ENCLOSURE 4

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Evaluation of Debris Loading Head Loss Tests for AP1000 Simulated Fuel Assembly During Post-Accident Recirculation

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1.0 INTRODUCTION

One of the concerns for long-term core cooling following a loss of coolant accident (LOCA) is that some the fibrous material transported by the recirculation fluid might pass through the sump screen and collect at the core inlet. This debris could interact with particulates and chemical products in the coolant, causing excessive head loss. The purpose of this report is to provide test data and evaluations that demonstrate that this concern is not an issue for the AP1000.

The amount of debris (fibers, particles and chemical products) in the AP1000 that could be transported to the containment recirculation screens and into the core has been determined (Reference 1). The potential buildup of chemical deposits on the fuel have been calculated and shown to be acceptable with large margins (Reference 1). The possible head loss that could occur across the core due to the debris that could be transported to the core were estimated (Reference 1). The purpose of this report is to provide test data demonstrating that the head loss that would occur in the AP1000 due to debris entering the core would be acceptable.

2.0 BACKGROUND

The AP1000 has two Containment Recirculation Screens (CRS) and two In-Containment Refueling Water Storage Tank (IRWST) Screens. Consistent with the response of the nuclear industry to NRC guidance on the evaluation of sump screens, the AP1000 has been provided with large screens (Reference 5). [

]^{a,c}.

The primary loop of a Pressurized Water Reactor (PWR) is normally very clean and has little, if any, debris circulating in the water. However in some circumstances (such as those that follow refueling / maintenance outages), it is possible to have a small amount of debris circulating in the coolant. An example of such debris might be metal shavings from maintenance and repair. Should this debris be captured by fuel grids, the high velocity of coolant passing through the core can result in wear and fretting of the fuel clad until the cladding is breached, thereby allowing the fuel rod to "leak" radioactive material into the recirculating coolant. Current fuel designs incorporate devices to capture this debris before it enters the fuel in order to minimize or preclude such "leakers."

During a LOCA, after the initial injection of water into the reactor, water is recirculated from the water pool that forms in the containment into the reactor. The debris capturing features of the fuel would also collect debris that might enter the Reactor Coolant System (RCS) during these post-accident conditions. This is true for both current operating plants and the AP1000. For operating plants the source of debris entering the RCS is passage through the screens. For the AP1000 the limiting source of debris entering the RCS includes both passage through the screens and some bypass around the screens. Some of the recirculation water could bypass the screens and enter the RCS at a LOCA break location located below the post accident containment flood level. Note that the AP1000 has a very low debris loading by design which greatly reduces the amount of debris that could bypass around or pass through the screens. As a result, the total amount of debris entering the RCS is comparable to the amount entering operating plants. In addition, the AP1000 has much lower chemical debris loadings due to specific design features that have been incorporated such as encapsulation of the aluminum excore detectors in a non-reactive metal (SS or titanium) and the elimination of fibrous debris sources.

Depending on the amount and types of debris that could be transported to the fuel, it is possible for this debris to be captured at the entrance to the core, resulting in an increase to the flow resistance across the fuel. This increased resistance could affect the cooling of the core.

This report includes the following:

1. A summary of AP1000 core debris loading conditions during post-accident long-term core cooling recirculation operation.
2. A comparison of previous testing conducted by Westinghouse using a simulated fuel debris capture screen with the AP1000 and its post-LOCA debris loadings and operating conditions. The test conditions are shown to be conservative relative to the AP1000 debris loadings.
3. [ ][a,c].

The purpose of this report is to demonstrate that, with the debris loading and post-accident long-term core cooling recirculation flow conditions applicable for the AP1000, that long-term core cooling of the AP1000 core is not challenged.

3.0 DEBRIS LOADING FOR AP1000

Calculations were performed for the AP1000 to determine the amounts and types of debris that might collect on the recirculation screens, the IRWST screens and at the entrance to the fuel. The following sections discuss the evaluation of the types and amounts of the debris used in this calculation and described in Revision 3 of APP-GW-GLR-079 (Reference 1).

3.1 AP1000 Debris Sources

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

- Metal reflective insulation (MRI), is used on components that might be subjected to direct jet impingement loads; MRI is not transported to the AP1000 Containment Core Screens with the low AP1000 flow rates. As a result, no fibrous debris is generated by the LOCA blowdown. [ ] a,c.

- Because passive safety systems are used, the core flow rates that occur during recirculation are significantly reduced. In addition, the AP1000 containment floods up to a higher level. The reduced recirculation flow rates and deeper flood levels, significantly reduces the velocities that would occur during recirculation operation thereby minimizing the potential for debris transport. Note that the AP1000 has a nonsafety-related containment spray system; however, this system has no recirculation capability and it is not permitted to be used in a DBA (Reference 1).

- Protective overhangs prevent coatings and other debris from either falling onto or just in front of the Containment Recirculation Screens and being transported to them.

- The screens are large and have an advanced geometry in order accommodate collected debris without impacting core flow.

- The AP1000 has several features that significantly reduce the amounts of materials that could contribute to the formation of chemical precipitants. For example, [ ]a,c. This design minimizes the production of Calcium Phosphate by chemical reactions between the buffer agent (TSP) and concrete after an accident.

As a result of the AP1000 design approach, there are only two sources of potential debris that might impact the AP1000 core flow path.

1. 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 when a LOCA occurs. The amount of latent debris is limited / controlled by plant the cleanliness program.
2. Post-accident chemical effects are the result of containment sump fluid reacting chemically with materials inside containment and producing chemical products (precipitants).

3.2 AP1000 Latent Debris Composition and Amount

The types of latent containment debris and their relative volumes applicable to the AP1000 were described in Reference 1. Operating plant walk down data were used as an input to this evaluation. The composition of the AP1000 latent debris is:

- Particulate material: [ ] a,c

- Coatings: [ ] a,c

- Fiber: [ ] a,c

From Reference 1, different LOCA break locations do not generate different amounts and compositions of debris that may be transported to the core screens of the AP1000. The reason for this is that AP1000 uses Metal Reflective Insulation (MRI) insulation rather than other types of insulation (such as fiberglass or calcium silicate) in locations where it could be damaged by a LOCA jet and transported to the screens. This design choice eliminates fibrous and particulate insulation as a debris source for the AP1000.

3.3 AP1000 Post-Accident Latent Debris Load at the Core Entrance

Reference 1 evaluated how much of the latent debris could be transported to the screens and to the core. Several different debris loading cases were evaluated.

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

The AP1000 is expected to have debris amounts close to the B.E. loading. As shown in Table 5-4, [ ] a,c.

Table 3-1 AP1000 Core Debris Loading Cases (B.E., Bounding, Sensitivity)

Variable	**AP1000**		
Flow (gpm)	1068$^{(1)}$		
Case	B. E.	Bounding	Sensitivity
Particulate & Coatings (lb_m)	14.21	48.71	98.01
Fiber (lb_m)	0.14	0.49	0.99
Total (lb_m)	14.35	49.2	99.0

Notes:
1. [

]^{a,c}.

3.4 AP1000 Post-Accident Chemical Debris Load Entering the Core

The types and amounts of post-accident chemical precipitants that might form in the AP1000 reactor building pool are identified in Reference 1. Following a design basis LOCA the recirculation water pool volume in the AP1000 containment has been determined to be as little as [ ]^{a,c}. The amount of chemical debris produced is maximized in the chemical model by assuming that the entire sump liquid volume is homogeneously mixed and reacts chemically with all materials located within the flooded volume of the containment.

The concentrations of the chemicals was determined assuming the minimum post-accident recirculation volume of coolant for the AP1000 in order to maximize the concentrations. The results of this calculation are summarized in Table 3-2.

Table 3-2 Chemical Precipitate Formation Predicted for the AP1000

Precipitants	Mass (lb_m (kg))	Mass Fraction (%)
$NaAlSi_3O_8$	3.3 (1.5)	6.92
AlOOH	43.4 (19.7)	90.78
$Ca_3(PO_4)_2$	1.1 (0.5)	2.30
Total	47.8 (21.7)	100.0

3.5 AP1000 Flow Rate

The AP1000 DCD long-term core cooling analysis reports the following flow rates:

- At [ ] a,c into the LOCA transient:
  - Average flow rate into the core is calculated as: [ ] a,c
  - Peak flow rate into the core is calculated as: [ ] a,c
- At [ ] a,c into the LOCA transient, and at the minimum containment water level:
  - Average flow rate into the core is calculated as: [ ] a,c
  - Peak flow rate into the core is calculated as: [ ] a,c

The average flow is used in this test because the time between min and max flows is short, on the order of [ ] a,c, as shown in the AP1000 DCD safety analysis and in the supporting APEX testing. Note that as shown above the recirculation flows decrease with time, so the flow at the start of recirculation [ ] a,c is the maximum.

4.0 AP1000 TEST SCALING

This section addresses the approach to scaling the AP1000 debris parameters to the test facility.

For the flow rate, the scaling approach is to use the test fixture area compared to the AP1000 core flow area. This approach provides for the same flow velocity through the "screen" which will produce the same debris bed formation and head loss with the debris amounts properly scaled.

For the latent debris, the scaling approach is to use the ratio of the test fixture flow area to the AP1000 core flow area. This approach produces same debris bed formation and resulting head loss. Note that the test facility ensures that all of the debris added to the test facility will be recirculated, so that if it is not trapped on the screen in the first pass it will continue to circulate so that it can be trapped during a subsequent pass.

For the chemical debris, the scaling approach is the same as for the latent debris. This approach makes available the same amount of chemical precipitants per square inch of flow area which allows for the same bed formation.

4.1 Scaling of Latent Debris

The test fixture is a [ ]^{a,c} pipe, which has an area of [ ]^{a,c}. The AP1000 has [ ]^{a,c} that are located on [ ]^{a,c} centerlines. This results in an area of [ ]^{a,c} for the core. The ratio of the test fixture area to the AP1000 core area is then [ ]^{a,c}. This scale factor is used to reduce the flow rate and latent debris amounts.

Using the peak flow rate shown in section 3.5:

[ ]^{a,c}

Using the AP1000 B.E. particle loading shown in Table 4-1:

[ ]^{a,c}

The mass of particles and fibers for all the AP1000 cases is scaled down in the same manner. Table 4-1 lists the mass of all of the latent debris for the three different cases.

Table 4-1 AP1000 Latent Debris Amounts Scaled Down

[

][a,c]

4.2 Scaling of Chemical Debris

The same ratio is used for scaling the chemical products as for the latent debris, or [ ][a,c]. Multiply the amounts from Table 3-2 by this ratio to derive the chemical amounts that would be applicable to this test, as listed in Table 4-2.

Table 4-2 AP1000 Chemical Debris Amounts Scaled Down

[

][a,c]

5.0 DESCRIPTION OF TEST FACILITY

The experimental facility was designed to simulate the phenomena in a 3 inch tube. This chapter describes the facility and the test procedures. Figure 5-1 shows a photograph of the test loop.

[

] a,c

Figure 5-1 Photograph of DLC Test Loop

5.1 Components of the Test Facility

As shown in Figure 5-2, the major components of the test facility are a make-up tank, a [ ]^{a,c} test section, a pump, a stirring pump, instrumentation, associated piping, and the data acquisition system. The subsystems are described in the following sections.

[

]^{a,c}

Figure 5-2 Schematic Diagram of DLC Test Loop

The following requirements were developed for the test facility:

R1 Tests must measure pressure drop across a screen with up-flow

R2 Flows should span the range from limiting cold leg to hot leg velocities

R3 Simulated debris should include fibers, particulates, and chemical products[1]

R4 Fiber should be added at concentrations which could produce a "thin bed" although the production of a thin bed is not required

R5 The fiber particle size distribution should be representative of fibers that are transported through a sump screen. Note that this requirement results in fibers that are considered representative of latent fibers that could have entered the RCS through a LOCA break that was flooded by the recirculation pool.

R6 The maximum fiber added to the test should bound what is expected to be transported into the core for the AP1000

R7 The screen size used in the test must represent the smallest openings in fuel assembly debris filter

R8 The surrogate particulates and chemical product(s) must not dissolve during the test

R9 The test apparatus must recirculate fiber and particulates not trapped at the screen (i.e., that is the fiber should not collect in valves, meters, etc.)

R10 Pump recirculating fluid must be able to produce a pressure drop of at least 10 psi

R11 No bubbles in fluid (can reduce effective fiber-bed area)

[1] Section 5.3 discusses the fibers, particulates and chemical products used in this test.

5.1.1 Test Loop

The specific design of the test section used for this research is described in the scaling section. The test section is a conservative representation of an actual AP1000 bottom nozzle as discussed in Section 5.1.2. A schematic of an AP1000 bottom nozzle fuel assembly is shown in Figure 5-3; a small portion of the assembly's lower right-hand bottom nozzle is shown in Figure 5-4.

[

] a,c

Figure 5-3 AP1000 Fuel Assembly Drawing

(illustrated as seen from below)

[

] a,c

Figure 5-4 Photograph of Portion of AP1000 Fuel Assembly

(photographed as seen from below)

Figure 5-4 is a photograph of a cut-away of the lower right-hand corner of Figure 5-3. [

] a,c.

[

] a,c.

The tube is connected to the pump. [

] a,c.

5.1.2 Fuel Debris Filter

The main function of the fuel debris filter is to simulate the fuel assembly screen with a square grid screen. It is backed with an array of [

] a,c, as shown in Figure 5-2.

The use of the [ ] a,c is conservative because [

] a,c:

[ ] a,c

[ ] a,c

Because the screen mesh has a smaller limiting dimension, it provides less clearance for longer or wider fibrous or particulate debris than the AP1000 bottom nozzle and P-Grid configuration. Therefore, the use of [ ] a,c is a conservative representation of the debris capturing capability of an AP1000 fuel nozzle.

[

] a,c

Figure 5-5 Picture of Fuel Debris Filter for 3 inch test

5.1.3 Pump

[

]a,c.

5.1.4 Magnetic Stirring Pump

[ ]a,c.

5.2 Instrumentation

[

]a,c.

5.2.1 Thermocouple

[

]a,c.

[

]a,c

Figure 5-6 T-type Sheathed Thermocouple

5.2.2 Flow Meter

[

] a,c.

5.2.3 Differential Pressure Transducer

[

] a,c.

5.3 Test Procedures

The typical sequences of steps taken to perform a test with the 3-inch loop are described in Table 5.1. The Sequence of debris addition shown in Table 5-1 is consistent with the sequence that has been used by the industry in sump screen testing.

Table 5-1 Typical Test Sequence with Chemical Surrogate Added

[

] a,c

Table 5-2 Material Used in Testing to Simulate AP1000 Debris

[

] a,c

The basis for selecting the debris materials used in this testing is as follows:

- Fiber – the fiber used [

  ] a,c. The use of low-density fiberglass is consistent with the NRC Safety Evaluation of NEI 04-07 (Reference 6).

- Particle – the particles used in the test are a surrogate for latent particle debris. [

  ] a,c. The NRC Safety Evaluation for NEI 04-07 identified several features for the particulate component of containment latent or resident debris; the recommended specific gravity was 1.5, and ". . . the major contributors to the head loss are the increasing smaller particles (less than 75 μm) . . ." (Reference 6). [

  ] a,c. Thus, use of silicon carbide particles is consistent with and conservative relative to the characteristics identified in the NRC Safety Evaluation of NEI 04-07 for containment latent particulate debris classified as "dirt."

- Chemical Product - As shown in Table 3-2, the AP1000 has several different chemical precipitates. [ ][a,c]. The post-accident chemical surrogates were generated using the method described in WCAP-16530-NP (Reference 7). The use of this method has been reviewed and accepted by NRC in their Safety Evaluation dated December 21, 2007 (Reference 8).

The fiber distribution is to have a length distribution that is comparable to latent fiber measured during plant walkdowns. This was to be accomplished using the fiber preparation procedure was patterned after the Argonne National Laboratory (ANL) fiber preparation procedure (Reference 4). [ ][a,c].

5.4 Test Results

The results of a test conducted with this test facility are presented in this report. The test was performed with flows and debris amounts that bound the AP1000 scaled down values as shown in following Table 5-3:

Table 5-3 AP1000 Scaled Latent Debris Amounts Compared With Test Amounts

[ ][a,c]

Notes:
1) [ ][a,c].
2) [ ][a,c].
3) [ ][a,c].
4) [ ][a,c].

Table 5-3 shows the test flow is slightly less and the test debris loadings are significantly larger than the AP1000 scaled value. Based on this comparison it is considered that these test parameters bound the AP1000 scaled down parameters and the resulting measured head loss will bound the AP1000 head loss.

Figure 5-7 shows the measured head loss. [

]a,c.

This testing demonstrates that the debris that might be transported to the AP1000 core following a LOCA, will result in an increase in head loss that is much less than the plant can tolerate. As a result, it is concluded that this testing demonstrates that debris reaching the AP1000 core will not adversely affect long-term core cooling.

[

]a,c

Figure 5-7 Measured Head Loss

5.5 Testing Conclusions

1. The test fixture adequately simulates the AP1000 fuel assembly.
2. The test was conducted with more debris than is expected to be seen in the AP1000 with a flow rate that is approximately equal to the AP1000 flow. [ ] [a,c].
3. The measured increase in head loss was low, [ ] [a,c]. This head loss is much less than the head losses that have been shown to be acceptable in the AP1000; Reference 2 shows that [ ] [a,c].

To summarize, this testing shows that the debris that might enter the AP1000 core following a LOCA will not challenge long-term core cooling.

6.0 REFERENCES

1. APP-GW-GLR-079, Rev. 3, "AP1000 Verification of Water Sources for Long-Term Recirculation Cooling Following a LOCA"
2. APP-PXS-GLR-001, Rev. 0, "Impact on AP1000 Post-LOCA Long-Term Cooling of Postulated Containment Sump Debris"
3. NEI-04-07, Rev. 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology"
4. JCN 3216. "Technical Letter Report on Evaluation of Chemical Effects; Studies on Precipitates Used in Strainer Head Loss Testing", January 20, 2008.
5. APP-GW-GLN-147, Rev. 1, "AP1000 Containment Recirculation and IRWST Screen Design"
6. NEI 04-07, Rev. 0, "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," December 6, 2004.
7. WCAP-16530-NP-A, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191"
8. Letter from H. K. Nieh (NRC) to G. Bischoff (PWROG), "Final Safety Evaluation for Pressurized Water Reactor Owners Group (PWROG) Topical Report (TR) WCAP-16530-NP, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191" (TAC No. MD1119)," December 21, 2007.