PWROG
PWR Owners Group

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Project Number 694
WCAP-16793-NP, Revision 2

July 20, 2012

OG-12-287

Mr. Stewart Bailey
Chief, Safety Systems Resolution Branch,
Division of Safety Systems
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Subject: PWR Owners Group
Submittal of Supplement to WCAP-16793-NP, Revision 2 (PA-SEE-0312, Revision 4)

References:

1. PWROG Letter OG-11-290, "PWR Owners Group, Submittal of WCAP-16793-NP, Revision 2, 'Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid,' (PA-SEE-0312, Revision 2)," October 12, 2011.
2. WCAP-16793-NP, Revision 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," October 2011.
3. PWROG Letter OG-12-204, "PWR Owners Group, Submittal of 'Proposed Supplement to WCAP-16793-NP, Revision 2,' PA-SEE-0312, Revision 4," May 25, 2012.

Dear Mr. Bailey:

PWROG Letter OG-11-290 (Reference 1) transmitted WCAP-16793-NP, Revision 2 (Reference 2) for NRC review and approval in October of 2011.

Attachment 1 to this letter summarizes the technical considerations that support the conclusion that the per-fuel-assembly fiber limits established in WCAP-16793-NP, Revision 2 (Reference 2) are conservative, bounding values. This conclusion is based on the associated cumulative limiting conditions under which these tests were performed. Consequently, margin exists that will allow utilities to evaluate operability concerns should a plant licensed under Reference 2 discover additional debris sources.

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The purpose of this letter is to request the NRC to review and approve Attachment 1 as part of WCAP-16793-NP, Revision 2, previously submitted to your office under letter OG-11-209 (Reference 1). This letter supersedes OG-12-204 (Reference 3).

Attachment 1 will be incorporated into the approved version "-A," of WCAP-16793-NP, Revision 2, as a Supplement, after the NRC issues the Final Safety Evaluation for these two documents.

The three main topics presented in Attachment 1 are:

- The basis of the conservative, bounding, 15g/fuel assembly fiber limit defined in WCAP-16793-NP, Revision 2 (Reference 2), and a potential future program that may be pursued to determine more realistic debris limits that can be implemented by all PWROG members.
- A discussion of the conservatisms inherent in the fuel assembly testing that was performed in support of WCAP-16793-NP, Revision 2 (Reference 2), including the effects of those conservatisms on PWROG generic per-fuel-assembly fiber limits.
- A discussion regarding the consideration of break sizes (small versus large break) with respect to the fuel assembly testing that was performed.

Correspondence related to this transmittal, including requests for additional information, should be addressed to:

Mr. W. Anthony Nowinowski, Program Manager
PWR Owners Group, Program Management Office
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If you have any questions, please do not hesitate to contact me at (205) 992-7037 or Mr. W. Anthony Nowinowski at (412) 374-6855.

Sincerely,

Norman J. Stringfellow

Jack Stringfellow, Chairman
PWR Owners Group

KJN:jtm:rfn

Attachment (1):
1. Supplement to WCAP-16793-NP, Revision 2

cc: PWROG Management Committee
PWROG Steering Committee
PWROG SEE Subcommittee
PWROG LSC Subcommittee
PWROG PMO
J. D. Andrachek – Westinghouse
T.S. Andreychek – Westinghouse
T.D. Croyle – Westinghouse
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F. Gartland – AREVA NP
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ATTACHMENT 1

Contents

1.0 Executive Summary

The Pressurized Water Reactor Owners Group (PWROG) sponsored a program to evaluate the effect of in-vessel debris on long-term core cooling (LTCC) to support the resolution of Generic Safety Issue GSI-191. WCAP-16793-NP, Revision 0 (Reference 1) was written with the intention of demonstrating reasonable assurance that LTCC requirements are satisfied using then currently available tools and information (not testing) to consider the effects of debris and chemical products in the recirculating coolant delivered from the sump to the core (i.e., in-vessel effects). WCAP-16793-NP, Revision 1 (Reference 2) was written to present an assessment of the effects of debris and chemical products in the recirculating coolant delivered from the sump to the core through generic fuel assembly (FA) testing. Efforts to address requests for additional information (RAIs) have been completed, and additional FA testing was performed to establish a very conservative, generic, in-vessel fiber limit that is documented in WCAP-16793-NP, Revision 2 (Reference 3), to which this document is a Supplement.

The generic testing approach included large break loss of coolant accident (LBLOCA) flow rates and debris loads for both hot- and cold-leg break FA tests in the PWROG fuel assembly test program to resolve GSI-191 in-vessel effects. To achieve the goal of determining a very conservative generic FA fiber limit, the PWROG used conservative parameters compounded by conservative test conditions to create a test program that would be applicable to and bound all PWRs. Based on the data obtained from the generic testing, the compounded conservatisms necessary to support a generic program resulted in a very restrictive FA fiber limit for the majority of the operating PWR fleet.

Due to the conservative parameters and conservative test conditions, the fiber limits discussed in WCAP-16793-NP, Revision 2 (Reference 3) will be utilized by the PWROG as a starting point to determine more realistic fiber limits in the future, since these fiber limits are not an absolute limit. Some utilities may incorporate these conservative limits discussed in WCAP-16793-NP, Revision 2 into their licensing basis until more realistic limits are determined.

This document, and WCAP-16793-NP, Revision 2, discuss the basis of the 15g/fuel assembly limit with respect to the conservative parameters and conservative test conditions that were used to determine the limits. The PWROG may pursue a more prototypical in-vessel program in the future that will determine more realistic debris limits that can be implemented by all PWROG members, rather than the limits in WCAP-16793-NP, Revision 2. Potential future programs will utilize analyses, evaluations, and potential additional testing to develop more realistic FA debris limits. Such a program will consider lessons learned, previous RAIs, and questions associated with Reference 3. Many of the conservatisms within this document may be reduced as part of the path forward. These conservatisms can be used to provide a basis for operability determinations for plants who have incorporated WCAP-16793-NP, Revision 2 into their licensing basis (e.g. a low fiber plant meeting a 15g/fuel assembly fiber limit) and subsequently discover additional debris sources in containment during operation that result in exceeding the WCAP-16793-NP, Revision 2, FA debris limits. The bounding nature of these conservatisms provides a sound basis for identifying the margin that is available to address an increase in FA debris until further action can reasonably be taken to address such debris or until more realistic debris limits are determined.

The following provides a summary of several of the key conservatisms that are included in the Reference 3 analysis, evaluation, and testing. These conservatisms can be used for operability determinations to provide a reasonable assurance of long term core cooling.

2.0 PWROG Fuel Assembly Test Program

Questions from both the Nuclear Regulatory Commission (NRC) Staff and Advisory Committee on Reactor Safeguards (ACRS) on WCAP-16793-NP Rev. 0 (issued in 2007) led to a commitment by the PWROG to initiate a testing-based approach to address debris challenges on the post-LOCA ECCS flow through the core.

Following a loss of coolant accident (LOCA), the reactor containment building emergency sump begins to fill with the discharge of the reactor coolant system (RCS) inventory, the containment sprays, and the high temperature break flow as the emergency core cooling system (ECCS) flow removes decay heat from the core. When the refueling water storage tank (RWST) (also called borated water storage tank or BWST) reaches a predetermined level, the ECCS suction is switched from injection from the RWST/ BWST to recirculation from the containment sump. It is the time period between the ECCS switchover to containment sump suction and the time of Hot Leg Switch Over (HLSO) that is of concern for in-vessel debris effects. The initiation of HLSO reduces ECCS flow to the bottom of the core which, in turn, lowers the head loss across the core and provides an alternate ECCS flow path to ensure long term core cooling (LTCC).

2.1 Fuel Assembly Test Program Acceptance Criteria

The PWROG fuel assembly test program acceptance criteria defines a per assembly fiber limit that ensures LTCC.

1. The testing conducted in support of this program demonstrated that 15 g of fiber/FA does not cause a blockage that will challenge LTCC, the maximum pressure drop (ΔP) due to debris (ΔP_{DEBRIS}) is very small, and all plants have an available driving head (ΔP_{AVAIL}) that is considerably greater than ΔP_{DEBRIS}. Therefore, all PWROG plants can demonstrate LTCC is not impeded if the plant-specific fibrous debris load is less than or equal to 15 g of fiber/FA.
2. Tests conducted with AREVA and Westinghouse fuel assemblies performed at CDI demonstrated that flow was able to continue to enter the core with 25 g of fiber/FA, even though the flow rate had to be reduced during the tests (Reference 3). Therefore, plants with AREVA and Westinghouse fuel that have a driving head greater than or equal to this ΔP_{DEBRIS} value and operate at conditions similar to those tested, can withstand up to 25 g of fiber/FA.

Bounding guidelines have been developed that plants can use to determine the maximum allowable fiber load that can reach the core and not impede core cooling (Reference 3, Section 10.3).

Details on the conservatisms of the testing that was performed are provided in Section 2.2 below.

2.2 Fuel Assembly Test Program Conservatisms

The PWROG FA test program was designed to be conservative with respect to actual post-accident ECCS conditions by assuming the following test parameters:

2.2.1 Conservatism: Ambient temperature

Immediately following the LOCA, the sump fluid temperature will be near 265°F[1] (Reference 8). In the days following the event, the sump temperature decreases but generally remains at temperatures higher than approximately 120°F.

Although none of the operating PWR sumps will experience temperatures as low as 70°F in the first 24 hours following a LOCA, the generic FA testing was conducted at ambient conditions. This temperature was chosen to maximize the water viscosity and promote higher head losses through the debris beds. All testing (beyond a few specific test cases) was conducted at ambient conditions (around 72°F). Actual plant conditions will have much higher sump temperatures in the time following the accident and prior to HLSO, which is the period of interest for in-vessel debris effects. The higher temperature will minimize chemical effects (Reference 9) and maintain a lower water viscosity. A lower water viscosity results in a lower pressure drop through the debris bed. Darcy's Law provides the basis for the pressure drop (ΔP)–viscosity (μ) relationship:

Darcy's Law (Equation 1)

$$\frac{\Delta P}{\omega} = \frac{L\mu}{\kappa}$$

where:

ΔP	=	pressure drop across bed
ω	=	flow velocity (ft/s)
L	=	length of porous bed (ft)
μ	=	dynamic viscosity (lbf=sec/in^2)
κ	=	permeability (ft^2)

2.2.2 Conservatism: Constant flow rate

Hot-leg Break:

The maximum post-LOCA ECCS flow rate representative of a Westinghouse 4-loop plant with all trains injecting is ~44.7gpm / FA. Most Westinghouse 3-loop plants have ECCS flows that are lower than 44.7 gpm / FA, and Westinghouse 2-loop plants and Combustion Engineering (CE) plants have ECCS flow rates that are significantly lower (~40% and ~60% lower, respectively) than 44.7 gpm / FA. B&W plants have ECCS flows in the range of Westinghouse 3-loop and 4-loop plants. In an actual HL break, debris delivered to the core will continue to build beds until the resistance becomes great enough to back up the ECCS flow through the cold leg and into the steam generator (SG) U-tubes until it spills over the U-tubes. In this case, the coolant from the broken loop will spill out of the break, while spillover flow in the other loops will return to the top of the core.

In order to bound the majority of the operating PWR fleet, the generic hot-leg FA tests used a constant flow rate value of 44.7 gpm / FA, and the available driving head calculations assumed

[1] These values are for "large, dry" containments. The temperature of the fluid in the sumps of ice condenser containment plants ranges from about 190°F immediately following the postulated break, to a long-term temperature of about 130°F.

both a water solid core and the shortest steam generator U-tubes. The maximum flow rate of 44.7 gpm ensured that the pressure differential (ΔP) due to fiber was calculated at the most limiting condition. FA testing performed at lower flow rates than the conservative maximum value of 44.7 gpm resulted in a lower FA ΔP. The use of the shortest steam generator U-tubes to establish a minimum driving head and a water-solid core provided for a conservatively low driving head. Conservatively, the hot-leg break FA tests did not credit the reduction in core ΔP due to steam generator spillover or the flow to the top of the core from steam generator spillover. Allowing the flow rate to decrease commensurate with the buildup of debris would be more prototypic and result in a reduction in FA head loss. Using plant specific ECCS flow values and actual steam generator tube heights would provide for additional driving head.

Cold-leg Break:

Following a LOCA, the containment sump fills with RCS discharge, containment spray flow, and break flow. When the sump reaches a predetermined level, ECCS suction switches from the RWST to the containment sump. After the start of sump recirculation, LTCC is demonstrated by showing that there is sufficient flow to replace core boil off, thus keeping the core covered and preventing additional fuel clad heat-up. The highest expected core boil off rate at approximately 20 minutes after a LOCA corresponds to a core flow rate of ~3 gpm / FA and at one hour after the event, the decay heat has decreased to a point at which the core boil off requirement is approximately 2/3 of the boil off rate of ~3 gpm / FA at 20 minutes, based on a 4-loop plant.

To bound the operating PWR fleet, the generic cold-leg FA test program was conducted at a constant flow rate of 3.0 gpm / FA, representing a decay heat load early in the transient (~20 minutes after initiation of the postulated LOCA). Assuming this flow rate ensured the development of debris beds with maximum resistance and the highest pressure loss. The available driving head calculations assumed a water solid core and did not credit the increase in available driving head if considering a core with a large void fraction. Maintaining a constant flow rate in the FA tests results in a conservatively high head loss value as FA testing has shown that as the flow rate decreases, the pressure drop also decreases (see Figure 3-60 CIB34, Reference 7), thus ensuring continued cooling of the core.

Allowing the test flow rate to decrease commensurate with the buildup of debris would be more prototypic and result in a reduction in FA head loss while still maintaining adequate flow through the core.

2.2.3 Conservatism: Uniform flow

Following a LOCA, the assembly-to-assembly power difference will initially promote non-uniform flows which will result in a non-uniform debris distribution throughout the core. This non-uniformity of flow will promote the continuance of sufficient flow to provide for LTCC even in the presence of debris.

In order to promote the development of uniform debris beds, the generic FA test program included certain design features to promote uniform flow. The promotion of uniform flow and uniform debris bed formation is a conservative assumption, since only small variations in the flow profile or FA orientation are required to promote non-uniform debris bed buildup.

Note that non-uniform debris bed buildup was observed to be self correcting in sump screen testing; however, there is a limited fibrous debris source term available for in-vessel effects.

Consider the per-assembly fiber limit on a core wide basis; a small variation in fibrous buildup that exceeds the limit on a single assembly would mean that another assembly would have less than the per-assembly limit. Analyses discussed in Reference 3 indicate that the equivalent of only one FA needs to be open to remove core decay heat and ensure LTCC.

2.2.4 Conservatism: Recirculating debris

Once ECCS switchover to the containment sump is complete, the ECCS flow now contains post-accident debris that will travel through various pumps, valves, heat exchangers, and extensive piping runs prior to injection into the RCS. Some of this debris laden ECCS flow may also be directed to the containment sprays. Debris that enters the RCS but does not settle or is not captured in the core would be carried out of the break into the sump where it could settle out or be rescreened before entering the ECCS again. Any reduction in the amount of debris entering the RCS will result in a lower core ΔP promoting adequate flow through the core to ensure LTCC.

The generic FA testing was conducted within a closed loop system. Any debris that initially bypassed the FA was reintroduced into the mixing tank and forced to circulate through the assembly until it eventually was captured. The feed tank for the FA testing was continuously agitated; essentially no settling of debris was allowed. The test fixture was also constructed so as to not allow settling; all debris was carried into the assembly. These features were designed to ensure that all of the debris was well mixed and forced to enter the test assembly.

2.2.5 Conservatism: Surrogate chemical effects

Following a LOCA, the reactor containment building emergency sump begins to fill with the discharge of the RCS, containment spray flow, and high temperature break flow as the ECCS flow removes decay heat from the core. Immediately following the LOCA, the sump fluid temperature will be near 265°F (Reference 8) for large dry containments. Since the LOCA will produce debris, and the containment sprays will fall on systems, structures, and components, it is expected that corrosion will occur and that chemical products will be produced in the sump, but not necessarily in sufficient quantities to generate chemical precipitates prior to HLSO, which is the time of interest for in-vessel effects. Many plant-specific conditions may be non-conducive to chemical product development; plants maintain temperatures above solubility limits, and many plants use buffering agents to reduce precipitate generation under post-accident conditions.

Testing sponsored by the PWROG showed silicate and phosphate inhibition of aluminum corrosion was found at all temperatures in the range of 140°F to 260°F. There are very specific thresholds (ppm of various materials) at which inhibition and confirmed solubility occur. These thresholds are plant specific and are based on the quantities of materials present and at defined temperatures. Additional testing identified suitable buffering agents to reduce precipitate generation under post-accident conditions, while maintaining comparability to those buffers currently in use. The candidate buffers included sodium tetraborate decahydrate (NaTB) and sodium metaborate tetrahydrate (NaMB), with NaTB replacing trisodium phosphate (TSP) in a number of plants to reduce the calcium phosphate production in calcium silicate insulated plants.

The generic FA testing used aluminum oxyhroxide (AlOOH) prepared in accordance with the method provided in WCAP-16530-NP-A (Reference 8) as a surrogate representative of all chemical precipitate products. Tests and analyses performed by the PWROG and the NRC have shown that the WCAP-16530-NP-A surrogate is the most effective chemical agent for causing head loss across a debris bed. Testing summarized in Reference 4 supports the use of AlOOH as a conservative chemical surrogate for strainer head loss testing. Further, this testing demonstrated that an ALOOH surrogate made with high purity water (used in the RCS and ECCS) was not as effective or as stable as that made with tap water (as used in the FA test program). The ALOOH surrogate is not representative of, but rather bounds, the chemical products and precipitates expected in most plants. The addition of the WCAP-16530-NP-A surrogate has been the limiting particulate debris source in the FA testing. Using plant specific chemical products and precipitates would reduce the head loss due to chemical effects for many plants where aluminum oxyhydroxide is not representative.

2.2.6 Conservatism: Staging of debris additions

Following a LOCA, debris would be washed to the containment sump as it fills with the discharge of the reactor coolant system (RCS), high temperature break flow, and containment spray flow. The timing and distribution of the debris reaching the sump is highly speculative as the pool fills pool prior to the initiation of recirculation. Debris generation and transport calculations are used to define the quantities of debris to be used in evaluations and testing. The NRC guidance on the preparation and sequencing of materials for screen head loss testing (Reference 5) was adopted for the generic FA test program.

The generic FA test program was designed to model the worst case transport scenario for particulate, fiber, and chemical precipitates into the core region; debris was selected and sequenced to promote the worst case debris bed formation using NRC guidance regarding the order of addition. The debris used in FA testing included particulates, fibers, and chemicals.

<u>Particulate</u> (P)

The silicon carbide particulate is consistent with Reference 6 ("The GR provides the guidance to assume all particulate mass is composed of 10-μm diameter grains."), as this size will also readily fill interstitial gaps in a fiber bed. As described in Reference 5, "During the bed formation process, the prompt accumulation of particulate in the interstitial areas of the fiber bed appears to create a thinner and more homogeneous bed".

In FA testing, a pressure drop associated with particulates alone has never been observed. Introducing the particulates at the outset of a FA test allows them to be available to build the bed as the fiber collects. This sequence of particulate followed by fiber promotes the lowest porosity debris bed. As described in Reference 5, "The subsequent particulate buildup within the fiber bed results in a debris bed with a porosity similar to that of a bulk accumulation of that particulate".

<u>Fiber</u> (F)

The fiber size distribution used in FA testing is based on PWROG strainer bypass testing samples.

Fiber is added, after particulates, in small increments. The incremental addition allows for a slow buildup of the debris bed with particulates and allows observation of thin-bed behavior.

<u>Chemical Surrogate</u> (C)

AlOOH is used to "bound" the head loss characteristics of all species of chemical precipitates that may form in the post-accident sump. Surrogate is added after the particulate and fiber bed has formed. The effect is to compress the established debris bed and further increase the pressure drop across the bed.

This sequencing approach was adopted from sump screen testing for FA testing to promote the most limiting debris bed formation because it is not known with any certainty when any particular type of debris will reach the core. Variations in the sequence in which debris arrives at the core may promote the formation of a debris bed with a lower pressure drop than what was tested. The NRC guidance on strainer head loss (Reference 5), which was adopted for FA testing, indicates that the sequence of 100% particulate followed by fiber may be overly conservative and offers alternative methods of debris introduction, including a series of tests using homogeneous debris addition.

2.2.7 Conservatism: Limiting particulate to fiber ratio (p:f)

Following a LOCA, the reactor containment building emergency sump begins to fill with the discharge of the reactor coolant system (RCS), containment sprays, and high temperature break flow as the emergency core cooling system (ECCS) flow removes decay heat from the core. The timing and distribution of the debris reaching the sump screens is not known with any certainty. Since there is no way to determine the amounts and timing of debris transport to the sump screen following a LOCA, RAIs on FA testing led the PWROG to study the impact of particulate to fiber (p:f) ratio on debris bed resistance.

Sensitivity testing of p:f was performed and it was found that a p:f of 1:1 was limiting at the 44.7gpm limiting flow rate used in the hot-leg testing, resulting in a conservatively high head loss upon the introduction of ALOOH for the limiting hot-leg break. PWROG FA testing has shown that as p:f increases to values greater than 1:1, the head loss due to the effect of ALOOH is reduced for hot-leg conditions.

For the cold-leg break tests, the limiting p:f ratio for testing was determined via testing to be 45:1.

2.2.8 Conservatism: Absence of boiling

In the event that a total blockage occurs at the core inlet, the coolant will begin to boil and disrupt any previously formed debris beds, thus decreasing the resistance to flow and allowing ECCS liquid to flow through the core again.

The generic FA testing assumed no boiling within the fuel bundle. Industry data indicates that debris beds will not form in the presence of boiling.

- Hot-Leg Break Effect: Boiling is minimized in the event of a hot-leg break. In the event that a total blockage would occur at the core inlet, the coolant will begin to boil. The presence of boiling also provides a greater core void fraction than what has been assumed. This results in a greater available driving head, which, in turn, provides the capability to withstand a greater head loss due to debris.
- Cold-Leg Break Effect: At the onset of the event, there will be boiling in the core. This will prevent the buildup of debris on spacer grids throughout the core. The turbulent nature of the boiling higher in the core will cause the water-solid areas to be turbulent, thus minimizing the debris collection in those areas. The presence of boiling also provides a greater core void fraction than what has been assumed. This results in a greater available driving head, which, in turn, provides the capability to withstand a

greater head loss due to debris.

2.2.9 Conservatism: Absence of alternate flow paths

Many PWRs have core designs that provide alternate flow paths around the periphery (baffle) of the core. Plants incorporating these alternate flow path designs include B&W plants and a number of Westinghouse 3 and 4 loop plants with 'upflow' barrel designs (Figure 1). Additionally, if the maximum debris bed resistance is reached at the core entrance that would cause ECCS water to back up through and spill over the lowest SG tubes, water would drain through the hot-legs to the top of the core, providing an additional source of cooling.

The generic FA test program ignores flow through the baffle region or possible spillover of the SG tubes or hot legs. For plants with upflow baffle geometries, some debris accumulation in the core inlet may divert flow into these regions, which will lead to debris and additional flow introduction higher in the core. These paths are available to provide flow to the core in the unlikely event the core inlet is completely blocked with debris.

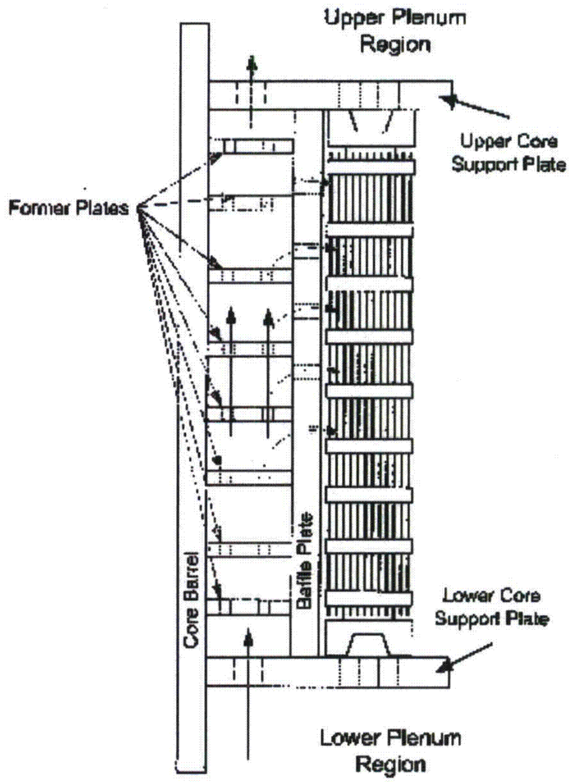

Figure 1- Alternate flow Paths

3.0 Fuel Assembly Testing

Initially, independent FA testing at separate facilities (Westinghouse Research & Technology Unit, or RTU, and AREVA/Continuum Dynamics, Inc., or CDI) showed that similar test results appeared to be independent of FA type or test facility. WCAP-16793 Rev. 1 was issued based upon this testing.

Based on questions and NRC RAIs, additional FA testing was performed at the Westinghouse RTU facility to define the limiting particulate to fiber ratio (p:f). Once the limiting p:f ratio was established, AREVA conducted a confirmatory test at the CDI facility and obtained different results.

A Westinghouse confirmatory FA test and an AREVA FA cross-test (AREVA FA at the Westinghouse RTU facility) were then performed. Both tests failed to meet the applicable pressure drop-related acceptance criteria and prompted industry representatives and the NRC staff to meet with the NRC Commissioners and commit to additional FA testing.

In late 2010-early 2011, Westinghouse performed a review of all fuel assembly testing that had been performed by Westinghouse and AREVA up to that time. This review combined the debris limits defined by FA testing, in conjunction with the analyses and evaluations presented in Reference 2, to demonstrate adequate heat-removal capability for all plant scenarios including: blockage at the inlet, collection of debris at spacer grids, deposition of fiber, and chemical deposition on fuel rods. In addition, the re-evaluation of the Westinghouse FA test results concluded that the difference in FA test results between facilities and vendors were not significantly different, and that these differences were small in comparison to the conservatisms inherent in the fuel assembly tests. It was also concluded that the most conservative test results were obtained from CDI and that testing at CDI defined the bounding fiber limit for the PWROG plants.

The PWROG FA tests performed up to that point in time did not attempt to model any of the prototypic conditions following a LOCA; the test program was designed to provide a conservative basis for setting the generic fiber limit for the PWROG plants. It was recognized that additional testing would need to be conducted to quantify the inherent conservatisms in the test process.

A review of Reference 2 and the proposed path forward - with testing to reduce conservatisms inherent in the test method used - was presented to the NRC Staff in a public meeting in March 2011. The conservative parameters that were evaluated and considered for further testing included:

- The effect of higher temperatures
- The effect of boron and buffering agents
- The rate of chemical introduction and solubility
- The effect of boiling

"Conservatisms tests" were performed at the Westinghouse RTU test facility beginning in April, 2011. Three (3) tests were run in the conservatisms test series including:

- A (boron/buffer),
- B (elevated temperature, HLSO), and
- C (elevated temperature).

In addition to these parameters being evaluated to reduce conservatism, the rate at which the chemical surrogate was introduced into the test was redefined to be more representative of the prototypic production of chemical precipitates.

The results of the conservatisms testing demonstrated that:

- A test performed with a buffered boron solution demonstrated no increase in the FA fiber limit
- A test performed at higher temperature and modeling a delay in chemical precipitation until HLSO demonstrated an increase in the FA fiber limit
- A test performed at higher temperature alone demonstrated an increase in FA fiber limit
- Reducing the rate in which the chemical surrogate is added to the test did not demonstrate an increase in the FA fiber limit

The effect of boiling was not evaluated in the PWROG FA test program during this testing; however, small-scale tests related to boric acid precipitation in the presence of post-LOCA debris showed that boiling prevented the formation of fiber beds.

Since the results obtained at the CDI test facility were the most conservative, it was decided to repeat test **C** at the CDI test facility with the Westinghouse FA to determine whether small facility differences had any impact on the preliminary fiber limits obtained from the conservatisms testing. In early August 2011, an additional test "**D**"[2] was conducted with the Westinghouse FA in the CDI facility. The result of test **D** was more conservative than the result of test **C**, consistent with previous results. Test **D** also demonstrated that flow was able to pass through the core, even though the flow rate had to be reduced during the test. This result is similar to a test performed with the AREVA FA with a p:f = 1:1 with 25 g of fiber / FA. Therefore, plants that have an available driving head greater than or equal to the test **D** value, and which operate at conditions similar to the test **D** conditions, can attain a higher in-vessel fiber limit.

Test **D** concluded the generic FA testing that the industry had committed to in the September 29, 2010 public meeting with the NRC Staff and Commissioners.

[2] Test "D" was conducted with the same test parameters as test "C"; elevated temperature, p:f= 1:1 with 25 grams of fiber

4.0 Current Fiber Load Limits

The generic FA test program concluded with proposed fiber limits applicable to the PWR fleet. The testing conducted by AREVA at the CDI facility in support of this program demonstrated that 15 g of fiber/FA will not result in a filtering bed that will restrict flow into the core and challenge LTCC (Reference 3). The maximum ΔP attributed to 15 g / FA was negligible, demonstrating the magnitude of conservatism associated with this limit. Therefore, all plants utilizing either AREVA or Westinghouse fuel can demonstrate LTCC is not impeded by post accident debris if the plant-specific debris load is less than or equal to 15 g of fiber/FA.

In addition to the proposed fiber limit, an AREVA FA test conducted with a p:f = 1:1 and 25 g of fiber/ FA (14-FG-FPC) demonstrated that flow was able to continue to enter the core even though the flow rate had to be reduced during the test. Westinghouse performed a similar test (1-W-FPC-0811) in the same facility with similar results as those obtained by AREVA. Therefore, plants with AREVA or Westinghouse fuel that have a driving head greater than or equal to 16 psid and operate at conditions similar to those tested can withstand 25 g fiber/ FA.

5.0 Configuration Tests

In light of the FA test at CDI that provided the 15 g / FA in vessel fiber limit, the PWROG initiated an investigation into the differences between the CDI and RTU test facilities. Facility differences such as lower plenum configuration, flow diffuser, gap size, and water type were tested. Of the facility differences tested at RTU, the water used in the tests produced the largest difference in FA ΔP as seen in the following results.

- RTU tap water
- CDI tap water
- Deionized water

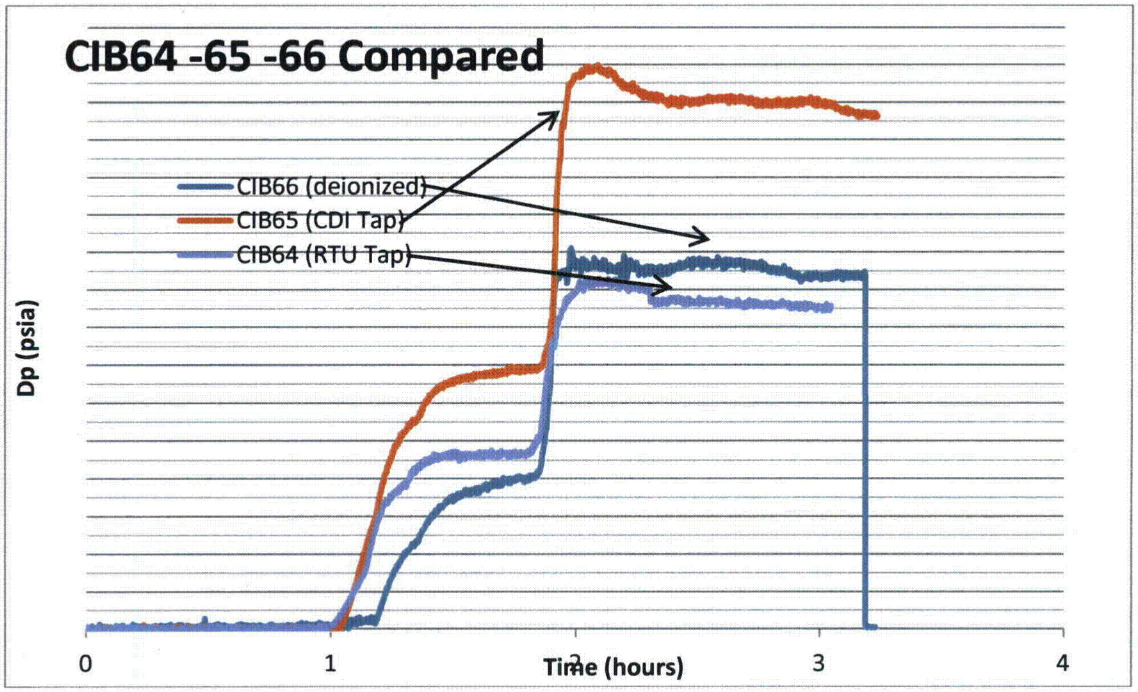

Figure 2 – PWROG Water Test Results

The conclusion of these tests identified the water source as having a direct influence on the test results. Tests with RTU tap water and deionized water were well below the pressure drop limit established for FA testing, while the test performed with CDI tap water was near the available pressure drop limit. This new data indicates that differences in water type are a potential cause of the differences in FA test results from the two facilities. The PWROG will potentially evaluate the impact of water chemistry on the maximum head loss values recorded in the FA testing conducted in a future program.

6.0 Break Size Considerations

The Pressurized Water Reactor Owners Group (PWROG) fuel assembly (FA) test program was designed to evaluate the in-vessel consequences of the LBLOCA, as this break has the greatest potential to affect long term core cooling. The PWROG concludes that small break LOCAs (SBLOCAs) are bounded by LBLOCAs in all respects when considering debris generation, debris transport, and downstream in-vessel effects as described below.

The SBLOCA is defined as a break in the RCS, including hot and cold legs, and unisolable lines connected to the RCS both inside and outside the crane wall. Small breaks generally range in size from 2 inches up to ~13.5 inches in diameter. The NRC Safety Evaluation (SE) for NEI 04-07 states that break sizes of 2 inches or less can be excluded from GSI-191 consideration.

6.1 SBLOCA Scenarios

For the very small (less than ~6 inches in diameter) SBLOCA scenario, the RCS system pressure remains high following the initiation of the break. ECCS injection flow is drawn from the RWST at a significantly lower rate (<5 gpm/FA) than in the fully depressurized LBLOCA scenario due to RCS back pressure. RCS holdup is higher for a SB LOCA, since less RCS inventory would discharge through the break. Smaller RCS inventory loss and lower break flow, combined with spray flow (for the larger small breaks), slowly fills the containment sump. Switch over to containment recirculation takes place later after accident initiation than in the LBLOCA scenario. ECCS recirculation flow remains low due to high RCS system pressure. If the break is small enough, the RCS could stabilize at a pressure that would allow the operators to secure the safety injection accumulators, further reducing sump filling. After core recovery and stable conditions are reached, the operators would bring the plant to cold shutdown.

Larger SBLOCAs (~6 inches to ~13.5 inches diameter) that undergo sufficiently rapid depressurization would cause the SI accumulators to discharge and release a significant discharge of RCS inventory into the containment building (i.e. steam generator inventory would discharge). The sump fill-up and recirculation time would still be somewhat longer than the LBLOCA scenario. These SBLOCAs would behave very similarly to the LBLOCA with very notable exceptions; the amount of debris generation would be significantly less than the LBLOCA, since the largest SBLOCA material ZOIs would be approximately 1/9 of the LBLOCA ZOIs.

6.2 Debris Generation

The criteria for debris generation remain the same regardless of break size; insulation and coatings within the zone of influence (ZOI) of a high energy line break are considered to be sources of debris. The amount of debris generated is directly related to the volume of the ZOI. The ZOI radius is linearly dependent on the break size; however, the volume of the ZOI is dependent upon the cube of the ZOI radius, making the SBLOCA ZOI considerably smaller than the LBLOCA ZOI. Take for example the 17D ZOI for NUKON®[3] insulation. Considering a 29 inch hot-leg pipe LBLOCA, the ZOI radius is 41 feet (29*17/12). The ZOI radius for the largest SBLOCA, a 13.5 inch diameter break, is 19.125 feet (13.5*17/12). More importantly, the volume of the LBLOCA ZOI is 290,459 cubic feet ($4/3\pi(29*17/12)^3$) while the volume of the largest SBLOCA ZOI is 29,279 cubic feet (more than 9 times smaller). As the break size decreases, so do the ZOIs; for a 6 inch diameter SBLOCA, the ZOI volume

[3] NUKON is a registered trademark of Performance Contracting Group, Inc.

for NUKON® insulation is only 2,572 cubic feet (more than 100 times smaller), demonstrating that the potential for debris generation decreases significantly for the SBLOCA. Therefore, the quantity of debris generated for a SBLOCA is considerably less than the quantity of debris generated for a LBLOCA.

6.3 Debris Transport

Following a SBLOCA, as the sump begins to fill with water via RCS break flow and containment sprays (depending on break size), the sump fluid temperature remains high as the ECCS flow removing core decay heat exits the break. Since a SBLOCA will produce debris, and the containment sprays will fall on systems, structures, and components, it is expected that corrosion will occur and that chemical products will be generated in the sump; however, these same conditions (high temperature, low flow) should also reduce and delay the formation of chemical precipitates. The impact of chemical production is therefore less for a SBLOCA.

Debris transport to the sump screens is influenced by both the amount of debris generated and by the amount of water flowing to the sump screens. In a SBLOCA without rapid depressurization, the content of the RCS is not lost to the sump immediately, since the break flow is significantly lower due to the reduction in break size. Due to the higher RCS backpressure on the ECCS pumps, the RWST will drain slower, lengthening the time to sump recirculation as compared to a LBLOCA. The delay in sump recirculation provides additional time for the considerably smaller amount of debris generated to settle, resulting in less debris available for transport to the containment sump screen. This reduction in the amount of debris reaching the screens significantly reduces the downstream consequences for a SBLOCA. Larger SBLOCAs more closely resemble LBLOCAs, however debris transport would be significantly less, since there is less debris to transport; the downstream consequences would be significantly less, since less debris is available to enter the ECCS in a SBLOCA scenario.

6.4 SBLOCA Considerations for the FA Test Program

The FA test program was designed with many conservatisms; one of those conservatisms was to define the maximum allowable fiber loading that would not cause coolant to spillover the lowest SG tubes. This was done in order to avoid questions regarding siphoning of the coolant from the core in a LBLOCA scenario. For a SBLOCA scenario, the coolant would not be siphoned, since the major components of the RCS remain intact. For a SBLOCA in the hot-leg, the ECCS liquid must pass through the core to exit the break. The primary driving force is the manometric balance between the liquid in the downcomer and the core. Should a debris bed with sufficient resistance to flow begin to build up in the core, the ECCS flow exceeding the break flow will backfill the cold-leg, reactor coolant pumps, pump suction piping, SG outlet plenum, and SG tubes, until the coolant spills over the lowest SG tubes. With all loops still intact (i.e., no guillotine break), the spillover flow provides coolant to the top of the core.

Once the debris buildup causes the coolant to spill over the lowest SG tube, the available driving head becomes fixed and the debris load can continue to increase until flow through the core reaches the boil off rate + 10%. (The 10% is added for conservatism with the intention of preventing the development of a two-phase state in the core.)

6.5 Summary

In summary, the NRC SE for NEI 04-07 states that break sizes of 2 inches in diameter or less can be excluded from GSI-191 consideration. Based on the ZOI of a SBLOCA, debris generation for a SBLOCA, and debris transport for a SBLOCA, it can be concluded that SBLOCAs are less limiting for GSI-191considerations in all respects than the LBLOCA upon which the applicable fiber limits are based. While all LOCAs are low probability events, the probability of a LBLOCA is considerably smaller than that of a SBLOCA (generally at least 2-3 orders of magnitude smaller). Therefore, the break size assumptions for the fuel assembly debris testing, which are based on a LBLOCA, are conservative.

7.0 Additional Design Margins that Provide Reasonable Assurance of Long Term Core Cooling

7.1 Introduction

10 CFR 50.46 (b) (5), "Long-term cooling," (Reference 10) requires that licensees design their Emergency Core Cooling Systems (ECCS) to provide the capability for long-term cooling. That is, following a successful system initiation, the ECCS shall be able to provide cooling for a sufficient duration that the core temperature is maintained at an acceptably low value. In addition, the ECCS shall be able to continue decay heat removal for the extended period of time required by the long-lived radioactivity remaining in the core. The ECCS is designed to meet this criterion, assuming the worst single failure. Prevention of sump blockage and the ability to realign to the sump for a water source can be critical to meeting these requirements.

7.2 Design Margins

There are several sources of analysis margin in PWR designs which may not be credited in the licensing basis for each plant. Several examples of these margins are as follows.

- NPSH analyses for most PWRs do not credit containment overpressure which would be present during a LOCA. Any containment pressure greater than assumed in the NPSH analysis provides additional margin for ECCS operability during a postulated event.

- NPSH margin for the recirculation mode of the ECCS system is dependent on several different factors including the flow rate, the height of the water level above the pump suction, the water temperature, and the containment pressure. For the purposes of design basis, plants have conservatively calculated a minimum NPSH margin based on the worst case for each factor. This conservative calculation ensures that the ECCS pumps can handle the worst-case scenario. A licensing basis NPSH margin is calculated at large-break LOCA conditions assuming the maximum pump flow rate (i.e., run out flow), the maximum water temperature, the minimum water level in the sump, and assuming little or no containment pressure above atmospheric conditions. This method of calculating the licensing basis NPSH margin results in ECCS pumps that are designed with additional safety margin.

- Another example of margin is the assumption that the ECCS and CSS pumps cease to function when $NPSH_{REQUIRED}$ exceeds $NPSH_{AVAILABLE}$. It has been demonstrated that some ECCS pumps are able to continue operation under reduced NPSH conditions.

Design margins, such as those identified above, either prevent complete loss of ECCS recirculation flow or increase the time available for operator action (e.g., refilling the RWST/BWST, additional water sources) to mitigate containment sump screen blockage.

7.3 Unique ECCS Design Features

Westinghouse 2-Loop PWR's have a unique ECCS design feature called Upper Plenum Injection (UPI). This design feature provides for their ECCS configuration in the post-LOCA recirculation mode to provide for flow into the upper plenum and down through the core; at some point during recirculation, simultaneous flow into the upper plenum and the cold leg occurs. Therefore, some portion of the debris may not reach the core for a hot-leg break, and the debris that does reach the core may collect at different elevations in the core. Westinghouse two-loop plants also typically have lower total ECCS flow rates; the total ECCS flow rate to the RCS with all trains running is approximately 19 gpm per fuel assembly. This is less than one half (1/2) of the flow rate used in the hot-leg break tests to define the bounding fiber limit. Fuel assembly debris capturing testing with flow rates at 15.5 gpm resulted in a head loss across the fuel that was approximately 40% less than tests with the same debris loads run with a flow rate of 44.7 gpm.

In addition, Westinghouse 2-Loop plants typically do not have debris-filtering bottom nozzles (DFBNs). Should debris be collected by the spacer grids of the fuel, the lack of the restrictive debris-filtering bottom nozzle is expected to provide for distributed debris beds within the fuel. PWROG FA testing has demonstrated that distributed debris beds are less limiting than debris beds that form at the fuel bottom nozzle and debris filtering grid. However, the PWROG UPI testing utilized a DFBN for additional conservatism, so it would remain applicable for a 2-loop plant that utilizes such a nozzle.

Therefore, Westinghouse 2 –Loop plants with their lower ECCS flow rates are less susceptible to development of head loss due to debris collection on fuel than are other PWR designs with higher ECCS flow rates.

8.0 Conclusion

The PWROG has performed 44 Westinghouse FA tests and 21 AREVA FA tests in the generic FA test program to define acceptable fiber limits that could be applied to the entire PWR fleet. The approach included large break LOCA conditions and both hot and cold leg break tests to resolve GSI-191 in-vessel effects. To achieve the goal of a generic fiber limit, the PWROG used conservative parameters compounded by conservative conditions to create a test program that would be applicable to all PWRs. The results of the program demonstrated that the generic FA test program included considerable conservatisms and resulted in an in-vessel fiber limit that would be very restrictive for the majority of the PWRs.

The generic FA test program resulted in a proposed fiber limit of 15 g / FA for all plants utilizing either AREVA or Westinghouse fuel, with some plants capable of utilizing a limit of 25 g/FA, depending on plant conditions. The program also provided bounding guidelines which plants can use to determine the maximum allowable fiber load that can reach the core and still not impede core cooling (Reference 3). The conservatisms utilized in performing the FA test program and developing proposed FA fiber limits ensure that plants have margin to these assumptions. This margin, based on the identified conservatisms, along with other plant margins, conservatisms, and compensatory measures, can be used by plants licensed under Reference 3 that later identify additional debris sources and need to address operability concerns.

To complement the Reference 3 guidelines, the PWROG presented a ‘path forward’ to the NRC staff in September 2011 that introduced a set of tools that utilities could use, either individually or in groups, that would provide specific FA testing to increase the allowable fiber load above the applicable in-vessel fiber limits established in Reference 3. These tools included utilizing and testing plant-specific groups (UPI, 3&4 loop, and CE plants), plant-specific flow rates, elevated temperatures, and delayed chemical precipitation to leverage HLSO conditions. In addition, FA scoping tests identified that the water source used in FA testing can have an influence on the ΔP result. The results of these water chemistry tests, combined with the proposed “tools” presented to the NRC staff in September 2011, may be used as the bases for a future PWROG effort to establish a more prototypical in-vessel evaluation program to determine more realistic debris limits that can be implemented by all PWROG members, rather than the limits defined in WCAP-16793-NP, Revision 2. This future program could be used by the PWROG membership to perform more plant specific/less generic assessments that will produce reasonable, realistic debris limits that are both acceptable to the plants, and also provide reasonable assurance of long term core cooling capabilities. Successful completion of these projects and others would likely support an increase in the in-vessel debris limits beyond those identified in Reference 3.

References

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10. Title 10, Code of Federal Regulations, Part 50, Section 46, Subsection (b), Paragraph (5), "Long-term cooling".