes in the design such that the current design features a [ ][a,c] neutron shield block.

Jet impingement tests were performed on neutron shield blocks to ensure suitable equivalency with the objective to assess the robustness of the neutron shield block construction by eliminating all of the surrounding intervening structures and testing the fully exposed blocks.

Each neutron shield block subjected to jet impingement testing consists of three main components;

1. [ ][a,c]
2. [ ][a,c]
3. [ ][a,c]

The jet impingement test program tested three configurations of the neutron shield block.

- [ ]a,c
- [ ]a,b,c
- [ ]a,b,c

In total, five neutron shield block tests were performed at the jet impingement test facility meeting all system requirements for valid tests. The tests were performed with the blocks placed at [ ]a,c in front of the exit nozzle. All types of neutron shield blocks tested at 4=L/D were undamaged by the jet. The results of the neutron shield blocks jet impingement tests at 3=L/D showed that:

- [ ]a,b,c
- [ ]a,b,c
- [ ]a,b,c

In all cases, there was [ ]a,b,c.

The Type III configuration [ ]a,c was shown to be a suitable equivalent to MRI with respect to debris generation. The current **AP1000** plant neutron shield design features a [ ]a,c stainless steel exterior.

In parallel with neutron shield block jet impingement testing, Westinghouse completed a neutron shield block component submergence test program to assess the chemical implications of neutron shield blocks in the flood-up zone of the **AP1000**. This program involved a 30 day test with a [ ]a,b,c (Type I) in fluid representative of the expected post-accident conditions. The submergence test program showed that the [ ]a,b,c it has been concluded that there are no physical or chemical debris implications, making the neutron shield blocks a suitable equivalent to MRI.

In conjunction with the test data obtained from the jet impingement test program, Westinghouse implemented the alternate evaluation methodology for demonstrating acceptable containment sump performance as described in NEI-04-07 and companion safety evaluation (References 4 and 5). This methodology determines a debris generation break size, which in turn is used to define a ZOI for potential debris sources.

The conclusions of the neutron shield block jet impingement and submergence test programs show that [ ]a,b,c neutron shield blocks of the current design meet the definition of 'suitable equivalent' insulation provided in the **AP1000** plant licensing basis, APP-GW-GL-700, "AP1000 Design Control Document" (Reference 3), and do not contribute to the **AP1000** plant debris source term. [ ]a,b,c neutron shield blocks may therefore be used in the **AP1000** plant as a suitable equivalent to MRI.

REFERENCES

1. GSI-191, "Assessment of Debris Accumulation on PWR Sumps Performance," Footnotes 1691 and 1692 to NUREG-0933, 1998," Nuclear Regulatory Commission, May 14, 1997.

2. NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors," September 13, 2004. (U.S. NRC ADAMS Accession No. ML042360586).

3. APP-GW-GL-700, Rev. 19, "**AP1000** Design Control Document," June 2011.

4. NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 1," Revision 0, December 6, 2004.

5. NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 2 – Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02," Revision 0, December 6, 2004.

1 INTRODUCTION

The **AP1000** plant safety evaluation addressing Generic Safety Issue (GSI)-191 (Reference 1-1) and Generic Letter (GL) 2004-02 (Reference 1-2) accounts for zero LOCA generated debris from insulation or cables. This is documented in the licensing basis in subsection 6.3.2.2.7.1 of the **AP1000** design control document (DCD), "AP1000 Design Control Document" Reference 1-3, which states that "a LOCA in the **AP1000** does not generate fibrous debris due to damage to insulation or other materials included in the **AP1000** design." This is based on the use of MRI or a suitable equivalent and the elimination of fibrous insulation and other sources of fiber.

The **AP1000** plant design includes encapsulated non-metallic insulation and materials in the reactor cavity that are designed to be a suitable equivalent[1] to MRI. The encapsulated non-metallic insulation and materials are contained within the reactor vessel insulation system (RVIS) neutron shield blocks and water inlet doors and the refueling cavity floor module (CA31) neutron shield blocks. Additionally, the **AP1000** plant design includes cabling that may be directly impinged upon by a LOCA jet that may contain fibrous and other materials (jackets, wrappings, and filler materials).

To address the potential for LOCA generated debris from non-metallic materials in the reactor cavity and cables that may be directly impinged upon by a LOCA jet, Westinghouse embarked on a jet impingement test program at NTS to qualify the encapsulated non-metallic insulation and materials in the reactor cavity as a 'suitable equivalent' to MRI and to define a ZOI for cables.

1.1 PURPOSE

Westinghouse developed an extent of condition program to evaluate any potential impacts to the current licensing basis from the exposure of cables to direct jet impingement by a LOCA jet and to qualify the encapsulated non-metallic insulation and materials in the reactor cavity as suitable equivalent to MRI. The purpose of the program was to confirm that the encapsulated non-metallic insulation and materials meet the requirements of a suitable equivalent and may be used in place of MRI and to define a cable ZOI. The program included jet impingement testing of both neutron shield blocks and cable and submergence testing of neutron shield blocks.

1. A suitable equivalent insulation is one that is encapsulated in stainless steel that is [ ][a,b,c] so that LOCA jet impingement does not damage the insulation and generate debris. Another suitable insulation is one that may be damaged by LOCA jet impingement as long as the resulting insulation debris is not transported to the containment recirculation screens, to the In-containment Refueling Water Storage Tank (IRWST) screens, or into a direct vessel injection or a cold leg LOCA break that becomes submerged during recirculation. In order to qualify as a suitable equivalent insulation, testing must be performed that subjects the insulation to conditions that bound the AP1000 conditions and demonstrates that debris would not be generated. If debris is generated, testing and/or analysis must be performed to demonstrate that the debris is not transported to an AP1000 screen or into the core through a flooded break. It would also have to be shown that the material used would not generate chemical debris.

The purpose of this topical report is to obtain NRC approval for the following items:

- A threshold for incipient damage from the blowdown jet of [ ]^{a,b,c} for AP1000 plant in-containment cabling.
- A ZOI of 4D applicable for **AP1000** plant in-containment cabling.
- Suitable equivalency to MRI for [ ]^{a,b,c} RVIS upper and lower neutron shielding, the RVIS water inlet doors, and the CA31 module neutron shield blocks.
- The use of the NEI-04-07 (Reference 1-4 and Reference 1-5) Alternative Methodology for defining debris generation for postulated accidents in the **AP1000** plant.

The information within this document provides the background and justification that supports this request.

1.2 LIMITS OF APPLICABILITY

The results and the conclusions of the neutron shield block and cable test programs presented in this document are applicable to all **AP1000** plants with cable and non-metallic insulation designs as described in Section 2 of this report.

The conclusions of this topical report are not intended to be used for any nuclear plant designs other than **AP1000**.

1.3 REFERENCES

1-1. GSI-191, "Assessment of Debris Accumulation on PWR Sumps Performance," Footnotes 1691 and 1692 to NUREG-0933, 1998," Nuclear Regulatory Commission, May 14, 1997.

1-2. NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors," September 13, 2004. (U.S. NRC ADAMS Accession No. ML042360586).

1-3. APP-GW-GL-700, Rev. 19, "AP1000 Design Control Document," June 2011.

1-4. NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 1," Revision 0, December 6, 2004.

1-5. NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 2 – Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02," Revision 0, December 6, 2004.

2 POTENTIAL SOURCES OF ADDITIONAL DEBRIS

2.1 CABLES

The **AP1000** plant safety evaluation addressing GSI-191 (Reference 2-1) and GL 2004-02 (Reference 2-2) accounts for zero LOCA generated fibrous debris. The **AP1000** plant design includes cabling that may be directly impinged upon by a LOCA jet. These cables may contain fibrous and other materials (jackets, wrappings, and filler materials) that were not considered in the initial GSI-191 debris source term evaluation.

Jet impingement testing and component characterization was performed on **AP1000** plant cables that may be directly impinged upon by a LOCA jet. Submergence testing of cables was not necessary since submerged cables have been a part of the **AP1000** plant design since its inception and have been dispositioned as having a negligible chemical effects as discussed in the "Letter to the Honorable Gregory B Jaczko, Chairman, NRC, from Said Abdel-Khalik, Chairman, ACRS, dated December 20, 2010, "Long-Term Core Cooling For The Westinghouse AP1000 Pressurized Water Reactor" (Reference 2-3).

Additionally, the NRC performed a Phenomena Identification and Ranking Table (PIRT) on post-LOCA chemical effects ("Phenomena Identification and Ranking Table Evaluation of Chemical Effects Associated with Generic Safety Issue 191," NUREG-1918, February 2009, Reference 2-4) which concluded that the consequences of chemical effects based on cable debris are small when compared with other sources of chemical effects. The main concern with submerged cables is the formation of chloride ions due to radiolytic breakdown of the cable insulation. For many plants this may be more or less important based on the amount of polyvinylchloride (PVC) cable jacket and insulation used since the chloride in PVC is the dominant source of the chloride ions via radiolysis. The chloride ions bond with hydrogen creating acids. In sufficient quantities acids may affect corrosion of certain materials and can have an effect on the sump pH value. The impact of chlorides was simulated in the integrated chemical effects program (Reference 2-5). Cable jacket and insulation used in the **AP1000** plant is constructed of cross linked polyolefin and cross linked polyethylene respectively and does not have a major chloride component. Additionally, APP-G1-E1-002 (Reference 2-6) specifically states that [ ][a,b,c] "Final Report – Evaluation of Chemical Effects Phenomena in Post-LOCA Coolant," NUREG/CR-6988 March 2009 concludes (see Section 3.3, Reference 2-7) that even at maximum anticipated concentrations, chloride containing compounds (chlorate [ClO3], hypochlorite [ClO], and hypochlorous acid [HOCl]) sourced from electric cable insulation would have a "negligible impact on the pH in the RCS." Based on these conclusions, no further work is required to address chemical effects from submerged cables for AP1000.

2.1.1 Description of the Cables

Westinghouse obtained five types of **AP1000** plant cables (Table 2-1, Figure 2-1) for the cable jet impingement test program including low voltage (LV) jacketed insulated single conductor cables, LV jacketed multi-conductor cables, and medium voltage (MV) jacketed power cables. The cables utilized in the test met all wire and cable design criteria (Reference 2-6) and all cable design specifications (Reference 2-8, Reference 2-9, Reference 2-10). The configuration of the tested cable may be different from production cables, e.g., the number of conductors within the cable or the size of the conductor may be different, but the materials used in construction are identical. The **AP1000** plant cable specification includes cables that are comprised of [ ][a,c]. Cables used in the AP1000 plant jet impingement test program were procured from cables produced for in-containment equipment (EQ) testing. These cables met all cable material design criteria and specifications for cables that will be utilized in the AP1000 plant containment.

Table 2-1. Cable Jet Impingement and Characterization Test Program Samples (Figure 2-1)

a,c

Descriptor	Type (designation)	Configuration
Large – single conductor	MV Power (RCP)	
Large – three conductor	Multi-conductor LV Power (PZR)	
Small – seven conductor	Control (7C)	
Small – single conductor (seven strand)	Single conductor (1C)	
Small – two conductor	Instrumentation (2C)	

a,c

Figure 2-1. Cables used in the Cable Jet Impingement Test Program

2.2 REACTOR VESSEL CAVITY NON-METALLIC MATERIALS

The **AP1000** plant safety evaluation addressing GSI-191 (Reference 2-1) and GL 2004-02 (Reference 2-2) accounts for zero LOCA generated debris from insulation. This is based on the use of MRI or a suitable equivalent.

In the **AP1000** plant reactor vessel insulation system (RVIS) and the CA31 reactor cavity floor structural module non-metallic materials are utilized. The CA31 module and the RVIS have neutron shields. The neutron shielding is located in three locations in the reactor cavity. The CA31 neutron shielding is located at plant elevation 105′-2″ within the structural module that makes up the nozzle gallery ceiling. The RVIS has two locations of neutron shielding. The first location is in the nozzle gallery at plant elevation 98′-0″ and the second location of neutron shielding is in the lower reactor cavity at plant elevation 78′-0″ elevation. The neutron shields are [ ][a,c].

In addition to neutron shielding, the RVIS has buoyant water inlet doors that are designed to allow water free access to the region between the reactor vessel and insulation to promote in-vessel retention following severe accidents. These doors are made of [

]^{a,c}.

a,c

Figure 2-2. Reactor Cavity Non-Metallic Materials

All non-metallic materials in the reactor cavity are located below the LOCA flood-up level of 110′-2″ and have the potential to be fully submerged. The RVIS neutron shielding located in the nozzle gallery, referred to as the upper neutron shield (UNS) and the CA31 neutron shielding are in close proximity to the reactor coolant loop and direct vessel injection (DVI) piping. Potential debris from the reactor cavity non-metallic materials was not considered in the licensing basis since only suitable equivalent insulation to MRI is allowed in the **AP1000** plant containment.

Jet impingement testing and submergence testing were performed to qualify the neutron shielding and water inlet doors as a suitable equivalent to MRI. A suitable equivalent insulation is one that is [ ]^{a,c} so that LOCA jet impingement does not damage the insulation such that particulate, fibrous, or chemical debris is released.

2.2.1 Description of the RVIS Water Inlet Doors

The RVIS water inlet doors are located in the lower reactor cavity at the 71′-6″ plant elevation (Reference 2-11). These buoyant doors will float in the event the reactor cavity floods and allow water into the annulus between the reactor vessel and the reactor vessel insulation for in-vessel retention following a serious accident. The doors are made of [

]a,c.

2.2.2 Description of the RVIS Upper Neutron Shielding

The RVIS UNS is located in the nozzle gallery (98′-0″ elevation). The UNS consists of [

]a,c

The UNS is created by fabricating a [

]a,c

The individual shielding blocks are positioned [

]a,c

a,c

Figure 2-3. Individual Shield Blocks as Installed [(Prior to Seam Weld Design Change)][a,c]

a,c

Figure 2-4. UNS Block Support Structure

a,c

Figure 2-5. [ ][a,c] Cover Plate on Top of Shield Blocks

2.2.3 Description of the RVIS Lower Neutron Shielding

The second location of RVIS neutron shielding is in the lower reactor cavity (78'-0" elevation). This neutron shield, referred to as the lower neutron shielding (LNS), is made of [

][a,c]

The LNS is constructed in the same manner as the UNS with some notable differences due to [

][a,c]

2.2.4 Description of the CA31 Neutron Shielding

The CA31 neutron shielding is located at the 105'-2" plant elevation right below the reactor vessel closure flange (Reference 2-14). [

][a,c]

The CA31 neutron shielding boxes are made of [

]a,c

2.3 REFERENCES

2-1. GSI-191, "Assessment of Debris Accumulation on PWR Sumps Performance," Footnotes 1691 and 1692 to NUREG-0933, 1998," Nuclear Regulatory Commission, May 14, 1997.

2-2. NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors," September 13, 2004. (U.S. NRC ADAMS Accession No. ML042360586).

2-3. Letter to the Honorable Gregory B Jaczko, Chairman, NRC, from Said Abdel-Khalik, Chairman, ACRS, dated December 20, 2010, "Long-Term Core Cooling For The Westinghouse AP1000 Pressurized Water Reactor," (U.S. NRC ADAMS Accession No ML103140348).

2-4. NUREG-1918, "Phenomena Identification and Ranking Table Evaluation of Chemical Effects Associated with Generic Safety Issue 191," February 2009.

2-5. NUREG/CR-6914, "Integrated Chemical Effects Test Project: Consolidated Data Report," December 2006.

2-6. APP-G1-E1-002, "Wire and Cable Design Criteria."

2-7. NUREG/CR-6988, "Final Report - Evaluation of Chemical Effects Phenomena in Post-LOCA Coolant," March 2009.

2-8. APP-EW40-Z0-001, "Design Specification for Medium Voltage Power Cables for Various Systems."

2-9. APP-EW50-Z0-001, "Class 1E Low Voltage 600V Power Cables."

2-10. APP-EW21-Z0-002, "Class 1E Instrumentation and Thermocouple Extension Cables."

2-11. APP-MN20-V2-101, "RV Bottom Head Insulation Layout RBH1."

2-12. APP-MN20-V2-150, "RV Upper Neutron Shielding."

2-13. APP-MN20-V2-148, "RV Lower Neutron Shielding."

2-14. APP-CA31-S5-001, "Containment Building Areas 1, 2, 3 & 4 Module CA31 EL 107′-2″ Isometric View."

2-15. APP-CA31-GEF-005, "CA31 Neutron Block Details."

2-16. APP-CA31-S5-104, "Containment Building Areas 1, 2, 3, & 4 Module CA31 EL 107′-2″ Neutron Block Plate Details I."

2-17. APP-CA31-S5-301, "Containment Building Areas 1, 2, 3, & 4 Module CA31 EL 107′-2″ Neutron Block Sections & Details I."

2-18. APP-CA31-S5-302, "Containment Building Areas 1, 2, 3, & 4 Module CA31 EL 107′-2″ Neutron Block Sections & Details II."

3 GSI-191 TEST PROGRAM SUMMARY

A series of tests was conducted in order to better understand the effects of jet impingement and submergence on materials that are currently in question for debris production in the **AP1000** plant. These tests included

- Cable Jet Impingement Testing
- Reactor Vessel (RV) Insulation Jet Impingement Testing
- RV Insulation Submergence Testing

3.1 JET IMPINGEMENT TEST BACKGROUND

The jet impingement test program was initiated with two goals: establish the reactor cavity non-metallic materials as a suitable equivalent to MRI, from a debris production standpoint, and to establish a defensible cable ZOI based on the onset of incipient damage.

In order to show that an insulation type qualifies as a suitable equivalent to MRI, the **AP1000** plant DCD (Reference 3-1) states that a suitable equivalent insulation "is one that is [ ][a,c] so that LOCA jet impingement does not damage the insulation and generate debris. Another suitable insulation is one that may be damaged by LOCA jet impingement as long as the resulting insulation debris is not transported to the containment recirculation screens, to the IRWST screens, or into a direct vessel injection or a cold leg LOCA break that becomes submerged during recirculation," and that "testing must be performed that subjects the insulation to conditions that bound the **AP1000** plant conditions and demonstrates that debris would not be generated." The only form of testing that could subject the reactor cavity non-metallic materials to conditions that bound the **AP1000** plant is jet impingement testing performed at bounding conditions. The jet impingement testing focused on RVIS upper neutron shield blocks. The steel used in the RVIS UNS test samples [ ][a,c] is thinner than the steel used in the CA31 and the RVIS LNS and water inlet doors are located much farther from a potential pipe break than the UNS. The UNS construction and relative placement to potential breaks in the reactor vessel nozzle gallery made them the bounding insulation to test.

The method for resolving GSI-191 debris generation involves identifying specific materials, defining ZOIs for those materials and determining how much debris may be generated by those materials. A review of the current GSI-191 documentation discovered no data on the ZOI associated with cabling. Many of the ZOIs that are used by the nuclear industry to resolve GSI-191 were referenced from Boiling Water Reactor Owners Group (BWROG) testing, NEDO-32686-A, Volumes 1 through 4, "Utility Resolution Guidance for ECCS Suction Strainer Blockage" (Reference 3-2) performed using "air jets" at a pressure of about 1100 psia and testing funded by the NRC performed by Ontario Power, N-REP-34320-10000, Revision 0, "Jet Impact Tests – Preliminary Results and Their Application" (Reference 3-3), using saturated water jets at a pressure of about 1500 psia. Both test programs used jets with lower initial pressures and different fluid conditions than are representative of Pressurized Water Reactors (PWRs), which operate with subcooled water at a nominal pressure of 2250 psia. Both the BWROG and Ontario Power tests were cited in Reference 3-4, NEI-04-07 "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 1 and were used by the NRC as a basis for assigning a 'penalty' to the destruction pressure of materials in NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 2" (Reference 3-5) that resulted in increasing the

ZOI for all materials listed in Reference 3-5. The penalty was reported as being based, in large part, on the lack of applicable test data for those materials at PWR conditions.

To address the uncertainties in formulating ZOIs for specific materials based on non-prototypical conditions, a group of licensees within the Pressurized Water Reactors Owners Group (PWROG) chose to pursue jet impingement testing to establish technically defensible ZOI values for materials of interest and designs for their plants. The program had the following objectives:

- Perform jet impingement testing using subcooled water at PWR nominal pressure and temperature
- Perform jet impingement testing to determine the ZOI for the materials and designs of interest to the participating licensees

The PWROG tried twice to perform jet impingement testing at typical PWR conditions to decrease the ZOI of in-containment materials only to have both programs rejected because of a facility design flaw that placed the choke point of the system upstream of the exit nozzle instead of at the exit nozzle. With the choke point upstream of the exit nozzle, the program was called into question as to whether the jet was fully formed when it hit the target.

To address the upstream choke issue the PWROG redesigned the blowdown facility and met the following objectives in its most recent jet impingement test program:

- Designed a new discharge nozzle to ensure that the choke point was at the nozzle exit and that the resulting jet would be a fully formed jet
- Confirmed by inspection that the limiting flow area of the system was the discharge nozzle
- Performed instrumented tests to collect data to support the development of a subcooled jet expansion model to demonstrate the test jet was a fully expanded jet
- Performed jet impingement testing using subcooled water at near PWR nominal pressure and temperature
- Performed jet impingement testing to determine the ZOI for the materials and designs of interest to the participating licensees

The results of the PWROG jet impingement testing reported in FAI/110497, "PWROG Model for the Two Dimensional Free Expansion of a Flashing, Two Phase, Critical Flow Jet" (Reference 3-6) showed that the National Technical Systems (NTS, formerly Wyle Laboratories) facility was capable of producing a subcooled jet that was representative of the range of temperatures and pressures associated with a PWR large-break LOCA.

For the neutron shield block and cable jet impingement test program, the test loop was walked down and inspected to confirm that the limiting flow area was in fact the discharge nozzle assuring that the resulting jet would be a fully formed representative LOCA jet. The data collected by the PWROG and documented in Reference 3-6 will be shown to be applicable to the neutron shield block and cable jet impingement program.

The approach to qualifying neutron shield blocks as a suitable equivalent considers acceptance criteria that allows for some damage to the target material as specified in Reference 3-1:

- A suitable equivalent insulation is one that is [ ]^{a,c} so that LOCA jet impingement does not damage the insulation and generate debris or if debris is generated, the resulting debris is not transported to the containment recirculation screens, to the IRWST screens, or into a direct vessel injection or a cold leg LOCA break that becomes submerged during recirculation. It would also have to be shown that the material used would not generate chemical debris.

The approach to ZOI development for cable considers acceptance criteria that allows for and accounts for some damage to the cable material as seen in damage curves in Appendix II, "Confirmatory Debris Generation Analyses" provided in Reference 3-5. Using this approach requires both:

- Determining incipient damage (the amount of damage that resulted in the generation of a negligible amount of debris)

- An approach to measure the amount of debris generated or to clearly define damage/no damage ZOI

For both the neutron shield block and cable jet impingement test program, a simple process was developed to ascertain [ ]^{a,c}

3.2 JET IMPINGEMENT TEST FACILITY

The High Flow Test Facility at NTS shown schematically in Figure 3-1 and as built in Figure 3-2 is based on the High Flow facility setup developed by the PWROG (Reference 3-6).

The facility used for jet impingement testing is capable of simulating the conditions of a high-energy line break within the **AP1000** plant containment. The thermal hydraulic conditions (pressure, temperature, and flow) were selected so that conditions associated with a postulated break in the primary piping were accurately simulated, and the data from the experiment will be directly applicable to and bounding of the **AP1000** plant. The high energy line break condition will be representative of a [ ]^{a,c}

3.2.1 Comparison of PWROG Facility with AP1000 Facility

Figure 3-3 shows the PWROG as-built blowdown test facility. As seen when comparing Figure 3-2 to Figure 3-3, the major difference between the two facilities is [

][a,b,c]

[

][a,b,c]

As seen in Table 3-1 the major components of the two facilities are identical and a review of the components ensures that the choke point of the facility is at the nozzle exit. The notable differences between the two facilities are that [

][a,b,c]

The facility instrumentation used in the PWROG program and the **AP1000** program was recorded in the same locations with one exception: in the PWROG program, temperature and pressure were recorded in the [

][a,b,c]

Table 3-1. Blowdown Facility Components

a,b,c

Table 3-1. Blowdown Facility Components (cont.)

a,b,c

a,b,c

Figure 3-1. Schematic of NTS High Flow Blowdown Facility

a,b,c

Figure 3-2. As Built AP1000 High Flow Test Facility Configuration for Jet Impingement Testing

a,b,c

Figure 3-3. PWROG As-Built Facility

a,b,c

Figure 3-4. AP1000 High Flow Test Facility Configuration for Jet Impingement Testing

3.3 COMPARISON OF PWROG FACILITY DATA WITH AP1000 FACILITY DATA

Subsection 3.2.1 showed that the **AP1000** blowdown test facility was constructed from the same components as the PWROG blowdown test facility. The following comparisons ensure that the **AP1000** blowdown test facility reproduced the same conditions and output as the PWROG blowdown test facility.

The PWROG ran nine instrument tests at distances of [ ]a,b,c with two of the tests repeated due to facility anomalies for a total of seven valid instrumented tests (Reference 3-6).

Figure 3-5 through Figure 3-9 show the data recorded during the PWROG test program. As noted in subsection 3.2.1, the instrumentation was identical for both facilities except for the different instrument location noted in subsection 3.2.1 for the [ ] a,b,c. The PWROG tests are identified by run number in the figure legend. Note that the tests are manually terminated at

]a,b,c.

a,b,c

[ ]

Figure 3-5. PWROG Jet Impingement Test Program A3 Tank Pressure

a,b,c

Figure 3-6. PWROG Jet Impingement Test Program Reducer Pressure

a,b,c

Figure 3-7. PWROG Jet Impingement Test Program Mass Flow Rate

a,b,c

Figure 3-8. PWROG Jet Impingement Test Program Exit Nozzle Pressure

a,b,c

Figure 3-9. PWROG Jet Impingement Test Program Reducer Temperature

Figure 3-10 through Figure 3-14 show a comparison of the data recorded during the PWROG test program and the 2014 **AP1000** cable jet impingement test program runs. The 2014 **AP1000** cable tests are described in the legends by cable test (CT) number and facility test (FT) number (CT#FT#). Note that due to the large number of data points per second of test (approximately 350 data points) only the cable jet impingement test results are shown. A comparison of the neutron shield block impingement test results with the PWROG jet impingement test program can be found in WCAP-17616, "Jet Impingement Testing of **AP1000** Reactor Vessel Insulation System Neutron Shielding Blocks," November 2014, Reference 3-9.

a,b,c

Figure 3-10. PWROG/AP1000 Jet Impingement Test Program A3 Tank Pressure

Figure 3-11 and Figure 3-14 highlight the facility difference in the pressure and temperature measurement location. As noted in subsection 3.2.1, the AP1000 measured pressure and temperature at [

]a,b,c ensuring applicability of the PWROG test data to the current test program.

a,b,c

Figure 3-11. PWROG/AP1000 Jet Impingement Test Program Reducer Pressure

a,b,c

Figure 3-12. PWROG/AP1000 Jet Impingement Test Program Mass Flow Rate

a,b,c

Figure 3-13. PWROG/AP1000 Jet Impingement Test Program Exit Nozzle Pressure

a,b,c

Figure 3-14. PWROG/AP1000 Jet Impingement Test Program Reducer Temperature

The comparison of test data from the PWROG instrumented test runs and the **AP1000** plant cable tests shows good agreement in all aspects and confirms that the facility is repeatable and that the data recorded in the PWROG instrumented jet impingement test program is directly applicable to the **AP1000** plant jet impingement test program.

The following figures (Figure 3-15 through Figure 3-18) show stagnation pressures recorded at the target locations in the PWROG instrumented tests performed at [ ]a,b,c

a,b,c

Figure 3-15. Stagnation Pressure at [ ]a,b,c

a,b,c

Figure 3-16. Stagnation Pressure at [ ]a,b,c

a,b,c

Figure 3-17. Stagnation Pressure at [ ]a,b,c

a,b,c

Figure 3-18. Center line Stagnation Pressure at the Target

Based on the data comparisons between the PWROG jet impingement test program and the **AP1000** plant jet impingement test program, the stagnation pressures recorded at the target locations in the PWROG jet impingement test program shown in Figure 3-16 through Figure 3-18 were achieved at the corresponding target locations in the **AP1000** plant cable jet impingement test program.

3.4 COMPARISON OF AP1000 LICENSING BASIS WITH AP1000 FACILITY DATA

Section 3.2 showed that the **AP1000** plant blowdown test facility, constructed from the same components as the PWROG blowdown test facility, produced data that is in excellent agreement with the PWROG blowdown test facility and that data recorded during the PWROG test program is directly applicable to the **AP1000** test program.

Table 3-2 shows the nominal conditions for the **AP1000** plant and the two jet impingement test programs. Due to facility constraints, the initial steady state pressure and subcooling are higher in the **AP1000** plant.

Table 3-2. Nominal Conditions a,b,c

Reference 3-6 verified that the [

]a,b,c. To demonstrate that the experimental jet is conservative compared with a large-break LOCA in the full-scale **AP1000** plant reactor system, Figure 3-19 through Figure 3-21 show a comparison of the licensing basis **AP1000** plant large-break LOCA as documented in LTR-LIS-14-339, "AP1000 Plant LBLOCA DECLG Data for GSI-191 Jet Impingement Testing Support" (Reference 3-8), and the data recorded for the **AP1000** plant cable jet impingement test program. All three plots show that [

]a,b,c

Thus, in all respects, the high-pressure subcooled jet generated at the experimental facility is representative, compared with two-phase critical flow literature, and conservative, compared with a full-scale large-break LOCA in the **AP1000** plant.

a,b,c

Figure 3-19 Comparison of AP1000 Licensing Basis and the AP1000 Cable Jet Impingement Test Program – Stagnation Pressure

a,b,c

Figure 3-20 Comparison of AP1000 Licensing Basis and the AP1000 Cable Jet Impingement Test Program – Mass Flux

a,b,c

Figure 3-21 Comparison of AP1000 Licensing Basis and the AP1000 Cable Jet Impingement Test Program – Reservoir Pressure

The comparison of the **AP1000** plant licensing basis large break LOCA and the **AP1000** plant cable jet impingement test program shows that the **AP1000** plant cable jet impingement tests are conservative for the **AP1000** plant.

3.4.1 Jet Impingement Test Objectives

The objective of the **AP1000** plant neutron shield block jet impingement test program was to perform jet impingement tests on **AP1000** plant neutron shield blocks to determine the performance characteristics of the neutron shield block encapsulation and characterize damage when exposed to representative LOCA jet load conditions.

The objective of the **AP1000** plant cable jet impingement test program was to perform jet impingement tests on **AP1000** plant cables to determine the performance characteristics of the cables and to define the onset of damage when the cables are exposed to representative LOCA jet load conditions.

Data and observations collected from the tests and test specimens were used as follows:

- Determine suitable equivalency for neutron shield blocks
- Determine an appropriate, technically defensible, realistic ZOI for cables

The **AP1000** plant neutron shield block and cable jet impingement test program included a facility design that accurately and realistically reproduced the phenomena and processes associated with a postulated LOCA blowdown. Once the NTS facility was shown to meet the requirements of the **AP1000** jet impingement test program by reproducing the results from the PWROG instrumented jet impingement test program **AP1000** plant neutron shield blocks and cables were exposed to the phenomena and processes of a two-phase jet originating from a subcooled, high pressure, high temperature reservoir (WCAP-17617-P, "Jet Impingement Testing of AP1000 In-containment Cables" [Reference 3-7] and WCAP-17616-P, "Jet Impingement Testing of AP1000 Reactor Vessel Insulation System Neutron Shielding Blocks" [Reference 3-9]). The conditions of interest to which the targets were exposed included elevated temperature and pressure, and high mass flux.

3.4.2 Jet Impingement Test Specimens

3.4.2.1 Cable Specimens

Westinghouse tested five types of cable (Table 2-1, Figure 2-1) including low voltage (LV) jacketed insulated single conductor cables and LV jacketed multi-conductor cables (defined as 'small cables,' Figure 3-22), and medium voltage (MV) jacketed power cables (defined as 'large cables,' Figure 3-23) that were manufactured for the **AP1000** plant environmental qualification (EQ) test program.

To ensure that the life of the plant was represented in the cable jet impingement test program, each cable type was tested both with and without aging to bound cable conditions over 60 years of operation. The cable aging specification (Reference 3-10) included [

.]^{a,c}

[ ]^{a,c} Each cable test was performed with both fresh and aged (thermally and radiologically) cable specimens in each run.

The placement of cables in the AP1000 plant design is governed by specifications and standards as to the types of cable trays, cable tray supports, cable tray installation, cable clamps and ties, and associated fittings and conduits that can be used in the AP1000 containment.

The cable arrangement used in the cable JIT was primarily defined to place cables in the known jet field established in the PWROG instrumented test program (Reference 3-8) for the purpose of defining the cable material destruction pressure at the point of incipient damage to establish the cable ZOI (Reference 3-11).

There was no preheating of the cables prior to jet impingement. The cables as installed in the plant operate at a nominal temperature of [

]^{a,c}

a,b,c

Figure 3-22. Small Cables

a,b,c

Figure 3-23. Large Cables

3.4.2.2 Neutron Shield Block Specimens

There were three configurations of the neutron shield block test specimens included in the neutron shield block jet impingement test program:

- Type I test specimens represented the standard design of the neutron shield blocks at the time of testing. [ ]a,c (Figure 3-25)
- Type II test specimens represent a modification of the Type 1 test specimen [ ]a,c (Figure 3-26)
- Type III test specimens represent a modification of the Type 1 test specimen by [ ]a,c (Figure 3-27)

Each neutron shield block design consists of three main components (Figure 3-24);

1. [ ]a,c
2. [ ]a,c
3. [ ]a,c

a,b,c

Figure 3-24. Typical Neutron Shield Block Construction

a,b,c

Figure 3-25. Neutron Shield Block (Type I)

a,b,c

Figure 3-26. [ ][a,c] Neutron Shield Block (Type II)

a,b,c

Figure 3-27. Current Design [ ][a,c] Design Neutron Shield Block (Type III)

3.4.3 Cable Jet Impingement Test summary

The purpose of the cable jet impingement test program is to define a ZOI for **AP1000** plant in-containment cables.

3.4.3.1 Cable Jet Impingement Test Matrix

The cable tests are run in two sequences; Large and Small as shown in the test matrix, Table 3-3.

Table 3-3. Cable Jet Impingement Test Matrix

a,b,c

3.4.3.2 Cable Jet Impingement Test Acceptance Criteria

The goal of cable jet impingement testing is to define a ZOI outside of which cables exposed to a LOCA jet do not contribute to the **AP1000** plant debris source term.

The acceptance criteria for cable jet impingement testing include:

- All facility requirements are met resulting in a successful blowdown of the facility that bounds the licensing basis **AP1000** plant large break LOCA

Following a successful test all cables are evaluated for:

- Any damage caused by the blowdown jet that will be used in the determination of the cable ZOI
- Any damage caused by interaction with the test fixture that will not be considered in the assessment of damage for determining the cable ZOI.

Prior to jet impingement testing, all cable specimens [

]a,b,c

- [

]a,b,c

- [

]a,b,c

3.4.3.3 Cable Arrangement in Test Fixture

Prior to testing, the cables were assigned positions in the fixture for ease of identification. The arrangement is shown in Table 3-4.

Table 3-4. Cable Arrangement in Test Fixture

a,b,c

3.4.3.4 Cable Jet Impingement Test Results

The cable jet impingement test results are presented in Table 3-5.

Table 3-5. Cable Jet Impingement Test Results

a,b,c

The ZOI as defined in the NEI 04-07 safety evaluation (SE) in Reference 3-5 is based on the production of small fines at the initiation of incipient damage, meaning that a loss of material indicates the point of failure and the initiation of debris generation. The material ZOI is based on incipient damage and is readily seen in Appendix II of the SE (Reference 3-5) for the various materials included in the Section.

Appendix II of the SE examines various materials from different fibrous materials to steel encapsulated RMI. Take for example K-Wool in Figure II-6 of Reference 3-5, there is ~4 percent fines production at a jet pressure of 24 psi which relates to a 5.4D ZOI in Table 3-2 of Reference 3-5. Similarly, calcium silicate produced as much as 22 percent small fines at its assigned jet pressure and ZOI (Figure II-12 of Reference 3-5).

These examples and review of the other materials presented in Appendix II of Reference 3-5 indicate that the onset of incipient damage (production of a measurable quantity of small fines) is the point at which the material specific ZOI is defined.

The **AP1000** plant cables were tested at [ ]^{a,b,c} in the cable jet impingement program. From the results compiled in Reference 3-7 and shown in Table 3-6 and Table 3-7 it is easy to infer where incipient damage occurs. At [

]^{a,b,c}

Table 3-6. Large Cable Damage Summary (percent loss of material)

a,b,c

Table 3-7. Small Cable Damage Summary (percent loss of material) a,b,c

For the large cable tests with cables in front of the jet (Table 3-6), damage to the cables at [

]a,b,c

For the small cable tests (Table 3-7), damage to the cables at [

]a,b,c

[

]a,b,c

The results of the cable jet impingement test program clearly show that [

]a,b,c

a,b,c

Figure 3-28. Large Cable [ ]a,b,c

a,b,c

Figure 3-29. Small Cable [ ]a,b,c

a,b,c

Figure 3-30. Large Cable [ ]a,b,c

a,b,c

Figure 3-31. Small Cable [ ]a,b,c

a,b,c

Figure 3-32. Large Cables at [ ]a,b,c

a,b,c

Figure 3-33. Small Cables at [ ]a,b,c

a,b,c

Figure 3-34. [ ]a,b,c Cable Test CT9FT12

a,b,c

Figure 3-35. [ ][a,b,c] Cable CT10FT13

3.4.3.5 Cable Jet Impingement Test Conclusions

The **AP1000** plant cable jet impingement test program identified the material-specific performance of the **AP1000** plant cables and identified where the onset of damage occurs when the cables are exposed to representative LOCA conditions. Meeting these overall objectives allowed the establishment of a material ZOI for the cables tested that can be applied to **AP1000** plant cables.

The cable jet impingement tests clearly show the transition between:

- [ ][a,b,c]
- [ ][a,b,c]
- [ ][a,b,c]

The transitions noted above were shown to be repeatable in both the large and small cable test series.

Based on the results of the cable jet impingement test program, a ZOI of 4D (4 equivalent inner diameters as defined by the debris generation break size assessment) is conservatively applicable to **AP1000** plant in-containment cables that may be directly impinged upon by a LOCA jet.

3.4.4 Neutron Shield Block Jet Impingement Test Summary

3.4.4.1 Neutron Shield Block Jet Impingement Test Acceptance Criteria

The goal of the neutron shield block jet impingement testing is to assess the behavior of the different configurations (Types) of neutron shield blocks so that the information from jet impingement testing can be used to determine if the standard Type III current design neutron shield block meets the definition of suitable equivalent insulation for the **AP1000** plant or if one of the alternate designs must be substituted. The acceptance criteria for neutron shield block jet impingement testing is that all facility requirements are met resulting in a successful blowdown of the facility that bounds the licensing basis **AP1000** plant large break LOCA.

3.4.4.2 Neutron Shield Block Jet Impingement Test Results

The neutron shield block test results are presented in Table 3-8.

Table 3-8. Neutron Shield Block Jet Impingement Test Results

a,b,c

Three neutron shield block configurations were tested. The results of the tests show that:

- The Type I neutron shield block design experienced [ ]a,b,c. (Figure 3-36)
- The Type II modified neutron shield block design [ ]a,b,c (Figure 3-37).
- The Type III current design neutron shield block showed [ ]a,b,c.

Each neutron shield block test exposed a pair of blocks to the blowdown jet. The results show that each block in the pair received similar damage providing a measure of repeatability for the test. In addition the facility repeatability justified that subsequent jet tests were similar and comparable. Therefore, use of two blocks in the Type III test coupled with the facility repeatability comparisons from cable jet impingement testing and PRWOG jet impingement testing demonstrate Type III block performance.

a,b,c

Figure 3-36. [ ]a,b,c Type I Neutron Shield Block at [ ]a,b,c

a,b,c

Figure 3-37. [ ]a,b,c Type II Neutron Shield Block at [ ]a,b,c

a,b,c

[ ]

Figure 3-38. [ ]^{a,b,c} Type III Neutron Shield Block at [ ]^{a,b,c}

3.4.4.3 Neutron Shield Block Jet Impingement Test Conclusions

The neutron shield block test program was developed and undertaken with the following objective:

- To assess the performance of neutron shield blocks under postulated large-break LOCA conditions

In total, five neutron shield block tests were performed meeting all system requirements for valid tests. The tests were performed with the blocks placed [ ]^{a,b,c}. The results of the neutron shield blocks jet impingement tests showed that:

- [ ]^{a,b,c}
- [ ]^{a,b,c}
- [ ]^{a,b,c}

In all cases, there was no breach of [ ]^{a,b,c}

For the Type III current design tested at [ ]^{a,b,c}

Based on jet impingement test results the [ ]^{a,b,c} design of the neutron shielding is a suitable equivalent to MRI. The **AP1000** plant RVIS neutron shielding, RVIS water inlet doors, and the CA31 neutron shielding utilize [ ]^{a,b,c} provides high assurance that no debris will be generated from the [ ]a,b,c non-metallic insulation and materials in the reactor cavity as a result of jet impingement from a LOCA.

3.4.4.4 Considerations Resulting from Confined Jet Behavior

The NMI is contained within the RV cavity. The RV cavity is fairly confined as opposed to the other regions of containment as depicted in Figure 2-2. The jet testing of the NMI was performed at a facility that prototypically re-created a free jet expansion test. To assess the potential for confined jet behavior and to ensure the conservatism of the NMI jet impingement testing a RV compartment pressurization analysis was performed for a double-ended cold leg guillotine (DECLG) break to quantify the extent of the compartment pressurization.

A quantification of the compartment pressurization is a good indicator of confined jet behavior as it relates the volume and venting capacity of the volume to determine if the potential for a large pressurization exists that could be greater than that tested to support the conclusions of the NMI jet testing.

It has been substantiated throughout the NMI jet impingement test program that the NMI, [ ]a,b,c. The goal of the sub-compartment pressurization analysis is to demonstrate that a backpressure phenomenon does not exist that would cause the NMI to be subjected to a greater pressurization than that tested as part of the NMI jet impingement test program.

In addition to the sub-compartment pressurization analysis a comparison to NUREG/CR-2913 (Reference 3-17) jet impingement testing data [ ]a,c will demonstrate further conservatism in the NMI jet testing and further substantiate the bounding conclusions of the NMI jet testing.

To quantify the extent of sub-compartment pressurization resulting from a DECLG break at the RV cavity [ ]a,c

The sub-compartment model conservatively neglected the venting area within the reactor vessel supports and only considered the gap between the insulation on the reactor coolant system (RCS) piping penetrations as the available vent area in the calculation.

Numerous sensitivities were performed within the calculation. These sensitivities included considerations for:

[

]a,c

a,c

Figure 3-39. 3-D Gothic Model Nozzle Gallery Nodalization X-Y Plane

a,c

Figure 3-40. 3-D Gothic Model Nozzle Gallery Nodalization X-Z Plane

a,c

Figure 3-41. 3-D Gothic Model Nozzle Gallery Nodalization Y-Z Plane

a,c

Figure 3-42. GOTHIC Nodalization Diagram for RV Subcompartment Pressurization Analysis

a,c

Figure 3-43. GOTHIC Sensitivities vs. Different Critical Flow Models

a,c

Figure 3-44. GOTHIC SEM comparison with Rake Data at [ ]a,b,c

[

]a,c

The Type III block did not lose its integrity. It did show some buckling damage, but it was not sufficient to cause a gross failure of the weld seams.

Table 3-9. Peak Pressure of Analysis vs. Rake Data at [ ]a,b,c

a,c

In order to ensure the adequacy of the jet testing facility as compared to other prototypic jet facilities [

]^{a,c}

Table 3-10. NTS Rake Data Comparison vs. [ ]^{a,c}

a,c

			[redacted]					
			[redacted]					

[

]^{a,c}

[

]a,c

a,c

Figure 3-45. Schematic View of [ ]a,c Test Facility (Reference 3-19)

a,c

[ ]

Figure 3-46 Photograph of Free Jet Discharge Region of the [ ]a,c Test Facility (Reference 3-19)

3.5 NEUTRON SHIELD BLOCK SUBMERGENCE TEST SUMMARY AND OBJECTIVES

Submergence testing was conducted in order to better understand how the neutron blocks would affect chemical debris generation. The objective was to determine if debris was generated by exposed RVIS components with both broken and intact encapsulation. The data from this test was then incorporated into the chemical effects model as appropriate.

3.5.1 Submergence Test Specimens

The neutron shield blocks submergence test tested seven specimens. They were chosen to study the different components of the RVIS separately. The seven specimens are as follows:

1. [ ]a,b,c
2. [ ]a,b,c
3. [ ]a,b,c
4. [ ]a,b,c
5. [ ]a,b,c
6. [ ]a,b,c
7. [ ]a,b,c

Note that none of the submergence samples tested were of the same configuration as the current neutron shield block design, which contains a [ ]a,c exterior.

3.5.2 Neutron Shield Blocks Submergence Test Summary

The **AP1000** plant RVIS utilizes non-metallic materials in four locations: the CA31 module, located at plant elevation 105′-2″, the UNS, located at plant elevation 98′-0″, the LNS, located at plant elevation 78′-0″, and the water inlet doors, located at plant elevation 71′-6″. All four of these locations are below the maximum floodup level, and therefore have the potential to be fully submerged following a LOCA.

A submergence test program was performed that evaluated the neutron shield blocks constituent components for potential generation of debris, Reference 3-12. Additionally, results were taken from this test and integrated into the **AP1000** plant chemical effects model to determine the integrated effects on chemical precipitate formation, Reference 3-13.

The objective of the neutron shield blocks' submergence test was to observe how the specimens behaved in post-LOCA fluid, examine the specimens after the test, and obtain data from the test fluid to draw conclusions about the effects of submergence on the RVIS in relation to debris generation.

3.5.2.1 Acceptance Criteria

The acceptance criteria of this experiment is that the tests were carried out in accordance with the test procedure, including that [ ]a,b,c were maintained within the specified bounds (Reference 3-14). Because the acceptance criteria were met, the results of the test are valid and applicable to use in terms of GSI-191 debris generation determination and disposition.

3.5.2.2 Test Conditions

The specimens were tested in [

]a,b,c

a,b,c

Figure 3-47. Schematic of Autoclave Test Vessel

3.5.2.3 Sampling Procedure

Samples were taken at [

]a,b,c

Between the bounding maximum temperature of fluid that the samples were subjected to during testing, which would encourage dissolution and degradation of material, and the bounding minimum temperature before the sample fluid was filtered, the test creates a scenario that drives for the highest possible amount of chemical precipitate and other elemental release from the samples.

3.5.2.4 Submergence Test Results

The following results refer to Specimen 1 only. The Type I neutron shield block submergence test showed that [

]a,b,c

[

]a,b,c (Reference 3-12). Therefore, the conclusion can be drawn that no additional debris would be produced from any of the current design RVIS components due to submergence in the event of a LOCA.

The submergence testing showed [

]a,b,c (Reference 3-15).

The allowable amount of [

]a,b,c which is well below the current licensing basis allowable limit. The **AP1000** plant chemical effects model was updated to reflect the NMI as a suitable equivalent, which means that [

]a,b,c. The appropriate results of that analysis can be found in Table 3-11.

Table 3-11. Expected AP1000 Chemical Debris Generation

a,b,c

3.6 REFERENCES

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4 DEBRIS GENERATION BREAK SIZE DETERMINATION

The documents providing guidance for resolution of GSI-191 (NEI-04-07 Volume I [Reference 4-1]) and Volume II (Reference 4-2) provide an alternative method to the baseline calculations that may be used for demonstrating acceptable containment sump performance relative to the requirements identified in the baseline methods.

This alternative methodology allows for both an alternate design basis break size in conjunction with the baseline methodology for the RCS and attached piping, and the use of realistic analysis assumptions, credit for non-safety systems and structures, and operator actions when evaluating up to a full double ended guillotine break (DEGB) of the RCS main loop piping.

The alternative methodology consists of three main components: the alternate debris generation break size (DGBS), the Region I analysis, and the Region II analysis. Each of the components and their application to the **AP1000** plant will be discussed in the following sections.

4.1 DEBRIS GENERATION BREAK SIZE

The debris generation break sizes for the evaluation of sump performance are defined as:

1. For all ASME Code Class 1 auxiliary piping (attached to the **AP1000** RCS main loop piping) up to and including a DEGB of any of these lines, the GSI-191 design-basis rules apply.

2. For breaks in the **AP1000** RCS main loop piping (hot leg and cold leg piping) up to a size of equivalent break diameter to that of a 14 inch Schedule 160 pipe (approximately 11.188 inches), the GSI-191 design-basis rules apply. (Applicable to Region I)

3. For breaks in the **AP1000** RCS main loop piping (hot leg and cold leg piping) with equivalent diameter greater than that of a 14 inch Schedule 160 pipe (approximately 11.188 inches) and up to the DEGB, mitigative capability must demonstrated, but GSI-191 design-basis rules may not necessarily apply. (Applicable to Region II)

Per the safety evaluation (SE) on NEI-04-07 (Reference 4-2), the basis for acceptance of the alternate break sizes stems from the information developed by the NRC's Office of Nuclear Regulatory Research (RES) regarding the frequency of RCS ruptures of various sizes. The RES study determined the frequency of primary pressure boundary failures under normal operational loading and transients and concluded that the probability of a PWR primary-piping system rupture is generally very low and that the break frequency decreases with increasing piping diameter.

Reference 4-1 reports that the NRC staff considered the fact that there is a substantial difference from a deterministic, "margins to failure" or "flaw tolerance" perspective between large diameter main coolant loop piping and the next largest ASME Code Class 1 attached auxiliary piping and the fact that certain ASME Code Class 1 auxiliary piping systems may be more susceptible to failure as a result of environmental conditions which are conducive to known degradation mechanisms and/or loading conditions which routinely apply significant stresses to the piping system. The Staff provided an example of both of these considerations citing a typical PWR pressurizer surge line in which Alloy 82/182 dissimilar metal welds are subjected to a high-temperature operating environment known to abet primary water stress-corrosion cracking (PWSCC) and are subjected to significant bending loads during startup/shutdown conditions because of the large temperature gradient between the pressurizer and the hot leg of the main coolant loop.

Per the **AP1000** plant DCD (Reference 4-3), the **AP1000** plant reactor coolant system piping is fabricated of forged seamless Series 300 austenitic stainless steel without longitudinal or electroslag welds or cast fittings. The piping complies with the requirements of the ASME Code, Section II (Parts A and C), Section III, and Section IX and adheres to the requirements of Regulatory Guide 1.44 for the use of Series 300 stainless steel materials. These fabrication features, including no dissimilar welds for attached RCS loop piping, minimize the risk of PWSCC failure throughout the RCS piping system.

The Reference 4-2 SE on NEI 04-07 concluded that the division of the pipe break spectrum noted above for evaluating debris generation was acceptable and that licensees could use the defined DGBS for distinguishing between Region I and Region II analyses when using the alternative methodology. These conclusions are applicable to the **AP1000** plant RCS loop piping and the associated RCS main loop branch piping.

4.2 REGION I ANALYSIS

The Region I analysis is applicable to the **AP1000** plant and includes evaluation of the RCS main loop piping and every branch line attached to the RCS main loop piping. For the Region I analysis, all lines are evaluated for debris generation and transport using the baseline methods as defined in NEI 04-07 (Reference 4-1) and modified by the SE on NEI 04-07 (Reference 4-2).

In the Region I analysis a DEGB with full separation and an inner break diameter equivalent to that of a 14 inch Schedule 160 pipe is assumed for determining debris generation from the **AP1000** RCS main loop piping due to the low probability of a DEGB of the main loop piping. The RCS main loop piping is identified as the hot leg and cold leg piping only. For RCS main loop branch piping, a DEGB with full separation and an inner break diameter equivalent to that of the branch line inner diameter must be assumed. This remains applicable for RCS main loop branch lines with inner diameters larger than that of a 14 inch Schedule 160 pipe, including but not limited to the following:

1. [ ]a,c
2. [ ]a,c
3. [ ]a,c

For Region I analyses, the spherical model defined in NEI 04-07 (Reference 4-2) shall be used for the determination of the Zone of Influence (ZOI) from the RCS main loop piping and the RCS main loop branch piping. In accordance with this model, the ZOI is defined as a sphere with a radius equivalent to the inner diameter of the assumed DEGB size multiplied by a scaling factor, N, determined for the specific material to be evaluated.

$$ZOI_r = ND_{inner}$$

In the Region I analysis, the radius of the spherical ZOI for the RCS main loop piping and a material with a 4D ZOI is determined as follows based on the inner diameter of a 14 inch Schedule 160 pipe.

$$ZOI_r = 4 \times 11.188\ inches = 44.752\ inches$$

The radius of the spherical ZOI for an RCS main loop branch line is determined in a similar manner except that the inner diameter of the line in question is used, even when larger than the 14 inch Schedule 160 inner diameter. For example, the ZOI radius for the [ ]a,c as applied to a material with a 4D ZOI, is calculated below.

$$ZOI_r = [\qquad\qquad]^{a,c}$$

The spherical ZOI is modeled with the defined radius applied to the axial centerline of the pipe. Following this methodology, the ZOI and subsequent debris source term calculations can be determined for all Region I break evaluations.

4.3 REGION II ANALYSIS

The Region II analysis includes evaluations of break sizes in the RCS main loop piping (hot and cold) greater than the DGBS defined in the Region I analysis (approximately 11.188 inches in equivalent diameter) and up to a DEGB of the largest pipe in the RCS. The Region II analysis considers only RCS main loop piping because all primary-side attached auxiliary piping is fully addressed as part of the Region I analysis.

The Region II analysis is performed in the same manner and with the same methods used in the baseline analyses with respect to ZOI models and assumptions; however, the Region II analysis allows for more realistic analytical methods and assumptions; credit can be taken for limited pipe displacement, operation of non-safety systems, structures and components, and operator actions where applicable. Crediting a limited pipe displacement requires the application of results from pipe break analyses and/or pipe stiffness analyses which may be utilized to limit the maximum break size to be evaluated. If no piping analyses have been performed for the RCS main loop piping application, then a DEGB assuming the full hot leg or cold leg pipe inner diameter must be evaluated; however, other reasonable best estimate assumptions may still be employed in the analysis. If structural analyses have been performed for the RCS main loop piping showing that limited pipe displacement, also referred to as a limited separation break, will occur, then an equivalent break diameter as determined for the limited separation break may be used to determine the ZOI for the Region II analysis.

4.3.1 Full Separation Break

If a pipe displacement or structural analysis is not performed, or if the analysis results in a break with lateral pipe displacement greater than 1-diameter and axial displacement greater than 0.5-diameter, then a full separation DEGB of the RCS main loop piping must be assumed. The radius of the spherical ZOI used in the Region II analysis is defined using the inner diameter of the RCS main loop piping multiplied by a scaling factor, N, determined for the specific material to be evaluated. Therefore, the ZOI radius for a material with a 4D ZOI is defined below for the RCS hot leg and cold leg piping.

Hot Leg:

$$ZOI_r = [\qquad\qquad\qquad\qquad]^{a,c}$$

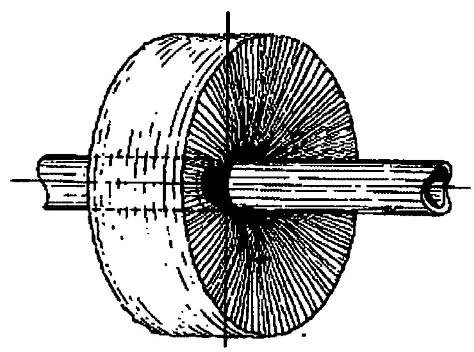
Cold Leg:

$$ZOI_r = [\qquad\qquad\qquad\qquad]^{a,c}$$

The spherical ZOI is modeled with the defined radius applied to the axial centerline of the pipe.

4.3.2 Limited Separation Breaks

If a structural or pipe displacement analysis is performed which results in a lateral pipe displacement, d, of less than 1-diameter and an axial displacement, W_f, of less than or equal to 0.5-diameter, then a limited separation break may be utilized in the Region II analysis in determining the alternate break size. The geometry of a limited separation break is discussed in ANSI/ANS 58.2-1988 (Reference 4-4) and is shown in Figures 4-1 and 4-2, below. ANSI/ANS 58.2-1988 defines a limited separation break as having an axial displacement, W_f, of less than or equal to 0.5-diameter and a lateral displacement, d, of less than or equal to the pipe wall thickness, t; however, this definition is extended for the purposes of **AP1000** Region II analyses to include lateral displacements greater than the pipe wall thickness and up to 1-diameter.



(B) Jet From Circumferential Break with Ends Restrained

Figure 4-1. Circumferential Break with Limited Separation

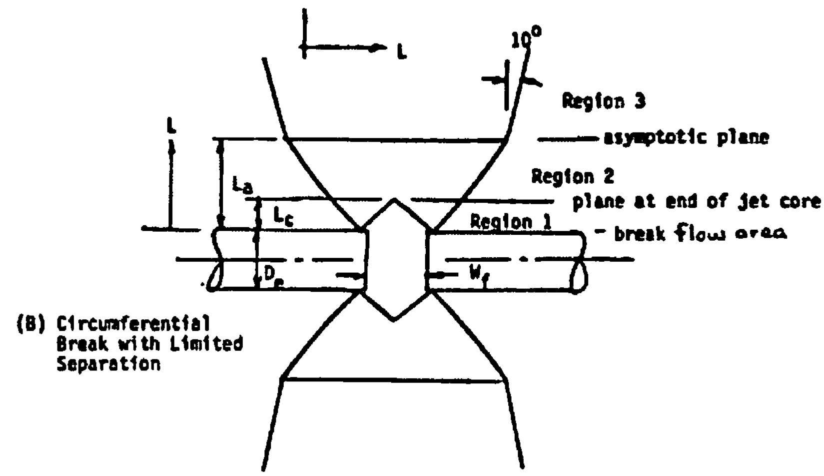


Figure 4-2. Geometry of Circumferential Break with Limited Separation

One of the key parameters of the circumferential break with limited separation is the value of the axial displacement, W_f. Similar to the inner diameter of the pipe, D_e, for a full separation break, the axial displacement acts as the characteristic length for the simplified expanding jet model proposed in Appendix C of ANSI/ANS 58.2-1988 (Reference 4-4). The length of the jet core region for a full separation break is provided below as a function of the pipe inner diameter, D_e.

$$\frac{L_C}{D_e} = 0.26\sqrt{\Delta T_{sub}} + 0.5$$

Similarly, the length of the jet core region for a limited separation break is defined using the same expression where the axial displacement, W_f, acts as the characteristic length.

$$\frac{L_C}{W_f} = 0.26\sqrt{\Delta T_{sub}} + 0.5$$

From the two-phase jet loading model documented in NUREG/CR-2913 (Reference 4-5), the centerline jet pressure for a subcooled two-phase flow jet is proportional to the ratio of the characteristic length of the break, D, to the distance from the break plane to the target, L, as shown in the expression below.

$$P \propto \frac{D}{L} \propto \frac{W_f}{L}$$

4.3.2.1 Limited Separation Break; $0 \leq d \leq t$

A limited separation break with lateral displacement, d, less than or equal to the pipe wall thickness, t, shall be defined by the characteristic length, W_f, where:

[ ]^{a,c}

In this case, the radius of the spherical ZOI used in the Region II analysis is defined [

]^{a,c}.

$$ZOI_r = [\qquad]^{a,c}$$

Therefore, the ZOI radius for a material with a [

]^{a,c}.

$$ZOI_r = [\qquad]^{a,c}$$

The spherical ZOI is modeled with the [ ]^{a,c}.

4.3.2.2 Limited Separation Break; $t < d < D_e$

A limited separation break with lateral displacement, d, greater than the pipe wall thickness, t, and less than 1-diameter shall be defined, [

]^{a,c}. The expression for the equivalent diameter, $D_{equivalent}$, of such a limited separation break is provided in the equation below.

$$[\qquad]^{a,c}$$

The characteristic length component contributed by the exposed cross-sectional break area, $D_{lateral}$ is determined by [equating the cross-sectional break flow area to that of a DEGB with full separation. In the case of a DEGB with full separation, the break flow area for a ZOI defined by the pipe inner diameter, D_e, is twice the cross-sectional area of the inside of the pipe with diameter, D_e. Therefore, the lateral characteristic length component, $D_{lateral}$, is defined based on the total exposed break flow area, A_{break}, of both sides of the pipe break]^{a,c} using the expression below.

$$[\qquad]^{a,c}$$

In this case, [

]^{a,c}.

$$ZOI_r = [\qquad]^{a,c}$$

The spherical ZOI is modeled with [

]^{a,c}

4.4 RCS MAIN LOOP PIPING DISPLACEMENT ANALYSIS

4.4.1 Analysis Overview

In support of the Region II analyses, a structural evaluation of the RCS main loop piping was performed using ANSYS™ LS-DYNA™ to evaluate pipe whip and displacement in the RCS main loop piping. This analysis, documented in APP-PL01-P0C-003 (Reference 4-7), used finite element models run on LS-DYNA™ to demonstrate that the hot legs and cold legs do not fully separate as a result of a LOCA. The LOCA pipe reaction forces assumed for each DEGB scenario in Reference 4-7 were calculated in APP-PL01-P0C-002 (Reference 4-6). The Reference 4-7 structural analysis postulated DEGB's in multiple locations on both the RCS hot legs and cold legs. The following five break scenarios were analyzed:

1. [ ]a,c
2. [ ]a,c
3. [ ]a,c
4. [ ]a,c
5. [ ]a,c

The locations of the five postulated break scenarios are shown in Figure 4-3.

a,c

Figure 4-3. Primary Coolant Loop Break Locations (Reference 4-7)

4.4.2 Pipe Displacement Results

The results of the hot leg and cold leg pipe displacement analyses performed in APP-PL01-P0C-003 (Reference 4-7) are provided in Table 4-1 for the five postulated break locations discussed in subsection 4.4.1.

Table 4-1. Results of Pipe Displacement Analysis – APP-PL01-PL0C-003 (Reference 4-7)

a,c

4.4.3 Application of Results to Region II Analyses

The Region II analyses, as discussed in Section 4.3, need only be performed for RCS main loop piping under the alternative methodology and may credit the results of a piping displacement or structural analysis in the determination of the break size. Therefore, the hot leg and cold leg displacement results from the ANSYS™ LS-DYNA™ analysis presented in Table 4-1 may be used to support the **AP1000** plant Region II debris source term calculations in addition to any best estimate assumptions that are deemed reasonable for the individual analysis.

Following the methodology described in Section 4.3, the equivalent break diameter was determined for each of the five DEGB scenarios, and was compared to the 14 inch Schedule 160 break size already used as the basis for the Region I analyses. [

]a,c (Reference 4-4).

[

]a,c

[

]a,c

4.4.3.1 Hot Leg Break Evaluations

4.4.3.1.1 Hot Leg DEGB at the Reactor Vessel Nozzle

From results presented in Table 4-1, the hot leg break at the reactor vessel nozzle resulted in an axial displacement, W_f, [

]a,c

Given that the [

]a,c is bounded by the Region I analysis.

4.4.3.1.2 Hot Leg DEGB at the Steam Generator

[

]a,c

[ ]a,c

Given that the [ ]a,b,c is bounded by the Region I analysis.

4.4.3.2 Cold Leg Break Evaluations

4.4.3.2.1 Cold Leg DEGB at the Reactor Vessel Nozzle

From results presented in Table 4-1, the cold leg break at the reactor vessel nozzle resulted in [ ]a,c

4.4.3.2.2 Cold Leg DEGB at the Reactor Coolant Pump

From results presented in Table 4-1, the cold leg break at the reactor coolant pump [ ]a,c would also conservatively bound this limited separation break.

The ZOI for a fully separated break of a 14 inch Schedule 160 pipe would bound the parameters of the limited separation jet; however, the calculated equivalent break diameter, $D_{equivalent}$, was found to be greater than the inner diameter of the 14 inch Schedule 160 pipe (11.188 inches). As a result, a Region II analysis must be assessed for the cold legs from the reactor coolant pump to the CA01 module penetration and must use a [ ]a,c.

4.4.3.2.3 Cold Leg DEGB at the CA01 Module Penetration

From results presented in Table 4-1, the cold leg break at the module penetration resulted in [ ]a,c

[

]a,c

Based on the break results for the cold leg at the reactor vessel nozzle and the reactor coolant pump presented in subsections 4.4.3.2.1 and 4.4.3.2.2, respectively, Region II analyses should be performed for the cold leg with a spherical ZOI based on a diameter of [ ]a,c from the reactor vessel nozzle to the CA01 module penetration, and a spherical ZOI based on an equivalent diameter of [ ]a,c from the CA01 module penetration to the reactor coolant pump.

4.5 REFERENCES

4-1. NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 1," Rev. 0, December 6, 2004.

4-2. NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 2 – Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02," Rev. 0, December 6, 2004.

4-3. APP-GW-GL-700, Rev. 19, "AP1000 Design Control Document," June 2011.

4-4. ANSI/ANS 58.2-1988, "Design Basis for Protection of Light Water Nuclear Power Plants Against the Effects of Postulated Pipe Rupture," American Nuclear Society, October 6, 1988.

4-5. NUREG/CR-2913, "Two-Phase Jet Loads" Sandia Labs, Albuquerque, NM January 1983.

4-6. APP-PL01-P0C-002, "Pipe Reaction Force Determination for Large Break LOCA."

4-7. APP-PL01-P0C-003, "RCL Pipe Movement in Large Break LOCAs."

5 NON-METALLIC INSULATION SUITABLE EQUIVALENCY

The RVIS upper and lower neutron shield blocks, CA31 neutron shield blocks, and RVIS water inlet doors, all with [ ]^{a,c} are a suitable equivalent to MRI.

5.1.1 Debris Generation

There is no expected additional debris production from the neutron shield blocks or the water inlet doors. Their [ ]^{a,c} construction maintains integrity under direct jet impingement outside a [ ]^{a,c}. The neutron shielding and the water inlet doors are located outside of the [ ]^{a,c} for any of the potential pipe breaks in the reactor vessel cavity, therefore no debris will be generated from the LOCA jet impingement. The shield blocks are not expected to create chemical debris when submerged because of the [ ]^{a,c} design.

5.1.1.1 Jet Impingement Debris

The results of the jet impingement testing were used to determine the ZOI for the RVIS upper and lower neutron shielding, the CA31 neutron shielding, and the water inlet doors. With the ZOI defined it was possible to verify that debris would not be generated from a break of the hot leg, cold leg, or direct vessel injection (DVI) piping.

5.1.1.1.1 Establishing the Zone of Influence

The ZOI is defined as the spherical volume about a break in which the fluid escaping from the break has sufficient energy to generate debris from insulation, coating, and other materials within the zone. The center of the spherical ZOI is located at the center of the break site.

The jet impingement testing was conducted on a [ ]^{a,c} neutron shield block. The test results can be applied to the CA31 neutron shielding, the water inlet doors, and to the RVIS UNS and LNS. The UNS and the LNS will have [

]^{a,c}

a,c

[ ]

The construction of CA31 uses [

]^{a,c} provides

additional margin.

The water inlet doors are constructed of [

]a,c

5.1.1.1.2 NEI-04-07 Approach to Determining the Zone of Influence

The secondary approach to determining the zone of influence requires experimentally determined impingement pressures within the jet for the location in which the neutron shielding test samples were positioned. The experimentally determined impingement pressures can be matched to the guidance report recommended ZOI values in Table 5-1 (Reference 5-1).

Table 5-1. NEI 04-07 Comparison of Computed Spherical ZOI Radii from Independent Evaluations of the ANSI Jet Model

Impingement Pressure (psig)	ZOI Radius/Break Diameter		
	Guidance Report Recommendation	Calculated Value	SE Appendix I
1000	1.0	0.24	0.89[a]
333	1.0	0.55	0.90
190	1.3	1.11	1.05
150	1.6	1.51	1.46
40	3.8	3.73	4.00
24	5.5	5.45	5.40
17	7.8	7.72	7.49
10	12.1	12.07	11.92
6	17	16.97	16.95
4	21.6	21.53	21.60

*ZOI radius/break diameter ratios within the red box are used.

The jet impingement test facility used for the neutron shielding testing was previously used by the pressurized water reactors owners group (PWROG). Their testing utilized an array of pressure sensors to determine the impingement pressures at various locations within the jet. The centerline pressure data recorded during the PWROG testing (Reference 5-2) at a distance of [ ]a,c from the nozzle can be seen in Figure 5-1. The peak recorded pressure during the jet testing [ ]a,c psig.

The above approach for determining a ZOI is not endorsed by this submittal; it is provided to demonstrate conservatism in the empirically determined ZOI based on prototypic two-phase jet impingement testing.

a,b,c

Figure 5-1. Centerline Stagnation Pressure at [ ]a,c from the Jet Nozzle

The correlation between impingement pressure and the ZOI from NEI 04-07, shown in Table 5-1, provides information for several pressures. To find the ZOI associated with the experimentally determined pressure, the guidance report recommended ZOI radius/break diameter information was plotted (Figure 5-2) and trend lines were added. The resulting trend line equations provide a method of calculating the ZOI.

$$\frac{\text{ZOI Radius}}{\text{Break Diameter}} = \begin{cases} 58.915 \times P^{-0.719} & 0 < P < 333 \text{ psig} \\ 1 & P \geq 333 \text{ psig} \end{cases}$$

$$P = \text{Impingement Pressure (psig)}$$

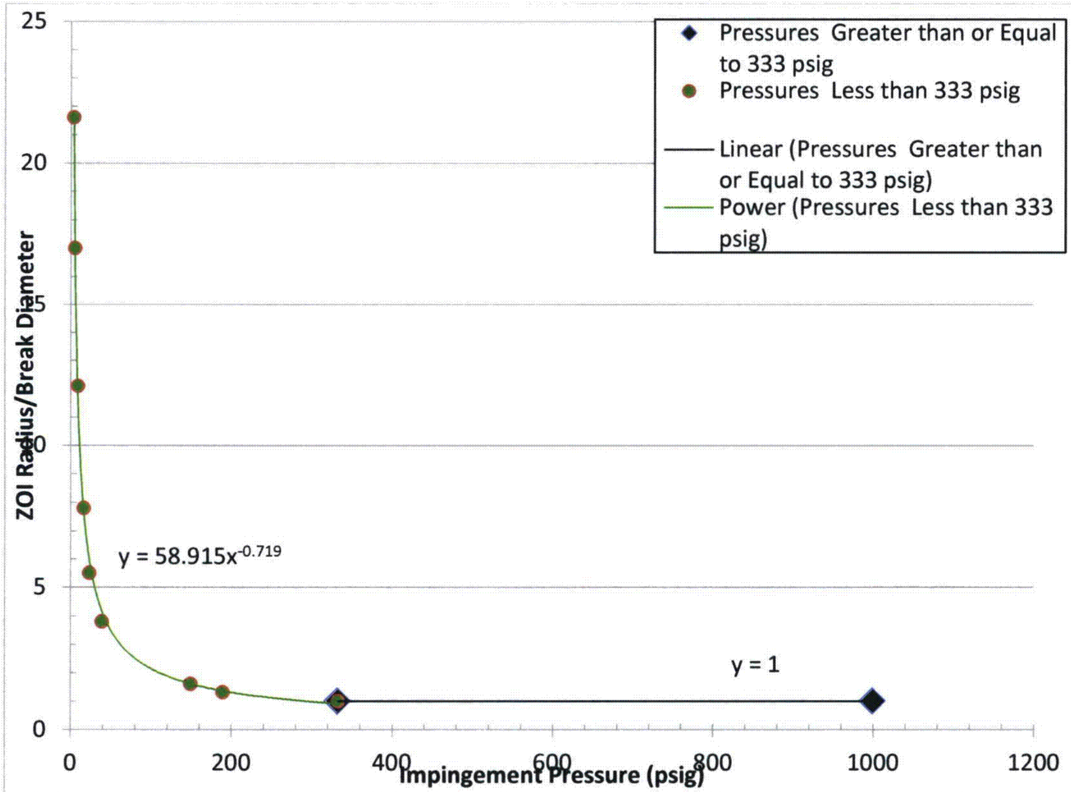


Figure 5-2. Plot of NEI 04-07 Spherical ZOI Radii

As previously stated, the jet impingement testing of the [

$]^{a,b,c}$

5.1.1.1.3 Debris Generation Assessment

A LOCA debris generation assessment was performed for each potential pipe break in the reactor vessel cavity for the RVIS upper neutron shielding and the CA31 module neutron shielding.

The RVIS lower neutron shielding and the water inlet doors are far enough from the potential pipe breaks that they are not within a [$]^{a,b,c}$. The lower neutron shielding and the water inlet doors do not generate debris from a LOCA jet.

5.1.1.1.3.1 Direct Vessel Injection Pipe Break

The debris generation assessment of the direct vessel injection (DVI) piping was performed for a DEGB. The ZOI was calculated using the full inner diameter of the DVI pipe [ ]a,c. The assessment determined that a [ ]a,c upper neutron shielding and the CA31 neutron shielding would not generate debris from a break at the DVI nozzle. The ZOI would be small enough that the upper neutron shielding and the CA31 neutron shielding are outside ZOI sphere (Figure 5-3).

a,b,c

Figure 5-3. DVI Break Zone of Influence [ ]a,c

5.1.1.1.4 Hot Leg Pipe Break

As discussed in Section 4, NEI 04-07 (Reference 5-1) allows the use of an alternative methodology to evaluate the debris generation potential of breaks in the RCS main-loop piping. The alternative methodology requires that a Region I and Region II analysis be performed in the debris generation assessment of the hot leg piping.

5.1.1.1.4.1 Region I Analysis

A Region I analysis of the hot leg piping is evaluated for a maximum debris generation break size (DGBS) equivalent to the DEGB of a 14 inch schedule 160 pipe. The spherical ZOI, used to assess the debris generation potential from a hot leg break, was generated using the inner diameter of a 14 inch schedule 160 pipe (11.188 in.). The resulting ZOI sphere is small enough that the RVIS upper neutron shielding and the CA31 neutron shielding are outside the ZOI (Figure 5-4). The Region I analysis determined that no debris would be generated from a break at the hot leg nozzles.

a,b,c

Figure 5-4. Hot Leg Break Zone of Influence [ ]a,c

5.1.1.1.4.2 Region II Analysis

Region II analyses allow for more realistic analysis methods and assumptions such as limited pipe displacement, operation of non-safety systems, intervening structures, and operator actions. A pipe break analysis was performed for a break at the reactor vessel hot leg nozzle to determine the amount of movement and the resulting break area. The analysis showed that the resulting pipe break area was less than the break area of a DEGB of a 14 in. schedule 160 pipe. Because the break size used in the Region I analysis is greater than the break size used in the Region II analysis, the Region I analysis findings are more conservative.

5.1.1.1.5 Cold Leg Pipe Break

Similar to the hot leg piping, the debris generation assessment for the cold leg piping utilized the alternative methodology as discussed in Section 4. A Region I and Region II analysis was performed for the cold leg piping.

5.1.1.1.5.1 Region I Analysis

The spherical ZOI used to assess the debris generation potential from a cold leg break, was generated using the inner diameter of a 14 inch schedule 160 pipe (11.188 in.). The resulting ZOI sphere is small enough that the RVIS upper neutron shielding and the CA31 neutron shielding are outside the ZOI (Figure 5-5). The Region I analysis determined that no debris would be generated from a break at the cold leg nozzles.

a,b,c

Figure 5-5. Region I Analysis Cold Leg Break Zone of Influence [ ]a,c

5.1.1.1.5.2 Region II Analysis

As with the hot leg piping, a pipe break analysis was performed for a break at the reactor vessel cold leg nozzle to determine the amount of movement of the cold leg piping and the resulting break area. The analysis indicated that [ ]a,c

The Region II analysis allows for more realistic assumptions to be used in the debris generation assessment such as taking credit for intervening robust structures. Reference 5-1 states that when the spherical ZOI extends beyond robust barriers, such as walls, or encompasses large components, the extended volume can be truncated. At the cold leg nozzle break location, the UNS is located

[

]a,c

The CA31 neutron shielding is located [

]a,c

a,c

Figure 5-6. CA31 Module and Neutron Blocks – Top View; Top Liner Plate Removed

The RVIS upper neutron shielding and the CA31 neutron shielding are outside the ZOI (Figure 5-7). Both the Region I and Region II analyses have shown that no debris would be generated from a break at the cold leg nozzle.

a,b,c

Figure 5-7. Cold Leg Break Zone of Influence [ ]a,c

5.1.1.2 Submergence Debris

The design of the neutron shield blocks and water inlet doors is such that little to no communication between the components and the post-LOCA fluid would occur since:

- [ ]a,c
- [ ]a,c
- The current design [ ]a,c neutron shield blocks are a suitable equivalent to MRI and do not produce debris

Therefore, no additional chemical effects have to be considered.

5.1.2 Aging Effects

The test samples used in the submergence and jet impingement testing were not thermally or radiation aged. The effects of thermal and radiation aging would not impact the conclusion that the neutron shielding and water inlet doors would not generate debris as a result of a LOCA jet or submergence. The materials used in CA31 neutron shielding, UNS, LNS, and RVIS water inlet doors are a combination of [

]^{a,c}

5.1.3 Additional Conservatisms

The jet impingement testing on the [ ]^{a,c} block was performed at [ ]^{a,c} with direct jet impingement. [

]^{a,c}

The submergence test also had a few inherent conservatisms in the test procedure. The blocks were [

]^{a,c}

Also, the sampling system for the NMI submergence testing [

]^{a,c}

5.2 REFERENCES

5-1. NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology, , Volume 2 – Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02," Revision 0, December 6, 2004.

5-2. Report No.: FAI/110497, Revision 1, PWROG Model for the Two Dimensional Free Expansion of a Flashing, Two Phase, Critical Flow Jet, February 2012.

5-3. APP-CA31-S5-404, "Containment Building Areas 1, 2, 3, & 4 Module CA31 El 107'-2" Installation Sequence III."

5-4. Haley, T. (2012). Boraflex, RACKLIFE, and BADGER.

5-5. APP-CA31-S5B-002, "Containment Building Areas 1, 2, 3, & 4 Module CA31 El 107'-2" Bill of Materials II."

5-6. EPRI Report "Materials Reliability Program A Review of Radiation Embrittlement of Stainless Steels for PWRs (MRP-79) – Revision 1 1008204.

6 REGULATORY IMPACTS

Revisions to the **AP1000** plant Licensing Basis are proposed in support of the integrated debris evaluation approach. Appendix A of this report provides representative examples of proposed Final Safety Analysis Report (FSAR) markups based on the NRC reviewed and approved **AP1000** DCD Rev. 19 (Reference 6-1). The final changes to the FSAR will be made by the Licensee, with an evaluation performed in accordance with 10 CFR 52, Appendix D, Volume VIII.

6.1 LICENSING BASIS CHANGES

It should be noted that this report does not propose any changes to **AP1000** DCD/ Updated Final Safety Analysis Report (UFSAR) Tier 2*, DCD Tier 1/COL Appendix C or Technical Specifications (Combined Operating License (COL) Appendix A).

The changes to DCD/UFSAR Tier 2 are as follows:

- In DCD/UFSAR Section 6.3.2.2.7.1, item 3, this WCAP is added as a reference that demonstrates suitable equivalency for **AP1000** reactor vessel neutron shield blocks.

- In DCD/UFSAR Section 6.3.2.2.7.1, item 12, this WCAP is added as a reference that supports a ZOI value of 4 for **AP1000** in-containment power and instrumentation cabling.

- In DCD/UFSAR Section 6.3.9, this WCAP is included in the Section 6.3 references subsection.

6.2 REFERENCE

6-1. APP-GW-GL-700, Rev. 19, "AP1000 Design Control Document," June 2011.

7 CONCLUSIONS

Cable jet impingement testing was performed on AP1000 plant in-containment cables to determine the appropriate ZOI radius for use in cable debris generation assessments for the AP1000 plant. The results of the testing demonstrated that the onset of incipient damage, as defined by NEI-04-07 Volume 2, from a bounding DECLGB, which is limiting as related by maximum subcooling, was found to be [ ]^{a,c} where "D" is taken to be the pipe diameter as defined in the applicable Region I and II analyses. For conservatism, the ZOI radius is substantiated to be 4D, which is the location where zero debris was generated. This was quantified as a result of [

]^{a,c}

The NMI located in the RV cavity of the AP1000 plant was subjected to jet impingement and submergence testing to qualify the insulation system as a suitable equivalent per the AP1000 plant licensing basis. Results of the jet impingement and submergence testing resulted in a change in the design [ ]^{a,c}. The results of the jet impingement testing demonstrate that the Type III block design (current design) would not generate debris when subjected to a bounding LOCA jet. The geometry of the RV cavity and the influence of confined jet behavior was addressed in a sub-compartment pressurization analysis and confirmed the jet impingement testing bounded the sub-compartment pressurization analysis. The jet impingement testing subjected the Type III block to pressures [ ]^{a,c} than the maximum calculated sub-compartment pressure. The [ ]^{a,c} intrinsic to the Type III design ensures no communication with sump fluid in the post-LOCA containment. This ensures no chemical debris is generated by the Type III design. Therefore, the Type III block design is a suitable equivalent insulation to MRI.

A methodology was presented to direct performance of Region I and Region II analyses for debris generation. The methodology included the assumption in the Region I analyses of a 14inch Sch. 160 pipe diameter analyzed under DBA assumptions for debris generation of RCS main loop piping. The Region I analysis assumed a DEGB for any RCS loop piping offtakes. These assumptions are commensurate with that contained in Reference 7-1 and 7-2.

The Region II analyses contain a pipe stiffness calculation to determine the break configuration for RCS loop piping. The results of the pipe stiffness calculation are used to develop the equivalent pipe diameter for determining the appropriate ZOI radius for use in Region II debris generation calculations. The Region II assessment includes the methodology for determining whether a limited separation break configuration jet volume bounds the assumed spherical ZOI geometry based on the quantified results of the pipe stiffness analysis. The largest ZOI volume is chosen to be limiting for performing debris generation calculations.

In conclusion, this document communicates and substantiates the results of the cable jet impingement test program, the NMI suitable equivalency program, and the application of the ZOI radius for Region I and Region II analyses into a conservative and bounding AP1000 plant methodology for integrated debris assessment. This methodology is applicable to:

A. ZOI radius determination for **AP1000** plant in-containment cables.

B. Demonstration of **AP1000** plant RV cavity NMI suitable equivalency.

C. Performance of debris generation calculations consistent with the alternate method for Region I and Region II analyses.

7.1 REFERENCES

7-1. NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 1," Revision 0, December 6, 2004.

NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology; Volume 2 – Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02," Revision 0, December 6, 2004.

APPENDIX A
AP1000 DCD REVISION 19 MARKUPS

6.3.2.2.7.1 General Screen Design Criteria

1. Screens are designed to Regulatory Guide 1.82, including:

- Separate, large screens are provided for each function.
- Screens are located well below containment floodup level. Each screen provides the function of a trash rack and a fine screen. A debris curb is provided to prevent high density debris from being swept along the floor to the screen face.
- Floors slope away from screens (not required for AP1000).
- Drains do not impinge on screens.
- Screens can withstand accident loads and credible missiles.
- Screens have conservative flow areas to account for plugging. Operation of the non-safety-related normal residual heat removal pumps with suction from the IRWST and the containment recirculation lines is considered in sizing screens.
- System and screen performance are evaluated.
- Screens have solid top cover. Containment recirculation screens have protective plates that are located no more than 1 foot above the top of the screens and extend at least 10 feet in front and 7 feet to the side of the screens. The plate dimensions are relative to the portion of the screens where water flow enters the screen openings. Coating debris, from coatings located outside of the ZOI, is not transported to the containment recirculation screens, to the IRWST screens, or into a direct vessel injection or a cold leg LOCA break that becomes submerged during recirculation considering the use of high density coatings discussed in subsection 6.1.2.1.5.
- Screens are seismically qualified.
- Screen openings are sized to prevent blockage of core cooling.
- Screens are designed for adequate pump performance. AP1000 has no safety-related pumps.
- Corrosion resistant materials are used for screens.
- Access openings in screens are provided for screen inspection.
- Screens are inspected each refueling.

2. Low screen approach velocities limit the transport of heavy debris even with operation of normal residual heat removal pumps.

3. [*Metal reflective insulation is used on ASME class 1 lines because they are subject to loss-of-coolant accidents. Metal reflective insulation is also used on the reactor vessel, the reactor coolant pumps, the steam generators, and on the pressurizer because they have relatively large insulation surface areas and they are located close to large ASME class 1 lines. As a result, they are subject to jet impingement during loss-of-coolant accidents.*]* A suitable equivalent insulation to metal reflective may be used. A suitable equivalent insulation is one that is encapsulated in stainless steel that is seam welded so that LOCA jet impingement does not damage the insulation and generate debris. Another suitable insulation is one that may be damaged by LOCA jet impingement as long as the resulting insulation debris is not transported to the containment recirculation screens, to the IRWST screens, or into a direct vessel injection or a cold leg LOCA break that becomes submerged during recirculation. In order to qualify as a suitable equivalent insulation, testing must be performed that subjects the insulation to conditions that bound the AP1000 conditions and demonstrates that debris would not be generated. If debris is generated, testing and/or analysis must be performed to demonstrate that the debris is not transported to an AP1000 screen or into the core through a flooded break. It would also have to be shown that the material used would not generate chemical debris. In addition, the testing and/or analysis must be approved by the NRC.

   [*In order to provide additional margin, metal reflective insulation is used inside containment where it would be subject to jet impingement during loss-of-coolant accidents that are not otherwise shielded from the blowdown jet.*]* As a result, fibrous debris is not generated by loss-of-coolant accidents. Insulation located within the zone of influence (ZOI), which is a spherical region within a distance equal to 29 inside diameters (for Min-K, Koolphen-K, or rigid cellular glass insulation) or 20 inside diameters (for other types of insulation) of the LOCA pipe break is assumed to be affected by the LOCA when there are intervening components, supports, structures, or other objects.

   [*The ZOI in the absence of intervening components, supports, structures, or other objects includes insulation in a cylindrical area extending out a distance equal to 45 inside diameters from the break along an axis that is a continuation of the pipe axis and up to 5 inside diameters in the radial direction from the axis.*]* A suitable equivalent insulation to metal reflective may be used as discussed in the previous paragraph.

   [*Insulation used inside the containment, outside the ZOI, but below the maximum post-DBA LOCA floodup water level (plant elevation 110.2 feet), is metal reflective insulation, jacketed fiberglass, or a suitable equivalent.*]* A suitable equivalent insulation is one that would be restrained so that it would not be transported by the flow velocities present during recirculation and would not add to the chemical precipitates. In order to qualify as a suitable equivalent insulation, testing must be performed that subjects the insulation to conditions that bound the AP1000 conditions and demonstrates that debris would not be generated. If debris is generated, testing and/or analysis must be performed to demonstrate that the debris is not transported to an AP1000 screen or into the core through a flooded break. It would also have to be shown that the material used would not generate chemical debris. In addition, the testing and/or analysis must be approved by the NRC.

[*Insulation used inside the containment, outside the ZOI, but above the maximum post-design basis accident (DBA) LOCA floodup water level, is jacketed fiberglass, rigid cellular glass, or a suitable equivalent.*]* A suitable equivalent insulation is one that when subjected to dripping of water from the containment dome would not add to the chemical precipitates; suitable equivalents include metal reflective insulation.

<u>The non-metallic insulation used in the AP1000 reactor vessel neutron shield blocks and the water inlet doors has been determined to be a suitable equivalent (Reference 5).</u>

4. Coatings are not used on surfaces located close to the containment recirculation screens. The surfaces considered close to the screens are defined in subsection 6.3.2.2.7.3. Refer to subsection 6.1.2.1.6. These surfaces are constructed of materials that do not require coatings.

5. The IRWST is enclosed which limits debris egress to the IRWST screens.

6. Containment recirculation screens are located above lowest levels of containment.

7. Long settling times are provided before initiation of containment recirculation.

8. Air ingestion by safety-related pumps is not an issue in the AP1000 because there are no safety-related pumps. The normal residual heat removal system pumps are evaluated to show that they can operate with minimum water levels in the IRWST and in the containment.

9. A commitment for cleanliness program to limit debris in containment is provided in subsection 6.3.8.1.

10. [*Other potential sources of fibrous material, such as ventilation filters or fiber-producing fire barriers, are not located in jet impingement damage zones or below the maximum post-DBA LOCA floodup water level.*]*

11. Other potential sources of transportable material, such as caulking, signs, and equipment tags installed inside the containment are located:

    - Below the maximum flood level, or
    - Above the maximum flood level and not inside a cabinet or enclosure.

    Tags and signs in these locations are made of stainless steel or another metal that has a density ≥ 100 lbm/ft^3. Caulking in these locations is a high density (≥ 100 lbm/ft^3).

    The use of high-density metal prevents the production of debris that could be transported to the containment recirculation screens, to the IRWST screens, or into a direct vessel injection or a cold leg LOCA break location that is submerged during recirculation. If a high-density material is not used for these components, then the components must be located inside a cabinet or other enclosure, or otherwise shown not to transport; the enclosures do not have to be watertight, but need to prevent water dripping on them from creating a flow path that would transport the debris outside the enclosure. For light-weight (< 100 lb_m/ft^3) caulking, signs or tags that are located outside enclosures, testing must be performed that subjects the caulking, signs, or tags to conditions that bound the AP1000 conditions and demonstrates that debris would not be transported to an AP1000 screen or into the core through a flooded break. Note that in determining if there is sufficient water flow to transport these materials, consideration needs to be given as to whether they are within the ZOI (for the material used) because that determines whether they are in their original geometry or have been reduced to smaller pieces. It would also have to be shown that the material used would not generate chemical debris. In addition, the testing must be approved by the NRC.

12. An evaluation consistent with Regulatory Guide 1.82, Revision 3, and subsequently approved NRC guidance, has been performed (Reference 3) to demonstrate that adequate long-term core cooling is available considering debris resulting from a LOCA together with debris that exists before a LOCA. As discussed in subsection 6.3.2.2.7.1, a LOCA in the AP1000 does not generate fibrous debris due to damage to insulation or other materials included in the AP1000 design. The evaluation considered resident fibers and particles that could be present considering the plant design, location, and containment cleanliness program. The determination of the characteristics of such resident debris was based on sample measurements from operating plants. The evaluation also considered the potential for the generation of chemical debris (precipitants). The potential to generate such debris was determined considering the materials used inside the AP1000 containment, the post-accident water chemistry of the AP1000, and the applicable research/testing.

    The evaluation considered the following conservative considerations:

    - [*The COL cleanliness program will limit the total amount of resident debris inside the containment to ≤ 130 pounds and the amount of the total that might be fiber to ≤ 6.6 pounds.*]*

    - In addition to the resident debris, the LOCA blowdown jet may impinge on coatings and generate coating debris fines, which because of their small size, might not settle. The amount of coating debris fines that can be generated in the AP1000 by a LOCA jet will be limited to less than 70 pounds for double-ended cold leg and double-ended direct vessel injection LOCAs. In evaluating this limit, a ZOI of 4 IDs for epoxy and 10 IDs for inorganic zinc will be used. A DEHL LOCA could generate more coating debris; however, with the small amount of fiber available in the AP1000 following a LOCA, the additional coating debris fines that may be generated in a DEHL LOCA are not limiting.

    - The total resident and ZOI coating debris available for transport following a LOCA is ≤ 193.4 pounds of particulate and ≤ 6.6 pounds of fiber. The percentage of this debris that could be transported to the screens or to the core is as follows:

        – Containment recirculation screens is ≤ 100 percent fiber and particles

- IRWST screens is ≤ 50 percent fiber and 100 percent particles
- Core (via a direct vessel injection or a cold leg LOCA break that becomes submerged) is ≤ 90 percent fiber and 100 percent particles

- Fibrous insulation debris is not generated and transported to the screens or into the core as discussed in Item 3.
- Metal reflective insulation, including accident generated debris, is not transported to the screens or into the core.
- Coating debris is not transported to the screens or into the core as discussed in Item 1.
- Debris from other sources, including caulking, signs, and tags, is not generated and transported to the screens or into the core as discussed in Item 11.
- <u>A ZOI radius of 4D will be used for AP1000 in-containment cables, where D is determined using a mechanistic pipe break methodology (Reference 5).</u>
- The total amount of chemical precipitates that could form in 30 days is ≤ 57 pounds.
- The percentage of the chemical precipitates that could be transported to the:
  - Containment recirculation screens is ≤ 100 percent.
  - IRWST screens is ≤ 100 percent.
  - Core is ≤ 100 percent.
- The range of flow rates during post-LOCA injection and recirculation is as follows:
  - CR screens: 2320 to 539 gpm
  - IRWST screens: 2320 to 464 gpm
  - Core: 2012 to 484 gpm

  These flows bound operation of the PXS and the RNS. Note that if the RNS operates during post-LOCA injection or recirculation, the RNS flow is limited to 2320 gpm. This limit ensures that the operation of the plant is consistent with screen head loss testing. In addition, the screens will be designed structurally to withstand much higher flow rates and pressure losses to provide appropriate margin during PXS and RNS operation.

  No chemical precipitates are expected to enter the IRWST because the primary water input to the IRWST is steam condensed on the containment vessel. However, during a direct vessel injection LOCA, recirculation can transport chemical debris through the containment recirculation screens and to the IRWST screens. As a result, 100 percent of the chemical debris is conservatively assumed to be transported to the IRWST screens.

The AP1000 containment recirculation screens and IRWST screens have been shown to have acceptable head losses. The head losses for these screens were determined in testing performed using the above conservative considerations. It has been shown that a head loss of 0.25 psi at the maximum screen flows is acceptable based on long-term core cooling sensitivity analysis.

Considering downstream effects as well as potential bypass through a cold leg LOCA, the core was shown to have acceptable head losses. The head losses for the core were determined in testing performed using the above conservative considerations. It has been shown that a head loss of 4.1 psi at these flows is acceptable based on long-term core cooling sensitivity analysis.

6.3.8.2 Verification of Water Sources for Long-Term Recirculation Cooling Following a LOCA

The Combined License information requested in this subsection has been fully addressed in APP-GW-GLR-079 (Reference 3), and the applicable changes are incorporated into the DCD. The design of the recirculation screens is complete. Testing to assess the screen performance and downstream effects is complete. A study of the effects of screen design and performance on long-term cooling is complete. No additional work is required by the Combined License applicant to address the aspects of the Combined License information requested in this subsection.

The following words represent the original Combined License Information Item commitment, which has been addressed as discussed above:

> The Combined License applicants referencing the AP1000 will perform an evaluation consistent with Regulatory Guide 1.82, Rev.n 3, and subsequently approved NRC guidance, to demonstrate that adequate long-term core cooling is available considering debris resulting from a LOCA together with debris that exists before a LOCA. As discussed in DCD subsection 6.3.2.2.7.1, a LOCA in the AP1000 does not generate fibrous debris due to damage to insulation or other materials included in the AP1000 design. The evaluation will consider resident fibers and particles that could be present considering the plant design, location, and containment cleanliness program. The determination of the characteristics of such resident debris will be based on sample measurements from operating plants. The evaluation will also consider the potential for the generation of chemical debris (precipitants). The potential to generate such debris will be determined considering the materials used inside the AP1000 containment, the post-accident water chemistry of the AP1000, and the applicable research/testing.

6.3.9 References

1. WCAP-8966, "Evaluation of Mispositioned ECCS Valves," September 1977.

2. WCAP-13594 (P), WCAP-13662 (NP), "FMEA of Advanced Passive Plant Protection System," Revision 1, June 1998.

3. APP-GW-GLR-079, "AP1000 Verification of Water Sources for Long-Term Recirculation Cooling Following a LOCA," Westinghouse Electric Company LLC.

4. APP-GW-GLN-147, "AP1000 Containment Recirculation and IRWST Screen Design," Westinghouse Electric Company LLC.

5. WCAP-17938 (P), "AP1000 In-Containment Cables and Non-Metallic Insulation Debris Assessment", Revision 0, March 2015.