15.6.5.4 IRWST Recirculation Cooling

During the long term cooling stage of a postulated loss-of-coolant-accident (LOCA) transient, the U.S EPR is designed to recirculate the fluid discharged from the break to the containment in-containment refueling water storage tank IRWST, through the RHR System and emergency core cooling system (ECCS) system back to the reactor vessel. This system layout is quite similar to the ECCS arrangement of a typical operating pressurized water reactor. Generic Safety Issue (GSI)-191, "Assessment of Debris Accumulation on PWR Sump Performance," raises the concern that the high-energy jet from a LOCA may generate debris from insulation, concrete, and other miscellaneous particulate sources. Debris generated and transported to the IRWST may potentially penetrate the strainers and screens, degrade the performance of plant mitigating systems, and block fuel bundles in the core. The U.S. EPR design reduces the potential for debris generation by using reflective metal insulation to insulate reactor coolant system (RCS) components. This insulation produces neither particulate nor fibrous debris that is easily transported to the SIS inlet and ingested. In addition, a defense in depth approach is used to enable heavy materials to settle out in the Containment Building. Multiple levels of filtration prevent debris from reaching the safety injection system (SIS) pumps and being transported to the RCS. This system is described in FSAR Tier 2, Section 6.3.

Even though the removal of fiber based insulation material results in significant reduction in the strainer blockage, the latent fiber debris alone has been found to be able to pass through the debris retaining baskets, the strainers and reach the SIS and RCS. Combined with particulate debris and chemical precipitates, sufficient latent fiber debris could form a debris bed at the inlet of the core and inhibit core flow if the pressure difference across the core region is not capable of driving sufficient flow through the debris blockage to remove the decay heat. Further, the reactor coolant boiled off in the core region may leave the precipitated chemical impurities and debris on the surface of the fuel rods and degrade the heat transfer of the core. If the debris deposition is combined with scale or crud formation, rod-to-rod bridging could occur and the peak cladding temperature could exceed the maximum allowable temperature.

To address these concerns, the applicant not only removed all of the fibrous insulation material from the Zone of Influence (ZOI), but also developed a containment cleanliness program to limit the maximum amount of latent fiber debris. For the anticipated amount of latent debris and chemical precipitates, the applicant performed strainer by-pass testing to determine the amount of debris available to the core, evaluated the available hydraulic driving head across the reactor core, conducted fuel bundle head loss tests to demonstrate that the pressure drop across the debris bed does not exceed the maximum allowable pressure loss, and developed a U.S. EPR-specific deposition model to calculate the cladding surface temperature increase due to the debris deposition. In ANP-10293NP, Appendix E and Appendix F (Technical Report, ANP-10293P, Revision 4, "U.S. EPR U.S. EPR Design Features to Address GSI-191" November 18, 2011), the applicant documented testing and analysis results and submitted to the staff for review. The following sub-sections discuss the staff's review results of fiber debris by-pass testing, available driving head and maximum allowable flow blockage analyses, fuel bundle head loss testing and the U.S. EPR deposition model.

Regulatory Basis and Acceptance Criteria

In accordance with Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50.46, Subsection (b)(5), licensees of domestic nuclear power plants are required to provide long-term cooling of the reactor core "after any calculated successful initial operation of the ECCS." Furthermore, the "calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core." This acceptably low value of the peak cladding temperature is 427 °C (800 °F). After the core has been reflooded, if the fuel cladding temperature is higher than 427 °C (800 °F), rapid nodular corrosion may occur and the hydrogen pickup rates may increase. Maintaining PCT below 427 °C (800 °F) reduces the cladding mechanical performance degradation to an acceptable level. Therefore, 427 °C (800 °F) PCT during the 30 day long term cooling time is used as the acceptance criterion.

15.6.5.4.3.1 Core Differential Pressure Acceptance Criteria for Different Break Locations

The potential core blockage and its impact on core cooling are significantly affected by the break locations and the ECCS injection modes. Different break locations and the ECCS injection modes require different driving force or core pressure difference to establish sufficient flow through the core. The U.S. EPR design has two distinct most limiting break locations and two different ECCS injection modes during a postulated LOCA event which requires in-containment recirculation through the IRWST. The cold leg and the hot leg break, in combination with the cold leg injection mode and the simultaneous ECCS injection through both hot leg and cold leg, result in four conditions which were evaluated by the applicant. The first is the cold leg break with ECCS injection through the cold leg cold leg break/cold leg injection (CLB/CLI). The second is the cold leg break with ECCS injection coming from both the hot leg and the cold leg, CLB/hot leg injection (HLI). The third and fourth scenarios are the hot leg break with either cold leg injection or the injection from both legs (i.e, hot leg break (HLB)/CLI and HLB/HLI). In ANP-10293P, Revision 4, Section F.3, the applicant analyzed these four scenarios, developed the minimum flow required to remove decay heat, and established the maximum allowable debris bed pressure drop acceptance criteria. These criteria were used as the acceptance criteria for the fuel assembly head loss testing to demonstrate that the maximum allowable flow blockage will not be exceeded with the given loading.

Debris Arrival Time And Decay Heat Level For Both Injection Modes

One of the common parameters determining the decay heat level used for the analysis is the debris arrival time. The applicant estimated that the starting point of debris arrival is when the IRWST liquid turns over one time with the assumption that there is no mixing between the liquid originally residing in the IRWST and the recirculated liquid from the containment floor. Once this time is reached, the applicant assumed that the debris would reach the strainer and at the same time reach the core. The staff considered this assumption is considered acceptable, as the recirculated liquid entering the IRWST is expected to have higher temperatures and the buoyant fiber debris tend to stay with the hot water on the surface of the IRWST. In reality, it will take some time for the fiber debris to be transported from the strainer and reach the reactor vessel and the reactor core. The fiber debris travel time between the strainer and the reactor core was conservatively assumed to be zero. In addition to this, as stated in ANP-10293P, Revision 4, Section F.5 and the applicant's November 18, 2011, responses to RAI 493, Questions 15.06.05-99 and 15.06.05-100, the applicant assumed that all the particulate/fiber debris and chemical precipitates generated in 30 days would reach the core inlet at the time when the first piece of fiber debris reaches the strainer. The staff finds this assumption to be conservative.

With this assumption, the actual time of debris reaching the reactor core depends on the IRWST inventory and the number of ECCS trains available for the injection. ANP-10293P, Revision 4,

Figure F.3-7 shows the sensitivity analyses of the debris arrival time for different initial IRWST water level and number of available ECCS trains during the cold leg injection phase.

In ANP-10293P, Revision 4, the applicant stated, the shortest arrival time was used to determine the core power level using the American Nuclear Society (ANS) ANS-5.1-1973, "Decay Energy Release Rates Following Shutdown of Uranium-Fueled Thermal Reactors," decay heat curve with a 1.2 multiplier. For the hot leg injection case, the decay heat level at the time of hot leg switch-over was used by the applicant, which is at the highest level during 30 day period of long term cooling. In this respect, the technical report follows the guidance in NRC Information Notice 96-39, July 5, 1996,, therefore, the staff finds that the decay heat level used for the analysis is conservative.

Darcy Equation and [redacted]

To simplify the development of conservative acceptance criteria for the fuel bundle head loss testing, the applicant applied the commonly used form loss pressure drop calculation method, the Darcy-Weisbach equation, to capture the first order effect of pressure drop versus flow (Section F.3.1 of ANP-10293P Rev.4). [redacted]

The staff does not believe that the Darcy-Weisbach equation has sufficient details to model the pressure drop across the porous debris bed with chemical precipitates, although the equation has been widely used to predict the pressure drop across solid structures in a one dimensional fluid flow path. The method is not accurate enough to correlate the fuel bundle head loss testing data and either extrapolate or interpolate the data to cover the untested conditions. [redacted] the staff finds that the concept of defining acceptance criteria [redacted] is acceptable.

Cold Leg Break and Cold Leg Injection

For this break and safety injection system configuration, the applicant assumed that the minimum core flow allowable with core blockage is the boil-off flow to remove the decay heat and maintain the two phase level above the core. The total core flow rate is calculated using the decay heat level at the time the debris arrives at the core inlet. The total pressure drop across the debris bed at the assumed boil off flow rate is calculated using a quasi-steady state one dimensional flow pressure drop model with a set of conservative assumptions.

Core Inlet Subcooling

The applicant assumed that the core inlet liquid is at saturated condition so that the core average void fraction is conservatively calculated to reduce the available driving head across the debris bed. During the post dryout and reflood phase, the core inlet temperature is usually below the saturation temperature. Therefore, the staff finds this assumption conservative.

Downcomer Void Fraction

ANP-10293P, Revision 4, Figure F.3-6 shows the calculated downcomer average void fraction using S-RELAP5 for the cold leg LOCA analysis. To bound many different parameters affecting the downcomer void fraction, a conservative constant value is selected for downcomer void fraction at the time of debris arrival. The value chosen is greater than the downcomer void fraction calculated from a representative set of S-RELAP5 simulations. The staff considers this assumption conservative because it reduces the liquid level in the downcomer.

Boron precipitation

At the time the reactor core is reflooded, no boron precipitation is expected based on the Boron precipitation calculation completed by the applicant. The hot leg switch-over at 1 hour was designed by the applicant to prevent Boron precipitation. Therefore, it is reasonable to assume that Boron concentration change in the core region does not affect the available pressure drop across the debris bed.

Core averaged void fraction

To calculate the bounding core average void fraction, the top-peaked axial power distribution was selected from the LOCA analyses performed by the applicant. Using this power shape and zero inlet sub-cooling, the applicant applied the Cunningham-Yeh correlation to calculate the core average void fraction. In RAI 241, Question 15.06.05-51, the staff requested that the applicant clarify whether the correlation was appropriate for low pressure conditions. In a May 25, 2010, response to RAI 241, Question 15.06.05-51, and the May 31, 2011, response to RAI 403, Question 15.06.05-69, that was a follow-up to RAI 241, Question 15.06.05-51, the applicant presented comparisons of mixture levels computed using the Cunningham-Yeh correlation versus experimental data. The correlation was validated using data from an electrically heated 7x7 rod bundle level-swell experiment at atmospheric pressure (Hitachi), and data from the ACHILLES level swell Test A1L066. The applicant's responses demonstrated the appropriateness of the Cunningham-Yeh correlation and are acceptable to the staff.

In addition to these major assumptions, a containment pressure of 71 psia was assumed and the SI flow is also assumed at saturation pressure corresponding to the assumed containment pressure. The staff finds this assumption conservative because it neglects the increase of the flow to remove decay heat. A bounding pressure loss due to condensation of steam on the cold SI flow in the cold legs is determined based on the steam momentum flux at the point of ECCS injection.

[redacted] These pressure drops include form loss through the downcomer, lower plenum and the reactor core and the two-phase pressure drop across the core if boiling occurs. The two-phase pressure drop normally includes the two-phase friction pressure drop and the two-phase acceleration pressure drop. ANP-10293P, Revision 4 does not provide information demonstrating that these two-phase pressure drops were considered when developing the maximum allowable pressure drop across the debris bed, nor does it show

K/A^2 values developed for all four scenarios were conservative if the contribution of these pressure drops are considered properly. Draft RAI 573, Question 15.06.05-116, the staff requested that the applicant address this issue. **Draft RAI 573, Question 15.06.05-116 is being tracked as an open item**. Based on this open item, and the discussion above, the staff cannot find this particular methodology to be acceptable in accordance with the requirements of NRC regulations.

Hot Leg Break and Cold Leg Injection

For the hot leg break, the applicant considered a manometric balance between the liquid in the core and the liquid in the downcomer and cold legs as the basis for determining the minimum available driving head. For this calculation the applicant assumed that the liquid density was the same everywhere, the core flow is equal to four trains of ECCS flow.

No boiling is assumed to be at the top of the core region. The applicant postulated that, as blockage increased at the core inlet and core flow was retarded, the liquid on the cold leg side would rise until it reached the level of the steam generator tube sheet. The elevation difference between the tube sheet and the hot leg break is, therefore, assumed to be the driving head across the debris bed. For this case, it is unclear to the staff how the single phase pressure drop across the downcomer, lower plenum and the core is excluded in the process of calculating the minimum available pressure drop across the debris bed. This issue is addressed by the open item in draft RAI 573, Question 15.06.05-116 discussed above.

Hot Leg Break and Combined Injection

At a certain time after the break, the operator realigns the operating LHSI trains from injecting solely into the cold legs to a combined injection into both the hot and cold legs. This realignment is done to mitigate the build up of boric acid in the core. The combined injection mode is referred to as HLI.

At the time of initiation of HLI for a hot leg break, the core is completely covered with liquid. The applicant specified the hot-to-cold leg flow split such that the amount of ECC being injected into the cold legs is greater than that is needed to remove the decay heat. Thus, the hot leg break with HLI case is addressed by the hot leg break with cold leg injection. The liquid injected into the hot legs flows out the break. The staff notes that the applicant's proposed HLI flow split would result in adequate core flow into the core inlet assuming the maximum core inlet ΔP from the cold leg break with cold leg injection case. However, until the open item draft RAI 573, Question 15.06.05-116 is resolved, the staff has insufficient evidence to agree with the criteria developed for this scenario.

Cold Leg Break and Hot Leg Injection

When HLI begins after a cold leg break, steam is flowing from the core. ECC injected into the hot legs may build up in the upper plenum and may also flow down the lower power fuel assemblies and the core bypass regions. The cold leg break with hot leg injection addresses the case of flow downward through the bypass regions. Once the core becomes liquid full, it is possible to get blockage near the outlet of every fuel assembly. As the blockage increases, the liquid level in the upper plenum and hot legs also increases. The applicant conservatively assumed that this liquid level can rise no higher than the SG tube sheet. [redacted]. Based on staff review, the applicant must provide additional information demonstrating the proper treatment of all the pressure drops along the flow path (draft RAI 573, Question 15.06.05-116).

The applicant analyzed all four scenarios with different safety injection modes and break locations. The staff finds that conservative assumptions have been developed to simplify the analysis and the results appeared to be conservative. However, the staff has identified an open item in draft RAI 573, Question 15.06.05-116 to obtain additional information for evaluation.

15.6.5.4.3.2 Debris By-pass Testing And Debris Source Term to the Core

The debris transport process between IRWST and reactor core determines the amount of debris reaching the core. The applicant assumed that all the particulate debris and chemical precipitates transported from containment to IRWST would reach the reactor core and are available for core blockage and deposition.

The applicant assumed that all large size debris is blocked by the retaining baskets and the strainers. The fiber debris, however, is only partially blocked. The applicant performed fiber-only bypass testing using the same test facility for strainer performance evaluation. The results of the by-pass testing and the debris source term available to the core region are evaluated below.

Based on the open item discussed above, the staff cannot find the approach for cold leg break and hot leg injection to be acceptable in accordance with the regulations.

Fiber Only By-pass Testing

During operation of ECCS to recirculate the coolant from the IRWST, debris in the containment carried by the recirculating fluid passes through the retaining baskets and the downstream strainers to reach the reactor core. Large debris are completely blocked by the retaining baskets (discussed in Section 6.2.2.4.7 of this report), while most of the latent fiber, particulate and chemical precipitates pass through the retaining basket. Some debris accumulates on the strainer surface and the remainder reaches the core. To conservatively predict the amount of debris reaching the reactor core, the applicant performed fiber-only by-pass testing to eliminate the complex interactions between different types of debris. The staff finds this approach conservative, as the presence of particulate debris and chemical precipitates tends to reduce the fiber debris by-pass fraction and cause debris bed formation on the strainer surface.

Testing Apparatus for Fiber-Only By-Pass Tests

The test was conducted using a specifically configured test loop at Alden Research Laboratory to create a prototypical flow environment around the U.S. EPR retaining baskets and the strainers. The test loop contains one retaining basket and one strainer, which is representative of one of four ECCS trains in the U.S. EPR design. As described in ANP-10293P, Appendix E, the test loop simulates the free-fall flow of water from the heavy floor by introducing the return flow at an elevation above the flume water surface. After the water enters the test flume, it flows through the retaining basket, towards the strainer and into the strainer sump. From the strainer sump, the water enters a recirculation loop with a full flow filtration system. The water is pumped back to the top of the retaining basket to simulate the flow of water on the heavy floor through the floor opening.

Initially, the applicant relied on the water sampling system to take water samples downstream of the strainer and measure the by-pass fiber concentration in the solution using a scanning electron microscope. The applicant later found this method inaccurate as the fiber passing through the strainer is recirculated back to the strainer. In response to staff comments made during the testing observation trip, the applicant installed the 1 micron filter bags to capture all the fiber by-passing the strainer. This filtration system captures all the fiber debris by-passing the strainer as long as the debris size is greater than 1 micron. This by-pass debris measurement method is considered conservative as the filtration system filters 100 percent of the flow passing through the strainer and the by-passed debris was not circulated more than once. Therefore, the staff finds the design concept of this test apparatus to be acceptable for debris by-pass fraction measurement.

Scaling and Test Configuration

In ANP-10293P, Section E.3.1, the applicant scaled the facility to represent the retaining basket and the strainer using the Full Height scaling concept. All the elevation changes starting from the containment floor drainage flow entrance to the strainer discharge are preserved. The strainer and the retaining basket surface area are scaled down from the actual strainer. The identical surface screen of the designed strainer and retaining basket is used. Therefore, identical localized filtration effect on the surface of the retaining basket and the strainer is properly preserved. The total surface area of the prototypical strainer is reduced from the actual strainer using the ratio of the test loop flow over U.S. EPR single ECCS train maximum flow. In this way, the average fluid velocity perpendicular to the strainer surface is preserved and the dominant debris by-pass driving mechanism is properly simulated.

During the post_LOCA condition, the number of ECCS trains available varies from two to four trains. Although from the perspective of maximizing the strainer head loss, the applicant applied maximum amount of available debris based on the debris source term analysis, the by-pass testing was performed by gradually introducing four batches of fiber debris into the test loop, while the amount of each batch is equivalent to one-quarter of total scaled debris loading. As shown in ANP-10293P, Revision 4, Table E.6-8, the measured by-pass fraction is based on the maximum value from the measured fraction among the individual batches and the total by-pass fraction. Since, the debris loading and the surface area are properly scaled to maximize the debris by-pass, the staff considers the scaling approach used by the applicant acceptable.

Testing Protocols And Testing Results

The applicant only used latent fiber surrogate material during the fiber by-pass testing as all other debris were excluded from the testing for the purposes of being conservative. The latent fiber surrogate form was heat treated NUKON that was shredded into fiber fines. As stated in ANP-10293P, Section E.4.3, the surrogate material was soaked in warm water and diluted before test apparatus insertion. The surrogate material preparation procedure was reviewed by the staff. The evaluation results were documented in Section 6.2.2.4 of this report. Since the same fiber surrogate material preparation procedures were used, the staff considers the fiber-only by-pass testing debris preparation procedures to be appropriate.

The total amount of fiber used during the test was consistent with revised debris source term determined by the debris generation calculation reflecting the final committed containment cleanness program requirements. The fiber was introduced into the test loop in small batches equal to the approximate amount of fiber that could form a 1/16-inch fiber bed in the wetted retaining basket. The incremental fiber addition continued until 25 percent of the total fiber loading was introduced into the test flume. Then, the filtration system was switched to a new one while the original filter bags were taken out of the system for measurement. The test continued until all the fiber debris was introduced. The flow rate through the test loop was maintained at constant according to the area-ratio scaling method to maintain the same average surface flow rate. In this way, the bypass fraction is obtained for each 25 percent of the fiber loading as documented in ANP-10293P,Revision 4, Table E.6-8.

The maximum bounding value was selected to define the fiber debris by-pass fraction. The results showed that the strainer and the retaining basket would retain a significant portion of the fiber debris generated in the containment.

Since the applicant used conservative testing protocols and the scaling method, the staff finds the resulting measured fiber debris by-pass fraction acceptable for further fuel bundle head loss and heat transfer evaluations.

Total By-passing Debris Amount

Except for the latent fiber debris, all other kinds of particulate debris and chemical precipitates are assumed 100 percent transportable between the containment and the reactor core by the applicant. Therefore, the amount of all other debris assumed from the debris source term analysis is used for fuel bundle blockage testing and deposition evaluations. The applicant took credit for the strainer filtration effect on fiber debris and used the conservatively measured by-pass fraction to reduce the amount of fiber debris reaching the reactor core. For the reasons discussed above, the staff considers the measured fiber by-pass fraction and the estimated debris source available to the core to be conservative.

15.6.5.4.3.3 Fuel Bundle Head Loss Testing

This section provides the staff evaluation of the applicant's fuel assembly head loss testing approach and results. As a part of resolution to the in-vessel downstream effect, the applicant conducted fuel assembly tests to demonstrate that the amount of debris that can reach the RCS would not impede long-term core cooling, that is, with the amount of debris reaching the RCS, the measured head loss or flow blockage (K/A^2) is within the maximum allowable fuel assembly blockage such that sufficient flow (more than the minimum required flow) enters the core for long-term decay heat removal.

Testing Acceptance Criteria: Maximum Allowable Fuel Assembly Blockage

Demonstration of sufficient, long-term core cooling depends on the break location and ECCS injection configuration postulated. The U.S. EPR ECCS design operates in two configurations: initial cold-leg injection and subsequent switchover, by the operator at 60 minutes after a break, to simultaneous hot- and cold-leg injection. As discussed in ANP-10293, Revision 4, Section F.3, the core head loss acceptance criteria were developed for different break locations and ECCS injection configurations. Based on the phenomena of interest in the periods before and after the switchover to the simultaneous hot- and cold-leg injection, a [redacted] for each break and ECCS injection scenario was first calculated. [redacted] Section 15.6.5.4.3.1 of this report describes the staff's evaluation of the applicant's derivation of the [redacted] for combinations of break locations and injection configurations is provided in ANP-10293P, Revision 4, Table F.5-1.

[redacted]

Debris Characterization: Fiber, Particulates, and Chemical Precipitates

The quantity of debris generated following a LOCA was evaluated for a number of break locations. The applicant's discussion of post-LOCA debris characteristics is contained in ANP-10293, Appendix C, "Debris Generation Evaluation for the U.S. EPR." The analyzed debris includes reflective metal insulation (RMI), Microtherm (microporous), coatings, and latent debris. The maximum debris generated from all break locations is summarized in ANP-10293, Table F.3-3, which includes 4.63 kg (10.2 pounds mass (lbm)) of fiber, and 668.96 kg (1474.8 lbm) of particulates. The staff notes that these debris amounts include 68 kg (150 lbm) of latent debris. For fuel assembly testing, the applicant assumes 6.8 percent of latent debris is fiber 4.63 kg (10.2 lbm) and 93.2 percent is particulates. This latent debris amount and distribution are the design basis latent debris, which provides the containment cleanliness program requirements that a Combined License (COL) applicant is required to meet.

The applicant performed a strainer performance test to determine the amount of fiber that passes through the retaining baskets and strainers and might reach the RCS and the core. The results showed the percentage of the fiber passes through the sump strainer over a 30 day period. The staff's evaluation of the debris bypass testing is discussed in Section 15.6.5.4.3.2 of this report. All particulate (including Microtherm) is assumed to pass through the sump screen and reach the reactor core. ANP-10293, Table F.3-3 also shows, on per fuel assembly basis, the maximum amount of debris generated from all break locations that can transport to the RCS and core over a 30-day period. The average fiber amount per fuel assembly was calculated with the percentage of fiber debris bypass to the core and 241 fuel assemblies in the core. When conducting fuel assembly testing, the applicant conservatively assumed that this quantity of debris (with margin) reaches the core at the first opportunity.

The applicant conducted the fuel assembly head loss testing with [redacted] (which is more than the design basis fiber amount shown in ANP-10293, Table F.3-3) or more fiber debris, and used Nukon fiberglass as a surrogate for the fiber debris. As discussed in Section 6.2.2.4.4 of this report, the staff finds the use of small fines from low-density fiberglass, such as Nukon, as a surrogate debris for latent fiber in head loss analysis acceptable because the hydraulic properties of latent fiber are similar to those of Nukon fiberglass.

Following a LOCA, the chemistry of the fluid in the IRWST and the core could produce chemical precipitates which could affect the pressure drop in a debris bed. The specific compounds and quantities of materials that may precipitate within the reactor containment pool following a LOCA is described in ANP-10293, Appendix D. The chemical precipitates are predicted to include sodium aluminum silicate, calcium phosphate, and aluminum hydroxide. ANP-10293, Table D.3-10 provides the total elements released and solids formed as a function of time following a cold leg break. The quantity and composition of total solids at one hour and 30 days, respectively, are provided in ANP-10293, Tables F.3-4 and F.3-7. From these tables, the amount of chemical precipitate amount of 169 grams (5.96 oz)/FA and 587 grams (20.7 oz)/FA, respectively, are used as the basis for the fuel assembly testing for the cold leg injection and the simultaneous hot- and cold-leg injection.

The applicant used aluminum oxyhydroxide (AlOOH) as a surrogate to represent all of the chemical debris, which is consistent with the testing summarized in WCAP-16793-NP, Revision 1, “Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid,” April 2009. The staff finds this acceptable because of the agglomeration effect of this surrogate on head loss. The staff’s evaluation of the use of AlOOH as chemical debris surrogate and the amount of chemical debris in fuel assembly testing are described in Section 6.2.2.4.13.7 of this report.

Testing Rigs and Testing Protocols

The fuel assembly head loss test facility is described in ANP-10293P, Revision 4, Section F.5.3. The test loop consists of a mixing tank, a submersible pump, piping to deliver flow to a clear test chamber, and piping to return the flow to the mixing tank. The test chamber consists of a core support plate located approximately 0.31 m (12 inches (in.)) above the bottom of the chamber, a 1.3 m (52-in.) tall 17x17 fuel assembly that includes a lower end fitting (LEF), four spacer grids, simulated fuel rods, control rod guide tubes, and an instrument tube.

The test loop is configured to be capable of simulating cold-leg injection and hot-leg injection, respectively. During cold-leg injection testing, flow enters from the bottom of the chamber, passes through the fuel assembly, and exits out of the top of the chamber. A submersible pump pumps water and debris from the mixing tank through a flow meter and flow control valve, and into the test chamber. The mixing tank allows debris to be added to the system and is well agitated by the pump bypass flow and motor-driven agitator to minimize settling and agglomeration. During hot leg injection testing, the flow is reversed in the test chamber so that it enters from the top and exits the bottom.

The enclosure around the fuel assembly was fabricated from transparent PVC plastic. Pressure taps were installed to allow differential pressure (dP) measurements across the full assembly and any grid or combination of grids to be measured. The pressure taps were installed on the walls two to three inches below the spacer grids and centered between fuel rods. Each pressure tap had a valve installed on it to facilitate switching dP measurements.

Test Fuel Assembly

The fuel assembly testing used four-grid and seven-grid partial-length fuel assemblies, respectively. The majority of tests were conducted with the four-grid fuel assembly, which contains a 17x17 array of fuel rods, including 264 simulated fuel rods, 24 guide tubes and a center instrumentation tube. The guide tubes extended approximately [redacted] above the top of the lower end fitting, and the fuel rods had a length of [redacted]). The bottom, second, and top grids are standard “keyed” spacer grid designed with hard and soft stops (or springs), which hold the fuel rods in place. (A representation of the grids is shown in ANP-10239, Figure F.5-30.) The third grid is a mixing vane intermediate grid, which is essentially the keyed grid with mixing vanes at the exit of the grid and also holds the rods in place.

Two tests were performed using a test assembly with seven intermediate spacer grids. The test assembly is approximately 1.4 m (4.5 feet(ft)) tall, and represents the AREVA NP Mark-BW fuel, which is a 17x17 fuel assembly designed for use in Westinghouse-designed 3- and 4- loop plants. The bottom and top grids are straight flow-channel high mechanical performance (HMP) spacer grids.

The U.S.EPR design uses high thermal performance (HTP) and HMP spacer grids, which are different from the keyed type grids used in the tests. The HMP spacer grids are similar to the HTP spacer grids except that the flow channels created by the doublets are straight and do not produce swirling flow around the fuel rods. The HTP/HMP grids do not have the same design as the keyed type grids to hold the fuel rods in place. Instead of springs, the HTP/HMP grids use a "tube" that runs the height of the spacer grid. [redacted]

The U.S. EPR fuel assembly test results, described in ANP-10293, Revision 4, Section F.5.5 indicated that the debris accumulates predominantly at the leading edge of the spacer grids. [redacted] Therefore, the staff agrees with the applicant that the grids tested adequately represent the HTP and HMP grids, and the results are equally applicable to the HTP and HMP grids.

Test Procedure

ANP-10293, Section F.5.4.1 describes the test procedure used in the fuel assembly testing. Though the number of particulates, fiber, and chemical batches, size of chemical batches, flow configuration, and turnover time varied among the tests, the following procedure was used for all tests.

1. The tests were conducted with tap water, with water temperature maintained at 21 °C ± 5.5 °C (70 °F ± 10 °F).

2. The dry debris was soaked with water from the mixing tank and mixed in preparation for addition to the mixing tank.

3. The particulate was added to the mixing tank first.

4. After five turnover times (i.e., the amount of time needed for one mixing tank volume turnover), the first batch of fiber was added.

5. At least two turnover times were allowed between each fiber addition.

6. After all the fiber had been added and the head loss had stabilized, the first batch of chemical surrogate was added to the mixing tank.

7. At least two turnover times were allowed between each chemical addition.

8. If the measured pressure drop across the fuel assembly reached 97 kPa differential (14 psid) during a test, the flow rate was reduced to maintain the pressure drop below 97 kPa differential (14 psid.)

The order of debris addition of the testing is particulates first, fiber second, and chemical precipitates last. This debris addition order would maximize the pressure drop of the debris bed by minimizing the porosity of the debris bed as it forms.

Particulates are small debris types that readily pass through the debris filters or fuel assemblies, and, therefore, do not catch in the core unless the debris is large enough to plug the opening. Fibrous debris, however, is fairly porous and more readily trapped by the fuel assembly grids (snag on the leading edges of spacer grids) to form a debris bed that could potentially capture the smaller debris types. Particulates can fill the interstitial gaps among the fibers and decrease the porosity of the debris bed and increase the pressure drop. Having all of the particulates available in the test loop from the start of the test ensures that the openings in the fiber bed can be filled as the bed forms.

Since chemical precipitates do not form until well into the transient, they are added after the addition of particulates and fiber. Chemical precipitates are expected to form a layer on top of the established debris bed and could possibly compress the bed, further increasing the pressure drop of the bed. The fuel assembly test results indicated that the amount of chemical precipitates have a limited effect on the overall pressure drop through the debris bed. The initial formation of the chemical precipitates causes an increase in the pressure drop, but the pressure drop stops increasing after a small quantity has been introduced.

Debris in the mixing tank is kept in suspension by agitation by the return flow from the loop and by a mechanical variable speed mixer. This mixing prevents debris from settling, floating, and remaining in the mixing tank during a test. The test loop continually recirculates debris, thus providing multiple opportunities to catch debris on an obstruction and restrict flow. The staff finds this method conservative because, depending on the break location and ECCS configuration, this is not likely to occur in the core. For example, following a hot leg break with cold leg injection, the fluid passes through the core and returns to containment where it must be re-filtered by the retention baskets and strainers before it re-enters the RCS.

Test Conditions: Debris Amounts and Flow Rate

The applicant conducted a total of 21 fuel assembly head loss tests. ANP-10293, Table F.5-3 provides a summary of test input conditions for each test, including initial test flow rate, amounts of particulates, fiber, and chemical precipitates, and the mixing tank volume turnover time. Twelve of the 21 tests simulated HLB/CLI; two tests simulated CLB/CLI; and the remaining seven tests simulated cold leg break with hot leg injection. All tests were conducted with 4-grid test assembly, except for two HLB/CLI tests which used test assembly containing seven grids. The tests were conducted with silicon carbide with an average diameter of 8.64 μm (0.340 mils) representing particulates, Nukon low density fiberglass representing fiber, and AlOOH as chemical surrogate.

The earlier tests (conducted in December 2009 and January 2010) were performed with fiber amount of [redacted] per fuel assembly. The later tests were conducted with lower fiber amount, 7 tests with [redacted]/FA of fiber and 9 tests with [redacted])/FA of fiber, which is the U.S. EPR design basis latent debris amount. [redacted]

The applicant concluded that the highest fuel assembly pressure drop occurred in cases with a particulate-to-fiber ratio of [redacted]. Therefore, the later fuel assembly tests were performed with particulate-to-fiber ratio of [redacted] using [redacted] of fiber for all ECCS configurations.

As discussed in Section 15.6.5.4.3.3 of this evaluation, the earlier tests with high and low particulate/fiber ratios, respectively, demonstrated that [redacted] tests resulted in higher flow blockage. Therefore, the staff finds that testing with a particulate/fiber ratio of [redacted] is conservative.

The fuel assembly testing conservatively assumes that the debris generated within the period of interest arrives at the core at first opportunity. For cold leg injection, the debris arrival time was conservatively assumed to be 15 minutes after a break, which is one-half of the minimum time calculated based on the maximum ECCS injection rate with all four trains operating, as shown in ANP-10293, Figure F.3-7. Since the ECCS injection switchover from cold leg injection to simultaneous hot leg/cold leg injection at 60 minutes after a LOCA, only those debris amounts formed within the first hour of the initiating event are used in the testing of cold leg injection period. As discussed earlier, 169 grams (5.96 oz)/FA was generated within the first hour. Therefore, 169 grams (5.96 oz) of AlOOH was used for the cold leg injection.

For the simultaneous hot- and cold-leg injection, the applicant assumed that debris arrives at the instant of switchover at 60 minutes. The test uses 30-day mission time for the quantity and composition of solids formed by chemical precipitates. Therefore, 587 grams (20.7 oz) of AlOOH was used for the hot leg tests.

Some earlier tests, seven HLB/CLI tests and one CLB/HLI tests, were conducted with 833 grams (29.4 oz) of AlOOH, which is more than the amount of chemical precipitates generated within 30 days, and the staff finds this conservative.

For the hot leg break with cold leg injection configuration, all of the injected ECCS flow passes through the core to reach the hot leg break. The maximum flow through the core is the maximum ECCS flow rate of 65.1 m^3/min (17,200 gallons per minute (gpm)), which assumes all pumps and trains are operating. The maximum fuel assembly flow rate is calculated from the maximum ECCS flow rate and 241 fuel assemblies in the core. The maximum assembly flow rate was used in later HLB/CLI tests including the tests with [redacted] FA fiber. However, the earlier HLB/CLI tests were conducted with a lower flow rate representing two trains of ECCS operation. The staff finds the variation of the flow rate used in the tests acceptable, because the objective of the tests is to determine the [redacted]. The [redacted] using the Darcy equation based on the flow rate and the corresponding differential pressure measurement.

For the cold leg break with cold leg injection configuration, the required ECCS flow into the core is the flow required to replace the core boil-off due to decay heat removal. The initial flow rate for the CLB/CLI tests would be the required flow rate at 15 minutes, which is the conservatively assumed debris arrival time. However, the CLB/CLI tests were performed at an initial flow rate more than twice the required flow rate at 15 minutes, which the staff finds acceptable.

In the cold leg break with hot leg injection configuration, all of the ECCS injected into the hot leg passes through the core to reach the break. The ECCS water flows into the reactor vessel upper plenum, mixes with the steam water fluid and condenses the steam generated in the core, and then falls as a plume into the core through several peripheral lower power fuel assemblies located below the hot leg nozzle. Therefore, the downward flow includes the ECCS flow and the entrained condensate. In a November 18, 2011, response to RAI 493, Question 15.06.05-103, the applicant provided a detailed calculation which resulted in a range of actual flow into each of the downward flowing fuel assemblies depending on the mixing efficiency of the ECCS flow in the upper plenum. The CLB/HLI testing includes both the maximum and minimum flow rates from the calculated range. The testing with [redacted] FA fiber used the minimum value.

The applicant did not perform testing for the hot leg break with cold hot leg injection configuration. The applicant stated that the HLB/HLI configuration is addressed indirectly by the hot-leg break with cold leg injection. One objective of the combined hot- and cold-leg injection is the suppression of core steaming. However, the hot leg injected flow is not credited as contributing to the flow required to suppress core steaming, and only the flow from the bottom of the core is relied upon to suppress core steaming. The applicant assumes that in a HLB/CLI configuration just prior to the switch-over to the combined injection and just prior to debris arrival, the top of the active fuel is covered by flowing ECCS liquid and core boiling is suppressed. This initial core condition persists when the safety injection is switched to the combined injection mode. The liquid level will decrease only if the ECCS flow is insufficient to match core boil-off rate. Core steaming is suppressed if the debris blockage is insufficient to reduce the flow below the core boil-off rate. In two of the HLB/CLI tests (Tests 1-FG-CLI-FPC-2 and 4-FG-CLI-FPC), at the end of the CLI test when the measured flow and pressure stabilize after the final debris addition, [redacted] Therefore, the HLB/HLI configuration need not be tested.

Test Results

From September 2009 to August 2011, the applicant conducted a total of 21 fuel assembly tests. ANP-10293, Revision 4, Section F.5.5 presents the results of each of the 21 tests, and ANP-10293, Table F.5-27 provides a summary of the test results.

For the HLB/CLI tests, the test acceptance criterion or the maximum allowable fuel assembly [redacted] is provided in ANP-10293, Table F.5-1. Of the 12 HLB/CLI tests, 9 tests passed the acceptance criteria and 3 failed. The three failed tests were conducted with high fiber amount of [redacted], respectively. The staff noted that there were three tests conducted with [redacted]/FA of fiber. Two of the [redacted])/FA fiber tests passed the acceptance criteria with big margin, but the third test failed with the blockage far exceeding the acceptance criteria. There were five tests with [redacted] of fiber, one test with p:f ratio of [redacted] and the other 4 tests with p:f ratio of [redacted] All five [redacted]/FA fiber tests passed the maximum allowable blockage with huge margin of greater than 99 percent.

There were two CLB/CLI tests, both conducted with [redacted] of fiber and particulate/fiber ratio o[redacted] The results of both test passed with greater than 50 percent margin to the maximum blockage acceptance limit.

For the CLB/HLI tests, the two tests with [redacted] of fiber passed the maximum blockage acceptance limit with greater than 81 percent margin. Of the four tests with [redacted] of fiber, three tests passed the acceptance limit with the debris induced blockage less than 16 percent of the limit value. One test failed with the debris induced blockage value exceeding the limit. The variation of the results indicates that the debris [redacted] is sensitive to fiber amount. The [redacted]/FA of fiber appears to be enough to build a debris bed that is in a transitional region where the bed can be porous or nonporous after chemical addition. While the majority of the tests passed the acceptance limit, the results of the failing tests indicate that [redacted]/FA of fiber may be enough to impede long-term core cooling.

Early in the fuel assembly test program, the applicant performed two HLB/CLI tests (3-FG-FPC and 5-FG-FPC) with high fiber amount of [redacted] One test (3-FG-FPC) had high particulate to fiber ratio of [redacted] and the other had a p/f ratio of [redacted]. [redacted] The applicant also performed two HLB/CLI tests (Tests 4-FG-FPC and 6-FG-FPC) using 7-grid test assembly. These tests had the test conditions similar to the two 4-grid assembly high fiber tests. The test results were similar to the 4-grid tests (i.e., [redacted] These tests demonstrated that [redacted] ratio tests resulted in higher debris-induced blockage, and therefore, the use of p/f ratio of [redacted] for the rest of the tests is conservative.

The applicant also compared the behavior of the 7-grid and 4-grid tests. [redacted]

Overall, there are nine tests that were conducted with the U.S. EPR design limit of [redacted] of fiber: seven cold leg injection tests and two hot leg injection tests. The results of all nine tests successfully meet the maximum allowable blockage limits with huge margin. The ability to repeatedly pass the CLI and HLI tests demonstrates that limiting the fiber debris load to [redacted] FA would prevent sufficient core blockage to impede long-term core cooling.

Summary and Conclusion

Fuel assembly testing performed at [redacted] FA of fiber resulted in fiber bed resistance and final flow rate varied between acceptable and unacceptable values. To move away from this transition region, the applicant re-evaluated the latent fiber source term and accounting for strainer efficiency, and used a fiber loading of [redacted]/FA for nine of the fuel assembly tests. All nine [redacted]/FA tests obtained consistent acceptable results with margin to the maximum [redacted] acceptance limits, indicating that this fiber loading was sufficiently below the transition region. The staff concludes that limiting the fiber loading to [redacted]/FA would prevent the formation of sufficient post-LOCA in-vessel debris blockage to impede the long-term core cooling.

15.6.5.4.3.4 Deposition of Chemical Precipitates and Debris on Fuel Rods (U.S. EPR LOCA Deposition Analysis Model (EPRDM))

After recirculation is established through the IRWST during a postulated LOCA, the pH buffer agent, the corrosion products and the latent debris are carried into the reactor core region. The applicant analyzed the chemical process in the post-accident containment sump fluids and identified two specific chemical compounds, sodium aluminum silicate and calcium phosphate, which could precipitate during the decay heat removal process in the core. Concerns were raised by the staff that these chemical impurities could result in crud formation and cause the core peak cladding temperature to increase. To address these concerns, the applicant performed a conservative evaluation of the possible deposition thickness of these chemicals and the resulting peak cladding temperatures under the postulated buildup for up to 30 days following a LOCA. The staff reviewed the assumptions of the evaluation, the analytical approach of the calculation and the analysis results based on the following acceptance criteria.

DM Method Approach

The applicant developed a spreadsheet calculation model to calculate the crud or scale thickness due to the deposition of fiber, particulate and the chemical precipitates. The model divides the coolant into two control volumes. The first volume represents the fluid in the core region. The second volume represents the water volume of IRWST and the remaining coolant volume. The method assumes that all the impurities (i.e, fiber, particulates and chemical precipitates) deposit on the fuel rod surface proportional to the decay heat release. The higher the heat flux and the concentration of the chemical species the thicker the crud (scale) layer. The method also assumes that the crud would form on the fuel rod surface even if there is no localized boiling and only the single phase heat transfer occurs. The duration of 30 days is used to simulate the IRWST environment and the core long term cooling.

This simplified two-volume calculation method captures the first order debris transport and deposition mechanism as the fiber, the particulate and the chemical precipitates would be first washed into the IRWST from the containment floor and then transported to the core region. If the debris is not captured at the spacer grid locations, they are subject to deposition on the fuel rod surface. Conceptually, the significant debris deposition occurs around the fuel rod surface where the localized boiling causes precipitation of all the chemical species. If there is only the single phase flow around the fuel rods, the debris deposition is significantly reduced although normal continuous oxidation and convective deposition are expected. Therefore, the duration of the core boiling is a significant factor affecting the debris deposition.

The duration of the core boiling is highly dependent on the break locations. During the LOCA event with a hot-leg break, after the Low Head Safety Injection (LHSI) starts to inject ECCS coolant into the reactor vessel, the core is quickly flooded with the water and the boiling is suppressed with two trains of LHSI in operation (AREVA NP Topical Report ANP-10278P, Revision 1, “U.S. EPR Realistic Large Break Loss of Coolant Accident, January 2010.” After the hot leg LHSI switch over at 60 minutes into the transient, all the localized boiling ceases and the single phase decay heat removal continues for 30 days. For a LOCA with a cold-leg break the core wide boiling lasts longer than 60 minutes. As stated in FSAR Tier 2, Section 6.2.2, the hot-leg LHSI injection serves both as a mechanism for removing core decay heat, leading to the complete cessation of steaming through the break, and for maintaining core boron concentrations below the threshold concentration for precipitation.

Although the steaming through the break ceases, the boiling in the core region is expected to last more than an hour and eventually stops during the early stage of the 30 days long term cooling.

The implicit assumption used by this method is that all the decay heat energy released from the core would vaporize a certain amount of the reactor coolant and the debris contained in the vaporized coolant would deposit on the fuel rod resulting in the formation of crud or scale. In reality, a significant portion of the decay heat is removed through single phase heat transfer. The method may tend to conservatively predict the debris deposition and the peak cladding temperature, provided a set of conservative assumptions and model input parameters are used.

DM Assumptions

The applicant made 19 assumptions to simplify the complicated recirculation and debris deposition processes and capture the first order deposition phenomena. These assumptions are evaluated below.

The applicant assumed that all large debris is trapped upstream of the reactor vessel. Only dissolved chemical species or small debris can reach the core. The staff finds this assumption acceptable because the large debris retainer and the sump strainer captured all the large debris, such as RMI debris. This was demonstrated by the applicant through strainer head loss testing and by-pass testing and the staff evaluation is documented in Section 15.6.5.4.3.2 of this report. Therefore, the staff concludes that the large debris does not contribute to the scale or crud formation.

The types of reactive elements considered in the evaluation are Aluminum (Al), Calcium (Ca), Silicon Si, fiber and particulate. According to ANP-10293P Revision 4, Appendix 4, no other chemical specifies are located in the reactor coolant system nor in the IRWST. This was also observed by NRC-sponsored ICET test (NUREG/CR-6914 Integrated Chemical Effects Test Project: Consolidated Data Report). Therefore, the staff finds this assumption to be acceptable.

The scale formation and distribution in the reactor core region is assumed to be proportional to the relative power of each core section. The staff finds this assumption conservative as the deposition process is dominantly driven by the decay heat release through the fuel cladding. Without heat transfer through the cladding to the coolant, the debris deposition on the fuel rod surface is the same on any other interior surface of the reactor coolant system. Therefore, the localized power distribution dictates the deposition distribution and the assumption is proper for this application.

The coolant saturation pressure is assumed to be the same as that of pure water. This assumption results in overestimating the initiating point of boiling as the debris and dissolved chemical species tend to raise the boiling point above pure water. The overestimated boiling results in conservative deposition rate. Therefore, the staff considers this assumption conservative.

The applicant assumed that all dissolved elements for the entire coolant volume are deposited only on the fuel rod cladding. In addition to the fuel rod surface, all the interior surfaces in the reactor vessel and relevant piping are subject to deposition. Therefore, this assumption not only captures the dominant effect but also makes the results conservative.

The debris deposition rate under non-boiling condition is assumed to be 1-80 of the rate under the boiling condition according to the testing results documented in a technical paper (A. Helalizadeh, H. Muller-Steinhagen, M. Jamialahmadi, “Crystallization Fouling of Mixed Salts During Convective Heat Transfer and Subcooled Flow Boiling Conditions,” 2003 ECI Conference on Heat Exchanger Fouling and Cleaning: Fundamentals and Applications, Paper 6, Santa Fe, NM). In RAI 493, Question 15.06.05-108, the staff requested that the applicant explain the validity of this assumption. In a November 18, 2011, response to RAI 493, Question 15.06.05-108, the applicant stated that this assumption was developed based on the empirical data for mixed Calcium salts under boiling and non-boiling conditions and the results were conservative. The staff reviewed these two documents and considers the assumption acceptable as the coolant chemical condition during the deposition process is similar to the Calcium salts solution. In addition, the treatment of fiber and particulate debris as chemical compound being deposited on the fuel rod surface introduced significant conservatism to override the potential uncertainties of the empirical data.

To conservatively maximize the dissolved material concentration in the core liquid region, the applicant assumed that the fluid exiting the reactor vessel is pure steam and the mass increase due to the precipitation is contained in the core region control volume. These two treatments lead to significant conservatism as major portion of the fluid discharged through the break is liquid which contains large quantity of dissolved chemical, and, adding precipitated chemicals to the liquid mass arbitrarily increased the chemical concentration. Therefore, the staff finds these two treatments acceptable.

A low generic heat transfer coefficient of 400 w/m^2-K (70.4 Btu/h ft^2 R) was assumed for the heat transfer from the surface of the deposits to the bulk fluid inside the fuel assembly. The applicant's intent is to simplify the calculation model and conservatively predict the deposit surface and cladding surface temperatures. In part of RAI 493, Question 15.06.05-108, the staff requested that the applicant justify this assumption. In the November 18, 2011, response to this RAI, the applicant indicated that a natural circulation system has a typical heat transfer coefficient between 50 w/m^2-K (8.8 Btu/h ft^2 R) and 1000 w/m^2-K (180 Btu/h ft^2 R) and about 2500 w/m^2-K (440Btu/h ft^2 R) for the surface under boiling conditions. By choosing a lower bound heat transfer coefficient, the deposit surface and fuel cladding surface temperatures are conservatively estimated.

For this two-volume model, the applicant assumed that the concentrations of all the chemical solute are uniformly distributed in each of these two control volumes and the concentration change in the core region does not inhibit the dissolution of calcium, aluminum or silicon by the common ion effect. The simplification made the solute mass conservation calculation possible. As discussed above, the debris deposition is assumed to be proportional to the localized heat flux and the uniform mixing assumption conservatively maintains higher concentration of solute than the actual where the solute is depleted the most. Therefore, these two assumptions are expected to result in conservative levels of debris deposition and scale thickness.

During the 30 day period of long term cooling, the latent fiber debris is being washed from the containment through IRWST to the reactor vessel. It is difficult to predict the time that all the latent fiber will be filtered out in the core region for different break locations as some of the latent fiber may be carried out through the break by the excessive ECCS injection. The applicant assumed all the latent fiber is captured inside the core region and deposited on the fuel rod surface within one hour before the hot leg switch over is introduced by the operator. This is considered conservative because not only some of the latent fiber continues to flow through the containment, but also, it is not expected to adhere to the fuel rod surface due to boiling.

The closest geometrical representation of the scale/crude layer is the cylindrical geometry. The applicant decided to simplify the conduction solution using 1-D Cartesian geometry. This is conservative because, for the same scale/crud thickness, the Cartesian geometry solution maintains the same heat transfer surface area and predicts higher cladding temperature.

Element solubility of the chemical species including latent fiber and particulate is assumed by the applicant to be zero. This introduces significant conservatism as the precipitates are usually the major contributor to the scale/crud formation.

In ANP-10293, Page F-64, the applicant assumed the mass of the Aluminum Oxyhydroxide formed during the 30 day period of long term cooling is negligible in the calculation. The basis of this assumption is not evident to the staff at this point since ANP-10293P Revision 4, Appendix D clearly shows that significant amount of Aluminum Oxyhydroxide would form during the 30 days of long term cooling in addition to other chemical species is available for deposition. In RAI 573, Question 15.06.05-117, the staff requested that the applicant provide this information. **RAI 573, Question 15.06.05-117 is being tracked as an open item**.

The applicant introduced these assumptions to simplify the model. Except for the open item identified above, the staff considers these assumptions conservative and the method based on these assumptions can predict conservative scale thickness and peak cladding temperature if conservative input parameters are used.

DM Input Parameters

The decay heat of the core is put into the model assuming initial reactor power at nominal rated power level plus the calorimetric uncertainty. The decay heat power is modeled based on a curve-fit to the ANS 1971 standard plus 20 percent including actinides. This decay heat input is more conservative than the decay heat used by the applicant in its Large Break LOCA methodology approved by the staff. Therefore, the decay heat input is conservative.

The selection of power distribution also affects the scale distribution and the maximum thickness. The applicant used the core power distribution consistent with the report and divided the core into five radial regions with 52 axial nodes. Since the consistent power distribution is used in conjunction with a fine nodalization, the staff considers the power distribution applicable.

The liquid mass in the core region is determined using the corresponding core region liquid mixing volume for the boric acid precipitation analysis and a reduction of liquid density from the saturated liquid density is applied to minimize the total amount of the liquid available. This approach is conservative as the core is expected to be completely filled with water for the hot leg break scenario after one hour and several hours for the cold leg break scenario.

ANP-10293P, Appendix D identified the amount of fiber and particulate available from the containment floor. The particulate debris includes the latent particulate and the Microtherm debris. Although all particulate debris is assumed to reach the core region, only a fraction of the fiber debris would pass the strainer and the reach the core region. The fiber only bypass testing results demonstrated that only a fraction of the fiber would pass through the strainer surface. In Section 15.6.5.4.3.2, of this report, the staff accepted the by-pass fraction testing results and agreed that not all the fiber debris would be available in the core region to form the scale. With significant margin available, the applicant assumed all the fiber and particulate debris are available in the core region to be deposited on the fuel rod surface. In reality, the fiber, particulate and other chemical precipitates could be stopped by the fuel assembly bottom nozzle, spacer grids and all the piping system. The actual filtration effect of all the components reduces the available debris to form the crud. Therefore, the staff finds the amount of debris assumed in the calculation conservative.

The density and the thermal conductivity of the scale or crud are two important parameters to determine the scale thickness and the fuel cladding surface temperature. Based on the measured density of calcium carbonate, magnesium hydroxide and calcium hydroxide during the boiling test, and the measurements on cross-sectioned calcium sulfate scale, the applicant used the lowest density for the scale to maximize the scale thickness and the surface temperature. Since the applicant used the lower bound scale density based on relevant testing and evaluation, the staff considers the selected scale density value conservative as discussed in the November 18, 2011, response to RAI 493, Question 15.06.05-108. The scale thermal conductivity is also strongly affected by the formation structure of the scale. Two types of precipitates were predicted to form the scale. They were calcium phosphate and sodium aluminum silicate. According to a published technical paper (Hans Muller-Steinhagen, “Heat Exchanger Fouling-Mitigation and Cleaning Technologies,” Institution of Chemical Engineers, Rugby, UK, 2000 p. 4.), the lower bound conductivity value is 0.2 w/m^2-K (0.035 Btu/h-ft^2 R).

For conservative purposes, the applicant used 0.1 w/m^2-K (0.018 Btu/h-ft^2 R) as the conductivity input value. Therefore, the staff considers this selected thermal conductivity value acceptable.

IRWST and Reactor Coolant Temperature

The applicant stated that the IRWST liquid temperature was provided in ANP-10293NP, Table F.4-2, and the reactor coolant temperature was assumed 2.7 °C (5 °F) above the IRWST liquid temperature to account for vessel pressure slightly higher than that of the containment pressure.

DM Calculation Results

Using this simplified two-volume model in conjunction with a set of conservative assumptions and input parameters, the applicant has performed the analysis to identify the bounding scale thickness and peak cladding temperature. The calculated maximum cladding temperature is significantly less than the 427 °C (800 °F) limit. Based on the open item in RAI 573, Question 15.06.05-117 discussed above, the staff cannot find the design acceptable.

15.6.5.4.3.5 Conclusions

In ANP-10293NP, Appendix E and Appendix F, the applicant has documented a significant effort to evaluate the U.S. EPR in-vessel downstream effects during long term core cooling with recirculation through the IRWST. The effort included the development of the acceptance criteria, debris by-pass testing, fuel bundle head loss testing, and EPR deposition analysis. Overall, the staff finds that both the testing program and the analysis effort are extensive and technically sound. Based on the open items in RAI 573, Question 15.06.05-116 and RAI 573, Question 15.06.05-117 discussed above, the staff cannot find the design to be acceptable in accordance with the requirements of NRC regulations. Further information is needed from the applicant to close these two open items.