PWROG
PWR Owners Group

Program Management Office
1000 Westinghouse Drive, Suite 380
Cranberry Township, PA 16066

Project Number 694

May 25, 2012

OG-12-204

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 "Proposed Supplement to WCAP-16793-NP Revision 2," PA-SEE-0312 Revision 4

References:

1. WCAP-16793-NP, Revision 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," October 2011.

Dear Mr. Bailey:

Attachment 1 to this letter presents a concise summary of items for consideration in supporting the conclusion that the per-fuel-assembly fiber limit established in WCAP-16793-NP , Revision 2 (Reference 1) is a bounding number, based on bounding test conditions, and that plant-specific testing is required to increase this fiber limit. The main points included in Attachment 1 are as follows:

- A discussion of the conservatisms inherent in the fuel assembly testing that was performed in support of WCAP-16793-NP, Revision 2 (Reference 1), including the effects of those conservatisms on fleetwide generic per-fuel-assembly fiber limits.
- Also discussed in Attachment 1 is discussion regarding the consideration of break sizes (small versus large break).

It is the intent of the PWROG to use the information in Attachment 1 as the basis to supplement Reference 1 so as to both establish a higher per-fuel-assembly generic limit, and to allow individual plants or groups of plants to pursue higher limits based upon the use of fuel assembly test parameters for which a degree of excessive has been reduced.

D048

In addition, the PWROG is currently in the process of initiating a third-party independent review of the testing performed to establish the fuel fiber limits identified in Reference 1. The supplement to Reference 1 will also include the results of that review.

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
Westinghouse Electric Company LLC
1000 Westinghouse Drive, Suite 380
Cranberry Township, Pennsylvania 16066

If you have any questions, please do not hesitate to contact me at (704) 382-8619 or Mr. W. Anthony Nowinowski at (412) 374-6855.

Sincerely,

K. Nemit Approving for M. Dingler

Maurice E. Dingler, Chairman
PWR Owners Group

KJN:jtm:las

Attachment (1)

cc: PWROG Management Committee
PWROG Steering Committee
PWROG SEE Subcommittee
PWROG LSC Subcommittee
PWROG PMO
T.D. Croyle – Westinghouse
T.S. Andreychek – Westinghouse
J. T. Maruschak – Westinghouse
K. F. McNamee - Westinghouse
J. Rowley, U.S. NRC

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 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 long-term core cooling (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) and additional FA testing performed to establish a generic in-vessel fiber limit have been completed and are documented in WCAP-16793-NP, Revision 2 (Reference 3).

The generic testing approach included large break loss of coolant accident (LBLOCA) conditions and 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 a generic FA fiber limit, the PWROG used conservative parameters compounded by conservative conditions to create a test program that would be applicable to all PWRs. Based on the data from the generic testing, it is concluded that the generic test program was too conservative and resulted in an in-vessel fiber limit that was unrealistic and too restrictive for the majority of the operating PWR fleet.

To alleviate the burden of this unrealistic and excessively restrictive FA fiber limit on plants, the PWROG 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 (2 loop, 3&4 loop, CE plants), plant-specific flow rates, elevated temperatures, and delayed chemical precipitation to leverage hot leg switchover (HLSO) conditions.

In addition to the tool set, additional FA tests have brought into question the prototypicality of the water used in the Continuum Dynamics Incorporated (CDI) FA test facility. These recent FA tests indicate there may be additional, previously unrecognized, excessive conservatism in the CDI FA test results used to set the in-vessel fiber limits in Reference 3. The findings of these FA water tests resulted in a PWROG project to determine the impact of water chemistry of FA testing.

The following provides a summary of the actions related to resolution of GSI-191 in-vessel effects, the testing that defined the applicable in-vessel fiber limits for the entire PWR fleet, and PWROG programs designed to increase in-vessel fiber limits while maintaining 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 to post-LOCA 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) reaches a predetermined level, ECCS suction switches from injection from the RWST 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 results in reduced ECCS flow that lowers the head loss across the core and provides an alternate ECCS flow path to ensure LTCC.

2.1 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:

2.1.1 Conservatism: Ambient temperature

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

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. 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)

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

L	=	length of porous bed (ft)
μ	=	dynamic viscosity (lbf=sec/in^2)
κ	=	permeability (ft^2)

2.1.2 Conservatism: Constant flow rate

Hot-leg Break:
The maximum post-LOCA ECCS flow rate representative of a large 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; spill over flow in the other loops will return to the top of the core. Therefore, in addition to the flow that is still entering through the bottom of the core (because the available driving head is not exceeded), the core is also being cooled by coolant from the intact loops entering the top of the core.

In order to bound 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 both a water solid core and the shortest steam generator U-tubes. The maximum flow rate ensured the pressure differential (ΔP) due to fiber was calculated at the most limiting condition. The use of short steam generator U-tubes to establish a minimum driving head and a water-solid core provided for a conservatively low driving head. 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 values and actual steam generator tube heights will 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 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 boil-off flow rate of 3.0 gpm / FA. 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 fostering continued cooling of the core.

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

2.1.3 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 designfeaturesto promote uniform flow The promotion of uniform flow and uniform debris bed formation is a conservative assumption since only small variations in flow or FA orientation are required to promote the formation of multiple debris beds.

Note that non-uniform debris bed buildup was seen 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 build up that exceeds the limit on a single assembly would mean that another assembly would have less than the per-assembly limit. Analyses in Reference 3 indicate that the equivalent of only one FA needs to be open to remove core decay heat and assure LTCC.

2.1.4 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.

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; no settling of debris was allowed. The test fixture was also constructed so as to not allow any 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.

2.1.5 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). 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 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 as a surrogate representative of all chemical precipitate products. Tests and analyses performed by the PWROG and the NRC have shown that the WCAP 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. Further, this testing demonstrated that ALOOH surrogate made with high purity water was not as effective nor as stable as that made with tap water (as used in the FA test program). ALOOH surrogate is not representative of, but rather bounds, the chemical products and precipitates expected in most plants. The addition of the WCAP 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.

2.1.6 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.

Particulate (P)

The particulate is 10 microns in size, which 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".

Fiber (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.

Chemical Surrogate (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.

2.1.7 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.

Sensitivities on p:f were performed and it was found that a p:f of 1:1 was most the limiting, resulting in a conservatively high head loss upon the introduction of ALOOH for the limiting HL 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 lessens. Debris generation calculations and latent debris walkdowns have shown that particulate debris is generated in much larger quantities than fibrous debris, strongly indicating that the p:f ratio at the fuel will be greater than 1:1. For the cold-leg tests conducted at 3.0 gpm, a maximum core flow rate representative of early in time following a cold leg break, the limiting p:f ratio for testing was defined as 45:1. Since the metrics of debris transport following a LOCA are unknown, assuming the most limiting p:f determined via testing is conservative.

2.1.8 Conservatism: Absence of boiling

In the event 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 a total blockage would occur at the core inlet, the coolant will begin to boil. This would disrupt the blockages higher in the assembly and cause the coolant at the core inlet to be more turbulent. The increased turbulence at the core inlet would disrupt the blockage at the inlet, allowing flow to enter the core.
- 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 provides plants with a greater available driving head, which, in turn, allows them to withstand a greater head loss due to debris.

2.1.9 Conservatism: Absence of alternate flow paths

Many operating 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.

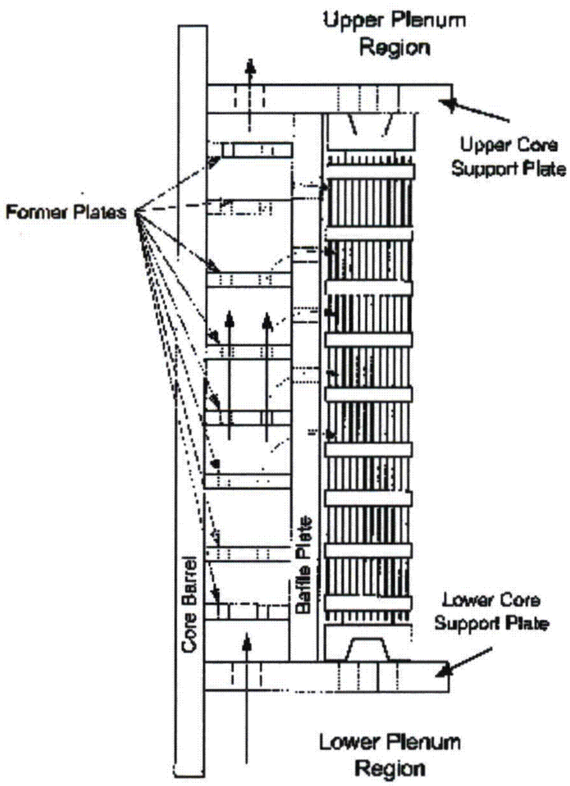

Figure 1- Alternate flow Paths

3.0 Fuel Assembly Testing

Initially, independent FA testing at separate facilities (Westinghouse/RTU, AREVA/CDI) showed that similar test results appear to be independent of FA type or test facility. WCAP-16793 Rev. 1 was issued based upon this testing.

Based on questions and 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 FA cross-test (AREVA FA at the Westinghouse RTU facility) was then performed. The results confirmed that there were performance differences observed between the two test facilities at certain conditions. Industry representatives and the NRC staff met with the NRC Commissioners and communicated this fact and industry committed 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 would be obtained from CDI and that testing at CDI would define the bounding fiber limit for the fleet.

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 operating fleet. It was recognized that additional testing would need to be conducted to quantify the inherent conservatisms in the test process.

The review of Reference2 and the proposed path forward - with testing of conservatisms inherent in the test method used - was presented to the NRC staff at a public meeting in March 2011. The parameters that were evaluated to provide conservatisms that could be tested 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 at this time; 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 it had been concluded earlier that the CDI test facility produced the most conservative result, 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**, supporting the earlier conclusion that the CDI test facility produced the most conservative result. Test **D** also demonstrated flow was able to pass through the core, even though the flow rate had to be reduced during the test. Therefore, Westinghouse fueled plants that have a driving head greater than or equal to the test **D** value, and which operate at conditions similar to test **D** conditions, can attain a higher in-vessel fiber limit. This result is similar to a test performed by AREVA with a p:f = 1:1 with 25 g of fiber / FA.

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 fiber

4.0 Current Fiber Load Limits

The generic FA test program concluded with a proposed fiber limit applicable to the operating 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, a test was conducted at CDI with Westinghouse fuel to evaluate the test facilities (Test 1-W-FPC-0811). This test used a loading of 25 g fiber/FA and demonstrated that flow was able to continue to enter the core even though the flow rate was reduced during the test. It is further noted that the reduced flow rate was in excess of that needed to match boil-off. Therefore, plants with 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[3].

[3] As noted previously, AREVA also conducted a test with a p:f = 1:1 with 25 g of fiber/ FA (14-FG-FPC) with similar results as obtained by Westinghouse. Thus, AREVA-fueled plants that meet certain conditions can also withstand up to 25 g fiber/FA.

5.0 Water 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 water used in the CDI and RTU test facilities. Three FA water tests were performed at the RTU test facility with the following results (see Figure 2):

- RTU tap water
- CDI tap water
- Deionized water

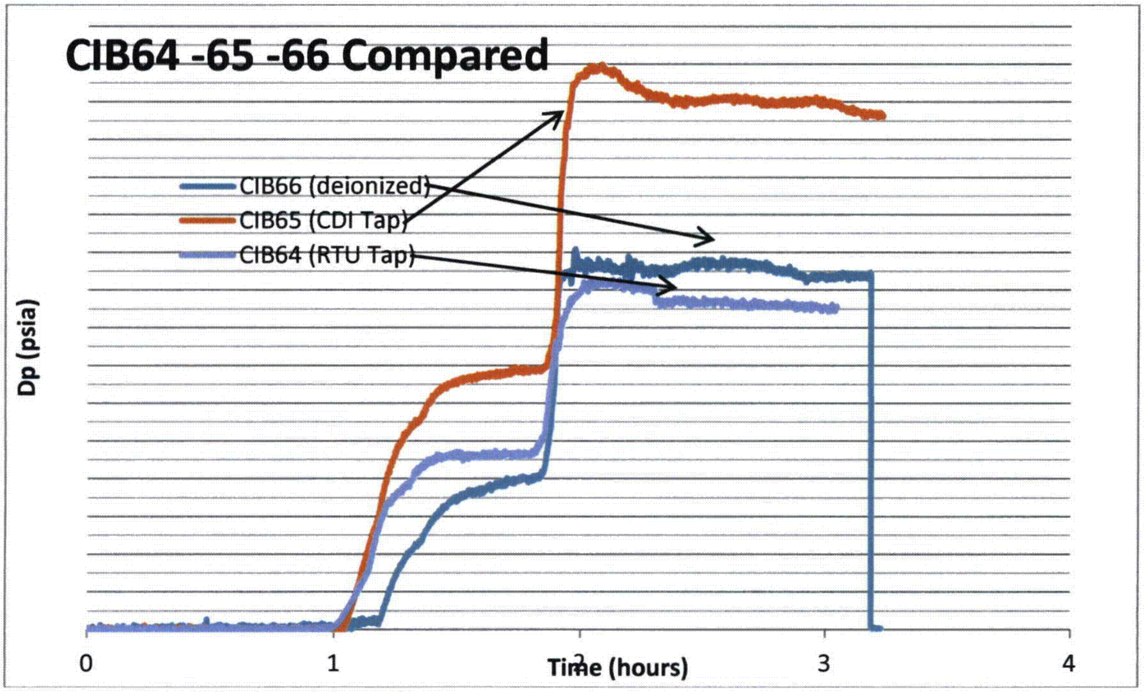

Figure 2 – PWROG Water Test Results

The conclusion of the 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 (implying that more fiber could be introduced before reaching the pressure drop limit), while the test performed with CDI tap water was near the available pressure drop limit. This new data indicates that differences in water type could cause the difference in FA test results from the two facilities, resulting in the definition of overly-conservative fiber limits. The PWROG has developed a project plan to further explore the impact of water chemistry on the maximum head loss values recorded in the FA testing conducted to support the in-vessel program.

Successful completion of the project would identify the overly-conservative test results from non-prototypical water used in CDI FA tests and will likely support an increase in the minimum in-vessel fiber limit to 25 g/FA for both Westinghouse and AREVA fuel.

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 contends that, for a given plant, all small break LOCAs (SBLOCAs) are no more limiting than the LBLOCA as LBLOCAs bound SBLOCAs 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 un-isolatable 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 Safety Evaluation (SE) on NEI 04-07 states that breaks of size 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 accident scenario, the RCS system pressure remains high following the initiation of the break. ECCS injection flow is drawn from the refueling water storage tank (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 fill. After core recovery and stable conditions are reached, operators 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 dump and release a significant discharge of RCS inventory into the containment building (i.e. steam generator inventory would discharge). 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. 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 (over 9 times smaller). As the break size decreases, so do the ZOIs; for a 6-inch diameter SBLOCA, the ZOI volume for NUKON is only 2,572 cubic feet (over 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 the 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 ECCS flow removing core decay heat exits the break. Since the 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 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 as 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 the 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 SBLOCA. Larger SBLOCAs more closely resemble LBLOCA, however debris transport would be significantly less since there is less debris to transport; downstream consequences would be significantly less since less debris is available to enter the ECCS in the SBLOCA scenario.

6.4 SBLOCA Considerations for 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 the SBLOCA scenario, the coolant would not be siphoned as 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 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 (R) can continue to increase until flow (v) through the core reaches the boiloff rate + 10%. (The 10% is added for conservatism with the intention of preventing the development of a two-phase state in the core.)

PWROG testing has demonstrated that the core inlet flow decreases as debris is added. Specifically, the following relationship has been defined:

$\Delta P = Rv^{1.6}$ **(Equation 2)**

Where ΔP = available driving head
R = debris load
v = flow

The following example makes the exponent of Equation 1 equal to one for conservatism in order to demonstrate the allowable debris load that could be generated in a SBLOCA and maintain LTCC.

- Assume $\Delta P_{available}$ = ΔP just *before* spillover = 15 psid
- Assume ΔP_{debris} = 15 psid when R_1 = 20 g/FA and v_1 = 44.7 gpm/FA
- Need to find out what R_2 = when v_2 decreases to boiloff +10% (assume 3.3 gpm/FA)
- $R_1(v_1) = R_2(v_2)$ (Equation 1 with exponent = 1 for conservatism)
- (20 g/FA)(44.7 gpm/FA) = (R_2 g/FA)(3.3 gpm/FA)
- R_2=270 g/FA

This example demonstrates a site could withstand a significantly larger amount of fiber (270 g/FA , an unreasonable amount of fiber generated in a SBLOCA) than defined by the FA testing that incorporated the LBLOCA conditions used to set the limit.

6.5 Summary

In summary, the SE on 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 of a SBLOCA, and, debris transport of a SBLOCA it must be concluded that SBLOCAs, for a given plant, are less limiting for GSI-191considerations in all respects to the LBLOCA on which the applicable fiber limits are based.

7.0 Conclusion

In total, the PWROG performed 44 Westinghouse FA tests plus 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 in the quest 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 was overly conservative and resulted in an in-vessel fiber limit that was both unrealistic and too restrictive for the majority of the operating PWRs.

The generic FA test program concluded with a proposed fiber limit of 15 g / FA for all plants utilizing either AREVA or Westinghouse fuel. The program also provides bounding guidelines with which plants can determine the maximum allowable fiber load that can reach the core and still not impede core cooling (Reference 3). 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, CE plants), plant-specific flow rates, elevated temperatures, and delayed chemical precipitation to leverage HLSO conditions.

In addition to the proposed set of tools available to the operating fleet, additional FA scoping tests have called into question the prototypicality of the water used in the CDI FA test facility and, consequently, the CDI FA test results used to set the in-vessel fiber limits have been determined to be highly conservative. The findings of these FA water tests resulted in a PWROG project to determine the impact of water chemistry of FA testing. The results of the water chemistry tests combined with the ‘tools’ presented to the NRC staff in September 2011 should be used by the PWROG membership to perform more plant specific/less generic testing that will produce reasonable fiber limits that are both attainable by the plants and provide reasonable assurance of long term core cooling capabilities. Successful completion of these projects and others will likely support an increase in the minimum in-vessel fiber limit beyond the 15 g of fiber / FA identified in Reference 3.

References

1. WCAP-16793-NP, Revision 0, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," June 2007.
2. WCAP-16793-NP, Revision 1, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," April 2009.
3. WCAP-16793-NP, Revision 2, "Evaluation of Long-Term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid," October 2011.
4. NRC Contract #JCN 3216, "Technical Letter Report on Evaluation of Chemical Effects; Studies on Precipitates Used in Strainer Head Loss Testing," January 30, 2008. [ADAMS Accession Number: ML080600223]
5. Revised Guidance for Review of Final Licensee Responses to Generic Letter 2004-02, "Potential Impact of Debris Blockages on Emergency Recirculation During Design Basis Accidents at Pressurized Water Reactors," March 2008. [ML080230112]
6. NEI-04-07 "PRESSURIZED WATER REACTOR SUMP PERFORMANCE EVALUATION METHODOLOGY, 'Volume 2 – Safety Evaluation by the Office of Nuclear Reactor Regulation Related to NRC Generic Letter 2004-02'", Revision 0, December 2004.
7. WCAP-17057-P, "GSI-191 Fuel Assembly Test Report for PWROG," September 2011.
8. WCAP-16530-NP-A, Revision 0, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," February 2006.
9. WCAP-16785-NP, Revision 0, "Evaluation of Additional Inputs to the WCAP-16530-NP Chemical Model," May 2007.