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"Evaluation of Debris-Loading Head-Loss Tests for AP1000™ Fuel Assemblies During Loss of Coolant Accidents"

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Evaluation of Debris-Loading Head-Loss Tests for AP1000™ Fuel Assemblies During Loss of Coolant Accidents

Westinghouse

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Evaluation of Debris-Loading Head-Loss Tests for AP1000™ Fuel Assemblies During Loss of Coolant Accidents

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RECORD OF REVISIONS

Revision	Date	Description
0	February 2008	Original
1	July 2009	Revision bars are not included in this document because this revision supersedes the original document in its entirety.
2	September 2009	This revision provides clarification on the licensing basis debris load and limiting case. Identified errors in Tables 4-2, 5-1, 6-3 and 9-1 have been corrected. Revision bars are provided for all changes to this revision.

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EXECUTIVE SUMMARY

Westinghouse has performed a series of experiments to quantify the effect of fibrous and particulate debris and containment chemical effects on the head loss across the fuel assemblies of an AP1000™[1] pressurized water reactor (PWR) during a postulated loss of coolant accident (LOCA). This report documents the fuel assembly head loss experiments that were conducted for the AP1000 design in consideration of Generic Safety Issue 191 (GSI-191), "Assessment of Debris Accumulation on PWR Sump Performance" (Reference 1).

The experiments, performed at the Westinghouse Science and Technology Center (STC) in Churchill, PA, used a fuel assembly design that is consistent with the fuel assembly design described in subsection 4.2.2.2 of the AP1000 Design Certification Document (DCD) (Reference 2). The flow rates and debris loadings were selected to conservatively bound those conditions expected following a postulated LOCA for the AP1000 as defined in Reference 2. The debris load for the AP1000, both particulate and fiber as well as chemical effects, has been significantly reduced by design. [ ]^{a,c}.

The data from this test program demonstrates the ability of the AP1000 to provide assurance of long term core cooling under debris loading conditions expected for the AP1000 following a postulated LOCA. Sixteen head loss experiments were performed that investigated a spectrum of resident debris loads and chemical effects. Data from these experiments indicate that the design basis amount of debris that might exist in an AP1000 containment resulted in [ ]^{a,c}. In addition, the data from all of the experiments that investigated sensitivities to [ ]^{a,c}.

The experiments demonstrate that with the expected AP1000 debris loading conditions, long term core cooling is assured. That is, head losses due to debris collection within the fuel assemblies will not challenge either long-term core cooling or the maintaining of a coolable core geometry.

As noted above, these experiments demonstrate that the AP1000 design provides for [ ]^{a,c} of debris within fuel assemblies with respect to long term core cooling. The long-term cooling analysis of the AP1000 has shown that the plant can withstand at least [ ]^{a,c} of head loss across the core, considerably higher than the experimental results, and still provide adequate core cooling.

As discussed in Reference 2, the AP1000 design is engineered to reduce the potential for head loss during long-term cooling operation:

- The AP1000 design eliminates the generation and transport of fibrous debris to the screens or to the core;
- The AP1000 design reduces the generation of post-accident chemical effects debris;

1. AP1000 is a trademark of the Westinghouse Electric Company LLC.

- The good housekeeping practices required by COL item 6.3.8.1 will limit the amount of resident containment debris;

- The AP1000 design [ ]^{a,c};

- The AP1000 design provides for increased time (between the accident and the start of recirculation) which together with the reduced long-term cooling flow rates enhances debris settling;

- The AP1000 requires the use of high density coatings on walls, floors and structural surfaces as well as on engineered components. [ ]^{a,c};

- The AP1000 requires signs and tags used inside containment to be made from high density materials so that if they are detached they will settle out without being transported to the screens, and

- The AP1000 incorporates large, advanced screen designs.

1 BACKGROUND

In consideration of Generic Safety Issue 191 (Reference 1), Westinghouse has performed a series of fuel assembly head loss experiments for the AP1000. The purpose of this test program was to quantify the head loss across the fuel assemblies during a loss of coolant accident considering the debris loadings applicable to the AP1000. The debris loadings considered fibrous and particulate debris and containment chemical effects applicable to the AP1000.

The experiments used a fuel assembly design that is consistent with the fuel assembly design described in subsection 4.2.2.2 of the AP1000 Design Certification Document (DCD) (Reference 2). The flow rates and debris loading conditions were selected conservatively so that they bound those expected following a postulated LOCA for the AP1000 as defined in Reference 3. Since the fibrous and particulate debris and chemical loadings bound the conditions calculated for a single AP1000 fuel assembly, the data collected from this program is applicable to the whole core.

Four initial head loss tests were performed in 2008 to obtain data to support resolution of GSI-191 for the AP1000. The results of these tests were presented in WCAP17028 Revision 0 and included a bounding resident debris load test, a sensitivity resident debris load test with oscillating flow, a "super sensitivity" resident debris load test and a repeat sensitivity resident debris load test with constant flow rate. All of these tests included chemical effects that bound the chemical debris load calculated for the AP1000. Only in the super sensitivity test was there a measurable increase in pressure drop across the assembly with the addition of debris. The resulting differential pressure (dP) increase of 1.57 psid was acceptable for maintaining coolant flow in the AP1000. However, after discussions with the Nuclear Regulatory Commission (NRC) on the resolution of GSI-191 issues related to the AP1000, Westinghouse concluded that the debris loads assumed in the first four tests were insufficient to satisfy the debris requirements contained in the safety evaluation report (SER) on NEI 04-07 (Reference 4).

In order to resolve outstanding AP1000 issues related to the resolution of GSI-191, Westinghouse chose to perform additional head loss tests. Resident fiber and particulate debris loads were recalculated to be more in line with the debris loads associated with currently operating plants (Reference 5). Chemical effects were recalculated based on the revised debris load and aluminum content in the AP1000 containment (Reference 5). Twelve additional tests, beyond the initial four reported in WCAP-17028 Revision 0, were conducted utilizing increased amounts of fiber and a broader range of fibrous debris types. Several variations in the flow rates, types of fiber and the method of chemical debris addition were included in the twelve additional tests. The results of the fuel assembly head loss testing (References 7, 8, and 16) performed for the AP1000 are summarized herein.

The purpose of this report is to demonstrate and confirm the assurance of long term core cooling under debris loading conditions including chemical effects that include a spectrum of plant specific debris characteristics in order to satisfy GSI-191. This document summarizes the results of thirteen head loss experiments that were performed with [ ]^{a,c}. All of the experiments were performed to demonstrate the margin available in the AP1000 design. These head loss experiments were performed under the Westinghouse Quality Management System (QMS) requirements.

2 OBJECTIVE

The objective of this project was to perform experiments that complied with the Westinghouse QMS for debris loading on the AP1000 fuel assembly design. These experiments were carried out in conformance with the test procedures as given in the approved test plan, Reference 9 (attached in Appendix A of this document). A program including multiple tests with representative and bounding debris load was executed. The results of the test program presented in this report are used to provide the reasonable assurance of long term core cooling considering the Design Basis Accident (DBA) conditions as specified in Reference 2 for the AP1000.

3 APPROACH

The test loop, described in detail in Appendix D of the Test Procedures attached in Appendix C of this document, consists of a single [ ]a,c fuel assembly inside a Plexiglas®[1] case, a make-up tank and the pumps and plumbing required to circulate water and debris. In order, from top to bottom, the fuel assembly contains [ ]a,c. The [ ]a,c just as it would in the actual AP1000 design. The test loop flow rates were scaled to a [ ]a,c to represent the flow rate at the entrance to the [ ]a,c. The selected flow rates bound the maximum flows that can exist during [ ]a,c.

The debris loadings that were used in the tests of the fuel assembly were selected to bound the amounts that could be transported to [ ]a,c. The specified debris loadings were tested in the fuel assembly test loop located at the Westinghouse STC. The debris loadings included resident fibrous and particulate debris and chemical effects. The fibrous and particulate debris load and chemical precipitates were prepared outside of the test loop and then added to the make-up tank (MUT) per the test plan, Reference 9. All of the experiments included fibrous and particulate debris and chemical reaction products that were added to the MUT as water suspensions.

The manner in which the debris is added has been observed in prior industry testing programs to make a difference in the overall head loss through the fuel assembly. Therefore, the following sequence of debris addition was used.

- The desired assembly flow rate was obtained and allowed to stabilize for thirty minutes until a steady-state condition was verified.
- An aliquot of the water from the MUT was removed and placed in a container for each addition of particulate. The particulate was then well mixed into this water until completely suspended before being added to the MUT. The MUT volume was allowed to [ ]a,c.
- The fiber was added per the test plan using a similar technique to that described above for the particulate. [ ]a,c.
- Surrogates for chemical reaction products were added to the test loop after all of the fiber and particulate had been added. As defined in the test plan, the chemical precipitate was mixed outside the test loop per the WCAP-16530-NP-A methodology and then added to the test loop in measured batches.

This approach to sequencing the introduction of debris in the test loop is consistent with the guidance issued on March 31, 2008 (Reference 10).

1. Plexiglas® is a registered trademark of Arkema, Incorporated.

The tests were terminated based on either of the following criteria;

- exceeding the maximum head loss value established for the test, or
- by meeting the equilibrium criterion determined by calculating the slope in differential pressure across the full fuel assembly [

]^{a,c}.

A long term core cooling sensitivity calculation reported in Reference 3 set the licensing basis head loss termination criterion to [ ]^{a,c}.

4 DESCRIPTION OF EXPERIMENTAL APPARATUS

A complete description of the test loop used in the conduct of the AP1000 debris loading head loss testing is included in Section 5 of the test plan provided in Appendix A of this document and will not be repeated in detail here. Summarized in this section are those items considered important to facilitate an overall understanding of the testing process.

4.1 COMPONENTS USED IN HEAD LOSS TESTING

4.1.1 Physical Components

See Figure 4-1 for the loop layout of the AP1000 debris loading head loss test facility. For additional information on the physical arrangement of the test loop, see Section 5 of the test plan provided in Appendix A of this document.

The follow components were used in the construction of the test loop at the Westinghouse STC:

- Mixing tank system
- Recirculation system
  - [ ]a,c
- Test column
  - [ ]a,c
- Computer monitoring system

Mixing Tank System

The mixing tank system includes [ ]a,c. The mixing tank is where debris can be added during the test. The [ ]a,c helps preclude the settling and loss of debris on the bottom of the tank. The recirculating water in the loop flows out of the [ ]a,c of the tank and into the top of the tank. The temperature of the water in the tank [ ]a,c. The water temperature can be controlled from a low temperature [ ]a,c to a high temperature of [ ]a,c and the temperature of the water is measured continuously in the tank [ ]a,c. Mixing of the tank is achieved by the use of a Performance Pro Cascade pump [ ]a,c at the top of the tank.

a,c

Figure 4-1 Schematic of the Test Loop

Recirculation System

The recirculation system pumps the water from the tank, through the test column and back into the tank. A Performance Pro Cascade 3/4 HP pump draws the water out of the bottom of the mixing tank. The flow rate is controlled [

]a,c regulates the flow rate to maintain that value. The recirculation system is continuous duty to accommodate longer tests.

Test Column

The test column contains the fuel assembly and [
]a,c inside the reactor vessel. Most of the column is made from [
]a,c to allow easy viewing of what occurs during testing. The test column is made up of two boxes, [
]a,c. These two boxes [

]a,c.

As debris catches on the fuel assembly, the differential pressure is measured constantly [

]a,c. There are [
]a,c a specific portion of the fuel assembly is required. At the beginning of the test, the fuel assembly is [

]a,c. The fuel assembly is held down by [

]a,c. The temperature of the water in the column is measured continuously [
]a,c.

The height of the [

]a,c of the fuel assembly.

Computer Monitoring System

The computer monitoring system continuously records the following data:

- Temperature of the water in the mixing tank
- Temperature of the water in the test column
- Flow rate
- Differential pressure (dP) measurements [ ]a,c

This data can be recorded at a time interval chosen by the operator. The computer is also used to [ ]a,c.

4.1.2 Instrumentation

Table 4-1 gives a listing of instrumentation that was used for the experiments. The following parameters were monitored and recorded during the head loss experiments:

- Debris sample mass
- Volumetric flow rate
- Loop water temperature
- Loop pressure drop across the bundle

Table 4-1 Instrumentation for Debris Loading Head Loss Testing a,c

Note that the test facility ensures that [ ]a,c. This conservatively bounds the actual plant.

4.1.3 Debris Loads

The AP1000 design minimizes the potential for a LOCA to generate debris that might challenge the core flow path as discussed in Reference 2:

- Metal reflective insulation (MRI) is used on components that might be subjected to direct jet impingement loads; [

]a,c.

- The AP1000 containment [ ]a,c, thereby minimizing the potential for debris transport.

- The AP1000 requires the use of high density coatings on walls, floors and structural surfaces as well as on engineered components. The use of high density coatings together with the other AP1000 features and characteristics prevents coatings, should they detach, from being transported to the screens.

- The AP1000 requires signs and tags used inside containment to be made from high density materials so that, if they detach, they will settle out without being transported to the screens,

- [ ]a,c prevent heavier debris, [ ]a,c the containment recirculation screens and from being transported to them.

- The containment recirculation screens are large with a complex geometry in order to 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 precipitates. [

]a,c.

The licensing basis fibrous and particulate debris and chemical load that could be transported [ ]a,c defined for use in the AP1000 fuel assembly head loss tests, are presented in Table 4-2. These debris loads are based on a total latent debris load of [

]a,c.

Table 4-2 AP1000 Licensing Basis Latent Debris Load a,c

4.1.4 Scaling Considerations

A scaling rationale was used to determine the parameters for flowrate, debris, and chemical precipitates for the experiments. The basic scaling rationale for all three parameters was:

- For the flow rate, [ ]a,c.
- For the resident debris, [ ]a,c.
- For the chemical debris, [ ]a,c.

The test fixture [ ]a,c simulated fuel assembly (FA) with the [ ]a,c. The cross-section of the fuel assembly has an [ ]a,c. The AP1000 has [ ]a,c. This results in a total core area of [ ]a,c. The scale factor is the ratio of the [ ]a,c.

[ ]a,c

Fuel assembly scale factor = [ ]a,c

- For determining the mass concentration of debris in the plant, [ ]a,c.

[ ]a,c

[ ]a,c

See Section 4.2 of Reference 9 (attached in Appendix A of this document) for additional discussion of scaling considerations used in the fuel assembly debris head loss experiments.

4.2 TEST FACILITY OVERVIEW

The following figures show the test facility, debris preparation, and test operation (see Section 4.1 for a description of the components). Prior to the start of each experiment, all of the debris planned for introduction into the test loop was prepared according to procedure. The fiber and particulate were weighed out and the chemical precipitate was prepared per WCAP-16530-NP-A procedure. A test was performed on the chemical surrogate to assure that the chemical mix met the settling requirements provided in the preparation procedure.

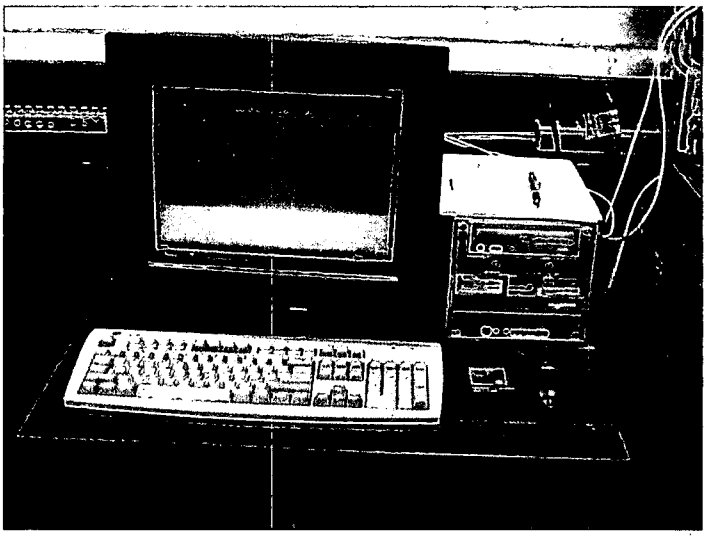

Figure 4-2 Data Acquisition System

a,c

Figure 4-3 Recirculation System

a,c

Figure 4-4 Flow Diverter at Test Column Inlet

a,c

Figure 4-5 Test Column with Bottom Nozzle

a,c

Figure 4-6 Upper Test Column with Top Nozzle

a,c

Figure 4-7 Preparing the Debris Load

a,c

Figure 4-8 Weighing the Chemical Constituents

a,c

Figure 4-9 Weighing the Chemical Constituents

a,c

Figure 4-10 Mixing the Chemical Constituents

a,c

Figure 4-11 Introducing Particulate Debris

a,c

Figure 4-12 Introducing Fibrous Debris

a,c

Figure 4-13 Introducing Chemical Surrogate

5 INITIAL CONDITIONS AND TEST MATRIX

The initial conditions and test parameters of each of the head loss experiments are thoroughly covered in the test procedures captured in Appendix C of this document and summarized in Table 5-1 below.

The maximum core flow was [ ]a,c. For most of the AP1000 fuel assembly tests, the maximum flow rate was assumed since higher flow is conservative for head loss.

For constant flow rate tests, the flow rate was [ ]a,c.

In the AP1000, the post-LOCA core flow rate oscillates with a frequency measured in minutes. At 14 days into the LOCA transient, the maximum core flow drops to an average flow of [ ]a,c. from the conservative maximum value listed above. Some tests were performed to evaluate the impact of this oscillating flow on the head loss across the fuel assembly. In these tests, the flow rates were varied from a maximum of [ ]a,c to a minimum of [ ]a,c.

For variable flow rate tests, the flow rate varied between [ ]a,c.

These flow rates are based on the AP1000 long term cooling (LTC) analysis (Reference 3) that was performed with no added pressure loss across the screens and core.

For test CIBAP16, the flow rate is based on the core flow rate of a LTCC sensitivity analysis, [ ]a,c.

The flow rate for test CIBAP16 was [ ]a,c.

The AP1000 uses natural circulation to provide flow through the reactor during LTC following a LOCA. As a result, when additional pressure loss is introduced in the flow circuit [ ]a,c.

Tests CIBAP01 through CIBAP15 used a flow rate of [ ]a,c.

Loop temperature is set to [ ]a,c.

Table 5-1 AP1000 Fuel Assembly Test Matrix

a,c

6 DEBRIS PREPARATION

Debris preparation is an important factor in the justification of the applicability of these tests to the AP1000. The following discussions on the preparation of the debris used in the experiments are taken from References 7 and 8.

6.1 PARTICULATE

Silicon carbide (SiC) with a 9.5-micron median particle size was used to simulate the particulate component of the containment debris. The NRC Safety Evaluation for NEI 04-07 identified several features for the particulate component of containment debris: the recommended specific gravity is 1.5 and ". . . the major contributors to the head loss are the increasing smaller particles (less than 75 μm) . . ." (Reference 13). Silicon carbide has a specific gravity of about 3.2; although these particles have a relatively high specific gravity, the test loop design prevents them from settling out. Because these silicon carbide particles are about 9.5-microns in size, they act as a fine particulate debris that collects within a fiber bed and results in a maximum head loss across the recirculation screen. All particulate material is well mixed into an aliquot of loop water until completely suspended before being introduced in the test. Based on the above, the particulate used in the experiments is applicable to AP1000.

6.2 FIBERS

Six different fiber configurations were used to represent the fibrous component of the AP1000 resident debris. Fiber Configurations A through F were tested to [ ]a,c. The fiber preparation procedure is based on the Argonne National Laboratory (ANL) procedure found in Reference 14. The method employed to produce the various fibrous debris types can be found in the test procedures in Appendix C.

Fiber A: [ ]a,c.

Fiber B: [ ]a,c.

Fiber C: [ ]a,c.

Fiber D: [ ]a,c.

1. NUKON® is a registered trademark of Performance Contracting, Incorporated.

Fiber E: [

]a,c.

Fiber F: [

]a,c.

The fiber [

]a,c must be a function of the difference between the two measurements.

NUREG/CR-6877, Reference 15, indicates that fiberglass can be used as surrogate for latent fibers. It goes on to say that for latent debris, "the fibrous surrogate fraction should be prepared such that the length-to-diameter ratio is large and that it is conservative to assume that the latent fiber component has similar hydraulic properties to those of fiberglass." [

]a,c. For these reasons, the fibers used in the AP1000 fuel assembly head loss tests are applicable to the AP1000. The NRC SER on NEI 04-07, Reference 4, states that when latent fiber is the dominant fibrous debris source and there is sufficient quantity to form a thin-bed filter, as is the case for the AP1000, "the properties of particulates captured on the fiber bed will dominate maximum head loss." This statement implies that the interaction of the particulate with the fiber is more dominant in creating head loss than the characteristic lengths of the fiber forming the bed. For the AP1000, fibers prepared as described above are applicable for the AP1000 when introduced into the loop following the introduction of particulates. [

]a,c. From the discussion above, it is reasonable to assume that all of the fibers used in the AP1000 fuel assembly head loss tests are applicable to the AP1000.

a,c

Figure 6-1 Fiber Length Distribution for Fiber A

a,c

Figure 6-2 Fiber Length Distribution for Fiber B

a,c

Figure 6-3 Fiber Length Distribution for Fiber C

a,c

Figure 6-4 Industrial Latent Dust

a,c

Figure 6-5 Office Latent Dust

a,c

Figure 6-6 Residential Latent Dust

a,c

Figure 6-7 Natural and Manmade Fibers

a,c

Figure 6-8 Natural and Manmade Fibers Suspended in Water Prior to Introduction

a,c

Figure 6-9 Fiber Length Distribution for Fiber F

a,c

Figure 6-10 Comparison of the Fiber Length Distributions of Fibers A, B, C, and F

a,c

Figure 6-11 Comparison of Individual Measurements of Fiber Length for Fibers A, B, C, and F

Figures 6-12 through 6-14 show the fiber Types A, B, and C in a water suspension as they would be prepared prior to introduction into the test loop. From these photos, it can be seen that the NUKON® fibers are readily suspended in the water as individual fibers and not as clumps or agglomerations.

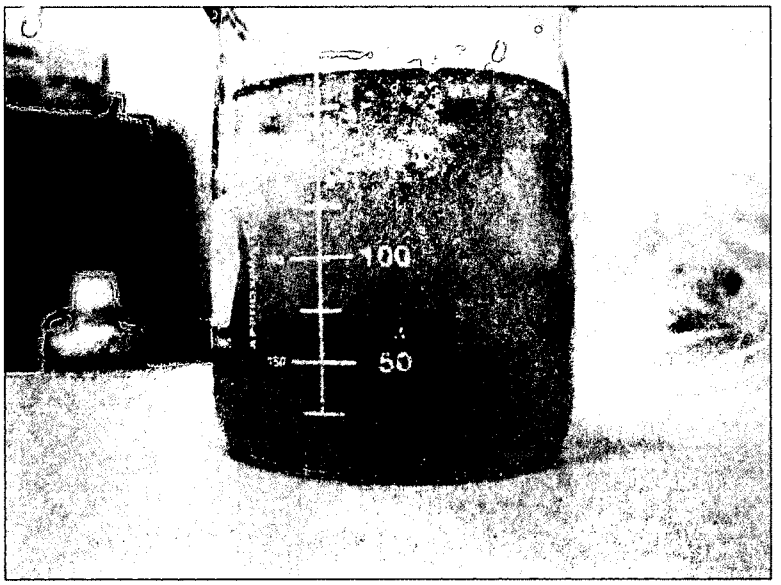

Figure 6-12 Fiber Type A as Prepared for Testing

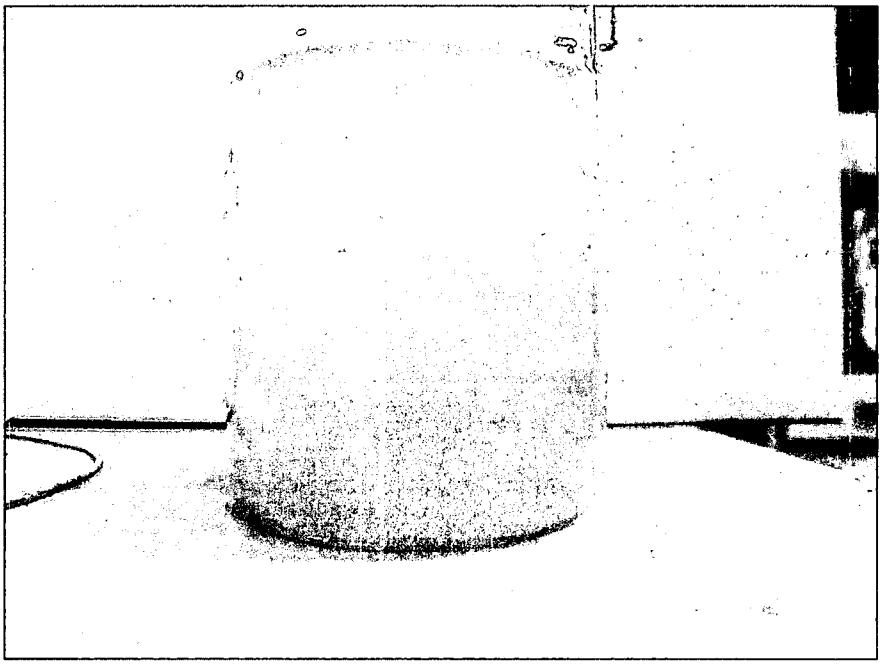

Figure 6-13 Fiber Type B as Prepared for Testing

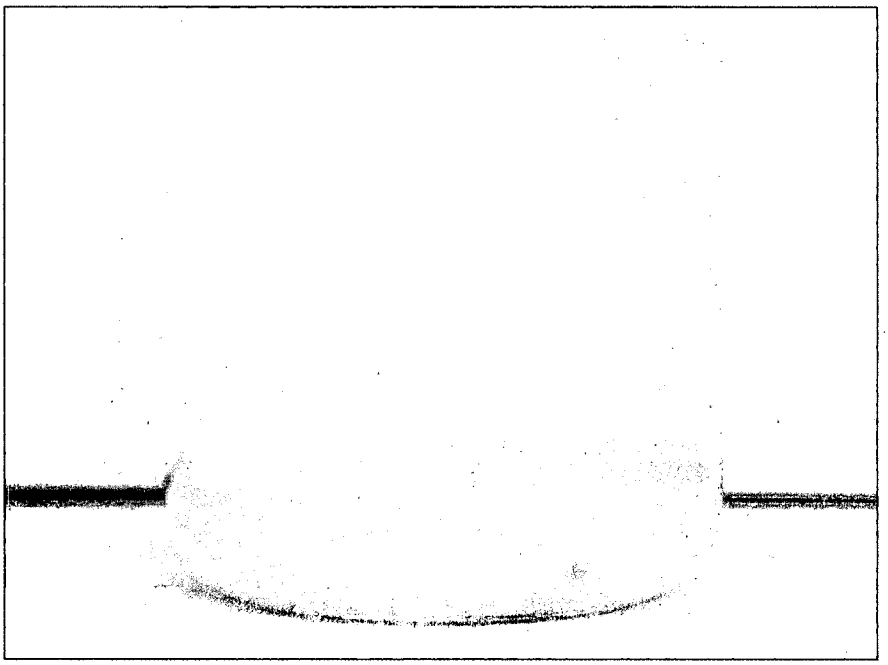

Figure 6-14 Fiber Type C as Prepared for Testing

6.3 CHEMICAL PRECIPITATES

For the AP1000, [ ]a,c of the chemical product is aluminum oxyhydroxide (AlOOH). AlOOH is conservatively used as the surrogate for the other chemical products (sodium aluminum silicate, calcium phosphate) generated in the AP1000 post-accident sump. The post-accident chemical surrogate used in the head loss tests was generated outside of the test loop using the method described in WCAP-16530-NP-A (Reference 12). The use of this method has been reviewed and accepted by the NRC in their Safety Evaluation dated December 21, 2007 (Reference 6) and in the guidance issued on March 31, 2008 (Reference 10).

For the AP1000 fuel assembly test program, all chemical surrogate was made [

]a,c.

By following the WCAP-16530-NP-A method of producing chemical surrogate and by following the guidance of Reference 10, the chemical surrogate used in the AP1000 fuel assembly head loss tests is applicable to the AP1000 plant.

6.3.1 Chemical Precipitate Concentration

[

]a,c

[

]a,c.

Table 6-1 Chemical Additions a,c

The guidance provided in the SER on WCAP-16530-NP-A states that "the TR chemical model release rate under-predicts aluminum release by about a factor of 2 for the active corrosion part of ICET 1" and "If a licensee performs strainer head loss tests with TR WCAP-16530-NP-A surrogate precipitate and applies a time-based pump NPSH margin acceptance criteria (i.e., timed precipitate additions based on TR model predictions), the NRC staff expects the licensee to use *an aluminum release rate that does not under-predict the aluminum concentrations during the initial 15 days of ICET 1*". For this test program, the SER guidance is interpreted to mean that the concentration of chemical precipitates must remain at or above twice the plant concentration for the duration the test.

[

]a,c.

To ensure that the goal of maintaining the loop concentration above twice the calculated plant concentration, samples were taken during tests CIBAP13 and CIBAP14 for further analysis. The results of the chemical analysis of samples (Table 6-2) taken during the conduction of tests CIBAP13 and CIBAP14 determined that the [

]a,c.

As seen in Figures 6-15 and 6-16, the final measured concentration [

]a,c.

Table 6-2 Aluminum Content of the Loop Measured by ICP-MS a,c

a,c

Figure 6-15 Chemical Concentration – Test vs. Plant for Test Duration

Note that the 'Plant Chemical Debris' in Figure 6-15 represents twice the actual calculated concentration for the plant which is less than 0.3 ppm over the 8 hours of the test

a,c

Figure 6-16 Chemical Concentration – Test vs. Plant for Test Duration

Note that the 'Plant Chemical Debris' in Figure 6-16 represents twice the actual calculated concentration for the plant which is less than 0.6 ppm over the 24 hours of the test

6.4 DEBRIS LOADS

Table 6-3 provides an overview of the debris loads used in the overall AP1000 fuel assembly head loss test program and design basis test.

Table 6-3 Original vs. Current AP1000 Debris Load Design Basis

a,c

7 TEST RESULTS

7.1 SUMMARY OF TEST RUNS

The Test Reports, References 7 and 8, provide a detailed record of test runs, debris loadings, and flowrates. Table 7-1 provides a summary of the debris loads and test results for the 'Evaluation of Debris Loading Head Loss Tests for AP1000 Fuel Assemblies During Loss of Coolant Accidents.' [ ]a,c

a,c

Table 7-1 AP1000 Fuel Assembly Debris Head Loss Test Results

7.2 TEST #1 (CIBAP01)

This was the first of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-08-79 captured in Appendix C of this document. The acceptance criterion for this test was [ ]a,c.

As described in test procedure STD-MCE-08-79, [ ]a,c.

Full details of experiment CIBAP01 are captured in Section 4.1 of Reference 7.

a,c

Figure 7-1 Head Loss and Flow Rate History – Bounding Debris Load – CIBAP01

7.3 TEST #2 (CIBAP02)

This was the second of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-08-80 captured in Appendix C of this document. The acceptance criterion for this test was [ ]a,c.

Test #2 was a sensitivity experiment with an increased debris loading as compared to Test #1. [ ]a,c.

Following test procedure STD-MCE-08-80, [ ]a,c.

Similar to the results of Test #1, the amount of debris that was introduced into the test loop [ ]a,c.

Full details of experiment CIBAP02 are captured in Section 4.2 of Reference 7.

a,c

Figure 7-2 Head Loss and Flow Rate History – Sensitivity Debris Load Test CIBAP02

7.4 TEST #3 (CIBAP03)

This was the third of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-08-81 captured in Appendix C of this document. The acceptance criterion for this test was [ ]a,c.

Test #3 was a sensitivity experiment with an increased debris loading as compared to Tests #1 and #2. [ ]a,c.

NOTE: There was a data acquisition error at the beginning of this experiment which caused a loss of recorded data from the beginning of the test until shortly after the second addition of fibrous debris. The first recorded data shown in Figure 7-3 was taken approximately one-half of a loop turnover after the second introduction of [ ]a,c of resident fiber.

[ ]a,c. The AP1000 has been shown to provide adequate long-term core cooling following a LOCA [ ]a,c.

Full details of experiment CIBAP03 are captured in Section 4.3 of Reference 7.

a,c

Figure 7-3 Head Loss and Flow Rate History – Sensitivity Debris Load – CIBAP03

7.5 TEST #4 (CIBAP04)

This was the fourth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-08-82 captured in Appendix C of this document. The acceptance criterion for this test was [ ]a,c.

Test #4 was a repeat of Test #2 [ ]a,c.

Following test procedure STD-MCE-08-82, [ ]a,c.

Similar to the results of Test #2, there was [ ]a,c.

Full details of experiment CIBAP04 are captured in Section 4.4 of Reference 7.

a,c

Figure 7-4 Head Loss and Flow Rate History – Sensitivity Debris Load – CIBAP04

7.6 TEST #5 (CIBAP05)

This was the fifth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-08-85 captured in Appendix C of this document. The acceptance criterion for this test was established at 2.5 psid.

In this case, the debris loadings were the values used in test CIBAP03 (test plan STD-MCE-08-81). The goal was to use the debris loading that was used in Test #3 but with [ ]a,c.

Test CIBAP05 was different from the first four core inlet blockage tests conducted for the AP1000 primarily because of the difference in the [ ]a,c. The amounts of debris were the same as those used in test CIBAP03. NUKON® fiber was still used in the case of test CIBAP05, but the distribution of the [ ]a,c. The rest of the conditions, including flow rate, temperature, and debris additions, were the same as those used in test CIBAP03 (see Section 6.2, Resident Fibers).

The results of test CIBAP05 are summarized in Figure 7-5. After the particulate and fiber had been added, [ ]a,c. Since the fiber used in this test was non-typical of the latent fiber (individual fibers) expected in the AP1000 containment, the rapid rise in headloss associated with the large addition of chemicals cannot be readily attributed to only the large addition of chemicals. Since the test was very similar to Test 3, the results indicate that the interaction of the non-typical fiber and the chemicals together, and not the length of the fiber, played a larger role in the headloss attained in this test.

The head loss termination criterion for the AP1000 at the time this test was run was [ ]a,c so this debris loading was considered to have failed after the first chemical addition. Later analysis determined that the actual maximum head loss criterion for the AP1000 should be [ ]a,c. Since the test was run until the termination criteria were met in order to glean as much information as possible, the data obtained can actually be used to show this as a successful debris loading.

The average temperature in the test column for the test was [ ]^{a,c}. The plot of flow rate versus time in Figure 7-5 shows that there were a number of jumps in the flow rate. Many of these corresponded to the additions made to the loop and were probably the result of rapid changes in conductivity in the magnetic flow meter rather than real changes in the flow rate. The flow rate did go outside of the allowable range of [ ]^{a,c} at some points but only for brief periods.

Full details of experiment CIBAP05 are captured in Section 4.1 of Reference 8.

a,c

Figure 7-5 Head Loss and Flow Rate History for Test CIBAP05

7.7 TEST #6 (CIBAP06)

This was the sixth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-09-18 captured in Appendix C of this document. The acceptance criterion for this test was established at 2.5 psid.

In this experiment, the debris loadings were based on a total AP1000 containment resident debris load of [ ]a,c.

Test CIBAP06 was conducted because CIBAP05 had failed under the original maximum head loss criterion of [ ]a,c. The amounts of fiber, particulate, and chemical debris [ ]a,c. This change in fiber type [ ]a,c.

The debris loading in test CIBAP06 [ ]a,c. Figure 7-6 summarizes the data obtained during the test along with the timing of the debris additions. The maximum head loss [ ]a,c. There were occasional spikes in the head loss as it was dropping off, which were generally associated with further additions of chemical debris.

The average flow rate during the test was [ ]a,c. There were a few large spikes in the flow rate during the test. The spikes in most cases corresponded to the addition of the chemical debris. At the time of the first addition, it appears that the addition of the chemical produced a rapid increase in the conductivity of the solution which produced a few seconds of erroneously high flow values at the magnetic flow meter.

The temperature in the test column was an average of [ ]a,c. The pressure drop decreased continuously after addition of all of the chemical debris, so the test was terminated after 7.7 hours, even though the equilibrium termination criterion was not met.

Full details of experiment CIBAP06 are captured in Section 4.2 of Reference 8.

a,c

Figure 7-6 Head Loss and Flow Rate History for Test CIBAP06

7.8 TEST #8 (CIBAP08)

This was the eighth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-09-28 captured in Appendix C of this document. The acceptance criterion for this test was established at 2.5 psid.

In this experiment, the debris loadings were based on a total AP1000 containment resident debris load of [ ]a,c.

Test CIBAP08 used the same total fibrous and particulate debris loading as was used in test CIBAP06. The same fiber as used in test CIBAP06, [ ]a,c (see Section 6.2, Resident Fibers). CIBAP08 had [ ]a,c. The primary differences between CIBAP08 and CIBAP06 were the use of [ ]a,c in CIBAP08.

Test CIBAP08 was successful in that the head loss did not go over the acceptance criterion of [ ]a,c. The flow rate and pressure drop results, as well as the timing of the debris additions, are summarized in Figure 7-7. Neither the SiC particulate nor the fibrous debris additions [ ]a,c. The first chemical debris addition [ ]a,c.

The average temperature in the test column and the mixing tank during test CIBAP08 was [ ]a,c. For both of these flow rates, the value stayed within the allowed flow range throughout the test, though it is obvious that there was some variation at different points in the test as the flow rates were manually adjusted. The upper flow rate was closer to 8 gpm during the test, which was still within the allowed range.

For termination, the test was allowed to run for 75 minutes after the final addition of chemical debris. The termination criteria were checked, but since the oscillating flow had an effect on the measured head loss, the termination criterion was not precisely met. The test was ended anyway because the oscillating flow precluded the possibility of reaching an exact equilibrium condition.

Test CIBAP08 was also allowed to run overnight to determine what would happen with pressure, settling, and debris movement after running for an extended period. The pressure and the locations of debris capture did not change during this extended operation but [ ]a,c.

Full details of experiment CIBAP08 are captured in Section 4.4 of Reference 8

a,c

Figure 7-7 Head Loss and Flow Rate History for Test CIBAP08

7.9 TEST #9 (CIBAP09)

This was the ninth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-09-34 captured in Appendix C of this document. The acceptance criterion for this test was established at 2.5 psid.

In this experiment, the parameters were the same as those used for CIBAP08. The debris loadings were based on a total AP1000 containment resident debris load [ ]a,c.

The only difference between this test and test CIBAP08 was that the fiber used for this experiment was [ ]a,c.

Test CIBAP09 was conducted to determine the pressure drop characteristics of a debris mix with a [ ]a,c. Therefore, the results of test CIBAP09 and test CIBAP08 should be compared to one another as if they were run under the same conditions.

The results of CIBAP09 were generally similar to those obtained in test CIBAP08. The pressure and flow rate data and the timing of the debris additions for CIBAP09 are given in Figure 7-8. Addition of the SiC particulate [ ]a,c.

The temperature in the test column and the mixing tank during the test [ ]a,c. For both the upper and the lower flow rates, the measured values were within the allowed ranges.

The termination criterion was checked at the end of the test despite this being an oscillating flow test. The slope of the differential pressure versus time curve was below the termination criterion.

Full details of experiment CIBAP09 are captured in Section 4.5 of Reference 8.

a,c

Figure 7-8 Head Loss and Flow Rate History for Test CIBAP09

7.10 TEST #10 (CIBAP10)

This was the tenth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-09-38 captured in Appendix C of this document. The acceptance criterion for this test was established at 2.5 psid.

In this experiment, the debris loadings were based on a total AP1000 containment resident debris load of [ ]a,c. These are the same values that were used in tests CIBAP08 and CIBAP09. This test also employed a [ ]a,c in the AP1000.

The fiber used for this experiment was [ ]a,c.

Test CIBAP10 had similar conditions to tests CIBAP08 and CIBAP09. The only difference between test CIBAP10 and tests CIBAP08 and CIBAP09 was [ ]a,c.

The pressure and flow rate results as well as the timing of the debris additions for CIBAP10 are summarized in Figure 7-9. Some difficulties with the data acquisition system were encountered during this particular test. The flow control program caused the flow rate to hold at 8.4 gpm for about a third of an hour just after four hours had passed in the test. Then, at just over six hours into the test, the data collection program froze and stopped collecting data. It took about 45 minutes to correct this problem, so the pressure and flow data between these points were lost. The flow control program continued to operate during this time, so the test itself was not disturbed. These problems, corrected after the test by rebooting the computer, were not experienced in subsequent tests.

Despite these difficulties, the test was successful in showing that the debris loading used was acceptable. The addition of SiC particulate had no effect on the head loss and the addition of the fiber [ ]a,c. The first chemical debris addition [ ]a,c.

The average temperature in the test column [ ]a,c. The flow rate was within the acceptable range for the high and low flow rates throughout the test except at three points which can be seen on the plot in Figure 7-9. The first was a number of low spikes in the flow rate during the first hour of the test. These low spikes had no effect on the test because they occurred before any debris was added. The second was when the flow control program caused the flow rate to hold at the high value for

much longer than it was programmed to. During this time period, the flow rate did not go outside of the allowable range for the higher flow rate. The final excursion was at about 6 hours into the test when the upper flow rate spiked to a value of approximately 9.5 gpm. This spike at six hours was brief and did not cause a change in pressure drop or a visible rearrangement of the debris bed.

Full details of experiment CIBAP10 are captured in Section 4.6 of Reference 8.

a,c

Figure 7-9 Head Loss and Flow Rate History for Test CIBAP10

7.11 TEST #11 (CIBAP11)

This was the eleventh of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-09-39 captured in Appendix C of this document. The acceptance criterion for this test was established at 6.5 psid.

In this experiment, the debris loadings were based on a total AP1000 containment resident debris load of [ ]a,c. It was assumed that all of this resident debris [

]a,c.

The fiber used for this experiment [ ]a,c. Table 7-2 specifies the quantities for each of the types of fibrous debris used to create this particular fibrous representation of the latent debris.

Table 7-2 Fibrous Debris Mix Used in Test CIBAP11 a,c

Test CIBAP11 was conducted with the same debris amounts as Tests 8, 9, and 10, but [

]a,c.

The head loss and flow rate results as well as the timing of the additions are summarized in Figure 7-10 Neither the addition of SiC particulate or the addition of the fiber caused an increase in the head loss. [

]a,c.

In the earlier tests, the debris bed [

]a,c. Prior to the additions of chemical debris to test CIBAP11 (Figures 7-11 and 7-12), [ ]a,c.

[

]a,c. Comparing Figure 7-14 to Figure 7-15, one can see [

]a,c.

The average temperature in the test column during the test [

]a,c. Both of these spikes in the flow rate coincided with debris additions and were probably side effects of the variations in the local conductivity of the fluid passing through the magnetic flow meter.

The equilibrium criterion for termination was met at the end of the test with the slope of the head loss curve over the last hour being less than 0.05 psid/hr.

Full details of experiment CIBAP11 are captured in Section 4.7 of Reference 8.

a,c

Figure 7-10 Head Loss and Flow Rate History for Test CIBAP11

a,c

Figure 7-11 Photograph of the Fibrous Debris that Settled Out on Top of the Simulated Core Support Plate After the First Fiber Addition During Test CIBAP11

a,c

Figure 7-12 Photograph of the Fibrous Debris that Settled on the Simulated Core Support Plate or Caught on the Bottom Nozzle and P-grid After the Second Fiber Addition in Test CIBAP11

a,c

Figure 7-13 Photograph of the Bottom Nozzle and P-grid in Test CIBAP11 After the First Addition of AlOOH Chemical Surrogate

a,c

Figure 7-14 Photograph of the Bottom Nozzle and P-grid in Test CIBAP11 After the Fourth Addition of AlOOH Chemical Surrogate

a,c

Figure 7-15 Photograph of the Bottom Nozzle, P-grid, and a Support Grid in Test CIBAP11 After Seven Additions of AlOOH Chemical Surrogate

a,c

Figure 7-16 Photograph of the Bottom Nozzle and P-grid in Test CIBAP11 after Seven Additions of AlOOH Chemical Surrogate Showing How the Fibrous Material Also Caught on the P-grid

7.12 TEST #13 (CIBAP13)

This was the thirteenth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-09-42 captured in Appendix C of this document. The acceptance criterion for this test was established at 6.5 psid.

In this case, the fibrous debris loadings were set at [ ]a,c was used in test CIBAP13 (see Section 6.2, Resident Fiber). The fiber load was based on [ ]a,c. It was assumed that all of this resident debris [ ]a,c. The chemical surrogate was generated outside of the loop using the standard WCAP-16530-NP-A procedure.

Test CIBAP13 was similar to test CIBAP08 in terms of the type of debris used. [ ]a,c.

[ ]a,c into the mixing tank at a specified rate. Per test procedure STD-MCE-09-49 captured in Appendix C, the chemicals were [ ]a,c. Figure 7-17 summarizes the AlOOH concentration during the test and compares it to twice the calculated amount of chemical concentration in the AP1000 during a LOCA. The use of the factor of two conservatism is in accordance with NRC recommendations. These plots demonstrate that the amount of AlOOH added to test CIBAP13 [ ]a,c.

The pressure and flow rate results, as well as the timing of the additions for test CIBAP13, are summarized in Figure 7-18. After the addition of the SiC particulate, [ ]a,c. The addition of the fiber caused only a [ ]a,c.

The average temperature in the mixing tank during test CIBAP13 was [ ]a,c. The temperature in the test column was slightly outside of the specified temperature range in the test plan, but this deviation should have no effect on the test results.

The average flow rate during the test was [ ]a,c. The flow had some small spikes during the test, but none of these went outside of the allowable range in the test plan. Full details of experiment CIBAP13 are captured in Section 4.9 of Reference 8.

a,c

Figure 7-17 Concentration of Chemical Debris with Time

a,c

Figure 7-18 Head Loss and Flow Rate History for Test CIBAP13

7.13 TEST #14 (CIBAP14)

This was the fourteenth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-09-45 captured in Appendix C of this document. The acceptance criterion for this test was established at 6.5 psid.

In this experiment, the particulate, fiber, and chemical debris loadings were set to the same values used in Test CIBAP13. However, the type of fiber used was different, type [ ]a,c. The chemicals were added slowly but at a rate intended to exceed twice the concentration predicted for the AP1000. This was accomplished with a peristaltic pump as in test CIBAP13. Figure 7-19 compares the chemical concentration in the test loop with time to the chemical concentration predicted in the AP1000 during a LOCA. For conservatism, the concentration of chemical debris in the test loop was targeted to be above twice the calculated concentration in the AP1000 during a LOCA event. [ ]a,c.

The pressure and flow rate results, as well as the timing of the debris additions for test CIBAP14, are summarized in Figure 7-20. The [ ]a,c of chemical debris are noted on the plot. The addition of the SiC particulate [ ]a,c. The first continuous addition of AlOOH chemical debris [ ]a,c. After this first addition of AlOOH, the test plan [ ]a,c. The test was then allowed to stabilize for 8.5 hours until the equilibrium criterion was met. At this point, additional chemical debris was added by pouring the liquid into the mixing tank rather than by pumping it into the tank. The head loss reached [ ]a,c.

Figure 7-21 shows the initial size and coverage of the debris bed on the bottom of the bottom nozzle. There was also some [ ]a,c.

In Figure 7-23, [ ]a,c.

Figure 7-25 shows the appearance of the debris bed on the bottom of the bottom nozzle at the end of test CIBAP14. The overall appearance of the debris bed was [

]a,c.

The average temperature in the test column during test CIBAP14 was [

]a,c.

There were some small spikes in the flow rate throughout the test, but only one of these went outside of the allowable range given in the test plan. At just over four hours into the test, [

]a,c. This appeared to have no effect on the results of the test.

Full details of experiment CIBAP14 are captured in Section 4.10 of Reference 8.

a,c

Figure 7-19 Concentration of Chemical Debris with Time

a,c

Figure 7-20 Head Loss and Flow Rate History for Test CIBAP14

a,c

Figure 7-21 Photograph of the Bottom Nozzle in Test CIBAP14 After the First Continuous Addition of AlOOH Chemical Surrogate

a,c

Figure 7-22 Photograph of the Bottom Nozzle and P-grid in Test CIBAP14 Seven Hours After the Second Continuous Addition of AlOOH Chemical Surrogate

a,c

Figure 7-23 Photograph of the Water in the Loop ~2 Hours After the Second Addition of AlOOH Chemical Surrogate

a,c

Figure 7-24 Photograph of the Water in the Loop ~7 Hours After the Second Addition of AlOOH Chemical Surrogate

a,c

Figure 7-25 Photograph of the Bottom Nozzle and P-grid at the End of Test CIBAP14

7.14 TEST #15 (CIBAP15)

This was the fifteenth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-09-61 captured in Appendix C of this document. The acceptance criterion for this test was established at 6.5 psid based on a core flow rate of 8.5 gpm.

In this case, the fibrous debris loadings were set at [ ]a,c was used in test CIBAP15 (see Section 6.2, Resident Fiber). The debris load was based on [ ]a,c. It was assumed that all of this fibrous and particulate debris [ ]a,c.

Test CIBAP15 included more [ ]a,c.

[ ]a,c into the mixing tank at a specified rate. For conservatism, the concentration of chemical debris in the test loop was targeted to be above twice the calculated concentration in the AP1000 during a LOCA event. The use of the factor of two conservatism is in accordance with NRC recommendations.

The pressure and flow rate results, as well as the timing of the debris additions for test CIBAP15, are summarized in Figure 7-26. After the addition of the SiC particulate, [ ]a,c. The addition of the fiber caused only a [ ]a,c.

The pressure drop increase occurred [ ]a,c. This is demonstrated by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 7-26. The pressure drop increase across [ ]a,c.

No visible debris beds or blockages formed when the particulate debris was added. [ ]a,c

[

]a,c.

The average temperature for both the test column and the mixing tank during the test was [

]a,c, so any dissolution of the chemical product surrogate was insignificant.

Full details of experiment CIBAP15 are captured in Section 3.1 of Reference 16.

a,c

Figure 7-26 Head Loss and Flow Rate History for Test CIBAP15

a,c

Figure 7-27 Photograph of the Bottom Nozzle in Test CIBAP15 After the Addition of Fiber

a,c

Figure 7-28 Photograph of the Bottom Nozzle in Test CIBAP15 After the Third Addition of AlOOH Chemical Surrogate

7.15 TEST #16 (CIBAP16)

This was the sixteenth of the AP1000 fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to the test plan STD-MCE-09-71 captured in Appendix C of this document. The acceptance criterion for this test was established at 3.5 psid based on a scaled core flow rate of 5.3 gpm. The 5.3 gpm resulted from an accurate conversion of the core flow of 111 lb/sec based on the actual plant temperature and pressure analysis data.

In this case, the fibrous debris loadings were set at [ ]a,c was used in test CIBAP16 (see Section 6.2, Resident Fiber). The fiber load was based on [ ]a,c. It was assumed that all of this fibrous and particulate debris [

]a,c.

Test CIBAP16 included more [

]a,c.

]a,c into the mixing tank at a specified rate. As in test CIBAP14, the chemicals were initially added slowly with a peristaltic pump at a rate intended to exceed twice the concentration predicted for the AP1000. For conservatism, the concentration of chemical debris in the test loop was targeted to be above twice the calculated concentration in the AP1000 during a LOCA event. The use of the factor of two conservatism is in accordance with NRC recommendations.

The pressure and flow rate results, as well as the timing of the additions for test CIBAP16, are summarized in Figure 7-29. After the addition of the SiC particulate, [ ]a,c. The addition of the fiber caused only a [

]a,c.

The pressure drop increase occurred [ ]a,c. This is demonstrated by comparing the trace labeled "dP Upper" to the trace labeled "dp Lower" in Figure 7-29. The pressure drop increase across [

]a,c.

No visible debris beds or blockages formed when the particulate debris was added. [

]a,c.

The average temperature for both the test column and the mixing tank during the test was 73°F. The average flow rate during the test was [ ]a,c. The flow had some small spikes during the test and a brief excursion when the fiber added. This excursion occurred before the bed formed, so it had no effect on the test results. The maximum pH during the test was 7.7. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

Full details of experiment CIBAP16 are captured in Section 3.2 of Reference 16.

a,c

Figure 7-29 Head Loss and Flow Rate History for Test CIBAP16

a,c

Figure 7-30 Photograph of the Bottom Nozzle, P-grid, and a Support Grid After the Addition of 12.1 grams of Fiber

a,c

Figure 7-31 Photograph of the Bottom Nozzle and P-grid After the First Chemical Addition

a,c

Figure 7-32 Photograph of the Bottom Nozzle and P-grid After the First Chemical Addition

a,c

Figure 7-33 Photograph of the Bottom Nozzle, P-grid, and a Support Grid After the Last Chemical Addition

a,c

Figure 7-34 Photograph of the Bottom Nozzle, P-grid, and a Support Grid After the Last Chemical Addition

7.16 INVALIDATED TESTS

CIBAP07 - This test was excluded due to a modification of the test loop that had been implemented prior to CIBAP07. A bypass line was added after the pump to reduce the back pressure on the pump during these relatively low flow rate tests. In this case, the valve in the bypass line was open too wide and when the back pressure increased due to the increased head loss, too much flow was diverted through the bypass line and reduced the flow to the test column below allowable levels as set in the test plan. With the rapid drop in flow rate below the allowable level set forth in the test plan, the data was deemed to be unusable.

CIBAP12 –This test was excluded due to the addition of the constituent chemicals to the loop. The procedure for testing chemicals in the loop requires that the chemicals be mixed outside the loop per WCAP-16530-NP-A. For this test, the chemical constituents were added to the loop individually to see the effect of in-situ mixing of the chemicals. When the chemical constituents were added to the mixing tank there was a large fluctuation in the measured flow rate. This fluctuation was due to the rapid change in conductivity when the chemicals were added to the loop. The magnetic flow meter can account for changes in conductivity, but not if the changes occur too rapidly. Since the flow control system adjusts the flow rate based on feedback from the flow meter, the flow control system was attempting to compensate for the perceived spikes in the flow rate resulting in large fluctuations in the recorded data. With the rapid fluctuations in the recorded data, the data was deemed to be unusable. Additionally, this test would not have been allowed as part of the licensing basis since the chemicals were not created outside of the loop per the accepted WCAP-16530-NP-A procedure.

8 CONCLUSIONS

8.1 TEST PROGRAM SUMMARY

This report documents fourteen experiments that were performed for the AP1000 to quantify the head loss across the fuel assemblies when considering post-LOCA containment fibrous and particulate debris and chemical effects applicable to the AP1000.

The head loss limits for the fuel assembly experiments, were initially at [

]a,c. Table 8-1 lists a summary of the Head Loss Test Observations for fourteen head loss experiments performed to assess the impact of post LOCA debris on the AP1000 long term core cooling.

a,c

Table 8-1 Summary of Head Loss Test Observations

The experiments performed to assess head loss across the AP1000 fuel assemblies during loss of coolant accidents looked at a variety of parameters to determine if a [

]a,c.

A series of four tests (#08 - #11) were conducted to evaluate the importance of different mixes of longer fibers. All of these tests were run with the same conditions and procedures; the only difference was the type of fiber used. All four of these tests behaved similarly as follows:

- They had almost no head loss after the addition of particles and fibers.
- The addition of chemicals cause a significant increase in the head loss.
- The difference in the head losses between the tests was not significant.
- The first three of these tests used fiberglass fibers of different lengths. The fourth test used some fiberglass as well as some natural and manmade fibers in order to evaluate even longer fibers.

Because the small amounts of chemicals present in the AP1000 fuel assembly experiments [

]a,c.

Since it has been shown that the [

]a,c.

Note that test CIBAP16 is considered to be the test that bounds the design basis of the AP1000. The debris load used in this test was based on [

]a,c. It was assumed that all of this debris

[

]a,c.

The results of the experiments provided in Section 7 indicate that head loss across the fuel [

]a,c.

8.2 APPLICABILITY OF TESTING TO AP1000 DESIGN

The experiments performed for the 'Evaluation of Debris Loading Head Loss Tests for AP1000 Fuel Assemblies During Loss of Coolant Accidents' used a fuel assembly design that for the purposes of this testing is consistent with the fuel assembly design described in subsection 4.2.2.2 of the AP1000 DCD (Reference 2). The specific AP1000 bottom nozzle design was used to ensure that the actual geometry of this component was included in the AP1000 test. The other components (spacer grids, top nozzle, etc., – see Section 3) used in the test are representative of the AP1000 fuel assembly components. The flow rates, debris loading, and chemical effects were selected conservatively so that they bound those expected following a postulated LOCA for the AP1000 as defined in Reference 2.

The fibrous and pariculate debris types and chemical effects used in the AP1000 fuel assembly head loss experiments have been identified as those that would be expected in an operating AP1000. The flow rates (Section 5) and debris loads (Section 6) [

]a,c. Based on the discussion provided in the noted sections, the scaled debris loads and flow rates used in the experiments are applicable to the AP1000.

The fibrous and particulate debris and chemical effects used in the experiments were prepared per procedure [ ]a,c the debris and chemical effects used in the experiments are applicable to the AP1000.

The experiments were performed with representative resident debris and chemical precipitate at flows that bound the flows expected in the post accident AP1000. As can be observed from the experimental data, including graphs and photographs, [

]a,c the reasonable assurance of long term core cooling for the AP1000.

Considering the test apparatus, the debris loads, the flow rates, and the preparation of materials, the resulting data from this test program is directly applicable to the AP1000 design.

9 SUMMARY

Fuel assembly head loss experiments were conducted for the AP1000 design as part of the response to GSI-191, "Assessment of Debris Accumulation on PWR Sump Performance." These fuel assembly head loss experiments were performed for the AP1000 to quantify the head loss across the fuel assemblies considering fibrous and particulate debris and containment chemical effects applicable to the AP1000.

The experiments performed used a fuel assembly design that for the purposes of the testing is consistent with the fuel assembly design described in subsection 4.2.2.2 of the AP1000 DCD (Reference 2). The flow rates and fibrous and particulate debris loading conditions were selected conservatively so that they bound those expected following a postulated LOCA for the AP1000. The fuel assembly, debris loads, and flow rates are directly applicable to the AP1000 as described in Section 4.0 of this report.

The sixteen fuel assembly head loss experiments that were performed for the AP1000 design investigated a spectrum of fibrous and particulate debris loads and chemical effects. The results from fourteen[1] of these experiments, Table 9-1, demonstrate the ability of the AP1000 to provide reasonable assurance of long term core cooling under the fibrous and particulate debris loading and chemical effects conditions expected for the AP1000 following a postulated LOCA.

The AP1000 design [

]^{a,c} and required good house keeping practices. The AP1000 is engineered to reduce the potential for head loss during long-term cooling operation. These experiments show that the [

]^{a,c}.

[1] Tests 7, and 12 were invalidated due to technical difficulty. See Section 7.15.

Table 9-1 Summary of Results a,c

(1) Note Test #15 was not a design basis test. The AP1000 will not operate at the tested flow rate at the DP shown to occur in the test. Should the tested amount of debris accumulate on the fuel, the core flow would decrease to a value similar to that found in test #16 which provides sufficient core cooling with an acceptable DP.

10 REFERENCES

1. Generic Safety Issue, GSI-191, "Assessment of Debris Accumulation on PWR Sump Performance," 1998.

2. APP-GW-GL-700, Revision 17, "AP1000 Design Control Document," 2008.

3. APP-PXS-GLR-001, Revision 1, "Impact on AP1000 Post-LOCA Long-Term Cooling of Postulated Containment Sump Debris," May 2009.

4. NEI 04-07 PRESSURIZED WATER REACTOR SUMP PERFORMANCE EVALUATION METHODOLOGY Revision 0 December 2004 Volume 2 – Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02, Revision 0, December 2004.

5. APP-GW-GLR-079, Revision 4, "AP1000 Verification of Water Sources for Long-Term Recirculation Cooling Following a LOCA," June 2009.

6. 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 2007.

7. STD-MCE-09-8, Revision 0, "Summary of the Results from the AP1000 Core Inlet Blockage Tests," February 2009.

8. STD-MCE-09-47, Revision 0, "Summary of the Results from the AP1000 Core Inlet Blockage Tests: CIBAP05 to CIBAP14," June 2009.

9. APP-FA01-T1P-001, Revision 1, "Test Plan For AP1000 Debris Loading Head Loss Across Fuel Assembly," June 2009.

10. Revised Guidance for Review of Final Licensee Responses to Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized Water Reactors," March 2008. [ML080230234]

11. APP-PXS-GLR-001, Revision 0, "Impact on AP1000 Post-LOCA Long-Term Cooling of Postulated Containment Sump Debris."

12. WCAP-16530-NP-A, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," April 2008.

13. NEI 04-07, Revision 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004.

14. JCN 3216, "Technical Letter Report on Evaluation of Chemical Effects; Studies on Precipitates Used in Strainer Head Loss Testing," January 20, 2008.

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

16. STD-MCE-09-74, Revision 0, "Summary of the Results from the AP1000 Core Inlet Blockage Tests: CIBAP15 and CIBAP16," July 2009.

APPENDIX A
APP-FA01-T1P-001 REVISION 0: TEST PLAN FOR AP1000 DEBRIS LOADING HEAD LOSS ACROSS FUEL ASSEMBLY

A.1 TESTS CIBAP01 THROUGH CIBAP04

This section is proprietary in its entirety

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APPENDIX B
APP-FA01-T1P-001 REVISION 1: TEST PLAN FOR AP1000 DEBRIS LOADING HEAD LOSS ACROSS FUEL ASSEMBLY

B.1 TESTS CIBAP05 THROUGH CIBAP14

This section is proprietary in its entirety

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APPENDIX C
TEST PROCEDURES FOR AP1000 DEBRIS LOADING HEAD LOSS ACROSS FUEL ASSEMBLY

C.1 TEST PLAN FOR LOOP TEST CIBAP01

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C.2 TEST PLAN FOR LOOP TEST CIBAP02

STD-MCE-08-80

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C.3 TEST PLAN FOR LOOP TEST CIBAP03

STD-MCE-08-81

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C.4 TEST PLAN FOR LOOP TEST CIBAP04

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C.5 TEST PLAN FOR LOOP TEST CIBAP05

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C.6 TEST PLAN FOR LOOP TEST CIBAP06

STD-MCE-09-18

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C.7 TEST PLAN FOR LOOP TEST CIBAP08

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C.8 TEST PLAN FOR LOOP TEST CIBAP09

STD-MCE-09-34

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C.9 TEST PLAN FOR LOOP TEST CIBAP10

STD-MCE-09-35

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C.10 TEST PLAN FOR LOOP TEST CIBAP11

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C.11 TEST PLAN FOR LOOP TEST CIBAP13

STD-MCE-09-42

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STD-MCE-09-42

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C.12 TEST PLAN FOR LOOP TEST CIBAP14

STD-MCE-09-45

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STD-MCE-09-45

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C.13 TEST PLAN FOR LOOP TEST CIBAP15

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C.14 TEST PLAN FOR LOOP TEST CIBAP16

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