Long Term Core Cooling – In-Vessel Effects

Future Options to Move Forward

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1.0 Executive Summary

Generic Safety Issue 191 (GSI-191) (Reference 1) addresses a variety of concerns associated with the operation of the emergency core cooling system (ECCS) and the containment spray system (CSS) in the recirculation mode. GL 2004-02 (Reference 2) was issued to request utilities to address the effect of debris in the sump on long-term core cooling (LTCC). To address in-vessel effects, the industry issued WCAP-16793-NP, Revision 0 to demonstrate there is reasonable assurance that the LTCC requirements of 10 CFR 50.46 are satisfied in the event particulate, fibrous, and chemical products in the recirculating coolant are delivered from the containment sump to the core. This evaluation was intended to be applicable to fleet of PWRs, regardless of design.

Due to RAIs related to the work documented in WCAP-16793-NP, Revision 0, specifically related to fuel blockage in the presence of particulate, fibrous, and chemical debris, the Pressurized Water Reactor Owners Group (PWROG) undertook a program to perform fuel assembly (FA) testing. The program was generic in nature and assumed the presence of chemical precipitates along with particulate and fiber in a closed loop with a single FA at a single flow rate, to be bounding and applicable to all plants regardless of design (Westinghouse, Combustion Engineering [CE], or Babcock & Wilcox [B&W]), fuel vendor (Westinghouse or AREVA), NSSS type (2, 3, 4, loop plants), or insulation system (RMI, high fiber).

The test program was intentionally designed to be conservative and thus resulted in the definition of a bounding fiber limit of 15 g per FA applicable to all plants regardless of design (Westinghouse, Combustion Engineering [CE], or Babcock & Wilcox [B&W]), fuel vendor (Westinghouse or AREVA), NSSS type (2, 3, 4, loop plants), or insulation system (RMI, high fiber).

To move forward toward the resolution of GSI-191 in-vessel effects, the PWROG has considered development of a set of tools that a plant or group of plants can use to demonstrate compliance with the 15 g/FA limit and/or increase plants' limit beyond 15 g/FA. The course of action may include the development of plant or plant group specific analyses, evaluations, and/or testing. The tools are summarized here and discussed in the following sections. Other options may be available to increase the fiber limit however the tools presented below are seen as providing the most benefit to the PWROG membership.

1. Chemical precipitation delayed until after hot leg switchover
2. In-vessel particulate-to-fiber mass (P:F) ratio is greater than 1:1
3. Plant-specific flow rate evaluation
4. Alternate flow path evaluation
5. In-vessel hardware evaluation
6. Chemical effects production and type evaluation

1.1 Overview of Tools

Up to this point in time, the PWROG FA test program has focused on defining the bounding debris load based on conservative assumptions that would bound all plants irrespective of plant design or fuel type. This has now been accomplished with the establishment of the 15 g/FA bounding fiber limit. The development and utilization of the tools described herein is the next step in the process to resolve the in-vessel effects of debris in the ECCS.

The cost estimates associated with each tool are orders of magnitude for the development of new methods, analysis, and testing required for implementing the tools presented herein and do not include the cost of plant modifications, changes to EOPs, or revisions to other analyses of record (AOR) that may be impacted as a result of implementing a tool or set of tools. It is noted that tools 1, 3, and 6 all have the potential to require plant modifications, changes to EOPs, and changes to current AORs.

Other costs to consider, but which are not reflected in the cost estimates below, include those to be determined in any NEI programs that may be initiated to look at upstream effects - including debris generation, transport, and strainer bypass, all of which contribute to the downstream in-vessel fiber source term.

The basis for presenting the tools as a means to increase a plant's fiber limit is provided below. The detailed discussions of these tools presented in Sections 2.2 through 2.8 are examples of how the tools may be utilized by a specific plant or group and are not meant to exclude any plant or group from utilizing any of the tools. These tools are available to all plants to pick and choose from to find a combination that meets their needs. The greatest benefits to be gained are from using greatest combinations of tools.

1. **Demonstrating chemical precipitation does not start until after hot leg switchover (HLSO)**

   Description: It may be possible for all plants to demonstrate that chemical precipitates do not form until after HLSO when core flows have been reduced. It has been repeatedly demonstrated in FA testing that a decrease in flow rate corresponds to a decrease in overall head loss. If no chemical precipitation occurs until HLSO switchover is complete then the combination of reduced flow after HLSO and the absence of chemical precipitation will allow an increase in the fiber limit.

   Allowable fiber load benefit: The PWROG test program has data that indicates this tool has the potential to result in an allowable fiber load of 65 g fiber/FA. The basis for this potential fiber limit increase is as follows:

   - A PWROG FA test with HLSO was performed with 65 grams of fiber at 130°F.
   - The reduced flow following HLSO, together with delayed chemical precipitation or no chemical precipitation, will result in a decrease in the in the head loss across the core due to debris.
   - A decrease in head loss provides for an increase in the fiber limit.

   Cost estimate: $500K based on chemical effects testing and analysis and FA testing to define a revised fiber limit.

   Implementation note: Successful implementation of this tool will show chemical precipitates were delayed or not observed prior to HLSO. The technical basis will involve chemical analysis and testing to demonstrate that chemical precipitates will not form until after HLSO. Potential changes to HLSO time through plant safety analysis, Technical Specification (TS) changes, changes to EOPs, and changes or additions to existing plant hardware are possible. This tool is not applicable for plants with certain ECCS alignments (e.g., back-and-forth full-flow ECCS cold-leg injection after HLSO). Plants choosing to use an alternate chemical surrogate will be required to address the chemical effects PIRT Panel.

2. Demonstrating the particulate-to-fiber (p:f) mass ratio reaching the core is greater than 1:1

Description: FA testing performed by the PWROG showed that p:f ratios greater than the limiting 1:1 resulted in an increase in the allowable fiber limit, and that large amounts of fiber will not prevent LTCC at high particulate to fiber (p:f) ratios.

Allowable fiber load benefit: It is anticipated that this program will demonstrate that a fiber load of at least 65g fiber/FA does not pose a risk for impeding LTCC for p:f ratios greater than 1:1. This estimate is based upon observations from the PWROG FA test program. The basis for this potential fiber limit increase is as follows:

- The PWROG performed many FA tests with p:f ratios greater than 1:1 that showed acceptable results with fiber loads greater than 50 g.
- Tests at p:f ratios > 10:1 demonstrate that up to 150g fiber/FA is achievable.

Cost estimate: $200K based on plant specific upstream debris and strainer bypass testing and FA testing.
Implementation note: Successful implementation of this tool will require plants to provide justification of a particulate to fiber ratio greater than 1:1.

3. Testing plant-specific ECCS flow less than the 44.7 gpm/FA value tested

Description: FA testing performed by the PWROG showed that head loss due to debris is reduced as the flow rate is reduced. This tool will use this relationship to increase allowable fiber load for plants with flow rates less than tested flow rates.

Allowable fiber load benefit: A fiber limit increase up to 50 g is potentially achievable. The fiber limit increase is directly proportional to the magnitude of decrease in flow. The basis for this potential fiber limit increase is as follows:

- The PWROG performed a number of FA tests at flow rates less than the 44.7 gpm flow rate used to define the limiting condition, with head loss results below that of the limiting condition. Specifically, the PWROG demonstrated at a flow rate of 15.5 GPM, 50 g fiber/FA would be allowable.
- A decrease in head loss provides for an increase in the fiber limit.

Cost estimate: $200K based on plant-specific ECCS cold-leg flow analysis and FA testing.

Implementation note: Successful implementation of this tool will require plants to meet ECCS cold-leg flow rates no greater than 60% of the value used to define the limiting condition. Although Combustion Engineering and Westinghouse two-loop plants have ECCS cold-leg flow rates significantly less than that used to define the limiting condition, any plant whose ECCS cold-leg flow is less than that tested to define the limiting fibrous debris load could implement this tool.

4. Evaluating alternate flow paths

Description: Upflow plants have baffle holes (from 2 inches to 2.75 inches in diameter, located circumferentially around the core at various heights above the core plate) that are magnitudes larger than the flow paths provided by the fuel bottom nozzle and protective grids used in the FA tests to define the applicable fiber limit. Due to the small size of the bypass debris, blockage of these alternate flow paths is unlikely. Plants that do not have an upflow design do not have these baffle holes, and thereby those plants would not benefit from this approach.

Allowable fiber load benefit: A potential fiber limit increase of >100 g is based the assumption that the alternate flow paths cannot be blocked ensuring cooling flow to the core. The basis for this potential fiber limit increase is as follows:

- The amount of debris entering the vessel would be inconsequential if an assured source of water is available to the core. Reasonable assurance of LTCC would be independent of blockage of the bottom of the fuel.

Cost estimate: $500K based on the development of new methods to analyze and test alternate flow paths.

Implementation note: Successful implementation of this tool will require plants to provide justification of the viability of the flow path. Currently, the development of alternative flow paths is applicable to B&W and certain Westinghouse plant designs that have the upflow barrel design and baffle holes.

5. Evaluating plant specific current hardware

Description: PWROG FA testing used fuel assemblies that resulted in conservative pressure drops that could be applied generically to the PWR fleet. Fuel hardware other than that tested for the limiting condition may produce lower head loss.

Allowable fiber load benefit: A potential fiber limit increase of >50 g is based upon observations from the PWROG FA test program. The basis for this potential fiber limit increase is as follows:

- The limiting condition of 15 g /FA was obtained with the Westinghouse DFBN/P-GRID and the AREVA FUELGUARD
- PWROG testing showed that plants with the Combustion Engineering Guardian Grid®[1] or without a protective grid (Westinghouse two-loop plants) would be able to tolerate considerably higher fiber loads.

Cost estimate: $100K based on plant specific FA testing.

Implementation note: Successful implementation of this tool will require plants to perform FA tests. Currently, plants utilizing CE Guardian Grid fuel and Westinghouse two-loop plants with no protective grid would benefit from testing their current hardware.

[1] Guardian Grid is a registered trademark of Westinghouse LLC

6. Chemical effects testing

Description: Aluminum oxyhyroxide (AlOOH) was chosen as the chemical surrogate due to its conservative head loss properties. The use of the AlOOH chemical surrogate in FA testing has been overly-conservative for many plants whose actual chemical debris load may not be aluminum-based or those whose plant specific chemical loads and conditions may be less limiting. The basis for this option lies in numerous studies and tests performed for the PWROG and Industry.

Allowable fiber load benefit: A fiber limit increase of up to 50 g is possible, based upon observations from the PWROG and industry chemical effects test programs. The basis for this potential fiber limit increase is as follows:

- PWROG AlOOH surrogate is not representative of most post-LOCA chemical production.
- PWROG studies and tests related to post-LOCA chemical production indicate chemical production can be reduced via alternate buffers.
- Chemical testing and analysis may show a delay in chemical precipitation or possibly no chemical production/precipitation.
- Chemical testing and analysis may provide an alternate surrogate to ALOOH.

Cost estimate: $200K based on specific chemistry effects analysis and FA testing.

Implementation note: Successful implementation of this tool will show chemical precipitates were decreased/delayed/not observed. Plants choosing to use an alternate chemical surrogate will be required to address the chemical effects PIRT Panel (See NUREG/CR-6988, and NUREG/CR-1918)

1.2 Application of Tools

Once the appropriate set of tools is developed, a plant or group of plants can utilize these tools individually or in combinations to achieve the desired outcome of demonstrating compliance with the 15 g/FA fiber limit or to increase the applicable fiber limit.

It is the purpose of this paper to help utilities define what tool or combination of tools should be developed by the PWROG to best suit the resolution of in-vessel effects. Each of the tools noted above will be developed based on its plant or group specific applicability. Quantification of the benefit of each tool can only be obtained through the development and application of each tool. Plant or group specific testing is required since no testing, analyses, or evaluations have been performed at intermediate conditions (15.5 gpm < flowrate <44.7 gpm) that can be referenced to define a specific increase in the available fiber limit.

2.0 Plant Specific Applicability

2.1 Overview

A benefit/cost table is presented for each specific plant type in the following sections. The tools referred to are described in the Executive Summary section of this document. Each tool is rated on its own merit or in combination with other tools that may be implemented in conjunction with or simultaneous to each other. The potential fiber limit increase is in addition to the current 15 g/FA limit.

It is noted that both the potential fiber limit increase and the potential costs associated with deploying a particular tool or set of tools is only estimated. The PWROG may allocate resources to develop tools based on the perceived benefit to members and the members' willingness to support the development of tools to resolve the in-vessel effects portion of GSI-191.

The information in each benefit/cost table is for order-of-magnitude purposes only, and the actual costs must be evaluated in detail. It is anticipated that up to three FA tests at $35k each will be required where FA testing is noted in the tables. Plant specific chemical analysis is expected to cost as much as $200K to determine plant specific and alternate chemical surrogates as well as to make recommendations on buffering agents that may reduce overall chemical debris loads. Additional costs for development of new methods, analysis techniques, or facilities may be as high $500K or more for the development and licensing.

Each option for a given plant application reflects a potential increase in the applicable fiber limit and the potential cost (Low, Medium, and High in magnitude) to develop and implement the tool. Costs (in $) should be considered as a basis for implementing a tool or tools.

2.2 Combustion Engineering (CE) Plants

The configuration of CE plants is such that the post-accident recirculation flow rates are significantly lower (<1/3) than those tested to define the bounding fiber limit. PWROG FA testing has shown that lower flow rates across a debris bed will result in lower pressure drops. In addition to lower flow rates, a number of CE plants employ the CE Guardian Grid® fuel filter. In the PWROG FA testing to define the limiting hardware, the Guardian Grid® fuel filter was shown to produce a lower FA head loss than the hardware tested. For CE plants, plant specific tests with a combination of options 3 (lower recirculation flow rates) and 5 (fuel inlet hardware) would increase the applicable fiber limit for CE plants over the bounding 15 g/FA fiber limit.

Tools:

3 Testing plant specific ECCS flow less than the 44.7 gpm/FA tested

CE plants have post-LOCA ECCS flow significantly lower than tested and therefore have a high probability of increasing their fiber limit based on PWROG FA test observations.

5 Evaluating plant specific current hardware

CE plants have different hardware than tested and therefore have a high probability of increasing their fiber limit based on PWROG FA test observations.

OPTION	FIBER - Potential	COST – Potential	COST ($)
3 & 5 (combination)	Limit increase (>>50g)	Medium – ECCS evaluation and FA tests	200K

The combination of tools listed above is for illustrating the use of the tools. Any tool can be used on its own or in combination with other tools to suit the needs of the plants. For example, participation in the Chemical Effects evaluation described in Section 2.7 and utilizing reduced flow after HLSO may lead to further increases in the applicable fiber limit beyond those realized by plant specific flow rates and hardware.

Note that CE plants with AREVA fuel are addressed by PA-SEE-0781.

2.3 Babcock and Wilcox (B&W) Plants and Upflow Westinghouse Plants

The configuration of B&W plants is such that they do not enter into a post-accident hot-leg switch over (HLSO) flow. At a specified time after the accident (per EOP), the plant moves to a hot-leg let down configuration instead of hot-leg, simultaneous hot-leg/cold-leg, or back and forth hot-leg/cold-leg flow. For B&W plants and those applicable Westinghouse plants that have upflow baffle designs, option 4 (Evaluating alternate flow paths) presents a tool that can be developed to demonstrate assured LTCC. Analysis of the flow through the large baffle holes (from 2 inches to 2.75 inches in diameter, circumferentially located around the core at various heights above the core plate) would demonstrate that adequate flow is available to ensure LTCC. In addition to the analysis of the baffle flow holes, testing could be performed to demonstrate core cooling is maintained due to cross flow in the FAs. A combination of analysis and testing would provide defense in depth and support the feasibility that the baffle holes would supply adequate flow in all debris load scenarios to assure LTCC.

Tools:

4 Evaluating alternate flow paths

B&W and applicable Westinghouse plants that have baffle holes and therefore have a high probability of increasing their fiber limit.

OPTION	FIBER - potential	COST - Potential	COST ($)
4	Limit increase (>100g)	High – Development of alternate flow analysis and testing	>500K

In addition to the option suggested above, participation in the Chemical Effects evaluation described in Section 2.7 and utilizing reduced flow after HLSO may lead to further increases in the applicable fiber limit beyond those realized by plant specific flow rates and hardware.

2.4 Westinghouse Two-Loop Plants

Westinghouse two-loop plants are unique in that they have no debris-filtering bottom nozzles, and their post-LOCA recirculation configuration is generally simultaneous upper plenum injection (UPI) and cold-leg injection. Two-loop plants typically have lower ECCS RCS flow rates (total ECCS RCS flow rate with all trains running is ~28 gpm per assembly) than that tested to define the bounding fiber limit. PWROG FA testing indicated that distributed debris beds are less limiting than debris beds that form at the fuel bottom nozzle and debris filtering grid.

Toolss:

3 Testing plant specific ECCS flow less than 44.7 gpm/FA tested
   Westinghouse two-loop plants have post-LOCA ECCS flow significantly lower than tested and therefore have a high probability of increasing their fiber limit based on PWROG FA test observations.

5 Evaluating plant specific current hardware
   Westinghouse two-loop plants do not have DFBN/P-grid combination and therefore have a high probability of increasing their fiber limit based on PWROG FA test observations.

Note: The combination of tools listed below is for illustrating the use of the tools. Any tool can be used on its own or in combination with other tools to suit the needs of the plants.

OPTION	FIBER - Potential	COST – Potential	COST ($)
3 & 5 (combination)	Limit increase (>>50g)	Medium – ECCS evaluation and FA tests	200K

For two-loop plants, the absence of a debris-filtering bottom nozzle/grid and upper plenum injection lend themselves to an increased applicable fiber limit. For two-loop plants, a combination of options 3 (lower recirculation flow rates) and 5 (fuel inlet hardware) would increase the applicable fiber limit for two-loop plants over the bounding 15 g/FA fiber limit.

2.5 Westinghouse Three-Loop Plants

The configuration of Westinghouse three-loop plants is such that the post-LOCA sump recirculation alignment provides ECCS flow to the cold legs. After HLSO, the configuration varies from plant to plant, for example, some plants maintain HL-only injection, some perform simultaneous HL/CL injection, and others switch back and forth between HL and CL flow per the plant's emergency operating procedures (EOPs). Other post-HLSO ECCS configurations may be applicable.

Tools:

1 Demonstrating chemical precipitation does not start until after hot leg switchover (HLSO)
   This option has the potential to increase the applicable fiber limit based on observation from PWROG FA testing.

2 Demonstrating the particulate-to-fiber (p:f) mass ratio reaching the core is greater than 1:1
   This option has the potential to increase the applicable fiber limit based on observation from PWROG FA testing.

3 Testing plant specific ECCS flow less than 44.7 gpm/FA tested
   Three-loop plants have post-LOCA ECCS flow comparable to that tested. Using this option alone, the plant would have to justify flow rates at least 40% less than tested to achieve a benefit.

4 Evaluating alternate flow paths
   For those applicable upflow three-loop plants, this option provides the potential of a large increase in the applicable fiber limit.

5 Evaluating plant specific current hardware
   Three-loop plants that have different hardware than tested may increase their applicable fiber limit based on PWROG FA test observations.

6 Chemical effects tests
   Chemical effects testing has the potential to increase the applicable fiber limit by demonstrating post-LOCA chemicals differ than tested (ALOOH), delayed chemical precipitation, or no chemical precipitation.

Note: The combination of tools listed below is for illustrating the use of the tools. Any tool can be used on its own or in combination with other tools to suit the needs of the plants.

OPTION	POTENTIAL - Fiber	COST - Potential	COST ($)
1 & 6 (combination)	Limit increase (>50g)	High – Chemistry testing, plant analysis, FA testing up to 3 FA tests.	500k
2	Limit increase (≥50g)	Medium – Upstream evaluation	200k
3	Limit increase (<25g)	Medium – ECCS evaluation + up to 3 FA tests	200k
4	Limit increase (>100)	High – Development of alternate flow path analysis and testing	>500k
5	Limit increase (<25g)	Low – Perform FA tests	100k
3 & 5 (combination)	Limit increase (=25g)	Medium – ECCS evaluation + up to 3 FA tests	200k

For three-loop plants, plant-specific tests with option 5 (fuel inlet hardware) for those whose fuel inlet hardware differs from that tested may increase the applicable fiber limit for three-loop plants over the bounding 15 g/FA fiber limit.

It may be possible for certain three-loop plants to demonstrate that chemical precipitates do not form until after HLSO, provided that adequate technical basis can be established (Option 1). This technical basis will involve plant-specific chemical analysis and testing, potential changes to HLSO time through plant safety analysis, Technical Specification (TS) changes, changes to EOPs, and changes or additions to existing plant hardware.

This option could be beneficial to three-loop plants that can demonstrate that post-LOCA conditions are controllable to inhibit the production of chemical precipitates until after HLSO occurs and those that maintain simultaneous (providing the CL flow is reduced) or HL-only ECCS injection after HLSO, since the benefit of this option is the reduced CL flow rate prior to the generation of chemical precipitates along with ECCS flow to the top of the core (other post-HLSO ECCS configurations may be applicable). The technical basis that shows that chemical precipitates do not form until after HLSO, along with plant specific testing, would increase the applicable fiber limit for three-loop plants over the bounding 15 g/FA fiber limit.

Option 1 would not be beneficial to three-loop plants that perform back and forth full flow ECCS injection after HLSO, since the benefit of the reduced CL flow rate after the generation of chemical precipitates would not be available.

Option 2 may be considered since PWROG FA testing has shown that large amounts of fiber will not prevent LTCC at high particulate to fiber (p:f) ratios. Although the allowable fiber load could increase substantially, option 2 presents both technical and licensing challenges since current upstream evaluations have assumed the maximum debris loads. Revised debris generation, transportation, strainer bypass, and settling evaluations would likely be necessary to demonstrate a p:f ratio greater than 1:1 to increase the applicable fiber limit for three-loop plants over the bounding 15 g/FA fiber limit.

Most three-loop plants may have RCS recirculation flow rates (total ECCS RCS flow rate with all trains running is ~42 gpm/FA) comparable to that used in the PWROG FA test program. Option 3 on its own is viable if the ECCS RCS flow rate is ≤60% of the flow rate tested. Currently, ECCS cold-leg flow rates for three-loop plants are nominally the same as that tested in the PWROG FA program. To use option 3 alone as a means to decrease its fiber load, the plant would have to demonstrate that the ECCS cold-leg core flow rate is no greater than 60% of that tested or that it can tolerate lower (≤60%) ECCS cold-leg flow rates than found in the plant's current ECCS configuration to receive a benefit from this option. This demonstration may require plant-specific evaluation of the ECCS system at reduced flow rates and may require changes to the plant's EOPs and possible changes to the plant's ECCS configuration and safety analyses. Option 3 could also involve the development of water management techniques and evaluation. Demonstrating an RCS cold-leg flow rate no greater than 60% of the tested flow rate would increase the applicable fiber limit for three-loop plants over the bounding 15 g/FA fiber limit.

Option 4 may be considered by upflow plants with baffle holes. In addition to the analysis of the baffle flow holes, testing must be developed to demonstrate core cooling is maintained due to cross flow in the FAs. A combination of analysis and testing would provide defense in depth and support the feasibility that the baffle holes would supply adequate flow in all debris load scenarios to assure LTCC. Demonstrating adequate alternate flow to maintain LTCC could possibly eliminate the current 15 g/FA fiber limit.

Success for three-loop plants using tools 1 and 6 would require demonstration that precipitates do not form before hot leg switchover or to utilize other assumptions on chemical effects would require plants to perform specific chemical effects testing and may require plants to address the chemical effects PIRT Panel (References 3 and 4). Implementation would likely involve revisiting various safety analyses of record and possible EOP and plant modifications. Demonstrating a p:f ratio greater than 1:1 has potential for large improvement, but the technical and licensing challenges may result in a reduced probability of gaining an increase. A significant ECCS flow rate reduction (>40%) would be necessary to provide a benefit. A flow reduction of the magnitude required would likely involve revisiting various safety analyses of record and possible EOP and plant modifications. Successful implementation of alternate flow paths will require plants to provide justification of the analysis methods and address regulatory concerns.

2.6 Westinghouse Four-Loop Plants

The configuration of Westinghouse four-loop plants is such that the post-LOCA sump recirculation alignment provides ECCS flow to the cold legs. After HLSO, the configuration varies from plant to plant, for example, some plants maintain HL-only injection, some perform simultaneous HL/CL injection, and others switch back and forth between HL and CL flow per the plant's emergency operating procedures (EOPs). Other post-HLSO ECCS configurations may be applicable.

Tools:

1 Demonstrating chemical precipitation does not start until after hot leg switchover (HLSO)
   This option has the potential to increase the applicable fiber limit based on observation from PWROG FA testing.
2 Demonstrating the particulate-to-fiber (p:f) mass ratio reaching the core is greater than 1:1
   This option has the potential to increase the applicable fiber limit based on observation from PWROG FA testing.
3 Testing plant specific ECCS flow less than 44.7 gpm/FA tested
   Four-loop plants have post-LOCA ECCS flow comparable to that tested. Using this option alone the plant would have to justify flow rates at least 40% less than tested to achieve a benefit.
4 Evaluating alternate flow paths
   For those applicable upflow four-loop plants, this option provides the potential of a large increase in the applicable fiber limit.
5 Evaluating plant specific current hardware
   Four-loop plants that have different hardware than tested may increase their applicable fiber limit based on PWROG FA test observations.
6 Chemical effects tests
   Chemical effects testing has the potential to increase the applicable fiber limit by demonstrating post-LOCA chemicals differ than tested (ALOOH), delayed chemical precipitation, or no chemical precipitation.

Note: The combination of tools listed below is for illustrating the use of the tools. Any tool can be used on its own or in combination with other tools to suit the plants needs.

OPTION	POTENTIAL - Fiber	COST - Potential	COST ($)
1 & 6 (combination)	Limit increase (>50g)	High – Chemistry testing, plant analysis, FA testing up to 3 FA tests.	500k
2	Limit increase (≥50g)	Medium – Upstream evaluation	200k
3	Limit increase (<25g)	Medium – ECCS evaluation + up to 3 FA tests	200k
4	Limit increase (>100)	High – Development of alternate flow path analysis and testing	>500k
5	Limit increase (<25g)	Low – Perform FA tests	100k
3 & 5 (combination)	Limit increase (=25g)	Medium – ECCS evaluation + up to 3 FA tests	200k

For four-loop plants, plant-specific tests with option 5 (fuel inlet hardware) for those whose fuel inlet hardware differs from that tested may increase the applicable fiber limit for four-loop plants over the bounding 15 g/FA fiber limit.

It may be possible for certain four-loop plants to demonstrate that chemical precipitates do not form until after HLSO, provided that adequate technical basis can be established (Option 1). This technical basis will involve plant-specific chemical analysis and testing, potential changes to HLSO time through plant safety analysis, Technical Specification (TS) changes, changes to EOPs, and changes or additions to existing plant hardware.

This option could be beneficial to four-loop plants that can demonstrate that post-LOCA conditions are controllable to inhibit the production of chemical precipitates until after HLSO occurs and those that maintain simultaneous (providing the CL flow is reduced) or HL-only ECCS injection after HLSO, since the benefit of this option is the reduced CL flow rate prior to the generation of chemical precipitates along with ECCS flow to the top of the core (other post-HLSO ECCS configurations may be applicable). The technical basis that shows that chemical precipitates do not form until after HLSO, along with plant specific testing, would increase the applicable fiber limit for four-loop plants over the bounding 15 g/FA fiber limit.

Option 1 would not be beneficial to four-loop plants that perform back-and-forth full-flow ECCS injection after HLSO, since the benefit of the reduced CL flow rate after the generation of chemical precipitates would not be realized.

Option 2 may be considered since PWROG FA testing has shown that large amounts of fiber will not prevent LTCC at high particulate to fiber (p:f) ratios. Although the allowable fiber load could increase substantially, option 2 presents both technical and licensing challenges since current upstream evaluations have assumed the maximum debris loads. Revised debris generation, transportation, strainer bypass, and settling evaluations would likely be necessary to demonstrate a p:f ratio greater than 1:1 to increase the applicable fiber limit for four-loop plants over the bounding 15 g/FA fiber limit.

Most four-loop plants may have RCS recirculation flow rates (total ECCS RCS flow rate with all trains running is ~45 gpm/FA) comparable to that used in the PWROG FA test program. Option 3 on its own is viable if the ECCS RCS flow rate is ≤60% of the flow rate tested. Currently, ECCS cold-leg flow rates for four-loop plants are nominally the same as that tested in the PWROG FA program. To use option 3 alone as a means to decrease its fiber load, the plant would have to demonstrate that the ECCS cold-leg flow rate is no greater than 60% of that tested or that it can tolerate lower (≤60%) ECCS cold-leg flow rates than found in the plant's current ECCS configuration to receive a benefit from this option. This demonstration may require plant-specific evaluation of the ECCS system at reduced flow rates and may require changes to the plant's EOPs and possible changes to the plant's ECCS configuration and safety analyses. Option 3 may also involve the development of water management techniques and evaluation. Demonstrating an RCS cold-leg flow rate no greater than 60% of the tested flow rate would increase the applicable fiber limit for four-loop plants over the bounding 15 g/FA fiber limit.

Option 4 may be considered by upflow plants with baffle holes. In addition to the analysis of the baffle flow holes, testing must be developed to demonstrate core cooling is maintained due to cross flow in the FAs. A combination of analysis testing would provide defense in depth and support the feasibility that the baffle holes would supply adequate flow in all debris load scenarios to assure LTCC. Demonstrating adequate alternate flow to maintain LTCC could possibly eliminate the current 15 g/FA fiber limit.

Success for four-loop plants using tools 1 and 6 would require demonstration that precipitates do not form before hot leg switchover or to utilize other assumptions on chemical effects would require plants to perform specific chemical effects testing and may require plants to address the chemical effects PIRT Panel (References 3 and 4). Implementation would likely involve revisiting various safety analyses of record and possible EOP and plant modifications. Demonstrating a p:f ratio greater than 1:1 has potential for large improvement, but the technical and licensing challenges may result in a reduced probability of gaining an increase. A significant ECCS flow rate reduction (>40%) would be necessary to provide a benefit. A flow reduction of the magnitude required would likely involve revisiting various safety analyses of record and possible EOP and plant modifications. Successful implementation of alternate flow paths will require plants to provide justification of the analysis methods and address regulatory concerns.

2.7 Chemical effects

The use of the aluminum oxyhydroxide (AlOOH) chemical surrogate in FA testing would be overly- conservative for many plants whose actual chemical debris load may not be aluminum-based, or those whose plant specific conditions may be less limiting. Plant specific bench top or small-scale testing on plant specific materials and conditions can be used to define the plant specific chemicals species to use in FA testing. The PWROG sponsored chemical effects programs to determine the plant specific chemical load and to identify both conservatisms in the generic chemical model and suitable buffering agents to reduce precipitate generation under post-accident conditions while maintaining comparability to those buffers currently in use.

WCAP-16785-NP (Reference 6) identifies conservatisms in the generic chemical model, which could be addressed through the inclusion of more plant specific inputs. The conservatisms expected to provide the greatest benefit in precipitate reduction were selected by comparing the Integrated Chemical Effects Test (ICET) program (Reference 5) results to the model predictions using ICET conditions. Based on this comparison, the areas chosen for testing were silicate and phosphate inhibition of aluminum corrosion, the variability in corrosion rates between aluminum alloys, and the solubility of key precipitates. Solubility testing of the sodium aluminum silicate (NAS) and ALOOH precipitates demonstrated aluminum and silicon concentrations at which the precipitates remained soluble for the range of temperature and chemistry conditions tested.

The calcium phosphate precipitate was confirmed to be insoluble even at low concentrations over the range of temperature and pH evaluated. Silicate and phosphate inhibition was shown with all buffers. The effects of silicate and phosphate inhibition are applicable to both submerged and non-submerged aluminum metal. Both silicate and phosphate form conversion coatings (i.e., protective silicate or aluminum phosphate) that impart corrosion resistance.

Silicate and phosphate inhibition of aluminum corrosion was found at all temperatures in the range of 140°F to 200°F. Some conditions were extendable to ambient conditions. The solubility limit of ALOOH was noted at 40 ppm aluminum and valid at temperatures between 140°F and 200°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.

Sodium aluminum silicate (NAS) is soluble in trisodium phosphate-buffered solutions at defined conditions. Silicate and phosphate should be treated as insoluble in sodium hydroxide, sodium tetraborate and sodium metaborate buffered solutions. NAS is the dominant aluminum-based chemical product produced. Calcium phosphate should be treated as insoluble in trisodium phosphate buffered solutions.

WCAP-16596-NP (Reference 7) 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).

Sodium tetraborate and sodium metaborate buffers were determined from the test phases to be the most comparable alternatives to TSP and NaOH. Sodium tetraborate was recommended as the best alternative to TSP and sodium metaborate in solution form was identified as a suitable replacement for NaOH solution. The testing confirmed that TSP is an excellent buffering agent for plants with a low loading of calcium-bearing materials (calcium silicate insulation).

Tools:

6 Chemical effects tests

Chemical effects testing has the potential to increase the applicable fiber limit by demonstrating post-LOCA chemicals different than tested (AlOOH), delayed chemical precipitation, or no chemical precipitation.

OPTION	FIBER – Potential	COST - Potential	COST
6	Limit increase(>100g)	Medium – Chemical effects testing to address specific buffers, insulation types, and chemical surrogates	200K

Evaluation of specific chemical species to reduce chemical production and precipitation is a viable option for plants to increase their applicable fiber limit. It has been shown in sump strainer and FA testing that a small amount of the chemical surrogate ALOOH can result in large increases in head loss. Bench top testing has shown that sodium aluminum silicate (NAS) will form more readily than ALOOH, and NAS was also found to be less limiting than ALOOH in terms of pressure drop. It is likely that the integrated tests would involve the staged production of a more realistic chemical surrogates which could be used in FA testing.

Chemical analysis and evaluation includes:

- Review of buffers, insulation type, debris quantities, temperatures, flows, etc., related to GSI-191
- Identify conservatisms in the analysis that could be removed in a future integrated test
- Development of an integrated-effects test plan that would remove conservatisms
- Analysis of results and reporting recommendations

Pursuing alternate chemical species to reduce chemical production and precipitation may require the plants to address the regulator's evaluation of 41 chemical effects PIRT items (References 3 and 4).

NOTE: Using plant specific chemical surrogates in FA testing does not guarantee that improved margins will be observed.

Insulation Types

The dominant RCS insulation types used in containments include reflective metal insulation (RMI) and jacketed fiber (Nukon®[2], Thermal-Wrap®[3], Kaowool®[4], etc). These and other insulations such as calcium silicate (Calsil) and microporous insulations should be considered when addressing chemical effects.

As noted in Section 2.7, the choice of buffering agents can reduce the amount and types of precipitates formed in the post-LOCA sump when considering dominant insulation types.

For plants that have Nukon® and Thermal-Wrap® as a dominant fiber, post-LOCA conditions can result in high amounts of dissolved aluminum and silicon; both NaTB and TSP were rated 'good' with respect to precipitate generation, while plants with high calcium silicate loads would benefit from NaTB as the buffer.

[2] Nukon is a registered trade mark of Performance Contracting Incorporated
[3] Thermal-Wrap is a registered trademark of Cabot Corporation
[4] Kaowool is a registered trademark of Thermal Ceramics

2.8 Fuel Assembly Testing

For most of the tools described herein, FA testing will be required to demonstrate an increase in the applicable fiber limit for in-vessel effects. Previous PWROG FA test programs were conducted at the Westinghouse Research and Technology Unit (RTU) for Westinghouse fuel components and at Continuum Dynamics Incorporated (CDI) for AREVA fuel components.

Note that all FA testing options could include test protocols that call for elevated temperatures, buffering agents, plant specific chemical species, debris loads, flow rates, hardware, etc., as required.

Tools:

1 Testing plant specific ECCS flow less than 44.7 gpm/FA tested
For those plants whose post-LOCA ECCS core flows are comparable to that tested in the PWROG FA test program, they would have to justify flow rates at least 40% less than tested to achieve a benefit. CE plants and Westinghouse two-loop plants can test with their plant specific ECCS core flow rates. Testing would be performed with a common test protocol and plant specific or group specific test procedure in either the Westinghouse RTU test facility or at the CDI test facility.

2 Evaluating plant specific current hardware
CE plants and Westinghouse two-loop plants can test with their plant specific fuel hardware. Testing would be performed with a common test protocol and plant specific or group specific test procedure in either the Westinghouse RTU test facility or at the CDI test facility.

3 Evaluating p:f ratio greater than 1:1
Plants that can justify p:f ratios greater than 1:1 will test with their plant specific debris load. Testing would be performed with a common test protocol and plant specific test procedure in either the Westinghouse RTU test facility or at the CDI test facility.

4 Development of Integrated test Facility
Development of an integrated test facility to perform prototypical testing to determine head loss if more prototypic conditions were modeled; conditions like: settling due to a downcomer, non-uniform lower plenum flow patterns, boiling, multiple passes of debris through a sump screen, and settling due to approach velocities between the sump and the core.

5 Development of plant specific test apparatus
Development of a fuel specific test apparatus. Previous FA test programs used a conservative FA configuration to bound all fuel types (FUELGUARD® to bound all AREVA fuel types and 17X17 RFA to bound all Westinghouse fuel types including CE, 15X15 and 14x14 fuel products).

OPTION	FIBER - Potential	COST – Potential	COST ($)
1 & 2 & 3 (combination)	Limit increase (>50g)	Medium – ECCS evaluation and fuel tests a existing facilities	>200K
4	Limit increase (>100g)	High – build new integrated fuel test facility	>>500K
5	Limit increase (>50g)	High – build new fuel type specific facility	>500K

NOTE: Plants who have AREVA fuel may be participating in the FA test options provided below.
AREVA has undertaken the work scope below to improve upon the 15 g/FA assembly threshold that has been established for AREVA PWR fuel under hot-leg break conditions. As noted in previous sections, for CE plants, a large reduction in the test loop flow rate can be applied, relative to prior testing. This has the potential for a significant impact on the debris accumulation process on the fuel. For B&W plants, the flow rates will remain the same as the prior testing, but the geometric conditions are different and could produce an improvement in the debris threshold if alternate flow path analysis is successful.

A phased approach has been implemented, and the preparation of additional test bundles has been executed and completed as part of Phase I. Testing of the new bundles will be initiated in Phase II of the work scope. The reason for separating the work scope into phases was to allow any verification of the debris test facilities to occur prior to any AREVA-specific testing in Phase II. This ensured that any results obtained would be considered adequate to support revision to the GSI-191 RAI's related to testing.

Task 1.0 – Fabrication of Test Assemblies (Completed)

To support the Phase II work scope described below, AREVA fabricated two test bundles that are considered representative of the fuel used by CE and B&W fuel customers. These test bundles resemble the AREVA fuel test bundle currently being tested (bottom nozzle, fuel rods, guide tubes, 4 grids, approximately 4 feet tall, etc.).

Task 2.0 - Additional Testing of AREVA Fuel Assembly at CDI (On-going)

A specific test configuration has not yet been designed, but based on AREVA's evaluation and current test results (15 g of fiber/FA) additional tests specific to AREVA's CE and B&W designs would be conducted. Each of the two test assemblies would potentially be used for three tests – the first would use a particulate to fiber ratio of 1:1 and a higher fiber content (i.e. 60g) to determine if a higher fiber load can be tolerated with the CE or B&W bundle. If this test is successful, the remaining tests would be used to define the limiting p:f ratio. If this test is not successful, then the remaining tests would be iterative to determine an acceptable fiber threshold above 15 g/FA.

Test costs are given below. These costs include CDI costs and costs for AREVA support of the test campaigns.

AREVA fueled CE specific testing = $ 100K (three tests)

AREVA fueled B&W specific testing = $ 100K (three tests)

Results of the tests would be included in revisions to the existing RAI responses that summarize the AREVA FA debris testing.

3.0 Summary

To move forward, the PWROG has proposed a set of tools that could be developed that a plant or group of plants can use to demonstrate compliance with the 15 g/FA fiber limit or to increase the applicable fiber limit. The course of action may include plant- or group-specific analyses, evaluations, and/or testing. The proposed tools are listed below in no particular order.

1. Demonstrating chemical precipitation does not start until after hot leg switchover (HLSO)
2. Demonstrating the particulate-to-fiber (p:f) mass ratio reaching the core is greater than 1:1
3. Testing plant specific ECCS flow less than 44.7 gpm/FA tested
4. Evaluating alternate flow paths
5. Evaluating plant specific hardware
6. Chemical testing to reduce chemical impacts on in-vessel effects

It is envisioned that a plant or group of plants can utilize these tools individually or in combinations to achieve the desired outcome of demonstrating compliance with the 15 g/FA fiber limit or to increase the applicable fiber limit.

In addition to the tools described herein, all plants may benefit from the development of water management techniques, installation of, or credit for additional plant hardware to decrease fiber downstream of the sump (e.g., debris interceptors, screen modifications). The development of upstream effects programs to reduce the debris sources term, including debris transport, generation, and strainer bypass, will also contribute to the reduction of the downstream in-vessel fiber source term.

4.0 References

1. Generic Safety Issue, GSI-191, "Potential of PWR Sump Blockage Post-LOCA," 1998.

2. Nuclear Regulatory Commission Generic Letter GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized Water Reactors," September 2004.

3. NUREG/CR 6988, "Final Report — Evaluation of Chemical Effects Phenomena in Post-LOCA Coolant," January 2009.

4. ML102280594, "Evaluation Of Chemical Effects Phenomena Identification And Ranking Table Results," March 2011.

5. NUREG/CR 6914, "Integrated Chemical Effects Test Project: Consolidated Data Report," December 2006.

6. WCAP-16785-NP, "Evaluation of Additional Inputs to the WCAP-16530-NP Chemical Model," May 2007.

7. WCAP-16596-NP, "Evaluation of Alternative Emergency Core Cooling System Buffering Agents," July 2006.