ENCLOSURE 4

APP-GW-GLR-079-NP

Revision 3

"AP1000 Verification of Water Sources for Long-Term Recirculation Cooling Following a LOCA"

Technical Report 26

(Non-Proprietary)

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****Plant Applicability**: ☒ All AP1000 plants except: No Exceptions
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AP1000 Standard Combined License Technical Report

AP1000 Verification of Water Sources for Long-Term Recirculation Cooling Following a LOCA

Revision 3

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I. INTRODUCTION

This technical report provides the information for closing the following Combined Operating License (COL) Information Item from APP-GW-GL-700, AP1000 Design Control Document (DCD), Revision 15:

COL Information Item	Design Control Document Section and Title	Description
6.3-2 Verification of Containment Resident Particulate Debris Characteristics	6.3.8.2 Verification of Water Sources for Long Term Recirculation Cooling Following a LOCA	The Combined License applicants referencing the AP1000 will perform an evaluation consistent with Regulatory Guide 1.82, revision 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.

In addition, this technical report presents an additional requirement to COL Information Item 6.3-1, shown here as it currently appears in DCD Revision 15:

COL Information Item	Design Control Document Section and Title	Description
6.3-1 Containment Cleanliness Program	6.3.8.1 Containment Cleanliness Program	The Combined License applicants referencing the AP1000 will address preparation of a program to limit the amount of debris that might be left in the containment following refueling and maintenance outages. The cleanliness program will limit the storage of

		outage materials (such as temporary scaffolding and tools) inside containment during power operation consistent with COL item 6.3.8.2.

The additional requirement is that the containment cleanliness program must provide cleanliness conditions consistent with the conditions used for this evaluation.

Based on this report, the NRC should consider the above COL Information Item closure to be acceptable and generally applicable to COL applications referencing the AP1000 design certification.

This technical report has been updated to include information from the three following sources:

1. Head loss testing that was done specifically for AP1000.
2. A downstream effects evaluation of the impact on the Passive Core Cooling System (PXS) equipment.
3. A downstream effects evaluation of the chemical deposition on the fuel following a LOCA.

Specific Containment Recirculation and In-Containment Refueling Water Storage Tank (IRWST) screen design information is contained in Technical Report 147 (Reference 2). The head loss test results are reported in WCAP-16914-P (Reference 9).

II. REFERENCES

1. Nuclear Regulatory Commission Regulatory Guide 1.82, Rev.3, "Water Sources for Long-Term Recirculation Cooling Following a Loss-of-Coolant Accident, November 2003
2. APP-GW-GLN-147, Revision 1, Technical Report 147, "AP1000 Containment Recirculation and IRWST Screen Design", February 2008
3. Nuclear Regulatory Commission Generic Letter GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized-Water Reactors," September 2004
4. NEI 02-01, Rev. 1, "Condition Assessment Guidelines: Debris Sources Inside PWR Containments," September 2002
5. NEI 04-07, Revision 0 "Pressurized Water Reactor Sump Performance Evaluation Methodology", December 2004
6. NUREG-1793, "Final Safety Evaluation Report Related to Certification of the AP1000 Standard Design," September 2004
7. WCAP-16530-NP, Revision 0, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," February 7, 2006
8. NUREG/CR-6224, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris," October 1995
9. WCAP-16914-P, Revision 0, "Evaluation of Debris Loading Head Loss Tests for AP1000 Recirculation Screens and In-containment Refueling Water Storage Tank Screens," March 2008
10. WCAP-16914-NP, Revision 0, "Evaluation of Debris Loading Head Loss Tests for AP1000 Recirculation Screens and In-containment Refueling Water Storage Tank Screens," March 2008
11. WCAP-16406-P, Revision 1, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191," September 2007
12. U.S. Nuclear Regulatory Commission Safety Evaluation on WCAP-16406-P, Revision 1, "Evaluation of Downstream Sump Debris Effects in Support of GSI-191," September 2007
13. WCAP-16793-NP, Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," June 2007
14. APP-GW-GLE-002, Revision 0, "Impacts to the AP1000 DCD to Address Generic Safety Issue (GSI)-191", March 2008
15. NEI 04-07, Revision 0 "Pressurized Water Reactor Sump Performance Evaluation Methodology", December 2004

III. TECHNICAL BACKGROUND

The AP1000 Nuclear Power Plant uses natural recirculation for cooling the core following a loss of coolant accident (LOCA). This capability of the AP1000 plant is presented in the design control document (DCD).

The containment recirculation sump for the AP1000 is the loop compartment. Screens are provided in strategic areas of the loop compartment to remove debris that might migrate with the water in containment and adversely affect core cooling. Accordingly, it must be assured that the screens themselves are not susceptible to plugging.

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This technical background section has three major sections. The first section describes the AP1000 Post-LOCA screen performance evaluation. The second section describes the head loss testing that was performed specifically for the AP1000. The final section describes the "downstream effects" calculations that were performed for AP1000. Two different evaluations were performed; the first described the "ex-vessel" effects, i.e. those that occur in the piping and valves of AP1000's long term recirculation flow path. The second, determines the amount of chemical deposition that can occur on the fuel rods during long term core cooling.

IV. AP1000 SCREEN DESIGN

The AP1000 has two Containment Recirculation Screens and two IRWST Screens. Consistent with the response of the nuclear industry to NRC guidance on the evaluation of sump screens, the AP1000 screen sizes have been made significantly larger. This increase is judged to be prudent because of the standardized approach for the AP1000 design, the potential for additional industry testing and regulatory guidance, and the reduced impact of incorporating larger screens at this time.

The AP1000 screen designs have complex geometries; the design of these screens is described in detail in Reference 2.

V. AP1000 POST-LOCA SCREEN PERFORMANCE EVALUATION

Introduction

The AP1000 containment building is designed both to contain radioactive material releases and to facilitate long term core cooling in the event of a LOCA. Water discharged from a break is collected in the lower portion of the containment for recirculation to the core by the PXS as described in DCD Section

6.3.2.1.3. The AP1000 Containment Recirculation Screens protect the flow path and components of the PXS from debris that is generated by a postulated pipe break and any debris that is being transported in the recirculating water.

The NRC identified its concern regarding maintaining adequate long-term core cooling in Generic Safety Issue (GSI)-191 Assessment of Debris Accumulation on PWR Sump Performance and Generic Letter (GL) 2004-02 (Reference 3), issued in September 2004, identified actions that utilities must take to address the sump blockage issue. The NRC position is that plants must be able to demonstrate that debris transported to the sump screen after a LOCA will not lead to unacceptable head loss for the recirculating flow. For the AP1000, this requirement is interpreted as demonstrating that debris transported to recirculating screens will not significantly impede flow through the PXS and will not adversely affect the long-term operation of the PXS.

Applicability to the AP1000 Design

The AP1000 design minimizes the potential for a LOCA to generate debris that might challenge the recirculation flow path:

- Because passive safety systems are used and because there is no containment spray system used during a design basis accident (DBA) LOCA, the recirculation flow velocities are low thus minimizing the potential for debris transport. The AP1000 does have a non-safety containment spray capability (injection only) which is provided for use in a severe accident. This capability is manually actuated (requiring a locked closed manual valve to be opened). Operating procedures prevent its use during a DBA.
- The flow velocities have been reduced further by the increase in face area of the screens (approximately 55% larger for containment recirculation).
- Metal reflective insulation (MRI), which contains no fibrous material, is used on components that may be subjected to jet impingement loads; MRI is not transported to the AP1000 Containment Recirculation Screens with these low flow rates. As a result, there is no fibrous debris generated by the LOCA blowdown.
- Other insulation inside containment outside the zone of influence is jacketed or not submerged.
- Protective plates guard the Containment Recirculation Screens against coatings and other debris from falling onto or just in front of the Containment Recirculation Screens and being transported to the screens. These plates are described in detail in Reference 2.
- Screen area is exceptionally large to provide for the collection of debris on the screens without impacting recirculation flow.

Two sources of potential debris are therefore evaluated for impact to the AP1000 recirculation flow path. These sources are:

1. Latent containment debris. Latent containment debris, or resident containment debris as it is sometimes called, is dirt, dust, lint and other miscellaneous materials that might be present inside containment at the initiation of a LOCA. The concern is that latent debris might be present in large enough quantities to collect on screen-like surfaces and inhibit flow through them.
2. Post-accident chemical effects. Post-accident chemical effects are the result of containment sump

fluid reacting chemically with materials inside containment and producing chemical products (precipitants). The concern is that chemical products might be generated in sufficient quantities to collect on screen-like surfaces (or on fiber beds on screen-like surfaces) and challenge their ability to pass flow.

The following is an evaluation of both the latent containment debris and chemical products that may be present inside the AP1000 containment in the unlikely event of a LOCA, and an assessment of their impact on the recirculation flow path performance.

Evaluation Approach

The evaluation was performed in four steps:

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2. The post-accident chemical products were estimated using a tool generated by the PWR Owners Group and design features of the AP1000.

3. The resulting head loss from the transport and collection of latent debris and post-accident chemical products on AP1000 recirculation flow paths was evaluated using a head-loss code obtained from the NRC.

4. Head loss testing was performed to validate the results of the calculations.

The following summarizes the evaluations performed for each of the above steps.

Latent Containment Debris Evaluation

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- Specific consideration of "resident" debris - both fiber-form and particulate debris that accumulates on surfaces during plant construction, testing, and operations.
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- The potential for the generation of chemical debris (precipitants).

- A containment cleanliness program that limits the types and amounts of resident debris in the AP1000. This report adds that the containment cleanliness program must limit resident debris to be consistent with this evaluation.

Containment in existing operating plants and in AP1000 was categorized into four general types of surfaces:

1. Horizontal surface areas
2. Walls
3. Equipment
4. Piping

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Debris present on the various containment surfaces and components can be transported within the AP1000 containment by four different mechanisms: immersion in a pool of slowly-moving water, jetting of steam/water mixtures expelled through the break, wetting from liquid drops (caused by condensation and not by containment spray) falling from the containment dome (center region) and water film flowing down the containment walls during passive containment cooling system (PCS) operation. It is important to note that during PCS operation the majority of condensation is returned to the IRWST via filming on the walls and not through drops from the dome. For different postulated break locations, the total mass of latent containment debris divides into three categories: debris that can migrate to the Containment Recirculation Screens, debris that can migrate to the IRWST Screens, and debris that does not transport to either set of screens. For this evaluation, the debris that can migrate to either set of screens is considered. It is noted that the Westinghouse AP1000 design differs from the current PWR designs in that there is no containment spray that can be used during a LOCA.

Break Selection Criteria

The industry has provided guidance in Reference 5 for the selection of break location within a pressurized water reactor (PWR) and its effect on debris generation and composition. Westinghouse has reviewed Reference 5 and applied the applicable portions to AP1000. It should be noted that much of the criteria in Reference 5 is intended to determine the break locations that produce limiting amounts and compositions of debris that can be generated and transported to the screens. The situation is different for the AP1000 because of its design.

In the AP1000, different LOCA break locations do not generate different amounts and compositions of debris that are transported to the screens. The reason for this is that AP1000 does not use the types of insulation (such as fiberglass) that can be damaged by a LOCA jet and transported to the screens. Therefore debris generated by fibrous insulation is not a consideration in this analysis as stated in NUREG-1793 (Reference 6). AP1000 uses MRI insulation in the location where it may be damaged by LOCA jets. The density of the MRI material ensures that any debris generated by the damage of this insulation material to settle in the containment sump and not be transported onto the screens.

The only debris that can be transported to the AP1000 screens post LOCA is resident debris. As a result, Westinghouse modified the selection criteria to determine the maximum amount of latent debris that can be transported to the containment recirculation, IRWST screens as well as to the core. Westinghouse determined the break locations that would transport the limiting amount of resident debris to the three different locations (Containment Recirculation Screens, IRWST Screens and core).

The following lists the three break locations that resulted in the limiting amount of debris to be transported to the two sets of screens and the core.

1. A break of a DVI line at the reactor vessel, produces the maximum debris that may be transported to the core because the break becomes flooded which allows some debris to bypass the Containment Recirculation Screens.
2. A break in the automatic depressurization system (ADS) stage 1, 2, 3 lines near the top of the pressurizer produces the maximum debris that may be transported to the IRWST Screens Because it is assumed to wash part of the operating deck into the IRWST.
3. A break on the inlet line of a core makeup tank (CMT) produces the maximum debris that may be transported to for the Containment Recirculation Screens because water is assumed to flow down the CMT and into a PXS room.

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As the tables show, approximately 24 lb_m of latent debris would be expected to be transported to the AP1000 Containment Recirculation Screens through direct impingement, immersion or from being washed down during a high energy line break. Similarly, approximately 5 lb_m of latent debris would be expected to migrate to the AP1000 IRWST Screens through direct impingement, immersion or from being washed down during a high energy line break. As the tables show, the percentages based on the estimated volumes convert to approximately 85% particulates, approximately 14% coatings, and less than 1% fiber based on mass.

Table 1: Containment Recirculation Screens

Debris Type	Density (lb_m/ft^3)	% Volume	Volume of Debris (ft^3)	% Mass	Mass of Debris (lb_m)
Latent Particulate	100.00	85.00	0.21	85.85	20.52
Coatings (epoxy)	94.00	2.50	0.01	2.37	0.57
Coatings (IOZ)	457.00	2.50	0.01	11.54	2.76
Latent Fiber	2.40	10.00	0.02	0.24	0.06
Totals		100.00	0.24	100.00	23.91

Table 2: IRWST Screens

Debris Type	Density (lb_m/ft^3)	% Volume	Volume of Debris (ft^3)	% Mass	Mass of Debris (lb_m)
Latent Particulate	100.00	85.00	0.05	85.85	4.67
Coatings (epoxy)	94.00	2.50	0.00	2.37	0.13
Coatings (IOZ)	457.00	2.50	0.00	11.54	0.63
Latent Fiber	2.40	10.00	0.01	0.24	0.01
Totals		100.00	0.05	100.00	5.44

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Table 3: Debris Loadings Used in Head Loss Evaluation for Containment Recirculation Screens, IRWST Screens and Bottom of Fuel

Screen Type	Total Latent Containment Debris Applied to Screen (lb_M)	
	Best Estimate, Based on Average Walkdown Values	Bounding Case, Based on Maximum Walkdown Values
Recirculation Screens	23.91	82.0
IRWST Screens	5.44	17.0
Core	14.35	49.2

Note that the debris reaching the core is based on a DVI LOCA in the loop compartment. For this event the containment water level rises above the break so that some water can enter the reactor coolant system (RCS) directly and thereby bypass the Containment Recirculation Screens. It is calculated for such an event that no more than 60% of the total recirculation flow will bypass the screens. As a result, the core debris is set at 60% of the Containment Recirculation Screen amount.

The debris for all screens will have the same makeup as discussed previously: approximately 85% particulates, 5% coatings, and less than 10% fiber by volume or approximately 85% particulates, 14% coatings and 1% fiber by mass. Note that rounding upward to 1% fiber by mass adds additional conservatism in the assumed amount of fiber.

It is expected that AP1000 would have debris amounts close to the Best Estimate amounts but potentially slightly higher because averages were used for each area. The Bounding Case amounts, however, are expected to conservatively bound the expected AP1000 amounts.

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Post-Accident Chemical Effects

A consideration in evaluating the effects of the debris transported to the sump after a LOCA is the chemical products which may form in the post-LOCA sump environment. Materials present in containment may dissolve or corrode when exposed to the reactor coolant. This reaction would result in oxide particulate corrosion products and the potential for the formation of precipitants due to changes in temperature and reactions with other dissolved materials. These chemical products could become another source of debris loading and impact sump screen performance and recirculation flow.

An analysis was performed to determine the type and quantity of chemical precipitants which may form in the post-LOCA recirculation fluid for the AP1000 design. The analysis evaluated these post-LOCA chemical effects using the methodology developed in WCAP-16530-NP, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191" (Reference 7). The purpose of the bench testing and calculation methods documented in WCAP-16530-NP was to characterize the type and quantity of precipitates formed using a chemical model evaluation, and to support the downstream effects evaluation using the chemical precipitates predicted in the chemical effects model. These data and methods have been used to evaluate post-accident chemical affects and support sump screen performance testing for operating PWRs. These data and methods are applicable to the AP1000 for the following reasons;

1. The base chemical composition of the containment materials in the AP1000 was identified consistent with the classification groups listed in WCAP-16530-NP.
2. The sump temperature transient is within the bench test temperature range of 140 °F to 270 °F for more than 99.5% of the 30 days evaluated.
3. The sump pH transient for the AP1000 is within the range of 4.1 to 12.0 evaluated in WCAP-16530-NP.
4. The buffering agent for the PXS in the AP1000 plant is trisodium phosphate dodecahydrate (TSP) which was one of the buffering agents included in the bench testing.

Therefore, considering the above, the data and calculation methods described in WCAP-16530-NP are clearly applicable to the AP1000 design.

Table 4 lists the predicted precipitants for the AP1000 chemical model evaluation using conservative containment material amounts. The results have been calculated using the minimum post-accident recirculation volume of coolant for the AP1000. Table 4 also lists the chemical precipitants in terms of a mass concentration using the minimum recirculation water volume.

Table 4: AP1000 Predicted Chemical Precipitate Formation

Precipitants	kg	lb	ppm
$NaAlSi_3O_8$	1.5	3.3	0.6
AlOOH	19.7	43.4	8.3
$Ca_3(PO_4)_2$	0.5	1.1	0.2

Note that the AP1000 has several features that significantly reduce the amounts of materials that could contribute to the formation of chemical precipitants. The AP1000 containment has little concrete that can come in contact with the post accident water as a result of the use of structural steel module construction. The only identified aluminum in the AP1000 containment is in the excore detectors. These detectors are enclosed in stainless steel so that post accident containment water will not circulate against the aluminum. The AP1000 DCD Tier 1 Table 2.2.3 item 8c) xiv) has been revised by Reference 14 to require inspection of the excore detectors and ensure that they are enclosed in stainless steel. A limited amount of aluminum has been arbitrarily included in the above calculations for conservatism.

A sensitivity evaluation was also performed to determine the additional precipitant generation that might occur from zinc materials in containment being exposed to the sump liquid. This sensitivity determined that less than 1 kg of zinc is released into solution when the limiting case with contingency was considered. This amount is relatively small and is determined to be negligible to the overall precipitant generation.

This evaluation shows that the potential amount of chemical precipitants available in the AP1000 containment is significantly lower than in current plants.

Head Loss Calculations

The effect of latent containment debris on the performance of equipment used in post-LOCA recirculation is a part of the GSI-191 issue for the PWR Industry. In recent years, much data has been collected and programs have been developed to determine the amount and effects of latent debris on post-LOCA equipment and to mitigate the negative effects of that latent debris. One effect of latent debris in post-LOCA recirculation mode is the head loss due to debris building up on screens. A large loss of head across Containment Recirculation Screens could restrict the AP1000 recirculation flow required to cool the core effectively.

The pressure drop across the AP1000 Containment Recirculation Screens due to latent debris building up on the screen under natural circulation conditions was calculated. Calculations were also made for pressure drop across the AP1000 IRWST Screens resulting from latent containment debris accumulation on the screen under accident conditions. Finally, calculations were made for pressure drops at the AP1000 core resulting from debris accumulation on the bottom of the fuel. The reason for considering debris accumulation on the fuel is that for a DVI line break there is a potential for some flow from the sump to bypass the Containment Recirculation Screens by flowing into the reactor vessel downcomer directly through the break location. To evaluate the resulting head loss, the bottom nozzles of the fuel were treated as a screen.

The head loss correlation used to evaluate the head loss across the AP1000 Containment Recirculation Screens was the NUREG/CR-6224 correlation (Reference 8). The application of the NUREG/CR-6224 correlation is conservative for and applicable to the AP1000 for the following reasons:

- The NUREG/CR-6224 head loss correlation was developed for reactor building containment sump screens with a contiguous fiber bed.
  - Several types of fibrous materials were used to construct the beds used in the development of NUREG/CR-6224 head loss correlation, including fiberglass.
  - The NUREG/CR-6224 head loss correlation was developed in a vertical loop with comparatively high velocity downward flow compressing the fibrous and particulate debris bed. For the AP1000 design, the Containment Recirculation Screens would be vertical with low velocity flow through the screens that precludes debris bed compression observed in the testing used to develop the NUREG/CR-6224 head loss correlation.
- The only source of fibrous debris in the AP1000 design is from resident containment debris.
  - An evaluation of the deposition of expected resident fibrous debris for the AP1000 design on the Containment Recirculation Screens determined that there was an insufficient volume of fibrous debris to develop a uniform fiber bed equal to or greater than the ⅛ inch depth generally accepted as needed for a contiguous fiber bed on a sump screen. See Table 5 below.
  - By the NRC Safety Evaluation on NEI 04-07 (Reference 5), the fibrous component of resident containment debris is treated as fiberglass.
  - Without a contiguous fiber bed, the AP1000 Containment Recirculation Screens provide "clean screen" area; that is, there is screen area through which flow is unimpeded by a fibrous bed. This "clean screen" results in head losses lower than those predicted by the NUREG/CR-6224 head loss correlation.

Considering the items above, the NUREG/CR-6224 head loss correlation is not only applicable, but its application to the AP1000 design is conservative.

Two latent containment debris loading cases were evaluated:

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The amount of debris applied to the screen surfaces was apportioned based on flow to these surfaces.

Table 5 provides the debris loadings used for the Sensitivity Case as compared with the Table 3 debris loadings.

Table 5: Debris Loadings Used in Head Loss Evaluation for Containment Recirculation Screens, IRWST Screens and Bottom of Fuel

Screen Type	Total Latent Containment Debris Applied to Screen (lb_M)		
	Best Estimate, Based on Average Walkdown Values	Bounding Case, Based on Maximum Walkdown Values	Sensitivity Case
Recirculation Screens	23.91	82.0	165.0
IRWST Screens	5.44	17.0	35.0
Core	14.35	49.2	99.0

Table 6 summarizes the results of calculations performed for the AP1000 using the above debris loadings. Note that a calculated uncompacted fiber bed thickness of 0.125 inches is generally accepted as being required to form a debris bed.

Table 6: Summary of Head Losses for AP1000 PXS Containment Recirculation Screens, IRWST Screens and Core

Screen	Case	Screen Debris (lb)	% Fiber by Mass	Head Loss (ft_{H2O})	Calculated Uncompacted Bed Thickness (in.)
Containment Recirculation Screen	Bounding	82	1%	0.00	0.0008
	Sensitivity	165	1%	0.00	0.025
IRWST Screen	Bounding	17	1%	0.00	0.0017
	Sensitivity	35	1%	0.00	0.0122
Core	Bounding	49.2	1%	0.00	0.0387
	Sensitivity	99	1%	0.00	0.0780

From Table 6 the following conclusions are drawn:

For the Containment Recirculation Screens and the IRWST Screens:

- Because the calculated uncompacted bed thickness is less than 0.125 inches, there is insufficient fiber to form a continuous fiber bed on either screen.
- Since a continuous fiber bed cannot be formed, there would be "clean screen" area available.
- The availability of clean screen area and the small amount of post-accident chemical products predicted for the AP1000 design indicate that post-accident chemical precipitants will not challenge the flow through either the Containment Recirculation screen or the IRWST Screen.
- The resulting head loss across these screens is negligible.

For the Core:

- There is insufficient fiber to form a continuous fiber bed on the bottom of the fuel.
- Since a continuous fiber bed cannot be formed, there would be "clean screen" area available on the bottom of the fuel.
- The availability of clean screen area and the small amount of post-accident chemical products predicted for the AP1000 design indicate that post-accident chemical precipitants will not challenge the flow through the fuel.
- The resulting head loss at the bottom of the fuel is negligible.

Therefore, the existence of latent debris in containment and the formation of chemical products due to the post-accident reaction of materials that contact coolant collected on the containment floor are evaluated to not have an adverse impact on the performance of the PXS. Also, as the AP1000 Containment Recirculation Screens evaluation demonstrates that there is insufficient fiber available within the AP1000 containment to form ⅛ inch fiber bed on the Containment Recirculation Screens. This calculated information is supported by the AP1000 head loss testing results presented in the following section.

VI. AP1000 HEAD LOSS TESTING

Head loss experiments were conducted for AP1000 as part of the response for the AP1000 design to GSI-191 and Generic Letter (GL) 2004-02 (Reference 3). References 9 and 10 provide a detailed description of the head loss testing. The performance of the Containment Recirculation Screens was demonstrated under debris loading conditions (including chemical effects) that include a spectrum of AP1000 specific debris loadings. This debris loading includes particulates, fibrous materials, as well as chemical precipitates that may form in the containment water pool.

Discussion

The testing performed used a "pocket" type of screen design that is consistent with the design described in TR-147 (Reference 2). The flow rates and debris loading conditions were selected conservatively so that they bound those expected to be experienced by both the Containment Recirculation Screens and the In-Containment Refueling Water Storage Tank Screens following a postulated Loss of Coolant Accident (LOCA) for the AP1000. As the debris loading and fluid velocities bounded the conditions for both the Containment Recirculation and the In-Containment Refueling Water Storage Tank Screens, the data collected from this program is applicable to both screens.

Clean screen head loss behavior was tested over a range of flow rates that bound the flow rates of the AP1000 design. Three head loss tests, a design basis test and two sensitivity tests, were performed that investigated a spectrum of debris inventories, debris staging, chemical effects and flow rates. From the design basis test, it was concluded that acceptable head loss values were obtained for the tested sets of debris sources. The two sensitivity tests were performed to demonstrate the margin available in the AP1000 design. These head loss tests were performed under the Westinghouse Quality Management System (QMS) requirements and are documented in WCAP-16914-P and WCAP-16914-NP, References 9 and 10, respectively.

The data from this test program demonstrated the ability of the Containment Recirculation and the In-Containment Refueling Water Storage Tank Screens to successfully perform their design functions under debris loading conditions expected for the AP1000 following a postulated LOCA. Three head loss tests were performed to investigate the following conditions; 1) design basis latent and chemical effects, 2) double the design basis latent and chemical effects, and 3) double the design basis latent and 18 times the design basis chemical effects.

The test results demonstrate that, for the latent debris and post-accident chemical debris loads included in the test program, there is insufficient debris in the AP1000 design to form a contiguous debris bed on the screens. Test results showed very low head losses that were close to that of a clean screen. Data from the test with design basis amount of debris resulted in a screen head loss that was only about 1/8" of water greater than was measured for in the clean screen test. In addition, the data from a sensitivity test with twice the latent debris and 18 times the chemical effects debris relative to the design basis test case showed a similar increase in the head loss compared with a clean screen.

The testing also demonstrates that the AP1000 design provides for considerable margin in screen performance for the following reasons:

- The AP1000 passive safety systems utilize low recirculation flow rates, no containment spray during a LOCA, deep containment flood up levels and delayed initiation of recirculation operation;
- The AP1000 design utilizes large screen areas;
- The AP1000 design eliminates thermal insulation loading from fiberglass and minimizes thermal insulation loading from Min-K;
- The AP1000 design reduces the generation of post-accident chemical effects debris; and
- The good housekeeping practices required by COL item 6.3.8.1 will limit the amount of latent or resident containment debris.

The testing performed conservatively bounds the flow and debris loading conditions expected to be experienced by both the Containment Recirculation Screens and the In-Containment Refueling Water Storage Tank Screens. The data from this test program demonstrated the ability of the Containment Recirculation Screen and the In-Containment Refueling Water Storage Tank Screen to successfully perform its design function under debris loading conditions expected for the AP1000 following a postulated LOCA. Furthermore, as the test conditions bound the flow and debris conditions that both the Containment Recirculation and the In-Containment Refueling Water Storage Tank screens would experience in the recirculation mode following a postulated LOCA. The data applies to both of those screens.

Summary

The testing performed for the AP1000 Containment Recirculation Screen design demonstrates the pocket-design screens of the Containment Recirculation and the In-Containment Refueling Water Storage Tank Screens will not develop head losses due to debris collection that will challenge either long-term core cooling or maintaining a coolable core geometry under the expected AP1000 debris loading conditions. This result confirms the calculated head loss presented in this report.

VII. AP1000 DOWNSTREAM EFFECTS EVALUATION

The term, "downstream effects" refers to effects of debris that is ingested through the recirculation screens on systems, structures and components located downstream of the recirculation screens. These effects are evaluated for operating plants to support closure of GSI-191 using data and methods and developed by the PWR Owners Group. There are two evaluations that were performed for the AP1000 downstream effects evaluation. The first evaluation describes the effects of debris on the system and components outside the core. This evaluation looks specifically at the disruption of the long term core cooling flow path (outside the core) by debris. The second downstream effects evaluation performed for AP1000 conservatively calculated the amount of chemical deposition that can occur on the fuel rods following a LOCA and subsequent boiling in the core. The AP1000 is unique in the fact that throughout a LOCA the ADS stage 4 lines will vent significant quantities of water as well as steam. This venting of water significantly reduces the concentration of chemicals (boron, TSP, etc.) in the core. AP1000 DCD Tier 2 Section 15.6.5.4C.4 captures this effect as it has been applied to boron buildup following a LOCA. As a result of this characteristic hot leg recirculation is not provided in the AP1000.

Ex-Vessel Downstream Effects Evaluation Method

The data and methods used to evaluate ex-vessel downstream effects are outlined in Revision 1 of WCAP-16406-P (Reference 11). The evaluation methods identified in WCAP-16406-P Revision 1 that are applicable to long-term core cooling recirculation flow paths associated with the AP1000 design include:

- The fuel blockage evaluation as described in Section 5. This particular downstream effects evaluation method addresses the core evaluation from the NRC comment.
- Valve evaluations for plugging and erosive wear as described in Sections 7 and 8 and Appendix F. The screening criteria for valves that are identified in Revision 1 to WCAP-16406-P are applicable to valves in the long-term core cooling recirculation flow path of PWRs. Only the explosively actuated (squib) valves in the post-LOCA flow path are not covered by the screening criteria. Once the squib valves are open they exhibit, very closely, the characteristics of a standard gate valve.

There are design features of the AP1000 that eliminate the need for downstream effects evaluations of components that are included in Revision 1 of WCAP-16406-P. Evaluations excluded by the AP1000 design include:

- Pump evaluations, including hydraulic performance, disaster bushing performance, and vibration analysis. There are no safety related pumps in the AP1000 passive core cooling flow paths to evaluate.
- Heat exchanger evaluations for both plugging and erosive wear. There are no safety related heat exchangers in the AP1000 passive core cooling flow paths.
- Orifice evaluations for plugging and erosive wear as described in Sections 7 and 8 and Appendix F. There are no orifices in the post-LOCA recirculation flow path of the AP1000 design.
- Settling of debris in instrumentation lines as described in Section 8. There are no instrumentation lines used in the AP1000 post-LOCA containment recirculation flow path design that are required to support a safety related function.
- Containment Spray System (CSS). The AP1000 does not have a conventional CSS. The non-safety containment spray function is not permitted to be used during a DBA. Therefore, this system is excluded from consideration of the AP1000 design.

Thus, where applicable design features exist in the AP1000, the data and methods identified in Revision 1 of WCAP-16406-P are applied to evaluate ex-vessel downstream effects for the AP1000 design.

Ex-Vessel Downstream Effects Evaluation of AP1000 Recirculation Flow Paths

The evaluation included each valve and associated piping in the recirculation path of the PXS. The methodology and acceptance criteria used are described in WCAP-16406-P, Reference 11, consistent with the applicable amendments, limits and conditions of the NRC SE on WCAP-16406-P, Reference 12.

The equipment in the post-LOCA flow path was identified using current P&IDs for the AP1000 PXS. The AP1000 PXS P&IDs show no pumps, heat exchangers, orifices, and spray nozzles in the PXS. Therefore, although included in the method of WCAP-16406-P, the evaluation performed for the AP1000 PXS does not address pumps, heat exchangers, orifices, spray nozzles, and instrumentation tubing as these components and features are not included in the design of the AP1000 PXS. The following two tables show the components that are in the AP1000 long term core cooling flow path. Table 7 describes the containment recirculation flow path and Table 8 describes the IRWST injection flow path.

Table 7: Containment Recirculation Flow Path				
	Description	Size and Schedule (Piping / Valves)	Minimum Diameter (inches)	Note
1	Recirc Screens	-	0.0625	
2	Cross-Over Duct	7" x 10" (Rectangle)	N/A	1
3	Recirculation Pipe	10" / 8" Sch 40S	10.02 / 7.981	2
4	Gate Valve	8"	≥ 5.1	3
5	Check Valve	8"	≥ 5.1	3
6	Squib Valve	8"	≥ 5.1	4
7	DVI Pipe	8" Sch 160	6.813	-
8	Venturi	-	4.00	5

Notes

1. Two ducts connect the A and B screens each is 7" x 10".
2. The piping changes from 10" to 8" just before the containment recirculation squib valves in the PXS B subsystem.
3. The piping has two paths for each recirculation subsystem, each path travels through the following valves check or gate, squib, gate, check, and squib.
4. A squib valve, when open, has similar characteristics to a standard straight through gate valve.
5. This venturi represents the smallest passage in the recirculation piping. The venturi is used to choke reverse flow during an RCS blowdown and has no flow limiting function during recirculation.

Table 8: IRWST Injection Flow Path				
	Description	Size and Schedule (Piping / Valves)	Minimum Diameter (inches)	Note
1	IRWST Screen	-	0.0625	
2	IRWST Injection Pipe	10" Sch 40S	10.020	1
3	Reducer	10" x 8"	7.981	1
4	IRWST Injection Pipe	8" Sch 40S	7.981	2
5	Gate Valve	8"	≥ 5.1	
6	Check Valve	8"	≥ 5.1	
7	Squib Valve	8"	≥ 5.1	3
8	DVI Pipe	8" Sch 160	6.813	2
9	Venturi	-	4.00	4

Notes

1. IRWST injection pipe begins as 10" schedule 40S and reduces into 8" schedule 40 pipe.
2. The piping changes from Sch 40S to 160 downstream of the squib valves.
3. A squib valve, when open, has similar internal flow paths to a standard gate valve.
4. This venturi represents the smallest passage in the recirculation

piping. The venturi is used to choke reverse flow during an RCS blowdown and has no flow limiting function during recirculation.

In order to apply erosive and abrasive wear rate models, the debris size and concentration was first assessed. Identification of the debris types indicates that the debris appears to be made up of mostly latent debris. The latent debris is mostly particulate material, with a small amount of fibrous debris. The AP1000 design precluded transport of coatings to the Containment Recirculation Screens; a small amount of coatings debris was included in the mix for conservatism.

Each identified valve in the PXS was evaluated for plugging and wear against the applicable initial screening criteria in Reference 11. The PXS consists of open gate, check, and squib valves, all of which are greater than 1 inch based on their individual flow line diameters. Therefore, according to the initial screening criteria, the valves do not need further evaluation for plugging or wear. The squib valve design was not directly addressed in the screening criteria of Reference 11. However, the squib valves were treated as gate valves as this is the valve the squib valve most closely represents when activated.

All instrumentation sensors in the PXS recirculation lines are strapped to the outside of the piping. Therefore, there are no instrumentation tubes or sensing lines to evaluate for potential debris collection in the tubes or sensing lines. In addition, there is no reactor vessel level instrumentation system (RVLIS) or RVLIS-like system that is required to be operational post-LOCA for long-term core cooling. Therefore, no evaluation was needed.

For completeness, the potential debris collection in the PXS flow lines is evaluated. Based on the minimum flowrates for the PXS flow lines, it has been determined that the transverse velocity is sufficient to prevent debris settlement in the PXS flow lines. Therefore, blockage in PXS flow lines due to settle-out of debris is precluded.

In summary, the evaluation performed using the applicable methods and models in WCAP-16406-P (Reference 11) consistent with the applicable amendments, limits and conditions of the associated NRC SE on the WCAP (Reference 12) demonstrates that the AP1000 PXS equipment utilized in post-LOCA recirculation is acceptable for the expected debris loading in the recirculating fluid resulting from a postulated LOCA.

In-Vessel (Core) Downstream Effects Evaluation Method

With respect to downstream effects associated with the core, the potential for deposition of post-LOCA chemical products on the fuel cladding and the consequential effects on clad temperatures can be addressed using the methods developed and documented in WCAP-16793-NP (Reference 13). This evaluation method was developed to be generically applicable to all PWRs.

There is a concern that debris could also collect at the fuel assembly grids. The Nuclear Regulatory Commission (NRC) identified its concern regarding maintaining adequate long-term core cooling in GSI 191. Generic Letter (GL) 2004-02 (Reference 3), issued in September 2004, identified actions that utilities must take to address the sump screen blockage issue. The NRC's position is that plants must be able to demonstrate that debris transported to the sump screen after a LOCA will not lead to unacceptable head loss for the recirculation pumps, will not impede flow through the ECCS and CSS, and will not adversely affect the long-term operation of either the ECCS or the CSS.

To demonstrate acceptable AP1000 long term core cooling performance, an evaluation was performed to account for chemical reactions within the coolant that could lead to deposition of material within the core. The evaluation for the AP1000 accounted for the unique features of the AP1000 design. These features include the design features that significantly reduce the amounts of materials that could contribute to the formation of chemical precipitants and no containment spray during a LOCA or safety injection pumps to provide long term core cooling.

As noted in this report, the AP1000 has several features that significantly reduce the amounts of materials that could contribute to the formation of chemical precipitants. The AP1000 containment has little concrete that can come in contact with the post accident water as a result of the use of structural steel module construction. The only identified aluminum in the AP1000 containment is in the excore detectors. These detectors are enclosed in stainless steel so that post accident containment water will not circulate against the aluminum. Therefore, this mass of aluminum is excluded from the post-LOCA chemical reaction. However, for conservatism, a nominal aluminum mass of 53 lbm is used in the post-LOCA chemical reactions.

The calculation method of the LOCADM spreadsheet is described in WCAP-16793 (Reference 13). The evaluation makes some simplifications to the required inputs that are conservative for this evaluation. These data and methods are applicable to the AP1000 for the following reasons

- This evaluation effectively increases the aluminum surface area to conservatively account for the zinc release from galvanized steel. It is conservative to increase the aluminum amounts because the aluminum release rate is greater than any other material used in this evaluation. Although, the properties (i.e. rate) of core deposition for both aluminum and zinc are different, a bounding thermal conductivity for the chemical deposition on the fuel cladding is evaluated regardless of the material deposited on the core.
- This evaluation uses what is called "The Pre-Filled Reactor and Sump Option". Use of this option assumes that the entire sump volume is present in the sump at time $t = 0$, precluding the need to specify individual break flow rates. This is also conservative, as modeling the sump as full at the start of the transient allows the chemical reactions to begin at time $t = 0$ and provides for the calculation of a greater amount of precipitate deposition on the fuel.
- Although the AP1000 design precludes aluminum from contact with post accident containment recirculation fluids, this evaluation assumes a nominal aluminum mass of 53 lbm for conservatism.
- This evaluation uses a modified aluminum release method to satisfy NRC requirements in the draft Safety Evaluation prepared for WCAP-16793-NP. Including this requirement effectively doubles the release rate during the initial portion of the event as required by the NRC, yet holds fixed the total aluminum mass release. This is also conservative, as the release rate of aluminum is increased early in the transient when the deposition on the fuel is greatest due to high core decay heat rates and the boiling associated with the removal of that decay heat.
- This evaluation accounts for fibrous debris which may bypass the sump screen and be available for deposition in the core. A quantitative estimate of the effect of fiber glass on

deposit thickness and fuel temperature can be accounted for in LOCADM by use of a 'bump-up' factor. The 'bump-up' factor is applied to the initial debris load and is set such that total release of chemical products after 30 days is increased by the best estimate of the mass of the fiber glass that bypasses the sump screen. This is conservative as it allows the bypassed material to be deposited in the core in the same manner as a chemical reaction product.

The 'bump-up' factor is designed to address the possibility of fiberglass debris to bypass the sump screens in current operating plants and be available for deposition on the fuel cladding. The AP1000 plant design precludes the use of fiberglass insulation and therefore does not have a source of fiberglass debris. The inclusion of a 'bump-up' factor in this evaluation is conservative and provides margin to the evaluation of material deposited in the AP1000 core.

- This evaluation accounts for the AP1000 plant design which has automatic depressurization system (ADS) stage 4 valves in the hot-leg that, once actuated, vent significant quantities of water along with steam from the core to the containment throughout the LOCA event. This behavior was modeled in the LOCADM spreadsheet by defining core injection flowrates that exceeded the boiloff rate by an amount that was less then the amount calculated in the AP1000 long term core cooling accident analysis (DCD Tier 2 Section 15.6.5.4C). LOCADM tracks the chemical concentrations in the core region based on the relative water injection and steam/water venting.

Acceptance Criteria

As noted in Section A4 of Reference 13, the stated acceptance criterion is that the maximum cladding temperature maintained during periods when the core is covered will not exceed a core average clad temperature of 800°F [426.7 C]. This acceptance basis is applied after the initial quench of the core and is consistent with the long-term core cooling requirements stated in 10 CFR 50.46 (b)(4) and 10 CFR 50.46 (b)(5)."

An additional acceptance criterion is to demonstrate that the total debris deposition on the fuel rods (oxide + crud + precipitate) is less than 50 mils [1270 μm]. This acceptance criterion is based on Reference 4, which states that:

"The 50 mil [1270 μm] thickness is the maximum acceptable deposition thickness before bridging of adjacent fuel rods by debris is predicted to occur."

In-Vessel (Core) Downstream Effects Evaluation of AP1000

The evaluation was performed with the LOCADM spreadsheet using AP1000 plant specific data. The purpose of this evaluation was to use the LOCADM spreadsheet to predict the growth of fuel cladding deposits and to determine the clad/oxide interface temperature that results from coolant impurities entering the core following a LOCA. Three scenarios were evaluated for the AP1000 design;

1. Maximum sump volume – maximum water volume results in lower concentrations of post-accident chemical products.

2. Minimum sump volume – minimum water volume results in higher concentrations of post-accident chemical products.
3. Minimum sump volume with fibrous debris "bump-up" – minimum water volume and implementation of a "bump-up" factor results in the highest concentration of post-accident chemical products.

The AP1000 is expected to have similar or less severe results to operating plants with similar post-accident chemical loading, chemical concentrations, flowrates and core power profile. The large amount of water carryover from the ADS stage 4 lines significantly reduces the chemical concentration buildup in the core relative to operating plants. The results of this evaluation are presented in Table 9 below and discussed in the following text.

Maximum sump volume

For the maximum sump water volume case, use of the LOCADM spreadsheet predicted a maximum LOCA scale buildup of 0.4307 mils (10.94 microns). When added to the pre-accident oxide thickness of 5.984 mils (152 microns) and pre-accident crud thickness of 5.512 mils (140 microns), this yields a total of 11.93 mils (302.94 microns). This predicted deposition is significantly less than the acceptance criteria of 50 mils (1270 microns).

Minimum sump volume

For the minimum sump water volume case, use of the LOCADM spreadsheet predicted a maximum LOCA scale thickness of 0.4677 mils (11.88 microns). When added to the pre-accident oxide thickness of 5.984 mils (152 microns) and pre-accident crud thickness of 5.512 mils (140 microns), this yields a total of 11.96 mils (303.88 microns). Again, this predicted deposition is significantly less than the acceptance criteria of 50 mils (1270 microns).

Minimum sump volume with fibrous debris "bump-up"

For the minimum sump water volume case, LOCADM spreadsheet was also run with increased quantities of debris – in accordance with the "bump-up factor" methodology described in. The "bump-up factor" had a negligible effect on both the total deposition thickness and fuel cladding temperature as shown in Table 9.

Cladding Temperatures

In all three cases evaluated, the maximum temperature calculated for the outside diameter (OD) of the fuel cladding at the onset of recirculation was 304.4°F [151.3 C]. In all three cases evaluated, the temperature of the fuel clad OD was calculated to then decrease throughout the remainder of the event.

Table 9 – Results of All Cases

Case	LOCA Scale Thickness mils (microns)	Pre-Accident Deposition Thickness mils (microns)	Total Deposition Thickness mils (microns)	Max Clad Temperature °F [C]
Maximum sump volume	0.4307 (10.94)	11.50 (292)	11.93 (302.94)	304.4 [151.3]
Minimum sump volume	0.4677 (11.88)	11.50 (292)	11.96 (303.88)	304.4 [151.3]
Minimum sump volume and "bump-up"	0.4878 (12.39)	11.50 (292)	11.98 (304.39)	304.4 [151.3]

The LOCADM calculations performed for the AP1000 demonstrates that both acceptance criteria for long-term core cooling identified previously in this report are achieved. Specifically, for the three cases evaluated;

1. The maximum clad OD temperature calculated for the AP1000 of 304.4°F [151.3 C] is significantly less than the acceptance value of 800°F [426.7 C].
2. The total thickness of deposition calculated for the AP1000 fuel cladding is significantly less than the 50 mil [1270 μm] thickness at which bridging of deposited debris between adjacent fuel rods by debris is predicted to occur

Thus, the conservative calculation of deposition of post-accident chemical products on the fuel clad surface does not challenge long-term core cooling for the AP1000 design.

VIII. REGULATORY IMPACT

Design Function

The changes to the DCD presented in Reference 14 do not represent an adverse change to the design function or to how design functions are performed or controlled. The changes to the DCD do not involve revising or replacing a DCD-described evaluation methodology nor involve a test or experiment not described in the DCD. The DCD change does not require a license amendment per the criteria of VIII.B.5.b of Appendix D to 10CFR Part 52.

Severe Accident Change Criteria

The DCD changes do not result in a negative impact on features that mitigate severe accidents. There is therefore no increase in the probability or consequences of a severe accident.

Security

The closure of the COL Information Items will not alter barriers or alarms that control access to protected areas of the plant. The closure of the COL Information Items will not alter requirements for security personnel. Therefore, the closure of the COL Information Item does not have an adverse impact on the security assessment of the AP1000.