ENCLOSURE 6

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WCAP-17028-NP, Rev. 3

"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.
3	December 2009	This revision contains sixteen new fuel assembly tests that supplement the information provided in all previous revisions of WCAP-17028-P. This revision confirms the licensing basis for the reasonable assurance of long-term core cooling under core debris loading conditions for the AP1000. This revision supersedes all previous revisions. Executive Summary: Minor editorial revisions Section 1: Minor editorial revisions Section 2: Minor editorial revisions Section 3: Minor editorial revisions Section 4: Minor editorial revisions Section 5: New Section Section 6: Major Revision Section 7: Major Revision Section 8: Major Revision Section 9: Major Revision Section 10: Minor editorial revisions Section 11: Minor editorial revisions Appendix A: No Change Appendix B: No Change Appendix C: Updated Appendix D: New Appendix E: New

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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 Control 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 (LTC) under debris loading conditions expected for the AP1000 following a postulated LOCA. Thirty head-loss experiments have been performed that investigated a spectrum of resident debris loads and chemical effects. 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.

Data from the results of these experiments indicate that the design basis amount of debris that could exist in an AP1000 containment resulted in a fuel assembly head-loss that was well within the calculated head-loss limit established for the AP1000 in Reference 14. In addition, the data from all of the experiments that investigated sensitivities to [ ]a,c.

As noted above, these experiments demonstrate that the AP1000 design provides for a [ ]a,c of debris within fuel assemblies with respect to long-term core cooling. The long-term cooling analysis of the AP1000, Reference 14, has shown that the plant can withstand at least 4.1 psid (at a corresponding flow rate of 65.0 lbm/s) of head-loss across the core, considerably higher than the experimental results presented in this document, 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:

[1] AP1000 is a trademark of the Westinghouse Electric Company LLC

- The AP1000 design reduces the generation of fibrous debris following a LOCA. The small amount of fibrous debris present in the resident debris is assumed to transport to the screens or to the core;

- The AP1000 design reduces the generation of post-accident chemical effects debris;

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

- The AP1000 design has reduced long-term cooling flow rates compared to active emergency core cooling systems (ECCS) of currently operating PWRs;

- 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 the settling of debris;

- The AP1000 requires the use of high density epoxy 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 prevent failed high density coatings outside the zone of influence (ZOI) from being transported to the screens or core;

- 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 core, 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.

The evaluation of debris-loading head-loss tests for AP1000 fuel assemblies during a LOCA have been captured in WCAP-17028-P, Revisions 0, 1, 2, and 3. Each revision of WCAP-17028-P has increased the knowledge base and understanding of the head-loss across fuel assemblies in the post-LOCA AP1000.

WCAP-17028-P, Revision 0 consisted of four initial head-loss tests that were performed in 2008 to obtain data to support resolution of GSI-191 for the AP1000. The results of these tests included what was first considered to be the 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 bounded 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. 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).

WCAP-17028-P, Revision 1 was written to resolve outstanding issues related to the resolution of GSI-191 resulting from the testing reported in WCAP-17028-P, Revision 0. 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 tests were conducted utilizing revised debris loads and chemical effects. These test included a broader range of fibrous debris types, several variations in the flow rates and variation in the method of chemical debris addition. The results of nine of these twelve fuel assembly head-loss tests performed for the AP1000 were summarized in WCAP-17028-P, Revision 1.

During a meeting to discuss WCAP-17028-P, Revision 1, the NRC pointed out that the WCAP contained errors, that the results of the three tests that were excluded from WCAP-17028-P, Revision 1 should be included, that clarification on the licensing basis debris load and limiting case was needed, and that the assurance of AP1000 LTC success would require additional testing to complement and support the work that had been done to date.

In response to the concerns of the NRC regarding the information in WCAP-17028-P, Revision 1, Westinghouse issued WCAP-17028-P, Revision 2 to correct errors, provide additional clarification on the licensing basis debris load and limiting case, and to provide the results of the three tests that were excluded from WCAP-17028-P, Revision 1. Additionally, Westinghouse developed a test matrix to address the concerns of the NRC related to the debris-loading head-loss tests for AP1000 fuel assemblies.

Westinghouse has completed fourteen additional fuel assembly debris tests to support the findings and conclusions reported in WCAP-17028-P, Revisions 0, 1, and 2 that demonstrate the ability of the AP1000 to provide assurance of long-term core cooling under debris loading conditions expected following a postulated LOCA. The results of all AP1000 fuel assembly headloss tests performed to date are included in Section 7.0.

The results and conclusions presented in this revision of WCAP-17028-P demonstrate and confirm the assurance of long-term core cooling under debris loading conditions for the AP1000. The conditions include a spectrum of plant specific debris characteristics including chemical effects in order to satisfy GSI-191. This document presents the results of thirty fuel assembly head-loss experiments and summarizes the results of these 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 program 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 test procedures attached in Appendix C of this document, consists of a single [ ]a,c fuel assembly inside a Plexiglas®[1] case, a mixing 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 are representative of, or bound the flows that can be expected through the core during the recirculation phase that follows a LOCA.

The debris loadings that were used in the tests were selected and scaled to bound the amount of debris that could be transported to the AP1000 core. 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 mixing tank per the test procedures (Appendix C). All of the experiments included fibrous and particulate debris and chemical reaction products that were added to the mixing tank 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 debris additions schemes were used:

- Sequential additions of particulate, fiber and chemicals
    - For sequential debris addition tests, an aliquot of the water from the mixing tank 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 mixing tank. The mixing tank volume was allowed to [ ]a,c.
    - For sequential debris addition tests, the fiber was added per the test plan using a similar technique to that described above for the particulate. [ ]a,c.
    - For sequential debris addition tests, 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.

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

- Concurrent additions of particulate, fiber and chemicals

    - For concurrent debris addition tests, an aliquot of the water from the mixing tank was removed and placed in a container and the prescribed amounts of particulate and fiber were added to the container. The particulate and fiber were then well mixed in this water until completely suspended before being added to the mixing tank. Concurrent with the addition of particulate and fiber, chemical surrogate was added directly to the mixing tank in the amount prescribed in the test procedure. Concurrent debris additions were made at times specified in the test procedure.

These approaches to introducing the debris into the test loop (sequential or concurrent) are consistent with the NRC guidance on head-loss testing (HEAD-LOSS AND VORTEXING REVIEW GUIDANCE, Section 6) issued on March 31, 2008 (Reference 10).

"Sequencing the debris for thin bed testing by adding 100 percent of the plant particulate load to the test flume and subsequently adding fibrous debris in incremental batches of an appropriate size is an acceptable method for performing thin bed testing. Depending on the scaling ratios for the test, this procedure may be overly conservative. As an alternative, a series of tests using homogeneous debris addition is also acceptable provided that a sufficient number of tests is performed to provide confidence that the limiting thin bed head-loss has been achieved".

The tests could be terminated based on either of the following criteria;

- exceeding the maximum pressure safety limit established for the test facility, or

- by meeting the equilibrium criterion determined by calculating the slope in differential pressure across the full fuel assembly [

]^{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 following 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. 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.

An overview of the test facility complete with pictures of debris preparation and test operation is provided in Appendix E. 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 sample of the chemical surrogate was tested to assure that the chemical mix met the settling requirements provided in the preparation procedure.

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; MRI is not transported to the AP1000 Containment Recirculation or IRWST screens due to the relatively low AP1000 flow rates during recirculation. The AP1000 design prohibits the use of fiberglass within the ZOI and as a result no fibrous debris is generated by the LOCA blowdown. Fiberglass insulation used inside the containment but outside the ZOI is jacketed.

- The AP1000 containment floods up to a higher level. The deeper flood levels significantly reduce the velocities that would occur during recirculation operation, 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. Note that the use of inorganic zinc coatings inside the containment is restricted to the inside surface of the containment shell and to components whose surface temperature exceeds the applicable limit for epoxy coatings. Zinc coatings used inside containment are required to be safety Service Level I to prevent their failure outside the ZOI. All coatings located inside the ZOI are assumed to fail as fines and to transport to the screens or the core.

- 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,

- Protective overhangs prevent heavier debris, including the high density coatings used in the AP1000, from falling onto or just in front of 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. The excore detectors are enclosed in stainless steel or titanium which prevents circulation of post-accident water past the aluminum detectors. The containment uses a structural steel modular construction which reduces the amount of concrete that can come in contact with post-accident water. This design minimizes the production of calcium phosphate by chemical reactions between the buffer agent (TSP) and concrete post-accident.

The AP1000 licensing basis fibrous, particulate, and chemical debris that could be transported into the reactor vessel and possibly reach the fuel assemblies, are presented in Table 4-2. These debris loads are based on a total debris load of 180 pounds and a chemical debris load of 57 pounds (Reference 5). Of the 180 pounds of debris, no more than 6.6 pounds may be fiber. The chemical debris load is based on the

type and quantity of chemical precipitates which may form in the post-LOCA recirculation fluid for the AP1000 design as reported in Reference 5. It is conservatively assumed that 90% of the fiber, 100% of the particulate, and 100% of the chemical debris is transported to the core in the licensing basis scenario.

Table 4-2 AP1000 Licensing Basis Latent Debris Load	
Totals in Containment, Particulate	173.4 lb (78.65 kg)
Fiber	6.6 lb (2.99 kg)
Chemical	57.0 lb (25.85 kg)
Transported to Core, Particulate (100%)	173.4 lb (78.65 kg)
Fiber (90%)	5.94 lb (2.69 kg)
Chemical (100%)	57.0 lb (25.85 kg)

4.1.4 Scaling Considerations

A scaling rationale was used to determine the parameters for flow rate, debris, and chemical precipitates for the experiments. The basic scaling rationale for all three parameters was to use the ratio of the test fixture flow area to the AP1000 core flow area and apply it to the flow rate, particulate and fibrous debris, and the chemical debris. This approach produces the same debris mass, debris bed formation and resulting head-loss through the "test assembly" as in a full core][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, the test facility water mass and the AP1000 recirculation mass were used.

[ ][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.

5 ACCEPTANCE CRITERION

The AP1000 safety related systems are designed to provide cooling to the reactor core indefinitely following a LOCA. After the initial injection of water from the core make tanks and the accumulators, the reactor coolant system (RCS) is almost depressurized and water is injected by gravity drain from the in-containment refueling water storage tank (IRWST). After the IRWST level drops below a specified set point, containment recirculation valves are opened to provide a supply of water for the RCS.

In this recirculation phase, natural circulation provides the driving force; water flowing through the core cooling the fuel bundles is discharged from the stage 4 of the automatic depressurization system (ADS) in the containment as a two phase mixture of steam and water; the steam released from the ADS valves is condensed on the steel surface of the containment vessel (which itself is cooled on the outside by the passive containment cooling system). The condensed water drains by gravity into a gutter and is then returned to the IRWST for injection into the RCS through the direct vessel injection (DVI) lines. The liquid water flooding the containment is returned to the RCS by the passive safety systems (PXS) containment recirculation screen and piping. However, due to the high flood-up level of the AP1000 design, water could bypass the recirculation screens and enter directly into the reactor vessel as in the case of a cold leg break located below the flood level.

With maximum bypass flow, the debris present in the containment may be transported directly into the RCS and eventually into the core. If a uniform debris bed forms as a result of debris collecting in the core, the resulting additional resistance may reduce the core flow rate. In order to assess the impact of additional resistance to flow at the core inlet, a long-term core cooling analysis has been performed to determine the minimum flow/maximum differential pressure (dP[1]) across the core (Reference 14).

Because of the large amount of water that floods the containment and the relatively slow recirculation flow rate, it will take many hours for the debris to be transported into the RCS.

Using this information, a worst case condition was then postulated assuming that all the debris will reach the core entrance after one complete recirculation of the entire containment water volume. In this case the long-term analysis (Reference 14) found that the limiting differential pressure through the core is 4.1 psid with a corresponding minimum flow rate of 65.0 lbm/s (480.7 gpm core flow rate).

Using the scale factor discussed in section 4.1.4 and the minimum flow rate of 480.7 gpm, the corresponding minimum flow rate for the tests is 3.1 gpm. The acceptance criterion for the fuel assembly tests is that the dP across the fuel assembly test article must not exceed 4.1 psid at a flow rate of 3.1 gpm. This acceptance criterion of 4.1 psid at a flow rate of 3.1 gpm will be applied to each of the fuel assembly tests.

As seen in Table 8-1, many tests were performed with a constant flow rate higher than 3.1 gpm or [

]^{a,c} by means of the following relation:

[1] Note that DP, dP, and ΔP may be used to express the differential pressure in this document.

$$dP_{@3.1gpm} = dP_{@Q} \cdot \left(\frac{3.1}{Q}\right)^{b} \qquad \text{(Eq. 5.0.1)}$$

where:

dP = max dP from test in psi

Q = flow rate from the test in gpm

b = exponent from Table 5.1

The justification of this relation is given in section 5.1

Table 5-1 Values of the exponent 'b' to be used in equation (5.0.1) a,c

[ ]

* Note: These tests were performed at a constant flow rate so that a test specific exponent can not be determined. They use an exponent based on the average from all of the tests. The other tests had flow variations so that a test specific exponent was determined.

For example, test CIBAP23 was performed between [ ]a,c. Using the data from CIBAP23, the dP at 3.1 gpm is then:

[ ]a.c

In this case, [ ]a,c.

For the tests where concurrent additions of debris were performed, an additional limit has been considered, based on sensitivity Case 3 in the LTC analysis (Reference 14): in this case the max dP allowed in the core at the beginning of the recirculation phase is 3.5 psi with a flow rate of 5.3 gpm/FA.

The additional criterion adopted requires that the max dP measured during the test, scaled at the flow of 5.3 gpm, must be lower than 3.5 psi. In all the concurrent addition tests the flow rate was higher than 5.3 gpm at [

]^{a,c} would have been at a flow of 5.3 gpm by means of the following relation:

$$dP_{@5.3gpm} = \max dP_{@Q} \cdot \left(\frac{5.3}{Q}\right)^{b} \qquad \text{(Eq. 5.0.2)}$$

where:

max dP = max dP [ ]^{a,c} in the test, expressed in psi

Q = flow rate from the test at which the max dP was measured, in gpm

b = exponent from Table 5.1

For example, in test CIBAP22 the max dP [

]^{a,c}. Using the data from CIBAP22, the max dP at 5.3 gpm is then:

[ ]^{a,c}

In this case, [

]^{a,c}.

5.1 dP / FLOW DEPENDENCE RELATIONSHIP

This section will present the method used to relate the change in differential pressure across the fuel bundle to the change in flow for the AP1000 fuel assembly head loss test program. In order to provide a comprehensive account of this relationship, all AP1000 fuel tests performed to date will be considered. The results obtained from these tests can provided an experimental basis to investigate the dependence of the loss of pressure through the fuel assembly from the flow rate once the debris bed was formed. Tests CIBAP08 through CIBAP11 were performed with oscillating flow rates in order to simulate the long-term core cooling (LTC) behavior of the AP1000 (APP-PXS-GLR-001, Revision 3). Tests CIBAP18 through CIBAP30 were performed with flow sweeps after all the termination criteria were met.

The experimental results are reported as diagrams in section 8.30. Following is a general evaluation of those results, with particular reference to the acceptance criterion formulation as reported above.

In all the tests where the dependence of the differential pressure through the fuel assembly from the flow rate was investigated, it follows a power law relation:

$$dP = aQ^b \qquad \text{(Eq. 5.1.1)}$$

In other words, once the debris bed is formed and becomes stable, the pressure drop behavior of the debris bed will not change with flow variation as shown in the flow sweeps performed at the end of tests CIBAP18 through CIBAP30 and demonstrated by the dP versus flow relationship presented in section 8.30.

$$\frac{dP}{Q^b} = const. \qquad \text{(Eq. 5.1.2)}$$

This also means that if the value of the exponent 'b' and the dP are known at a particular flow rate, it is possible to predict the value of the loss of pressure at any flow rate, at least in the range of validity of this relation. On this basis, Eq. 5.0.1 above has been used to verify that the AP1000 fuel assembly head-loss tests meet the acceptance criterion established above.

In all of the tests where the dependence of the dP through the fuel assembly on the flow rate was investigated (17 tests out of 30, performed under different conditions) the experimental data follow the relationship very well.

The exponent b has been evaluated for each test by best fit of the experimental data and the results are summarized in the following tables:

Table 5-2 Exponent 'b' obtained by best fit of the experimental data from the tests performed with oscillating flow rates and sequential additions (P/F/C).

a,c

[ ]

Table 5-3 Exponent 'b' obtained by best fit of the experimental data from the tests performed with sequential debris additions (P/F/C).

a,c

[ ]

Table 5-4 Exponent 'b' obtained by best fit of the experimental data from the tests performed with coincident debris additions.

a,c

[ ]

The data from the above tables are also shown in Figure 5-1. Because the exponent 'b' is related to the nature of the debris bed, the data in Figure 5-1 has been grouped considering the way the additions were performed (observations of the debris bed made during the tests indicates some difference between the bed formed by sequential debris additions and the bed formed by concurrent additions; sequential additions tend to form single layers of debris while concurrent addition tests tend to form multi-layers of debris).

As shown in Figure 5-1, the variability of the data in the concurrent addition tests is lower than the variability of the data in sequential addition tests. However, all the data are close to an average value of [ ]a,c.

The observed good agreement of the experimental data with Eq. 5.1.2 and the small variability of the best fit results respect to their average value (considering the many differences among the 17 tests) allows the use of the [ ]a,c as the exponent in Eq. 5.0.1 to verify the acceptance criterion in those tests where an experimental value of the exponent is not available. Moreover, it should be noted that even if the worst case exponent value of [ ]a,c were be applied to Eq. 5.0.1, all of the tests would still meet the acceptance criterion.

a,c

Figure 5-1 Values of the exponent 'b' generated by a best fit of the experimental data

6 DEBRIS PREPARATION

Debris preparation is an important factor in the justification of the applicability of these fuel assembly tests to the AP1000. The following discussions describe the preparation of the debris used in the AP1000 fuel assembly head-loss experiments. In depth information on the debris used in the AP1000 fuel assembly head-loss experiments is available in Appendix D.

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

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."

As thoroughly discussed in Appendix D, [

]^{a,c}. Based on the above, the fibers used in the experiments are applicable to AP1000..

Fiber types that were used in the AP1000 fuel assembly head-loss test program include:

Fiber A: [

]^{a,c}.

Fiber B: [

]a,c.

Fiber C: [

]a,c.

Fiber D: [

]a,c.

Fiber E: [

]a,c.

Fiber F: [

]a,c.

6.3 CHEMICAL PRECIPITATES

For the AP1000 fuel assembly test program, all chemical surrogate was made outside of the loop according to the approved procedure at the maximum allowable concentration of eleven grams per liter. Each batch was tested for settling properties according to the approved procedure in WCAP-16530-NP-A (Reference 12) prior to introduction into the test loop. The batches of chemical debris were added to the test loop at various rates, depending on the requirements of the particular test.

By following the approved WCAP-16530-NP-A (Reference 6) 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.

6.4 DEBRIS LOADS

Table 6-1 provides an overview of the AP1000 post-LOCA design basis debris loads and the debris loads assumed in the AP1000 fuel assembly head-loss test program.

Table 6-1 Original vs. Current AP1000™ Post-LOCA Debris Load Design Basis

a,c

7 TEST MATRIX AND INITIAL CONDITIONS

The test matrix has been designed to improve the knowledge base of the behavior of the AP1000 design when debris is transported to the core. Sensitivity tests were performed to better understand the influence of several parameters such as the [ ]a,c. Tests were performed at constant, oscillating, and variable flow rates. For instance, tests CIBAP01, and CIBAP03 through CIBAP07 and CIBAP13 through CIBAP16 were performed at a constant flow rate, CIBAP02, and CIBAP08 through CIBAP12 were performed with oscillating flow while CIBAP17 through CIBAP30 were performed with variable (decreasing) flow rates. Tests CIBAP01 through CIBAP21 and test CIBAP23 were performed using sequential additions of particles, then fibers, then chemical surrogate. Tests CIBAP22, and tests CIBAP24 through CIBAP30 were performed with concurrent additions of particles, fibers and chemical surrogate.

The initial conditions and test parameters of the AP1000 fuel assembly head-loss experiments CIBAP01 through CIBAP30 are thoroughly covered in the test procedures captured in Appendix C of this document and are summarized in Table 7-1, Table 7-2, and Table 7-3 below.

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

For test CIBAP01 through CIBAP15, the flow rate was based on the DCD base case: in this case the plant flow rate is [ ]a,c, was a conservative round up of this value.

For test CIBAP16, the flow rate was based on the core flow rate of a LTC sensitivity analysis, case 3 of Reference 3, that has a total [ ]a,c. This case assumes debris dP on the core and screens which reduces the flow rates. The flow rate for test CIBAP16 was [ ]a,c. This minimum flow rate was also applied to tests CIBAP17 through CIBAP28. In these cases the flow started at higher rates and was reduced as the dP increased.

Note that Reference 3 has been updated to include additional sensitivity analysis cases with even higher core flow resistances. Sensitivity case 10 reports a total injection flow of about [ ]a,c.

According to the AP1000 Long-term Cooling analysis, Reference 14, in the case of a DVI break located at the reactor vessel, the maximum flow rate [ ]a,c. Note that this analysis assumed no debris dP so this flow represents a high initial flow. Scaling this flow rate to [ ]a,c.

Moreover, the analysis on the Double Ended Cold Leg Guillotine break indicates a maximum core inlet flow rate of about [ ]^{a,c}. In terms of gallons per minute, it is[ ]^{a,c}. Scaling this flow rate to one fuel assembly it results: [ ]^{a,c}.

The maximum flow rate for the tests was selected at [ ]^{a,c}. Note as in both the two cases above discussed, the maximum flow rate refers to a clean condition in the fuel assembly (no debris). This value has been used as starting flow rate during some of the variable flow rate tests. In these tests the flow is reduced as the dP caused by the buildup of debris increases, which simulates the behavior of the plant.

Finally, in order to collect data to understand the debris bed behavior and dP dependence from the flow rate, after all the termination criterions during the tests were meet flow sweeps were performed. The data acquired from the flow sweeps is captured in Reference 17. Examples of the flow sweeps can be seen in the figures accompanying test results CIBAP18 through CIBAP30.

The initial loop temperature is set to [ ]^{a,c}.

a,c

Table 7-1 Initial conditions of AP1000™ Fuel Assembly Head-loss Tests CIBAP01 through CIBAP10

a,c

Table 7-2 Initial conditions of AP1000™ Fuel Assembly Head-loss Tests CIBAP11 through CIBAP20

a,c

Table 7-3 Initial conditions of AP1000™ Fuel Assembly Head-loss Tests CIBAP21 through CIBAP30

8 TEST RESULTS

8.1 SUMMARY OF AP1000 FUEL ASSEMBLY TESTING

All of the AP1000 fuel assembly head-loss tests performed to date are presented in this section. Each of the tests performed in this program considered a debris load of particulate, fiber, and chemicals in various quantities that were intended to be representative of the AP1000 debris load. Each test had specific acceptance and termination criteria based on differential pressure and steady state conditions. Each test was allowed to run to its termination so that the relationship between debris load and fuel assembly differential pressure could be captured. As each test was performed, the body of information related to the accumulation of debris on an AP1000 fuel assembly was increased.

The following thirty experiments have been performed to investigate a spectrum of resident debris loads and chemical effects. The data from all of the experiments, [

]^{a,c}, showed acceptable head-loss across the AP1000 fuel assembly.

The results from this test program demonstrate the ability of the AP1000 design to provide assurance of long-term core cooling under debris loading conditions expected for the AP1000 following a postulated LOCA. These experiments demonstrate that with the expected AP1000 debris loading conditions, long-term core cooling is assured. Head-losses due to the collection of debris within the fuel assemblies will not challenge either long-term core cooling or the maintaining of a coolable core geometry.

Data from the results of these experiments demonstrate that the design basis debris load that could exist in an AP1000 containment resulted in a fuel assembly head-loss that was well within the calculated head-loss limit established for the AP1000 in Reference 14; 4.1 psid at a flow rate of 3.1 gpm.

Test runs CIBAP01 through CIBAP04 were initially presented in WCAP-17028-P, Revision 0 and detailed in the Reference 7 test report. Test runs CIBAP05 through CIBAP16 were initially presented in WCAP-17028-P, Revision 1 and detailed in the Reference 8 and Reference 16 test reports. Tests CIBAP07, CIBAP12, and CIBAP15, excluded from WCAP-17028-P, Revision 1, were presented and discussed in WCAP-17028-P, Revision 2. Test runs CIBAP17 through CIBAP30 are included along with the aforementioned tests in this WCAP revision and detailed in the Reference 17 test report.

The Test Reports, References 7, 8, 16, and 17, provide a detailed record of test runs, debris loadings, flow rates, and procedures used to perform these tests. Table 8-1 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'.

As described in Appendix E, the same facility and test apparatus configuration was used for each of the AP1000 fuel assembly head-loss tests (One noted exception is Test CIBAP17, see Section 8.17). Detailed photographic coverage is provided for tests CIBAP16 (sequential additions), CIBAP24 (concurrent additions), CIBAP27 (concurrent additions) and CIBAP30 (concurrent additions) that follows the progression of debris accumulation on the fuel assembly.

Table 8-1 Summary of AP1000™ Fuel Assemblies Head-Loss Tests a,c

a,c

8.2 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.

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

Figure 8-1 provides the head-loss and flow rate history for test CIBAP01.

a,c

Figure 8-1 Head-loss and Flow Rate History for Test CIBAP01

8.3 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.

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.

a,c

Figure 8-2 Head-loss and Flow Rate History for Test CIBAP02

8.4 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.

Test #3 was a sensitivity experiment with an increased debris loading as compared to Tests #1 and #2. The purpose of this experiment was to explore the limits of AP1000 resident debris loadings without compromising the reasonable assurance of long-term core cooling. The debris mass loading was significantly increased over the debris loads used in Tests #1 and #2. The amount of fiber was increased by approximately 14 times the amount of fiber used in the bounding case test (CIBAP01).

The goal for this experiment was to reach approximately three feet of head-loss. This value was chosen because it would define a debris load that was high for the AP1000 given the fact that the AP1000 design minimizes the potential to generate LOCA debris. The value of three feet of head-loss also allows a significant margin to the acceptable head-loss value, ensuring a reasonable assurance of long-term core cooling.

Following test procedure STD-MCE-08-81 (Appendix C), the experiment was performed with a constant flow rate of [ ]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 8-3 was taken approximately one-half of a loop turnover after the second introduction of [ ]a,c of resident fiber.

The amount of debris that was introduced into the test loop was sufficient to cause head-loss of approximately [ ]a,c.

a,c

Figure 8-3 Head-loss and Flow Rate History for Test CIBAP03

8.5 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.

Test #4 was a repeat of Test #2 [

]^{a,c}. Observations noted throughout the experiment and the recorded data showed that the head-loss recorded was inconsequential when considering the impact of resident and chemical debris on the assurance of long-term core cooling (Figure 8-4).

Following test procedure STD-MCE-08-82, the debris was introduced into the test loop in the same manner as in Test #2. After loop stabilization was reached, [

]^{a,c}.

Similar to the results of Test #2, there was no reportable head-loss recorded for Test #4. The amount of debris that was introduced into the test loop was not sufficient to cause head-loss that would compromise the reasonable assurance of long-term core cooling.

a,c

Figure 8-4 Head-loss and Flow Rate History for Test CIBAP04

8.6 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.

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, Fibers).

The results of test CIBAP05 are summarized in Figure 8-5. 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 average temperature in the test column for the test was [ ]a,c. The plot of flow rate versus time in Figure 8-5 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

a,c

Figure 8-5 Head-loss and Flow Rate History for Test CIBAP05

8.7 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.

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

The amounts of fiber, particulate, and chemical debris [ ]a,c. This change in fiber type [ ]a,c.

Fiber B was used in this particular test to obtain a greater fraction of [ ]a,c.

Figure 8-6 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.

a,c

Figure 8-6 Head-loss and Flow Rate History for Test CIBAP06

8.8 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.

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, Fibers). CIBAP08 had [ ]a,c. The primary differences between CIBAP08 and CIBAP06 were the use of [ ]a,c in CIBAP08.

The flow rate and pressure drop results, as well as the timing of the debris additions, are summarized in Figure 8-7. Neither the SiC particulate nor the fibrous debris additions caused an increase in the head-loss across the fuel assembly. The first chemical debris addition [ ]a,c.

The average temperature in the test column and 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 [ ]a,c 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 differential pressure nor the location of debris capture changed during this extended operation. However, [ ]a,c.

a,c

Figure 8-7 Head-loss and Flow Rate History for Test CIBAP08

8.9 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.

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 obtained from PCI in the [ ]a,c.

Test CIBAP09 was conducted to determine the pressure drop characteristics of a debris mix with a [ ]a,c were not significantly different from one another. 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 8-8. Addition of the SiC particulate had no effect on the head-loss and addition of the fiber [ ]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.

a,c

Figure 8-8 Head-loss and Flow Rate History for Test CIBAP09

8.10 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.

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 8-9. Some difficulties with the data acquisition system were encountered during this particular test. The flow control program caused the flow rate to hold at [ ]a,c 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 8-9. 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 [ ][a,c]. This spike at six hours was brief and did not cause a change in pressure drop or a visible rearrangement of the debris bed.

a,c

Figure 8-9 Head-loss and Flow Rate History for Test CIBAP10

8.11 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.

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 8-2 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 8-10. 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, [ ]a,c [

]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.

a,c

Figure 8-10 Head-loss and Flow Rate History for Test CIBAP11

8.12 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.

In this case, the fibrous debris loadings were set at [ ]a,c was used in test CIBAP13 (see Section 6.2, 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 8-12 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 [exceeded twice the calculated concentration in the plant]a,c.

The pressure and flow rate results, as well as the timing of the additions for test CIBAP13, are summarized in Figure 8-11. 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.

a,c

Figure 8-11 Head-loss and Flow Rate History for Test CIBAP13

a,c

Figure 8-12 Concentration of Chemical Debris with Time

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8.13 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.

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 pressure and flow rate results, as well as the timing of the debris additions for test CIBAP14, are summarized in Figure 8-13. The gradual additions 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.

Approximately two hours after the second continuous addition of the chemical debris, the water in the loop was cloudy white from the AlOOH in suspension. Five hours later the water had become much clearer. The chemical debris was gradually filtered out of the water making it clearer in appearance and at the same time increasing the head-loss.

The overall appearance of the debris bed was similar to that seen seven hours after the second continuous AlOOH addition. One difference at the end of the test was the accumulation of what was probably a layer of AlOOH and SiC particulate on the bottom face of the debris bed. Another difference was the amount of chemical debris and SiC particulate that had settled out on top of the fuel assembly and at some points on top of some areas of the support grids. This settling was also seen in other tests and it is reasonable that some settling of debris would take place in low-flow locations of an AP1000 reactor or in containment after a LOCA. However, the turbulence caused by boiling would likely minimize settling at the top of the assembly.

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.

a,c

[ ]

Figure 8-13 Head-loss and Flow Rate History for Test CIBAP14

8.14 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.

In this case, the fibrous debris loadings were set at [ ]a,c was used in test CIBAP15 (see Section 6.2, 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 8-14. After the addition of the SiC particulate, [ ]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 8-14. 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 [ ]a,c, which was well within the allowable flow rate. The flow rate did not spike outside of the control band except for a brief excursion when the fiber added. Since this excursion occurred before the bed formed, 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.

a,c

Figure 8-14 Head-loss and Flow Rate History for Test CIBAP15

8.15 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.

In this case, the fibrous debris loadings were set at [ ]a,c was used in test CIBAP16 (see Section 6.2, Fiber). The scaled debris load was based on [ ]a,c (Figure 8-16). It was assumed that all of this fibrous and particulate debris was transported to the recirculation screen area and that [ ]a,c.

Test CIBAP16 included more fiber and particulate than was used in earlier tests. The rate of chemical surrogate addition was the same as used for test CIBAP14. The reduced rate of chemical addition [ ]a,c.

[ ]a,c into the mixing tank at a specified rate. As in test CIBAP14, [ ]a,c. 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 times the concentration is in accordance with NRC recommendations.

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 8-15. The pressure drop increase across [ ]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.

The pressure and flow rate results, as well as the timing of the additions for test CIBAP16, are summarized in Figure 8-15. Starting with a clean assembly (Figure 8-17), the addition of the SiC particulate (Figure 8-18), [ ]a,c. The addition of the fiber caused only a [ ]a,c (Figure 8-19). At this time, the additions of particulate and fiber result in a uniform build-up of debris along the edge of the bottom nozzle and the bottom of the p-grid (Figure 8-18) that increases with the addition of the chemicals. With the more gradual addition of chemicals, the head-loss did not increase as suddenly. Still, the first two additions of the chemical surrogate did result in

the head-loss increasing gradually to [ ]a,c. Note that between the first and second chemical additions (Figure 8-20 and Figure 8-21), the debris bed on both the lower left and right shows significant break through and reduced accumulation along the bottom of the p-grid. By the third chemical addition, the debris has taken on a smoother appearance and essentially no debris remains at the bottom of the p-grid (Figure 8-22). After the third chemical addition, the differential pressure increase [ ]a,c. The pressure drop vs. time curve was fairly level after the fourth chemical addition. The seventh and last chemical addition shows a smooth and well defined debris bed with visible layers of chemicals and very little debris on the bottom nozzle or p-grid (Figure 8-23). The final addition resulted in no additional head-loss increases. Thereafter, the pressure drop began a slow decline and then leveled at a final value of [ ]a,c.

a,c

Figure 8-15 Head-loss and Flow Rate History for Test CIBAP16

a,c

Figure 8-16 Debris Load For Test CIBAP16

a,c

Figure 8-17 Clean Assembly For Test CIBAP16

a,c

Figure 8-18 Addition Of Particulates For Test CIBAP16

a,c

Figure 8-19 Accumulation Of Fiber At Bottom Nozzle And P-Grid For Test CIBAP16

a,c

Figure 8-20 Debris Bed After Chemical Introduction For Test CIBAP16

a,c

Figure 8-21 Debris Bed After Second Chemical Introduction For Test CIBAP16

a,c

Figure 8-22 Debris Bed After The Third Chemical Introduction For Test CIBAP16

a,c

Figure 8-23 Debris Bed After Final Chemical Introduction For Test CIBAP16

8.16 TEST #17 (CIBAP17)

This was the seventeenth of the fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [

]a,c. This experiment was performed according to test plan STD-MCE-09-101 captured in Appendix C of this document. All debris was added sequentially with particulate followed by fiber followed by chemical surrogate.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [

]a,c. The results of test CIBAP17 are plotted in Figure 8-24.

Note that on the day test CIBAP17 was to be performed, there were delays in starting the test. After the test was started and the particulate debris was introduced into the test loop, it was decided, that it was too late in the day to complete the test. The flow through the loop was inadvertently stopped overnight (this was a deviation from the test procedure). The test was completed the next day. Also note that the test loop piping associated with this test was configured differently (see loop diagram Figure 8-25) than that used in previous AP1000 fuel assembly head-loss tests. Because of these issues with how this test was run and the different loop configuration used the test is considered invalid. A root cause analysis has been initiated on this test.

The particulate debris that had been in the loop for approximately 24 hours had no effect on the head loss across the assembly. [

]a,c.

At the onset of chemical addition, [

]a,c.

The pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location. This can be deduced by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-24. The pressure drop increase across the bottom nozzle (dP Lower) was the same as total pressure drop increase

across the entire assembly. The pressure drop between the top of the p-grid and the top of the assembly (dP Upper) was recorded at a maximum of [ ]a,c at the time of test termination.

The average temperature for both the test column and the mixing tank during the test was 73°F. The flow rate was [ ]a,c. The pH was measured throughout the test reaching a maximum pH of 6.8. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-24 Head-loss and Flow Rate History for Test CIBAP17

a,c

Figure 8-25 Schematic Of The Test Loop Configuration For CIBAP17

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8.17 TEST #18 (CIBAP18)

This was the eighteenth of the fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-102 captured in Appendix C of this document. All debris was added sequentially with particulate followed by fiber followed by chemical surrogate.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [ ]a,c. The results of test CIBAP18 are plotted in Figure 8-26.

The addition of particulate and fiber had little effect on the head-loss across the full assembly. The particulate caused zero pressure drop increase and the combination of fiber and particulate resulted in an increase of [ ]a,c.

At the onset of chemical addition, [ ]a,c.

In this test, [ ]a,c per the test procedure and held until the acceptance criterion was met again.

At this point in the test, a series of flow sweeps were performed at higher and lower flows than the flow recorded at test termination. The flow sweeps were performed to determine the pressure drop dependence on flow rate.

In test CIBAP18, the pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location. This is demonstrated by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-26. The pressure drop increase across the bottom nozzle (dP Lower) was slightly less than the total pressure drop increase across the entire assembly indicating that some debris was accumulating in the upper portion of the bundle. The pressure drop between the top of the p-grid and the top of the assembly (dP Upper) was recorded at approximately [ ]a,c for the portion of the test prior to the flow sweeps.

No visible debris beds or blockages formed when the particulate debris was added. After the fiber addition, a fiber bed developed at the bottom nozzle/p-grid. The dP at this time suggested that the debris bed had significant porosity. When the chemical surrogate was first added, there was not a great deal of

visible change in the bed and bits of fiber were observed above the p-grid. By the time the last chemical addition was in, only a small amount of fiber was observed to remain above the p-grid.

The average temperature for both the test column and the mixing tank during the test was 73°F. The flow rate was [ ]a,c.
The pH was measured throughout the test reaching a maximum pH of 7.78. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-26 Head-loss and Flow Rate History for Test CIBAP18

8.18 TEST #19 (CIBAP19)

This was the nineteenth of the fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-103 captured in Appendix C of this document. [ ]a,c.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [ ]a,c. The results of test CIBAP19 are plotted in Figure 8-27.

The additions of particulate had very little impact on the recorded differential pressure. After the introduction of the fiber, the fiber and particulate together resulted in a differential pressure [ ]a,c. Following the recommended loop turnovers, chemical debris was introduced into the loop.

In conjunction with the introduction of chemicals, a flow reduction scheme was initiated to reduce the flow rate commensurate with the increase in dP across the bundle. The addition of chemical debris had a significant effect. The first two chemical additions increased the pressure drop from a value of [ ]a,c. At this point, the data was checked to see if it met the termination criteria. After successfully meeting the termination criteria, the flow rate was reduced to [ ]a,c and the differential pressure was allowed to equilibrate. After meeting the termination criteria flow sweeps were started to assess the impact of pressure drop dependence on flow rate.

In test CIBAP19, the pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location. This is demonstrated by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" Figure 8-27. The pressure drop increase across the bottom nozzle (dP Lower) was essentially the same as total pressure drop increase across the entire assembly. The pressure drop between the top of the p-grid and the top of the assembly (dP Upper) changed insignificantly during the test.

No visible debris beds or blockages formed when the particulate debris was added. After the first fiber addition, a fiber bed developed at the bottom nozzle/p-grid. The dP at this time suggested that the debris bed had significant porosity. When the chemical surrogate was first added, there was not a great deal of visible change in the bed. As more chemical was added, a dense white layer formed within the bed at the bottom of the bottom nozzle. Only small amounts of fiber were observed above the p-grid. By the end of the test, the debris bed loaded with chemical precipitates is easily seen.

The average temperature for both the test column and the mixing tank during the test was 73°F. The maximum pH during the test was 8.39. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-27 Head-loss and Flow Rate History for Test CIBAP19

8.19 TEST #20 (CIBAP20)

This was the twentieth of the fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-107 captured in Appendix C of this document. All debris was added sequentially with particulate followed by fiber followed by chemical surrogate.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [ ]a,c. The results of test CIBAP20 are plotted in Figure 8-28.

The additions of particulate and fiber had little effect on the head-loss across the full assembly. The particulate caused zero pressure drop increase and the addition of fiber caused an increase [ ]a,c.

In conjunction with the introduction of chemicals, [ ]a,c. Flow sweeps were initiated after all termination criteria were met.

The pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location. This is demonstrated by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-28. The pressure drop increase across the bottom nozzle (dP Lower) was the same as total pressure drop increase across the entire assembly. The pressure drop between the top of the p-grid and the top of the assembly (dP Upper), did not change during the test.

No visible debris beds or blockages formed when the particulate debris was added. After the first fiber addition, a fiber bed developed at the bottom nozzle/p-grid. When the chemical surrogate was first added, there was not a great deal of visible change in the bed. As more chemical was added, a white layer formed within the bed at the bottom of the bottom nozzle and the fiber seemed to migrate up the p-grid away from the nozzle. After meeting all termination criteria at [ ]a,c, significant amounts of fiber were observed above the p-grid and the debris bed under the bottom nozzle appeared to be settling on the core support plate.

The average temperature for both the test column and the mixing tank during the test was 73°F. The flow rate was initially at [ ]a,c over the course of the experiment. The pH was measured throughout the test reaching a maximum pH of 7.78. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-28 Head-loss and Flow Rate History for Test CIBAP20

8.20 TEST #21 (CIBAP21)

This was the twenty-first of the fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-108 captured in Appendix C of this document. All debris was added with sequentially with particulate followed by fiber followed by chemical surrogate.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [ ]a,c. The results of test CIBAP21 are plotted in Figure 8-29.

The additions of particulate and fiber had little effect on the head-loss across the full assembly. The particulate caused zero pressure drop increase and the fiber with particulate resulted in an increase [ ]a,c.

At the onset of chemical addition, a flow reduction scheme was used to reduce the flow rate commensurate with the increase in dP associated with the chemicals. The test flow and dP initially tracked well with the performed flow reduction. [ ]a,c.

Per the test procedure, the flow rate [ ]a,c held until the termination criterion was met. At this point in the test flow sweeps were performed to determine the pressure drop dependence on flow rate.

As in the other tests, the pressure drop increase occurred almost exclusively at [ ]a,c. This can be seen by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-29. The pressure drop increase across the bottom nozzle (dP Lower) was the same as total pressure drop increase across the entire assembly. The pressure drop between the top of the p-grid and the top of the assembly (dP Upper) measured [ ]a,c during the pre-flow sweep portion of the test.

When the particulate material was added, no blockages were observed at any location and the particulate was well distributed about the test article. After the fiber addition, a fiber bed developed between the bottom nozzle and the p-grid. The fiber bed appeared to have significant porosity as the dP due to fiber and particulate was about [ ]a,c. When the chemical product surrogate was added, the bed porosity appeared to go down as indicated by the rise in dP. After the second chemical addition, the fiber bed showed signs of instability such that the dP dropped, recovered and dropped again prior to the third chemical addition. Further chemical additions resulted in

small increases with [ ]a,c. Late in the test, the chemicals were readily seen in the debris bed with only small amounts of fiber observed above the p-grid. Even though the bed looked very thick, the makeup of the bed must have been such that fluid could pass through it with relative ease as no further increase in dP was seen.

The average temperature for both the test column and the mixing tank during the test was 73°F. The flow rate was initially at [ ]a,c.
The pH was measured throughout the test reaching a maximum pH of 7.78. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-29 Head-loss and Flow Rate History for Test CIBAP21

8.21 TEST #22 (CIBAP22)

This was the twenty second fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-109 captured in Appendix C of this document. [ ]a,c.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [ ]a,c. The results of test CIBAP22 are plotted in Figure 8-30.

The first concurrent addition of particulate, fiber, and chemical precipitates had little effect on the head-loss across the full assembly resulting in [ ]a,c.

As in the previous tests, a flow reduction scheme was used to reduce the flow rate commensurate with the increase in dP across the fuel assembly bundle. In previous tests, the reduction scheme was only applied at the introduction of the chemical precipitates. For this test, the reduction scheme was applied from the beginning of the test as the dP attributed to debris accumulation increased.

[ ]a,c.

An interesting observation from this test is that the fiber appeared to accumulate around the bottom of the p-grid prior to accumulating around the bottom nozzle. This accumulation begins to appear just prior to the second addition and continues through the fourth addition when a debris bed begins to form around the edges of the bottom nozzle. Also seen in this concurrent debris addition test is the accumulation of fibers in the middle of the first grid above the p-grid and along the bottom of the second grid above the p-grid.

The pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location as in the other tests. This can be seen by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-30. The pressure drop increase across the bottom nozzle (dP Lower) was approximately the same as total pressure drop increase across the entire assembly. [

]a,c held until termination criteria were met, and flow sweeps were to be initiated. As seen in Figure 8-30 the flow sweep program did not run.

The average temperature for both the test column and the mixing tank during the test was 73°F. The flow rate was initially at [ ]a,c. The pH was measured throughout the test reaching a maximum pH of 7.78. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-30 Head-loss and Flow Rate History for Test CIBAP22

8.22 TEST #23 (CIBAP23)

This was the twenty third fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-113 captured in Appendix C of this document. All debris was added sequentially.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [ ]a,c. The results of test CIBAP23 are plotted in Figure 8-31.

This is a repeat of test CIBAP17. For this test, there were no delays in starting the test as discussed in Section 7.17. This test uses the same loop plumbing as used in tests CIBAP01 through CIBAP30. This test was performed as described in STD-MCE-09-113.

The addition of the particulate had no effect on the loop dP. The particulate caused zero pressure drop increase and the addition of fiber resulted in an [ ]a,c.

The third chemical addition resulted in the [ ]a,c. At this point, the steady state termination criterion was met and flow sweeps were initiated.

As in the other AP1000 fuel assembly debris tests, the pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location. This is demonstrated by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-31. The pressure drop increase across the bottom nozzle (dP Lower) was the same as total pressure drop increase across the entire assembly. The pressure drop between the top of the p-grid and the top of the assembly (dP Upper), did not change during the test.

As in the previous sequential addition tests, a flow reduction scheme was used at the onset of chemical addition to reduce the flow rate commensurate with the increase in dP associated with the chemical additions. The test flow and dP initially tracked well with the performed flow reduction as seen in Figure 8-31. At approximately 4.19 hours into the test, the slope of the flow reduction was set to 0.0 at a flow rate of [ ]a,c. During this steady state condition the fourth through seventh chemical additions were prepared and introduced into the loop.

When the particulate material was added, no blockages were observed at any location and the particulate was well distributed about the test article. After the fiber addition, a fiber bed developed at the bottom nozzle and between the bottom nozzle and the p-grid. Due to the small increase in dP, it is assumed that the fiber bed must have had significant porosity. After the chemical surrogate was added the bed porosity

decreased as indicated by the rise in dP. At this point in the test, with all of the fiber, particulate, and first chemical addition in the loop, the debris looked rough and uneven. After the second chemical addition, the debris began to look smoother and the amount of debris located on the p-grid had been greatly reduced. By the seventh and final chemical addition, the debris was very smooth with visible layers of chemicals and only a small amount of fiber above the p-grid.

The average temperature for both the test column and the mixing tank during the test was 70°F. The flow rate was initially at [ ]a,c. The pH was measured throughout the test reaching a maximum pH of 7.4. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-31 Head-loss and Flow Rate History for Test CIBAP23

8.23 TEST #24 (CIBAP24)

This was the twenty fourth fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-115 captured in Appendix C. [ ]a,c.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [ ]a,c. The results of test CIBAP24 are plotted in Figure 8-32.

The first concurrent addition of particulate, fiber, and chemical precipitates had little effect on the head-loss across the full assembly resulting in [ ]a,c and held until termination criteria were again met, then flow sweeps were performed to provide insight on the pressure drop dependence on flow rate.

As in the previous tests in this series, a flow reduction scheme was used to reduce the flow rate commensurate with the increase in dP across the fuel assembly bundle (Figure 8-33). For this test, the reduction scheme was applied from the beginning of the test as the dP attributed to debris accumulation increased during the concurrent additions. The test flow and dP tracked well with the performed flow reduction as seen in Figure 8-32. [ ]a,c.

As witnessed in test CIBAP22, the fiber accumulated around the bottom of the p-grid (Figure 8-34, Figure 8-35, Figure 8-36) prior to accumulating around the bottom nozzle (Figure 8-37). This accumulation began to appear just prior to the second addition and continued through the fourth addition when a debris bed began to form around the edges of the bottom nozzle. Also witnessed in this concurrent debris addition test was the accumulation of fibers in the middle of the first grid above the p-grid (Figure 8-38) and along the bottom of the second grid above the p-grid (Figure 8-39). The accumulation of debris in these areas is atypical when considering the other AP1000 fuel assembly tests. It suggests that individual fibers arriving at the fuel assembly bottom nozzle in lesser amounts may have a greater chance of migrating through the fuel bundle. By the end of the test, the debris bed has taken on a smooth rounded appearance (Figure 8-40) and is not continuous around the edges of the bottom nozzle leaving many break-through areas where flow is not impeded.

Even with a noticeable accumulation of fiber away from the bottom nozzle, the pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location as in the other tests. This can be seen by

comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-32. The pressure drop contribution from the upper assembly [ ]a,c.

The average temperature for both the test column and the mixing tank during the test was 72°F. The pH was measured throughout the test reaching a maximum pH of 7.81. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant. The flow rate reached a steady state condition at [ ]a,c, held until termination criteria were met, and flow sweeps were initiated.

a,c

Figure 8-32 Head-loss and Flow Rate History for Test CIBAP24

a,c

Figure 8-33 Flow Versus dP During Test CIBAP 24

a,c

Figure 8-34 Accumulation Of Debris At The Bottom Of The P-Grid After Second Concurrent Debris Addition In Test CIBAP24

a,c

Figure 8-35 Accumulation Of Debris At The Bottom Of The P-Grid After Third Concurrent Debris Addition In Test CIBAP24

a,c

Figure 8-36 Accumulation Of Debris At The Bottom Of The P-Grid After Fourth Concurrent Debris Addition In Test CIBAP24

a,c

Figure 8-37 Accumulation Of Debris Around The Edge Of The Bottom Nozzle After Seventh Concurrent Debris Addition In Test CIBAP24

a,c

Figure 8-38 Accumulation Of Debris In The Middle Of The First Grid Above The P-Grid After The Ninth Addition In Test CIBAP24

a,c

Figure 8-39 Accumulation Of Debris Around The Bottom Of The Second Spacer Grid After The Ninth Addition In Test CIBAP24

a,c

Figure 8-40 Accumulation Of Debris Around The Bottom Nozzle And P-Grid At The End Of Test CIBAP24 Prior To Flow Sweeps

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8.24 TEST #25 (CIBAP25)

This was the twenty fifth fuel assembly debris loading head loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-116 captured in Appendix C. [ ]a,c.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [ ]a,c. The results of test CIBAP25 are plotted in Figure 8-41. This test is similar to test CIBAP24 except that the chemicals are [ ]a,c.

The first concurrent addition of particulate, fiber, and chemical precipitates had little effect on the head loss across the full assembly resulting in [ ]a,c.

During this time, the test procedure was being followed to reduce the flow rate commensurate with the increase in differential pressure attributed to debris accumulation within the fuel assembly.

Approximately 17 minutes following the eleventh chemical addition, a flow anomaly occurred that caused a flow excursion in the loop. The upper flow meter which was controlling the flow in the loop, registered a minimum flow of zero gpm which caused the flow to increase significantly. The increase in flow was monitored by the lower flow meter; it registered a peak flow of [ ]a,c. Then the dP reacted to the flow anomaly by falling to [ ]a,c (Figure 8-41). Observations at the time of the flow anomaly indicated that large 'chunks' of the debris formations around the bottom nozzle and p-grid broke off and were swept away. [ ]a,c.

Even though the test experienced a significant anomaly, it was continued as planed. The flow rate was [ ]a,c. All subsequent chemical additions were made. After the final chemical addition, the prerequisite number of loop turnovers was performed, the data was checked and found to meet the termination criteria. Flow sweeps were performed as written in the test plan.

As seen in CIBAP24, the fiber accumulated around the bottom of the p-grid prior to accumulating around the bottom nozzle. This accumulation began to appear just after the second addition and continued through the fourth addition when a debris bed began to form around the edges of the bottom nozzle.

Even with a noticeable accumulation of debris away from the bottom nozzle, the pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location as in the other tests. This can be seen by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-41. The pressure drop contribution from the upper assembly was [ ]a,c.

The average temperature for both the test column and the mixing tank during the test was 72°F. The pH was measured throughout the test reaching a maximum pH of 7.86. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-41 Head-loss and Flow Rate History for Test CIBAP25

8.25 TEST #26 (CIBAP26)

This was the twenty sixth fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-123 captured in Appendix C. [ ]a,c.

In this experiment, the debris loadings were based on a total AP1000 post-LOCA containment debris load [ ]a,c. The results of test CIBAP26 are plotted in Figure 8-42. This test is similar to test CIBAP25 except that the [ ]a,c.

The [ ]a,c of concurrent debris additions of particulate, fiber, and chemical precipitates resulted in a pressure differential across the full assembly of about [ ]a,c. The remaining four 'chemical only' additions resulted in no further increases in the recorded dP.

During this time, the test procedure was being followed to reduce the flow rate commensurate with the increase in differential pressure. By the fourteenth addition, the flow rate had been reduced from [ ]a,c. Over the next hour and 15 minutes the steady state test criterion was again met and the automated flow sweeps were initiated.

In this test, with the debris being added concurrently over 14 hours, the fiber just started to accumulate around the bottom of the p-grid after the third addition. After the fifth addition, with [ ]a,c.

Even with a noticeable accumulation of debris away from the bottom nozzle upper bundle dP, the pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location as in the other tests. This can be seen by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-42.

The pressure drop contribution from the upper assembly [
]a,c.

The average temperature for both the test column and the mixing tank during the test was 71.5°F. The pH was measured throughout the test reaching a maximum pH of 7.91. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-42 Head-loss and Flow Rate History for Test CIBAP26

8.26 TEST #27 (CIBAP27)

This was the twenty seventh of the fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c. This experiment was performed according to test plan STD-MCE-09-125 captured in Appendix C. This test was a repeat of test CIBAP25, except that [ ]a,c.

In this experiment, the debris loadings were based on a reduced AP1000 post-LOCA containment debris [ ]a,c. The results of test CIBAP27 are plotted in (Figure 8-43). All debris was added concurrently.

The first concurrent addition of particulate, fiber, and chemical precipitates had little effect on the head-loss across the full assembly resulting in [ ]a,c.

During this time, the test procedure was being followed to reduce the flow rate commensurate with the increase in differential pressure (Figure 8-44).

Similar to test CIBAP25, the fiber accumulated around the bottom of the p-grid (Figure 8-45) prior to accumulating around the bottom nozzle (Figure 8-46). This accumulation begins to appear just after the second addition and continues through the fourth addition when a debris bed begins to form around the edges of the bottom nozzle (Figure 8-47). By the time of the sixth addition, the debris buildup along the edges of the bottom nozzle and bottom of the p-grid are significant. Unlike test CIBAP25, there is no visible accumulation of debris at the first spacer grid. After the seventh and last concurrent addition, the accumulation of chemicals in the debris bed is easily seen (Figure 8-48) and the debris bed still has rough edges (Figure 8-49). Between the ninth (Figure 8-50) and twelfth (Figure 8-51) additions, the debris bed takes on a smoother appearance and there is a visible break through of the debris bed along the lower left and upper right edge of the bottom nozzle. Once these break through areas are established they remain clear for the remainder of the test as seen in Figure 8-53. The dP peaks at [ ]a,c. By the time of the fourteenth addition, the edges of the debris bed (Figure 8-52) are very smooth and well defined and continues to get thicker as the test progresses without a corresponding increase in dP. After the seventeenth addition, the dP is monitored until the steady state dP condition is met. With all acceptance criteria met, flow sweeps are initiated to determine the pressure drop dependence on flow rate. As seen in Figure 8-53 the debris is very thick and very smooth yet did not cause an increase in the steady state dP.

The pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location as in the other tests. This can be seen by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-43. The pressure drop contribution from the upper assembly was approximately [ ]a,c.

The average temperature for both the test column and the mixing tank during the test was 72°F. The pH was measured throughout the test reaching a maximum pH of 7.91. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-43 Head-loss and Flow Rate History for Test CIBAP27

a,c

Figure 8-44 Flow Versus Dp During Test CIBAP 27

a,c

Figure 8-45 Accumulation Of Debris Around The Bottom Nozzle And P-Grid After The Third Concurrent Addition In Test CIBAP27

a,c

Figure 8-46 Accumulation Of Debris Around The Bottom Nozzle And P-Grid At The Fourth Concurrent Addition In Test CIBAP27

a,c

Figure 8-47 Accumulation Of Debris Around The Bottom Nozzle And P-Grid At The Fifth Concurrent Addition In Test CIBAP27

a,c

Figure 8-48 Accumulation Of Debris Around The Bottom Nozzle And P-Grid 30 Minutes Into The Fifth Concurrent Addition In Test CIBAP27

a,c

Figure 8-49 Accumulation Of Debris Around The Bottom Nozzle And P-Grid 30 Minutes Into The Ninth Chemical Addition In Test CIBAP27

a,c

Figure 8-50 Accumulation Of Debris Around The Bottom Nozzle And P-Grid At The Time Of The Tenth Chemical Addition In Test CIBAP27

a,c

Figure 8-51 Accumulation Of Debris Around The Bottom Nozzle And P-Grid 30 Minutes Into The Twelfth Chemical Addition In Test CIBAP27

a,c

Figure 8-52 Accumulation Of Debris Around The Bottom Nozzle And P-Grid 15 Minutes After The Fourteenth Chemical Addition In Test CIBAP27

a,c

Figure 8-53 Accumulation Of Debris Around The Bottom Nozzle And P-Grid Prior To Flow Sweeps In Test CIBAP27

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8.27 TEST #28 (CIBAP28)

This was the twenty eighth of the fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c . This experiment was performed according to test plan STD-MCE-09-132. This test was a repeat of test CIBAP27 [ ]a,c.

In this experiment, the debris loadings were based on a reduced AP1000 post-LOCA containment debris load of [ ]a,c. The results of test CIBAP28 are plotted in Figure 8-54. All debris was added concurrently.

The first concurrent addition of silicon carbide particulate, fiber, and chemical precipitates had little effect on the head-loss across the full assembly resulting in a [ ]a,c.

During this time, the test procedure was being followed using the information in to reduce the flow rate commensurate with the increase in differential pressure.

Similar to test CIBAP25, the fiber accumulated around the bottom of the p-grid prior to accumulating around the bottom nozzle. This accumulation begins to appear just after the second addition and continues through the fourth addition when a debris bed begins to form around the edges of the bottom nozzle. By the time of the sixth addition, the debris buildup along the edges of the bottom nozzle and bottom of the p-grid are significant. Unlike test CIBAP25, there is no visible accumulation of debris at the first spacer grid. After the seventh and last concurrent addition, the accumulation of chemicals in the debris bed still has rough edges. Between the ninth and twelfth additions, the debris bed takes on a smoother appearance. The dP peaks at [ ]a,c. By the time of the fourteenth addition, the edges of the debris bed were very smooth and well defined and continued to get thicker as the test progressed without a corresponding increase in dP. After the seventeenth addition, the dP was monitored until the steady state dP condition was met. With all acceptance criteria met, flow sweeps were initiated to determine the pressure drop dependence on flow rate.

The pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location as in the other tests. This can be seen by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-54. The pressure drop contribution from the upper assembly was approximately [ ]a,c.

The average temperature for both the test column and the mixing tank during the test was 74°F. The pH was measured throughout the test reaching a maximum pH of 7.83. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-54 Head-loss and Flow Rate History for Test CIBAP28

8.28 TEST #29 (CIBAP29)

This was the twenty ninth fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c . This experiment was performed according to test plan STD-MCE-09-133 This test was a repeat of test CIBAP27, except the [ ]a,c.

In this experiment, the debris loadings were based on a reduced AP1000 post-LOCA containment debris load of [ ]a,c. The results of test CIBAP29 are plotted in Figure 8-55. All debris was added concurrently.

The first concurrent addition of particulate, fiber, and chemical precipitates had little effect on the head-loss across the full assembly resulting in a [ ]a,c.

During this time, the test procedure was being followed using the information in to reduce the flow rate commensurate with the increase in differential pressure.

Similar to previous concurrent debris addition tests, the fiber accumulated around the bottom of the p-grid prior to accumulating around the bottom nozzle. This accumulation begins to appear just after the second addition and continues through the fourth addition when a debris bed begins to form around the edges of the bottom nozzle . Similar to test CIBAP22, there is visible accumulation of debris at the second spacer grid but in this test there is very little on the first spacer grid . By the time of the sixth addition, the debris buildup along the edges of the bottom nozzle and bottom of the p-grid are significant. After the seventh and last concurrent addition, the accumulation of chemicals in the debris bed is easily seen and the debris bed still has rough edges The dP peaks at [ ]a,c. By the time of the fifteenth addition, the edges of the debris bed are very smooth and well defined and continue to get thicker as the test progresses without a corresponding increase in dP. After the seventeenth and final addition, the dP is monitored until the steady state dP condition is met. With all acceptance criteria met, flow sweeps are initiated to determine the pressure drop dependence on flow rate. As seen in the debris is very thick and very smooth at the time of the flow sweeps yet did not cause an increase in the steady state dP.

The pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location as in the other tests. The accumulation of debris in the second spacer grid shows a [ ]a,c.

The average temperature for both the test column and the mixing tank during the test was 74°F. The pH was measured throughout the test reaching a maximum pH of 7.86. This was within the allowable range for the test (5 to 9), so any dissolution of the chemical product surrogate was insignificant.

a,c

Figure 8-55 Head-loss and Flow Rate History for Test CIBAP29

8.29 TEST #30 (CIBAP30)

This was the thirtieth fuel assembly debris loading head-loss experiments performed in the STC test facility for the AP1000. [ ]a,c . This experiment was performed according to test plan STD-MCE-09-135 captured in Appendix C. [ ]a,c.

In this experiment, the debris loadings were based on a reduced AP1000 post-LOCA containment debris load of [ ]a,c. The results of test CIBAP29 are plotted in Figure 8-56.

The first concurrent addition of silicon carbide particulate, fiber, and chemical precipitates had little effect on the head-loss across the full assembly resulting in a [ ]a,c.

During this time, the test procedure was being followed using the information in to reduce the flow rate commensurate with the increase in differential pressure.

Similar to previous tests, the fiber accumulated around the bottom of the p-grid prior to accumulating around the bottom nozzle (Figure 8-57). This accumulation begins to appear just after the second addition and continues through the fourth addition when a debris bed begins to form around the edges of the bottom nozzle Figure 8-58. By the time of the fifth addition (Figure 8-59), the debris buildup along the edges of the bottom nozzle and bottom of the p-grid are apparent. Unlike test CIBAP29, there was very little accumulation of debris at the first and second spacer grids early in the test. After the seventh and last concurrent addition, the accumulation of chemicals in the debris bed was observed and the debris bed still had rough edges . Between the ninth and twelfth additions, the debris bed takes on a smoother appearance (Figure 8-60 and Figure 8-61) as the chemical coats the debris bed. The dP peaks at [ ]a,c. By the time of the seventeenth addition, the edges of the debris bed are very smooth and well defined and continue to get thicker as the test progresses with only small increases in dP. Between the fifteenth and sixteenth additions, the dP drops again due to a break though within the debris bed. After the seventeenth addition (Figure 8-62), the dP is monitored until the steady state dP condition is met. With all acceptance criteria met, flow sweeps are initiated to determine the pressure drop dependence on flow rate. Near the end of the flow sweeps, the debris is very thick and very smooth (Figure 8-63) yet did not cause an increase in the steady state dP.

Of note in this test is the initial accumulation of debris along the edge of the upper left of the bottom nozzle opening as seen in Figure 8-58. By the time of the fifth addition (Figure 8-58), an opening begins

to appear along the upper left edge. By the ninth addition, a clean path has been established (Figure 8-60) that remains open to test termination (Figure 8-63).

The pressure drop increase occurred almost exclusively at the bottom nozzle/p-grid location as in the other tests. This can be seen by comparing the trace labeled "dP Upper" to the trace labeled "dP Lower" in Figure 8-56. [
]a,c.

a,c

Figure 8-56 Head-loss and Flow Rate History for Test CIBAP30

a,c

Figure 8-57 Accumulation Of Debris At The Bottom Nozzle And P-Grid 30 Minutes After The Third Concurrent Addition In Test CIBAP30

a,c

Figure 8-58 Accumulation Of Debris At The Bottom Nozzle And P-Grid 30 Minutes After The Fourth Concurrent Addition In Test CIBAP30

a,c

Figure 8-59 Accumulation Of Debris At The Bottom Nozzle And P-Grid 30 Minutes After The Fifth Concurrent Addition In Test CIBAP30

a,c

Figure 8-60 Accumulation Of Debris At The Bottom Nozzle And P-Grid 30 Minutes After The Ninth Chemical Addition In Test CIBAP30

a,c

Figure 8-61 Accumulation Of Debris At The Bottom Nozzle And P-Grid 30 Minutes After The Twelfth Chemical Addition In Test CIBAP30

a,c

Figure 8-62 Accumulation Of Debris At The Bottom Nozzle And P-Grid 30 Minutes After The Seventeenth Chemical Addition In Test CIBAP30

a,c

Figure 8-63 Accumulation Of Debris At The Bottom Nozzle And P-Grid Near The End Of The Flow Sweeps In Test CIBAP30

8.30 PRESSURE DIFFERENTIAL WITH FLOW

The results obtained from the AP1000 fuel assembly tests have been used to provide an experimental basis to determine the dependence of the pressure loss through the fuel assembly on the flow rate once a debris bed was formed as described in section 5.1. The following three subsections describe this evaluation. The first shows the analysis of flow / dP data from the later portions of each test when the bed dP had stopped changing. The second subsection evaluates the stability of the bed resistance during these times. The third subsection evaluates the flow / dP at the peak dP condition and compares it with the stable bed behavior.

8.30.1 Variation of dP with Variation of Flow and End-of-Test Data

Tests CIBAP08 through CIBAP11 were performed with oscillating flow rates in order to simulate the long-term behavior of the AP1000 as discussed above in the test results section 8.0. The oscillatory nature of tests CIBAP08 through CIBAP11 provides another way to investigate the dependence of the loss of pressure through the fuel assembly on the flow rate. Tests CIBAP18 through CIBAP30 were performed with flow sweeps at the end of each test to investigate the dependence of the loss of pressure through the fuel assembly on the flow rate as discussed in section 5.0.

The pressure drop (dP) versus flow relationship plots for tests CIBAP08 through CIBAP11 and tests CIBAP08 through CIBAP11 are captured in Reference 17. Examples from each of the test series are provided below.

Tests CIBAP09 and CIBAP11 were sequential addition tests performed with oscillating flow between [ ]^{a,c} (see section 8.9, Figure 8-8 and section 8.11, Figure 8-10). The resulting dP vs flow curves are shown in Figure 8-64 and Figure 8-65 along with the power curve fit that provides the exponent used in Eq. 5.0.1 to define the relationship of the test data to the acceptance criterion of 4.1 psid (section 5.0). For tests CIBAP08 through CIBAP11 the data was taken after all debris had been added and the flow and dP had stabilized.

The "hysteresis" shown in Figure 8-64 and Figure 8-65 is peculiar to all of the oscillating flow tests. The two dense clouds of points at the bottom and at the top of the loop are the data collected when the flow rate was constant at [ ]^{a,c} respectively (steady state conditions). These data fit well the power law relationship as is shown in Figure 8-64 and Figure 8-65. The data collected during the increasing and decreasing flow rate phase of each cycle are distributed along a loop contour. In particular (see Figure 8-6);

- During the flow increase from [ ]^{a,c} the data follows the upper part of the loop, and,
- when the flow rate returns to [ ]^{a,c}, the data follows the lower part.

This behavior is related to an instrumentation time delay. The output signal of the flow meter is the average of five consecutive samples. This is not a running average; the next output signal is the average of the next five samples. The sample frequency of the flow meter is [ ]^{a,c}. Thus, the flow meter provides an output signal;

[ ]^{a,c}

Also, the data acquisition computer samples the flow meter [

]a,c when the changes in flow rate are slow as in the case of the flow sweeps performed in tests CIBAP18 through CIBAP30. However, during the rapid changes such as in test CIBAP08 through test CIBAP11, a hysteresis which is strictly an artifact of the sampling of the instruments appears in the data.

a,c

Figure 8-64 dP Versus Flow For Test CIBAP09

a,c

Figure 8-65 dP Versus Flow For Test CIBAP11

a,c

[ ]

Figure 8-66 dP First and last flow cycle in test CIBAP11

Tests CIBAP20 and CIBAP21 were sequential addition tests performed with flow between [ ]a,c (see section 8.19, Figure 8-28 and section 8.20, Figure 8-29). The resulting dP vs flow curves are shown in Figure 8-67 and Figure 8-68 along with the power curve fit that provides the exponent used in Eq. 5.0.1 to define the relationship of the test data to the acceptance criterion of 4.1 psid (section 5.0). For tests CIBAP17 through CIBAP21, and CIBAP23, the data was taken from the flow sweeps after all debris had been added and the flow had stabilized. In these cases the data follows the power law relationship between dP and flow rate very well. Moreover, for all of the tests, the debris bed quickly reaches a stable resistance that does not change when the maximum and minimum flow values for the flow sweeps is repeated. This is generally true for all tests in which flow sweeps were performed.

a,c

[ ]

Figure 8-67 dP Versus Flow For Test CIBAP20

a,c

[ ]

Figure 8-68 dP Versus Flow For Test CIBAP21

Test CIBAP25, CIBAP26 and CIBAP30 were concurrent addition tests performed with flow between [ ]a,c (see section 8.24, Figure 8-41 and section 8.25, Figure 8-42) and between [ ]a,c (see section 8.29, Figure 8-56). The resulting dP vs flow curve is shown in Figure 8-69, Figure 8-70 and Figure 8-71 along with the power curve fit that provide the exponents used in Eq. 5.0.1 to define the relationship of the test data to the acceptance criterion of 4.1 psid (section 5.0). For tests CIBAP22 and CIBAP24 through CIBAP30, the data was taken from the flow sweeps after all debris had been added and the flow had stabilized. In these cases the data follows the power law relationship between dP and flow rate very well. The debris bed remains stable once it is formed and pressure drops are repeated when the flow sweeps are repeated. Moreover, the exponent of the power law describing the data shows a lower variability among the concurrent debris addition tests in comparison to that seen in the sequential debris addition tests.

a,c

[ ]

Figure 8-69 dP Versus Flow For Test CIBAP25

a,c

Figure 8-70 dP Versus Flow For Test CIBAP26

a,c

Figure 8-71 dP Versus Flow For Test CIBAP30

8.30.2 Bed Stability During Flow Sweeps

As discussed above, the experimental data indicates that during the flow sweep operations the debris bed quickly reaches a stable resistance that remains constant when the maximum and minimum flow sweep value is repeated. For example, in Figure 8-72 the data from test CIBAP20 (Figure 8-28) is displayed. As can be seen in Figure 8-72 the curve that fits the data collected during the first 5.1 hours is nearly identical to the one that fits the data collected during the last 2.7 hours of flow sweeps operation. The coefficients for the two curves are nearly the same value, indicating that the debris bed resistance doesn't change.

a,c

[ ]

Figure 8-72 dP Versus Flow For Test CIBAP20

There is one test in which a small but well defined variation in the debris bed resistance was observed. The dP versus flow rate data from test CIBAP18 is shown in Figure 8-72.

As seen in Figure 8-73, the data collected during the first 3.4 hrs (this time includes 5.3 gpm constant flow rate and the first stack of flow sweeps,(see Figure 8-26) [

]a,c.

a,c

[ ]

Figure 8-73 dP Versus Flow During The First And The Last Part Of The Flow Sweeps In Test CIBAP18

The data collected during all the flow sweeps are shown Figure 8-74. When all the data are considered the exponent of the best fit curve became 1.41. For conservatism this value has been used in the equation 5.0.1 to calculate the scaled dP value for test CIBAP18.

From the data discussed above, it is concluded that for the AP1000 debris loads tested, the debris bed collected at the bottom of the fuel assembly is both stable and well behaved. Specifically, the hydraulic characteristics of the bed were not observed to change significantly as [

]a,c.

a,c

[ ]

Figure 8-74 dP Versus Flow Full Range Of Flow Sweep In Test CIBAP18

8.30.3 Variation of dP with Flow – Peak dP Test Data

An evaluation was undertaken to demonstrate the applicability of the exponent of the power law fit developed on the flow sweep data to the peak dP data from the same test. To support this demonstration, the data at and around the peak in the tests from CIBAP18 through CIBAP30 were considered. [

]a,c.

[

]a,c. Examples of the results of these fits are shown graphically in Figure 8-75 (CIBAP25), Figure 8-76 (CIBAP26), and Figure 8-77 (CIBAP30).

a,c

Figure 8-75 CIBAP25; Power Law Fit of Peak dP with Flow Sweep Exponent

a,c

Figure 8-76 CIBAP26; Power Law Fit of Peak dP with Flow Sweep Exponent

a,c

[ ]

Figure 8-77 CIBAP30; Power Law Fit of Peak dP with Flow Sweep Exponent

In general, two observations are made from these figures;

1) [ ]a,c.

2) [ ]a,c.

[

]a,c.

The bottom line is that the flow / dP data from the peat dP condition matches is fit well using the same power exponent developed from the flow sweep data, indicating that it is appropriate to use these power exponents to adjust the peak dP / flows to the analysis limit flow (3.1 gpm).

8.31 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.

CIBAP17 – This test is considered invalid because there were some issues with how it was run and with the loop configuration which was different from the other AP1000 tests. Section 8.16 provides additional discussion of the issues with this test.

9 CONCLUSIONS

9.1 TEST PROGRAM SUMMARY

This document presents the results of thirty fuel assembly head-loss experiments that were performed to quantify the head-loss across AP1000 fuel assemblies during post-LOCA long-term core cooling. The purpose of these experiments was to demonstrate that there is reasonable assurance that the AP1000 can provide adequate core cooling in the long-term following a LOCA.

The experiments, performed to assess the head-loss across the AP1000 fuel assemblies during loss of coolant accidents, considered a variety of parameters that might occur in the AP1000. In order to compare the different tests and to evaluate whether each test was successful, the LTC analysis (Reference 14) was considered. As discussed in section 5.0, the LTC analysis allows for a 4.1 psi head-loss at a flow of 3.1 gpm/FA. None of the tests performed for the AP1000 had flows that were this low during the debris addition phase. In fact, the more recent AP1000 tests are run with flow rates that are representative of no debris dP conditions and end with flow rates that are dependent on the magnitude of the core debris dP. If the debris dP remains relatively low compared to the acceptance criteria then the flow rate is not reduced very much and remains well above the minimum acceptance criteria. Only if the debris dP increases up to the acceptance criteria will the flow be reduced down to the minimum.

In order to determine whether a test meets the LTC criteria, the maximum dP measured in each test is scaled, as described immediately below, based on both the flow that existed when the maximum dP occurred and the minimum acceptance flow (3.1 gpm). This scaled flow provides a simple way to compare tests and to determine if the test met the acceptance criteria.

This scaling is made using the equation and parameters discussed in section 5.0. Note that for most tests the value of the exponent applied to flow was determined by flow / dP data taken from that test. For tests CIBAP18 through CIBAP30 flow sweeps were conducted at the end of the test that provide many data points (different flows / dPs).

Also note that the flow sweeps reduced the flow rate to the acceptance criteria flow so that this data is directly applicable. Such data is also available for tests CIBAP08 through CIBAP11 due to the use of oscillating flows during the tests. For all other tests an average exponent [ ]^{a,c} was used. These results are shown in Table 9-1 and also in Figure 9-1. Both show considerable margin between the scaled dP and the current LTC limit. The maximum scaled dP from the tests is [ ]^{a,c}.

For the concurrent debris addition tests that utilized flow reduction schemes, an additional limit was considered based on sensitivity Case 3 in the LTC analysis (Reference 14).

The additional criterion requires that the max dP measured during the test at an scaled flow of 5.3 gpm, must be lower than 3.5 psi. In all of the concurrent addition tests the flow rate was higher than 5.3 gpm at 9 hours into the test. The results of this additional acceptance criteria are shown in Table 9-2.

Table 9-1 AP1000 Fuel Debris Tests Scaled Results a,c

Table 9-2 Scaled Maximum dP at Flow Prior to 9 Hours for Concurrent Addition Tests a,c

a,c

Figure 9-1 AP1000 Fuel Debris Tests Scaled Results

The AP1000 FA debris head-loss experiments evaluated the following:

1. Latent fiber length;
2. Chemical addition rate;
3. Debris (particle, fiber, and chemical) amounts;
    a. Maximum amounts
    b. Reduced amounts
4. Flow variations, including continuous oscillations as well as reductions from beginning to end of test; and
5. Debris addition sequence.

The following sections discuss each of these areas.

9.1.1 Latent Fiber Length

The AP1000 by design is a very low fiber plant. No fiber is produced by the accident. All of the fiber available for transport is latent fiber and the amount of this fiber is carefully controlled. The limiting break locations are cold-leg (CL) or direct vessel injection (DVI) breaks that become flooded by the water in the containment. In such LOCAs, essentially all of the fiber that can transport into the RCS flows there through the break. As a result, the fiber that reaches the core will not have passed through a screen and will have characteristics of the original latent fiber.

Several tests were performed to determine the fiber length that produces the maximum head-loss. Six tests were performed in total to make this determination. [

]a,c.

Two additional tests (CIBAP13 and CIBAP14) were conducted to further evaluate [

]a,c.

In these tests as well as the other AP1000 tests, almost [
]a,c.

9.1.2 Chemical Addition Rate

The early AP1000 tests showed that there was very little if any head loss after the addition of all of the particles and fibers. However, when the chemicals were added [

]a,c.

For example, in some of the earlier tests (CIBAP01 through CIBAP05), [

]a,c.

In subsequent tests (for example, tests CIBAP06 through CIBAP11), the initial chemical addition was [

]a,c.

The final evolution of the chemical addition method was to make the addition [

]a,c.

In summary, [

]a,c, the addition of chemical surrogates to the AP1000 licensing basis debris loads induced an increase in head-loss across the fuel assembly.

Another phenomenon that was observed [

]a,c.

9.1.3 Debris Quantities

Most of the AP1000 FA testing used the maximum debris amounts. The maximum amounts of debris in the tests did vary some since this testing was used to establish some of the debris limits, especially for the amount of fiber.

Ultimately, a plant design limit of 6.6 pounds of latent fiber was established from this testing. Since 90% of the total amount of latent fiber is assumed to transport into the RCS through a double ended cold-leg (DECL) LOCA, up to 5.9 pounds can enter the RCS. Scaling this to the one FA used in the FA debris testing results in a maximum of [ ]a,c.

The maximum limits for particles and chemicals were developed from the AP1000 design characteristics and not from the FA tests. It was assumed that 100% of the particles and chemicals could transport to the core.

The plant design limit for particulate is 173.4 pounds of particles, based on 130 pounds total latent debris plus 50 pounds of ZOI coatings minus 6.6 pounds of fiber. All of this particulate was assumed to transport into the RCS with [

]a,c of particles used in the FA tests.

The maximum chemical production calculated for 30 days following a LOCA is 57 pounds. All of this chemical is assumed to transport into the RCS. When scaled, this results in a maximum of [ ]a,c AlOOH used in the FA tests.

In addition to assuming the maximum amounts of particle, fiber, and chemical debris, consideration was also given to smaller amounts of debris since less than 100% transport could occur in the plant.

Less fiber was not tested because increasing amounts of fiber have always resulted in higher head-losses in AP1000 fuel assembly testing. In addition, the concurrent debris tests showed that the head-loss increased as the fiber was added (together with particles and chemicals).

Less chemical was also not tested because every test run [

]a,c.

9.1.4 Flow Variations

In the AP1000 plant, the flow rates tend not to be constant following a LOCA because the flows are driven by a natural circulation process. As a result, as debris accumulates in the core region and the head-loss increases, the core flow will slow down. Note that the debris accumulation takes many hours because of the large containment water volume and low passive safety system flow rates.

In addition, at any point in time, the flow also oscillates with a period of several minutes and with a minimum flow rate of about [ ]a,c. This oscillation is seen in the LTC analysis and simulated in select AP1000 fuel assemble head-loss tests as discussed below.

Several FA head-loss tests were conducted where the flow rate was oscillated throughout the test. This included tests CIBAP08 through CIBAP11. The best comparison of these tests with non-oscillating tests is between test CIBAP08 and CIBAP06. These tests were identical except that test CIBAP06 used a constant flow rate of [ ]a,c and test CIBAP08 used an oscillating flow rate between [ ]a,c. Another difference between these tests is that in test CIBAP08 the initial chemical addition was smaller [ ]a,c. This difference is not thought to be significant since both tests had an initial head-loss peak that later decreased. In addition, test CIBAP08 had a lower peak head-loss [ ]a,c. The conclusion is that the oscillating flow characteristic of AP1000 seems to reduce the head-losses. It is thought that the oscillating flows benefits the head-losses because the variation in flow and head-loss tends to increase the tendency to form bed break throughs or "bore holes". The effect of such break throughs is commonly seen as sudden decreases in the head-loss during a test. Using oscillating flows during the AP1000 tests was dropped because of the complexity of running the tests and for concerns over wear of the flow control valve.

Later AP1000 tests have been conducted using varying flow rates where the flow was initially high and then was decreased during the test as the head-loss builds up. This process simulates the natural circulation interaction with the debris head-loss. Several different initial flows that represent different break sizes / locations have been tested. The final flow was based on the LTC analysis with the maximum head-loss. Except for the last two tests (CIBAP29 and CIBAP30) this minimum flow was [ ]a,c. The latest LTC analysis has shown that the minimum flow can be even [ ]a,c. The actual minimum flow used during these tests was dependent on the actual head-loss seen in the test. For some tests the head-loss was relatively low and as a result the flow was not reduced to the minimum just as would happen in the plant.

Tests CIBAP15 and CIBAP16 were conduced at similar debris loads but at constant flows. Test CIBAP15 was run at a constant [ ]a,c. Test CIBAP18 started at [ ]a,c, but since its head-loss was very low, the flow was only reduced to [ ]a,c. The maximum head-loss was much less than either of these two constant flow tests. However, some of the other varying flow tests resulted in higher head-losses. It has not been concluded whether varying the flow increases or decreases the head-loss. All of the subsequent AP1000 FA tests have been conducted with varying flows since that is how the plant will operate. The initial flow has been set at [ ]a,c since that flow seems to result in higher head-losses that other initial flows. [ ]a,c (comparing tests CIBAP20 and CIBAP23) for sequence debris addition. However for concurrent debris addition, (comparing tests CIBAP22 and CIBAP24), [ ]a,c but the initial head-loss trend was more severe.

9.1.5 Debris Addition Sequence

The initial AP1000 FA debris tests (CIBAP01 through CIBAP21) were conducted using sequential debris addition; all the particles were added, then all the fiber and finally all of the chemicals. It was determined that it could not be shown that the AP1000 would operate this way and it could not be shown that this debris addition sequence would result in bounding head-loss. As a result it was decided to repeat one of the sequential tests using a concurrent debris addition method where the particles, fibers and chemicals were added at the same time in multiple batches.

The rate of debris additions [ ]a,c is considered the minimum time since it assumes all of the particles and fibers are transported into the RCS in the time it takes to pass one containment water volume through the RCS and the core is assumed to trap 100% of this debris (none of the particles or fibers leaks / passes through the fuel).

Test CIBAP22 was the first concurrent addition test and was a repeat of test CIBAP20 which was a sequential test. Between these tests, the concurrent test had a head-loss that was 75% higher. As a result, additional concurrent tests were performed. These tests included:

- Thin bed effect – The particles and fibers were introduced in [ ]a,c more batches. Even with this gradual addition of debris there was no indication of a thin bed effect.

- Testing different initial flow rates [ ]a,c. As discussed in section 9.1.4, the flow rates in the concurrent debris addition tests were initiated at a higher flow rate and the flow was decreased as the dP increased. The final flow was determined by how much the dP increased. Both [ ]a,c were used as the initial flow rate. [ ]a,c but had a more rapid initial dP increase rate so it was considered bounding (or at least comparable).

- Adding the particles/fibers at a slower rate (CIBAP25). [ ]a,c.

- Adding the chemicals at a 67% slower rate (CIBAP26). [ ]a,c.

- Adding less particles. [ ]a,c.

- Repeat tests. The most limiting test observed (CIBAP27) was repeated two times. Test CIBAP27 used]a,c than test CIBAP27. So even though there was significant variation between these repeat tests none of them had a higher dP than the original test and all had considerable margin to the current acceptance limit.

9.2 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]a,c.

The fibrous and particulate 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 7) and debris loads (section 6) [ ]a,c as proposed for the AP1000. Based on the discussion provided in the noted sections, the flow rates and scaled debris loads and flow rates used in the experiments are applicable to the AP1000.

The fibrous, particulate, and chemical effects debris used in the experiments were prepared per procedure as discussed in Sections 6.1, 6.2, and 6.3 using the noted preparation procedures. The fibrous, particulate, and chemical effects debris used in the experiments are applicable to the AP1000.

The experiments were performed with representative debris and chemical precipitates at flows that bound the flows expected in the post-accident AP1000. As can be observed from the experimental data, including graphs and photographs, the amount of debris that can be transported to the AP1000 fuel assemblies is very low and is not sufficient to form a debris bed capable of reducing flow into the core to less than the minimum shown to provide adequate core cooling. This was shown to be true for the

licensing basis debris and chemical effects load. The resulting head-loss in all experiments is considered to be insufficient to preclude 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.

10 SUMMARY

Thirty 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 thirty 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 twenty seven[1] of these experiments 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, requires 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 design basis AP1000 fibrous and particulate debris, and chemical effects, (that is, the maximum amount of debris that could exist) does not induce a head-loss through the fuel assembly that would reduce flow into the core to less than the minimum shown to provide adequate long-term core cooling and the maintaining of a coolable core geometry following a LOCA.

[1] Tests 7, 12, and 17 were invalidated due to technical difficulty. See Section 8.31

11 REFERENCES

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

17. STD-MCE-09-139, Revision 0, "Summary of the Results from the AP1000 Core Inlet Blockage Tests: CIBAP17 Through CIBAP30," November 2009.

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

This Appendix is proprietary in its entirety and has been removed from this document.

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

This Appendix is proprietary in its entirety and has been removed from this document.

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

This Appendix is proprietary in its entirety and has been removed from this document.

APPENDIX D
TEST FACILITY OVERVIEW

This Appendix is proprietary in its entirety and has been removed from this document

APPENDIX E
TEST FACILITY OVERVIEW

This Appendix is proprietary in its entirety and has been removed from this document